GEOLOGY OF IRAQ



Edited by
Saad Z. Jassim and Jeremy C. Goff

2006

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In memory of Tibor Buday

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Preface

Iraq lies at the NE comer of the Arabian Peninsula. It is a land of contrasting geography with an arid desert in the west and the rugged mountains of the Taurus and Zagros in the NE, separated by the central fertile depression of Mesopotamia: long known as the cradle of civilization. This morphology facilitated early human migration and dispersion of knowledge between the East and West. Sumerian cities as old as 6000 years are a witness not only to a thriving early civilisation but also to the early industrial use of raw-materials.

In geological terms Iraq lies at the transition between the Arabian Shelf in the west and the intensely deformed Taurus and Zagros Suture Zones in the N and NE. The evolution of the Arabian Shelf has been influenced by the mobility of the Precambrian basement and by tectonism along the Neo-Tethyan margin. The tectonic framework of Iraq has been affected by intracratonic transpressional and transextensional movements controlled by the interactions of stress along the plate margin with the Precambrian basement fabric and structural grain.

This book offers a new interpretation of Iraq's Precambrian basement by extrapolating the geology of the exposed Arabian Shield to the north and beneath the Phanerozoic cover of Iraq. A new hypothesis for the opening of a narrow Southern Neo- Tethys Ocean in Early Cretaceous time is proposed (using data from adjacent countries) to explain the geological evolution of the NE margin of the Arabian Plate. The tectonic framework, fabric and tectonostratigraphy of Iraq are discussed in the context of the tectonic history of the Arabian Plate.

About half of the book deals with stratigraphy of Iraq. The stratigraphy of Iraq has been dealt with reference to the tectonostratigraphic development of the Arabian Plate based on the megasequence classification of Sharland et al. (2001). The megasequences are provisionally subdivided into sequences. This will provide a stratigraphic foundation for future generations of Iraqi geologists to build on and improve. The work of Bellen at al. (1959) and Buday (1980) and Buday and Jassim (1987) were published prior to the completion of the geological surveys of the Iraq. This book updates the stratigraphy incorporating new data collected by the Geological Survey of Iraq. The tectono stratigraphy, magmatism and metamorphism of the Zagros Suture are described in detail. This provides insights into geological problems requiring new research, and collaboration with geologists from Turkey and Iran, to better understand the geological evolution of the Zagros Suture Zone.

Quaternary sediments are discussed in detail in the book since the Mesopotamian Plain forms about 25% of the area of Iraq and sustains 60% of its population. Knowledge of the geology of this plain will help in dealing with the problem of soil salinisation which began to severly affect the area during the second half of the Twentieth Century.

The hydrogeology of Iraq is covered in great detail because of its importance for the future development of Iraq and its population. Although Iraq has two major rivers, they only irrigate narrow belts in Central and N Iraq and the Mesopotamian Plain in the south. The rest of Iraq (about 70% of its surface area) relies on groundwater. Groundwater resources are of ever increasing importance in Iraq because of climatic changes and the upstream damming of the major rivers. The hydrogeology chapter was compiled using data from hundreds of water boreholes and thousands of hand-dug wells. It will be a key reference for hydrogeologists and engineers concerned with water resources.

Iraq is rich in hydrocarbons and is one of the top five oil producing countries in the Middle East. The book provides a summary of the oil industry infrastructure in Iraq and provides an introduction to Iraq's petroleum resources and petroleum systems. A database of oil fields is a useful appendix of the book.

Iraq is rich in industrial minerals the most important of which are sulphur, phosphate and salts with numerous industrial rocks and minerals deposits that include aggregates, limestone, clay, sedimentary iron and bauxite as an example. Their distribution and origin are described. Iraq is not very rich in metallic deposits but the few known deposits are described and their origin discussed.

The book thus covers all the aspects of the geology of Iraq and is based on a wealth of hard data conveniently collated and interpreted in a single volume. It contains over 200 largely original coloured figures and maps.

The book is compiled by authors with first hand experience in the geology of Iraq and it has been carefully edited to ensure a concise consistent style. During the 1970's I was the Director General of the Czech Geological Survey and had the pleasure of witnessing the cooperation between our institute and the Geological Survey of Iraq. The book is an offspring of that cooperation.

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The Geological Survey of Iraq (presently the State Company for Geological Survey and Mining) and the Czech Geological Survey have indirectly but substantially contributed to the book through the hard work of their mapping geologists and the use of their archives.

During the early stages of the compilation of this book, Dr Tibor Buday unfortunately passed away. However, Mrs Buday kindly allowed the authors full access to his rich archive of notes and slides which were essential for completing his part of this book.

Saad Jassim wishes to acknowledge the assistance of Getech and the School of Earth and Environment, Leeds University in providing research facilities. In particular the help of Professors Derek Fairhead and Rob Raiswell is greatly appreciated.

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Chapter 1
Introduction

by

Saad Z. *Jassim*

Three previous publications in English describe the regional geology of Iraq. The first resulted from the systematic hydrogeological studies of the Parsons Company (Parson, 1956 and 1957). The second publication was the Stratigraphic Lexicon of Iraq (Bellen et al., 1959) which remains a key reference. This was based on data collected during oil exploration activities (geological fieldwork and drilling) in Northern and Southern Iraq, and during geological traverses along the routes of oil pipe lines in the Western Desert. The third publication was based on surface geological mapping and geophysical surveys carried out by the Geological Survey of Iraq from 1972 to 1984 (State Company of Geological Survey and Mining, referred to in this book as GEOSURV). Important new surface data was acquired during surveys of the Western Desert and the NE Iraq thrust belt. The work was published in two volumes. Volume 1 on stratigraphy (Buday, 1980) was published before the completion of the stratigraphic surveys. Volume 2 covered the tectonics and igneous and metamorphic geology (Buday and Jassim, 1987).

Regional publications on the Arabian Plate do not include new data from Iraq (e.g. Beydoun, 1991; Sharland et al., 2001; Al Sharhan and Kendal, 1986 and Ziegler, 2001). This book is an attempt to update the regional geology of Iraq incorporating new data from Iraq acquired during the last twenty five years. This book also covers the economic geology of Iraq. It is intended to be a reference for students, researchers and industrial geologists. It is hoped that the book will encourage a new generation of Iraqi geologists to tackle the many unsolved problems of Iraqi geology.

1.1 History of geological investigations in Iraq

The first reconnaissance geological surveys in Iraq were carried out during the First World War and culminated in the discovery of oil in the 1920's. The contribution of the oil industry in the early stages of the development of the country after independence in 1921 played an important role in advancing the geological profession in Iraq. The Iraq Petroleum Company (IPC) and its sister companies conducted surface geological mapping in N Iraq, and subsurface mapping of S Iraq. IPC geologists published key stratigraphic information in 1959.

In 1954 the establishment of the Development Council (Maj1is Al I'mar) led to an ambitious program for metallic mineral, building material and ground water exploration in Iraq carried out by foreign companies including the Site Investigation Company and Parsons. This program lasted until 1958. The geology of N and NE Iraq was mapped during this period. Six sheets of 1: 100,000 scale maps were completed for the important border region with Iran and Turkey. In 1954 the Geology Department at Baghdad University was established which immensely influenced the geological profession in Iraq. Mineral exploration was resumed again from 1961 through contracts with Soviet state companies who mapped NE Iraq for metallic deposits and W Iraq for phosphate, glass sand and clay.

Exploration rights of the IPC were restricted in 196) (Law 80). The Iraqi National Oil Company (INOC) was established in 1964. After the nationa1isation of IPC in 1972, INOC conducted seismic surveys and exploration drilling. INOC became the sole body responsible for exploration,

production, refining and marketing in Iraq.

Oil bearing structures were delineated by seismic surveys and drilling, and many new oil fields were discovered. Geological surveys in Iraq remained restricted until the establishment of the "Directorate General of Geological Survey and Mineral Investigation" (GEOSURV) in 1969 (presently the State Company for Geological Survey and Mining). Its initial task was to systematically cover the whole country with regional surveys at a final scale of 1: 100,000 and to establish the potential mineral wealth of Iraq. A ten year program (1972-1982) was conducted almost entirely by young Iraqi graduates from Iraqi universities and geological specialists. Some small areas were mapped through cooperation with the Czech Geological Survey whose experts also helped to establish many laboratories and advised on the survey policies. The completion of the regional geological surveys was followed by the compilation of maps. The next stage of the surveys included detailed geological mapping of high graded areas for mineral exploration or land use.

Detailed mapping for sulphur, phosphate, industrial clays, bauxite, glass sand, limestone and salt was conducted first. Areas of high population density were chosen for detailed engineering and environmental geological mapping. GEOSURV also embarked on the publication of the Geological Map Series at a scale of 1:1,000,000, starting in 1984. The published maps include: Geological, Tectonic, Neo-Tectonic, Mineral Resources, Hydrogeological, Geomorphological, Gravity and Magnetic maps. In 1991 GEOSURV began publication of the 1:250,000 Geological Map Series.

Following the regional studies of Parsons Company in the 1950's, systematic hydrogeological mapping was initiated by GEOSURV to evaluate major groundwater basins. Water investigations were previously the responsibility of a small department within the Ministry of Irrigation who drilled wells to obtain water for drinking and agricultural use, generally with poor documentation. GEOSURV took responsibility for sampling and evaluating thousands of hand-dug wells during the regional survey program. A major shift in hydrogeological investigations began in the late 1970's when contracts were signed with international companies and national bodies (Yugoslav and Italian, GEOSURV and the Directorate of Ground Water) for hydrogeological evaluation of the groundwater basins of the Iraqi Desert (Desert Development Project). For the first time deep water boreholes (up to 1600 m deep) were drilled and fully evaluated based on resistivity surveys and seismic profiles.

1.2 Morphology

Iraq is near the centre of the so-called "Fertile Crescent" which is characterised by a topographically-low, generally cultivated area (central depression) which extends from central Syria to the Arabian Gulf (Fig. 1-1). This NW-SE oriented trough contains the youngest sediments in Iraq and is flanked by a gently-inclined plateau to the Wand SW, and by a series of ridges and depressions passing into mountainous area in the NE. The highest elevation in W Iraq is near the Iraq-Saudi Arabia-Jordan triple border junction (936 m), from which the ground slopes towards the Euphrates River at a gradient of 10-20 m/km. This western inclined plain is a desert with rainfall ranging from 50-100 mm/year and can be divided into two sectors. The Western (Widyan) Desert lies N of latitude 32° and is characterised by numerous wadis of E-W, NW-SW and N-S orientation. The Southern Desert lies S of latitude 32° and WSW of the Euphrates River. It lacks the active drainage often seen in the Western Desert.

The central depression (Fertile Crescent) is divided into two regions; the Mesopotamian Plain in

the SE and the Jezira Plain in the NW. The Mesopotamian Plain extends from Wadi Tharthar in the NW to the Arabian Gulf in the SE. It is bounded by the Euphrates River in the west and the Makhul-Hemrin-Pesh-i-Kuh range in the east. It contains widespread Quaternary deposits of the Tigris and Euphrates rivers. The northern part of the plain is elevated and dissected, revealing older Pleistocene river fans which also characterise its eastern and western margins. The Jezira Plain area lies at a surface elevation of about 250 m; it lies between the Mesopotamian Plain and the Euphrates depression of E Syria.

To the E of the central depression lies an area with lines of hills, separated by broad depressions, forming the foothills of N and NE Iraq. These hills are associated with long anticlinal structures; the depressions correspond to broad synclines (Fig. 1-1). The boundary between the foothills and Mesopotamia Plain is abrupt and is defined by the SW flank of the Makhul-Hemrin-Pesh-i-Kuh anticlinal range. Further to the NE, anticlines become more frequent and their elevation increases. High anticlinal mountains to the E of Kirkuk and N of Mosul form well-defined surface features. They are generally of whale back character, built by Eocene limestone in their cores and flanked by Miocene and Pliocene clastics. Further to the N and NE the mountains are built by Cretaceous limestone cores flanked by Palaeogene clastics. Further E they are built by Upper Cretaceous and Jurassic limestones and flanked by Cretaceous clastics. Along the NE border of Iraq with Iran and Turkey the mountainous area is structurally more complex and comprises a series of thrust sheets which reach 3000 m in elevation and contain metamorphic and igneous rocks.

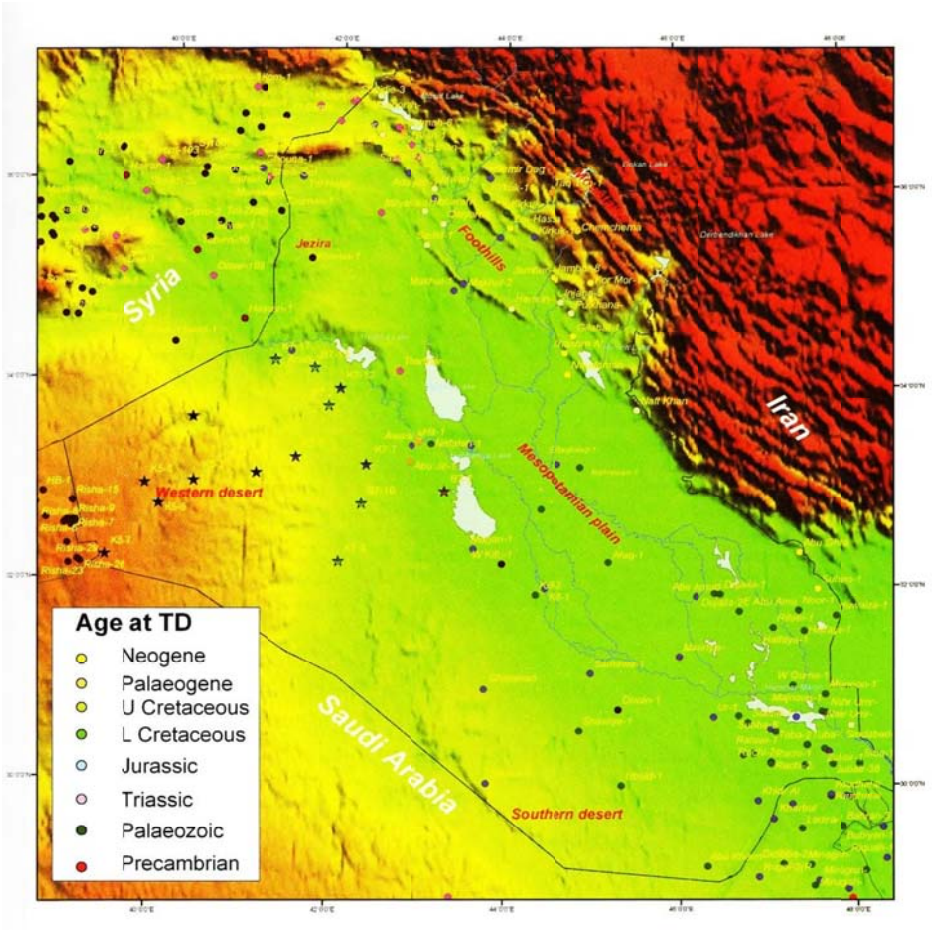


Fig. 1-1: Topography of Iraq with location of wells used in the book (oil wells as circles and deep water wells as stars)

1.3 Surface geology

The surface geology of Iraq roughly reflects it morphology. Generally, the youngest sediments (Quaternary and Neogene) lie within the central depression while the flanks expose older strata of Palaeogene to Palaeozoic age (Fig. 1-2).

The geology of the desert area to the SW of the Euphrates River is generally characterised by NE-dipping strata which are slightly more inclined than the land surface. However, in W Iraq near Rutba Town the strata dip to the west away from the axis of a major ENE-WSW trending anticlinorium in which rocks as old as Permian outcrop (Fig. 1-2). The erosion of the crest of the anticlinorium has created the Ga'ara depression. The geology of the Mesopotamian depression is produced by a complex system of river channels, levees, flood plain, marshes, sabkha and deltas, bordered on both sides by alluvial fans. The Jezira area in NW Iraq is dominated by a massive uplift (Tayarat). Middle Miocene sabkha deposits, exposed in the core of the uplift, are flanked in the E, N and W by Upper Miocene clastics. To the south erosion by the Euphrates River has exposed Oligocene and Lower Miocene carbonates along tight anticlinal structures controlled by E- W faults.

The foothills NE of the Mesopotamian depression comprise narrow (roughly 5-10 km wide) anticlines; Upper Miocene to Pleistocene molasse sediments or Middle Miocene evaporites are exposed in their cores. Some higher amplitude anticlines within the zone such as Sinjar and Qara Chauq have exposures of Palaeogene and locally Upper Cretaceous formations in their cores. The foothill anticlines are usually asymmetrical towards the SW and are often associated with decollement thrust faults (controlled by Middle Miocene evaporites) in the area south of the Lesser Zab River (Fig. 1-2).

The mountainous region to the NE of Kirkuk is characterised by harmonic folds. Cretaceous or older rocks are exposed in their cores; Palaeogene and Neogene rocks form the adjacent synclines. The amplitude of the folds increases towards the NE until the anticlines override each other due to thrusting with elimination of the intervening synclines. **In** N Iraq along the Turkish border, Palaeozoic to Cretaceous rocks are exposed in the cores of tight anticlines bounded by thrust faults.

Along the Iranian border there are thrust sheets of sedimentary and igneous rocks which where formed in the Neo- Tethyan oceanic domain. The lowest of these comprise radiolarian chert and volcanics which were thrust over the shelf carbonates of the Arabian Plate during the Late Cretaceous. These thrust sheets were later peneplaned and covered by onlapping Upper Maastrichtian to Palaeogene clastics and carbonates. These clastics were often structurally overridden during Late Neogene deformation by thrust sheets of calc-alkaline volcanics and associated clastics and carbonates of Palaeogene age. Cretaceous metamorphics and volcanics, intruded by large basic and ultrabasic plutons, form separate thrust sheets overlying the Tertiary volcanics. The structurally highest thrust sheets in Iraq are composed of metamorphic and igneous rocks and represent the extension of the Sanandaj Sirjan Zone of Iran into Iraq.

1.4 Outline of the book

The book deals with all aspects of the geology of Iraq. Chapter 2 describes the Late Precambrian Pan African development of the Arabian Plate. Successive periods of subduction and arc accretion resulted in the formation of basement terranes, which are mainly exposed within the Arabian Shield of W Saudi Arabia. These terranes played an important role in the subsequent development of the Phanerozoic basins of the plate. The extension of these terranes below the sedimentary cover is thus important for understanding the tectonic fabric and evolution of Iraq. An attempt is made to predict the composition of the Precambrian basement below the sedimentary cover in Iraq using potential field data.

Chapter 3 describes the Phanerozoic evolution of the Arabian Plate with emphasis on the evolution of the Tethyan plate margin that strongly influenced intraplate basin development in Iraq. This chapter describes the Early and Late Palaeozoic "Caledonian" and "Hercynian" arching events that were controlled by active margin development along the S margins of the Palaeo-Tethys Ocean. The opening of the Neo- Tethys Ocean in Late Permian time and the formation of a passive margin along the NE edge of the Arabian Plate is described. Evidence for Mid Triassic-Jurassic extension in the NE part of the Arabian Plate and the subsequent opening of a narrow ocean in Late Tithonian-Cenomanian time (Southern Neotethys) with the splitting off from the Arabian Plate of a narrow microcontinent is presented. The Late Cretaceous obduction of Neo-Tethyan oceanic crust on to the NE and N margin of the Plate with the formation of a foredeep basin is described. Finally the closure of the Neotethys and the continental collision of the Arabian Plate with the Turkish and Iranian Plates (and resultant foreland basin formation) are discussed.

Chapter 4 deals with the tectonic framework and tectonic development of Iraq, the effects of the Precambrian basement mobility on the tectonic framework, and the subdivision of Iraq into tectonic zones and subzones. The chapter also outlines the distribution and origin of major fault systems and longitudinal and transversal blocks. Chapter 5 describes the tectonic and structural style of the various zones and subzones of the Stable Shelf. Chapter 6 defines the units of the Unstable Shelf and the Zagros Suture Zone.

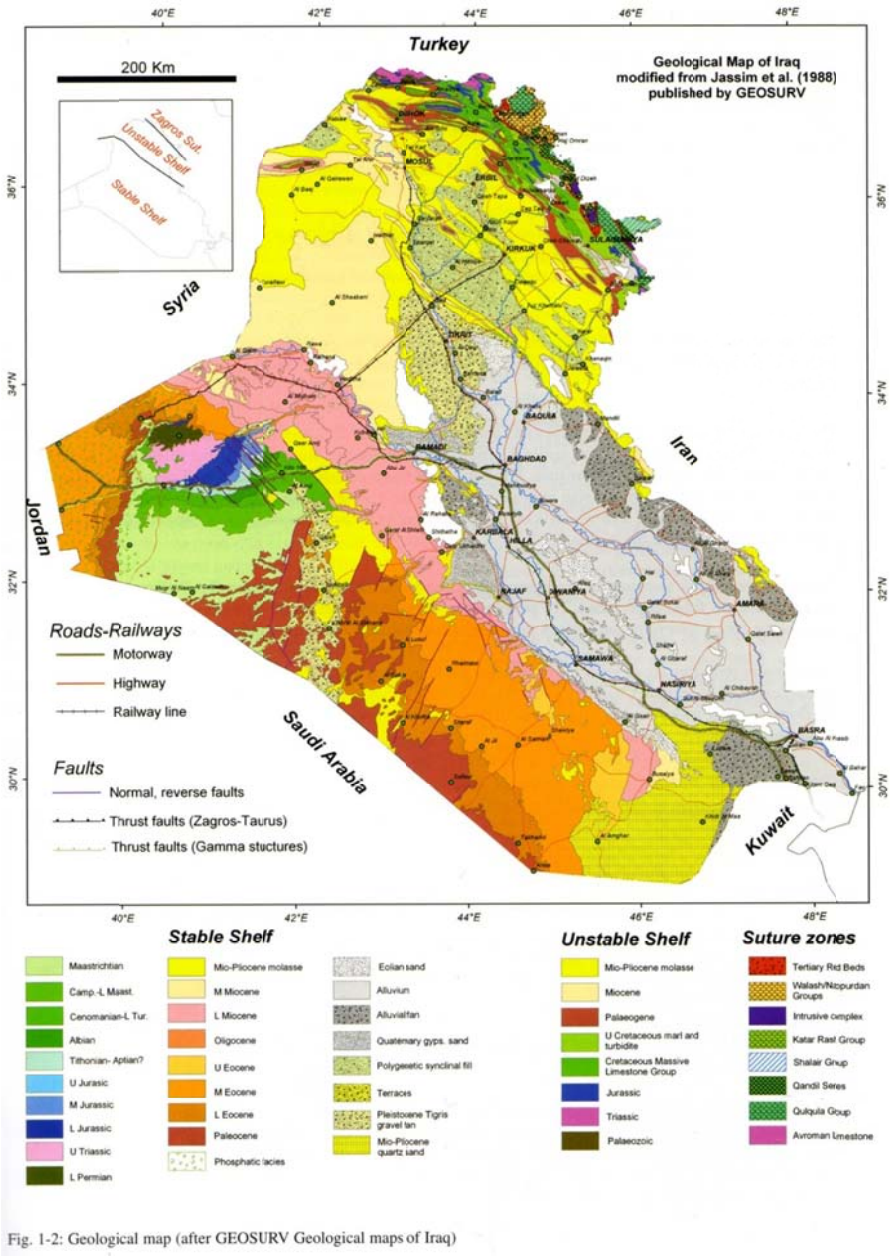


Fig. 1-2: Geological map (after GEOSURV Geological maps of Iraq)

Chapter 7 is concerned with the seismicity of Iraq. The history of seismic research of Iraq and the establishment of the seismic monitoring stations in the country is discussed. The seismotectonics, historical seismicity and the seismic zonation of Iraq are also described.

Chapter 8 describes the tectono stratigraphy of the Infracambrian to Early Permian Megasequences API to AP5 as defined by Sharland et al. (2001). Data from neighbouring countries was used extensively to better understand the Palaeozoic section which is only very locally exposed and penetrated by wells in Iraq. Chapters 9-14 deal with Megasequences AP6-APll (Late Permian-Recent). They have been subdivided into sequences bounded by unconformities. Their component formations are described in detail using new stratigraphic information. The palaeogeography of the sequences are discussed. Correlation charts were

prepared using the time scale of Gradstein and Ogg (1996) and the global sea level curves of Haq et al. (1988) after recalibration. The Maximum Flooding Surfaces (MFS) of Sharland et al. (2001) are also plotted on these charts. The type localities of formations and important geographical names used in this book are located on a map (Appendix 1).

The Quaternary sediments of Megasequence APII cover about 30% of the surface area of Iraq. They are important for agriculture and human activities and are thus given special attention and discussed separately in Chapter 15.

The tectono stratigraphy, magmatism and metamorphism of the Zagros Suture Zone are discussed in Chapters 16 and 17. These chapters update the earlier descriptions of this zone by Buday (1980) and Buday and Jassim (1987) and provide much new information. It is hoped that that publication of this data will encourage future co-operation with Turkish and Iranian geologists to tackle the geological structure and geological history of this complex and important area which is of great importance for the understanding of the evolution of the former Tethyan margin of the Arabian Plate.

Chapter 18 provides a summary of the hydrocarbon geology of Iraq. General information on the oil industry infrastructure, oil fields is provided. The petroleum systems of Iraq are briefly described with emphasis on their source rocks, reservoirs and seals. A database of Iraqi oil fields is provided as an appendix.

Groundwater resources are of great importance for the future development of Iraq. The hydrogeology of Iraq is thus described in detail in Chapter 19. Factors controlling groundwater flow composition and quality in Iraq are discussed. Six major aquifer systems are defined and the present and future use of their groundwater is discussed.

Chapter 20 deals with the mineral wealth of Iraq and discusses the distribution, evaluation, chemical composition and origin of metallic and non-metallic minerals and of industrial rock deposits.

1.5 Data used

The book uses the latest results of the Geological Survey of Iraq which include the final survey compilations and published maps. Gravity and magnetic maps were used to construct depth to basement maps, assess basement composition and identify major faults zones. Data from over 120 wells in Iraq (Fig.l-l) and over 300 wells from the surrounding countries were used in subsurface mapping and tectonostratigraphic evaluation. Data from deep water wells in the Western Desert region provided important stratigraphic and structural control in the area between the surface outcrops of the Western Desert and the deep oil exploration wells of Mesopotamia.

The interpretation of the tectonic elements also relied on satellite images downloaded courtesy of NASA'S public domain (https://zulu.ssc.nasa.gov/mrsid). Inclined scenes are downloaded courtesy of Google Earth. A large collection of published and unpublished manuscripts of regional nature, published in Iraqi Geological Journals (Journal of the Geological Society of Iraq and the Iraqi Journal of Science) and international geological journals were used in the compilation of this book.

Chapter 2
Late Precambrian development of the Arabian Plate

by

Saad Z. Jassim

2.1 **Tectonostratigraphy of the Late Precambrian**

The Precambrian basement of the Arabian plate was amalgamated through oceanic accretion within the Nubio-Arabian Mozambique ocean and plate collision between E and W Gondwana (Fig. 2-1) around a stable craton in E Africa through two orogenic cycles, the youngest of which is the Pan African cycle (900 to 540 Ma). The Arabian shield was initially subdivided into five terranes (Stoeser and Camp, 1985) and subsequently into ten terranes (Nehlig et al., 2002).

The tectonostratigraphy of the Arabian Shield was defined by Brown and Jackson (1960) and Schmidt et al. (1973). The Precambrian plate tectonic evolution and the amalgamation of the Arabian Plate were dealt with by subsequent work (Al-Shanti and Mitchell, 1976; Calvez et al, 1983; Stacey et al., 1984; Stacey and Agar, 1985; Stoeser and Camp, 1985; Pallister et al., 1987; Stoeser and Stacy, 1988; Agar et al., 1992; Walker et al., 1994; Husseini, 2000; nehlig et al., 2002).

Brown and Jackson (1960) divided the apparently similar stratified volcanosedimentary rocks of the basement into groups of different age. They were formed in a time period exceeding 300 Ma. The outcrops of these groups are shown in Fig. 2-2.

The tectonostratigraphy of the shield is thus defined as follows: The Baish-Bahah Group is the oldest stratified unit in the Arabian Shield (older than 1000 Ma). It can be divided into two units. The lower unit comprises metamorphosed spilitic pillow basalt and andesite with interbedded marine volcano-clastics. The upper unit comprises metasediments (graphitic schist, marble, calcschist and chert). The recorded thickness of the group of about 2600 m may have been tectonically increased by imbrication. The Baish-Bahah Group is older than the Mecca granites which intrude it (9651025 Ma using Lead isotopes and 719-760 Ma from K-Ar dating). The type and geochemistry of the volcanics, and the associated marine sediments suggest the group formed in an island arc setting (Nehlig et al., 2002).

The Jiddah Group is exposed on the W side of the Shield and comprises andesite and associated volcano-clastic sediments metamorphosed into the greenschist facies and dated as 912 Ma. The strata of the group are intruded by 890-848 Ma gabbros (Brown et al., 1989). The andesite volcanicity suggests the group was formed in a volcanic arc.

The Ablah and Fatima Groups comprise 2300 m of basal conglomerate, quartz wacke and red sandstone with beds of stromatolitic limestone. They outcrop in inverted grabens. The age of the groups is constrained at 816-763 Ma.

The Al Ays Group outcrops in the NW part of the shield (Fig. 2-2). It comprises 1400 m of metasediments and volcanic rocks with basal conglomerates, basaltic (spilitic) and silicic volcanics, passing into deep water greywackes containing silicic tuffs. The age of the group is not well defined but it is underlain by volcanic and plutonic rocks which are older than 800 Ma. Some tuffs are dated at 725 ±15 Ma (by the U-Pb method). The composition of the volcanics and the associated sediments indicate the group was formed in an island arc and fore-arc setting.

The Halaban Group forms the central part of the exposed Precambrian shield (Fig. 2-2). It comprises 6500 m of ultramafic rocks (pyroxenite and harzburgite), diorites, andesites and

associated volcano-clastic sediments metamorphosed into the greenschist facies (Delfour, 1977). The group is the product of a volcanic arc (Brown et al, 1989; Nehlig et al., 2002). The volcanics are dated at 785 to 724 Ma. Schist, amphibolite and meta-andesite at the base of the group are dated at 825 Ma. The Halaban Group overlies a granitic basement (> 1400 Ma). It is often overlain by molasse of the Murdama Group which may have been deposited in foredeeps formed during the Nabitah-Ar Rayan orogeny that began around 680 Ma.

The Shammar Group is restricted to NW-SE and NE-SW trending grabens in the NE part of the shield. It comprises a lower unit of basal conglomerate and clastics with associated rhyolite volcanics overlain by rhyolites and ignimbrites dated at 621 ± 21 Ma (Delfour, 1977). Radiometric dating of the rhyolites indicates a broad age range of 633 to 555 Ma.

Fig. 2-1: Late Precambrian plate reconstruction of East and West Gondwana at the time of their assembly into the Gondwanan super continent (after Johnson, 2000)

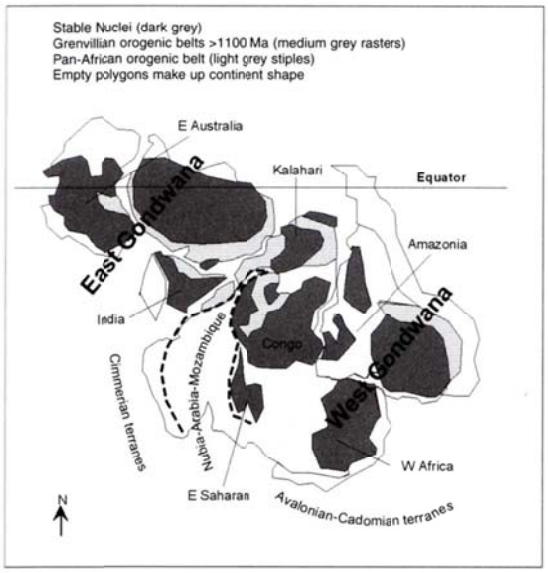
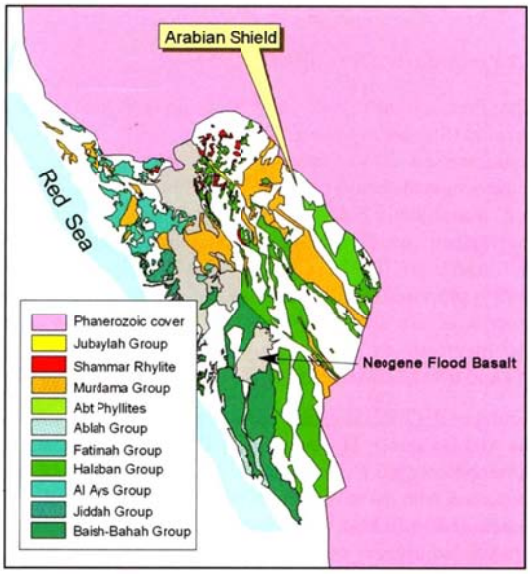


Fig. 2-2: Distribution of the stratified volcanosedimentary sequences of the Arabian Shield



2.2 Precambrian Terranes

The Precambrian Shield has been divided into several terranes (Stoeser and Camp, 1985; Nehlig et al., 2001), each characterised by an accretionary volcano sedimentary sequence, syntectonic magmatism (gabbro, diorite, tonalite and trondhjemite), a molasse basin and post tectonic magmatism (usually acidic but sometimes mafic). Frisch and AI-Shanti (1977), Camp (1984) and Jackson et al. (1984) proposed that the Arabian Shield formed through a process of arc accretion. Geochronological studies show that magmatic arc rock assemblages formed between 950 Ma and 670 Ma (Marzouki et al., 1982).

Nehlig et al. (2002) suggested four stages for the formation of the Arabian shield: 1) Oceanic accretion, subduction and arc development (900 to 680 Ma). 2) Suturing and gneiss dome formation with the development of the Najd orthogonal fault system (680-610 Ma). 3) Tectonic extension resulting from isostatic adjustment associated with intrusive and extrusive alkali magmatism (610-545 Ma). 4) Post tectonic magmatism which lasted until 345 Ma. These events occurred over a period of 300 Ma producing distinct terranes. The exposed Precambrian terranes can be divided into two groups, the western terranes sutured before 680 Ma and the eastern

terranes, which were sutured later. The position of theses terranes, their predicted extension below the sedimentary cover, and the location of other buried terranes are shown in Fig. 2-3.

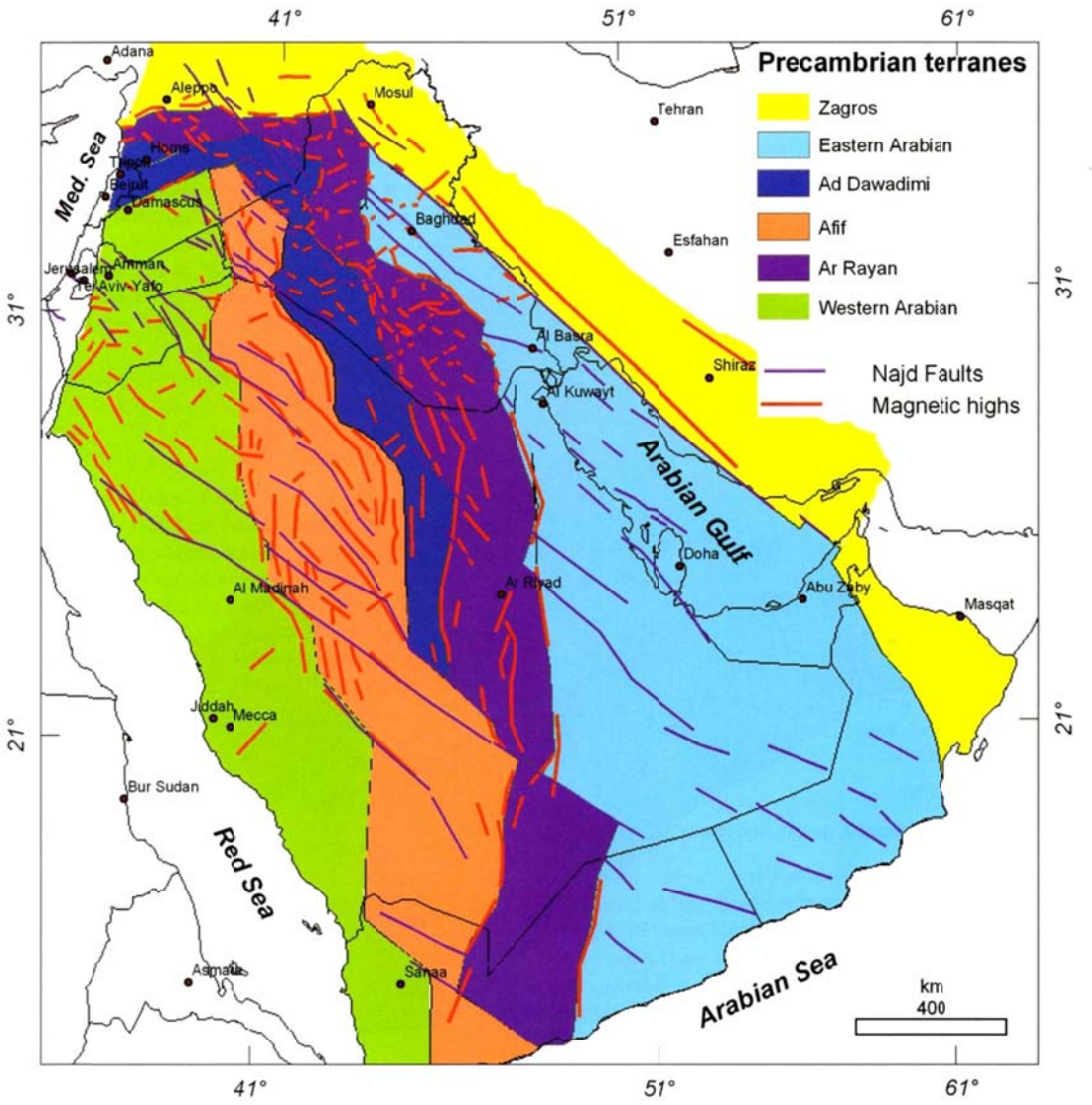


Fig. 2-3: Arabian Plate Precambrian Terranes. Magnetic highs are shown in red solid lines and the Najd Fault System is shown in thin purple lines

2.2.1 Western Terranes

The Asir Terrane is the oldest and forms the SW part of the Arabian shield. It consists of arc-related magmatic units dated at 760 to 800 Ma (Stoeser and Camp, 1985) and as young as 716 Ma (Brown and Jackson, 1960). Some age determinations exceed 1000 Ma. The terrane is separated from the Hijaz Terrane to the N by the Bir *Umq* suture which contains ophiolites dated at 838-828 Ma (Nehlig et al., 2002) or 838 ±10 Ma (Dilek and Ahmed, 2003). The Hijaz Terrane consists of magmatic rocks as old as 805 Ma and was probably formed within a volcanic arc system associated with calc alkaline plutonic activity from 680 to 700 Ma. The terrane contains the

stratified volcanosedimentary sequence of the Jiddah Group. The Midyan Terrane includes volcanics and a volcano sedimentary unit (710 Ma) belonging mostly to the Al Ays Group which, according to Shanti and Roobal (1979), comprises calc alkaline volcanic and ophiolites. The Midyan Terrane is separated from the Hejaz terrane by the ophiolites of the Yanbu suture (782-706 Ma) or 770-740 Ma according to Dilek and Ahmed (2003).

2.2.2 Eastern Terranes

The Afif Terrane is the most westerly terrane of the eastern terranes. It is composed of andesites and volcano sedimentary rocks of the Halaban Group (825 Ma) and is overlain by molasse of the Ablah, Fatima or Murdama Groups (678-655 Ma) deposited in N-S trending basins. Younger units of volcanics (Shammar Rhyolites 650-620 Ma) and volcano sedimentary rocks (Jubaylah (J'bala) Group) 619-558 Ma; Schmidt et al., 1973) formed in extensional basins. Husseini (2000) considered that the Halaban Group formed in a fore-arc basin setting. The volcano sedimentary Halaban Group is intruded by syntectonic magmatic bodies: mainly gabbro, tonalite and post-tectonic granites. The underlying Halaban crust composed of large granodiorite intrusions and gneiss, outcrops in N-S major anticlinal systems and may also form the major part of the Hail Terrane in the N part of the shield defined by Johnson and Stewart (1995). The Afif Terrane contains some of the oldest rocks of the Arabian Shield; the Khida crust (1800-1600 Ma) outcrops between two Najd shear zones in the southern part of the shield. The Afif Terrane is separated from the Western Arabian Terranes by the Halfaya-Ruwah Suture with ophiolites dated as 843-821 Ma (Dilek and Ahmed, 2003).

Johnson and Stewart (1995) referred to the Amar suture zone of Stoeser and Camp (1985) as the Ad Dawadimi Terrane. This terrane is composed of sericite-chlorite phyllites (Abt Phyllites) with underlying ultramafic imbricates and large intrusions of diorite and granite. Mitchel (1976) and AI Shanti and Gass (1983) considered mat the phyllites were originally deposited as fine grained clastic sediments in a fore-arc basin, although this is disputed by Johnson and Stewart (Op. Cit.) and Nehlig et al. (2002). The Ad Dawadimi Terrane is separated from the Afif Terrane to the west by the Halaban Suture with ophiolites dates as 694-680 Ma (Dilek and Ahmed, 2003).

The *Ar* Rayan Terrane is the easternmost exposed part of the Arabian shield. It consists of volcano-sedimentary rocks (Amar Group) that have been dated as older than 670 Ma
(Stoeser and Camp, 1985), formed in an oceanic island arc or at an active continental margin (AI Shanti and Mitchell, 1976), and intruded by syntectonic mafic rocks and post tectonic granites. Slates drilled in the Ain Dar and Khab fields to the E of the Arabian shield, which have been dated at 671 to 604 Ma (McGillivray and Husseini, 1992), may be part of this terrane. The Ar Rayan Terrane is separated from the Ad Dawadimi Terrane to its west by the AI Amar Suture with ophiolites dated as 698 Ma (Dilek and Ahmed, 2003).

2.3 The buried Precambrian basement in Iraq

The magnetic and gravity signature of the exposed basement terranes of the Arabian Shield were studied and integrated with the gravity and magnetic data from the Arabian Plate. Particular attention was paid to the potential field data of Iraq. Magnetic highs were traced from the Arabian Shield into Northern and Southern Arabia beneath the Phanerozoic cover (Fig. 2-3).

The magnetic anomalies were integrated with the fault systems identified from gravity interpretation to predict the extension of the buried basement terranes in Iraq.

The Afif Terrane is characterized by N-S trending magnetic highs and lows corresponding to magmatic rocks and molasse basins respectively. It extends into W Iraq (Fig. 2-4). In the Rutba area of W Iraq the Precambrian basement is predicted to be composed of Halaban Group andesites with associated Murdama Group molasse basins, separated by areas of gabbro, diorites and granodiorite syntectonic intrusions and post-tectonic alkali granites. The Afif Terrane in W Iraq is probably dominated by longitudinal N-S trending major structures that were arranged parallel to the Halaban microplate boundary (Nabitah Suture Zone).

The Ad Dawadimi Terrane of the Arabian Shield has a characteristic low gravity and magnetic signature (Chapter 4, Fig. 4-1). It can be traced through Western Iraq into Northern Syria (Fig. 2-4). Its potential field signature may be due to the presence of thick phyllites bounded to the east by highly magnetic ophiolites and to the west by plutonic rocks. The terrane has an overall N-S longitudinal trend associated with the Amar (Idsas) collisional belt.

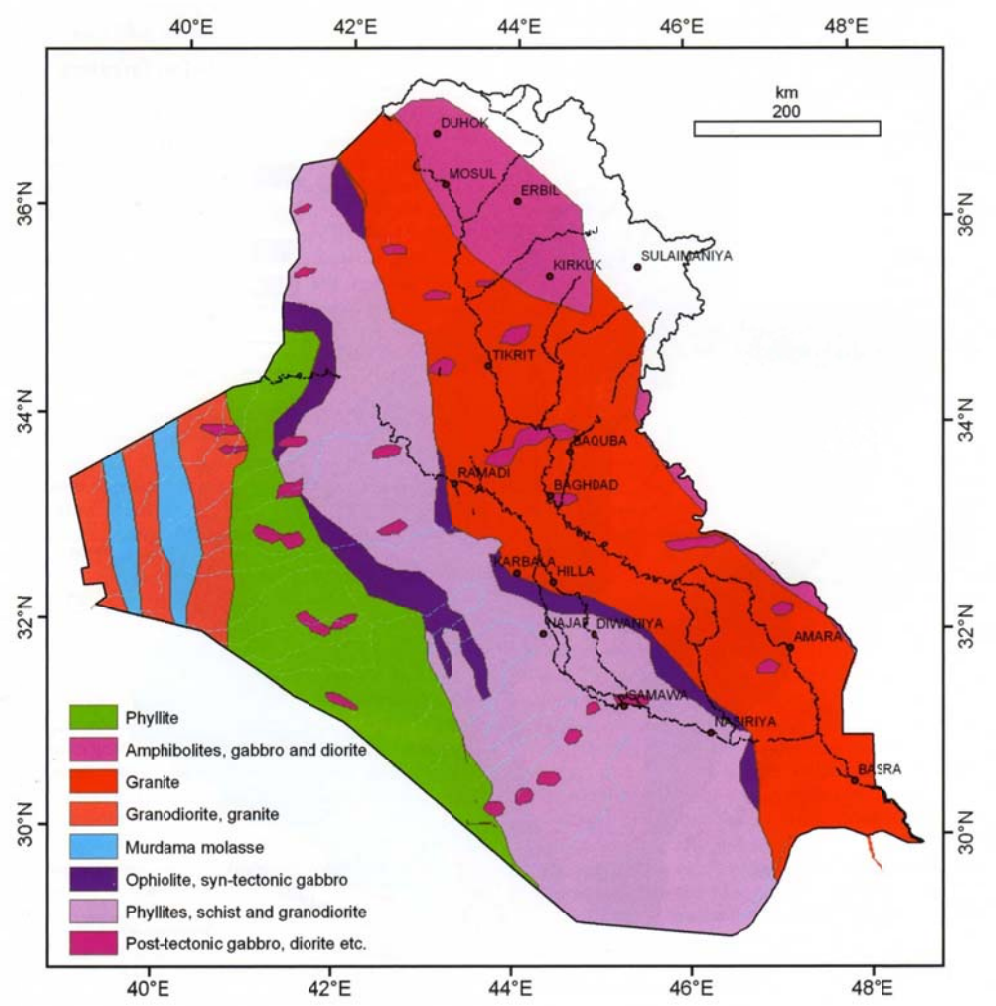


Fig. 2-4: Postulated Precambrian basement composition, derived from aeromagneic surveys

The Ar Rayan Terrane outcrops in the easternmost exposure area of the Arabian Shield and is associated with high gravity and magnetic anomalies. These anomalies can be traced to the north and south beneath the Phanerozoic cover. The eastern limit of the terrane is associated with a gravity and magnetic high which could be interpreted as an ophiolitic suture overriding the Ar Rayan Terrane. The Ar Rayan Terrane can be confidently traced into SW Iraq, passing through the Southern Desert and then swinging to the NNW into the Jezira area of NW Iraq. It might also correspond to the magnetic high to the north of the Palmyrides (Fig. 2-3). In Iraq the terrane is predicted to contain Amar Group volcanosedimentary rocks, intruded by syn-tectonic gabbro and post-tectonic granites. The strike of the eastern boundary of the terrane changes direction from N-S to NW-SE in central S Iraq which may be due to deformation during the Najd shearing event.

In eastern Saudi Arabia, the buried basement of low magnetic and gravity character is attributed to the Eastern Arabian Terrane (Getech and Jassim, 2002). The western boundary of this terrane with the Ar Rayan Terrane is placed at the western boundary of a magnetic high associated with the Summan structure. The Eastern Arabian Terrane is predicted to extend along the Arabian Gulf into S and Central Iraq, as far as Mosul in N Iraq. The overall low magnetic character of the terrane suggests it has a gneissic basement with large granite plutons. The terrane is characterized by N-S trending structures in the south and by NW-SE trending structures north of latitude 32° (Fig. 4-3). Some basic to intermediate post tectonic intrusions may be present in a NE-SW trending zone along the Diyala (Sirwan) River.

The folded mountains of the Zagros and Taurus ranges are associated with relatively large magnetic anomalies which might be related to the presence in the underlying basement terrane of basic volcanics and plutons. The long wavelength of the anomalies may be due to burial depth rather than compositional uniformity. The terrane might represent a highly imbricated ophiolitic belt of NW-SE orientation. This structural trend was reactivated during Late Tertiary deformation. The nature of the Precambrian basement of the adjacent Sanandaj-Sirjan Zone is poorly understood. No Precambrian igneous rocks have been identified on the western side of the Sanandaj-Sirjan Zone, but Ghazi et al. (2003) noted that volcano sedimentary rocks of the Kahar Formation occur to the east of the zone. This suggests that the Sanandaj-Sirjan microplate might have been an integral part of the Arabian Plate during the Late Precambrian. The Central Iranian microplate may have been a distinct and separate Precambrian terrane. The Zagros terrane swings westwards into NW Iraq (Sinjar region) and then into N Syria (Abdul Aziz region).

The boundaries of the Precambrian terranes (Fig. 2-3 and Fig. 2-4) appear to have influenced basin development (in particular the positions of basin margins) throughout subsequent Phanerozoic time; these terrane boundaries are thus important for understanding the tectonic framework and tectonostratigraphy of Iraq.

2.4 Summary of Precambrian evolution

The Arabian Plate formed during Late "Pan African" orogenic cycle which lasted from 900 to 610 Ma (Stoser and Camp, 1985; Vail, 1991; Johnson and Stewart, 1995; Nehlig et al., 2002; Husseini, 2002). The Arabian Plate formed during oceanic accretion and microplate collisions in three stages as follows:

2.4.1 Oceanic accretion and subduction

This stage lasted from 900 Ma to 680 Ma in which oceanic lithosphere formation and subduction led to accretion of the oceanic crust and volcanic arc formation. At least three well dated ophiolite belts are recognized within the Arabian shield; these include the Bir Umq Ophiolite (830 Ma), .the Yanbu ophiolites (770 Ma) and the Al Amar ophiolites (680 Ma). The former two are found in NE-SW trending sutures in the western part of the shield; the latter is found in a N-S trending suture in the easternmost part of the shield. A fourth ophiolite belt is located at the W margin of the NS trending Nabitah suture in the central part of the shield. The age of the Nabitah ophiolites lies between the ages of the Bir Umq and Al Amar ophiolites (Nehlig et al., 2002) and is established as 843-821 Ma (Dilek and Ahmed, 2003).

2.4.2 Orogenesis

The orogenic stage, according to Nehlig et al. (2002), lasted from 680 to 610 Ma and was characterised by collisions of accretionary units and the associated microplates along the N-S trending Nabitah and Al Amar suture zones, probably around 680 Ma. The Nabitah suturing resulted in the formation of major molasse basins in foredeeps within the orogenic belt. The E- W compression during this orogeny led to the formation of the NW-SE trending transpressional shear zones of the Najd system. These shear zones strongly influenced the subsequent tectonic development of the Arabian Plate.

2.4.3 Extension

The Amar collision was followed by destacking and crustal thinning, which resulted in the development of transextensional basins parallel with, or perpendicular to, the Najd shear zones. These extensional basins were the site of intrusive and extrusive post tectonic magmatism (Shammar magmatism) and were the precursors of the Infracambrian salt basins in S Arabia (Oman) and E Arabia (Gulf and SW Iran).

Chapter 3
Phanerozoic development of the Northern Arabian Plate

by

Saad Z. *Jassim and Jeremy* C. *Goff*

3.1 Introduction

The Arabian Plate is shown in Fig. 3-1. The western and southern boundaries of the plate are passive margins located at the spreading ridges of the Red Sea, and the Gulf of Aden. The north western boundary is located along the Levant transcurrent fault. The south eastern boundary in Oman is defined by the Masirah fault zone. The _northern and northeastern boundaries are compressional due to the late tertiary collision of the Arabian Plat with the Turkish and Iranian continents. The green line on Fig. 3-1 represents a Late- cretaceous suture zone.

The Phanerozoic evolution of the northern margin of the Arabian Plate is a complex and controversial subject. It has been established that the Arabian Plate formed by accretion of terranes along active continental margins during Late Precambrian time (Chapter 2). However, the subsequent evolution of the northern margin of the plate in Palaeozoic Eocene times is still poorly understood and no consensus has been reached on many geological issues late Cretaceous-tertiary—subduction and over thrusting along the NE margin of the Arabian Plate has fragmented, and frequently destroyed, evidence of Permian-Early Cretaceous extensional tectonic events and ocean spreading. Earlier Palaeozoic events are even more difficult to decipher. In **NE** Iraq the Neo-Tethyan suture (chapter 16) is a narrow tectonic zone which-has· been strongly deformed due to late Miocene Recent over thrusting.

Geopolitical instability in the critical region of the Turkey/Iraq/Iran geographic triple junction in the last thirty years has hampered geological mapping and research. This area provides many opportunities for future co-operative research to solve key outstanding geological problems. This chapter draws attention to many unsolved problems but also offers some suggestions about how the plate margin has evolved based on insights provided by correlation of stratigraphic units in NE Iraq with adjacent areas.

In Turkey there is no consensus on the timing of opening of Neo- Tethyan ocean basins along the northern margin of the Arabian Plate or of the number of branches of the Neotethys which formed and subsequently closed. Evidence for the opening of a southern branch of the Neo- Tethys in Late Tithonian-Cenomanian time extending along the northern margin of the Arabian Plate from the Eastern Mediterranean to Oman is described. This is a new concept which warrants further research and critical interrogation.

The origin of the Mid Cretaceous ophiolites which were obducted onto the northern Arabian Plate in Late Campanian-Early Maastrichtian time remains controversial. Many workers consider that these ophiolites were formed in a supra subduction zone setting (Pearce et al., 1981; Dilek and Thy, 1989; Searle and Cox 1999; Glennie 2005); others consider that these ophiolites formed at a new oceanic ridge (following a ridge jump) near the margin of the Arabian Plate (Ricou 1994). Even the direction of Cretaceous subduction in the comparatively well studied region of Oman is disputed (Searle et al., 2003; Gray and Gregory 2003). **In** Iraq the ophiolites emplaced in the Late Cretaceous have been buried beneath younger thrust sheets; their presence is confirmed by the composition of the flysch in the Late Cretaceous foredeep.

Some tectonic blocks of the Turkish and Iranian plates (now sutured to the Arabian Plate) were originally part of the Arabian Plate in Early-Mid Palaeozoic time. They later split off the Arabian Plate and became isolated micro continents during the opening of the Neo- Tethys Ocean. Some of these terranes may have completely disappeared due to subduction. Other parts of the terranes subsequently collided with the Arabian Plate during the closure of the Neo- Tethys. It is likely that they rejoined the Arabian Plate in very different locations to where they originally rifted off (because of strike slip movements during the opening and closing of the Neo-Tethys). Many of these terranes have reached their present positions following Late Tertiary compressional and strike slip movements. The presence of protrusions and embayment's along the margins of the colliding plates would have strongly influenced the style of deformation along the suture zones.

An outstanding problem critical to the understanding of the evolution of the northern margin of the Arabian Plate is the geological interpretation of the Bitlis Massif. This massif contains strongly deformed metamorphosed Precambrian Turonian rocks (Caglayan et al., 1984; Goncuoglu et al., 1984). The massif was metamorphosed in Late Cretaceous time and exhumed in Latest Cretaceous time after an ophiolite had been thrust over it. We offer a new interpretation of the Biltis Massif, that it represents a microcontinent which split off the northern margin of the Arabian Plate in Late Tithonian time, was subducted into an intra-oceanic subduction zone and was then ejected from the subduction zone. We consider that the exotic Avroman and Bisitoun carbonates of NE Iraq and SW Iran (now preserved as thrust sheets) were originally deposited on a continental root' equivalent to the Precambrian and Palaeozoic rocks of Bitlis : this continental root has now disappeared due to subduction and overthrusting. We interpret the Neyriz Exotic and possibly some of the Oman Exotics as also have been originally deposited on fragmented blocks of thinned continental crust.

The Neyriz Exotics were described by Stoneley (1981). They occur within a melange with a radiolarian chert matrix as blocks incorporated into the lower part of the peridotite. The exotic blocks in the melange comprise: Permian fusulinid bearing packs tones, Triassic megalodon-bearing limestones, grainstones and packstones, Jurassic platform limestones, Lower Cretaceous *Orbitolina* bearing limestones, and Cenomanian grainstones with aveolinids. Stoneley noted that many of these limestone facies were unknown at outcrop in SW Iran. He considered that they were derived from an unknown source area that has now disappeared by subduction. The exotic blocks which occur in *the basal part* of *the Neyriz ultramafic thrust sheet* consist predominantly of marbles and metacherts, but also include low grade pelites and thin metasandstones with well preserved ripple marks. The Bisitoun Limestone of the Kermanshah area of SW Iran (Braud 1973, 1989, Fontaine et a1. 1989) contains an imbricated succession of Triassic Cenomanian carbonates (of similar facies to the Neyriz exotics).

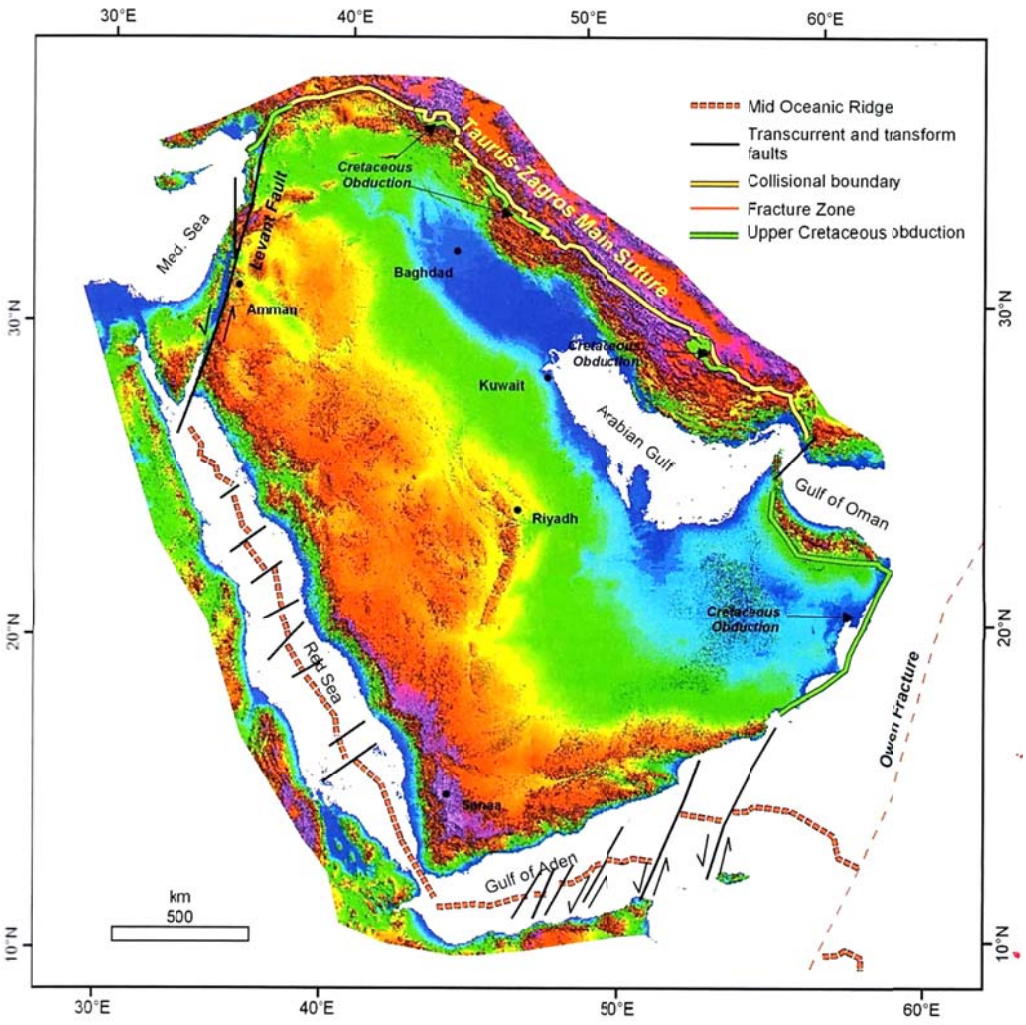
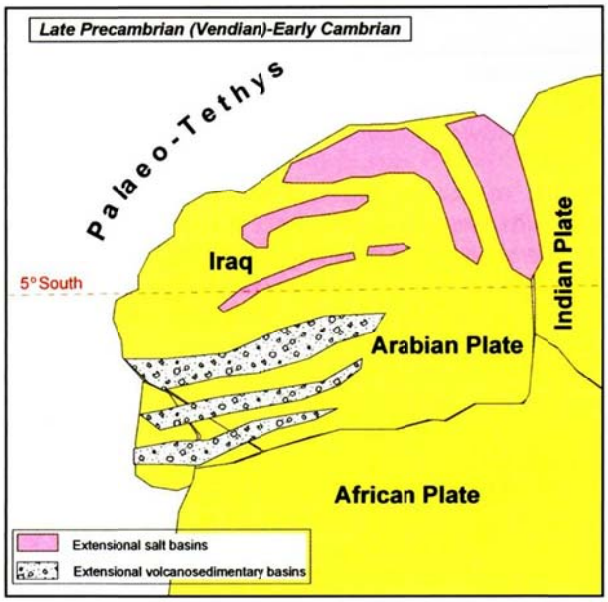


Fig. 3-1: The Arabian Plate boundaries at the present

3.2.1 Late Precambrian-Early Cambrian Rifting

In Late Precambrian time the collision of accreted continental terranes ceased at around 610 Ma (Chapter 2). At this time the Arabian Plate was joined to the African and Indian Plates and formed part of Gondwana. An important period of tectonic extension occurred in the northern Gondwana in Late Precambrian-Early Cambrian time. This led to the formation of NE-SW trending rift basins in southern Arabia (Gorin, 1975; Terkin, 1999; Husseini, 2002) and N-S trending grabens and half grabens in western and eastern Arabia (Hadley, 1974; Andrews et al., 1991; Getech and Jassim, 2002). These rift basins were infilled with thick clastics and basic and intermediate volcanics of Megasequence API (Sharland et al., 2001). In southern and eastern Arabia, thick marine evaporites were also deposited in the rift basins (Fig. 3-2). Throughout this period, the central Arabian N-S Nabitah orogenic belt dominated the Arabian Plate as a mountain range, separating east and west Arabia (Chapter 2). Rifting ended in late Early Cambrian time resulting in the development of broad fluvial basins on the western and eastern sides of the orogenic belt.

Fig. 3-2: The Late Precambrian-Early Cambrian geodynamic development of the Arabian Plate



3.2.2 Mid Cambrian-Silurian Intracratonic Subsidence

The peneplanation of the Idsas orogenic belt was completed in the late Early Cambrian time. A marine transgression then covered almost the whole of the Arabian Plate. The peneplaned Idsas belt was submerged but remained structurally high. The northern margin of the Arabian Plate was a passive margin (Fig. 3-3). Intracratonic subsidence in the Arabian Plate continued until the end of the Silurian only interrupted by the Late Ordovician glaciation (Fig. 3-4).

Megasequence AP2 (520-445 Ma) was deposited during passive subsidence in Mid Cambrian-Late Ordovician time. The Saharan glaciation was due to the southerly position of the Arabian Plate in Late Ordovician time. The Saharan glaciation (Husseini, 1991, Mahmoud et al., 1992; McGillivray and Hussein, 1992; Jones and Stump, 1999; Sharland et al., 2001) affected the western part of the Arabian Plate which was then at its lowest southerly latitude (Fig. 3-4). This glaciation was associated with a drop in sea level that led to deep incisions (exceeding 600 m) filled in with glacial moraines (McGillivray and Husseini, 1994).

Deglaciation at the end of the Ordovician caused a plate-wide marine transgression across the Afro-Arabian Plate; the resulting unconformity is the base of Megasequence AP3. Widespread deposition of graptolite shales occurred in Early Silurian time followed by deposition of shallow marine clastics during the Late Silurian. Over 2000 m of Silurian sediments were deposited in the western part of the Arabian Plate including western Iraq; about 1000 m of Silurian sediments were deposited in eastern Arabia.

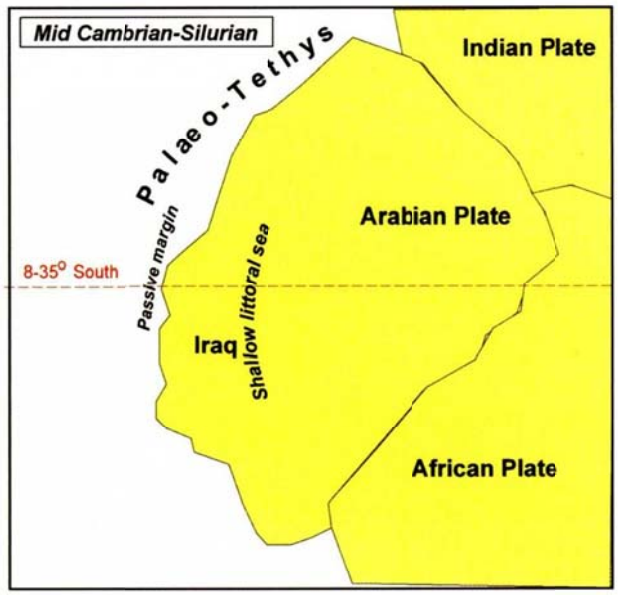


Fig. 3-3: Mid Cambrian-Silurian geodynamic development of the Arabian Plate

3.2.3 Latest Silurian-Early Late Devonian Uplift

During Latest Silurian-Mid Devonian time southerly subduction of Palaeo-Tethyan oceanic crust (Davoudzadeh and Weber-Diefenbach, 1987) occurred near the northern margin of the Arabian Plate (Fig. 3-5). Deformation occurred within the Arabian Plate following the formation of this active margin. The deformation has previously been correlated with the "Caledonian orogenic event" of Europe (Bellen et al., 1959). Early-Middle Devonian sediments are absent throughout the NE part of the Arabian Plate and in the Sanandaj-Sirjan Zone of Iran (Stocklin, 1968). NNESSW transversal uplifts and sag basins formed.

The basins included the Palmyride Trough in Syria, the, basin in NW Saudi Arabia and Iraq and Rub al Khali in southern Arabia. The intervening uplifted areas in N SE Syria, parts of SE Turkey, N and NW Iraq, N Jordan Oman were eroded. In Syria the Silurian Sequence was completely removed by erosion at the Swab-l well location prior to deposition of unconformably overlying Upper Devonian-Carboniferous sediments. This indicates uplift erosion occurred after the Late Silurian and prior to the late Devonian (Getech and Jassim, 2002).

Central Arabian Arch may have been initiated at this (Fig. 3-5). Fluvial-marine clastics and occasional carbonates were deposited in the sag basins; they form part of Megasequence AP3 .

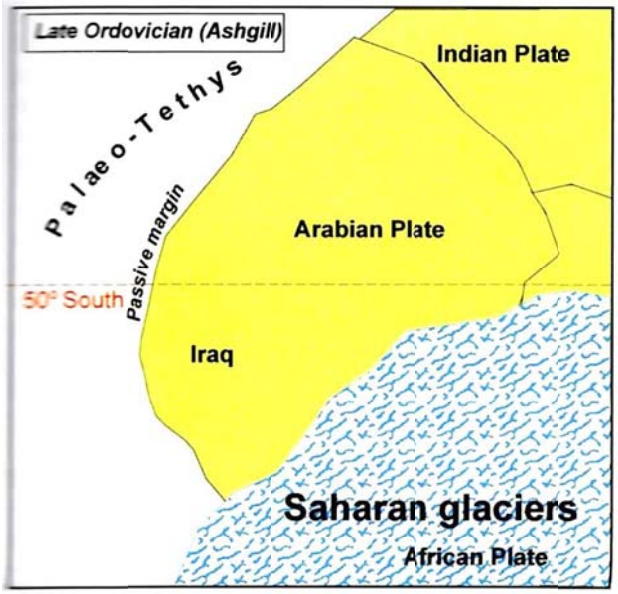
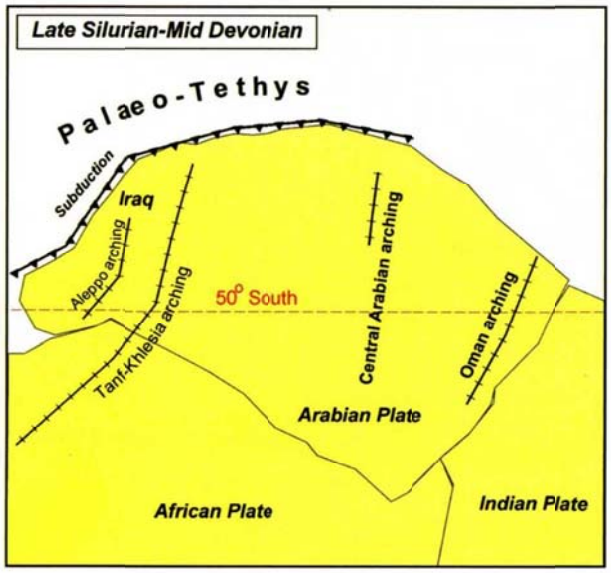


Fig. 3-4: The Saharan glaciation

Fig. 3-5: Latest Silurian-Early Late Devonian geodynamic evolution of the Arabian Plate



3.2. 4 Late Devonian-Early Late Carboniferous Intracratonic Subsidence

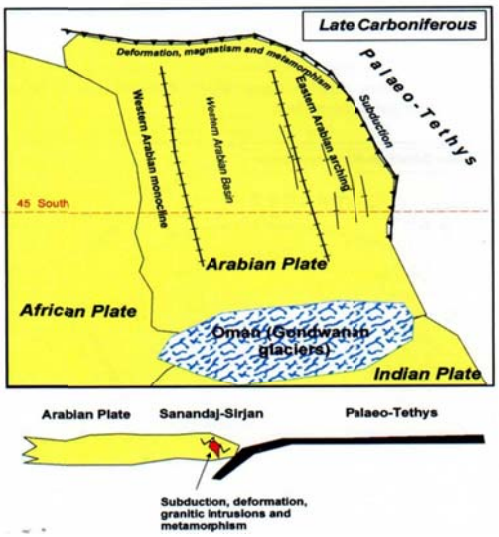
Sharland et al. (2001) interpreted the late Devonian-Early carboniferous time as a period of extension and compression with "Hercynian" back-arc rifting, inversion uplift. This interpretation suggests that the "Hercynian" event in the Arabian Plate may have started earlier than the late Carboniferous identified in both N Africa and N Arabia.

It is believed that the "Hercynian" upheaval in Arabia and N Africa was synchronous and restricted to the Permocarboniferous (Getech and Jassim, 2000; Guiraud et al 2001).
however, the absence of sediments of this megasequence in (Andrews et al., 1991) and southern Arabia (Levell et 1988) may be due to Late Carboniferous uplift and 'on rather than Late Devonian-Early Carboniferous as was suggested by Sharland et al. (op. cit.) who also the Chalki volcanics of N Iraq at the base of the Megasequence AP4 and considered that they formed in a back-arc setting behind the Palaeo- Tethyan subduction zone. However these volcanics are undated and could belong to the underlying Megasequence AP3.
Subduction along the southern margin of the Palaeo-Tethys is supported by the occurrence of Devonian-Carboniferous volcanics and metamorphics found in the Kuh-Sefid area of the Sanandaj-Sirjan Zone (Davoudzadeh and WeberDiefenbach, 1987). However the central part of the Arabian Plate was probably not significantly affected by this subduction. Widespread Late Devonian marine shales and limestones were deposited in a broad intracratonic basin throughout the central part of the Arabian Plate in Iraq, Syria and Turkey. Upper Devonian-Lower Carboniferous sediments are here assigned to Megasequence AP4 (Chapter 8).

3.2.5 Late Carboniferous "Hercynian" Compression

The Late Carboniferous was a period of great change in the Arabian Plate resulting in the formation of a major regional unconformity. In the west, the collision of N America with West Africa and Europe resulted in the development of the Hercynian collisional belt extending from the Mauritanides in the south, through the Atlas Mountains to central Europe in the north. This collision was associated with N-S compression in Morocco and Algeria (Haddoum et al., 2001), and major N-S arching in Libya (Getech and Jassim, 2000) and Egypt (Soliman and Fatouh, 1970; Guiraud and Bellion, 1995). In the east, data from the Sanandaj-Sirjan Zone (Davoudzadeh and Weber-Diefenbach, 1986) indicate a metamorphic event occurred during the Late Carboniferous. This metamorphism is likely to be the result of subduction along the southern margin of the PalaeoTethys (Fig. 3-6).

Fig. 3-6: Late Carboniferous "Hercynian" geodynamic development of the Arabian Plate



Sengor (1990) proposed that subduction of oceanic crust occurred the north eastern margin of Gondwana in Iran in Late Palaeozoic time and that subsequently Permian Triassic rifting occurred in a back arc setting. Husseini (1991, 1992) also concluded that subduction occurred beneath the northern margin of Gondwana in the Late Palaeozoic. Concuoglu et al. (2000) concluded that the Tepekoy Metamorphics and Sogut Metamorphics in, the Pontides of northern Turkey formed in an accretionary complex and volcanic arc respectively above a southerly dipping subduction zone along the northern margin of Gondwana in Late Carboniferous time. The Sogut Metamorphics contain granitic dykes; a granodiorite intrusion is dated at 295 Ma (Latest Carboniferous). The metamorphics comprise amphibolite, gneiss, schist, marble and quartzite, with lenses of metaserpentinites, pyroxenite and metagabbros. Late Carboniferous granites have recently been described from Greece and interpreted as the products of southerly subduction of Palaeotethys beneath Gondwana (Xypolias et al 2006). Melange containing exotic blocks of Silurian, Devonian and Carboniferous age occur in Karaburun and on Chios in western Turkey and may have formed in a southerly dipping Palaeotethyan subduction zone (Robertson and Pickett 2003).

Hercynian folding and metamorphism affected the active margin of the Arabian Plate in Iran along the Sanandaj-Sirjan (Davoudzadeh and Weber-Diefenbach, 1987). The resulting E-W compression led to the inversion of the N-S trending Late Precambrian basins. The Burgan and Ghawar structures and N-S trending buried structures were formed. The "Middle"-Upper Permian Khuff Formation unconformably overlies eroded Lower Palaeozoic sediments over these structures. Unconformities within the Upper Carboniferous clastic formations of Central Arabia suggest that the N-S trending structures were intermittently active.

Levell et al. (1988) who studied the Late Carboniferous glacial deposits of Oman and concluded that elevation rather than latitude of Oman put that region within the reach of the Gondwanan glaciation (i.e. Alpine-type glaciation). The elevation is assumed to be the result of a thermal uplift at the initial stages of the opening of the Neo-Tethys, developed between India and the Tibet block.

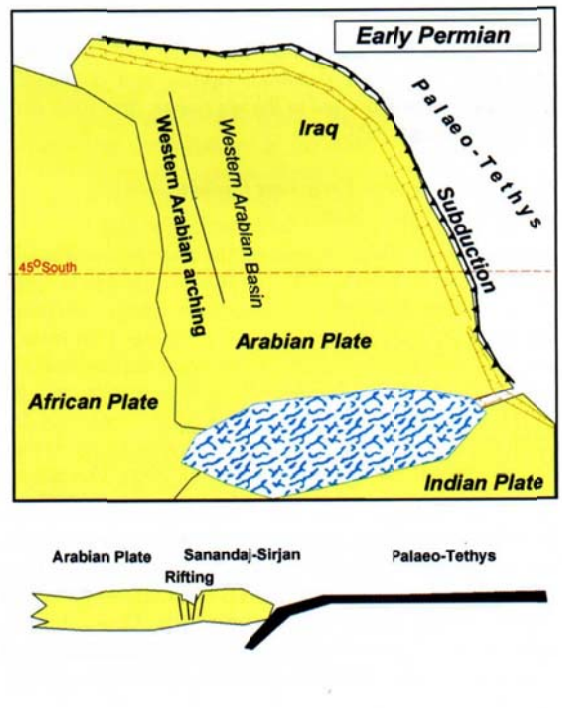
Western Arabia was uplifted (Fig. 3-6) and tilted eastward (Getech and Jassim, 2002). In Jordan, Upper Permian or Lower Triassic formations overlie progressively younger Lower Palaeozoic formations towards the east while the western Palmyride was uplifted during this time span too (Brew et al., 1999). The area between the east and west Arabian uplifts subsided (W Iraq, N-NW Saudi Arabia and E Syria) forming a basin in which about 1000 m of fluvial Late Carboniferous-Lower Permian clastic sediments were deposited (Chapter 8). Upper Carboniferous sediments are here placed in the Modified Arabian Plate Megasequence AP5. The upper and lower boundaries of Megasequence AP5 have here been modified.

3.3 Extension and passive subsidence associated with the opening of the Neo- Tethys Ocean

3.3.1 Early-'Mid" Permian rifting

Early-Mid Permian rifting is interpreted to have occurred in c-are setting around the northern margin of the Arabian plate, and at a triple junction located at the SE corner of the plate fig. 3-7). However the central parts of the Arabian including Iraq) were relatively unaffected by extension at this time; most of the extension is interpreted to occurred around the margin of the plate in Turkey and Lower Permian continental sandstones were deposited in a N-S trending basin in Wand Central Iraq (Chapter 8) inherited from Late Carboniferous time. Iraq was a gently uplifted landmass during most of Early-Mid Permian time.

Fig. 3-7: Early Permian geodynamic development of the Arabian Plate



3.3.2 Late Permian-Early Triassic passive margin development

In late Permian time the Neo- Tethys Ocean opened. The micro continent of Mega Lhasa (Ricou, 1994) comprising Precambrian basement and Palaeozoic sedimentary of the Sanandaj-Sirjan Zone, Central Iran and a narrow continenta1 sliver in northern Turkey, split of the Arabian Plate (Fig. 3-8). Detailed analysis of the biofacies of Permian carbonate sequences of the Taurides and the Platform of SE Turkey (Altiner, 1984; Altiner et al., 2000) strongly suggest that these areas were joined together in late Permian time and formed a single giant carbonate platform on the northern margin of Gondwanaland.

However, other authors have suggested that the Taurides split off the Arabian Plate during the Permian (Stampfli, 2000), and that sea floor spreading occurred in the Eastern Mediterranean at this time (Garfunkel, 2004).
The Neo-Tethys Ocean progressively widened during Early Triassic time. A break-up unconformity formed on the northern and eastern margins of the Arabian Plate. Thermal subsidence led to the formation of a passive margin megasequence along these margins, and the development of the Mesopotamian Basin (Chapter 9). Upper Permian basal clastics or carbonates overstep across older Palaeozoic rocks. The Rutba Basin which had subsided in earlier Palaeozoic time was gently inverted forming the Rutba Uplift. The shoreline of the Late Permian basin was located along the eastern flank of the Rutba Uplift. A fluvial basin formed in the Palmyrides in Late Permian time.

3.3.3 Mid Triassic-Norian rifting

During Mid Triassic-Late Triassic time further extension (Fig. 3-9) occurred around the northern and eastern margins of the Arabian Plate. This is recorded by the occurrence alkali basalts in three areas: in the Bitlis Massif of Turkey (Perincek, 1980) in the Zagros suture zone associated with the Triassic Avroman and Bistoun carbonates of NE Iraq/SW Iran, and in the Hawasina Complex of Oman. Radiolarian chert was deposited in the resulting rift basin along the margin (Bechennec et al., 1990).

Triassic carbonates are locally preserved as exotic blocks in the Zagros suture zone (Neyriz and Oman exotics). Many of these carbonate exotics have been interpreted as the covers of volcanic oceanic sea mounts (Pillevuit et al., 1997).
We propose that the rifting led to the formation of an outer ridge of thinned continental crust on which megaladon limestones were deposited which separated the rift basin from the deep water continental slope which formed during the Late Permian-Early Triassic opening of the Neo-Tethys. This ridge may have been discontinuous comprising a series of isolated blocks. Carbonate deposition on these blocks continued through Jurassic and Early Cretaceous time.

In Syria, Iraq and Iran differential subsidence occurred in the Palmyride and Mesopotamian Basin in Mid-Late Triassic time with deposition of evaporites and locally euxinic basinal carbonates in a highly restricted environment (Chapter 9). Extensional basins developed near and parallel to the plate margin from the Atlas Mountains in Morocco and Algeria to the Syrian Arc in N Egypt (Guiraud and Bellion, 1995), the Levant and Syria (Brew et al, 1999).
In addition to the above-mentioned longitudinal basins, minor transversal Triassic sags were developed in central Jordan (NW-SE, Shinaq, 1997) and SW Iran (E-W, Setudahnia, 1978).

Fig. 3-8: Late Permian-Early Triassic geodynamic development of the Arabian Plate

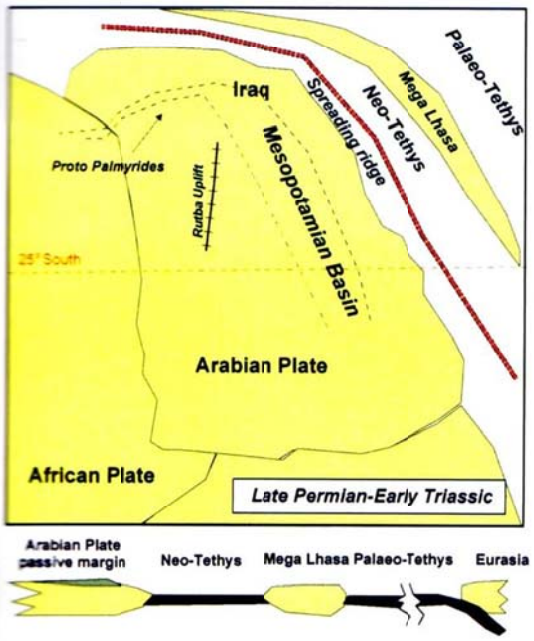
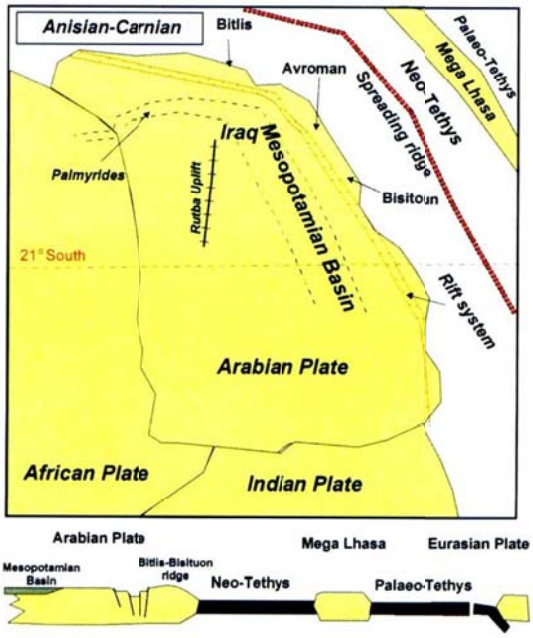


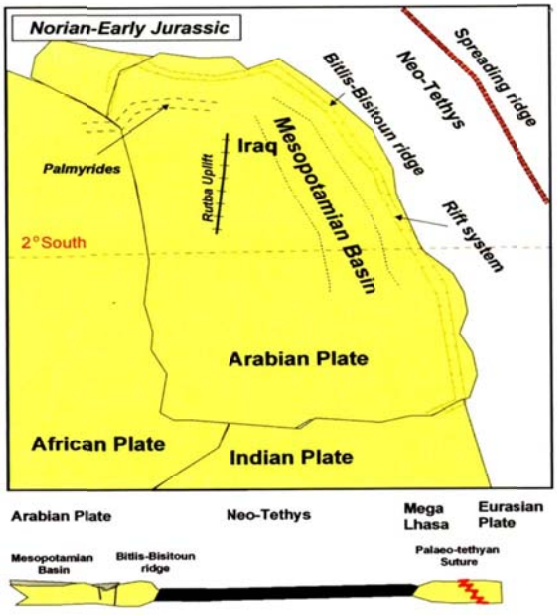
Fig. 3-9: Mid Triassic-Norian geodynamic development of the Arabian Plate



3.3.4 Norian-Mid Toarcian passive subsidence

In Late Norian-Mid Toarcian time the rate of subsidence on the northern Arabian Plate slowed and relatively uniform marginal marine clastics, evaporites and shallow water lagoonal carbonates were deposited across the Mesopotamian Basin (Chapter 9). Deposition of megaladon limestones occurred on the Bitlis-Bisitoun ridge on the NE margin of the Arabian Plate (Fig. 3-10).
The Late Permian to Early Jurassic sequences are equated with the Arabian Plate Megasequence AP6.

Fig. 3-10: Norian-Mid Toarcian geodynamic development of the Arabian Plate



3.3.5 Late Toarcian-Early Tithonian Differential Subsidence and Rifting

In Latest Toarcian time renewed differential subsidence occurred in the Mesopotamian Basin in Iraq (Chapter 10) and SW Iran with the onset of deposition of euxinic marine carbonate source rocks. By Oxfordian time the Mesopotamian Basin was a relatively deep restricted basin fringed by carbonate shoals along its rims. In Late Kimmeridgian-Early Tithonian time a phase of rapid subsidence occurred in the southern Mesopotamian Basin in southern Iraq with deposition of thick evaporites (including four units of halite). The Mesopotamian Basin was clearly isolated from the open marine waters of the Neo-Tethys Ocean. The northern rim of the basin was formed by carbonate shoals. In Iraq this carbonate rim was tectonically overridden in Late Cretaceous time by thrust sheets. However in SW Iran the rim is represented by the carbonates of the Surmeh Formation.

A phase of rifting in Mid-Late Jurassic time is documented in Oman (Rabu et al., 1990; Pratt and Smewing, 1990). We consider that this phase of rifting probably extended further north along the margin of the Arabian Plate separating an outer carbonate ridge along the edge of the Arabian Plate from the restricted Mesopotamian Basin (Fig. 3-11). A transtensional NW-SE oriented salt basin developed in Yemen (Maycock et al., 2001).

Schettino and Scotese (2002) have noted that important rifting events occurred in the Mediterranean region in Bajocian-Mid Tithonian time (175-148 Ma). It is likely that this rifting phase had begun in Latest Toarcian time (182 Ma). There are up to 2500 m of Early Jurassic basalts in northern Israel (May, 1991); early Jurassic rifting created horsts and grabens with up to 1000 m of relief. Schettino and Scotese suggested that rifting led to the formation of small fragments of continental lithosphere that rifted away from the northern margin of Gondwana. They proposed that the mechanism of this rifting was related to a tensional force related to the north easterly subduction of old Neo- Tethyan Ocean crust beneath the active margin of Eurasia extending from the Pontides of northern Turkey to the Sanandaj-Sirjan Zone of Iran.

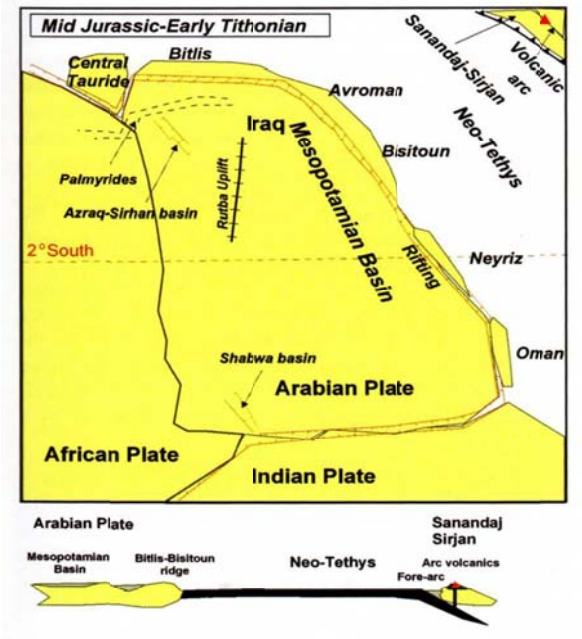


Fig. 3-11: Late Toarcian-Early Tithonian geodynamic development of the Arabian Plate

3.3.6 Late Tithonian-Cenomanian opening of the Southern Nee-Tethys

There is an important regional unconformity of Mid Tithonian age (149 Ma) on the Arabian Plate which marks the boundary between Megasequences AP7 and AP8 (Sharland et al., 2001). This unconformity may be a "break up unconformity" which formed as a result of a possible phase of ocean floor spreading around the northern margin of the Arabian Plate with the opening of a southern Neo- Tethys Ocean (Fig. 3-12). In Late Tithonian time major palaeogeographic changes occurred in the northern and eastern Arabian Plate which are not explained by previous plate tectonic models of the region. The continental margin of the Arabian Plate in Oman collapsed and the shelf edge retreated 250 km to the SW (Rabu et al., 1990). Deposition of widespread radiolarian chert began in Tithonian time in E Turkey (Karadut Complex) and in NE Iraq (Qulqula Group) and occurred with renewed vigour in SW Iran and Oman. Radiolarian chert deposition continued through Early Cretaceous time. Basic volcanism occurred in Tithonian-Cenomanian time all around the northern margin of the Arabian Plate from the Levant through the suture zone of SE Turkey, NE Iraq, SW Iran and Oman. In the Mesopotamian Basin (Chapter 11) deposition of basinal evaporites suddenly ceased consistent with a much - proved connection of the basin to the open marine Tethyan Ocean.
The supporting regional evidence for the Late Tithonian Cenomanian Ocean spreading is described below.

In Late Tithonian-Cenomanian time there was widespread basic volcanism around the northern margin of the Arabian Plate extending from the Eastern Mediterranean to Masirah in Oman. In the Levant the volcanics were derived from primitive basic magmas from an enriched mantle source (Laws and Wilson, 1997) with important eruptions dated-at 148 Ma (Late Tithonian), 137-130 Ma (Valanginian Hauterivian), 122-115 Ma (Barremian- Aptian), 105 Ma (Albian) and 90 Ma (Turonian).

The lower nappe of the Cilo Ophiolite in SE Turkey (Yilmaz, 1985) near the Iraq border comprises 300 m of basalts, pyroclastics and cherts; the cherts in the upper part of the nappe are dated as Mid-Late Hauterivian (130-127 Ma). Further west the lower and middle tectonic units of the equivalent Kocali Complex comprise up to 1000 m of basalt and agglomerate, and up to 1800 m of pelagic limestone, chert, manganese bearing silicified mudstone, and basalt respectively (Perincek, 1979). The lower part of the Kermanshah Ophiolite of Iran (Braud, 1973) comprises a melange of radiolarian chert, pillow lavas, basalt and slivers of serpentinite. In the Neyriz area of Iran (Stoneley, 1981) tectonic blocks with up to 1000 m of basalt and pillow lavas occur in the chert matrix of a melange beneath the Neyriz Peridotite; blocks of metamorphosed basalts occur immediately beneath the peridotite. The chert matrix of the melange contains Mid Coniacian-Santonian radiolaria, the entrained volcanic blocks are thus probably of Turonian or older age.

In Oman basic volcanism is recorded in the Dibba and Hatta zones (Robertson et al., 1990a, 1990b). In the Dibba Zone the metamorphic sole of the Semail Ophiolite is transitionally underlain by several hundred metres of highly deformed chert, siliceous mudstones, pelagic limestones, basalts and dolerite sills; the siliceous mudstones are dated as Late Tithonian-Valanginian. The metamorphic sole contains metamorphosed equivalents of these rocks with extensive metamorphosed basalts and pillow lavas. The Haybi Complex in the Dibba Zone comprises thrust

slices of basalts, radiolarites and pelagic limestones. The volcanics are dated as 92 and 96 Ma (Mid Cenomanian-Early Turonian); the cherts contain Early Cenomanian-Turonian radiolaria. Dolerite sills also occur in the Nayid Formation of the Hawasina Complex; cherts in the Nayid Formation in the Dibba Zone contain Early Cenomanian radiloaria. Robertson et al considered this Cenomanian volcanism to be due to "variable amounts of crustal stretching of older oceanic crust near the margin of the Tethyan Ocean". In the Hatta Zone the Haybi Complex comprises a lower unit of 300 m of highly deformed radiolarites, pelagic limestone, with basalts and dolerite sills; the radiolarites contain radiolaria of Late Jurassic-Early Cretaceous age. This unit is depositionally overlain by several hundred metres of basalts, pillow lavas, dolerite sills, cherts, pelagic limestones and calciturbidites. The volcanics are dated as 109-104 Ma (Albian) and 93 Ma (Early Turonian). The Cretaceous basalts of the Dibba and Hatta Zone have a MORB Tholeiite and Within-Plate composition.

In our model the opening of the Southern Neo- Tethys led to the drifting away from the Arabian Plate of a narrow continental block (or a series of isolated blocks) (Section 3.1). This concept had first been suggested by M.W. Hughes-Clark (Stoneley, 1981, P. 523). Stoneley refers to "an oceanic trough .... Within the original Arabian shelf margin" forming a "separated continental block lying between the Arabian Platform and the main Tethys to the NE" which was the "source of the shelf exotics". Robertson and Searle (1990, their Figure 14) based on review of Oman data also recognized a Tithonian "? Spreading event" related to "crustal extension and subsidence" and "inferred oceanic volcanism".

We postulate that Tithonian ocean floor spreading occurred mainly within stretched continental crust all along the northern margin of the Arabian Plate leading to the spreading away of a narrow microcontinent (or a series of isolated narrow continental blocks separated by small transform faults). These microcontinents are inferred to be the substrate on which the Triassic-Cenomanian platform limestones of the Bisitoun Limestone of Kermanshah (Iran) and the Avroman limestone of NE Iraq were deposited. It is also inferred to be the source of many of the exotic blocks of platform carbonates that occur in the radiolarian chert of Neyriz (Iran), in the Hawasina Complex in Oman, and in the Kocali Complex of SE Turkey .

The above events are here attributed to a new phase of ocean spreading along the outer rim of the Arabian Plate with the splitting of a narrow micro-continent (or a series of microcontinents) from the Arabian Plate (Fig. 3-12). The narrow ocean which formed is here referred to as the Southern NeoTethys. The southern passive margin of this ocean which now formed the northern margin of the Arabian Plate is represented in Iraq by the Qulqula Group which is equivalent to the Karadut Complex of SE Turkey, the Radiolarian Chert Series of Kermanshah and Neyriz, and part of the Hawasina Complex of Oman. Deposition of shallow water carbonates or deep water condensed sequences occurred on the narrow blocks of continental crust which split off the Arabian Plate. The onset of the spreading of the Southern Neo- Tethys in Late Tithonian time may have been caused by the formation of an intraoceanic subduction zone in the southern part of the NeoTethys.

The opening of the Southern Neo- Tethys can be considered to be part of a regionally extensive event linked to the breakup of Gondwana, including the opening of the Eastern Mediterranean (Beydoun, 1991) and the separation of Africa and India (Fig. 3-12). May (1991) suggest that an ocean opened in the Eastern Mediterranean in Early Cretaceous time and had widened to 300-400 km by the Aptian. In excess of 3000 m of Upper Aptian-Cenomanian carbonates, marls and turbidites were deposited along the continental margin and along the eastern shore of the ocean along the Levant. On the eastern margin of Oman, the Masirah Ophiolite comprises thick

Tithonian pillow lavas (Peters and Mercoli, 1997). This records the opening of the northern Indian Ocean and the separation of eastern Oman from India. This event clearly relates to successful Late Jurassic rifting within the Gondwanaland continental crust. In Masirah pelagic limestones associated with thick pillow lavas contain Tithonian radiolarian chert. Gabbro dykes are dated at 150 Ma. Alkaline volcanics are dated at 123-130 Ma (Hauterivian-Barremian).

The ophiolites emplaced onto the Arabian Plate during Late Cretaceous obduction are here interpreted to comprise a lower unit of ophiolitic melange and an upper unit of massive ophiolite which is interpreted to have formed in a supra subduction zone setting. These two ophiolite thrust sheets are locally separated by massive thrust sheets of massive carbonates which were sheared from their now subducted continental roots. The lower ophiolitic melange is interpreted to be the remnants of the Southern Neo- Tethys. The Southern Neo- Tethys is interpreted to have been a narrow deep ocean which spread at a low rate. Its oceanic crust is interpreted to have been subducted and corresponds to the basic and ultrabasic components of an ophiolitic melange. This melange is represented by the lower nappes of the Kocali and Cilo Ophiolites in SE Turkey, the Darband Rayat and Khwakurk Groups of NE Iraq, and the lower ophiolitic nappes of Kermanshah and Neyriz, and parts of the Haybi Complex of Oman. The upper thrust sheets of massive unmetamorphosed ophiolites of Cretaceous age have a chemical signature indicating formation in a supra-subduction zone setting (Section 3.1). These ophiolites extend from Cyprus to Oman. They are interpreted to have formed above the same subduction zone that is predicted to have formed in Late Tithonian time near the southern margin of the Neo-Tethys.

Other workers have suggested that ocean spreading in the southern part of the Neo- Tethys during the Early Cretaceous resulted from a ridge jump in Late Tithonian time to an intra-oceanic position close to the continental margin of the Arabian Plate. Ricou (1994) and Pillevuit et al., (1997) suggested that a new ocean ridge formed in Late Jurassic (Tithonian) time as a result of rifting within the old NeoTethyan oceanic lithosphere close to the margin of the . Arabian Plate adjacent to Oman. Ricou suggested this ocean ridge formed in Mid Tithonian time and extended to the NW along the margin of the Arabian Plate from Oman to Iran.

Metamorphosed ophiolites occur in the Mawat Group of NE Iraq comprising the Mawat, Penjween, Bulfat and Pushtashan phiolites and associated sediments (Chapters 16 and 17).

These ophiolites were metamorphosed in Late Cretaceous time and finally emplaced into the Zagros suture zone in late Miocene time; they have been thrust onto thrust sheets of Palaeogene arc volcanics. The Mawat Group ophiolites and associated metasediments require further study. They may represent fragments of the metamorphosed slab of oceanic crust above which was overthrust in late Cretaceous time by massive unmetamorphosed ophiolites described above.

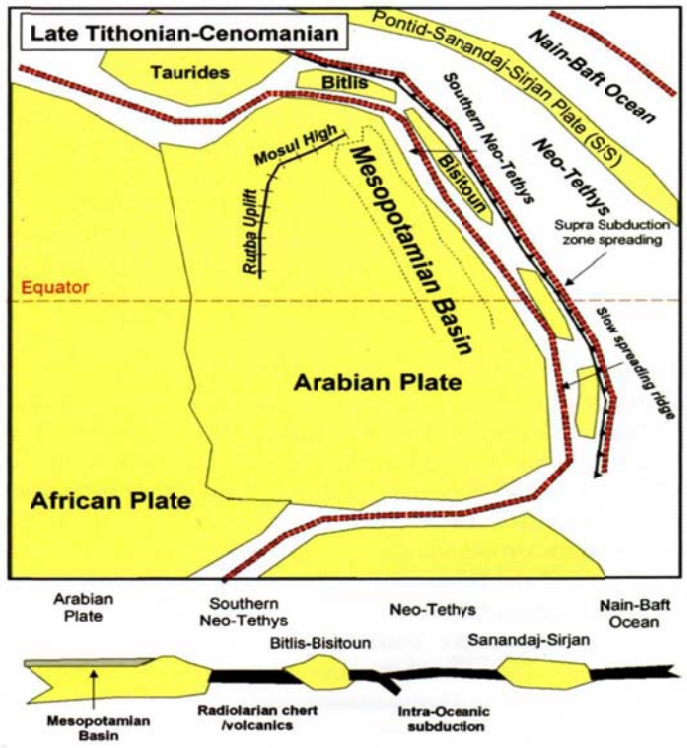
Alternatively they may have formed at a spreading ridge in central part of the Neo-Tethys.

Basement lineaments were reactivated beneath the Mesopotamian basin during the formation of the passive margin along the southern Neo-Tethys. Transversal faults Fig. 4-7) differentiated the Mesopotamian basin into strongly subsiding areas (Kirkuk and Rub al Khali Embayments) and relatively elevated blocks (Mosul and Central Arabian Highs).

Traverse tectonic lineaments controlled the location of depressions and blocks, and may also have controlled location of Early Cretaceous rivers and deltas along the SW margin of the Mesopotamian Basin. The failed Palmyride rift was associated with volcanicity evident in Lebanon Renouard, 1955) and the Palmyrides (Litak et al., 1998). The Rutba uplift reached its maximum

extends during this time span and was probably joined to the Mosul High in N Iraq. Sequences of this cycle are equated with Arabian Plate megasequence AP7.

Fig. 3-12: Late Tithonian-Cenomanian geodynamic development of the Arabian Plate



3.4 Turonian-Eocene foreland basin formation closure of the Neo- Tethys

3.4.1 Turonian-Early Campanian Closure Southern Neo-Tethys

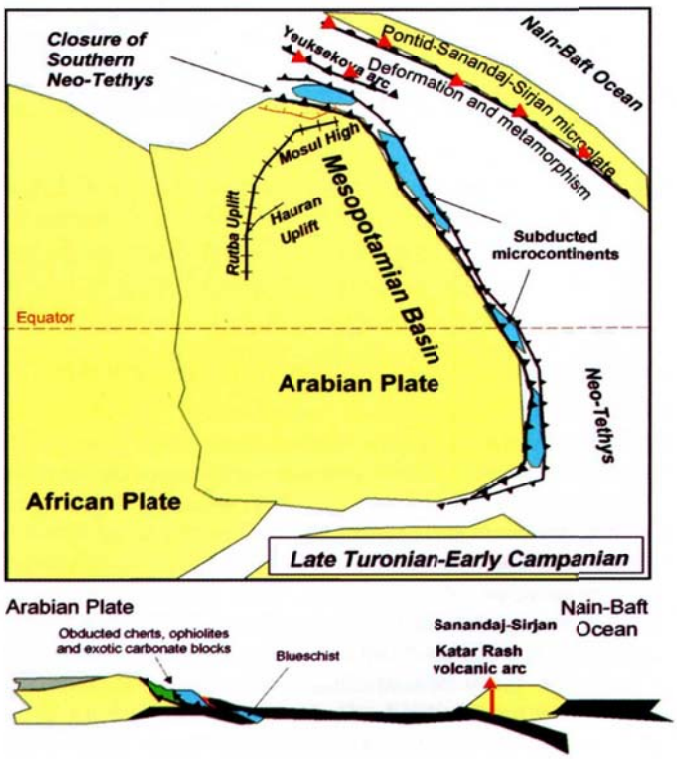
In late Cenomanian-Early Turonian time the micro continent that had split of the Arabian Plate in Late Tithonian time approached the trench of the intra-oceanic subduction zone. The onset of growth of N-S trending structures in S Iraq, Kuwait, and Saudi Arabia at this time may have been caused by the diachronous collision of these micro-continents with the fore-arc region above the trench. The onset of deformation of the north facing passive margin of the southern Neo- Tethys is recorded by the deposition of the Qulqula Conglomerates of NE Iraq (Chapter 16).

A foreland basin formed around the northern margin of the Arabian Plate in response to loading of the crust by thrust sheets generated as a result of compression. In Oman this foreland basin subsided in response to pulses of compression in Coniacian-Early Campanian time (Warburton et al., 1990).

At least two subduction zones are interpreted to have been active in the Neo-Tethys in Turonian-Early Campanian time. The continental roots of the Bitlis, Bisitoun and associated micro-continents, and the oceanic crust of the Southern Neo- Tethys are interpreted to have been subducted into the southern subduction zone (Fig. 3-13). The leading edge of the Arabian Plate was also subducted; peak high pressure metamorphism occurred in the Early Campanian with formation of blue schists and eclogites (Warren et al 2003, Searle et al 2004).
An additional subduction zone may have been active in the Neo- Tethys leading to the formation of a coloured melange with volcanics now represented by the Yuksekova Complex of eastern SE Turkey. In the suture zones of NE Iraq and SW Iran this arc complex has been tectonically overridden by the Sanandaj-Sirjan Zone.

Along the SW margin of the Sanandaj-Sirjan Zone a new subduction zone formed which resulted in the formation of the Katar Rash arc volcanics of NE Iraq (Chapter 16) and extensive arc volcanics of the Sanandaj-Sirjan Zone of SW Iran.

Fig. 3-13: Turonian-Early Campanian geodynamic development of the Arabian Plate



3.4.2 Late Campanian-Early Maastrichtian Ophiolite Obduction

In Late Campanian-Early Maastrichtian time (Fig. 3-14) Neo- Tethyan ophiolites were thrust further onto the Arabian Plate, elevated above sea level, and rapidly eroded. The erosion products were deposited as flysch (up to 2000 m thick) in a narrow foredeep basin along the northern and eastern margins of the Arabian Plate extending from SE Turkey through NE Iraq (Chapter 12) and SW Iran to Oman. Extensional basins subsided strongly during Late Campanian-Early Maastrichtian time. These include the Euphrates Graben, the Azraq-Sirhan Graben and the E- W trending Anah and Tayarat grabens. These basins had originally formed during rifting in early Late Cretaceous time.

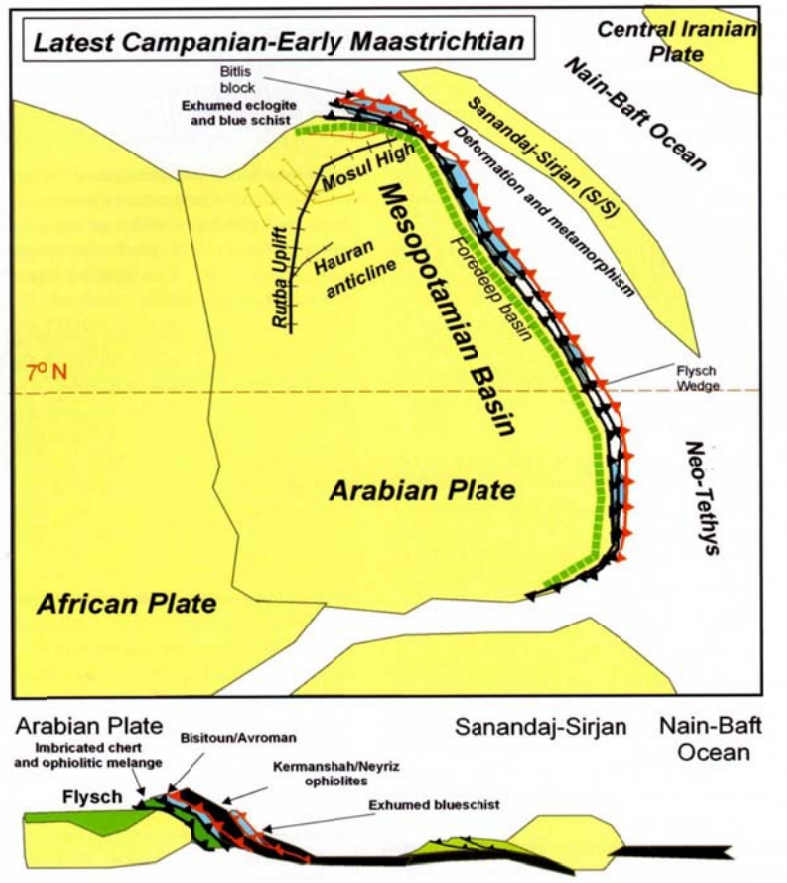


Fig. 3-14: Late Campanian-Early Maastrichtian geodynamic development of the Arabian Plate

3.4.3 Late Maastrichtian-Danian

In Late Maastrichtian time ophiolite obduction ceased and the flysch basin shallowed. The Cretaceous thrust belt was onlapped passively by Upper Maastrichtian Loftusia-bearing limestones. With the mass extinction at the end of the Maastrichtian, carbonate production slowed dramatically. Danian sediments are absent in NE Iraq and are of phosphatic facies in W Iraq (Chapter 13).

Sequences of this period are equated with Arabian Plate Megasequence AP9 (92-63 Ma).

3.4.4 Palaeocene-Eocene closure of the Neo-Tethys

Evidence of subduction and the final closure of the NeoTethys ocean is provided by calc-alkaline basic and intermediate volcanic rocks (and local igneous intrusions) of Palaeocene-Eocene age which have been mapped in Turkey, NE Iraq and SW Iran. These rocks have received remarkably little attention by geologists. They formed in island arcs or in back arc rifts probably in intra-oceanic setting. However the polarity of the subduction zone and the tectonic setting of these volcanics require further research.

In the thrust belt of NE Iraq the Walash and Naopurdan group are interpreted to have been formed as a calce alkaline volcanic arc and in a fore-arc basin respectively (fig.3-15) (Chapters 16 and 17). Their mutual position suggests that they formed above a NE dipping subduction zone in the closing Neo- Tethys Ocean. They can be traced to the NW into SE Turkey where they are equivalent to the Hakkari Complex which includes a thick tectonic melange

(Perincek, 1990) that clearly formed as an accretionary complex associated with a subduction zone. Further west they are equivalent to the Maden Complex and the Helete volcanics which have been interpreted to have formed in a back arc basin and volcanic arc respectively (Yilmaz, 1993a and 1993b). Calc-alkaline volcanics and associated sediments (very similar to the Walash and Naopurdan Groups) occur in the suture zone of SW Iran.

The rocks described above formed in an active margin setting within the closing Neo- Tethys adjacent to the Arabian Plate. At the same time as subduction was occurring two pulses of uplift in Palaeocene and Eocene time respectively occurred along the NE margin of the Arabian Plate. The old Upper Cretaceous thrust belt was uplifted and shed clastics to the SW into a new foreland basin in NE Iraq and adjacent areas of SE Turkey and SW

Iran (Kolosh and Gercus formations described in Chapter 13). Clastics were also shed eastwards into a molasse basin along the margin of the plate (Chapter 16). As the NeoTethys progressively closed the molasse basin merged with the accretionary prism of the Palaeogene subduction zone.

Sequences of this time span are equated with the Arabian Plate Megasequence APIO.

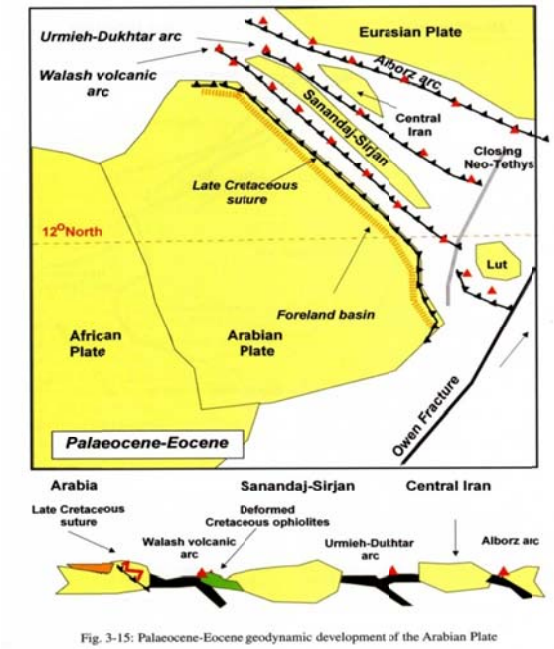


Fig. 3-15: Palaeocene-Eocene geodynamic development of the Arabian Plate

3.5 Oligocene-Recent compression and continental collision

The present day configuration of the NE margin of the Arabian Plate is a result of continental collision (Fig. 3-16). At the end of the Eocene the Neo- Tethys Ocean closed. The accretionary prism in the suture zone of the Neo- Tethys remained near sea level at this time. Shallow water carbonate deposition occurred on a broad platform extending from the NE part of the Arabian Plate (Euphrates and Jeribe formations of Iraq (Chapter 14), and Asmari *Formation of* SW *Iran), across the suture zone into Central* Iran (Qum Formation). Subsidence rates in Oligocene to Early Miocene time were relatively low. The Mesopotamian Basin became narrower and shallower as the western part of Arabia was thermally uplifted; by the beginning of the Middle Miocene it was a very shallow lagoon in which the Jeribe Formation was deposited.

In Middle Miocene-early Late Miocene time renewed compression occurred along the Tethyan suture zone. The accretionary prism formed of relatively soft sediment was uplifted and rapidly eroded with transport of fine silt and mud into a new foreland basin in NE Iraq and SW Iran (Fatha and Injana formations, the former Lower and Upper Fars formations).

In latest Late Miocene time further strong compression occurred, which propagated into the Mid Miocene foreland basin resulting in the growth of the large Zagros anticlines. A rapidly sinking foredeep basin formed in N and NE Iraq flanked by a thrust belt. An intermontane basin developed within the suture zone in which red beds were deposited (Chapter 16).

In Pliocene time further compression led to the progradation of huge alluvial fans into the Mesopotamian foreland basin. The progressive evolution of the Late Tertiary foreland basin is described in Chapter *14.* Quaternary sediments were deposited *on* a major regional unconformity surface following intense *deformation along the collision zone* between the Arabian and Iranian Plates.

The sequences of this cycle are equated with the Arabian Plate Megasequence AP 11.

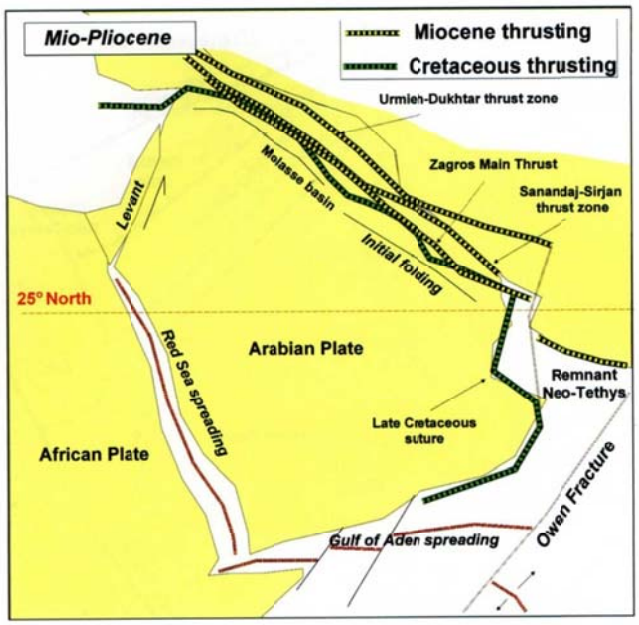


Fig. 3-16. Oligocene-Recent geodynamic development of the Arabian Plate

Chapter 4
Tectonic framework

by

Saad Z. Jassim and Tibor Buday

This chapter discusses the tectonic framework of Iraq. Magnetic, gravity and seismic data has been integrated with well and outcrop data to construct a series of isopach and structural maps covering the whole of Iraq, and a depth to basement map. Longitudinal and transverse fault systems have been interpreted from the horizontal derivative of gravity, magnetic and seismic data and satellite images. In addition faults were identified during geological mapping. Major tectonic zones are defined which have characteristic tectonic histories and structural styles. The major tectonic boundaries and zones have exerted a fundamental control on basin subsidence and uplift during Phanerozoic time. These boundaries have been traced into the neighbouring countries. Many of the tectonic boundaries correspond to terrane boundaries in the Precambrian basement (Chapter 2). The regional structure of Iraq was studied using potential field data.

4.1 Bouguer gravity field

Gravity surveys (compiled by GEOSURV into 1: 1 ,000,000 maps) have been re-digitized (Fig. 4-1). The gravity map shows two major gravity lows (blue and green colours) separated by a major central gravity high (red and orange colours). The highest Bouguer gravity value is in the central gravity high in the Jezira area of NW Iraq (-25 MGal) . The Bouguer gravity value gradually decreases along the same zone to the SE within this gravity high to about 5 MGal to the west of Razzaza Lake in Central Iraq and to -30 MGal near the Iraq-Saudi border. In the eastern gravity low the Bouguer gravity value decreases towards the east to -90 MGal near the Iranian border associated with two rapid decreases along the Euphrates and Tigris Rivers. In the N of Iraq, a sharp N-S gradient is located along the Wadi Tharthar (west of the Tigris River between Mosul and Tharthar Lake). These gradient changes are helpful in defining the boundaries of tectonic zones and subzones. The western gravity low of W Iraq is complex. Firstly two gravity lows (green colour in Fig. 4-1) exist between longitudes 42° and 44° which may be associated with thick Infracambrian salt. These gravity lows are separated from a gravity low in the Rutba area of W Iraq by a series of NNW-SSE trending gravity highs. The Rutba gravity low is associated with thick Palaeozoic sedimentary rocks up to 8000 m thick.

In most parts of Iraq, apart from the Jezira gravity high of NW Iraq, the Bouguer gravity value is indicative of basement depth. The anomalous Jezira gravity high may be attributed to thinner continental crust or high density basement rocks. Various derivations such as the horizontal gradient of the gravity and residual gravity were used for the study of fault systems and delineation of structural highs. Comparison of the gravity residuals with seismic data indicates some correlation between structural highs and positive gravity residuals, except for residuals in S Iraq and the gravity low between longitudes 42° and 44° of W Iraq.

4.2 Total magnetic field map

The total magnetic field map, derived from the aeromagnetic map of GEOSURV, is presented in Fig. 4-2. The magnetic and gravity high of Central Iraq is represented by two flanking highly magnetic zones probably corresponding to ophiolite-bearing suture zones along the boundaries of the Ar Rayan Terrane. The two prominent NE-SW trending anomalies of relatively short wavelength in Central and S Iraq may indicate basic intrusions along transversal faults. Other more subtle transversal E- W anomalies are present. The apparent differences between the gravity and magnetic fields can be explained by the pseudo-gravity field calculated from the magnetic field. The pseudo-gravity map (Fig. 4-3) shows a relatively good correlation with the gravity map apart from in the Rutba area of W Iraq where low gravity corresponds to high pseudo gravity. This difference suggests that rocks of high magnetic susceptibility are present in the Precambrian basement of that region.

4.3 Crustal thickness

The crustal thickness was estimated from gravity data using Bouguer gravity regionalized to 100 km-'. The crustal thickness (Z) was derived from this regional grid using Woolard's equation Z=32-0.08*Gravity Difference (Alsinawi and Al-Banna, 1990). The calculated crustal thickness (Fig. 4-4) shows that the thinnest crust lies between the Jezira area of NW Iraq and the Southern Desert of SW Iraq. The crust is 33 km thick in the Jezira area and 34-35 km thick west of the Euphrates River. This interpretation is generally consistent with a profile based on combined deep seismic refraction, gravity and magnetic data (Fig. 4-5), which indicates a central high between Mesopotamia in the E and Rutba in the W (Alsinawi and Al Banna, 1990). The values of crustal thickness derived from this transect that runs from the Jordanian border through Baghdad to the Iranian border are lower than those values obtained from gravity interpretation The transect estimates of crustal thickness (Fig. 4-5) are 34 km at the Jordanian'

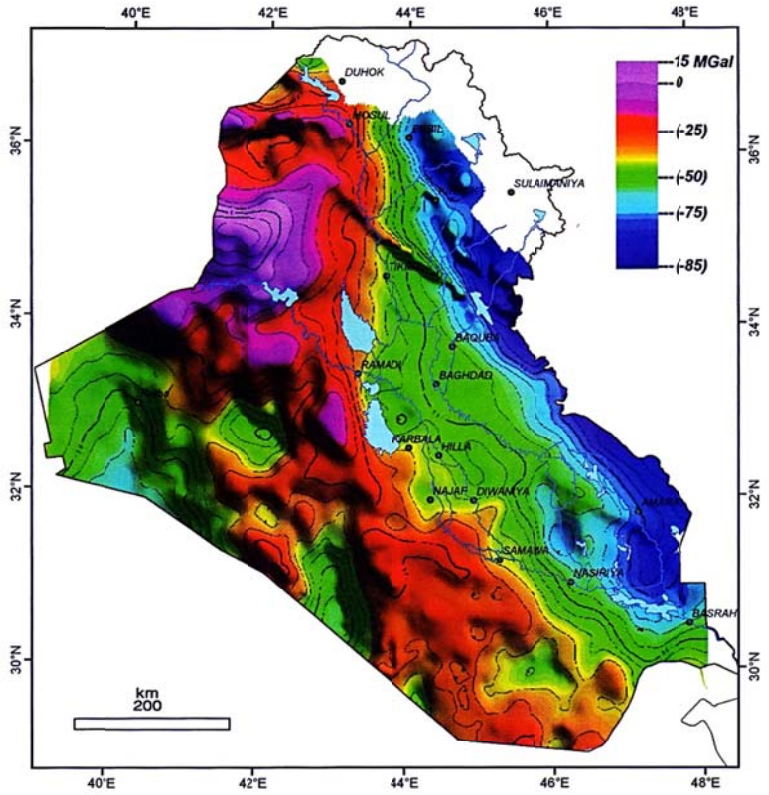


Fig. 4-1: Bouguer gravity

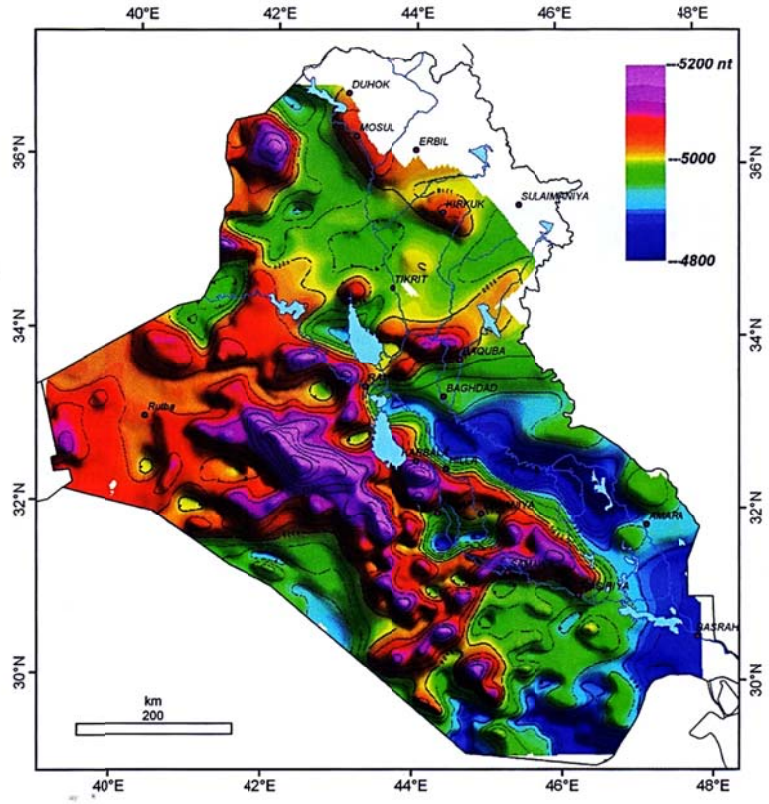


Fig. 4-2: Total magnetic field

Border, 27 km near the Euphrates River and 34 km at the Iranian border compared with estimates from gravity of 35.5, 35 and 37 km respectively. Additional information on crustal thickness IS

also given In Chapter 7.

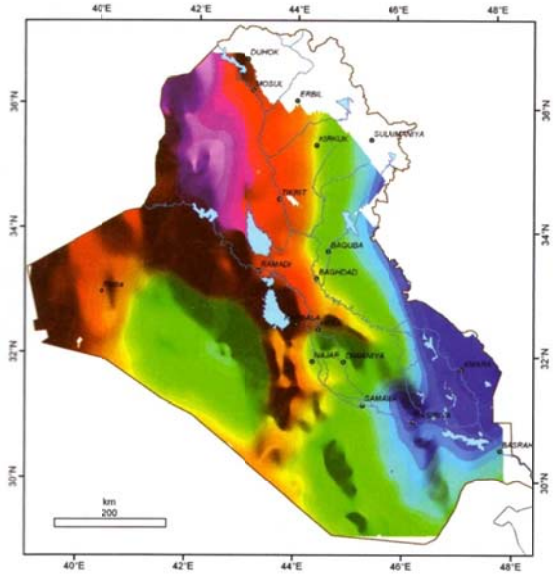


Fig. 4-3: Pseudo-gravity derived from the total magnetic field

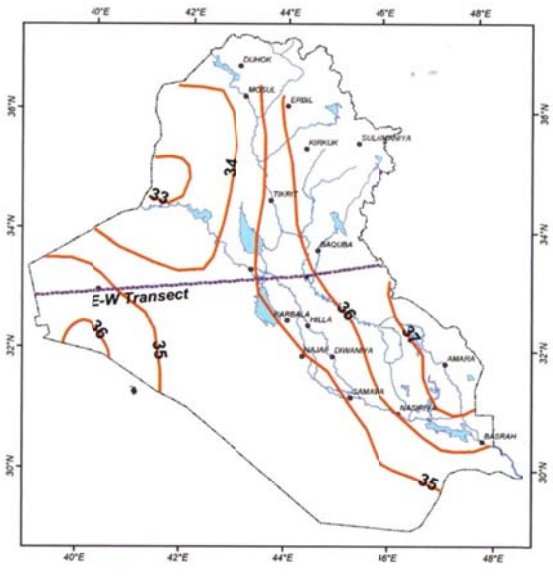
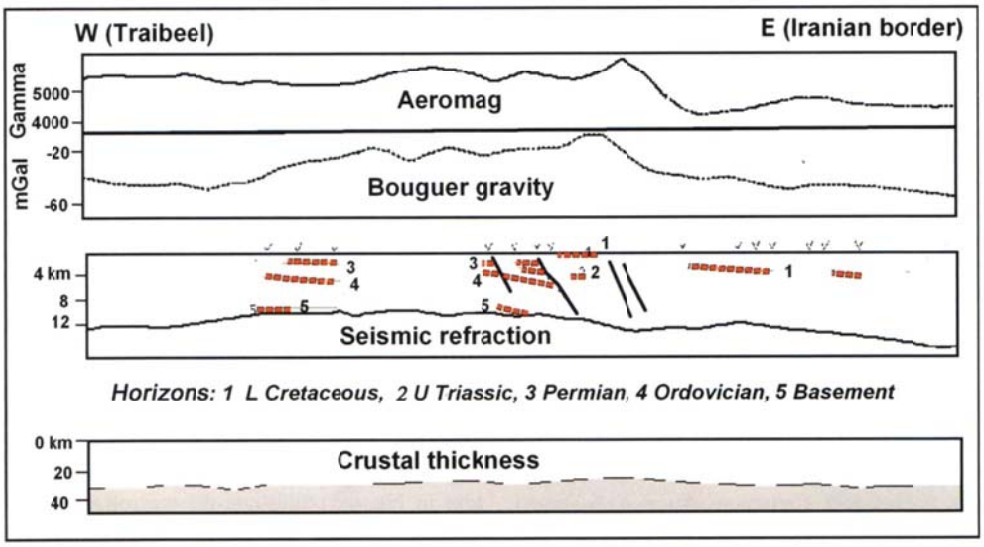


Fig. 4-4: Crustal Thickness in km derived from gravity

Fig. 4-5: E-W Transect. The seismological and tectonic data along this transect were compared with the available aeromagnetic, gravity and seismic refraction data (after Alsinawi and Al Banna, 1990)



4.4 Precambrian Basement Depth

The depth to basement map (Fig. 4-6) is the result of complex iteration between geological estimates and 3D inversion of gravity. The modeling was controlled by outcrops and wells (from Iraq and surrounding countries)

2D modeling of gravity profiles (21 profiles in Arabia, Iranian border, four of which were in Iraq). A model of basement depth was prepared from geological data based on thicknesses of Megasequences (Getech and Jassim, 2002). This approach provided an initial model which was then compared with the 3D gravity interpretation.

The map (Fig. 4-6) shows a central basement high (at depths of 5-7 km) flanked by two major structural lows on either side. This high was called the "Salman-Sharaf Divide" by Buday and Jassim (1987); in this book it is referred to as the Salman Zone. It is the northerly extension of a major Hercynian ridge, from central Arabia, containing N-S trending horst and graben structures with variable thicknesses of preserved Pre-Permian sediments. Directly bordering the Salman Zone in the W is a narrow area of deep basement in a graben active in Infracambrian and late Palaeozoic time probably associated with Infracambrian salt flanking the eastern side of Nukhaib Graben (Al-Bassam et al., 1992; Getech and Jassim, 2002). The interpretation shown in Fig. 46 is based on the assumption that both a complete Palaeozoic section and Infracambrian salt are present.

In the Rutba area of W Iraq, deep basement (at 7-11 km) indicates an inverted Palaeozoic basin in which an almost complete Palaeozoic section (up to 9 km thick) is present. This basin was inverted from the Late Permian and formed a major N-S trending high until the Tithonian when an ENE-WSW oriented structure was formed. N1S, E- Wand NWSE trending Upper Cretaceous basins were located within this inverted Palaeozoic basin. The basement low of Eastern Iraq is associated with the Mesopotamian Basin in which thick and continuous sedimentation took place from the Late Permian until the present. This basement low is segmented transversally into areas of deep and shallow basement (basement depth -6 Ian to -13 km).

In NW Iraq, an E- W trending basement low represents the Sinjar-Abdul Aziz Upper Cretaceous basin. A basement high that runs along this basin is associated with the Pliocene inversion which formed the Sinjar anticline. In NE Iraq, bordering the Zagros suture, the top of the basement is predicted to be at about 9 km depth beneath a thick Upper Cretaceous-Palaeogene flysch wedge. Between the basement low of the foothills and the basement low of the Plate margin there is a basement high (Qamchuqa Ridge) associated with the high mountains of the Zagros.

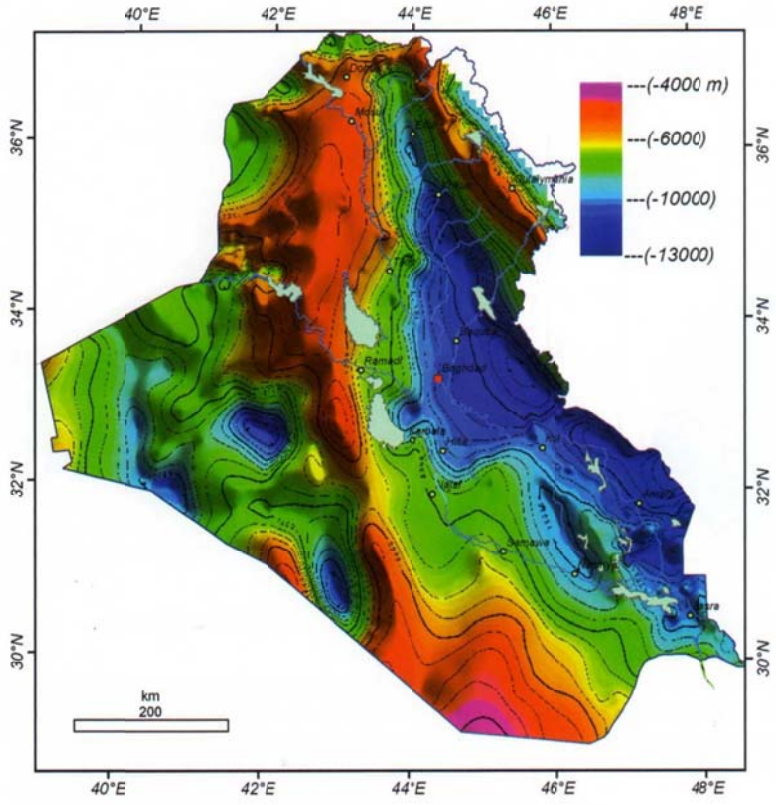


Fig. 4-6: Depth to the crystalline Precambrian basement (in metres relative to Sea Level) derived from 3D inversion of gravity (after Getech and Jassim, 2002)

4.5 Fault Systems

Faults were derived from various sources including satellite images, gravity and magnetic gradients, and to a lesser extent seismic data. The Total Horizontal Derivative of the gravity was found to be the most useful parameter for determining fault trends. The distribution of faults (background brown lines) is shown in Fig. 4-7. Major fault zones correspond to the NW-SE Najd Fault System (red) and the NE-SW Transversal System (blue). Five major transversal blocks are identified bounded by major transverse faults. The three major fault systems are the N-S Nabitah (Idsas) System, the NW-SE Najd System and the NE-SW or E- W Transversal System. These fault systems formed during Late Precambrian Nabitah orogeny. They were re-activated repeatedly during the Phanerozoic. The transversal blocks are shown in Fig. 4-8. A series of eight isopach maps presented in Figs. 4-9 and 4-10 and structural tops in Fig. 4-11 illustrate the control of the Transversal Fault Systems on regional subsidence.

Fig. 4-7: Distribution of faults and fault zones (see text for description of individual systems)

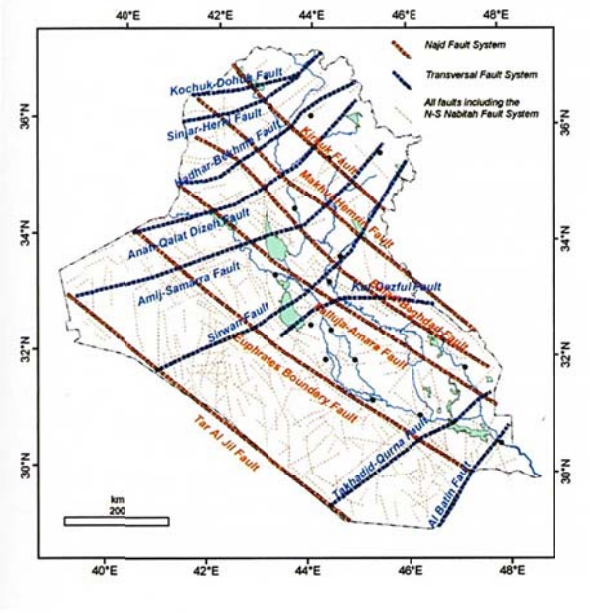
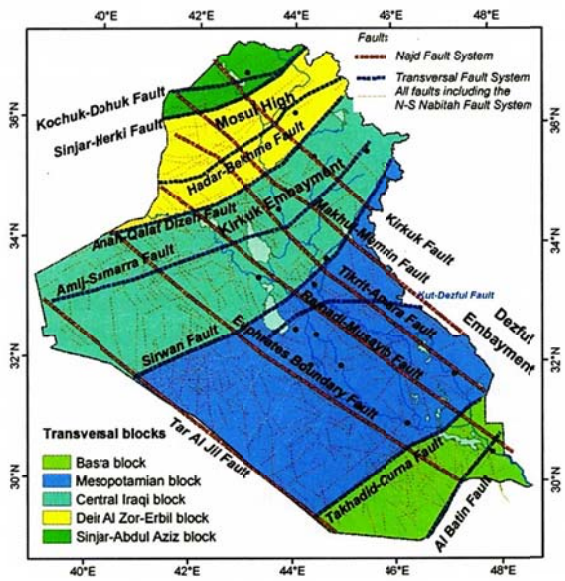


Fig. 4-8: Transversal blocks



4.5.1 Nabitah (1dsas) Fault System

The N-S trending Nabitah Fault System is prominent in S and W Iraq. It affects the thickness of the Infracambrian and Palaeozoic sections (Fig. 4-9A and B) and, to lesser extent, the Triassic section (Fig. *4-9C).* To understand *this fault sy*stem it is instructive to *look* in detail at the tectonic trends within the Arabian Shield. An aeromagnetic total field map of an area within the Arabian Shield was kindly provided by Dr Saad Al Mogren (Fig. 4-12). It shows N-S trending long wavelength anomalies with low magnetic intensity (blue areas) representing sedimentary basins. These anomalies alternate with N-S trending anomalies of high magnetic intensity in the Afif Terrane, which correspond to either intrusive rocks of the older Halaban Crust or to syn- and post-tectonic intrusions. These N-S structures are offset and deformed by the NW-SE trending Najd shears.

The fault system resulted from E- W compression, which formed major N-S trending thrust anticlines and associated molasse-filled foredeep (collapse) basins during the Nabitah Collision

(680-620 Ma). The aeromagnetic map (Fig. 4-12) shows that the Nabitah system is offset by the sinistral shear zones of the NW-SE Najd System. Similar features are seen in Central Iraq along the Euphrates River where the N-S trending horizontal gradient gravity-defined structures (discontinuities) are dragged and bent along the NW-SE trending Najd faults (Fig. 4-13).

The system in Iraq has been mostly identified from gravity data and is most commonly observed in SW, Sand W Iraq and less commonly in NW Iraq. Not all the N-S trending features shown are faults; some may be due to lateral changes in basement composition. The Nabitah System is older than the Najd system and originated around 680 Ma.

'Extension probably occurred along this trend to form the NS Infracambrian rift basins (Fig. 4-8A). It was reactivated during the "Hercynian" events in Late Carboniferous time as indicated by the isopach of the Palaeozoic. Erosion occurred over the Salman Zone which forms the central longitudinal unit in Iraq (Fig. 4-9B). Further reactivation of the Nabitah system occurred in the Late Cretaceous as indicated by depositional thinning and the presence of unconformities over some of the N-S trending structures of Kuwait and E Saudi Arabia. Neotectonic movements may have occurred along some structures of this system, including the Abu Jir and Tharthar faults in central and N Iraq and the Nukhaib Graben in SW Iraq (Fig. 4-7).

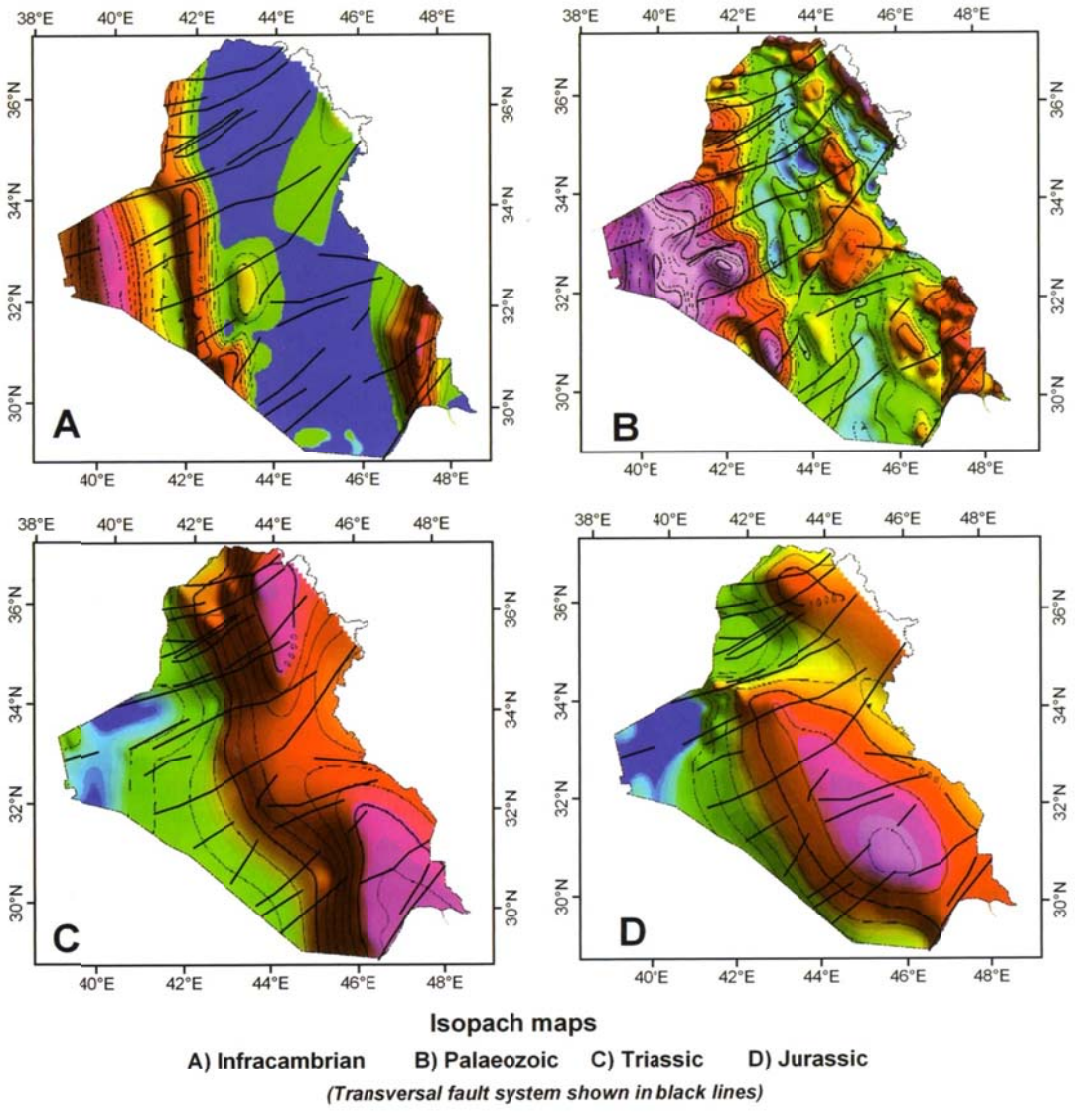


Fig. 4-9: Isopach maps with superimposed transversal faults for the Infracambrian-Jurassic. The Infracambrian isopach is based on gravity interpretation and published data from outside Iraq. The Palaeozoic isopach is based on limited data from W Iraq and data from the neighbouring countries. The colours indicate the relative thickness (purple/red is thick, blue is thin)

4.5.2 Najd Fault System

The Najd Fault System is very significant in Iraq as it forms boundaries not only of the Precambrian terranes but also of the tectonic zones, especially in central, E and NE Iraq. The faults of this system are best mapped from gravity interpretation but also have surface expression and can be identified on satellite images.

The system developed in a sinistral transpressional shear zone during the Nabitah orogenesis. It is spectacularly developed in the Arabian Shield (Fig. 4-12) in zones about 50 to 100 km apart. Some of the faults have up to 80 km of horizontal displacement. Three fault zones can be mapped within the Arabian Shield. Getech and Jassim (2002) mapped further shear zones outside the Arabian Shield; some of these zones occur in Iraq (Fig. 4-7). The displacement along some of the Najd shears decreases to the NW, largely due to partitioning of stress along some of the N-S trending Nabitah shear zones (AI Mogren, 2004).

The Najd System originated as a sinistral strike-slip faulting system around 670 Ma and was associated with deep ductile deformation that resulted in the rise of gneiss domes (Nehlig et al., 2002). It later developed as an extensional system from 640 Ma to 530 Ma. Al Mogren (2004) suggested that the Najd shearing can be dated as 680-640 Ma, based on the age of the dyke systems that may have been associated with the faulting. The NW-SE and NE-SW trending extensional volcanosedimentary basins are related to crustal thinning due to destacking of the Nabitah orogen (Husseini, 2000). Vertical movement along the Najd Fault System occurred during Jurassic to Quaternary time as demonstrated by the isopach maps of figs. 4-6 D and 4-10 A to D. The following fault zones are related to the Najd Fault System.

The **Tar Al Jil Fault Zone** runs along the Iraqi-Saudi border and is well defined on satellite images and from gravity data. It is associated with an escarpment of Palaeocene strata, facing a depression to the SW filled in with Mio-Pliocene clastics and fresh water limestones. The fault has thus been active in Late Tertiary time. It continues into W Iraq, NE Jordan and SE Syria.

The Euphrates Boundary Fault Zone is one of the most prominent Najd fault zones. It runs along the Euphrates River in S Iraq and continues towards the Rutba area in W Iraq. In the S the fault zone comprises a series of step faults sometimes associated with grabens, and forms the boundary between the Quaternary Mesopotamian Plain and the rocky desert of SW Iraq. It is associated with a large number of sulphur springs. In W Iraq the fault zone was reactivated during Late Jurassic and Cretaceous time forming small fault bounded depressions filled in with fluvial sandstones.

The **Ramadi-Musaiyib Fault Zone** is a prominent feature on the gravity gradient map. It controls the course of the Tigris River between Baghdad and Kut. It is associated with long NW-SE buried anticlines in S Iraq and controls the location of the buried W Baghdad structure. It continues NW toward Anah in W Iraq to the point where the Euphrates River changes direction from E to SE. The fault zone was probably active during the Mio-Pliocene time.

The **Tikrit-Amara Fault Zone** extends from the Jezira region in NW Iraq through Tikrit and Balad into Baghdad and Nahrawan. It continues along the SE trending stretch of the Tigris River between Kut and Amara. Major buried anticlines are located along this fault zone (Rafidain, Nahrawan, E Baghdad, Balad and Tikrit). Seismic and gravity data indicate that the zone is associated with a Late Cretaceous graben system (Aljawadi, 1990).

The **Makhul-Hemrin Fault Zone** has a magnificent surface expression represented by one of the longest anticlinal chains in the Middle East that includes Makhul in the NW, Hemrin North and Hemrin South in the Middle and Pesht-i-Kuh along the Iraq-Iran border in the SE. The same trend continues into SW Iran along some of the anticlines forming the NE coastline of the Arabian Gulf. This fault zone may be the boundary between the Eastern Arabian and Zagros Precambrian terranes (Chapter 2) and also forms the

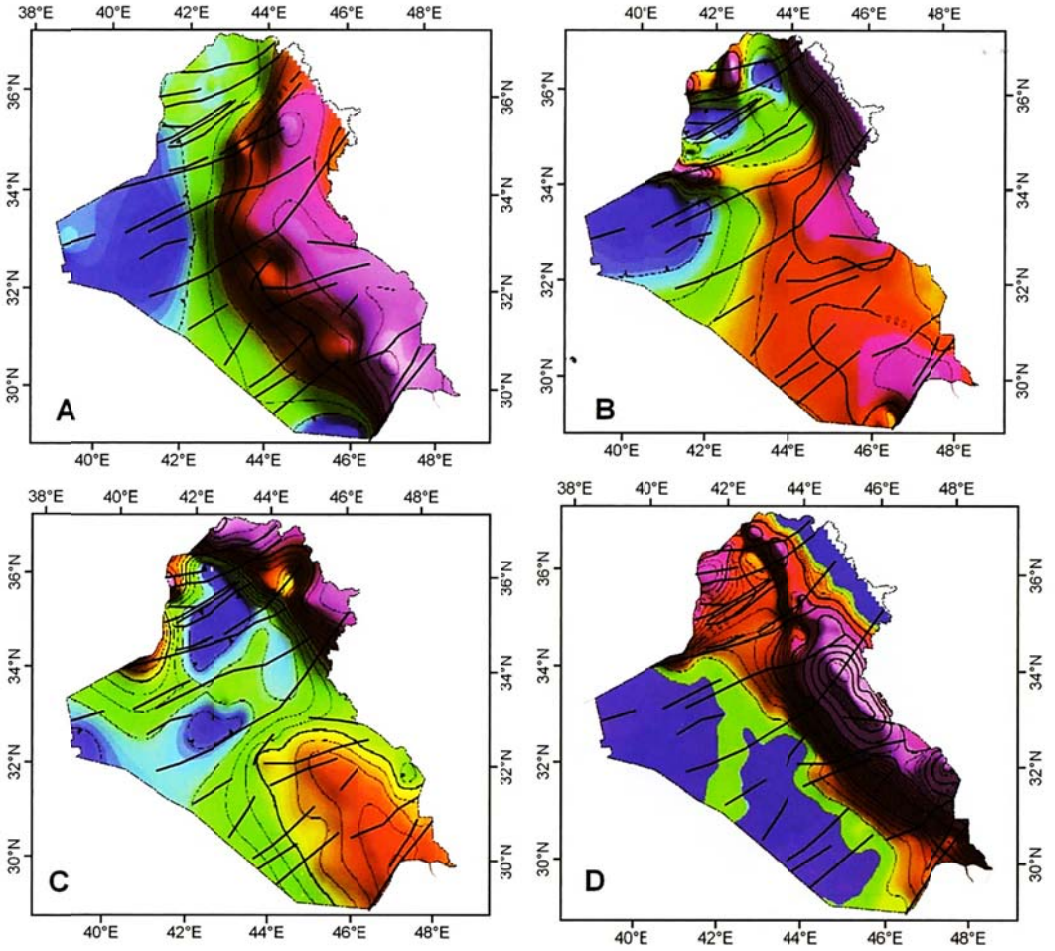


Fig. 4-10: Isopach maps with superimposed transversal faults for the Lower Cretaceous-Neogene. The colours indicate the relative thickness (purple/red is thick, blue is thin)

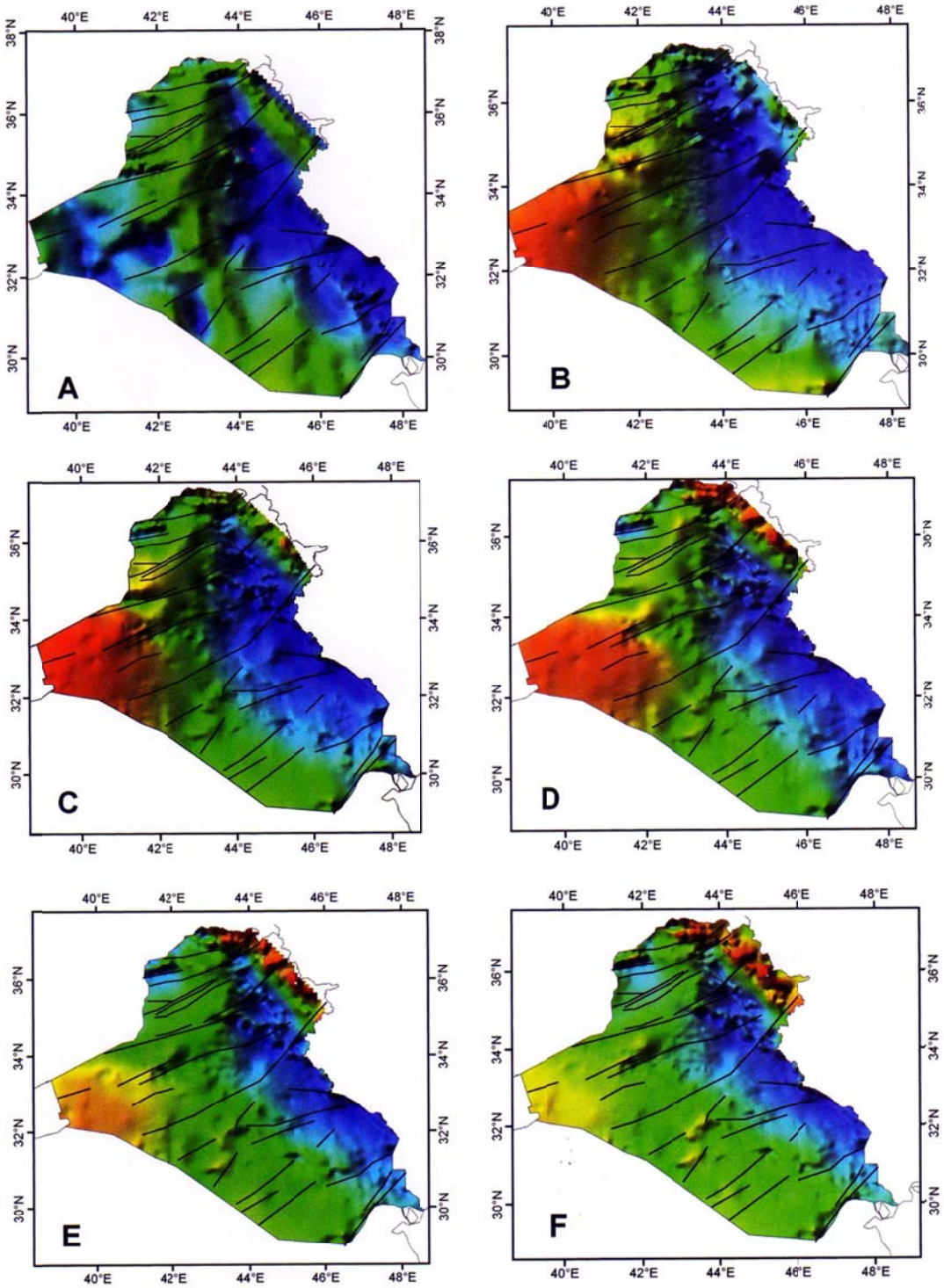


Fig. 4-11: Depths to tops of key horizons (datum Sea Level); red is shallow, blue is deep (after Getech and Jassim, 2002)

Boundary between the Stable and Unstable Shelf. Late Cretaceous extension may have occurred along this fault zone. It was strongly reactivated during the Pliocene and forms the SW boundary of the area affected by Late Tertiary folding. It is still active at the present day.

The Kirkuk Fault Zone is expressed on the surface by the 300 km long anticlinal range of Kirkuk and forms the boundary between two subzones of the Foothill Zone. It was active during the Plio-Pleistocene.

4.5.3 Transversal Fault System and transversal blocks

The Transversal system includes two main trends, the easterly trend which is more dominant in Wand NW Iraq and the northeasterly trend that dominates the E and N parts of Iraq. These two trends merge into each other to form arcuate faults. The Transversal systems may have formed in Late Precambrian times. Poorly defined E- Wand NE-SW trends occur in the Arabian Shield. The NE-SW trend might be a conjugate trend to the Najd Fault System. The easterly trend may have formed during Late Precambrian extension associated with igneous intrusions.

The Transversal System was reactivated from Late Jurassic times onwards resulting in the formation of transversal blocks. Some faults of this system underwent sinistral strike slip movement in Quaternary time; at least 2 km of horizontal displacement has occurred along the Anah-Qalat Dizeh Fault at Al Fatha in the last few million years. Many Foothill Zone anticlines are segmented into separate domes and their fold axes are bent at the intersections with transversal faults.

The Transversal Fault System may represent old planes of weakness which controlled the position of transform faults active during Neo- Tethyan Ocean spreading, and during the opening of the Red Sea. Their SW continuation into Africa is confirmed by satellite and gravity interpretations (Getech and Jassim, 2002). This suggests that this fault system extends from the Arabian Plate into the African plate. The transversal faults influenced the thickness of the Jurassic to Neogene sequences (Figs. 4-9 A and 4-10 A-D). Locally the transversal faults significantly affect the subsurface structure (Fig. 4-11 A-F), especially on the top of the Precambrian basement (Fig. 4-11 A). The system has been divided into major fault zones (Fig. 4-7). These are described below starting in the south:

The Al Batin Fault Zone runs from the SW to the NE along the Wadi Al Batin that forms the border between Kuwait and Iraq and originates from the eastern extremity of the Arabian Shield. It is very prominent on satellite images and also on gravity gradient maps. The sense of movement on the fault has varied but the fault has an overall downthrow towards the NW.

The Takhadid-Qurna Fault Zone comprises a series of faults defined on gravity gradient maps. It forms the N boundary of the Zubair Subzone and the Hormuz salt basin of Iraq. It influenced Palaeogene palaeogeography with down throw towards the SE. However, an overall downthrow towards the NW is evident along the fault on the Precambrian basement depth map (Fig. 4-11 A). The position of the fault, based on more recent magnetic and gravity data has been shifted slightly to the north in comparison to the position given by Buday and Jassim (1987). The Takhadid-Qurna transversal fault forms the northern boundary of the Basra Transversal Block (Fig. 4-8) whose S boundary is in Kuwait. This block subsided during the Late Cretaceous and Palaeogene. N-S trending structures are predominant in the Stable Shelf. In the Mesopotamian Zone they comprise prominent long buried anticlines and faults. The boundary between the Stable Shelf and the Mesopotamian Zone swings to an N-S direction in this block. In the SW of the block NW-SE structural trends occur.

The Kut-Dezful Fault Zone is defined on gravity gradient maps as a series of E- W, parallel, sometimes arcuate, faults which control the course of the Tigris near Kut. There is very limited displacement across the fault in Iraq (Fig. 4-7). To the east it passes into the Bala Rud flexure of SW Iran which forms the northern boundary of the Dezful Embayment and is associated with differential subsidence of over 5000 m during Mio-Pliocene time. W of the Euphrates Boundary Fault the Kut-Dezful Fault splits into a series of en-echelon faults. These faults influenced subsidence and sedimentation in Palaeogene time. They separated the Palaeogene phosphatic facies in the NW from the lagoonal- evaporitic facies in the SE. The Precambrian basement is displaced along the fault zone (Fig. 4-11 A).

The Sirwan Fault Zone runs along the Sirwan (Diyala) River in N Iraq. It extends into central and SW Iraq, defined by the horizontal gravity gradient. It forms the SE limit of the Kirkuk Embayment. The Sirwan Fault forms the N boundary of the Mesopotamian Transversal Block (Fig. 4-8) whose S boundary is controlled by the Takhadid-Quma fault. The Mesopotamian Block contains thick Cretaceous and Palaeogene sequences (Fig. 4-10 A, Band C) that thin to the NW of the Sirwan Fault. In NE Iraq the axis of the Cretaceous basins swings to the NE to the N of the Sirwan Fault. The Mesopotamian block is the largest Transversal Block with the deepest basement which dips uniformly to the NE. It contains low amplitude NW-SE and NE-SW trending swells and depressions.

The Amij-Samarra Fault Zone runs from the W towards central Iraq, just N of Samarra. It is mapped from gravity interpretation, and may have an overall downthrow towards the S.

The Anah-Qalat Dizeh Fault Zone is the most impressive transversal fault both morphologically and tectonically. It controls the course of the Euphrates River for a distance of over 100 km. The fault zone starts in W Iraq as a series of E- W trending step faults producing the so-called Anah Graben. They were active during the Late Cretaceous, producing a graben with over 2000 m of Upper Cretaceous sediments; on the adjacent footwall blocks the Upper Cretaceous section is less than 300 m thick. The E- W trending faults seem to continue into central Iraq but without significant displacement. They pass into a fault zone that intersects and displaces the Makhul-Hemrin range at Al Fatha. Plio-Pleistocene tectonic activity in the Stable Shelf is indicated by monoclines along the southern fault of the Anah-Qalat Dizeh Fault zone. Neotectonic activity is proven by several recorded earthquakes (Chapter 7). The fault forms the N limit of the Kirkuk Embayment, the Central Iraqi Block (Fig. 4-8) and the SE boundary of the Mosul High.

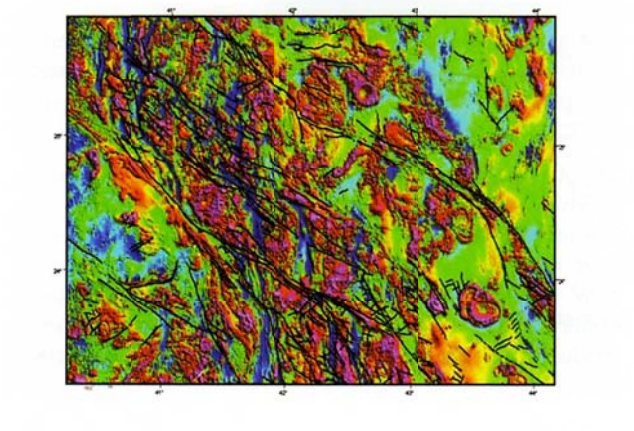
The Hadhar-Bakhme Fault Zone starts in Syria and NW Iraq. Its strike changes from W-E to NE-SW towards the folded belt. It passes through Qaiyarah and runs along, and slightly S of, the Greater Zab River. Recent salt playas are located along the fault zone suggesting that it is active at present. The overall vertical displacement of the fault zone is towards the south. The fault forms the southern boundary of the crestal block of the Mosul High.

The Sinjar-Herki Fault Zone forms the southern boundary of the Foothill Zone of NW Iraq and the Sinjar-Abdul Aziz Basin of Syria. It was active during Late Cretaceous time and probably during the Triassic. The fault zone has an easterly trend in the Stable Shelf area and a northeasterly trend in the folded belt. It forms the N boundary of the crestal block of the Mosul High with an overall displacement towards the N. The Sinjar-Herki transversal fault forms the N boundary of the Deir Al Zor-Erbil block (Fig. 4-8) whose S limit is located along the Anah-QalatDizeh transversal fault. The Deir Al Zor-Erbil block consists of two sub-blocks, the northern higher Khlesia-Mosul Subblock and the southeastern Anah-Kirkuk Sub-block. The former is the most prominent; it

forms the main divide between the Taurus and Zagros segments and divides the foredeep area into the Taurus and Zagros Foredeeps. The Khlesia-Mosul Sub-block is the most prominent and highest transversal structural unit in Iraq. It defines the Mosul High, which strongly influenced Cretaceous palaeogeography as recognized by Dunnington (1958), Chatton and Hart (1960 and 1961) and Buday and Jassim (1987). This transversal sub-block has affected all the longitudinal units of Iraq. It has formed the broadest basement elevation in the N part of the Stable Shelf since the Mesozoic. Palaeogeographically the sub block remained a high at least until the Palaeogene. The westernmost part of the sub-block subsided in Neogene time as a result of the Late Tertiary subsidence of the Euphrates Basin in Syria (Ponikarov et al., 1967).

The Kutchuk-Dohuk Fault Zone is traced on gravity gradient maps as an E- W trending structure. However, very little is known about this fault zone. It may have an overall displacement towards the south and hence may form the N limit of the Sinjar-Abdul Aziz Upper Cretaceous basin. It may also form the N limit of the Triassic Palmyride system that may have extended into N Iraq.

Fig. 4-12: Reduced-to-pole magnetic field map of the central part of the Arabian Shield. Red is high magnetic, blue is low magnetic and faults in back



4.6 Basic structural units of Iraq and basis of zonation

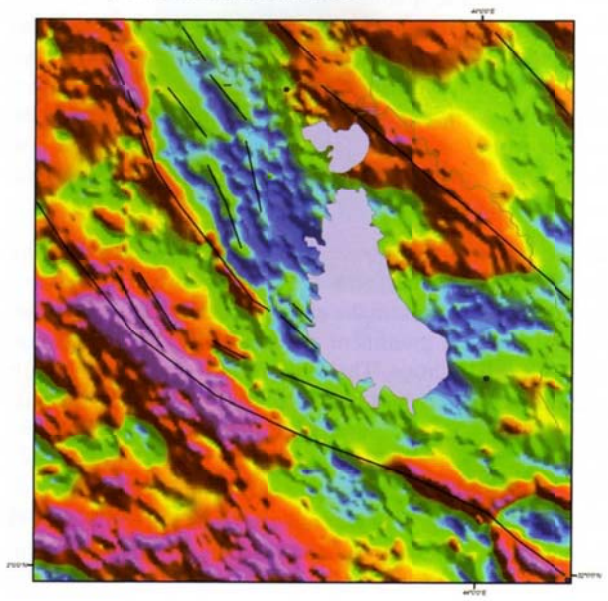
The two basic tectonic units of Iraq are the Arabian Shelf and Zagros Suture Zone. Henson (1951) placed the boundary between these units along the eastern border of the folded zone. In this book, the boundary of the Arabian Shelf with the Zagros Suture units is simply defined as the thrusted contact of the allochthonous Cretaceous radiolarian chert, Tertiary volcanosedirnentary units, or metamorphosed Mesozoic units with the underlying autochthonous platform carbonates, flysch and molasse. The Balambo-Tanjero Zone and the Ora Zone, which were included within the "geosynclinal" units by Buday and Jassim (1984 and 1987), are now considered to be an integral part of the Arabian Shelf.

The main structural elements recognized and described before the zonation of Buday and Jassim (1987) were often related to structures caused by the Alpine orogenic events. The principal tectonic units thus trend parallel to the Alpine chain; NW-SE in NE Iraq or E-W in N Iraq. Tectonic units of other orientation include the Ga'ara (or Rutba) and Mosul uplifts and the Anah Graben.

The two major units of the Arabian Shelf are the Stable Shelf and Unstable Shelf (Fig. 4-14). According to Buday and Jassim (1984 and 1987), the boundary between these two units was located at the western boundary of the Mesopotamian depression. The boundary is defined by a N-S gravity gradient in S Iraq. It continues along the Euphrates River near Nasiriya. It then follows the Euphrates Boundary Fault to Razzaza Lake, and the Abu Jir Fault line to Hit. To the north of Hit it swings along a transversal fault system towards the E and then swings N, running along the Tharthar Line until Hatra. From Hatra it swings NW towards the Sinjar-Herki Fault changing direction towards the Syrian border along a WSW trend. The definition of the boundary of the Stable Shelf has been changed in this book: the Mesopotamian Zone is now considered to be part of the Stable Shelf. The SW boundary of the Stable Shelf is now taken at the limit of the Late Tertiary deformation defined by the long anticlines of Makhul-Hemrin-Pesht-i-Kuh. The Mesopotamian Zone is now considered to contain the N-S trending structural elements that dominate all the units of the Stable Shelf especially evident in Kuwait, Saudi Arabia and S Iraq. The N-S trending units of the Stable Shelf are truncated by the E-W (Tauride) and NW-SE (Zagros) trends.

The Alpine longitudinal units of the Unstable Shelf define the zones and subzones. In the Stable Shelf the zone boundaries generally follow N-S trending lineaments; subzones are delineated by transverse faults.

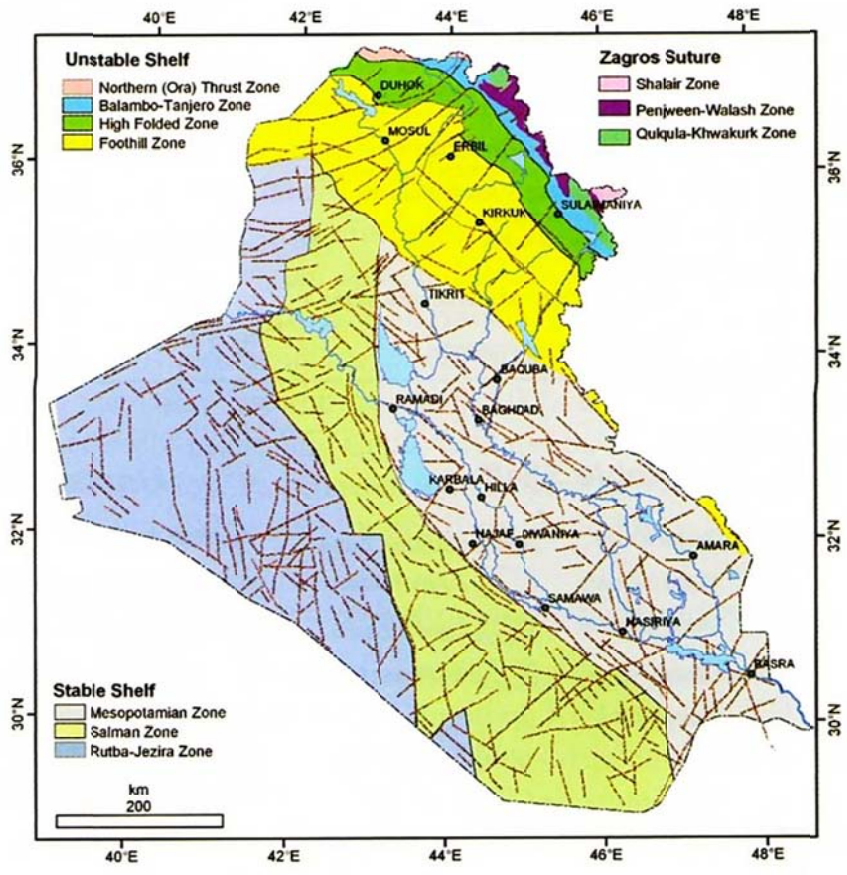
Fig. 4-13: Gravity horizontal gradient of central Iraq showing bending of N-S structures along the NW-SE Euphrates Boundary Fault. Interpreted faults are black lines



4.7 Longitudinal Zones

Iraq can be divided into three tectonically different areas: the Stable Shelf with major buried arches and anti forms but no surface anticlines, the Unstable Shelf with surface anticlines, and the Zagros Suture which comprises thrust sheets of radiolarian chert, igneous and metamorphic rocks. These three areas contain tectonic subdivisions which trend N-S in the Stable Shelf and NW-SE or E-W in the Unstable Shelf and the Zagros Suture. The N-S trend is due to Palaeozoic tectonic movements; the E- Wand NE-SW trends are due to Cretaceous-Recent Alpine orogenesis. The longitudinal tectonic units are shown in Fig. 4-14.

Fig. 4-14: Longitudinal Zones of Iraq



The **Stable Shelf** which covers most of central, Sand W Iraq extends westwards into Syria and Jordan and Southwards into Kuwait and Saudi Arabia. It is divided, in Iraq, into three major tectonic zones comprising the Rutba-Jezira Zone in the W, the Salman Zone, and the Mesopotamian Zone in the E. The three tectonic zones of the Stable Shelf are described briefly below. More detailed descriptions are given in Chapter 6.

The Rutba Jezira Zone is an inverted Palaeozoic basin with a Syn-Hercynian basin. It is dominated by the Rutba Uplift which is a major dome. The flanks of the dome dip to the E and SE towards the Euphrates River and to the Wand NW towards Jordan and Syria. The Salman Zone is a syn-Hercynian high. It subsided strongly in latest Palaeozoic-Triassic time. It forms
'a monocline; the Tertiary section dips towards the Euphrates River. The Mesopotamian Zone contains the Tigris and Euphrates rivers in central and S Iraq and is covered with Quaternary sediments which overlie a complete Mesozoic and Cainozoic section.

The Unstable Shelf can be divided into four tectonic zones. The Foothill Zone is characterised by long anticlines with Neogene cores and broad synclines containing thick Miocene-Quaternary molasse. The High Folded Zone is characterised by anticlines of high amplitude with Palaeogene or Mesozoic carbonates exposed in their cores. The zone was uplifted in Cretaceous, Palaeocene and Oligocene time but was also the site of an Eocene molasse basin.

The Balambo- Tanjero Zone formed a basin near the plate boundary, which subsided strongly from the Tithonian onwards. It was filled in by thick fluvial and marine clastics from Maastrichtian time onwards. It is characterised by imbricated structures with overriding anticlinal structures.

The Northern Thrust (Ora) Zone is an uplifted zone which developed along the plate margin during the Cretaceous and is characterised by thrusted anticlinal structures.

The Zagros Suture can be divided in Iraq into three tectonic zones. From SW to NE these are the Qulqula-Khwakurk, Penjween- Walash and Shalair zones.

The Qulqula Khwakurk Zone is characterised by isoclinally folded radiolarian cherts with volcanics and occasional ultramafic rocks (Coloured Melange) with imbricates of the underlying Arabian Shelf carbonates (Permian to Jurassic). It is overthrust in the SE by Triassic carbonates. Its sediments were deposited on the margin of the Southern Neo- Tethys Ocean during the Tithonian-Cenomanian and obducted onto the Arabian *Shelf* in Late Cretaceous time.

The Penjween Walash Zone comprises metamorphosed volcanic and sedimentary rocks of Cretaceous age derived from the NeoTethys, and Eocene arc and fore-arc units.

The **Shalair Zone** is part of the Sanandaj-Sirjan Zone of Iran. It is characterised by metamorphosed Palaeozoic sequences of the Sanandaj-Sirjan microplate, overlain by Triassic to Cretaceous low grade meta-sediments and meta-volcanics formed at the margin of the Neo-Tethys, including Upper Cretaceous arc volcanics.

The tectonic map of Iraq reconstructed from Buday and Jassim (1984) is presented in Fig. 4-15. In addition to the tectonic zones, the map also locates oil fields and drilled structures, surface structures, buried anticlines and faults. Locations of oil fields and prospects are derived from Al-Gailani (2003).

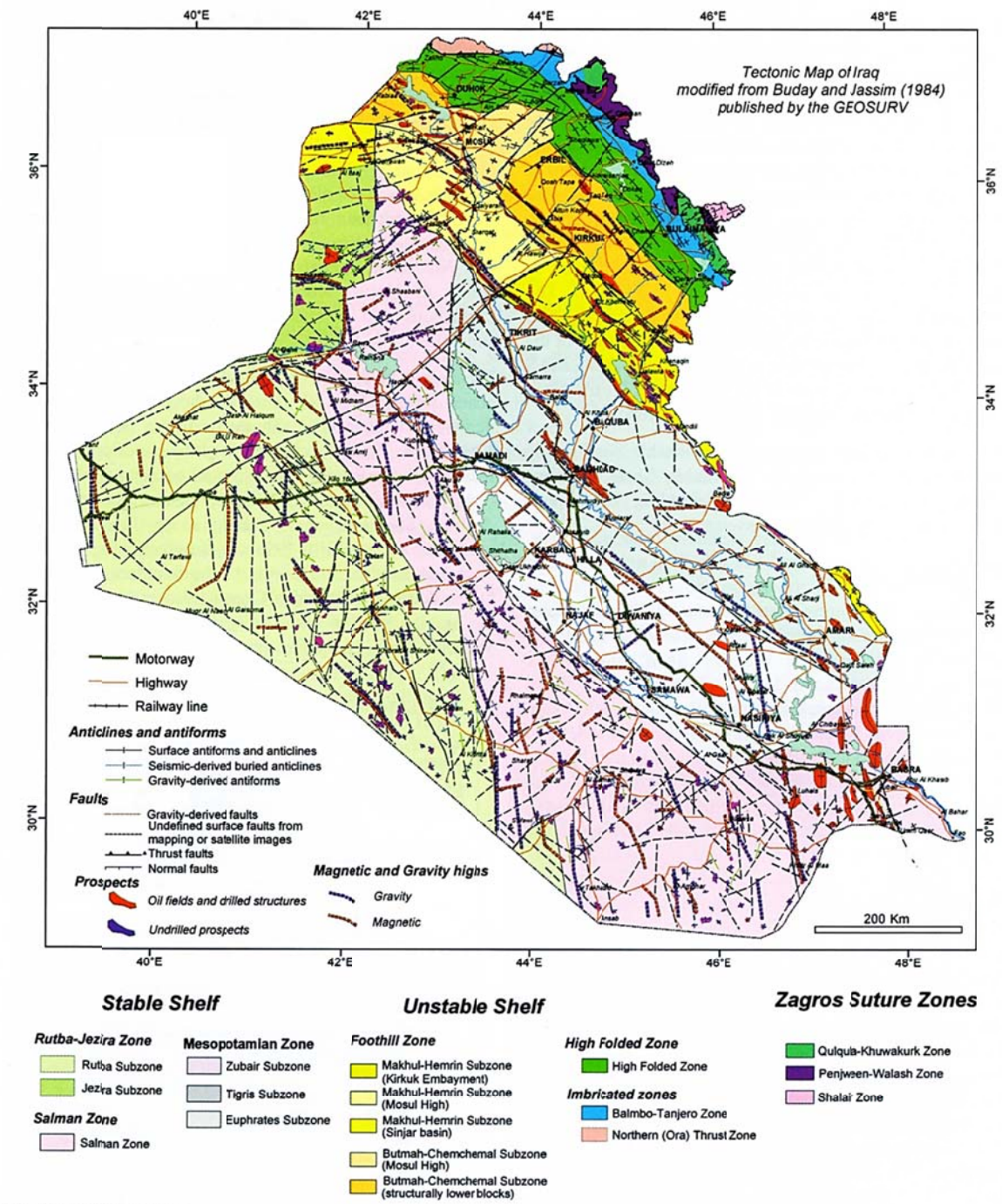


Fig. 4-15: Tectonic map

CHAPTER 5

Units of the Stable Shelf

by

Saad Z. Jassim and Tibor Buday

5.1 Outline of major divisions

The Stable Shelf is a tectonically stable monocline little affected by Late Cretaceous and Tertiary deformation. The orientations of the structures in this tectonic unit were influenced by the geometry of the underlying basement blocks and faults, Palaeozoic epirogenic events and Mesozoic arching. The depth of the Precambrian basement varies between 5 km in the centre of the shelf to 11 km in the Wand 13 km in the E (Fig. 4-4).

The original definition of the Stable Shelf (Buday and Jassim, 1987) has been modified to include the Mesopotamian Zone as discussed in Chapter 4. The E boundary of the Stable Shelf is now located along the SW flank of the long anticlinal range of Makhul- Hemrin- Pesht I -Kuh. The Stable Shelf is now divided into three major tectonic zones, from the west, these are: the Rutba-Jezira, Salman and Mesopotamian Zones.

5.2 The Rutba-Jezira Zone

The Rutba-Jezira Zone is an inverted Palaeozoic basin; the inversion began in the Late Permian. Its basement was relatively stable during Mesozoic-Tertiary time and more mobile during Infracambrian and Palaeozoic times. Basement depth ranges from 5 km in the Jezira area to 11 km S of Rutba (Fig. 4-4). The Jezira area was part of the Rutba Uplift domain in Late Permian to Early Cretaceous time. Following the Cretaceous the Jezira area subsided while the Rutba area remained uplifted; these two areas are thus differentiated as separate subzones.

The Rutba Uplift dominates the Rutba-Jezira Zone. It has previously been linked to the wider Hail-Rutba-Mardin High. However the thickness and facies of its Mesozoic sequences suggests it has often acted as a separate block sometimes affecting NW Saudi Arabia and NE Jordan but mostly affecting E Syria and Wand NW Iraq. The Hail Uplift, based on gravity data, is a N-S trending Hercynian uplift that terminates in SW Iraq; it was later partially affected by Mesozoic arching. The Mardin High is an E- W trending uplift that affected SE Turkey and persisted from Triassic to Albian time.

The eastern boundary of the Rutba-Jezira Zone lies along the W slopes of the Sinjar-Sharaf gravity high. The previously established boundary of Buday and Jassim (1984 and 1987) has been modified. The western boundary can be traced along the Iraq-Jordan border, along a N-S gravity and magnetic high. In Jordan the Stable Shelf belongs to the Risha -Tabuk Zone (Getech and Jassim, 2002) which represents a Hercynian easterly-tilted monocline; the Rutba Jezira Zone represents a syn-Hercynian depression.

The Anah-Qalat Dizeh Fault divides the Rutba-Jezira Zone into the more stable Rutba Subzone in the S and the Jezira Subzone in the N; the latter being more mobile since the Late Cretaceous. Both subzones contain large basement highs: the Rutba-Ga'ara high in the S and the Deir Al Zor - Khlesia high in the N. The unit between the two highs is the Anah Trough (often referred to as the Anah Graben).

The Rutba-Jezira Zone contains thick Palaeozoic sediments. Upper Permian, Lower to Middle Triassic and pre Albian Lower Cretaceous sediments are absent. The Jezira subzone was uplifted and eroded during Mid Devonian (Caledonian) time; the Rutba Subzone was mostly not affected by this deformation. The Jezira Subzone also subsided during Late Eocene to Miocene time when the Rutba Subzone was uplifted. A NW-SE cross section from Syria to the Rutba area is shown in Fig. 5-1. The Tanf- Khlesia Zone of Getech and Jassim (2002) shown in the cross section is a continuation of the Jezira Subzone of Iraq; the Silurian sequence has been deeply eroded. The Upper Permian and most of the Triassic section is absent in both subzones.

5.2.1 The Rutba Subzone

The Rutba Subzone is the most extensive and uplifted part of the Rutba-Jezira Zone, dominated by the huge Rutba Uplift active in Late Permian-Palaeogene time, the Cretaceous Ga'ara anticline and the ENE-WSW trending Hauran anticlinorium. The sedimentary cover of the Rutba Subzone starts with the Infracambrian section (300-1500 m thick). The Palaeozoic section thickens from 3500 m in the N to 8500 m in the S. Triassic, Jurassic and Lower Cretaceous sediments are absent in the northern part of the subzone; they are up to 800, 1000 and 300 m thick respectively in the SE. Upper Cretaceous sediments are up to 800 m thick. Palaeogene and Neogene sediments are up to 500 and 200 m thick respectively in the SE.

5.2.1.1 Geological and geomorphological characteristics

The Rutba Subzone contains the Ga'ara depression which is located above the broad N-S trending Rutba Uplift, and the E-W trending Ga'ara anticline. Numerous unconformities occur within the Mesozoic and Palaeogene section. The Lower Permian Ga'ara Formation is unconformably

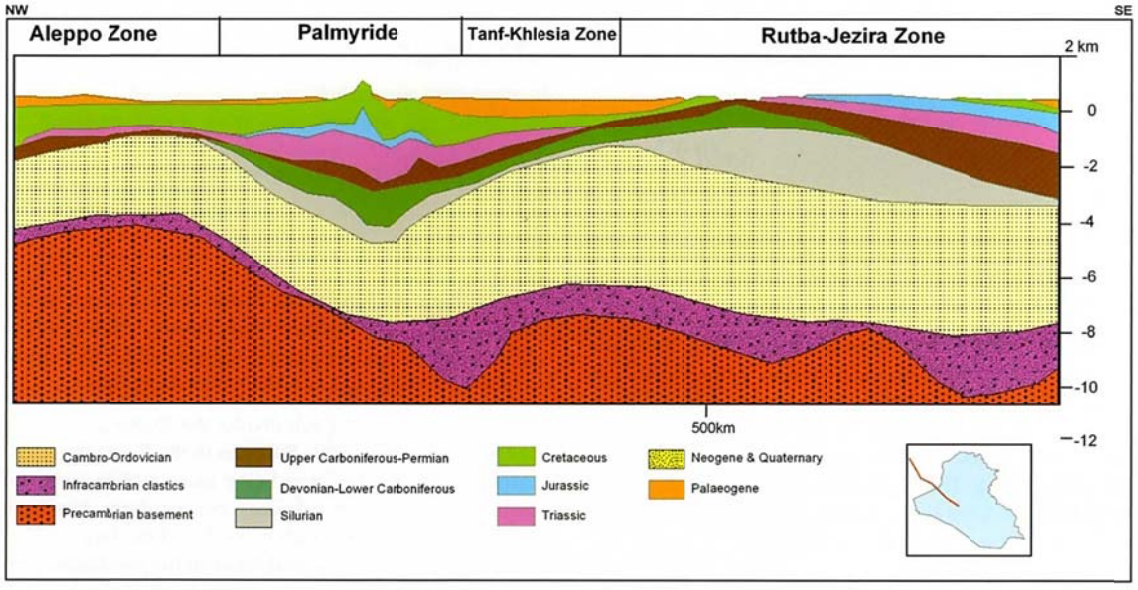


Fig. 5-1: Cross section within the Stable Shelf of Western Arabia starting from Aleppo in the NW and terminating at the Nukhaib Graben in the SE

Overlain by Upper Triassic carbonates that form the cliffs on the southern rim of the depression. Along the W, N and E side of the depression, the Lower Permian sediments are unconformably overlain by Upper Cretaceous, Palaeocene and Eocene beds. To the SE, the Triassic carbonates are unconformably overlain by Jurassic cyclic sequences (Fig. 52); each sequence comprises fluviatile and shallow marine clastics which pass transitionally up into neritic carbonates. The Jurassic strata strike NE-SW; the Lower Cretaceous beds strike ENE-WSW and the Upper Cretaceous beds strike E- W. Numerous NW-SE trending normal faults were mapped in the outcropping Jurassic sequences (Fig. 5-2). They were probably active in Tithonian to Early Senonian time.

The area W of Rutba is dominated by N-S trending Campanian-Palaeogene strata that are characterised by relatively deep water phosphorites. On the SE flank of the Rutba High, Lower Miocene transgressive shallow water carbonate and clastics outcrop. Quaternary gravel deposits fill surface depressions. A profile through Iraq (connecting the Risha area in NE Jordan and Naft Khaneh in the Foothill Zone in E Iraq) shown in Fig. 5-3 indicates the subzone is mainly an inverted Palaeozoic basin with an almost complete Palaeozoic sequence compared to the neighbouring zones to the E and W.

The western desert of Iraq has a NE-inclined land surface with a gradient of 10-20 m per kilometer from the Iraq Jordan-Saudi border point (980 m elevation) to the Euphrates River (l00-200 m elevation). It is usually a plane surface mostly covered by desert pavement (Serir) but locally it is very rocky where dissected by active wadis producing the Hamada land surface (Central and SE parts, Fig. 5-4).
There are four distinct drainage systems: **1**) a strongly incisive E- W wadi system to the Sand SE of Rutba. **2**) the incisive NE-SW trending Wadi Hauran and its tributaries which are controlled by the strike of the Triassic and Jurassic sequences that contain alternating softer clastics and relatively harder carbonates (Fig. 5-8 inset B). **3**) a shallow, broad N-S trending system Wand SW of Rutba controlled by the N-S strike of Palaeogene strata (Fig. 5-8, inset C) and **4)** a moderately incisive NNE-SSW trending system north of the Ga'ara area flowing through Miocene outcrops to the Euphrates River.

Important depressions within the Rutba Subzone comprise the Ga'ara depression (a structural-denudational unit), the Umm Chaimin crater (formed by an impact or gas explosion) and the Ma' ania depression (a structural depositional unit). The Ga'ara depression formed by erosion of thin carbonate beds which overlie softer less resistant Permocarboniferous clastics.
The Ma'ania depression which lies above the Nukhaib Graben (Figs. 5-8 and 5-9) is over 100 km long, 20 km wide and 20 m deep. Palaeocene rocks outcrop on both sides of the depression; Middle Eocene limestones occur in isolated outcrops protruding through -20 m of gravel (Nukhaib Gravel) in the middle of the depression. All the E- W wadis SE of Rutba drain into the depression forming coalescing fans which lead into one exit drainage point (Wadi Ubayidh). The depression is structurally controlled by the Nukhaib Graben. AI-Bassam et al. (1992) indicated that 50 m of extension has occurred in the graben. They noted that a gravity low in the northern part of the graben is associated with a major dome at Top Cambrian level (Fig. 5-5). They suggested that the gravity low may indicate the presence of Infracambrian salt. Getech and Jassim (2002) modeled the gravity low to the east of the Nukhaib Graben and also oncluded that Infracambrian salt is probably present.

Fig. 5-2: Geological map of the Rutba Subzone. Solid purple lines are mapped faults

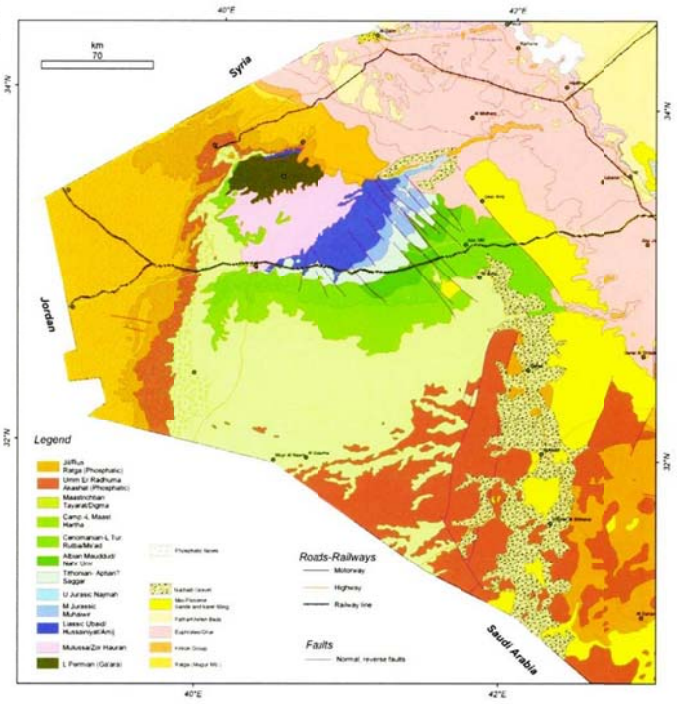
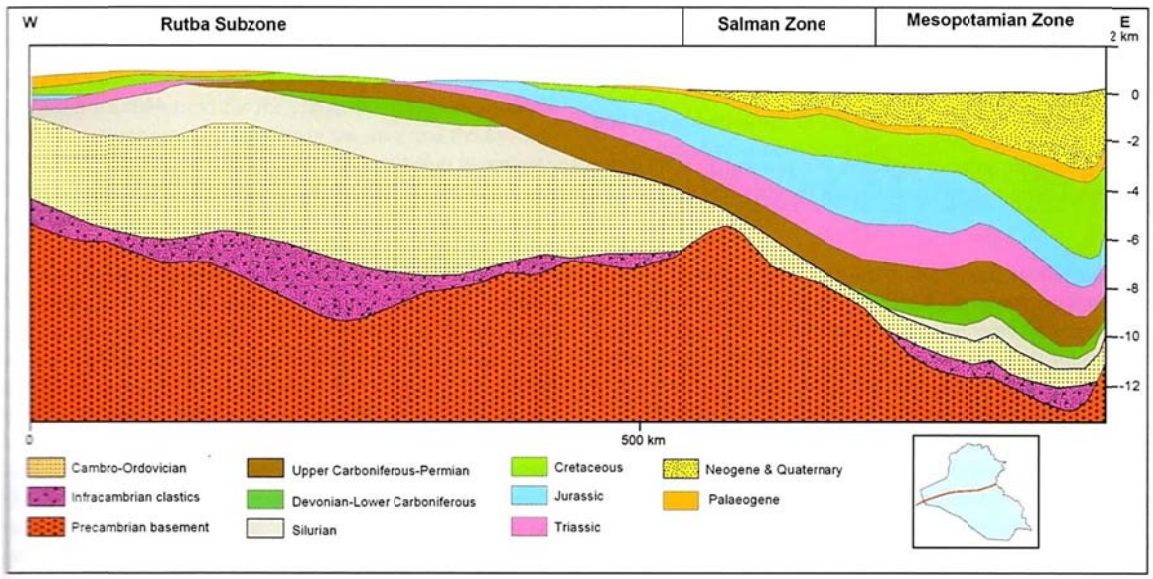


Fig. 5-3: Profile between Risha, NE Jordan to the Iranian border near Naft Khana



The Urn Chaimin crater is located about 45 km WSW of Rutba. It is 2 km wide (Fig. 5-8, inset B and Fig. 5-6) and was previously assumed to be an impact feature. The crater is hidden in a flat desert plain formed of Lower Eocene carbonates. Massive metric size boulders of silicified limestone of Lower Eocene age are strewn around the crater. The rim of the crater is formed of massive to thick-bedded, silicified Lower Eocene carbonates (about 45 m thick); which are overlain in the N and NW by Middle Eocene silicified lithographic limestone with chert nodules. The rim area is also covered by about 3 m of ejected material consisting of fragments of marly limestone, marl and limestone of Palaeocene and Maastrichtian age sitting on Middle Eocene chalky limestone.

Inside the crater, the relatively steep cliff gives way at a depth of about 40 m to a gentler slope of pediment material which lead from all sides to a central clay playa 1 km wide. The playa and the pediment apparently overlap and interfinger. Drilling in the central playa (by GEOSURV) showed that centre of the crater contains 76 m of compact fine illite clay underlain by 35 m of breccia. The bottom of the well reached Cretaceous strata at a depth of 110 m (Jassim, 1981b). Observations by numerous geologists have failed to establish the presence of high pressure structures and minerals that would have resulted from an impact. Geochemical sampling of soils in the surrounding desert mantle did not reveal anomalies of base metal; thus a volcanic origin may be eliminated. Gravity and magnetic surveys of GEOSURV in 1968 indicate that igneous rocks do not occur below the crater. Satellite images of the surrounding area show numerous buried circular features suggesting the depression may not be the result of an isolated event.

The crater was first described by Mitchell (1953) who assumed it to be of impact origin. AI-Din et al. (1968) proposed a karst origin for the crater, but this is inconsistent with the proportion of limestone in the area and the low rain fall of <100 mm/year which do not support this hypothesis. Jassim (198Ib) suggested the crater formed by a gas explosion. The scattered surface boulders and fragments around the rim were clearly ejected from deeper levels. The crater is located only 25 km E of the Risha gas field in NE Jordan where gas occurs in Ordovician and Silurian sandstones reservoirs. It is located on the mega Hauran anticlinorium and is associated with a N-S and E-W trending fracture system indicated by the drainage orientation and satellite image interpretation. The Silurian gas may have seeped from Palaeozoic sandstones through fractures and accumulated in reservoirs below Upper Cretaceous shales. when gas pressure increased above the hydrostatic pressure at roughly 100 m depth an explosion followed by gas combustion may have occurred.

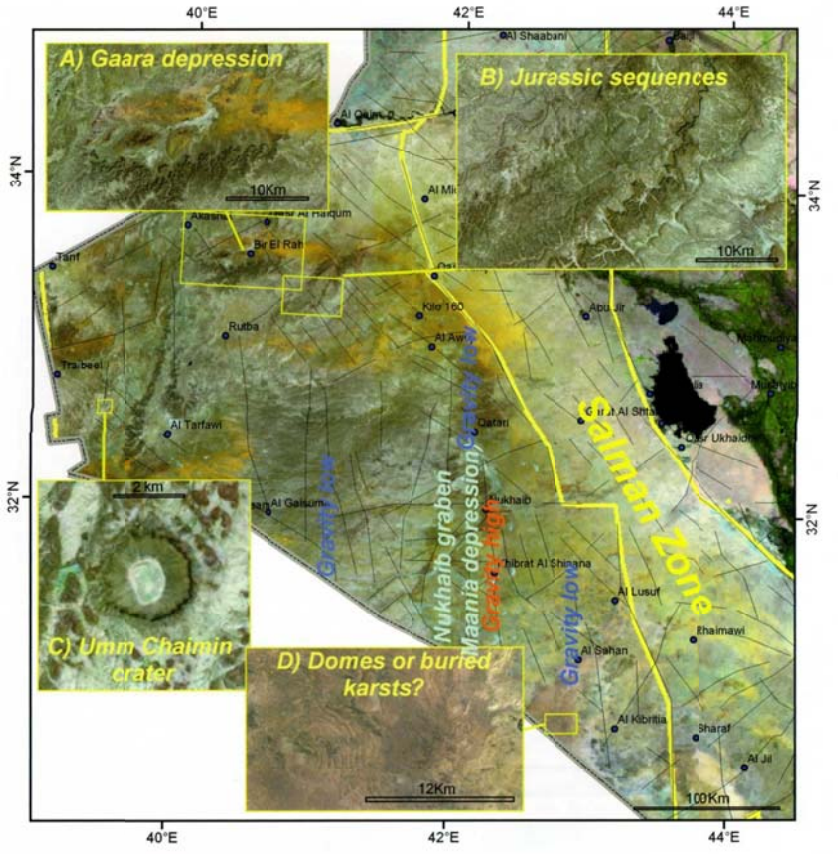


Fig. 5-4: Satellite image of the Rutba Subzone with inset for the Ga'ara depression (Inset A), the Jurassic system exposure area (Inset B), the Umm Chaimin crater (Inset C), and the contorted Palaeogene sequence east of the Nukhaib graben (Inset D)

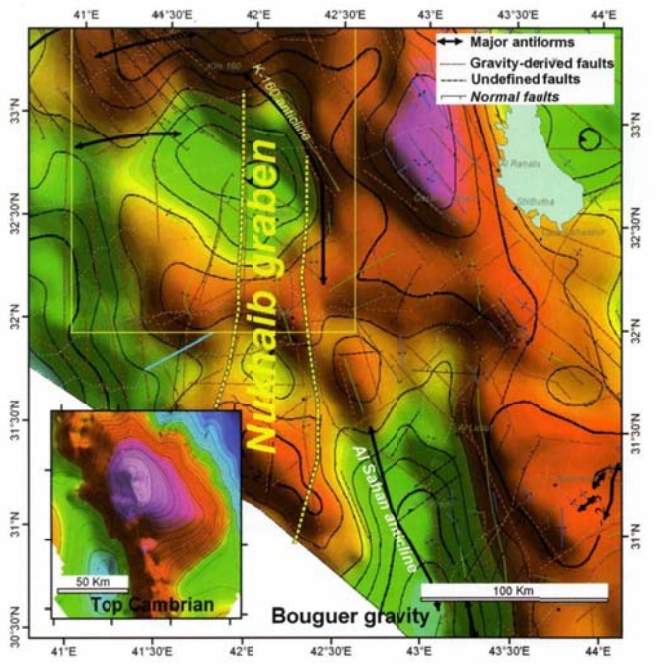


Fig. 5-5: The gravity low associated with the northern part of the Nukhaib Graben and the inset Top Cambrian map (modified from Al-Bassam et al., 1992). Red (main map is high gravity, in inset map is structural high) blue (main map low gravity, in inset map structural low)

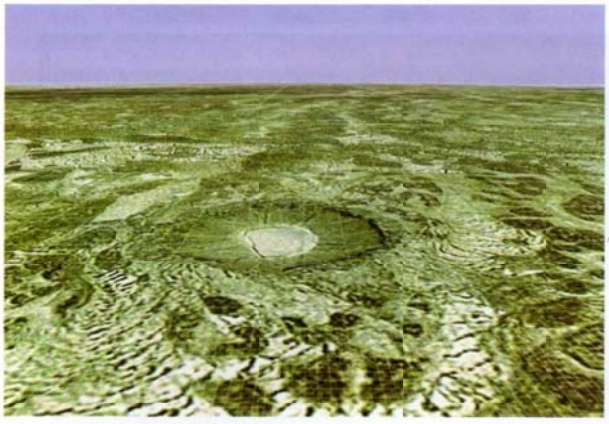


Fig. 5-6: Inclined view of the Umm Chaimin crater with 3 times vertical exaggeration. Note the N-S trails of the Walaj and Wulaij wadis on both sides of the crater (Courtesy of Earth Google)

5.2.1.2 Structures

The Rutba Subzone is dominated by the mega Rutba Uplift which formed due to inversion of the Palaeozoic basin of W Arabia during Latest Permian-Middle Eocene time. Major anti forms or arches are located on the flanks of this megastructure. The most prominent structures were active during the Cretaceous and Palaeogene. They include the ENE-WSW trending Hauran anticlinorium, the E-W Ga'ara anticline, the NW-SE trending Akashat anticline, the Traibeel anticline in the NW and the E- W trending Tlaiha and Qatari anticlines in the SE. These structures are shown on the base Cretaceous structure map (Fig. 5-7) compiled by Al-Bassam et al. (1999). Some N-S antiforms occur in the E part of the zone especially to the E of the Nukhaib graben (Fig. 5-8).

The Hauran anticlinorium is over 300 km long and consists of a series of culminations (Fig. 5-7) cut by several NW-SE trending normal faults forming horst and grabens displacing pre Campanian strata. These NW-SE striking grabens are often associated with thick alluvial sandstones at the

base of the Saggar Formation. The structure is visible on the structure map (Fig. 5-7). It is truncated by Lower Miocene sediments in the NE.

The Ga'ara anticline is identified on geological maps and air photos. It is an E- W trending 130 km long structure associated with a 1 km high subsurface elevation on top of the Precambrian basement that extends into SE Syria through the Akashat anticline (see Fig. 5-7). Facies changes within the Upper Cretaceous and Palaeogene sediments around these structures suggest that it was active in Late Cretaceous-Palaeogene time. The E- W trending Traibeel anticline deforms the Eocene strata and is associated with a well-defined surface lineament. There are two smaller E- W trending antiforms SE of the Hauran anticlinorium (Tlaiha and Qatari anticlines).

Two important antiforms were mapped near the E boundary of the *Rutba Subzone; these are* the NNW-SSE *trending* Kilo160 and the N-S trending Al Sahan antiforms (Fig. 5-9). The Kilol60 antiforms start near K-160 settlement in the N (half way between Ramadi and Rutba towns) and extends as far south as Wadi Ubayidh (latitude 32°). South of this wadi, the fold axis swings to the S, forming the Al Sahan anticline which extends through Al Kibritia into Saudi Arabia (Fig. 55). The Palaeocene strata are here strongly deformed often forming small domes. Both of these anticlines are associated with prominent gravity lows and are thus probably located above the Infracambrian salt graben mentioned above.

Subsurface structures within the subzone have been mapped from residual gravity anomalies (Fig. 5-8). However, few seismic-derived structural anomalies have been mapped. Many of the gravity residuals may be associated with N-S trending lineaments possibly related to Precambrian fabric or "Hercynian" structures. The NW-SE trending anomalies may be associated with Cretaceous horsts and grabens. They mostly occur along the Najd fault system to the E of Rutba and along the Iraq-Saudi border. The Akkas structure in the northern part of the subzone is one of these NW-SE trending structures. Along Wadi Hussainiyat some NW-SE trending folds were also observed. E- W trending anomalies are rare and are mostly restricted to the northern boundary of the subzone and to the Anah-Qalat Dizeh Fault. These structures are collectively referred to as the Anah anticline or more correctly monocline.

The fault systems of the Rutba Subzone were described in detail in Chapter 4. The Rutba Subzone is dominated by the N-S Nabitah (Idsas) system which is a Precambrian system reactivated during the Late Carboniferous and Early Permian (Syn-Hercynian). It is often associated with N-S trending residual gravity anomalies. The second system is the NW-SE Najd system which is well developed near and E of Rutba (extension of the Euphrates Boundary Fault), and along the Iraq-Saudi border (extension of the Al Tar Fault). These faults formed in the Late Precambrian and were probably reactivated during the Cretaceous. The E-W fault system is best developed in the SE and S part of the Subzone where it controls the Widyan drainage system (extension of the Sirwan and Amij-Samarra Transversal Faults), and along the northern margin of the subzone near the Euphrates River (Anah-Qalat Dizeh Fault).

Fig. 5-7: Structural map of the base of the Cretaceous (metres from Sea Level) based on data of Al-Bassam et al. (1999)

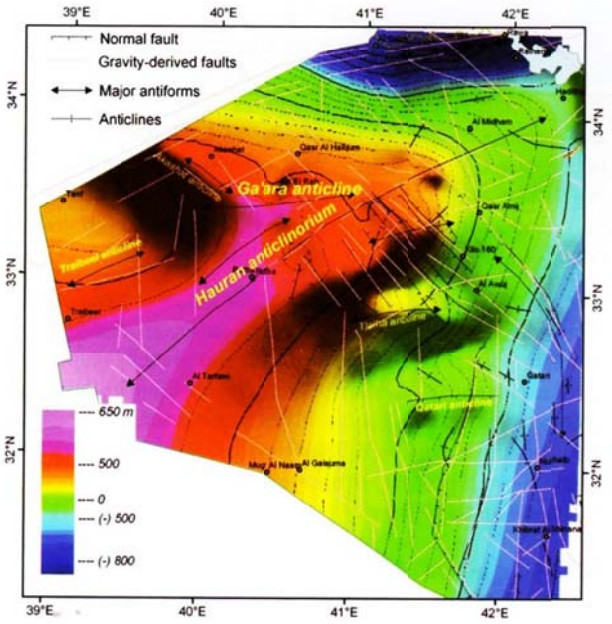
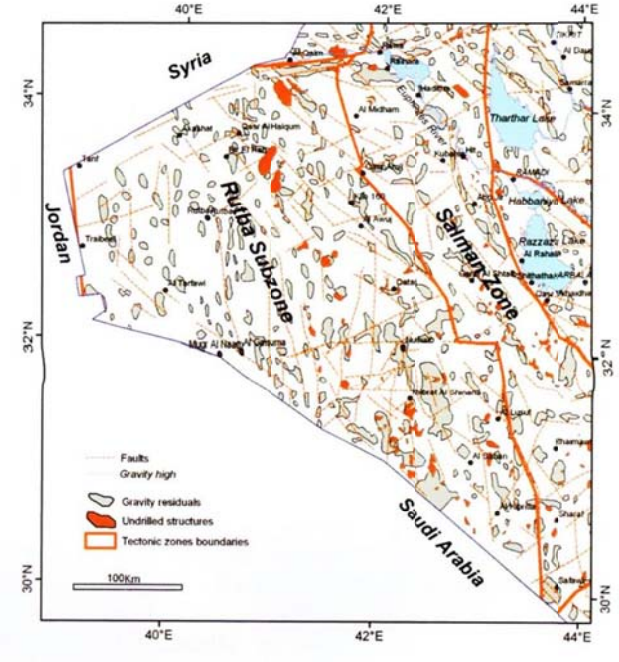


Fig. 5-8: Residual gravity anomalies (grey polygons) and undrilled structures (red polygons) and the fault systems of the Rutba Subzone



5.2.2 The Jezira Subzone

The Jezira subzone was part of the greater W Arabian Palaeozoic basin until the Late Silurian. It was uplifted in Late Silurian-Mid Devonian time forming a NE-SW trending arch. It formed part of the Rutba-E Palmyride Permocarboniferous N-S trending basin. It was part of the Rutba Uplift from Late Permian to Early Eocene time though it was intermittently submerged. It subsided during Eocene to Middle Miocene time. It was uplifted in Late Miocene-Recent time. It is dominated by the Khlesia Basement Uplift which is part of the N-S trending Rutba Uplift. It is segmented by two E- W trending grabens and a trough; these are the Anah Trough and the Tayarat and Khlesia Grabens.

The sedimentary column of the Jezira Subzone consists of Palaeozoic (3300-5000 m thick), Triassic (mainly Upper Triassic, 200-700 m thick), Lower Cretaceous (100-250 m thick), Upper Cretaceous (generally 50 m but over 1500 m thick in the Anah and Tayarat grabens), Palaeogene (300 m thick), and Neogene sediments (200-1000 m thick).

5.2.2.1 Geological and geomorphological characteristics

The oldest rocks outcropping in the Jezira Subzone are the Upper Oligocene Kirkuk Group, which outcrops at the S boundary of the subzone along the E- W section of the Euphrates River between the Syrian border and Anah. The Middle Miocene Fatha and the Upper Miocene Injana formations outcrop over most of the subzone. One major surface anticline is observed north of the Euphrates river (the ENE-WSW trending Tayarat anticline); the N flanks of this anticline are visible on satellite images (Fig. 5-9, inset B). The Tayarat anticline forms a topographic high. It drains towards the Euphrates River in the S, the Khlesia Graben in the N, the Tuwaila playa in the Wand the Tharthar valley in the E. The short drainage systems end in small playas which suggest active karstification in the evaporites of the Fatha Formation is occurring.

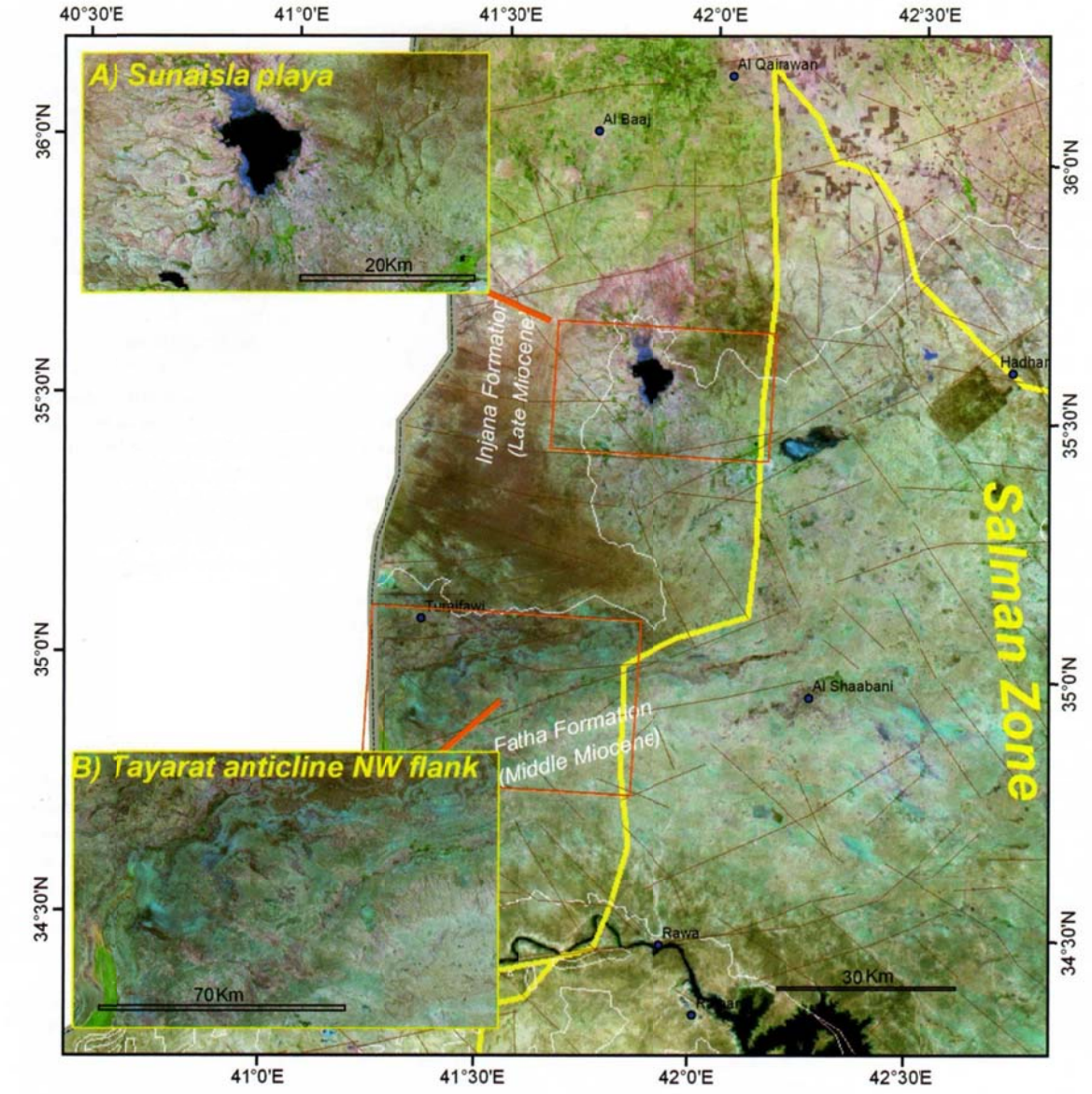


Fig. 5-9: Satellite image of the Jezira Subzone with insets showing the Sunaisla playa (A) and the NW flank of the ENE Tayarat anticline (B)

5.2.2.2 Structures

The Jezira Subzone is part of the ancient wider Rutba Uplift. It is segmented into two highs by the Tayarat Graben: the Tayarat High in the S and the Khlesia (Abu Rassain) High in the N (Fig. 5-10). The Khlesia Graben overlies the Khlesia High. Both the Tayarat and Khlesia grabens are visible on the satellite images and on the Top

Triassic structure map (Fig. 5-10). The Tayarat anticline overlies the Tayarat Graben indicating inversion occurred during Plio-Pleistocene compression. The Tayarat High is separated from the Rutba High by the Anah Trough of the Jezira Subzone. The structural highs and grabens of the Jezira Subzone are shown in the profile of Fig. 5-11 which starts from the Jordanian border and ends near the Turkish border in the N.

The Anah Trough lies between the Rutba and Jezira Subzones. The trough appears narrow at the

surface. At depth it is bounded by a series of E- W trending step faults. The Anah Graben formed by transtension in Late Cretaceous time; it contains up to 2000 m of Upper Cretaceous sediments. The Tayarat Graben strikes E- Wand probably formed synchronously with the Anah Graben. Its bounding faults have 1700 m of displacement on the top of the Triassic Kurra Chine Formation (Fig. 5-9 and 5-10). The Khlesia Graben (Fig. 5-9) shows very little displacement at the top of the Kurra Chine Formation (-150 m). Drainage patterns suggest it was active in the Quaternary; salt playas developed along it.

The northern boundary of the subzone is located along the Sinjar-Herki Transversal Fault which defines the southern boundary of the Foothill Zone and the Late Cretaceous Sinjar-Abdul Aziz basin which extends into N Syria. Small anticlines occur throughout the zone. They have been mapped at the level of the Middle Miocene Fatha (Lower Fars) Formation; many have been mapped at top Triassic level (Fig. 5-10). The gravity residuals (Fig. 5-12) have predominant E- W or ENE-WSW and N-S or NW-SE orientations. N-S and NW-SE trending anomalies mostly occur along the eastern boundary of the zone; E- W and ENE-WSW trending anomalies are located along the Transversal fault system.

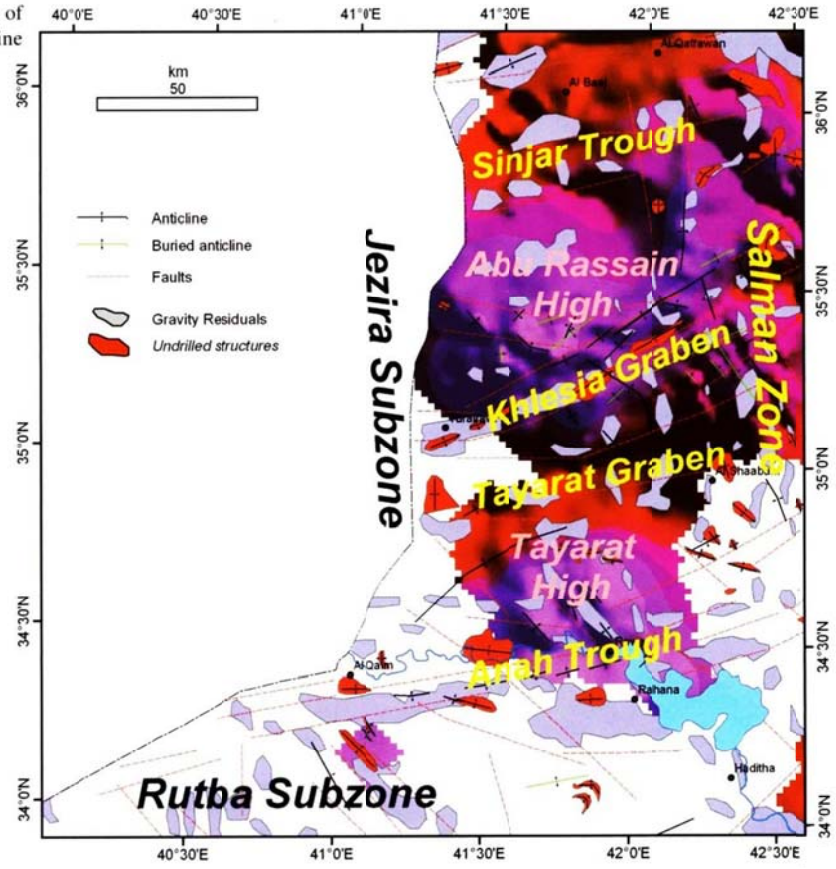


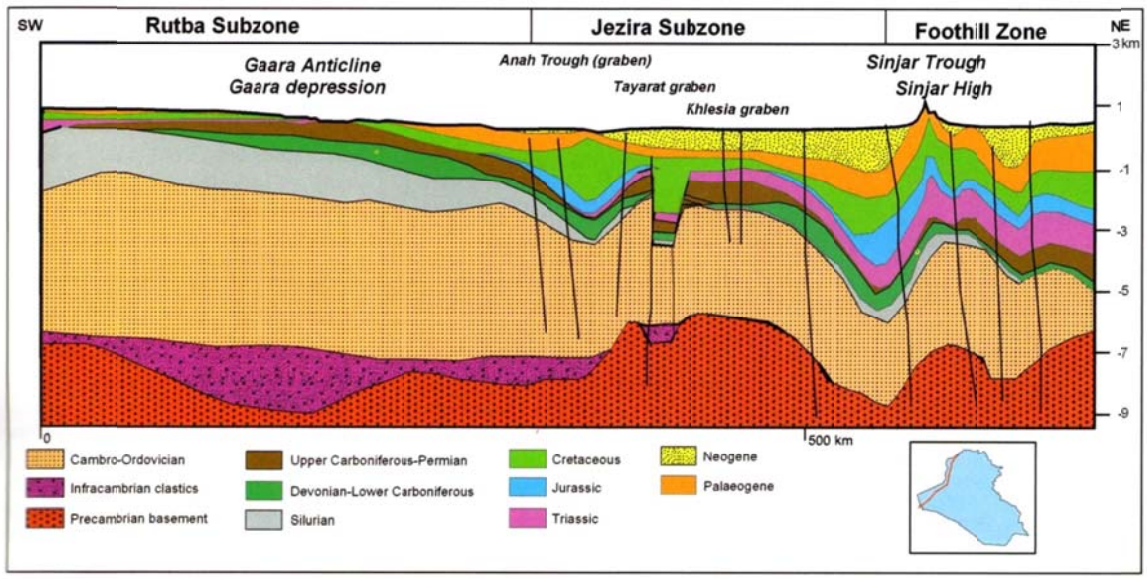
Fig. 5-10: Structural map on the top of the Upper Triassic Kurra Chine Formation

5.3 Salman Zone

The Salman Zone is part of the Salman-Summan Zone of Getech and Jassim (2002) which extends into W Kuwait and central E Saudi Arabia. It is generally associated with gravity and magnetic highs indicating a shallow basement at a depth of 5-7 km. It was formed during the Late Precambrian Nabitah orogeny, and reactivated during Late Carboniferous and Early Permian time. As in Saudi Arabia and Kuwait, the Upper Permian sediments unconformably overlie older Palaeozoic strata or the Precambrian basement. The western boundary is poorly defined in the north; in the south the western boundary is associated with a line of faults and residual gravity anomalies and strong karstification of the Eocene strata. The eastern boundary is associated with a strong gravity gradient along the Euphrates Boundary Fault in the S and along the western shores of the Razzaza and Habbaniya lakes, and with the Tharthar faults in the N. The eastern boundary has been slightly modified from the original definition of Buday and Jassim (1984, 1987), especially near the lakes. Some small changes to the boundary were also made near the Sinjar-Herki Fault.

The Salman Zone has a shallower basement than the Rutba Jezira Zone to the Wand the Mesopotamian Zone to the E. It is part of the Upper Precambrian Ar Rayan Terrane that was uplifted during the Late Carboniferous (Hercynian) time and partly during the Early Permian; the Lower Palaeozoic section was deeply eroded prior to Late Permian transgression. Basement depth in the Salman Zone is 5-8 km, mostly 6-7 km; along the boundary with the Mesopotamian Zone the basement depth increases to 8-9 km. The Infracambrian megasequence is thought to be absent. The Lower Palaeozoic section is 1500-3000 m thick; Permocarboniferous sediments may be preserved locally in Hercynian grabens. The thicknesses of the Mesozoic and Tertiary units are as follows: Triassic: 700-2000 m, Jurassic: 1000-1400 m, Lower Cretaceous: 300-1000 m, Upper Cretaceous: 800-1000 m, Palaeogene: 400-900 m and Neogene: 0-200 m.

Fig. 5-11: Profile from the Risha area in NE Jordan to the Mushorah area in N Iraq passing through the Rutba Subzone, Jezira Subzone and the Foothill Zone. Cretaceous troughs and grabens are clearly visible in this profile



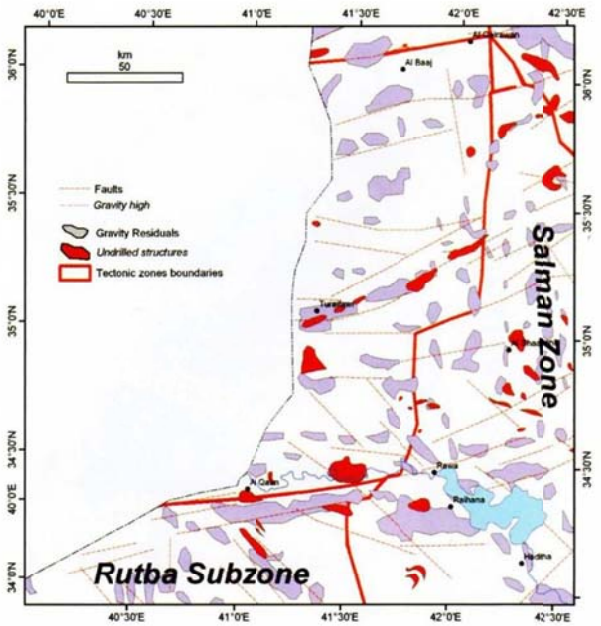


Fig. 5-12: Residual gravity anomalies (grey polygons) and undrilled structures (red polygons) of the Jezira Subzone

5.3.1 Geological and geomorphological characteristics

The Salman Zone is a monocline dipping towards the Euphrates River; Middle-Upper Eocene strata outcrop in the W and Lower and Middle Miocene beds outcrop in the E. The S part of the zone is a sandy plain formed by Miocene clastics. Eocene carbonates are pock-marked; depressions are filled by Pliocene fresh water limestones and clastics (Fig. 5-13 B). There are also numerous buried (or abandoned) river courses that have been strongly influenced by karst. They are usually aligned with the NE-SW trending faults (Fig. 5-13 A and 5-14). These features are associated with present day wadi courses. They need to be investigated in detail due to their importance for groundwater exploration.

5.3.2 Structures

The Salman Zone subsided from Late Permian time onwards. It comprises NE-SW and prominent NW-SE trending uplifts and depressions, bounded by faults. The most conspicuous structures in the Salman Zone strike NWSE. They are relatively narrow, long anticlines, often accompanied by faults. Broader N-S trending structures, indicated by gravity data are buried Hercynian horsts which are mostly restricted to the Sand SW part of the zone. Other parts of the zone contain relatively short anticlines and structural noses, many of which are located along transversal faults. In the north, these structures trend N-S to NW-SE. Transversal faults control the sinuous course of the zone's borders. Other faults mostly trend NW-SE in the centre of the Zone and along the NE margin of the zone. NS trending faults are frequent in the Sand SW. The northern part of the zone has fewer faults.

Folds of unknown origin occur in the S part of the zone. Gravity residuals (Fig. 5-15, grey colour) show a series of N-S trending anomalies possibly indicating buried Hercynian antiforms. However such features have not been identified from seismic surveys. NW-SE trending faults are dominant in the southern part of the zone. Transversal faults occur throughout the zone. NW-SE trending

faults are common in the NE part of the zone.

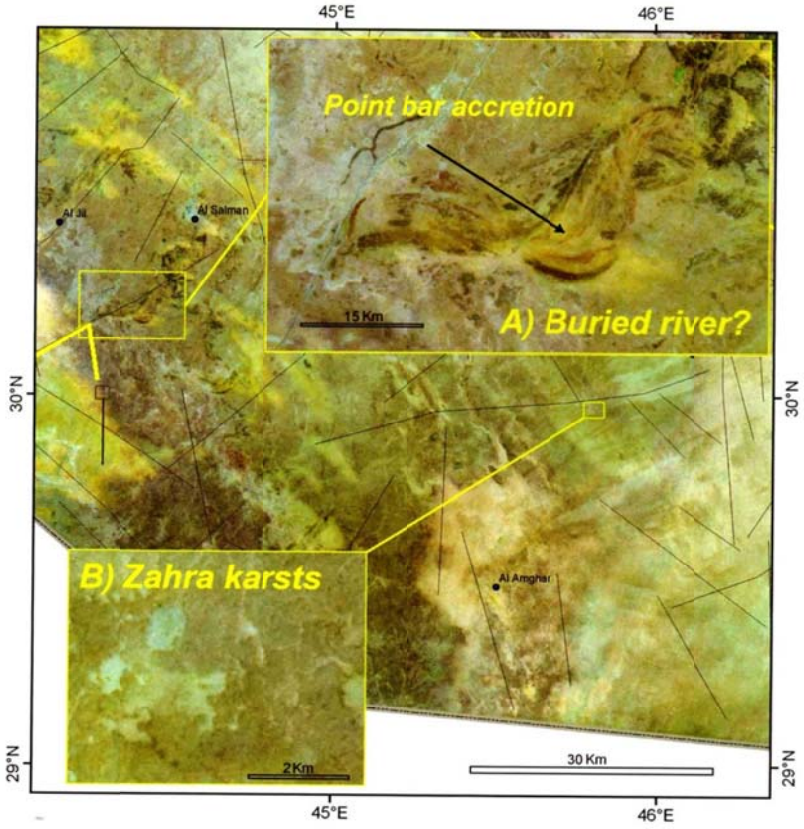


Fig. 5-13: Satellite image of the southern part of Salman Zone with insets showing buried river beds W of Salman depression (A) and the typical karsts scattered throughout the zone (B)

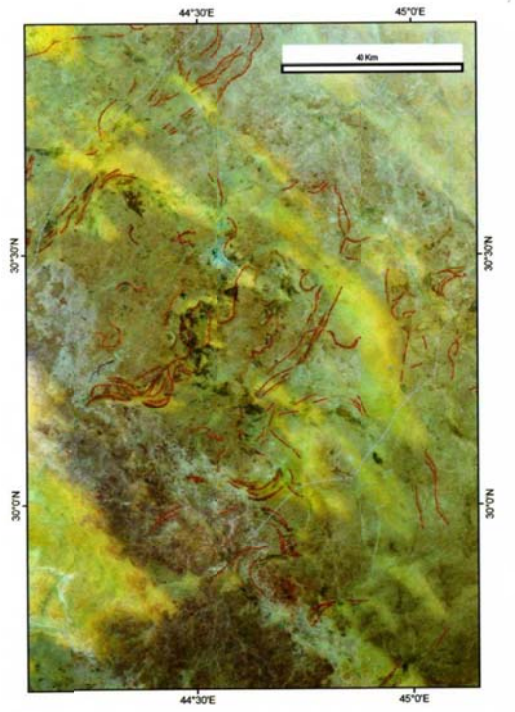
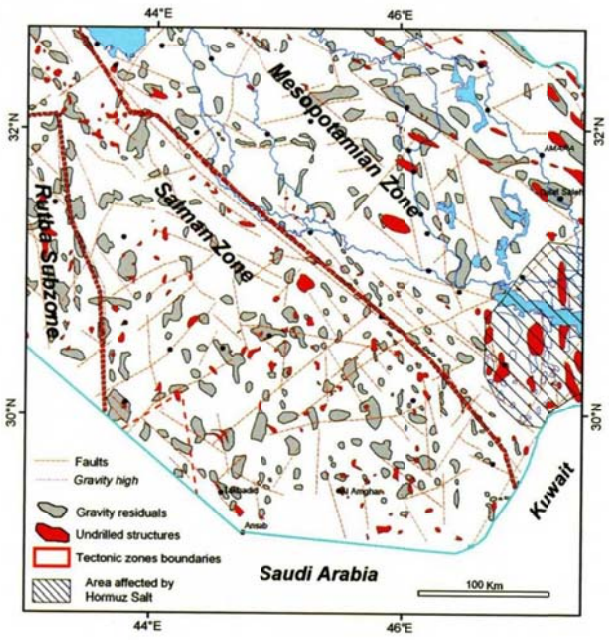


Fig. 5-14: Satellite image of the Salman Zone with tracing of some of the arcuate features that may be related to buried or abandoned river systems

5.4 Mesopotamian Zone

The Mesopotamian Zone is the easternmost unit of the Stable Shelf. It is bounded in the NE by the folded ranges of Pesh-i-Kuh in the E, and Hemrin and Makhul in the N. The SW boundary is controlled by faults (Fig. 5-15). The zone was probably uplifted during the Hercynian deformation but it subsided from Late Permian time onwards. The sedimentary column of the Mesopotamian Zone thickens to the east. It comprises up to 1500 m of Infracarnbrian, 25005000 m of Palaeozoic, 1500-2200 m of Triassic, 1100 m of Jurassic, 500-700 m of Lower Cretaceous, 700-1400 m of Upper Cretaceous, 200-900 m of Palaeogene, and 150-1500 ill of Neogene and Quaternary section. Quaternary sediments alone are up to 300 m thick.

Fig. 5-15: Residual gravity anomalies (grey polygons) and undrilled structures (red polygons) of the southern part of the Salman Zone



5.4.1 Geological and geomorphological characteristics

Quaternary sediments of the Mesopotamian Zone were deposited by the interacting Tigris, Euphrates, Diyala and Adhaim Rivers, on the alluvial fans emanating from the surrounding elevated areas, and following marine incursions from the Arabian Gulf. Flood plain deposits include channel deposits, levees and crevasse splays, flood plain depression, marsh, sabkha and deltaic deposits (see Chapter 15). The alluvial fans are derived from rivers passing through the Foothill Zone (Fig. 5-16 B) in the NE or from desert wadis flowing from the desert plain in the W (Fig. 5-16 A). Fluvial-marine sediments are represented by the Shat Al Arab delta.

The Mesopotamian Zone is a relatively flat terrain with a gradient of less than 10 cm per kilometer extending from Baiji in the NW to the Arabian Gulf in the SE. The major geomorphological features formed by sediment accumulation. The most prominent feature is a complex system of natural levees following the courses of each river, which gradually pass into a flood plain and finally into a flood basin. Natural levees of the Euphrates begin near Fallujah, and

those of the Tigris near Dujaila; they extend down the rivers to the marsh area on the SE of the Plain. The natural levees rise only 2-3 m above the bottom of the flood basins resulting in many catastrophic floods. River terraces of the Euphrates and Tigris occur N of Fallujah along the Euphrates and N of Dujaila along the Tigris. The distribution of relict terraces suggests that the rivers may have been connected during high water conditions.

The zone has three major depressions resulting from the interaction between the dejection cones of the main rivers and the dejection cones of the alluvial fans and the elevated monocline of the Salman Zone. The eastern depression lies between the dejection cones of the Tigris River in the W and the dejection cones from the foothills in the E. It has been segmented into three parts by the dejection cones of the Adhaim River in the N and the Diyala River in the S. The three major sectors are the Baiji dune field and Shari Lake depression N of the Adhaim River, the Mukdadiya dune field between the Adhaim and Diyala River and the Badra depression south of the Diyala River. These depressions are associated with aeolian fields, playas or flood plain sabkhas. The central depression is bounded by the dejection cones of the Tigris and Euphrates River and lies between W Baghdad and. Nasiriya. The western depression lies between the

Euphrates dejection cone in the E and the Salman Zone monocline in the W and includes the Tharthar, Habbaniya and Razzaza depressions (which have been used as flood reservoirs) and the Bahr Al Najaf depression. These depressions may be tectonically controlled by the NW-SE trending Euphrates Boundary Fault and the N-S trending Tharthar fault line (Fig. 5-16 C).

Large coalescing alluvial fans occur along the contact of the Mesopotamian Zone with the Foothill Zone forming an impressive bajada plain. Fans were also developed along the SW boundary of the Mesopotamian Zone especially S of the Razzaza Lake. Man-made features include walls of irrigation canals and small moulds and hillocks called "Tells". Canal walls can stretch over distances of tens of kilometres; some ancient ones are over 100 km long, e.g. the Nahrawan and Kharidge Canals in the Adhaim-Numania area. Great floods may have occurred due to the combination of maximum river discharges, spring storms, and easterly winds blowing Gulf waters inland blocking the Shatt al Arab outlet; these may have led to the flooding of tens of thousands of square kilometres of Plain with 2-3 m of water in the past. A great flood on this scale may have occurred once since the beginning of the Holocene during the early human occupation of the region.

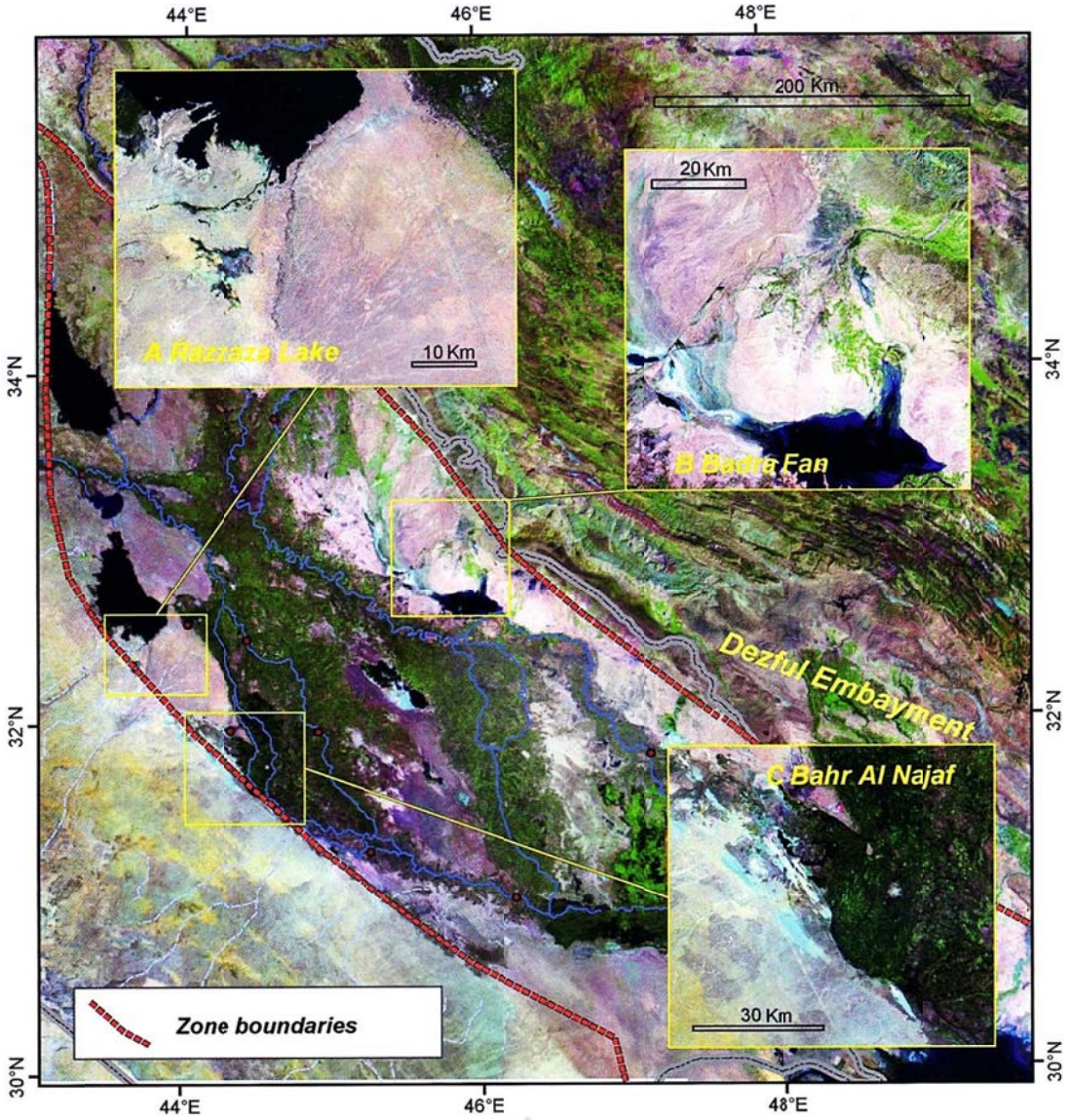


Fig. 5-16: Satellite image of the Mesopotamian Zone bound by the Foothill Zone in the NE and the Salman Zone in the SW Inset maps show alluvial fans on both side of the zone (see text)

5.4.2 Structures

The Mesopotamian Zone contains buried faulted structures below the Quaternary cover, separated by broad synclines. The fold structures mainly trend NW-SE in the eastern part of the zone and N-S in the southern part; some NE-SW trending structures occur (Fig. 5-15). A major N-S trending gravity and magnetic high is located along the Gharraf River, between the Tigris and Euphrates which may indicate a buried Hercynian structure. Structures in the Mesopotamian Zone usually have positive residual gravity anomalies (Fig. 5-15). However the well-defined structures of Zubair, Rumaila, and Nahr Umr in the Zubair Subzone in the S are associated with negative residual gravity anomalies and suggest salt is present below some of the structures in S Iraq (Section 5.4.3)

The Mesopotamian Zone is divided into three subzones: the Zubair Subzone in the S with N-S trending structures in the S, the Euphrates Subzone in the W, and the Tigris Subzone in the NE with NW-SE trending structures.

5.4.3 Zubair Subzone

The Zubair Subzone is bounded in the north by the Takhadid-Qurna Transversal Fault. The southern boundary of the subzone is either located at the Al Batin Fault or along a transversal fault in Kuwait. The northern dome of the Zubair anticline is associated with a negative gravity anomaly. However the southern dome of this anticline and the structures to the south in Kuwait are not. These structures and the southern Zubair dome could be included in another subzone (Fig. 5-17).

This subzone forms the southernmost unit of the Mesopotamian Zone and has a uniform structural style controlled by the underlying basement. It contains prominent N-S trending structures which continue hundreds of kilometres southwards into Kuwait and E Saudi Arabia. These structures originated during the Late Nabitah orogeny and were reactivated during Permocarboniferous, Mesozoic and Tertiary time. The association of negative gravity residuals with the main structures of S Iraq Fig. 5-18) strongly suggests they are underlain by Infracambrian salt. The Sanam salt plug (Fig. 5-19) indicates Infracambrian salt is present in the south of the subzone. It is described in Chapter 8.

The amplitudes of the N-S trending structures of the subzone increase with depth and reach 300 m at Lower Cretaceous level. The structures are long and relatively narrow anticlines separated by broader synclines especially in the east. Shorter and oblique trending structures also occur (Fig. 5-17). The most prominent narrow elongated antiforms are the Zubair and Rumaila structures. Shorter, often broader structures include Nahr Umr, Majnoon, Rachi, Ratawi, Subba and Luhais. The Zubair Subzone is the most prolific petroleum region in Iraq.

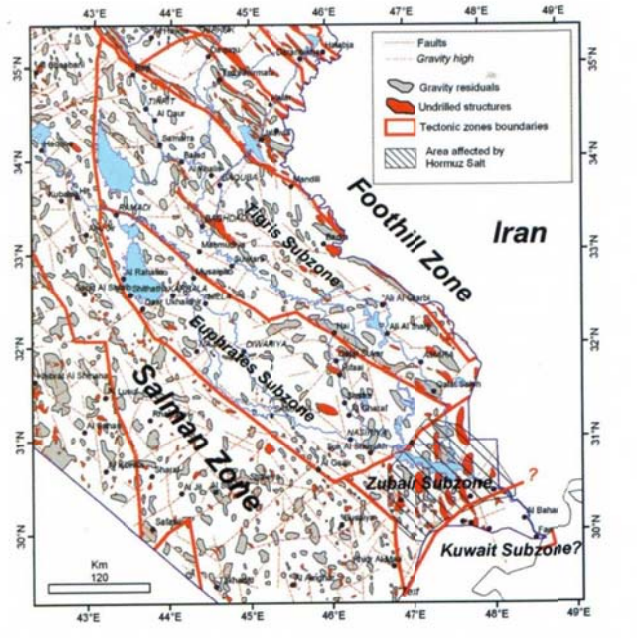


Fig. 5-17: Residual gravity anomalies (grey polygons) and undrilled structures (red polygons) of the Mesopotamian

Fig. 5-18: Structural map to the top of the Ahmadi Formation showing the position of residual gravity anomalies (open polygons) in relation to the anticlines. Most of the residual gravity highs are associated with structural lows

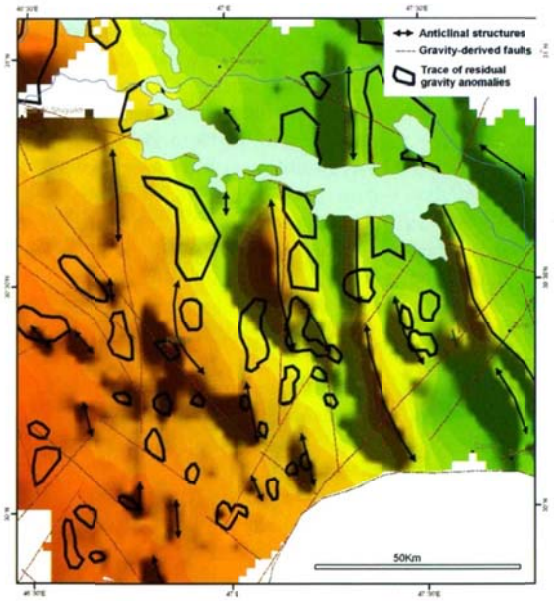
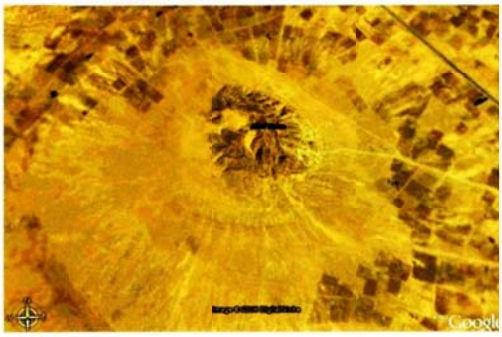


Fig. 5-19: Oblique view of Sanam Plug in S Iraq, 5 km W of Safwan Town on the Basra-Kuwait High way. Steeply dipping, locally vertical Upper Miocene grit beds of the Dibdibba Formation form visible circles around the central salt extrusion (Courtesy of Google Earth)



5.4.4 Tigris Subzone

The Tigris Subzone is the most extensive and mobile unit of the Mesopotamian Zone. It contains broad synclines and narrow anticlines trending predominantly NW-SE, accompanied by long normal faults. It is bounded by the Foothill Zone in the NE and by the long gravity gradient and line of residual gravity anomalies between Qalat Saleh in the SE and Fallujah in the NW. The extent of the subzone has been modified from the original definition of Buday and Jassim (1984 and 1987).

The western boundary coincides with a palaeoridge that influenced sedimentation in the Mesopotamian Zone from Late Jurassic time, separating inner shelf facies in the SW from outer shelf facies to the NE.

The Tigris subzone contains two NW-SE trending groups of buried anticlines of relatively low amplitude associated with longitudinal faults (confirmed by seismic surveys) and an EW transversal trend. These anticlines lie on the Ramadi Musaiyib and the Tikrit-Amara Fault Zones of the Najd Fault System and on the Kut-Dezful Fault. The anticlines are associated with sharp gravity gradients and straddle deeper but broader basement blocks which were tectonically active from the Late Jurassic onwards. They also influence the course of the Tigris River today.

The first line of anticlines runs from Tikrit to Amara. Where the basement deepens in the N the anticlines are cut by normal faults. The total length of anticlinal line from Tikrit to Amara is over 500 km; it is segmented into shorter domes about 20 to 70 km in length. The line straddles the Samarra Amara palaeoridge. The second, less pronounced, line of anticlines is the Ramadi-Musaiyib anticlinal trend corresponding to the West Baghdad basement structure of Ditmar et al. (1971 and 1972) and the western 'boundary of the subzone. This structural trend (at Mesozoic level) consists of a series of SE plunging structural noses. It is roughly 150 km long, and extends from Ramadi to Musaiyib. Its amplitude in the Mesozoic cover does not exceed a few hundred meters. The amplitude at basement level is < 1 km.

The third anticlinal structural trend of Najaf-Kut is an oblique structure trending approximately E-W. It comprises a series of faulted anticlines. They are not visible on the regional basement maps, but have been detected by seismic and other geophysical methods. The basement maps show only E- W trending gradients, indicating the course of the faults. The Najaf-Kut antiforms are connected with movements along the Kut-Dezful Transversal Fault. The area to the south is a depression that may be the continuation of the Dezful Embayment. Individual anticlines are 30-50 km long. The amplitudes of these structures are low.

5.4.5 Euphrates Subzone

The Euphrates Subzone lies in the W of the Mesopotamian Zone. It is a monocline dipping to the NE with short anticlines « 10 km) and structural noses. Some longer NWSE oriented anticlines (20-30 km long) lie near to and parallel with the Euphrates Boundary Fault especially between Samawa and Nasiriya. They are related to horsts and grabens developed along the fault zone. The Euphrates Subzone is the shallowest unit of the Mesopotamian Zone. The basement is generally 7-9 km deep but has thicker Quaternary sediments compared with the Tigris Subzone.

CHAPTER 6

Units of the Unstable Shelf and the Zagros Suture

by

Saad Z. Jassim and Tibor Buday

This chapter covers both the Unstable Shelf and the Zagros Suture units. The Unstable Shelf in Iraq is divided into four zones: the Foothill Zone, the High Folded Zone and the imbricated Northern (Ora) and Balambo- Tanjero Zones. The Mesopotamian Zone of Buday and Jassim (1984 and 1987) is now included in the Stable Shelf. The Zagros Suture Zone comprises three tectonic units: the Qulqula Khwakurk, the Penjween- Walash and the Shalair zones (Fig. 6-1).

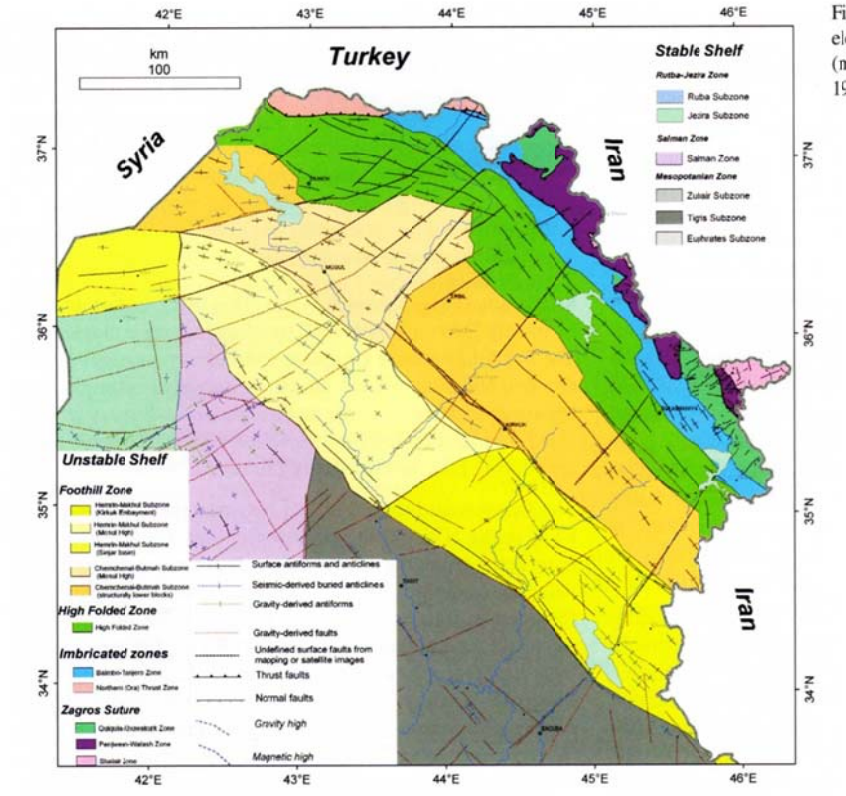
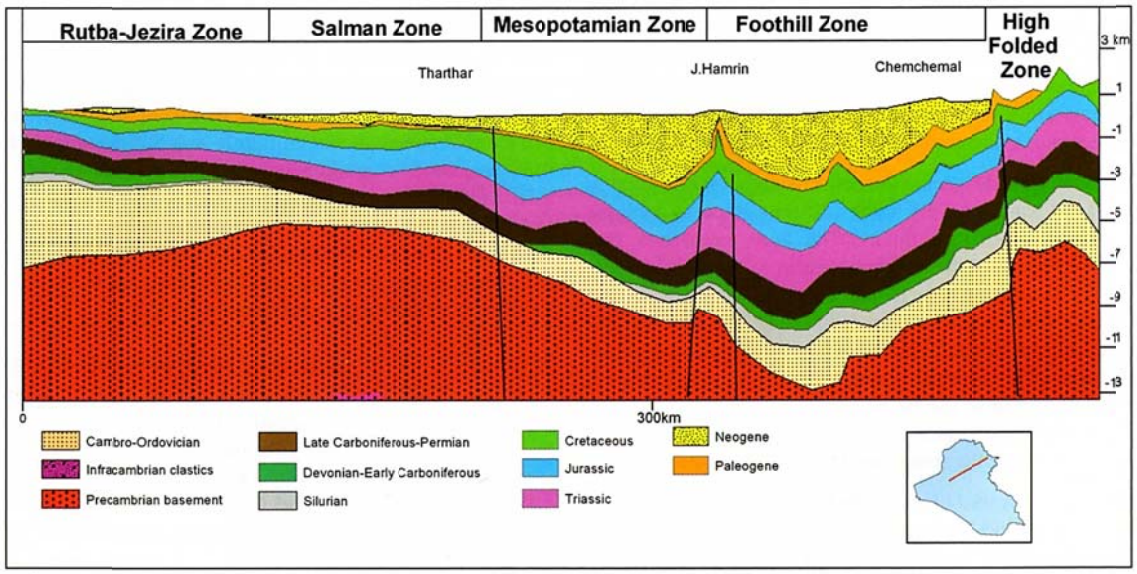


Fig. 6-1: Tectonic zones and structura elements of the Unstable Shelf unit (modified form Buday and Jassim 1984)

6.1 Units of the Unstable Shelf

The Unstable Shelf had been the most strongly subsiding part of the Arabian Plate since the opening of the Southern Neo- Tethys in the Late Jurassic. Maximum subsidence occurred during the Late Cretaceous ophiolite obduction onto the NE margin of the Arabian Plate and during Mio-Pliocene continental collision. The Unstable Shelf is thus characterised by structural trends and facies changes that are parallel to the Zagros-Taurus suture belts. Surface folds are a characteristic feature of the unit. A cross section through the Foothill and High Folded zones is shown in Fig. 6-2.

Fig. 6-2: Cross section through central Iraq passing through the Stable Shelf, the Foothill and High Folded zones showing the deepest basement in Iraq in the Foothill Zone



6.1.1 The Foothill Zone

The SW boundary of the Foothill Zone lies along the SW flank of the impressive anticlinal line of Makhul, Hemrin and Pesht-i-Kuh. North of Hatra the boundary of the Zone runs along the Tharthar valley then westwards into Syria along the southern flank of the Sinjar anticline (Fig. 6-1). To the SE the boundary passes through the Dezful Embayment in SE Iran and along the eastern coast of the Arabian Gulf. Its eastern boundary lies along high anticlines with Palaeogene or Cretaceous formations exposed in their cores.

The Foothill zone has the deepest Precambrian basement in Iraq (-13 km) and very thick Miocene-Pliocene molasse sediments (-3000 m thick). The zone comprises two longitudinal units, the Makhul-Hemrin Subzone in the SW and the Butmah- Chemchemal Subzone in the NE. The Foothill Zone contains four transversal basement blocks with different structural histories. The satellite images of the E and NW Foothill Zone (Fig. 6-3 and Fig. 6-4 respectively) show the variations in the structural style of different transversal blocks. Inclined views of some of the structures of the zones are shown in Fig. 6-5. The NW transversal block of the Foothill Zone (here termed the Sinjar Block) lies to the N of the Sinjar-Herki Fault and covers the Sinjar area (Fig. 6-1). Top basement is usually at 8-10 km but ranges from 5-11 km. This block is dominated by mostly E- W or WNW-ESE trending basement elements. The block has a more complete sedimentary sequence than the neighbouring Mosul Block; it subsided strongly in Mesozoic and Tertiary time and its Mesozoic-Tertiary cover is 6-7.5 km thick. However the Rutba Uplift influenced this area during Late Jurassic-Early Cretaceous time.

The transversal block that lies between the Sinjar-Herki Fault in the NW and the Hadhar-Bakhme Fault in the SE is referred to as the Mosul High. It forms an important palaeogeographic and structural divide across· the foredeep of Iraq, including the Foothill Zone. It overlies shallow Precambrian basement at 6-9 km. The basement structural features trend in WNW and NE directions. The Mesozoic- Tertiary cover contains several stratigraphic gaps (mainly in the Mid Jurassic, Late Jurassic and Early Cretaceous). Anticlines within the block are generally short (10-

30 km long), and en echelon with NW-SE, and rare E- W trends.
The third transversal block lies between the Hadhar-Bakhme Fault in the NW and Anah-Qalat Dizeh Faults in the SE. Top basement in this block is at 8-11 km rising to 7 km in the NW and dropping to 12 km in the SE. NW-SE and subordinate E- W striking structural elements occur in the basement in addition to anticlines trending NW-SE.
The largest transversal block is the Kirkuk Embayment which lies between the Anah-Qalat Dizeh Fault in the NW and the Sirwan Fault in the SE. It has the deepest Precambrian basement within the Foothill Zone at 10-14 km but locally rising to 8 km. Major basement structures and surface folds trend almost uniformly in a NW-SE direction. This deep block contains relatively narrow anticlines often associated with reverse and normal faults. They are 100 km to 200 km long. However on the structurally higher parts of the block in the NW, the anticlines are generally shorter. The anticlines are separated by broad synclines filled by thick Pliocene and Quaternary sediments.
The thickness of the sedimentary cover within the Foothill Zone is variable. The Infracambrian is most likely missing. Thicknesses of other units are as follows: Palaeozoic (15004500 m), Triassic (1500 m), Jurassic (700 m), Lower Cretaceous (250-1500 m), Upper Cretaceous (400-1200 m), Palaeogene (500-800 m), and Neogene (400-3000 m). The Cretaceous and Neogene sequences are thinnest over the Mosul High.
The geology of the zone is generally simple. **In** the SE part of the Foothill Zone long anticlines, with general land relief of just over 100 m above the surrounding synclinal plains, are built by Neogene clastics, sometimes with anhydrite and carbonates (Fig. 6-3 and insets). Over the Mosul Block of the Foothill Zone shorter anticlines have similar relief of about 100 m above the surrounding synclinal plains. Lower and Middle Miocene carbonates and anhydrites form the cores of these anticlines (Fig. 6-4 B and C). The carbonates are usually pock-marked due to karstification with solution of gypsum beds and collapse of overlying carbonates (Jassim et al., 1997). The prominent anticlines of the Sinjar (Fig. 6-4 A) and Qara Chauq structures are generally built by Palaeogene carbonates; Upper Cretaceous marls are exposed in deep incised valleys.

6.1.1.1 Hemrin-Makhul Subzone

The Hemrin-Makhul Subzone (Fig. 6-1) is the structurally deepest part of the Foothill Zone. The subzone was the depocentre of the Neogene molasse but has been a subsiding unit throughout the Mesozoic and Tertiary. The SW boundary of the subzone coincides with the SW boundary of the Foothill Zone (Fig. 6-1). Its NE boundary lies along the N limb of the Sinjar anticline, passing along the anticlines of Ishkaft and Atshan (NW of Mosul), Mishraq s . Qara Chauq and Makhmur (SE of Mosul), and along Jambur and the SE part of the Kirkuk anticline. Towards the Iranian border it follows the Kor Mor, Chia Surkh and Qasr Shirin anticlines.

The Makhul-Hemrin Subzone comprises long prominent NW-SE (or E-W) trending anticlines with decollement thrust faults originating at detachments surfaces at the base of the saliferous beds of the Fatha (Lower Fars) Formation often producing "Gamma-structures" (Fig. 6-6). The anticlines of the Hemrin-Makhul Subzone are over 100 km long. The anticlines are also segmented into doubly plunging domes; the segmentation usually occurs at intersections with transversal faults where the axes of the anticlines are bent.
Anticlines in this subzone often have relatively broad crests and steep S or SW flanks. Opposite asymmetry towards the is generally rare and mostly seen N and NW of Mosul Sinjar Block) for example in the Sinjar anticline where the N flank is vertical. The SW flanks of anticlines in the

blocks SE of the Mosul High are often accompanied by reverse faults generally cutting through Mio-Pliocene strata; at deeper levels the anticlines are usually underlain by block folds mostly connected with basement highs. In the Hemrin Makhul Subzone these structures alternate with relatively short, unfaulted isometric antiforms.

The characteristic structural features of the subzone were described by Henson (1951), Naqib (1967), Ditmar and the Iraqi-Soviet Team (1971), and Zwain (1976; 1983) who claimed that the structures of this subzone are more affected the structure of the basement and the lithological composition of the cover than by the Alpine stresses. However the authors consider that Alpine deformation in association with the basement character has resulted in the rural development of the anticlines of the Foothill Zone.

Within the Sinjar block, the subzone is restricted to a relatively narrow belt which is the eastern continuation of folded zone of Syria (Ponikarov et al. (1967). The most prominent feature of this part of the subzone is the Sinjar line (Fig. 6-3 A and Fig. 6-5 A). It is a box-shaped line flanked in the subsurface by faults. The amplitude of the anticline on top Cretaceous level exceeds 2 km. It is the structurally the highest anticline in the Foothill Zone. It formed by inversion of a deep rift basin during Late Tertiary time. The platform to the S of the anticline (footwall) acted as a rigid block. No other significant structures, apart from some shorter buried antiforms of Tel Hajar occur on this part of the subzone.

The anticlines of the Mosul Uplift are generally dense and short (10-15 km) long, but increase in length towards the SE. They usually trend NW-SE except in the NW near Tel Afar (Fig. 6-3 Band C) where they trend E-W. The long prominent antiforms are accompanied by faults. Some shorter anticlines, mainly on the Mosul High, such as Adaiyah and Hibbarah are also accompanied by deep faults evident on seismic maps. Prominent synclines are not common on the Mosul High. The anticlines in this relatively uplifted part of the subzone are Ishkaft, Atshan, Mishraq, Qalian, Qara Chauq-Makhmur (>1000 m amplitude), Sasan, Ibrahim, Adaiyah, Jawan, Najmah, Qaiyarah, Hibbarah and Khanuqa. Numerous buried structures have been identified on seismic maps (Fig. 6-1).

The Kirkuk Block (Embayment) portion of the subzone contains the long anticlines of Hemrin (Fig. 6-5 B) that form the SW border of the subzone, and the Bai Hassan and Jambur anticlines that form the NE border. These anticlines are 130-200 km long, with several doubly-plunging domes (Fig. 6-3), often associated with longitudinal reverse faults on the S or SW flank, or occasionally on the N flank or on both flanks. They are up to 1000 m in amplitude. The Kor Mor, Chia Surkh and Qasr Shirin anticlines comprise the NE line of anticlines; the Hemrin anticline forms the SW anticlinal line. The Jambur, Pulkhana, and Gilabat anticlines lie in the middle of the subzone. Seismic surveys indicate the presence of buried structures (Fig. 6-1). Many of these long anticlines are associated with decollement thrust faults (Fig. 6-6).

6.1.1.2 Butmah-Chemchemal Subzone

The Butmah-Chemchemal Subzone is the NE unit of the Foothill Zone. It is the structurally highest part of the Zone. The SW boundary of the subzone is located along a line connecting the Sinjar, Qara Chauq, Kor Mor and Chi a Surkh anticlines. The NE boundary lies along the SW flank of the anticlines of the High Folded Zone (Fig. 6-1) that includes the anticlines of Chia-i-Spi, Dohuk, Aqra, Pirmam Dagh, Haybat Sultan and Qara Dagh (Fig. 6-3).

The Mesozoic-Tertiary sequence is up to 1.5 km thick. The subzone was intermittently uplifted during the Jurassic and Cretaceous, usually forming either a submerged or exposed ridge often associated with a carbonate platform (the Chemchemal- Taq Taq palaeoridge of the Iraqi-Soviet Team, 1979). In the Palaeogene, the subzone became a foredeep. In the latest Miocene-Pliocene the subzone became part of the Foothill Trough and was filled in by coarse molasse sediments.
The transversal Mosul Uplift affected the subzone, but to a lesser extent than in the Makhul-Hemrin Subzone. The anticlines are medium-sized, NW-SE trending in the SE and E-W trending in the NW. The Butmah-Chemchemal Subzone, however, has very conspicuous long and deep synclines with thick Pliocene molasse dominated by conglomerate.

The prominent features of the subzone are long anticlines often not associated with longitudinal faults with the exception of the Kirkuk structure. Broad and deep synclines are a feature of the subzone. The three transversal blocks of Sinjar, Mosul and Kirkuk have also influenced the structure of the subzone but to a lesser degree than in the Makhul-Hemrin Subzone.

The Sinjar Block in the NW part of the subzone contains EW trending depressions and one surface anticline (Mushorah anticline). The synclines are pronounced and -include the North Sinjar, Zummar and Dohuk synclines. The second part of the subzone lies on the Mosul High with numerous but mostly short, E- W trending anticlines in the NW and NW-SE trending anticlines in the SE; synclines are not conspicuous in this part of the subzone. The amplitudes of the Bashiqa, Maqlub and Ain Al Safra anticlines are high; Palaeogene beds form their cores at an elevation of 1000 m ASL. Buried anticlines may be present in the NE parts of the subzone where the molasse cover is thicker. The anticlines on the Mosul block include: Ain Zalah, Butmah, Gusair, Alan, Jabal Kand, Bashiqa, Maqlub, Ain AI Safra, and Demir Dagh. The Kirkuk Block of the subzone is characterized by broad and long synclines and long anticlines. The Kirkuk anticline which lies in the SW part of the subzone comprises three domes (from the NW: Khurmal, Avanah and Baba) with amplitudes exceeding 1000 m at Cretaceous level. Some buried structures have been identified from seismic (Fig. 6-1).

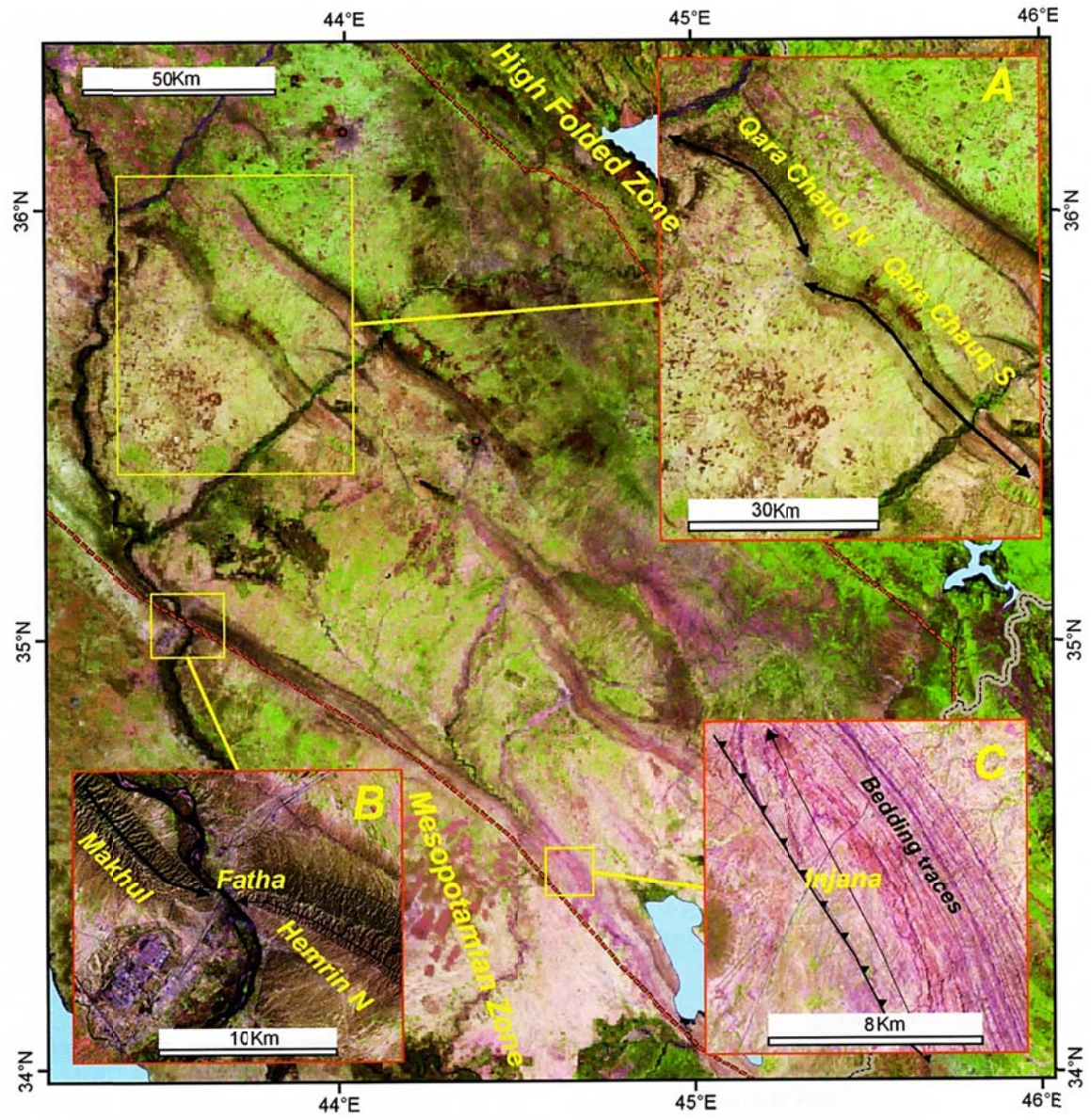


Fig. 6-3: Satellite image of the SE part of the Foothill Zone with insets showing close-up of three anticlines

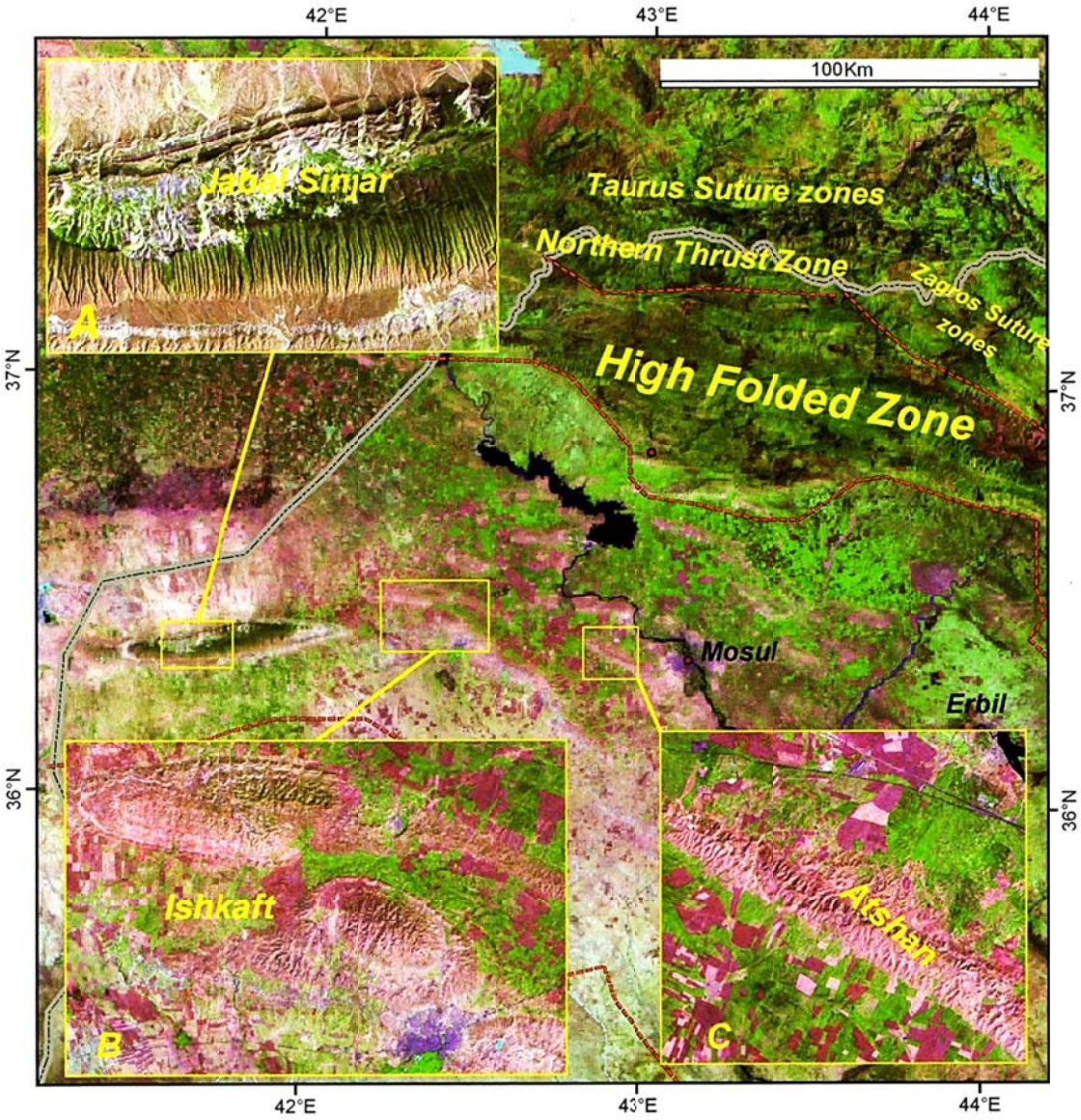


Fig. 6-4: Satellite image of the NW part of the Foothill Zone with insets showing close-up of three anticlines

6.1.2 The High Folded Zone

The High Folded Zone is located between the Zakho area, on the Turkish border in the NW and the Derbendikhan Halabja area near the Iranian border in the SE. The width of zone varies from 25 to 50 km. It is also affected by transversal blocks. The zone was intermittently uplifted in Cretaceous and Palaeogene time and strongly deformed in e Late Tertiary. The zone was the marginal part of the Palaeogene molasse basin.

The High Folded Zone covers most of the Iraqi Kurdistan region. It comprises harmonic folds with Mesozoic limestone in their cores and Palaeogene and Neogene limestone and clastics on their flanks. The Sand SW boundary runs along the Sand SW limbs of the first high anticlines, Chia-i-Spi, Dohuk, Ain Sifni, Aqra, Pirmam Dagh and Qara Dagh; this boundary coincides with a deep-seated fault with over 3000 m of displacement. In N Iraq the N boundary of the zone is the thrust fault of the Ora (Northern Thrust) Zone (Fig. 6-1). In NE Iraq, the boundary is more complex but runs from Amadiya to the area W of Rowanduz, to the SE along a reverse fault passing through

Qalat Dizeh, and then to the Sirwan gorge on the Iranian border. The anticlines of the High Folded zone generally trend NW-SE in NE Iraq and E-W in N Iraq.

The High Folded Zone has an elevated basement (-8 km) compared to the neighbouring Foothill Zone (-13 km) and the Balambo- Tanjero Zone (-10 km). The zone was a molasse basin during the Palaeogene and was elevated (forming the Qamchuqa ridge) during Cretaceous and early Palaeogene time. Due to lack of potential field data, the basement depth has been estimated from the thickness of the megasequences. The average depth is estimated to be 9-10 km in the Sand SW parts of the zone and <6 km on the Mosul High.

The sedimentary cover of the High Folded zone comprises: a possible Infracambrian section, Palaeozoic (1500-5000 m), Triassic (1500-2000 m), Jurassic (1100 m), Lower Cretaceous (250-1200 m), Upper Cretaceous (800 m) and Palaeogene (1000-1500 m) sediments. Neogene sediments occur only locally in some synclines.

The High Folded Zone comprises whale-back anticlines (Fig. 6-7 top inset) with Palaeogene carbonates in their cores and Neogene clastics on their flanks in the SW part of the zone. In the NE Cretaceous or older Mesozoic carbonates form the cores of the anticlines and Palaeogene rocks form the flanks with carbonate units forming resistant ridges (Fig. 6-8 both insets).

The high folds, often with a broad box like geometry, are separated by narrow deep synclines. The structures are mostly asymmetrical, with steep SW or S flanks with reverse faults. Along the NE boundary of the zone the synclines are over-ridden by reverse faults. The SE part of the zone (between Latitude 35.5° and the Iranian border) contains narrow NW-SE trending anticlines cored by Palaeogene formations and broad synclines with Neogene clastics. The anticlines are usually box-shaped, and asymmetrical; some are associated with visible longitudinal faults. Transversal faults and structural noses are present near Aqra in the NW and in the Derbendikhan area of the Sirwan Valley in the SE.

The Central part of the zone lies between the Rowanduz River in the NW and Latitude 35°N in the SE. Its main structural features are relatively long high anticlines, mostly asymmetrical to the S or SW. Reverse faults are sometimes present along the steep limbs. Narrow synclines are characteristic features of the High Folded Zone; the broad syncline near Zakho is an exception. The cores of the anticlines are often formed of Mesozoic rocks, usually of pre-Upper Cretaceous age. The amplitudes of the anticlines exceed 2000 m in most of the high structures.

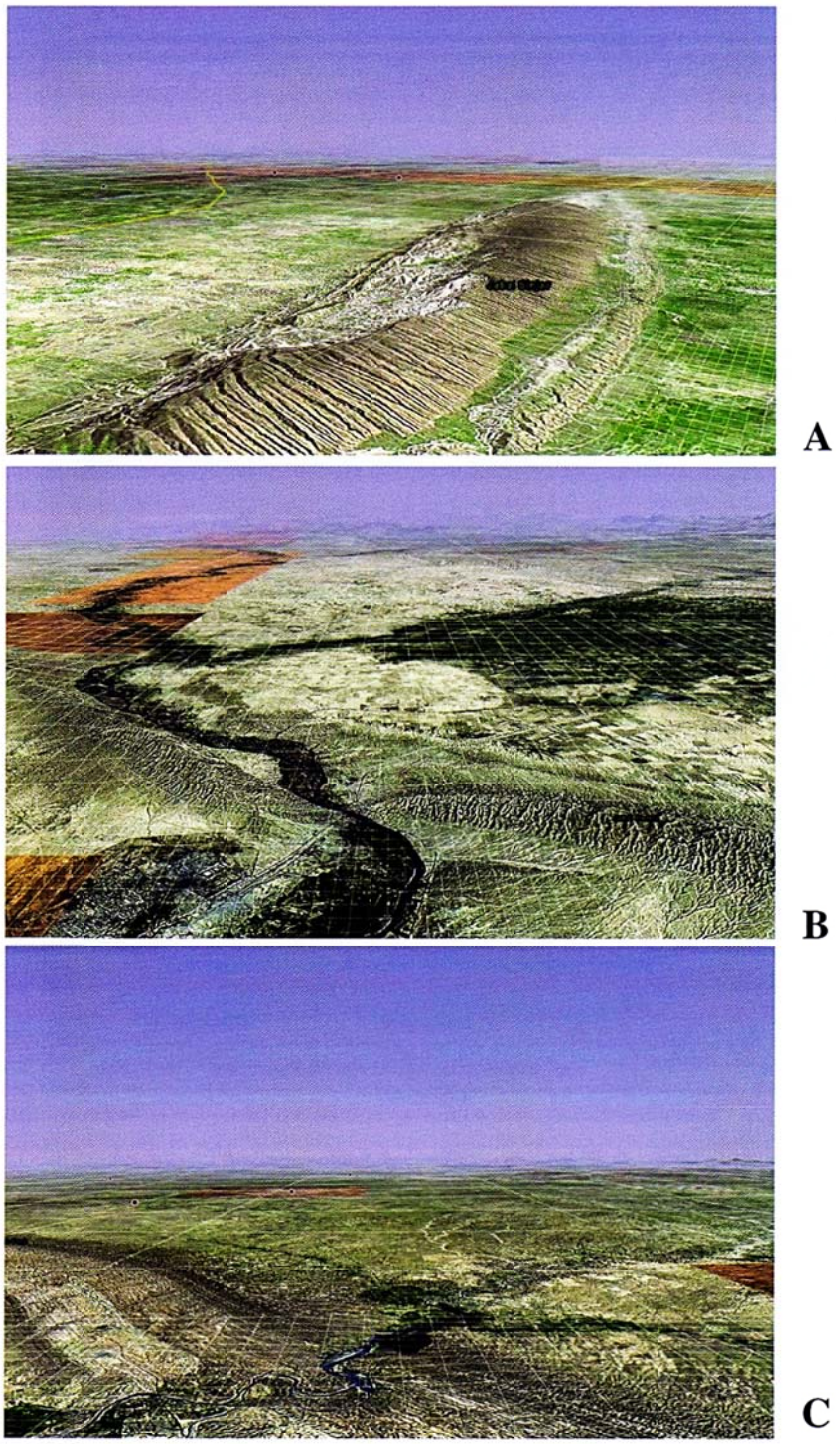


Fig. 6-5: Inclined views of some anticlines of the Foothill Zone: A) Looking east to the Sinjar anticline with Palaeogene whale back and incised northern limb with Cretaceous marls; located 100 km W of Mosul. B) The Al Fatha Col between Hemrin anticline (right) and Makhul anticline (left) with the Tigris River passing through it (220 km N of Baghdad). C) Kirkuk anticline with the Dibis col between the Avanah dome (right) and the Khurmala dome (left) (40 km NW of Kirkuk). All photos have 3× vertical exaggeration. Views are derived from Google Earth

6.1.3 The Imbricated Zones

6.1.3.1 The Balambo-Tanjero Zone

The Balambo- Tanjero zone was a trough that developed along the plate boundary during the opening of the Southern _ Neo- Tethys from Late Jurassic time. It is a narrow belt (up to 25 km wide) trending NW-SE. It extends from the Iranian border in the SE to the Turkish border in the NW. The zone may be completely over-ridden by the Northern 'Thrust Zone in N Iraq and partly by units of the Zagros Suture in NE Iraq.

The Mesozoic sedimentary section of the zone consists of pre- Tithonian platform carbonates, Tithonian-Lower Campanian marine basinal sediments of the Balambo and Shiranish formations, and the Tanjero flysch of Late Campanian-Early Maastrichtian age. The Palaeogene Neogene section consists of thick molasse deposited in an intermontane basin between the High Folded Zone and the suture zone.

The Balambo- Tanjero Zone is intensely folded and faulted throughout. Folded pre- Tithonian sediments have a structural style similar to the High Folded Zone; Cretaceous strata are isoclinally folded. Both Cretaceous and earlier units are traversed by reverse faults dislocating the anticlines into imbricates; the anticlines often over-ride the synclines. This structural style occurs to the S of the Greater Zab River.

Structures within the zone generally trend NW-SE except in the area NW of the Greater Zab River where their strike shifts to an E- W direction. The Tertiary section forms a NE dipping monocline. The structural pattern in the Zone is a result of two tectonic phases: Late Cretaceous obduction and Late Tertiary uplift. In Late Miocene-Pliocene time the zone was tilted towards the NE and overthrust in the NE by the thrust sheets of the Zagros Suture Zone. In the NE part of the zone an intermontane basin formed at the end of the Cretaceous and was filled with over 3000 m of Maastrichtian-Miocene marine and continental clastics.

The NW part of the Balambo- Tanjero Zone is characterized by shallow water facies of the Lower Cretaceous formations and by very thick Upper Cretaceous flysch. Three thrust sheets were identified by Hall (1957, 1958) which comprise, from SW to NE, the Kara, Baibu and Dairi-Govanda thrust sheets. The Kara Thrust Sheet is a relatively narrow WNW -ESE trending overturned anticline which is thrust over the marginal syncline of the High Folded Zone. The Baibu Thrust Sheet contains very complex imbricated internal structures of short, closely-packed anticlines and synclines cut by minor thrusts and reverse faults. The innermost and highest Dairi-Govanda Thrust Sheet is the largest; it is separated from the underlying Baibu Block by a gently dipping thrust fault which becomes steeper towards the E. The internal structure of this sheet is relatively simple, forming a NNE dipping monocline with small E- W trending anticlines occurring in the NW comer. The SE parts of the Balambo- Tanjero Zone comprise mostly short but strongly faulted anticlines and synclines.

Longitudinally, the Balambo- Tanjero Zone can be subdivided into two belts. The NE belt is a depression with Tertiary clastics and forms a monocline dipping to the NE below the thrust sheets of the Zagros Suture. The SW part (where Tertiary clastics are absent) is characterized by closely packed folds with several parallel or often obliquely (NNW-SSE) trending reverse faults or minor thrusts. SE of Chuwarta pre-Cretaceous rocks outcrop along the NE side of the zone. This area was uplifted in Tertiary time and formed a ridge between the Balambo-Tanjero Zone and the Zagros Suture.

The most conspicuous anticlines of the Balambo- Tanjero Zone include: the long Zozik-Barsarin anticline, the Zargali anticline in the NW part of the zone and the Azmur, Chart Dagh, and Barzinja-Shah Nadri anticlines in the SE.

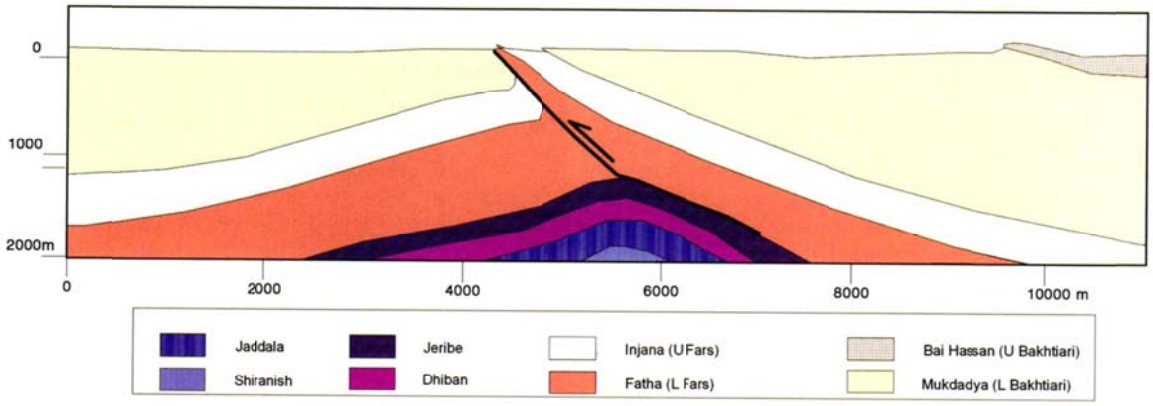


Fig. 6-6: Cross section across Hemrin South in the Injana area, 120 km NE of Baghdad (fault shows detachment in a salt bed at the base of the Fatha Formation)

6.1.3.2 The Northern (Ora) Thrust Zone

The Northern Thrust Zone (15 Ian at its widest in Iraq) is located along the Turkey-Iraq border. It is an E-W trending narrow belt between the Hazil Su valleys in the Wand the Dirri area in the E, running along the Turkish frontier. It contains Mesozoic and Palaeozoic formations, thrust over units of the High Folded Zone, usually with underlying Palaeogene and Neogene clastics and carbonates. Lower Palaeozoic clastics form the soft cores of the two major domes (Ora to E and Kaista to the W), flanked by Upper Palaeozoic and Triassic carbonates. Buday and Jassim (1987) considered the zone to be part of the Unstable Shelf which formed a Cretaceous ridge at the northern margin of the Arabian Shelf.

The depth and composition of the original Precambrian basement of the zone is unknown. In Iraq the zone can be considered allochthonous; its original basement mostly lies north of Iraq. In its present position, the zone is probably underlain by the Balambo- Tanjero Zone and the basement depth therefore may be 10 Ian.
The sedimentary cover is well known. The Infracambrian is absent (based on data from Turkey). The Palaeozoic section (-4000 m thick) is not complete due to the Silurian-Early Devonian and Late Carboniferous-Early Permian hiatuses. The Triassic and Jurassic sediments are shallow water carbonates (-2500 m thick). The Cretaceous consists of a thin succession of shallow water carbonates followed by detrital sediments (-500 m thick). Tertiary beds are absent. This sedimentary cover suggests the ridge was activated during the Cretaceous and during the opening of the Southern Neo- Tethys.

The S tectonic boundary of the zone is complicated by reverse faults. The structures of the Northern (Ora) Thrust Zone resemble those of the High Folded Zone. In Iraq the zone is widest in the W with three domal culminations (Sinat, Kaista and Ora). The domes are asymmetrical towards the S and occasionally the southern limbs are overturned. The low angle frontal thrust is dislocated by younger reverse faults. The northern limbs of the structures have lower dips and are

cut by reverse faults.

The E part of the zone, the Dirri Nappe of Hall (1957 and 1958), is a thrust sheet which overrides the Balambo Tanjero Zone and comprises Triassic rocks imbricated with Palaeogene shale. Buday (1975) assumed the Triassic rocks to be equivalent to the metamorphics of the Shalair Zone. In this book, these rocks are considered to be part of the Northern Thrust Zone; the rocks, however seem to be more deformed than in those to the W (with a phyllitic texture).

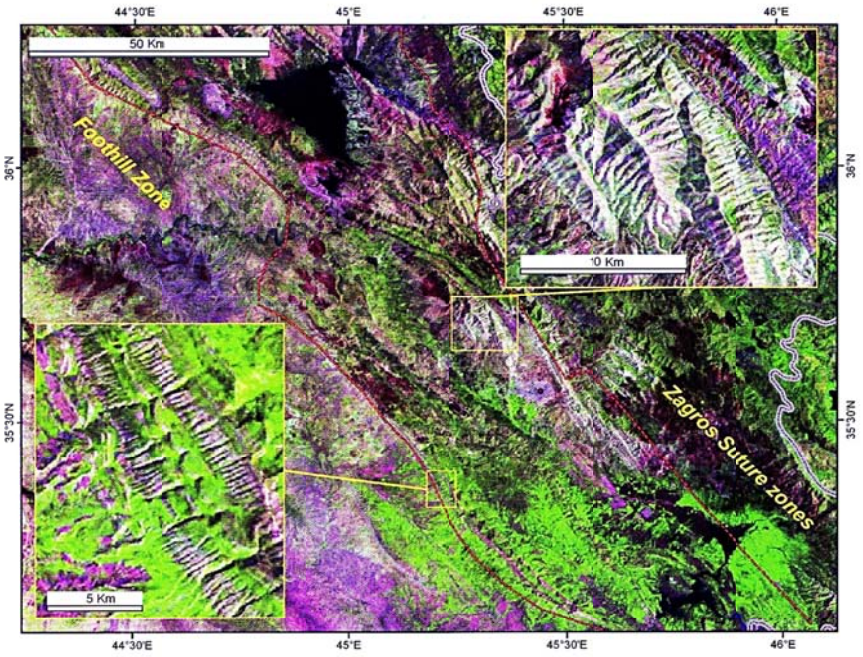
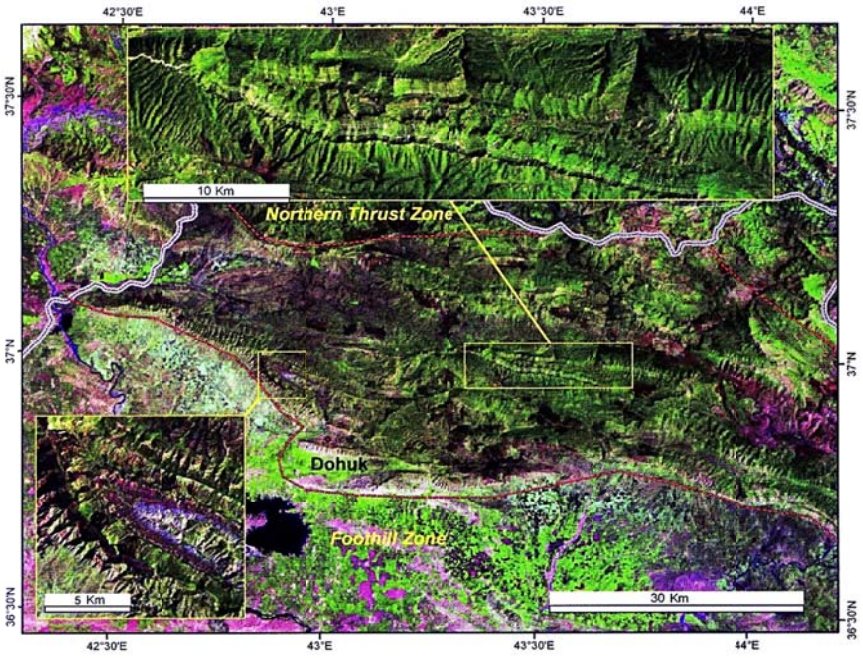


Fig. 6-7: Satellite image of the SE part of the High Folded Zone with two insets showing details of two anticlines

Fig. 6-8: Satellite image of the NW part of the High Folded Zone with insets showing details of two anticlines



6.2 Units of the Zagros Suture

The Zagros Suture units formed within the Neo- Tethys. They were thrust over the Arabian Plate during two distinct phases of obduction and collision, during the Late Cretaceous and Mio-Pliocene. Three tectonic zones are identified within Iraq and comprise from the SW: 1) The Qulqula-Khwakurk Zone with deformed radiolarites, carbonate turbidites and volcanics, and an upper thrust sheet of Triassic platform carbonates. The zone was obducted onto the Arabian Plate during the Late Cretaceous. 2) The Penjween- Walash Zone with upper thrust sheets of metamorphosed volcanics, carbonates and pelitic rocks, and lower thrust sheets of non-metamorphosed Palaeogene arc volcanics and fore-arc flysch. 3) The Shalair Zone comprising thrust sheets of meta-pelitic and metacarbonates of Mesozoic age, Upper Cretaceous arc volcanics of Late Cretaceous age, and metamorphosed Palaeozoic rocks of the Sanandaj-Sirjan Zone (Fig. 6-1).

The three tectonic zones are shown in cross sections (Figs. 6-9 SE part, 6-10, 6-11 central part and 6-12 NW part). The locations of these cross sections are shown on the geological maps of the Zagros Suture (Fig. 6-13 and Fig. 6-14). The cross section of Fig. 6-9 passes through the widest outcrop of the Qulqula-Khwakurk Zone which is unconformably overlain by Miocene clastics. These clastics are tectonically overridden by units of the Penjween- Walash Zone; plutonic rocks (ultramafic and mafic) are locally exposed along the thrust fault. Cretaceous units of the Shalair Zone contain imbricates of Triassic carbonate. The profile of Fig. 6-9 shows the Mawat Nappe which has been transported over the Qulqula- Khwakurk Zone and the Platform units. Just north of the Mawat Nappe in Iran (Shahidi and Jalali. 2004), a lower nappe with radiolarian chert, coloured melange and ultrabasic rocks is shown in the profile of Fig. 6-10. This ophiolitic melange is unconformably overlain by Tertiary clastics and over-ridden by thrust blocks of Eocene volcanics and is therefore comparable with the Qulqula Khwakurk Zone. The profile of Fig. 6-11 passes through the NW part of the Zagros Suture units, just SE of the Khwakurk area. The profile shows a volcano sedimentary sequence of Eocene age thrust over the Qulqula-Khwakurk Zone. A tectonic window exposes ultrabasic rocks that may be comparable with those seen in the profile of Fig. 6-10.

6.2.1 Qulqula-Khwakurk Zone

The Qulqula-Khwakurk Zone forms the units of the Southern Neo-Tethys that were folded, obducted and sutured to the Arabian Plate during the Late Cretaceous (Campanian-Maastrichtian). It contains Upper Tithonian Cenomanian sediments of deep water facies (radiolarian chert, mudstones, and limestones) with increasing proportions of basic volcanics to the NE and with conglomerates in the upper parts. The zone is strongly isoclinally folded and cut by reverse faults.

The Qulqula-Khwakurk Zone occurs as three disconnected outcrops between the Khwakurk area near the Iraq- Iran Turkey triple border point in the NW and the Halabja area in the SE. The NW outcrop near Khwakurk has a higher proportion of basic volcanics and ultramafic rocks associated with the radiolarian chert; this outcrop area may represent a more internal unit within the Southern NeoTethys. The second, smaller, outcrop area (the type area of the Qulqula Group) lies within Qulqula gorge N of Qalat Dizeh Town. The Qulqula Group is here unconformably overlain by Tertiary clastics of Maastrichtian-Pliocene age and thrust over the platform carbonates. It comprises radiolarian chert, limestone and conglomerate and lacks volcanics and may represent the outer part of the Southern Neo- Tethyan basin. The third and most extensive part of the zone forms

the Naorbab Plain between the Mawat Massif in the NW and Sirwan River near Halabja in the SE. The Qulqula Group here consists mainly of sediments with some volcanics towards the E. which have been thrust over platform carbonates of Jurassic to Late Cretaceous age. Imbricates of Jurassic rocks and locally Upper Permian carbonates are common. A massive Upper Triassic carbonate block is thrust over the radiolarian sequence and forms the high ridge of Jabal Avroman (Hauraman). This carbonate unit is more extensive and thicker to the SE in Iran, where it is referred to as Bisitoun Limestone (Geological Map of Iran, 1: 1 ,000,000 scale, sheet 2, North - Central Iran, National Iranian Oil Company), ranging in age from Cretaceous to Cenomanian. The zone is tectonically overlain by metamorphosed Cretaceous volcanics, sediments and plutons or by the non-metamorphosed Tertiary volcano sedimentary sequence of the Penjween Walash Zone.

Deformation of the Qulqula-Khwakurk Zone began during Cenomanian time with folding and uplifting of the eastern inner zones indicated by deposition of conglomerates with chert pebbles. The Cretaceous obduction culminated during the Campanian and Maastrichtian resulting in strong isoclinal folding, thrusting and flysch deposition. Both flanks of the obducted blocks subsided during the Late Maastrichtian and Palaeogene with deposition of the flanking clastics of the Red Beds Series.

The Qulqula-Khwakurk zone travelled a considerable distance (at least 15 km but possibly much more) over the Balambo- Tanjero Zone of the Platform. The depth to the Precambrian basement is thus likely to be about 14 km beneath the Qulqula-Khwakurk Zone.

The increasing proportion of volcanics in the chert sequence towards the NE suggests that the zone was located along the margin of the Southern- Neo- Tethys. The Triassic carbonates in the Avroman Range were derived from a carbonate platform which formed the north eastern margin of the Arabian Plate; this platform probably drifted away from the Arabian Plate during the Late Tithonian-Early Cretaceous (Chapter 3).

The main structural features are isoclinal and recumbent folds, reverse faults and thrusts. The whole zone is dislocated by longitudinal, high angle, faults bordering longitudinal blocks and is also cut by several transversal faults. The zone is thrust over the foreland units and is tectonically overridden by units of the Penjween- Walash Zone (Fig. 6-12).

The Qulqula-Khwakurk Subzone can be subdivided into three longitudinal belts (thrust blocks): the Outer, Central and Inner belts. The Outer Belt consists of partly shallow water sediments (including some conglomerates) belonging to the original SW marginal parts of the trough with outer shelf chert and limestone. It outcrops along the S margins of the Mawat Massif, near Halabja and in the type area. This belt is the most folded and disturbed part of the subzone. The Central Belt extends from the Lesser Zab River in the NW to Sirwan River in the SE. It is intricately folded with prominent anticlinal structures. It contains several small thrusted blocks (imbricates) of the underlying carbonate platform which are exposed in tectonic windows. It is a flatlying imbricated thrust sheet which had been subsequently faulted and folded. The Inner Belt is a thrust sheet which comprises thick conglomerates and frequent volcanics derived from the continental slope of the Southern Neo-Tethys.

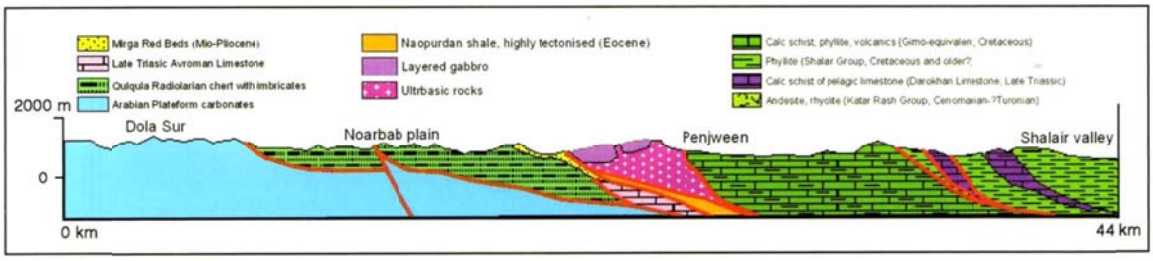


Fig. 6-9: Cross section between Sayid Sadik (SE of Sulaimaniya) through Penjween to the Shalair Valley (see Fig. 6-13 for location)

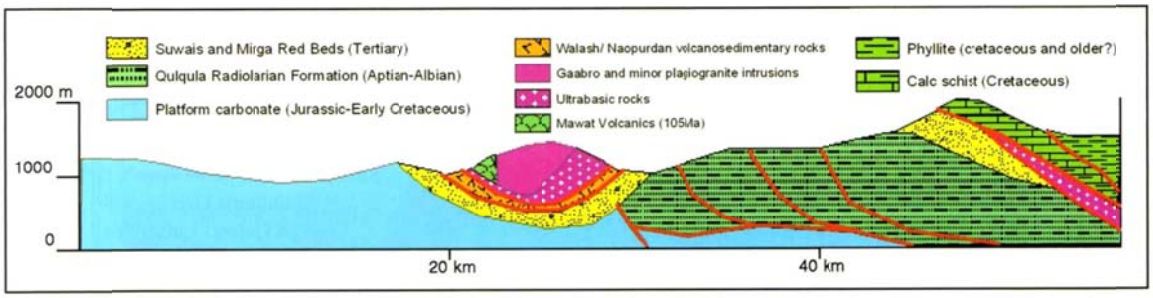


Fig. 6-10: Cross section passing through Mawat and the Naorbab plain (see Fig. 6-13 for location)

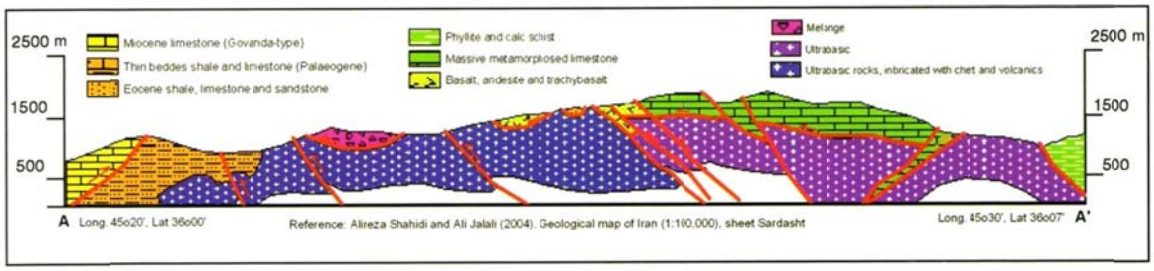


Fig. 6-11: Cross section in the Kuh-i-Sayid area of W Iran, N of Mawat (see Fig. 6-13 for location)

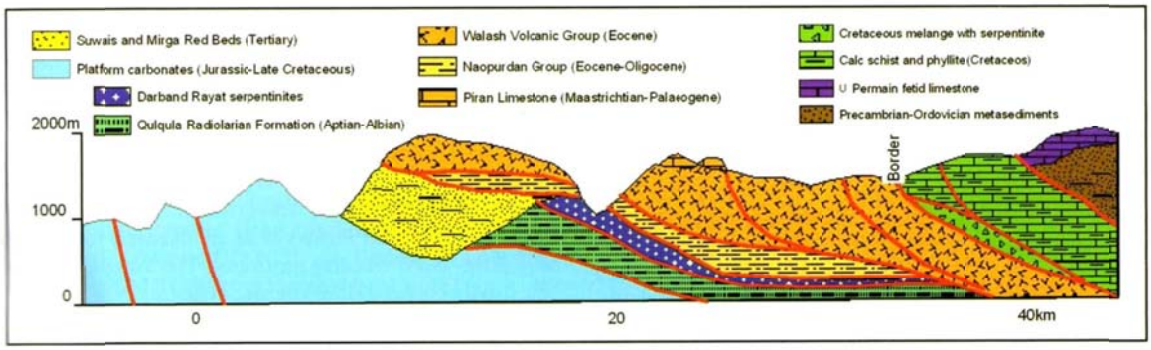


Fig. 6-12: Cross section through Darband Rayat and the Rowanduz River valley (see Fig. 6-14 for location)

6.2.2 Penjween- Walsh Zone

The Penjween-Walash Zone is a unit of the main (Central) Neo-Tethys. It comprises volcanosedimentary sequences formed during Cretaceous ocean spreading in the NeoTethys, and Palaeogene arc volcanics and syn-tectonic basic intrusions formed during the final closure of this ocean. The zone is thus a remnant of the Neo- Tethys which was thrust over the Arabian Plate during Miocene-Pliocene time.

The Penjween- Walash Zone forms an almost continuous belt along the Iraq-Iran border (Fig. 6-1). The zone is thrust over the Qulqula-Khwakurk Zone or the Balambo-Tanjero Zone. The Mesozoic sequences are mostly of Cretaceous age. They comprise alternating pelitic and carbonate beds with volcanics and pyroclastics that were metamorphosed during Late Cretaceous deformation; occasionally strong contact metamorphism can be seen near gabbro bodies such as Bulfat. Both volcanics and intrusions are dominantly basic in composition. The thickness of the Cretaceous sequences of the zone is about 4 km but they may be tectonically stacked. The Palaeogene succession comprises an outer unit of flysch with volcanics and an internal unit dominated by acid volcanics, andesite and basalt; both units pass laterally into each other. The thickness of the Tertiary units of the zone may reach 4000 m.

The main structural features of the zone are thrust sheets sometimes dislocated by reverse faults. The Cretaceous units form monoclines or massive domes where igneous intrusions occur. The Tertiary units are intensely folded into large ENE-WSW trending structures. The Walash volcanic unit locally contains large volcanic cones.

The Penjween- Walash Zone consists of three thrust sheets: the structurally lowest Naopurdan, the middle Walash and the upper Qandil (structurally highest). The upper Qandil thrust sheet contains basic igneous massifs, mostly along its SW margin. The massifs include, Penjween, Mawat, Bulfat and Pushtashan.

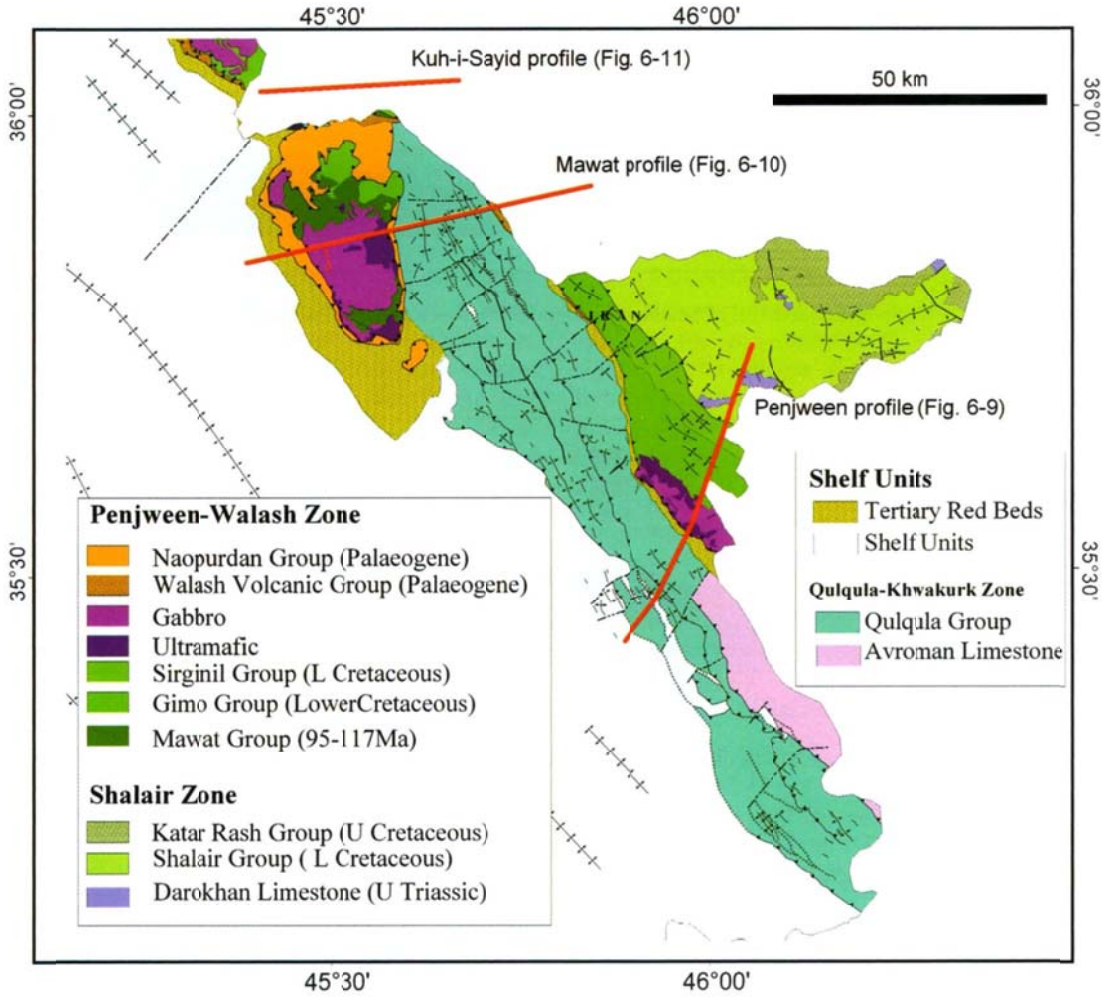


Fig. 6-13: Geological map of the SE part of the Zagros Suture

6.2.3 Shalair (Sanandaj-Sirjan) Zone

The Shalair Zone is an integral part of the Sanandaj-Sirjan Zone of Stocklin (1968) which comprises pre-Upper Permian metamorphosed rocks overlain, in Iraq, by ?Jurassic and Lower Cretaceous fore-arc metasediments and upper Cretaceous andesite arc volcanics with imbricates of Upper Triassic deep water carbonates (Fig. 6-1). The zone is e innermost metamorphosed unit, forming the structurally higher thrust sheets in Iraq. The zone outcrops in the Shalair valley. NE of Penjween Town; smaller, isolated outcrops comprise thrust sheets along the Iranian border in Jabal Qandil NE of Qalat Dizeh. In the Herb area in N Iraq, some deformed Triassic rocks considered to belong to this zone by Buday and Jassim (1987) are now included in the Ora Zone. The Cretaceous rocks of the zone were affected by low grade metamorphism in Cretaceous time. Palaeozoic rocks were metamorphosed during the Late Carboniferous. In the easternmost part of the Shalair valley syn-Hercynian Upper Carboniferous granite bodies occur. The volcanosedimentary sequences of proven Cretaceous age, reach a total thickness of 4-5 km. Triassic imbricates are up to 500 m thick.

The structure of the zone is characterised by a transversal (almost E- W trending) anticlinorium with Albian sediments and Triassic imbricates in the core and younger Albian Cenomanian

volcanosedimentary volcanics along its flanks. The lower, mostly pelitic beds are intricately folded whereas the upper volcanic unit forms a monocline, dipping N on the northern flank and S on the southern flank. Several longitudinal and transversal faults and folds are present. The zone was also strongly deformed in Late Cretaceous-Tertiary time. Sediments and volcanics of the Shalair Zone were formed on the SW margin of the Sanandaj-Sirjan microplate which formed the NE limit of the main Neo-Tethys. The W boundary of the zone is a reverse fault (Fig. 6-8) which can only be seen in outcrops outside the Shalair Valley.

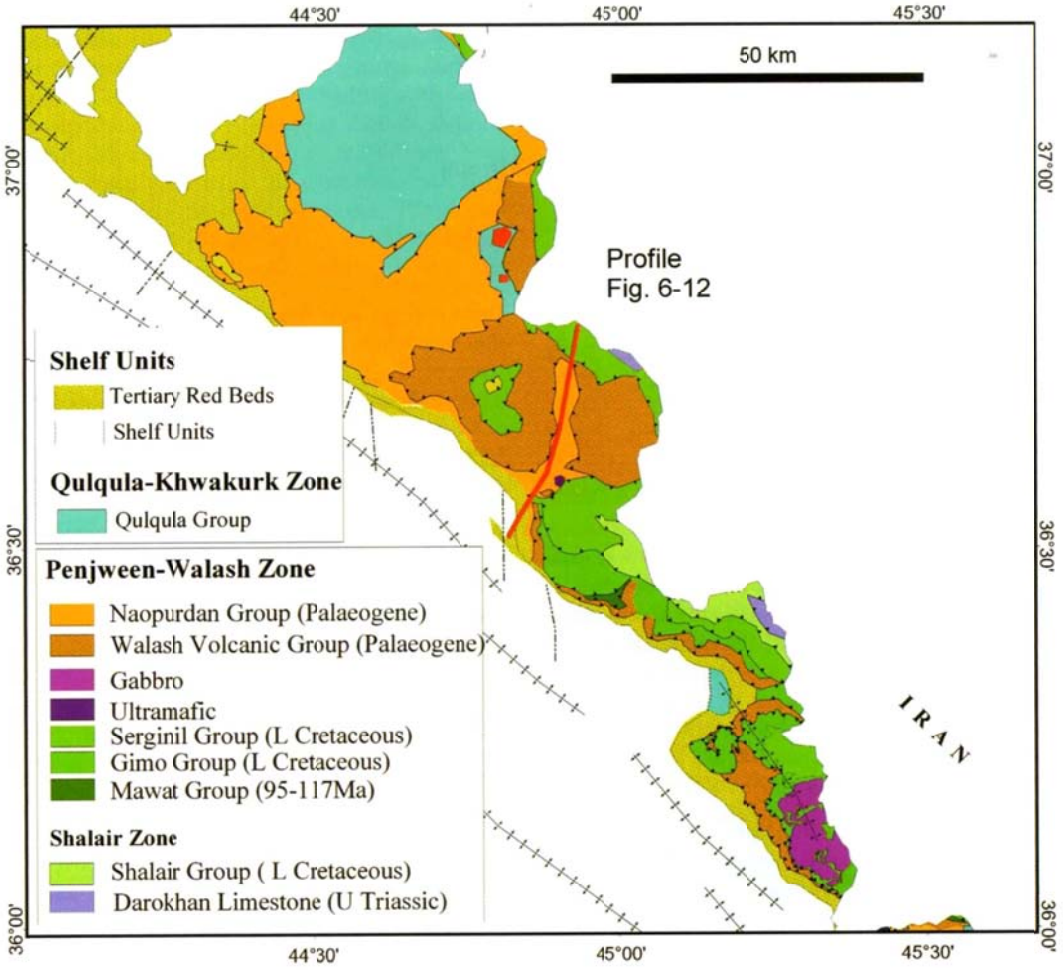


Fig. 6-14: Geological map of the NW part of the Zagros Suture

CHAPTER 7

Seismicity

by

Sahil A. Alsinawi

Iraq has a well documented history of seismic activity. The historical seismicity shows a well-defined pattern and follows the boundaries of the major tectonic elements. Tectonically, Iraq is located in a relatively active seismic zone at the tectonically active northern and eastern boundaries of the Arabian Plate. Earthquakes in this seismic zone can cause significant infrastructure damage, especially in the eastern part of NE Iraq.

Historical data for the period 1260 BC-1900 AD was used for historical isointensity determinations; this data is consistent with recent seismic observations (Alsinawi and Ghalib, 1975b and Alsinawi, 1988). Probabilistic seismic hazard analysis (PSHA) for Iraq was conducted by Ameer et al. (2004). The earthquake catalogue used contains more than one thousand events for the period 1905-2000.

7.1 Seismic monitoring in Iraq

Iraq established a seismic network (ISN) in 1976 consisting of five short-period stations located in Baghdad, Sulaimaniya, Mosul, Basra, and Rutba. Currently, only the stations at Baghdad and Mosul are believed to be operating. The centralized earthquake data processing facility is not presently available. A new broadband seismic network would help determine the potential seismic hazards that could damage infrastructure and cause injury or casualties. A new seismic network will help define seismic sources, intensities and hazards, and stimulate research in .seismology,

Seismological graduate studies were initiated at the Geology Department, Baghdad University in 1972 and expanded and accelerated during the 1980's to include more than 30 MSc and PhD projects. Most of these studies were concerned with microseismicity. Macroseismicity studies began after the Iraq Seismic Network work was set up.

In March 1976 the Foundation of Scientific Research (later Scientific Research Council-SRC) established the Seismological Unit as a dedicated independent seismological body. The original plan for the network envisaged a central station in Baghdad and four secondary stations located in Mosul, Sulaimaniya, Rutba and Basra. All the stations were built and became operational in the early 1980's, except for the Basra station which was never constructed. The coordinates of the ISN stations are:

Baghdad Observatory (BHD) 33.3 N and 44.4 E, Mosul Observatory (MSL) 36.3 N and 43.4 E, Sulaimaniya (SLY) 35.6 N-and 45.5 E, and Rutba (RTB) 33.03 N and 40.31 E.

These stations were functioning until the Gulf War in 1991 after which half of them ceased to operate. It is hoped that "state of the art" seismic and seismological engineering research on Iraq's seismicity will resume as soon as possible.

7.2 Geodynamic considerations

The neotectonic development of the Arabian Plate is related to the compressional Zagros and Taurus mountainous fold belts in the NE and N respectively, and to the opening of the Red Sea in the Sw. The NW-SE trending Zagros and E- W trending Taurus fold belts extend for 1500 km, passing through NE Iraq, from Oman in the SE to Turkey in the NW. The earthquakes in the Zagros province occur in a 200 km wide zone that runs along the Zagros High Folded and Imbricated Zones (Chapter 6).

The NE and N boundaries of the Arabian Plate mark the collision with the Cimmerian plates. The NW, Wand S boundaries are the left-lateral Dead Sea Fault Zone, the Red Sea and the Gulf of Aden ridges respectively. The SE boundary is defined by the obducted ophiolites of Masirah and Oman (Chapter 3, Fig. 3-1).

The compressional direction of the Foothill Zone is roughly from NE to SW perpendicular to the structural grain. The slip vectors, corresponding to the mechanism solution of earthquakes associated with the Zagros foothills, indicate a general motion towards the N and NE. Profiles across the seismic zones of the Zagros folded belt show that the Arabian plate is overthrust by the Iranian plate. The leading edge of the plate is a slab about 60 km thick that dips at about 10-20° to the NE. About 80 km of associated crustal shortening is estimated to have occurred. The rate of subduction of the Arabian Plate below the Iranian and Anatolian plates is a few centimetres per year which has resulted in uplift rates of similar magnitude. The continental collision in the Zagros began about 15 million years ago.

Buday and Jassim (1987) defined longitudinal tectonic zones parallel to the Alpine trend which decrease in stability towards the plate edge. Iraq mainly comprises units of the Arabian Platform (the Stable and Unstable Shelf). Units belonging to the Zagros Suture are present in a narrow belt along the Iraq-Iran border in NE Iraq. The tectonic framework of Iraq is presented in Chapters 4 to 6.

The sedimentary cover of the Arabian Plate of the Arabian Platform is currently being thrust obliquely under the Sanandaj-Sirjan microplate. The main expression of this continent-continent collision is a wide zone of folding and shallow earthquakes terminating abruptly to the northeast along a regional-scale thrust fault referred to as the Main Zagros Thrust. The thrusting is generally shallow and may be associated with a decol1ement along the Infracambrian Hormuz Salt (where present) or the numerous thick shale horizons of the Lower Palaeozoic sequences. Thrust belts are also associated with the boundaries of the Sanandaj-Sirjan and the Central Iranian microplates in NE Iran (Stocklin, 1965).

7.3 The crust and Moho

Information about the structure of the crust and upper mantle in Iraq is sparse. Most interpretations are based on analysis of gravity data as described by Alsinawi et al. (1986). Gravity interpretation indicates that the crustal thickness in Iraq ranges between 30 km in the Wand 45 km in E and NE. Other regional investigations of the deep structure of the northern Arabian Plate using seismic methods were based on surface wave dispersion data; an average crustal thickness of 34 km was calculated by Knopoff and Found (1975).

Mooney et al. (1998) considered several models for the Arabian Plate dependent on the crustal thickness that varies from 39 km to 46 km and a sedimentary cover thickness ranging from 0 km to 6 km. The NE edge of the Arabian Plate is a region of continental collision with thickened crust

and Quaternary volcanicity, and marks the eastern end of the convergence zone of the North and South Anatolian faults.

The Q values for Love and Rayleigh waves in the E and W parts of the Arabian Plate (over periods of 1-30 sec) range from 60 to 150, with highest values in the central region and in the Zagros fold and thrust belts (Seber and Mitchell, 1992).

Two major strike slip faults along the Zagros Suture Zone accommodate the westward motion of Turkish plate as the Arabian plate moves northward (Mooney et al, op. cit.).

Crustal structure determinations in Iraq were derived by utilizing 91 events recorded in four Iraqi Seismological seismic stations of the ISN Network, namely Baghdad (BHD), Mosul (MSL), Sulaimaniya (SLY) and Rutba (RTB). Teleseismic body wave forms have been used to infer crustal structure beneath Iraqi seismic stations. The data have been modelled in both frequency and time domains to determine the crustal structure (Tables 1 and 2). Alsinawi and Al Heety (1994) estimated the crustal thickness in Iraq and concluded that it increases towards the Zagros Suture (in agreement with gravity interpretation). The crustal thickness interpreted from seismicity provided values of 38 km (Vc 6.0 km/s) in the Baghdad area, 33-35 km (Vc 5.9 km/sec; Vm 8.2 km/sec) in the Rutba area, 3134 km (Vc 6.0 km/sec; Vm 8.3 km/sec) in the Mosul area and 41-43 km (Vc 6.1 km/sec; Vm 8.0 km/sec) in the Sulaimaniya area. Analysis of seismic body waves and surface dispersion measurements were used to estimate the depth of the Moho in the Arabian plate. The Moho depth was estimated to be 34 km with an upper mantle velocity of 8.17 km/sec.

Two transects were carried out in Iraq. The first was an E- W transect 650 km long between the Jordanian and Iranian borders which passed through Baghdad. The crustal thickness along this transects, ranges from 31 km in the W to 37 km in the E and averages 34 km. The seismological and tectonic data along this transect were compared with the available aeromagnetic, gravity and seismic reflection data (Alsinawi and Al Banna, 1990) and are shown in Chapter 4 (Fig. 4-5). The second transect profile trends NW-SE; it is 605 km long and 100 km wide. This was the first Global Geoscience Transect Project (GGT) in Iraq. Background surface and subsurface data were compiled from various sources to construct this profile which extends from the Iraq-Syria border in the NW to the Salman Depression in the SE. The thickness of the sedimentary layers ranges from 6 to 7 km in the Jezira region where the depth to the Moho was calculated as 37 km with Vc = 6.8 km/sec, Vm = 7.95 km/sec and where the depth to the Conrad discontinuity is at a depth of about 20 km (V c changes from 6.10 km/sec to 6.50 km/sec). This Moho depth is significantly higher than values obtained from gravity modeling of around 30 km (see Chapter 3).

Table 1: Crustal model for Iraq at the four seismic observatories of Iraq (data from Alsinawi and Al Heety, 1994)

IRAQI Seismological stations (ISN)	Vp km/s)	Vs (km/s)	Density (gm/cm^3)	Depth (km)
Baghdad (BHD)	5.2	3	2.52	8
	6.2	3.6	2.71	13
	6.7	3.9	2.84	17
	7.9	4.7	3.2	
Mosul (MSL)	5	2.9	2.49	5
	6.2	3.6	2.71	13
	6.6	3.8	2.81	17
	7.9	4.8	3.22	
Rutba (RTB)	4.9	2.8	2.48	5
	5.9	3.4	2.65	12
	6.4	3.7	2.77	17
	7.8	4.7	3.17	
Sulaimaniya (SLM)	5.2	3	2.52	10
	6.3	3.6	2.74	16
	6.7	3.7	2.84	17
	7.8	4.7	3.17	-

Table 2: Crustal velocity models for The Unstable Shelf and the Mesopotamian Zone of Iraq (after the crustal model of Mooney et al., 1995)

Tectonic Zone	Depth (km)	Vp (km/s)	Vs (km/s)	Density (gm/cm^3)
Folded Zones	0.0	2.5	1.1	2.1
	1.0	4.0	2.1	2.4
	8.0	6.0	3.5	2.7
	18.0	6.4	3.7	2.85
	38.0	7.1	3.9	3.05
Crust (50-60 km), Sediments (0-5 km)	50.0	8.0	4.52	3.35
Mesopotamian Zone	0.0	2.5	1.1	2.1
	2.0	4.5	2.4	2.5
	11.0	6.2	3.6	2.8
	20.0	6.6	3.7	2.9
	34.0	7.3	4.0	3.1
Crust 46 km, Sediments 2-10 km	42.0	8.1	4.58	3.4

7.4 Historical seismicity

Iraq has a long well documented history of seismic activity. Many seismic events have been documented for the period from 1260 BC through to 1900 AD. These historical events define a well established pattern of seismic activity which correlates well with the geological and tectonic setting of the country and agrees with the modern epicentre determinations after 1900 AD (Alsinawi and Ghalib, 1995b). The value of historical events in seismic risk analysis has to be assessed by checking the validity and authenticity of manuscripts. The value of historical records of earthquakes was assessed by Ambraseys (1971 and 1978) and by Poirier and Tahir (1980). Historical seismicity data for the period 1606 BC to 1900 A.D are distributed in three intensity zones within Iraq (VII-IX) and correlate well with recent seismicity. A historical catalogue was compiled containing 360 events for this period. Several isointensity -maps were constructed using historical events in Iraq and the surrounding region (Alsinawi and Ghalib (1975b), Alsinawi and Issa 1986, Ambraseys and Melville, 1982 and Alsinawi, 1988). The historical isointensity map of Iraq prepared by Alsinawi and Al Qasrani (2000) is shown in Fig. 7-1.

7, 5 Macro and microseismicity

7, 5, 1 Regional seismicity

More than 7000 events of various magnitudes have been documented in the Arabian Plate. 75.4% of these events have "mb" values of 4.0-5.5. 78% of these events have a focal depth range of 10-40 km. The frequency-magnitude relationship was computed giving a (b) value of 7.703 and an (a) value of 0.915. The seismic sources for the region were also investigated and modelled, resulting in 25 line sources and 10 area sources. The seismic sources identified by (Alsinawi and Hamad, 1992) are associated with four line sources that represent the Zagros, Arabian Sea, Gulf of Aden and Taurus zones, and the SE Gulf of Oman.

Fig. 7-1: Historical isointensity map (after Alsinawi and Al Qasrani, 2003)

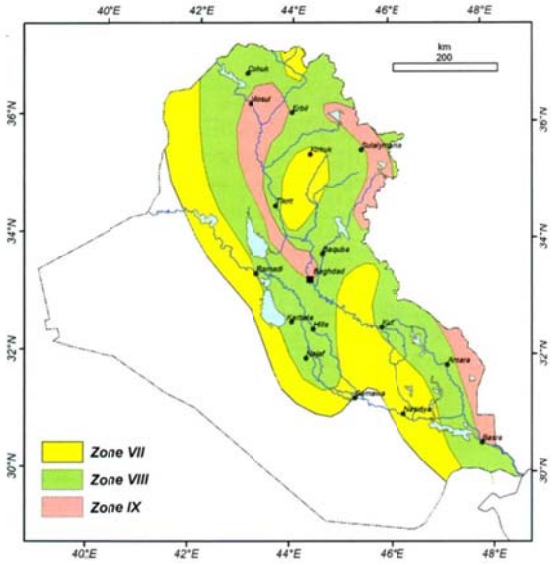
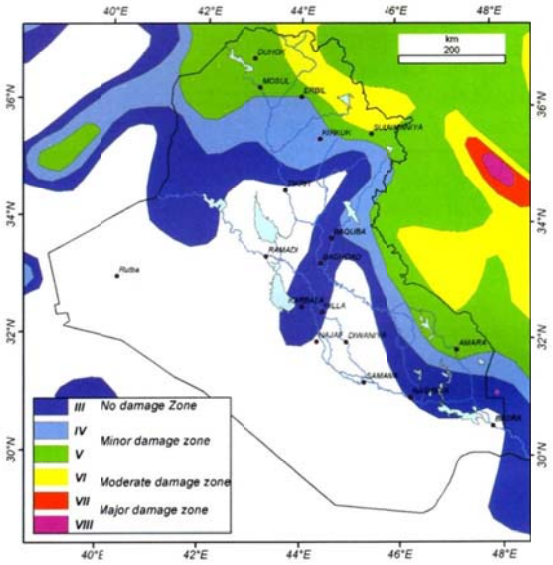


Fig. 7-2: Seismic isointensity map



7, 5, 2 Macroseismicity of Iraq

The distribution of seismicity is inhomogeneous and the activity is concentrated in the High Folded and the Balambo-Tanjero zones. The seismicity of Iraq is of intermediate character and the focal depth is shallow. The seismicity of the stable shelf is due to local deformation but the seismicity of the folded area is due to forces resulting from the movements of the Arabian plate towards the N and NE. The forces that formed the major geological structures along the plate boundaries are still active causing stress and strain accumulation and deformation. The overall seismicity of Iraq is influenced mainly by the Zagros and Taurus systems with partial neotectonic activation of the upper crust.

The isointensity map of Iraq (Fig. 7-2) shows that the maximum seismic intensity is related to the High Folded and the Balambo- Tanjero zones. This is the belt where the Arabian Plate is tectonised as it is pushed below the Sanandaj-Sirjan plate to the NE. Seismically it is considered an area of moderate earthquake damage. A zone of weak damage covers most of N Iraq and extends into the Palmy rides of Syria. The Sirwan and Anah-Qalat Dizeh transversal faults (see chapter 4) are generally more seismically active than the surrounding areas.

90% of the seismic events in Iraq occur at intermediate-shallow focus levels. 54% of the events have "mb" magnitudes of 4-5 with focal depths in the range 30-50 km. Less than 8% have magnitudes >5.5. The average recurrence relationship is given by the equation: Log N = 5.8-0.7 b

7.5.3 Microseismicity of Iraq

Microearthquake recording in Iraq was carried out for the period 1974-1990 for a total recording time of over 10,000 hours covering various physiographic and tectonic provinces. The microseismicity shows an increase in the NE direction; the frequency of microearthquakes varied between 1 and 8 events per day. There is an overall correlation between the macro and microseismicity of the country with minor deviations in certain areas particularly in the western desert where intraplate seismicity may be occurring (Alsinawi and Banno, 1976; Alsinawi and Al Heety, 1987 and Alsinawi and Al Ridha, 1988).

7.5.4 Focal mechanism studies

Fault plane solutions gave a trend parallel to the structural trends of the Zagros-Taurus belts and the pressure axes are approximately perpendicular to the major structures. A composite fault plane solution was also carried out using microearthquake records from north central Iraq and the results agree with data collected from the literature Alsinawi and Issa, 1986 and Alsinawi and Al Heety, 1987).

The data on focal mechanism solutions collected from various references indicate high angle thrust faulting occurs NW-SE trending planes dipping to the NE. Some 50~iOIllS in the Taurus Belt indicate a component of strike along fault planes dipping at low angle to the N. Generally, most solutions for earthquakes associated with el to the trends of structures of the Zagros.10 t pressure axes are approximately o e axes of the major structures in the area (Alsinawi and Ghalib, 1975a and Alsinawi and Issa, 1986).

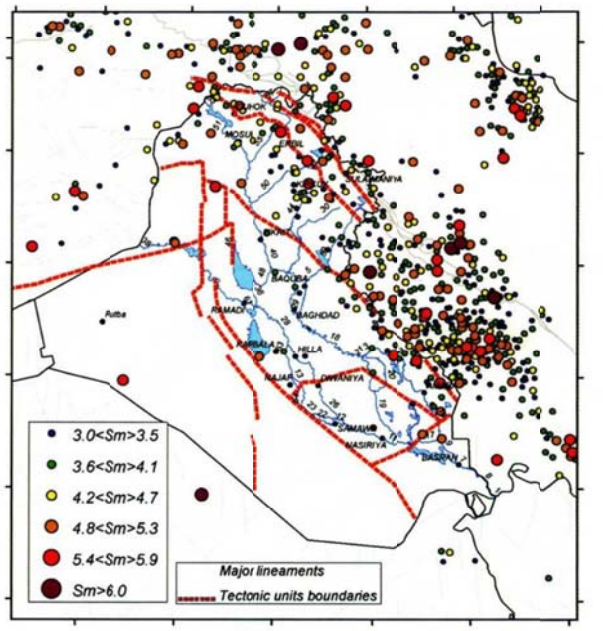
Microearthquake recording in the High Folded Zone of Iraq during the period 1989 to 1990 registered more than 500 events; 85 of these events were chosen for determination of composite focal mechanism solutions. They revealed reverse faulting solutions nearly parallel to the seismic trends. They are consistent with previous focal mechanism studies with epicentre locations close to the investigated area (Alsinawi and Al Heety, 1997).

Amplitude spectra of 38 micro earthquakes selected from ten different sites in Iraq, recorded during the period from 1975 to 1978, with a consistent digitised interval of 10 seconds, indicate that the predominant frequencies of the analyzed earthquakes fall in the range 0.23 to 3.5 Hz. The energy of the seismic waves decreases as the frequency increases (Alsinawi and Al Shukri, 1982).

7.5.5 Induced seismicity investigations

Induced seismicity was first noticed when an anomalous increase in the seismicity in the Kirkuk area was confirmed and was correlated with the water injection into the aquifers of oil fields (Alsinawi and Ghalib, 1975b). Induced seismicity was also observed during steam injection into the Mishraq sulphur mine, which was monitored and analysed by Alsinawi and Al-Eqabi (l980). Some of the tremors of Mishraq were felt more than 30 km to the north in Mosul. Dam sites in Iraq were systematically monitored from 1975 to 1986 before and after the filling of the lakes associated with the dams of Haditha, Al Baghdadi, Hemrin, Dokan, Bekhme, Derbendikhan and Mosul.

Fig. 7-3: Seismic epicentres of earthquakes in N Arabia and major tectonic elements (see tectonic map of Fig. 4-15 for tectonic elements)



7.6 Seismotectonics of Iraq

NE Iraq is directly influenced by the seismicity of the Alpine orogenic system (Zagros-Taurus range). This system, identified with high mountain ranges and shallow somewhat diffuse seismicity, is one of the most seismically active continental regions of the world with a long and well-documented history of earthquakes. The majority of the earthquakes, however, occur in the continental crust of the Arabian plate beneath the Zagros folded belt. The plot of earthquake epicentres and magnitudes (Fig. 7-3) indicates seismic activity in Iraq is inhomogeneous and scattered. Most of the epicentres are concentrated along the Zagros-Taurus folded belt. However, there is also seismic activity situated along the Sinjar-Herki, Hadhar-Bekhme, Anah-Qalat-Dizeh and Sirwan transversal faults. These transversal faults were active during Pliocene folding; they are still active at the present (see Chapter 6); the Hemrin and Makhul anticlines are visibly deformed along the Anah-Qala Dizeh sinistral slip at Fatha in N Central Iraq. The Hadhar-Bekhme Fault in the Jezira subzone has associated Quaternary salt playas (see Chapter 5) in depressions created by recent tectonic activity.

The distribution of seismic activity along the Zagros-Taurus folded belts is inhomogeneous and scattered. Deformation along the belt is inhomogeneous due to the changes in the geometry of the edge of the Arabian plate along the collision zone with the Iranian and Turkish plates, and due to the rotational movements within the Arabian plate itself (Alsinawi, 1997).

The Stable Shelf (including the Mesopotamian Zone) shows weak seismic activity. There is a sharp boundary between the folded zone (Unstable Shelf) and unfolded region (Stable Shelf) which suggests that stresses resulting from the movement of the Arabian plate to the N and NE are not transmitted to the unfolded region.

Many Earthquakes depths are thought to originate within the basement at >20 km depth. The depth to basement throughout Iraq (Chapter 3) ranges between 5 and 13 km. Seismic .activity in the Zagros is related to compression along thrusts distributed across the whole width of the belt. It might be partly explained by reactivation of normal faults in the basement as high angle thrusts during lateral compression.

A seismotectonic map, constructed by Alsinawi and Issa (1986), is given as Fig. 7-4 which indicates inhomogeneous distribution of seismic activity in relation to surface geology. This inhomogeneous distribution may indicate a change in geometry of the Arabian Plate edge due to its rotational movement (Alsinawi, 1997).

7.7 Seismic hazards

Although Iraq is seemingly secure from seismic hazards, seismic observations indicate otherwise. Earthquakes are likely to happen and may cause substantial damage, especially in NE Iraq and in the Mesopotamian Plain due to liquefaction of Quaternary sediments. It is therefore important to take into consideration seismic parameters in future design of large buildings.

7.7.1. Seismic zoning

Seismic zoning maps were published by Alsinawi and Ghalib (1975c), Alsinawi and Al Moosawi (1982), Mahmood et al. (1985), Alsinawi and Issa (1986), Fahmi (1989), Alsinawi and Hamad (1991) and Alsinawi and AI Qasrani (2003). They are based on an attenuation relationship given by Puttonen and Varpasu (1982). The seismic zoning map (isointensity map, Fig. 7-2) depicts four zones:

1) Zone of no damage (MM=III and less) which covers mainly the Stable Shelf region. **2**) Zone of minor damage which follows intensities MM=IV to V and covers the Mesopotamian and Foothills Zones. **3**) Zone of moderate damage following the intensity range MM=VI to VII which covers the High Folded and the Imbricated Zones. **4**) Zone with magnitudes ≥4.0. A region where an earthquake with M ≥4.0 is likely to occur and cause major damage with intensity MM=VIII is located in the Zagros Suture Zone and in the Sanandaj-Sirjan Zone outside Iraq.

Fig. 7-4: Seismicity Index map (after Alsinawi and Al Qasrani, 2003)

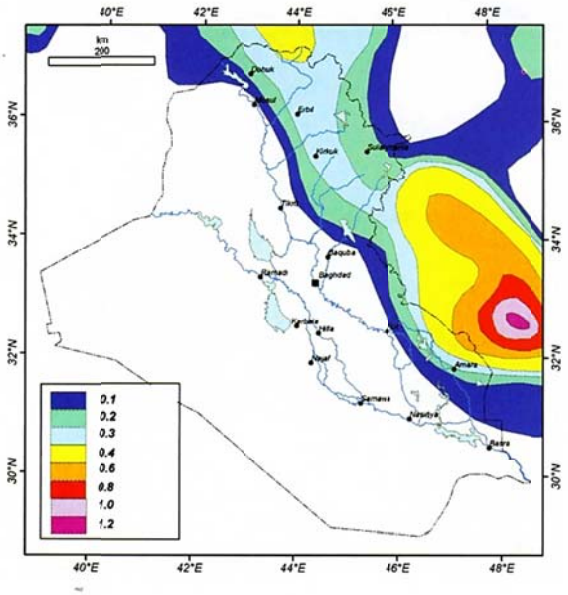
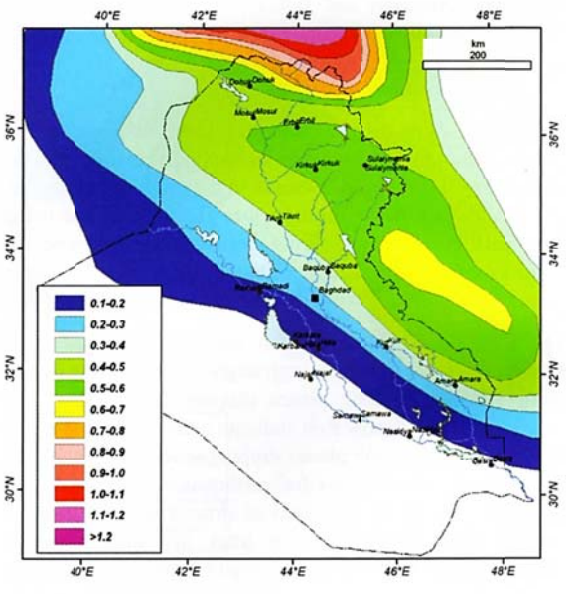


Fig. 7-5: Seismic acceleration map with design period of 100 years



7.7.2 Seismicity index "ST"

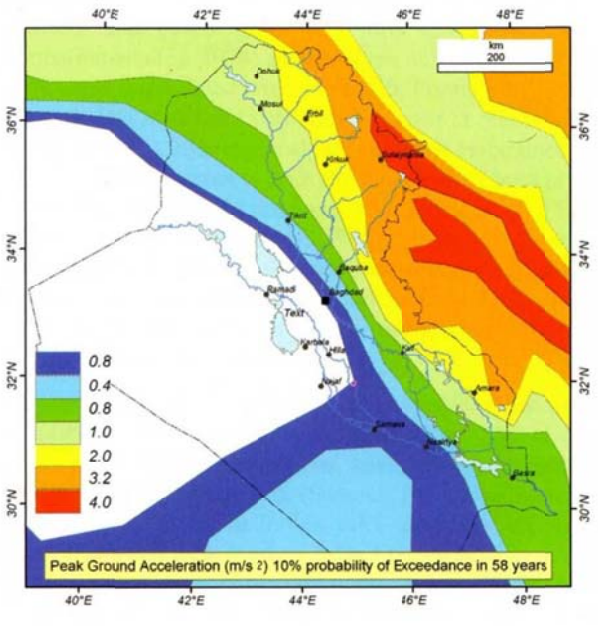
The seismicity index number (ST) is related to the frequency of occurrence of earthquakes magnitudes ≥4.0. A region with 0.1≤ ST ≥0.2 is a region where an earthquake with a M≥4.0 is likely to occur every five to ten years in an area with a diameter of 100 km.

The Sesimicity Index Map (Fig. 7-4) indicates that the region east of Tigris River suffers an earthquake with magnitude M≥4.0 every two to five years. The region between the Tigris and Euphrates Rivers experiences an earthquake of this magnitude every five to ten years. In the S and SW regions earthquakes of this magnitude occur over ten years apart (Alsinawi and Al Qasrani, 2003).

7.7.3 Isoacceleration map

Isoacceleration maps for Iraq with a contour interval of 0.01g using four return periods of25, 50,100 and 200 years were constructed using an approximated attenuation law. These maps reflect the increasing seismicity and seismic risk from SW to NE in Iraq. A "100 year" plot is shown in Fig. 7-5 and compared with the seismic hazard map redrawn for the Iraq and surrounding areas in Fig. 7-6.

Fig. 7-6: Seismic hazard map derived from the global seismic hazard map



7.7.4 Probabilistic hazard assessment

Probabilistic Seismic Hazard Analysis (PSHA) was conducted for Iraq by Ameer et al. (2004). The earthquake catalogue used in the present study covers an area between latitude 39°-50° E and longitude 29°-50° N containing more than one thousand events for the period 1905 to 2000. The catalogue compiled by Fahmi and AI-Abbasi (1989) has been updated and the size of events re-evaluated in terms of surface wave magnitude "Ms" (either observed or converted from "mb") for further use. The Iraq region is divided into thirteen seismogenic sources based on their seismic characteristics, geological setting and tectonic framework. Delineations of the source boundaries are based on neotectonic elements and sudden variations in the homogeneity of the seismicity.

The earthquake activity parameters (activity rate λ, b-value, maximum regional magnitude M_{max}) as well as the mean 'return period R with a certain lower magnitude $M_{min} \geq m$ along with their probability of occurrence have been determined for all thirteen seismic zones of Iraq. These values are close to the previously determined seismicity index "ST" values.
The maximum regional magnitude Mmax for Iraq is estimated at 7.87 ± 0.86. The probabilities of occurrence of different magnitudes in the seismic zones reveal that the probabilities of occurrence of earthquakes are higher in the E and NE parts of Iraq. The large difference between the "b" parameter and the hazard level from zone to zone reflects the high seisrnotectonic complexity and crustal heterogeneity.

The seismic hazard near the source boundaries is directly and strongly affected by the change in the delineation of these boundaries. The forces which have formed the geological structure along the plate boundary in E and NE Iraq are still active causing stress and strain accumulation, and deformation. Highly destructive earthquakes can be expected to occur in the future (Ameer et al., 2004).

The folded belt, especially the High Folded Zone, shows high seismic activity with M_{max} for these sources clearly higher than for other sources. For all source zones the slope (b-value) of FMD varies between -0.49±0.19 and -1.09±0.14 with most zones having values around -0.8.

7.7.5 Seismic wave attenuation

Studies of seismic wave attenuation by Alsinawi and AI Tikriti (2000) were based on the methods of Nuttli (1980). The attenuation of earthquake-generated P waves in Iraq was attempted for the Iraqi network (ISN) of the Baghdad (BHD) and Mosul (MSL) seismological observatories. P waves were picked from earthquakes originating in Turkey and Iran. Thirty seven events were chosen, twenty three were recorded at the Baghdad Observatory and fourteen at the Mosul Observatory. Earthquakes of magnitudes "mb" 4.1 to 5.7 have paths along the northern and central regions of Iraq. The amplitude distance curve of Nuttli (1980) was used in this investigation. The mean attenuation value obtained for the whole area was $a = 0.0035$ Km-1, the value obtained for Iran by Nuttli (1980) was $a = 0.0045$ Km-^{1}. The attenuation values are higher in NE Iraq than in N Iraq. The mean attenuation values recorded by the two stations resulted in higher values for events originating in Iran than for those originating in Turkey.

7.7.6 Strong motion seismology

A strong motion prediction computation was carried out using microearthquake data recorded in the Bekhme Dam site. Results show seismic activity along an exposed fault zone in the area, trending parallel to the Zagros Thrust. Low stress drop values suggest a tensile component of movement on this fault. This conclusion is in agreement with the anticlockwise rotation of the Arabian Plate in the region.

Numerical results show that rupture of the fault zone in the Bekhme region can produce a strong motion of local magnitude with PGV and PGD values of about 32 cm/sec and 20 cm respectively in the area close to the site (Alsinawi and Ziyai, 1995).

7.8 Recommendations

Iraq lacks a centralised earthquake data processing facility at present. A new seismic network will act as a stimulus for seismic research and define seismic source regions in and around Iraq. This is important in determining the intensity of shaking in major cities that may result from earthquakes in these source regions. A lot of work remains to be done, most prominently in the field of seismic tomography; neighbouring countries have carried out various sophisticated seismological studies and seismic hazard research work. A five-year plan to bridge the gap should be implemented starting with the revitalisation of the ISN network.

Chapter 8

Palaeozoic Megasequences (API-APS)

by
Saad Z. Jassim

Palaeozoic strata comprise five megasequences API to AP5 and the lower part of megasequence AP6 of Sharland et al. (2001). This chapter describes the lower five megasequences; the Late Permian part of Megasequence AP6 is discussed in Chapter 9.

The tectonic development of the Arabian Plate during Palaeozoic time was discussed in Chapter 3. Megasequence API is the product of tectonic extension following the Late Pan African orogenesis. AP2 is a passive margin megasequence, which formed a broad platform starting in the late Early Cambrian and ending with the Saharan Glaciation at the close of the Ordovician. AP3 represents the syn-Caledonian active margin development, starting in the Silurian and ending in the early Late Devonian when NE-SW (present day orientation) arches formed, the largest of which affected N and central parts of Iraq. AP4 represents a period of platform deposition in Late Devonian-Early Carboniferous time. AP5 represents syn-Hercynian active margin development starting in the Westphalian and ending in early Late Permian (Kungurian) time. Deposition was confined to a broad N-S trending fluvial basin in western Iraq. During the Late Permian (start of AP6), Eastern Arabia subsided regionally with formation of a broad carbonate platform. The Palaeozoic basin in W Arabia was inverted forming the N-S Rutba Uplift.

The stratigraphic column for megasequences API to AP5 for Iraq and surrounding countries is presented in Fig. 8-1.

8.1 The Vendian-late Late Cambrian Megasequence API (Infracambrian Megasequence)

8.1.1 Palaeogeographic considerations and regional distribution

The Infracambrian palaeogeographic setting was dominated by a central N-S trending structural high which is the extension of the Salman-Summan Zone of E Arabia into Central Iraq (Getech and Jassim 2002). Two distinct basins developed on either side of this high.

The western basin consists of numerous N -S trending depocentres (grabens and half grabens) that contain basic and intermediate volcanics and tuffs overlain by a sequence of coarse fluvial clastics, and subordinate intermediate and acidic lavas and tuffs. Marine transgression into the western basin during the final stages of rifting resulted in the deposition of occasional sabkha-type carbonates and evaporites represented by the Infracambrian sequence of SE Jordan and the Jifn Formation of Saudi Arabia. The easternmost part of this basin, which has a thick salt sequence (Fig. 8-2), is here referred to as the Nukhaib Salt Basin.

The eastern basin (Hormuz Basin) is restricted to E Arabia and SW Iran. Murris (1980) and AI-Sharhan and Kendall (1986) indicated that four sub basins existed in the Gulf area during Infracambrian time. These sub basins, from N to S are: the N-S trending Northern and Southern Arabian Gulf Basins, the ENE-WSW trending Fahud Basin in Oman, and the Ghaba- Hadramout Basin in Oman and Yemen.

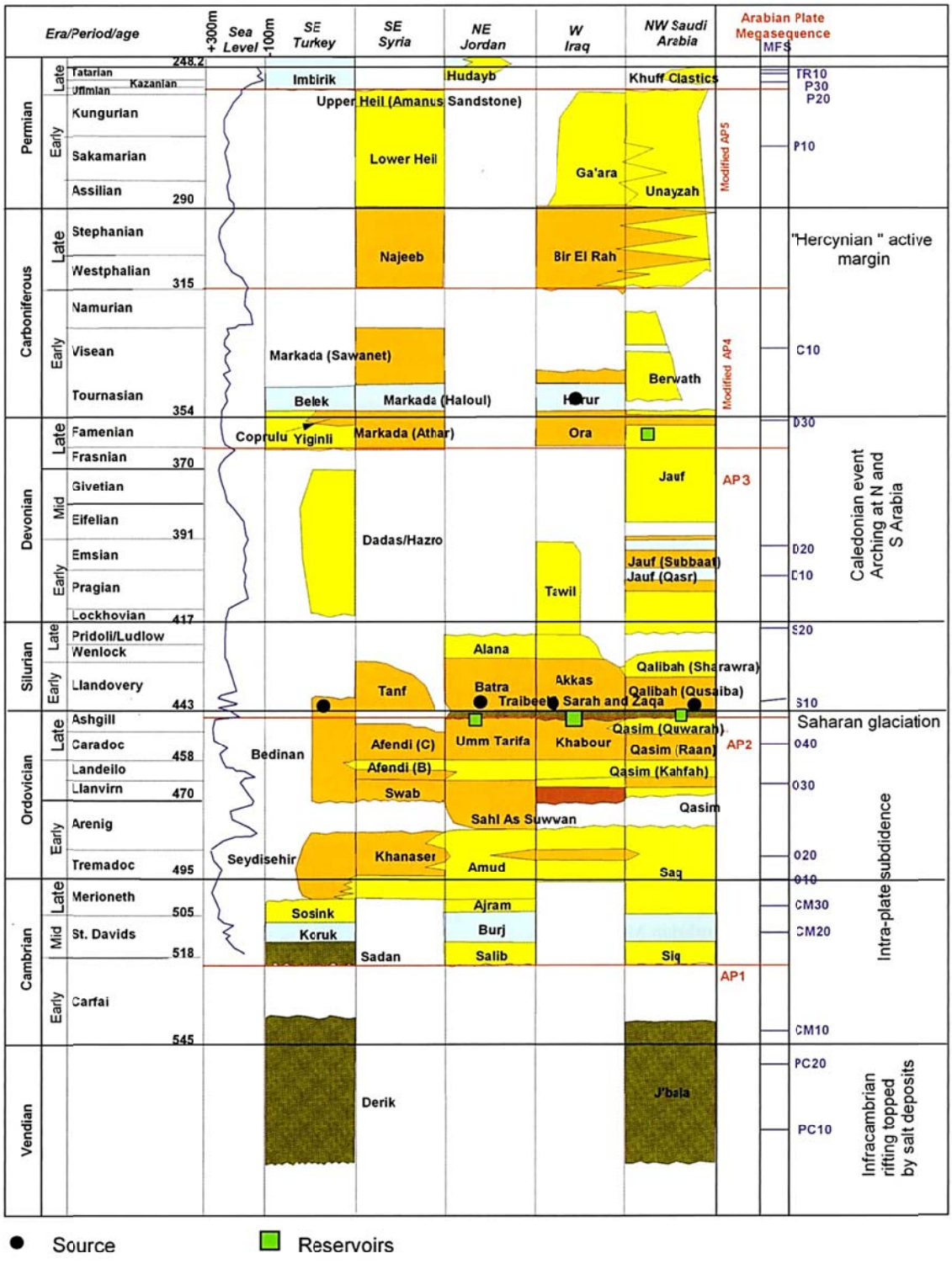


Fig. 8-1: Stratigraphic correlation of megasequences AP1 to AP5 for Iraq and surrounding countries

The Late Precambrian and Early Cambrian salt basins in S Arabia have been interpreted as extensional basins created by left lateral shear along the NW-SE trending Najd faults (Husseini, 2002). However, such movement does not explain the formation of the N-S trending basins of N

Arabia. Al Mogren (2004) demonstrated that shearing along the strands of the Najd fault system ceased before Infracambrian extension began. These basins may have formed by post-collision destacking (Nehlig et al., 2002).

In NW and W Saudi Arabia, the Infracambrian Megasequence is represented by the strongly folded, but unmetamorphosed, J'bala Group which is unconformably overlain by the AP2 megasequence. In its type section within the Arabian Shield, the J'bala Group consists of a lower unit of conglomerate and sandstone, a middle unit of andesite and basalt flows and tuffs (Umm Al Asiah Formation-Hadley, 1974) and an upper unit of argillaceous carbonates intercalated with chert (Jifn Formation-Hadley, Op cit.). The associated volcanics are dated at 500-520 Ma (Delfour, 1970). Blue green algae within the carbonates are dated as Infracambrian to Late Pre-Cambrian (Cloud et al., 1979). The thickness of the lower clastic unit of the J'bala Group varies greatly (Hadley, 1974) due to deposition in extensional grabens. In the An Nuqra area, within the Shield, the J'bala Group is >3000 m thick (AI-Laboun (1986). In the Mashhad area near the boundary of the shield the Group is 875 m thick (Hadley, 1974).

Megasequence API in W Jordan, described by Andrews et al. (1991), ranges in thickness from 90 to 500 m and comprises conglomerate in the lower part and arkosic sandstone in the upper part (Saramuj Formation in wells NH-l and SA-I). In SE Jordan, API comprises 400 m of basalt flows and tuffs overlain by red brown sandstone and mudstone with an evaporite unit in the upper part. API also outcrops along the Dead Sea shores and in Wadi (Araba Complex). In seismic profiles in S Jordan a 1500 m thick syn-rift sequence has been identified in N-S trending half graben. Gravity interpretation by the Natural resource Authority of Jordan (AI Zoubi, personal communication) supports the presence of several N-S tending grabens or half grabens in Jordan.

In Turkey, Megasequence AP I (Telbismi Formation) is unmetamorphosed and unconformably overlain by Early Palaeozoic megasequences. In imbricates near Mardin API consist of felsite porphyry and rhyolite with basaltic dykes conformably overlain by 110 m of red brown sandstone, 55 m of green conglomeratic sandstone (with reworked angular rock fragments) and beds of recrystallised limestone (Van Der Kaaden, 1978). The total thickness of API between Derik and Mardin is estimated to be >2500 m (Flugel, 1978). In the Hakkari area, directly north of Iraq, Infracambrian sediments are absent and fossiliferous Cambrian beds unconformably overlie the Precambrian crystalline complex (Altinli, 1966). In the Amanus region, east of Eskandarona Bay, 1500-2000 m of monotonous grey-green phyllitic shale, siltstone, quartzitic sandstone and greywacke (Camlipinar Formation) are assigned to the Infracambrian (Flugel, 1978).

The salt-bearing Hormuz Group is >1000 m thick in the Southern Arabian Gulf Basin (Davoudzadeh et al., 1986) and produces salt diapirs containing exotic blocks of Early Palaeozoic age. It also forms salt ridges underlying many of the anticlines in SW Iran (Kent, 1974; Ala, 1974). In the Northern Arabian Gulf Basin gravity interpretation shows that most oil bearing structures of S Iraq (S of the Takhadid-Qurna Transversal Fault) are associated with negative gravity residuals (see Chapter 6), which suggests that they are underlain by Infracambrian salt. This interpretation is supported by the presence of the Jabal Sanam salt plug on the Iraq-Kuwait border.

Jabal Sanam is an isolated hill 100 m high and 2 km in diameter. The surrounding desert plain for 5 km around the hill is formed of vertically-dipping beds of sandstone belonging to the Dibdibba Formation (Mio-Pliocene). The Jabal itself consists of variably dipping cross cutting slope sediments containing a mixture of rocks (unseen in the surrounding Dibdibba Formation) passing into a gently-inclined pediment that radiates and extends a few kilometres from the Jabal. Below this highly chaotic surface accumulation of the Jabal lie rafts (artificially exposed by quarrying) of black algal dolomite, anhydrite and altered dolerites. The black algal dolomite layers are similar to those found in the salt domes of SW Iran. Two dolerite samples were dated as 570 ±10 Ma and 580±10 Ma (Buday and Jassim, 1987).

The Nukhaib salt depocentre (west of the Salman Zone) was identified by AI Bassam et al. (1992) and Getech and Jassim (2002) based on an underlying N-S gravity low along the eastern edge of the Rutba Subzone in W Iraq (see gravity map, Chapter 4). Seismic data clearly indicates a domal structure at Cambrian level above the gravity low (see chapter 5) additionally 3D gravity interpretation (Getech and Jassim 2002) confirmed the presence of salt and provided an estimate of the Infracambrian sequence thickness (fig.8-3). The depocentres of W Iraq apart from the Nukhaib depocentre are postulated to consist of coarse clastics only.

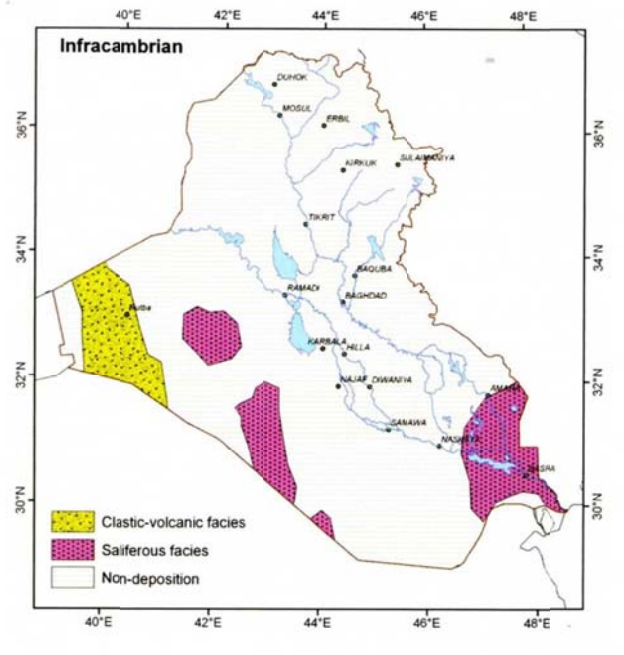


Fig. 8-2: Palaeogeography of the Late Precambrian-Early Cambrian AP1 Megasequence

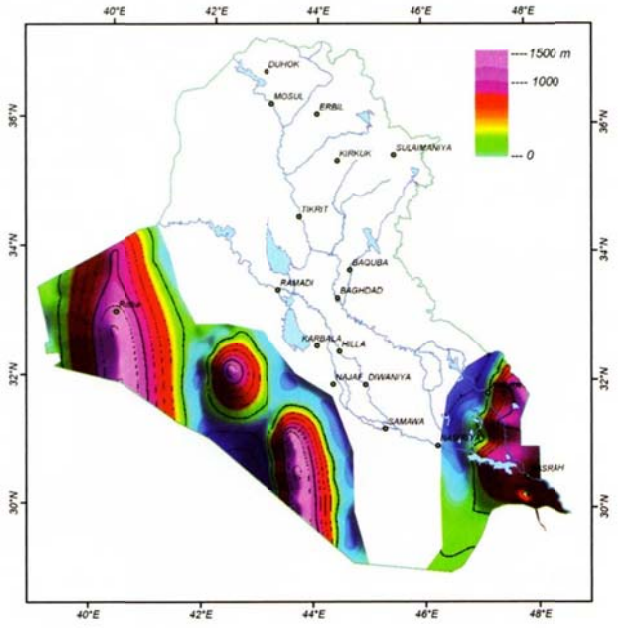
8.2 The late early Cambrian-early Ashgill Megasequence AP2 (Cambro-Ordovician Megasequence)

Rifting ceased at the end of the Early Cambrian. It was followed by post-rift continental deposition in both Wand E Arabia. The central part of Arabia, represented by the elevated broad Salman-Summan Zone, initially remained above sea level and was gradually submerged during the Late Cambrian.

The thickness of Megasequence AP2 in Iraq was estimated using data from Saudi Arabia, SW Iran, Jordan, Syria and SE Turkey, taking into consideration the shape of the basins from gravity data

(Fig. 8-4). The maximum thickness of the megasequence is predicted to be >3000 m in the western depocentre. The megasequence is predicted to be patchily distributed over the Salman Zone due to erosion during Late Carboniferous and Early Permian time as indicated in Kuwait (Burgan High) and in E Saudi Arabia (Ghawar and Summan Highs). In SE Turkey, the megasequence is only absent over the Mardin High where Cretaceous rocks overlie the Precambrian basement.
The megasequence contains three second order sequences. These are the: Late Early Cambrian-Late Cambrian Sequence, the Late Cambrian-Early Ordovician Sequence and the Mid-Late Ordovician Sequence.

Fig. 8-3: Postulated thickness of the AP1 Megasequence based on 2D gravity modelling by Getech and Jassim (2002)

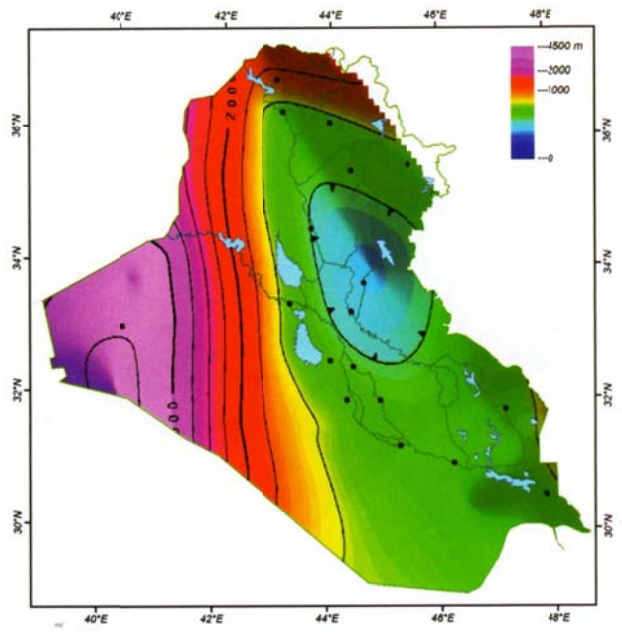


8.2.1 Late Early Cambrian-Late Cambrian Sequence

During the late Early Cambrian, the N-S Nabitah orogenic belt of Central Arabia was slowly peneplaned though the two earlier depocentres on either side of the Salman Zone were retained (Fig. 8-4). The eastern depocentre was located in the area that is now the Zagros folded belt of SW Iran, the easternmost part of the Mesopotamian Zone and the Foothill Zone of NE Iraq. The sequence is probably missing throughout the Salman Zone. The sequence does not outcrop in Iraq and has not been drilled. It cannot be identified on existing seismic surveys as the Burj Limestone is the deepest coherent reflector in western Iraq.

The Early Cambrian part of sequence comprises fluvial clastics throughout most of N Arabia. It is represented by the Siq Formation in NW Saudi Arabia (Aoudeh and Hajri, 1994), the Salib Formation in Jordan (Andrews et al., 1991), the Zabuk Formation in Syria (Barazangi et al., 1992), the Sadan Formation in SE Turkey (Flugel, 1971), and the Zaigun and Lalun formations in SW Iran (Davoudzadeh et al., 1986). The Salib Formation probably extends into W Iraq. The supplementary type section of the Salib Formation in well WS-3 (Long 37° 11' 29", Lat 30° 28' 19") was described by Andrews et al. (1991) and could also be used as the supplementary type section for Iraq.

Fig. 8-4: Thickness of Megasequence AP2



8.2.1.1 Salib Formation

The Salib Formation is reached at a depth of 3710 m in well WS-3 in Jordan and is 750 m thick. It comprises red, brown and purple arkosic sandstones with occasional micaceous red mudstone beds. It is overlain by the Burj Limestone and underlain by the Saramuj Formation. In Jordan it thickens to the east and may reach a thickness of about 1250 m in the central part of the western basin near Rutba in Iraq.

In NW Iraq the Lower Cambrian part of the Sequence may be equivalent to the Zabuk Formation of Syria and the Sadan Formation of Turkey. In Syria, the Zabuk Formation is only partly penetrated (13 m in Khanaser well). In SE Turkey, the Sadan Formation consists of 260 m of sandstone with dolomite and chert beds (Kamen-Kaye, 1971). The Salib Formation is predicted to be thin or absent in N Iraq.

8.2.1.2 Bur) Limestone Formation

A marine transgression in Mid Cambrian time led to deposition of shallow marine sediments throughout N Arabia comprising limestone and dolomite with associated clastics. The carbonate lithofacies of the Middle Cambrian is represented by the Burj Formation (Burj Limestone) which is a well-defined seismic marker in Syria, W Iraq and Jordan. Many boreholes in Jordan and Syria penetrate the Burj Formation. However, in NW Saudi Arabia carbonates are absent and the sandstone and shale in the lower part of Saq Formation may be time equivalent to the Burj Limestone.

In Jordan the thickness of the formation increases from 60 m in the S to 114 m in Wadi Sirhan, and may reach 150 m near the Iraq-Jordan border and 200 m in the Rutba area in Iraq. Seismic lines in the Rutba area show a clear reflector correlatable with the drilled Burj Formation in well Risha-2 in NE Jordan. The formation is probably absent or replaced by clastics on the Salman Zone.

The age of the Burj Limestone has been determined as Early-Mid Cambrian based on its trilobite and brachiopod fauna but constrained as Mid Cambrian by the diagnostic palynomorph species

Celtiberrium cf. dedalinum (Keegan et al., 1990: in Andrews et al., 1991). The formation was deposited in a peritidal to lagoonal environment.

In S Jordan the Mid Cambrian Sequence is dominated by clastics with only one thin carbonate unit. Powell (1989) suggested that the Burj carbonates form a stratigraphic wedge between two fluvial sandstone units (Salib and Ajram formations). These carbonates were deposited in a tide-dominated marine environment at the base, passing up into a shallow water carbonate lagoon in the middle returning to a clastic dominated marine environment near the top. The maximum flooding surface Cm 20 of Sharland et al. (2001) is located near the top of the Burj Limestone. In Jordan, the Burj Limestone passes both laterally and vertically into the Ajram (Umm Ishrin) Formation while in Saudi Arabia the Burj Limestone may pass into the lower part of the Saq Formation.
In Syria the formation consists of 225 m of carbonate and shale (well Khanaser-l). In SE Turkey the Burj Limestone is equivalent to the Koruk Formation which comprises peritidal-lagoonal carbonates (Carter and Tunbridge, 1992). It thickens from 100 m in the Amanus region in the west to 240 m in the Mardin area to over 400 m in the Hakkari area just N of the Iraq-Turkey border. In SW Iran, the Mid Cambrian Sequence is represented by the dolomitic Mila Formation. The Burj Formation is thus predicted to be present in N Iraq and to be about 400 m thick.

8.2.1.3 Ajram Formation

The Ajram Formation of Central Jordan, introduced by Andrews et al. (1991), is sandy in the W, becoming finer grained and silty towards the NE. The GR response of the formation is generally high (about 150 API) because of its relatively high clay content. The supplementary section of the formation (Andrews et al., 1991) is in well WS-3 (3290-3614 m, 324 m thick). It is predicted to thicken to 450 m in W Iraq.

The formation comprises reddish brown, white, purple and pale green sandstone with streaks of red shale. The basal part contains limestone streaks. The formation has a gradational contact with the underlying Burj Formation. It is overlain by thick and coarse sandstones of the Amud Formation with a sudden decrease in GR response to 20API.

The Ajram Formation is of early Late Cambrian age in most of Jordan. Towards the Sand SW it replaces the Burj Limestone and is therefore, partly of Mid Cambrian age. The environment of deposition ranges from coastal plain with marine incursions in the SW (based on architact and *Cruziana* facies) to inner and outer subtidal (represented by oolitic carbonate beds in N Jordan). The latter facies is also expected to be present in W Iraq.
The equivalent unit in SE Turkey is the Sosink Formation which comprises fine grained deltaic clastics (Carter and Tunbridge. 1992). It thickens from 200 m in the W to 800 m near Mardin in the E. Its thickness may exceed 1000 m in the Hakkari region north of the Iraq-Turkey border.

8.2.2 *Late Cambrian-Early Ordovician Sequence*

The close of the Early Ordovician was associated with a disturbance and/or sea level drop which resulted in an emergence that can be traced throughout Arabia and N Africa. Sea level rise and/or tectonic subsidence followed during the Mid Ordovician resulting in major submergence. The uplifted N-S zone of Central Arabia that separated the western and eastern depocentre during the Early and Mid Cambrian was finally permanently submerged during the Late Cambrian. Sediments of this age were deposited over almost the whole of the Arabian Plate.

This sequence does not outcrop in Iraq but may be penetrated in well Akkas-l in W Iraq as part of the Khabour Formation, probably comprising the lower 1170 m of the drilled section. The Late Cambrian-Early Ordovician Sequence is represented by the Amud Formation in Jordan, (Andrews et al., 1991), the Saq Formation in Saudi Arabia (McGillivray and Husseini, 1992), the Seydisehir Formation in SE Turkey (Carter and Tunbridge, 1992), the Khanaser Formation in Syria (Best et al, 1993) and the Mila Formation in SW Iran (Setudahnia, 1978 and Davoudzadeh et al., 1986). The upper 60 m of the Mila Formation is of Early Ordovician age; the lower 170 m is of Late Cambrian age.

The Saq Formation of Saudi Arabia consists of quartzitic sandstone, with conglomerate and shale beds in the middle part. It is divided into the Risha Member (Upper Cambrian) and the Sajir Member (Lower Ordovician- Tremadoc-Arenig). The Amud Formation of Jordan (Upper Cambrian Lower Ordovician) is 1200 m thick in wells in Wadi Sirhan and divided into two members (Lower and Upper Amud; Andrews et al., 1991). The formation comprises sandstone with occasional shale beds (Upper Cambrian) overlain by more argillaceous clastics in the upper 100 m (Lower Ordovician). It is predicted to be 1500 m thick in the Rutba region. In N Iraq, the facies is predicted to be argillaceous and to contain turbidites similar to the Seydisehir Formation of SE Turkey. This formation is expected to underlie the exposed Khabour Formation of the Ora anticline of N Iraq. Its thickness in N Iraq is predicted to be 1000 m as in the Hakkari region of Turkey (Tunbridge, 1986). In NW Iraq the sequence may be similar to that penetrated in well Khanaser-l where it comprises 582 m of sandstone, siltstone and black shale.
Three Maximum Flooding Surfaces were identified within the sequence in Oman (Sharland et al., 2001); these are Cm 30 at 502 Ma, 010 at 594 Ma and 020 at 487 Ma. They may correlate with three intervals of high GR response in the Amud Formation section in well WS-3 in Jordan.

8.2.3 Mid-Late Ordovician Sequence

During the Middle and Late Ordovician a gradual rise in sea level resulted in the development of an intracratonic marine shelf basin, with deposition of littoral sandstones with *Cruziana* trace fossils alternating with outer shelf graptolitic shales. The relatively deeper shelf conditions were terminated by a sudden drop of sea level triggered by the Saharan glaciation (Husseini, 1990; McGillivray and Husseini, 1992). This event marks the top of the AP2 Megasequence (Sharland et al., 2001). The sequence is represented by the Khabour Formation in Iraq.

8.2.3.1 Khabour Formation

The Khabour Formation was introduced by Wetzel in 1950 (Bellen et al., 1959) for an 800 m section exposed in the Khabour valley within the Ora Zone of N Iraq (cores of Ora and Kaista anticlines). It comprises beds of thin-bedded, fine-grained quartzite, siltstone and micaceous shale. The base of the formation is not exposed. The formation passes from littoral facies in the Ora anticline into a deeper marine turbidite facies in the Kaista anticline (20 km to the west) (Seilacher, 1963). The formation has been penetrated in wells Khlesia-I in the Jezira subzone and Akkas-l in the Rutba subzone.

The Khabour Formation comprises beds of sandstone and shale in wells Akkas-1 (2325-4228 m, >2103 m thick) and Khleissia-l (2544-3792 m, >1248 m thick). The equivalent formations in Syria, Saudi Arabia and Jordan are the Swab and Afendi (1025 m and 1500 m thick), Qasim (1680 m thick) and the Umm Tarifa (748 m thick in Wadi Sirhan) respectively. The lowermost 500 m of

the Khabour Formation in Akkas-l comprises shale which may be equivalent to the Swab Formation of Syria and the Sahl as Suwan Formation of NE Jordan. The Khabour Formation in Khlesia may be of Late Llanvirn-Ashgill age. The lower part of the Akkas section may be of Early Llanvirn age.

The equivalent formations in the Hakkari region of SE Turkey, (just north of the Khabour type section) are the sandy Upper Ordovician Sorte Tepe (Carter and Tunbridge, 1992) and the 600 m thick shaly Bedinan in the Mardin area (Kamen-Kaye, 1971; Carter and Tunbridge, 1992). However, the thickness of the Sorte Tepe Formation in the Hakkari region is reduced to only 25 m, probably due to erosion during the Devonian. In SW Iran, the Middle to Late Ordovician Sequence is represented by part of the Ordovician-Silurian Zard Kuh Formation (> 1 000 mSetudahnia, 1972).

The Khabour Formation was deposited (similar to the Qasim Formation) in a tide- and storm-dominated shallow marine environment (Duaiji, 2001) in the S, passing rapidly into a deep marine environment in the northernmost parts of Iraq and SE Turkey.

8.3 The late Ashgill-Frasnian Megasequence AP3

The southerly drift of the Afro-Arabian plate led to glaciation in Late Ashgill time. The glaciation was associated with a significant drop in sea level of 150-200 m (Haq, 1987) that triggered deep incisions in western Arabia. The ice sheet covered the whole of Africa and the western part of the Arabian Plate (Jordan, western Saudi Arabia and Yemen) (Chapter 3, Fig. 3-4). The glaciation probably lasted for a relatively short period during the latest Ashgill (Craig et al., 1998; Sharland et al., 2001) which was then followed by deglaciation in latest Ashgill time.

The deglaciation resulted in the deposition of glacial rebound moraines and a substantial eustatic sea level rise. Coarse moraine deposits and glacio-fluvial sands were deposited in the proximal areas of the retreating glaciers (S and W Jordan); finer-grained polymictic clastics of fluvio-marine origin were deposited in the distal parts (NE Jordan and W Iraq). Equivalent formations are the Traibeel Formation in Jordan and the coarse sandy and polymictic basal beds in the Akkas Formation in wells Akkas-I and Khlesia-l.

The eustatic sea level rise resulted in plate-wide submergence and deposition of outer shelf pelagic and hemi-pelagic graptolite-rich shales, locally very rich in organic matter (Qusaiba "hot shale"). These are overlain by outer shelf low energy mudstones, followed by proximal shelf, inner and outer sublittoral clastics (Andrews et al., 1991, Mahmoud et al., 1992). The depositional setting of the Qusaiba shales was probably similar to the present day Antarctic outershelf (Jones and Stump, 1999). Shallowing of the sea resulted in progradation and the development of intertidal to shoreface facies clastics of the Sharawra Member of the Qalibah Formation.

In Saudi Arabia a Wenlock hiatus is indicated (Sharland et al., 200 1; Al Hajri et al., 2002; Aoudeh and Al Hajri, 1994; Aoudeh and Owen) but not in NE Jordan where Wenlock sediments were recognised in the Alna Formation (Andrews et al., 1991).

Deposition continued throughout the Devonian in Saudi Arabia. N Arabia was differentially uplifted in Early and Middle Devonian time resulting in the formation of NE-SW trending highs (the Tanf Khlesia and Aleppo Highs) and a sag basin in the Palmyrides. A southerly dipping monocline developed south of the Anah-Qalat Dizeh Fault on which the Silurian sediments were partly eroded. A full Devonian section is probably present to the south in Saudi Arabia. This event

was a response to active margin development along the S shores of the Palaeo-Tethys.

The thickness of Megasequence AP3 is very variable due to Mid Devonian erosion (Fig. 8-5) in addition to Late Carboniferous "Hercynian" erosion. The megasequence can be subdivided into three second order sequences, these are the: Late Ashgill-Silurian and the Late Silurian (Pridoli) - Early Late Devonian (Frasnian) sequences.

8.3.1 Late Ashgill "Saharan Glaciation" Sequence (445-443 Ma)

The Saharan glaciation resulted in deposition of proximal glacial moraines in NW Saudi Arabia and distal fluvio-glacial clastics in NE Jordan and western Iraq. Highly incised landform and submarine canyons were formed in NW Saudi Arabia where striated glacial pavements are covered with till deposits.

In NW Saudi Arabia (McGillivray and Husseini, 1992; Vaslet et al., 1989 & 1990; Mahmoud et al., 1992; Aoudeh and Al Hajri, 1994) and S Jordan (Andrews et a!., 1991), sandstone with boulders of igneous and metamorphic rocks boulders of Late Ordovician age was deposited in deep valleys cut into the underlying Ordovician beds (Zarqa and Sarah formations).

In Jordan the Traibeel Formation comprises fluvial channel sandstones near Aqaba and pre/post glacial tidal sandstones in the Jafr area. In central Jordan the formation comprises diamictite with underlying and overlying tidal sandstones. In NE Jordan (Andrews et a!., 1991) the formation comprises glacio-marine clastics. A lithological unit similar to the Traibeel Formation has been identified in the Akkas and Khlesia wells. This unit is about 85 m thick in Akkas-I and about 20 m thick in Khlesia-l. It comprises coarse clastics and mudstones. In the Khabour Formation type section this unit was eroded in Mid Devonian time.

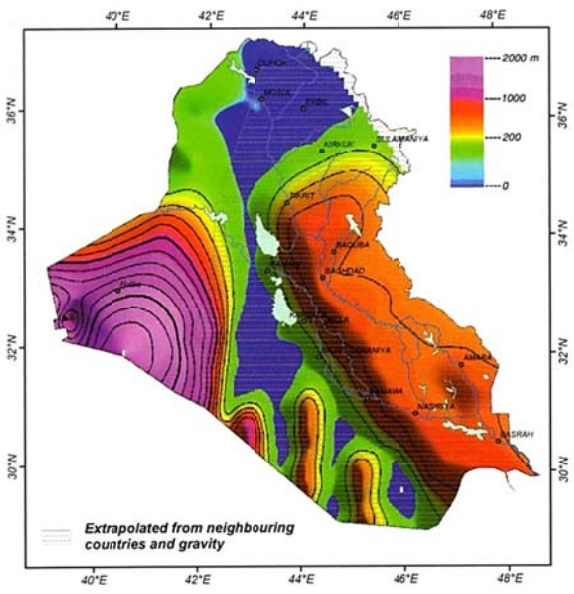


Fig. 8-5: The postulated preserved thickness of Silurian-Early Late Devonian Megasequence AP3 showing areas of patchy development in S and Central Iraq which may the result of erosion during the "Hercynian" events whereas in N Iraq, the missing Silurian is probably due to "Caledonian" erosion

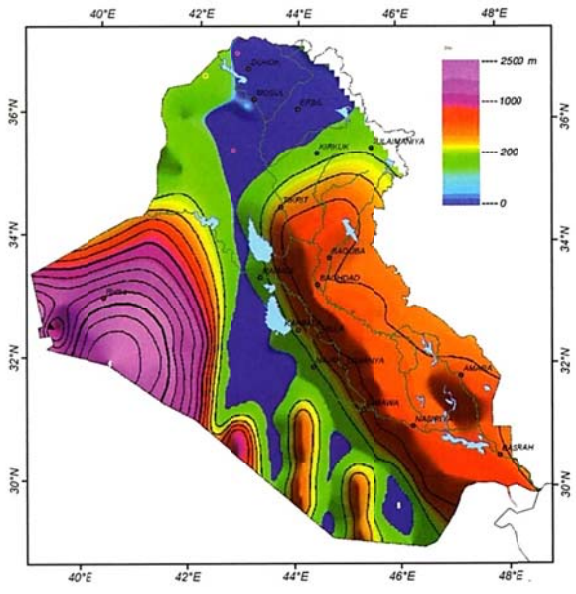


Fig. 8-6: The postulated preserved thickness of the Silurian. Low thickness values in the central longitudinal zone are due to subsequent removal during the "Hercynian" uplift of the Salman Zone

8.3.2 Silurian Sequence

To understand the distribution of the Silurian sequence in Iraq, it is essential to understand its distribution in the neighbouring countries: SE Turkey, E Syria, NE Jordan and Saudi Arabia. In Saudi Arabia the sequence is represented by the Qalibah Formation which is divided into two distinct members, the Qusaiba Shale and the overlying Sharawra Sandstone. In a complete section in NW Saudi Arabia the Qalibah Formation is >2000 m thick; each member is about 1000 m thick (Aoueda and Al Hajri, 1994). In central Saudi Arabia and Kuwait, the Silurian is sometimes missing (Fig. 8-6) on the N-S "Hercynian" structures of the region, (e.g. Ghawar, Summan and Burgan) or fully or partly preserved in the grabens between these structures (McGillivray and Husseini, 1992).

In NE Jordan, in the Risha wells (Andrews et a!., 1991), the Silurian Sequence comprises the Batra Formation (lower shale section) and the Alna Formation (upper sand section). The Silurian Sequence is up to 2300 m thick along the Jordan-Iraq border. Along the Syria-Jordan border in NE Jordan, the Silurian Sequence has been totally eroded below the "Caledonian" unconformity (well Risha-2). In Central and W Jordan the Silurian Sequence is truncated beneath the Hercynian Unconformity. The age of the hot shale basal layer of the Batra Formation, based on graptolite fauna, is earliest Llandovery. *Monoclimacis flumendosae* and *Pristograptus dubius* occur near the top of the formation suggesting a Mid Wenlock age (Andrews et a!., 1991). The Alna Formation is dated as Late Llandovery to Ludlow (Andrews et al., op cit). The Batra Formation thickens from 100 m in SW Jordan to 1300 m in NE Jordan. It comprises grey to black shale, fissile and micaceous with streaks of quartzitic sandstone. It has an average GR response of 100 API except in the lower part where it reaches 400 API. The Alna Formation is less widespread in Jordan. It is present in SE and NE Jordan but totally eroded in central and NW Jordan. In the Risha area it thickens to the SE from 250 m to 1000 m. It consists of three units, a lower mudstone and siltstone unit (140 m, GR response 100 API), a 600 m thick middle sandstone unit (GR response 50 API) and an upper black mudstone unit (55 m, GR response 80 API).

In SE Syria, apart from the Palmyrides, the Silurian sequence has been totally or partially eroded. In well Tanf-l, the Tanf Formation (870-1410 m, 530 m thick.) comprises graptolite-rich black shale interbedded with thin beds of siltstone and sandstone. It is equivalent to the Batra Formation of NE Jordan. In well Swab-l near the Iraq-Syria border, the Silurian Sequence is absent. In N and NE Syria, the Silurian is eroded. Seismic sections in the Palmyride region indicate the Silurian Sequence is about 800 m thick (Barazangi et al., 1994). In E Syria, 413 m of Silurian shale was penetrated in well Markada-l01.

In SE Turkey, a sequence of black shale has been attributed to the Silurian, represented by the upper part of the Bedinan Formation, exposed near the Taurus main thrust (Carter and Tunbridge, 1992). However, in the area immediately N of Iraq (Hakkari region), no Silurian rocks were recorded (Tunbridge, 1988). The Silurian is absent over large areas of SE Turkey. Both SE Turkey and N Syria were part of an elevated "Caledonian" block. The Silurian Sequence was also partially penetrated in water-wells K5-1 (Ga'ara depression) and K5-6 (Jordan Iraq border) in the Rutba subzone.

8.3.2.1 Akkas Formation

The Akkas Formation was introduced by Habba et al. (1994) from well Akkas-l in W Iraq between 1451 m and 2316 m depths and consists of black shale with occasional thin layers of sandstone. The sequence in general has high TOC but is exceptionally organic rich between 2191 m to 2316 m ("Hot Shale").

270 m of Silurian sediments were partly penetrated in water well K5-1 of the Ga'ara depression of W Iraq from 1330 m to the bottom of the hole at 1600 m. The section was attributed to the Ludlow part of the Silurian (Habba et al.,1994) and consists of shale with occasional 10 m thick sandstone layers. The Akkas Formation is estimated to be about 1000 m thick in K5-1; it is equivalent to the lower part of the Alna Formation of Jordan; the upper sandy part of the formation has been eroded.

Silurian shales have been identified in well Khlesia-l (Habba et al., 1994) in an interval originally considered part of the Upper Devonian-Lower Carboniferous section. The base of the formation in this well lies above a 20 m thick conglomerate (probably equivalent to the Traibeel Formation) at a depth of 2553 m depth. The lower 60 m of the formation is a "Hot Shale" equivalent to the lowermost part of Batra Formation of NE Jordan. The Silurian sequence was deeply eroded during the Late Silurian-Mid Devonian uplift of the Khlesia block; it is unconformably overlain by the Late Devonian-Early Carboniferous sequence.

In water well K5-6, located S of Traibeel check point at the Iraq-Jordan border, the lowermost 570 m of the well section consists of sandstone attributed to the Silurian (Habba et al., 1994) or Llandoverian and younger (AI-Naqshabandi, 1988). This sequence is overlain by Upper Devonian (Gedinian) sandstones. This section probably correlates with the upper part of Alna Formation which is present across the border in Jordan where it is >800 m thick. Therefore, it is expected that the whole Silurian sequence in W Iraq is >2000 m thick.

The thickness of the Silurian sequence has been compiled in Fig. 8-6 based on data from Saudi Arabia, Jordan, Syria, Turkey and Iran, and from the analysis of the gravity field of both central Saudi Arabia and SW Iraq. Extreme thinning of the Silurian sequence in central Iraq (Salman Zone) is due to Late Carboniferous erosion. In the Palaeozoic outcrops in N Iraq the Silurian sequence is absent due to Devonian erosion; Upper Devonian clastics unconformably overlie the Ordovician sequence. In well Swab-l in Syria, just across the border from Al Qaim, Upper Devonian-Carboniferous sediments unconformably overlie the Ordovician sequence.

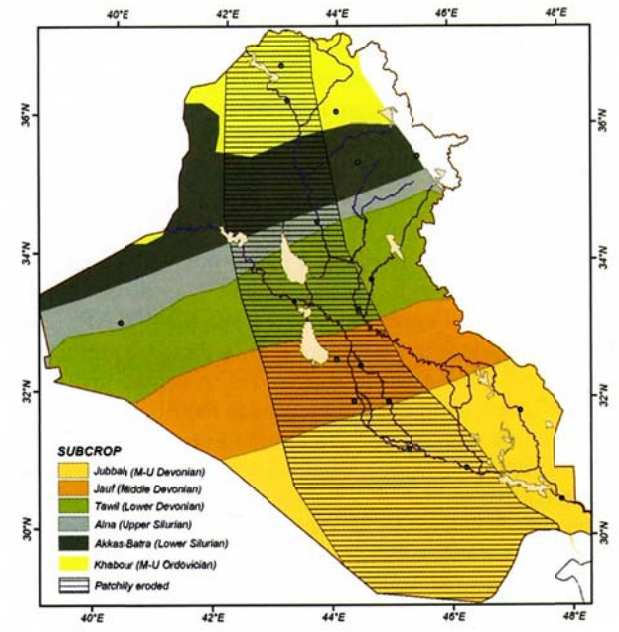
8.3.3 Late Silurian (Pridoli)-early Late Devonian (Frasnian) Sequence

8.3.3.1 The "Caledonian" disturbance

The "Caledonian" disturbance within the Arabian Plate was discussed in Chapter 3. In N Iraq, the unconformity surface is placed at the base of the Pirispiki Formation, at the base of a conglomerate layer in well Khlesia I and below a calcareous sandstone and shale sequence in wells Akkas-l and K5-1. The Caledonian unconformity subcrop map is shown in Fig. 8-7. Note the thinning of the Silurian, and the absence of the Lower-Middle Devonian, to the N of the Euphrates River.

The Latest Silurian-Early Late Devonian Sequence was deposited during active margin tectonism along the N margin of the Arabian Plate. A NE-SW trending uplift affected the Tanf-Khlesia area and part of the Jezira area (Chapter 3, Fig. 3-5).

Fig. 8-7: Subcrop map below the "Caledonian" unconformity. Raster represents area of subsequent erosion during the Late Carboniferous



3.3.2 Stratigraphy

This sequence has only been identified in Iraq in water well *KS-6* (Habba et al., 1994) where it comprises 80 m of sandstone. However, in the Nafud area of Saudi Arabia to the S it comprises the Tawil, Jauf and the lower part of the Jubbah formations (AI-Hajri and Filatoff, 1999; Sharland et al. 2001). The maximum thickness of the sequence (1220 m) is in NW Saudi Arabia. Here the Tawil Formation is 230 m thick, the Jauf Formation is 240 m thick and the Jubbah Formation is 650 m thick. In synclines flanking the Ghawar structure in E Saudi Arabia and Kuwait the Devonian section is thinner (650 m thick); on the crest of the Summan and Burgan anticlines the Devonian section is absent due to Late Carboniferous erosion. In SE Turkey, clastics of Early to Middle Devonian age were identified only from the Hazro region in front of the Taurus main thrust (Dadas Formation; Carter and Tunbridge, 1992).

The 80 m thick Devonian section in well K5-6 near the Jordanian border comprises sandstone and shale of Early Devonian (Gedinian) age (Habba et al., 1994). This succession may be correlated with part of Sayad Formation in Syria (Palmyride) and part of the Jubbah Formation in Saudi Arabia. No equivalents of the formation are present in Jordan. The sequence is predicted to be up to 700 m thick in E Iraq, and to thin gradually towards central Iraq; it is probably absent in N Iraq

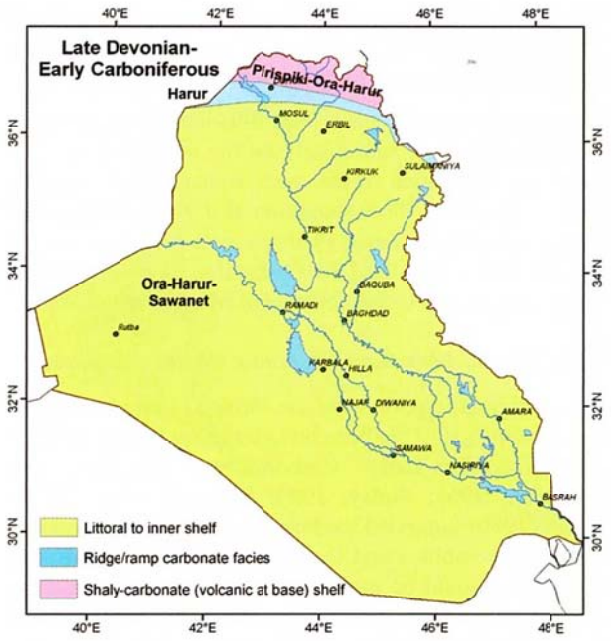


Fig. 8-8: Late Devonian to Early Carboniferous Palaeogeography

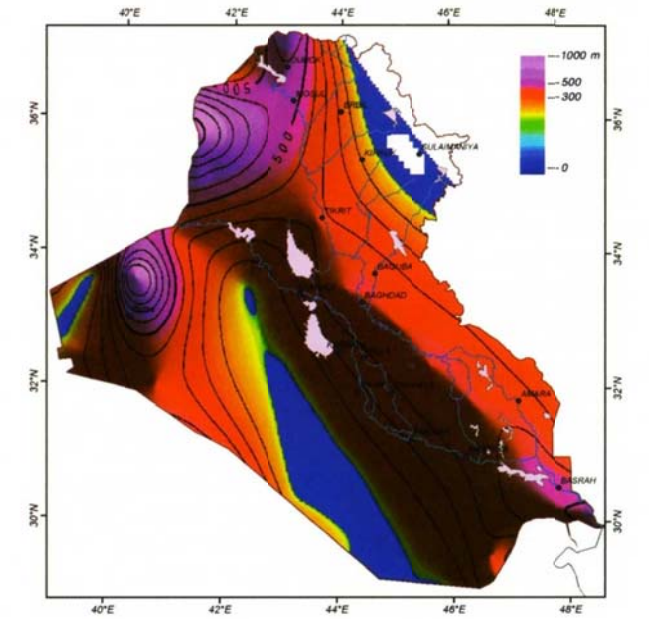
8. 4 The Frasnian-Namurian modified Megasequence AP4

Sharland et al. (2001) considered Megasequence AP4 to be of Frasnian-Late Stephanian age. The age of the megasequence is here considered to extend to the base of the Westphalian (see Section 8.5).

The emergence of most of N Iraq during the Late Silurian to mid Devonian uplift was followed by submergence during e Late Devonian. The volcanics associated with the clastics of the Pirispiki Formation have previously been assumed to form the base of the megasequence (Bellen et .al, 1959; Seilacher, 1963 and Sharland et al., 2001). However this volcano-clastic unit was probably developed in a back-arc basin associated with the Early and Mid Devonian subduction beneath the northern margin of the Arabian Plate. Thus the megasequence boundary between AP3 and AP4 may lie within the Pirispiki Formation. In Early Carboniferous time most of Iraq was covered by a shallow lagoonal basin; carbonate ramps developed over a palaeoridge positioned between the Bassit area in NW Syria and N Iraq, and in the area between Sinjar and the high Folded Zone. The presence of the ridge is indicated by the absence or reduced thicknesses of Devonian-Lower carboniferous sediments (Ponikarov et al., 1967) in the Qamishlie and Abba wells, and in the area of the Mardin uplift. According to Sharland et al. (2001), the area to the N of this ridge was part of a back-arc basin with siliciclastic and volcanicity (Pirispiki Red Beds). However this basin may have formed earlier in Early and Mid Devonian time. South of the ridge siliciclastics were deposited (well Khlesia-l ; Gaddo and Parker, 1959 and water well K5-1; Habba et al., 1994). Similar facies occur in E Syria and the Palmyrides (Dolaa and Dubayyat wells). In N and NW Iraq, Syria and SE Turkey sedimentation occurred in an inner shelf environment; in S Iraq, Saudi Arabia and SW Iran marginal marine and deltaic sedimentation occurred (Al-Hajri and Filatoff, 1999).

The megasequence isopach (Fig. 8-9) indicates substantial thickness variation, particularly on the Salman Zone. The predicted distribution of the megasequence in the Salman zone is based on the assumption that this feature is an extension of the Summan Platform in Saudi Arabia which' was elevated during the Late Carboniferous-Early Permian resulting in partial or full removal of Megasequence AP4.

Fig. 8-9: The postulated preserved thickness of the Late Devonian-Early Carboniferous Megasequence AP4. The area of low thickness in the Salman Zone is caused by removal during the Late Carboniferous uplift and erosion



8.4.1 Pirispiki Formation (including Chalki Volcanics)

The stratigraphic position of the Pirispiki Formation is not fully understood. It has been included in the basal part of the Late Devonian-Early Carboniferous Megasequence (Seilacher, 1963; Buday, 1980; Sharland et al., 2001). Buday (1980) suggested the Pirispiki and Chalki formations should be combined and that the lower part of the Kaista Formation should be included in the Pirispiki Formation. The original thickness of the Pirispiki Formation as described by Bellen et al. (1959) is 83 m. The thickness is here adjusted to 120 m by including the lower 37 m of the Kaista Formation. The formation comprises, from the base upwards: 1) 10 m of grey to green fine-grained soft sandstone with ribs of quartzite, 2) 16 m of yellow brown well-bedded sandstone with beds of brown shale, 3) 24 m of white hard quartzite and red to purple sandstone and shale, 4) 33 m of red marly sandstone with subordinate dolomite with occasional beds of conglomerate with pebbles of green basalt, quartzite and sandstone and 5) 37 m of green, occasionally purplish siltstone and silty shale with occasional beds of cross-bedded quartzite (formerly assigned to the Kaista Formation). The Chalki Volcanics comprise altered olivine basalt flows (Bellen et al., 1959) with beds of tuff, ash, shale and siltstone.

The depositional environment of the Pirispiki Formation is continental to marginal marine (Seilacher, 1963).

The Pirispiki Formation was not identified in any of the wells that penetrated the megasequence in Iraq. In well Khlesia-l, a conglomerate at the base of the Kaista Formation unconformably overlies the truncated Silurian sequence. Undifferentiated Devonian volcanics in SE Turkey in the Arras Basin in Eastern Anatolia (Altinli, 1966) are probably equivalent to the Chalki Volcanics; they comprise spilite and andesite with associated red-brown lithic sandstones. The Yiginli Formation in the Hakkari region of SE Turkey is another equivalent of the Pirispiki Formation.

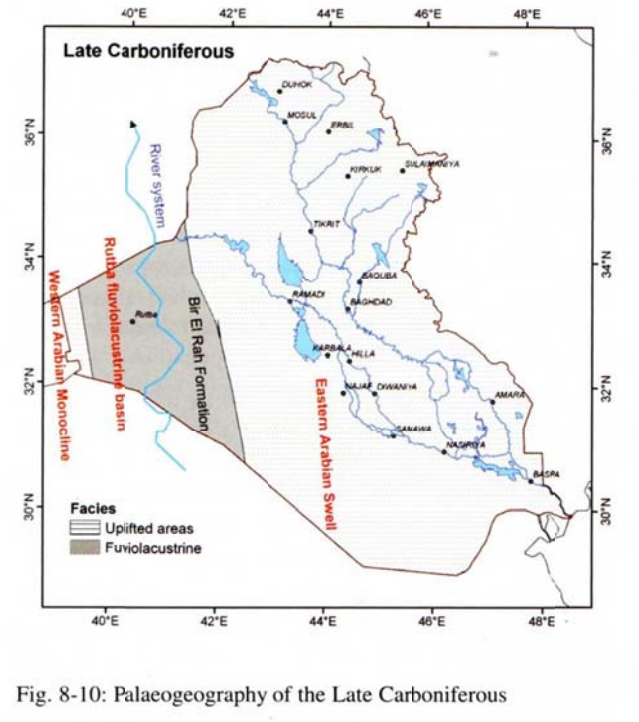


Fig. 8-10: Palaeogeography of the Late Carboniferous

8.4.2 Ora Formation (Famennian-L Tournasian)

The upper part of the Kaista Formation is now included in the Ora Formation and the name Ora Shale has been changed to Ora Formation. The thickness of the formation has been increased to 256 m at the type locality in the Ora anticline near the Iraq-Turkey border (Bellen et al., 1959). The formation comprises black micaceous and calcareous shale with olive green silty marl and lenses of detrital limestone. Fine-grained sandstone beds occur intermittently throughout the formation. The lower part (added from the upper Kaista) comprises thin-bedded dark blue argillaceous limestone with beds of silty shale and sandstone. A breccia occurs at the base of this unit.

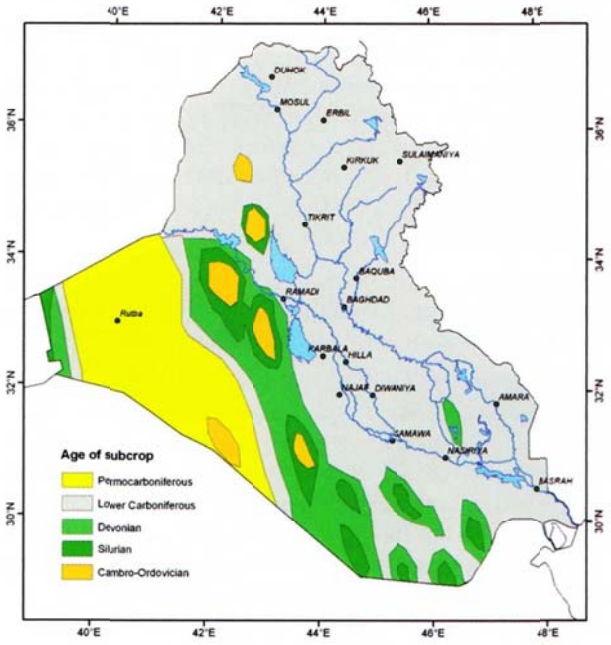
Abundant fossils in the Ora Formation (Bellen et al., 1959) indicate an Early Carboniferous (Early Tournasian) age.

The formation has been drilled in western Iraq in wells Khlesia-l and Akkas-l and in water well K5-1. In well Khlesia 1, the formation (1757-2250 m, 493 m thick) contains abundant sandstone interbeds up to 10m thick. In water well K5-1 the formation (940-1343 m, 103 m thick), comprises black shale and thin beds of black limestone.

The formation is probably present over most of N and W Central Iraq. It is probably absent over large parts of Sand SW Iraq due to erosion of the Salman Zone during Late Carboniferous time. The presence and extent of the formation in E Iraq is unknown.

The Ora Formation can be correlated with the Suke Formation (Altinli, 1966) and the Koprulu Formation (Carter and Tunbridge, 1991) of SE Turkey. It can also be correlated with the Tournasian mudstones of Jabal Abdul Aziz in Syria (Ponikarov et al., 1967) and the Tournasian Athar Formation of the Palmyrides.

Fig. 8-11: Hercynian subcrop map



8.4.3 Harur Formation

The Harur Limestone was defined by Wetzel and Morton in 1952 (Bellen et al., 1959) from the Ora Zone of N Iraq. The formation has been penetrated in wells Khlesia-l, Akkas-I and water well K5-1 and reached in well Jabal Kand-l. In the type area the formation consists of 62 m of thick-bedded detrital limestones with thin interbeds of black calcareous micaceous shale deposited as a marine neritic facies (mostly reef and forereef).

Rich fossil assemblages in the type section and in well KhIesia-1 indicate an Early Carboniferous (Tournasian) age.

The Harur Formation conformably and abruptly overlies the Ora Formation in the type area. In well Khleisia-l a transitional unit is developed, designated as the Ora Harur Formation by Gaddo and Parker (1959). The top is marked in both areas by an unconformity. In Khleisia-I the formation (1670-1757 m) is 87 m thick; the upper 30 m consists of shale. In water well K5-1, the Harm Formation (735-940 m, 205 m thick) is composed of 80 m of black fetid limestone (cavernous and partly oolitic) overlain by 125 m of black shale with sandstone and thin fossiliferous carbonate beds which may correlate with the Sawanet Formation penetrated in wells of the Palmyrides. A Tournasian age is assigned to the K5-1 section by Habba et al. (1994).

The Harur Formation is equivalent to the carbonates of the Suke Formation (Altinli, 1966) or the Belek Formation (Carter and Tunbridge, 1986) of SE Turkey. In Syria the Haloul Formation is identical in thickness and facies to the Harur Formation (well Doubayat- 2 penetrated 90 m of black carbonaceous limestone and mudstone of Tournasian-visean age).

8.5 The Modified Westphalian-Ufimian 8yn-Hercynian) Megasequence AP5

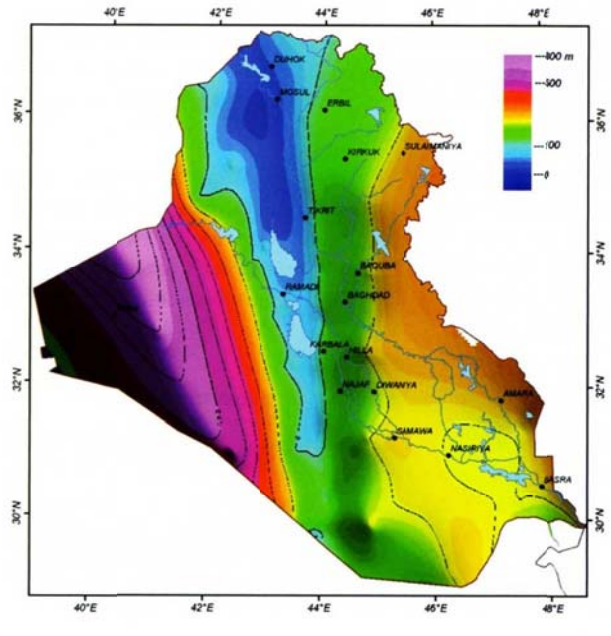
The original definition of AP5 of Late Stephanian to Ufimian (Sharland et al., 2002) has been modified. The type section of this megasequence in Oman lacks sediments of Westphalian and Early Stephanian age. However Westphalian and Stephanian fluvial sediments occur in the Rutba basin of W Arabia (Habba et al 1994) and in Syria Doubayat-2 well log). For this reason the lower boundary of the megasequence has been lowered to include the Westphalian succession of Iraq and Syria.

The Afro-Arabian Plate was influenced by two significant geodynamic events during Late Carboniferous and Early Permian time: the clockwise rotation of the plate, and compression followed by rifting along the eastern and western active margins of Gondwana. Southwesterly subduction affected the NE boundary of the Arabian Plate which resulted in the development of major swells or arches. On the other side of Afro-Arabia, compression associated with a collision with the N American Plate (Mauritanides collision) formed similar N-S arches throughout N Africa. The low latitude of S Arabia (See Chapter 3) and the thermal uplift associated with the opening of the Nee-Tethys led to the formation of major Alpine-type glaciers on the SE side of the Arabian Plate.

Both E and W Arabia were uplifted; a basin formed between the uplifts (the Rutba basin) in NW Saudi Arabia, W Iraq and E Syria. The western uplift was an easterly-dipping monocline that covered all of Jordan and W Syria. The eastern uplift covered the whole of E and Central Saudi Arabia, SW Iran and most of Central and E Iraq. The Rutba Basin contains fluvio-Lacustrine sediments with abundant plant remains.
During the Early Permian, E-W compression created N-S trending antiforms between which fluvio-glacial and aeolian sediments were deposited (Heine, 1993 and 2000). After glaciation the climate became more arid resulting in the deposition of the red mudstones and sandstones of the Ga'ara Formation with periodic flooding and desiccation. These N-S structures are evident in the Hercynian subcrop map (Fig. -II) which shows N-S trending structures in central and southern Iraq. Lower Palaeozoic sequences and probably even the Precambrian basement subcrop the Hercynian unconformity in the Salman Zone of Central Iraq.

The Late Carboniferous-early Late Permian Megasequence AP5 (Fig. 8-12) is >1000 m thick in the Rutba area; it is 1000 m thick in central E Syria (in well Doubayat-2). In SE Syria the megasequence is absent due to truncation below the lower Senonian unconformity (wells Tanf-1 and Swab 1 .A remnant (146m thick) occurs in well Akkas-1 in W Iraq. In the Salman and Mesopotamian zones the Megasequence is thin and Late Carboniferous sediments are probably absent (as in eastern Saudi Arabia). The AP5 Megasequence comprises two formations the Ga'ara and Bir El Rah formations. The Ga'ara Formation has been modified from its original definition by Bellen et al. (1959) to include the Nijili Formation and a subsurface succession penetrated in water well K5-1. The type section of the newly introduced Bir EI Rah Formation is also in this well.

Fig. 8-12: Thickness of the syn-Hercynian Permocarboniferous clastic sequence of megasequence AP5. The thickness in central and E Iraq is speculative



8.5.1 Bir El Rah Formation

The name, "Bir El Rah Formation", is proposed for a section of limnic claystone and shale with thin beds of cross-laminated sandstone with occasional immature clayey coal horizons at 360-856 m (496 m thick) in water well K5-1, 5 km west of Bir El Rah village in the Ga'ara depression. The formation was also penetrated in well Akkas-l to the NE of the type area (thickness 146 m, top eroded below Lower Senonian unconformity) and in water well K5-2 to the south of the type section (10 km east of Rutba town). Other water wells in the Rutba area may also reach the formation but are not well studied.

In well K5-1 the formation lies below an interval of thick red and green mudstones; the contact is gradational taken at base of a dark red mudstone layer. The lower contact with the underlying marine shales and thin limestone beds of the Harur Formation is disconformable and taken at the base of an interval of sandstone and shales.

The formation comprises grey to black shale with thin cross-laminated sandstone beds, occasionally forming layers up to 10 m thick. Numerous plant-rich shales occur, sometimes grading into fusinite grade argillaceous coal. A fossiliferous horizon present at 735 m depth in water well K5-1 indicates a marine incursion.

The Bir El Rah Formation is dated in wells *KS-l* and K5-2. In well K5-1, Habba et al. (1994) indicated the formation is of Westphalian-Stephanian age; palynomorphs were probably obtained from the plant-rich lower member in well K5-1. Detailed analysis of samples from the depth range 190-1000 m in well K5-2, (located 10 km east of Rutba town) by Kaiserova and Kalibova (1982) provided palynomorph assemblages at five horizons at depths of 228, 258, 319, 332 and 917 m. The four shallowest horizons are probably in the Ga'ara Formation. The deepest horizon at 917m in the Bir El Rah Formation contains the following plant macro- and micro-fossils (spores): *Punctatisporites (P. obliquus), Granulatisporites, Cyclogranisporites* (c. *jelenicensi),*

Apiculatisporis (A. levis), Laevigatosporites (L. scissus), Torispora laevigata, Florinites, Wilsonites, Vesicaspora, and uncertain *Vestigisporites, Cordaitina* (c. *uralensis).* The miospore assemblage consists mostly of trilete types; saccate types are scarce. The age of the formation in well *KS-2* thus probably ranges from Late Carboniferous (Westphalian Stephanian) to Early Permian (Autunian).

The richness in plants and reducing conditions of the sediments indicate that the formation was deposited in a fluvio-lacustrine swampy environment.

In SE Turkey Upper Carboniferous and Lower Permian sediments are usually absent; the Mardin High was uplifted and eroded in Late Carboniferous time. However in the Hazro region of SE Turkey, coals occur in the Hazro Formation (Carter and Tunbridge, 1994) which may correlate with the Bir El Rah and/or the overlying Ga'ara formations. A succession up to 400 m thick of similar facies and age to the Bir El Rah Formation was penetrated in wells in E Syria (e.g. Doubayat-2; Najeeb Formation).
No proven equivalents of the formation are known in E Saudi Arabia, Kuwait and SW Iran. However in W Saudi Arabia parts of the Wajid Sandstone and Haradh Formation near the Arabian Shield (Senlap et al., 1994) may be age equivalent to the Bir El Rah Formation. The Unayzah Formation is usually accepted to be Early Permian in age (Senlap et al., 1994 and Sharland et al., 2002) but some authors consider it is partly of Late Carboniferous age (Laboun, 1987; Heine, 1997 and 2000) and hence might be partly equivalent to Bir El Rah Formation.

8.5.2 Ga'ara Formation (Early Permian-early Late Permian /Ufimianl)

A clastic unit outcropping in the centre and rims of the Ga'ara morphological depression was originally assigned to two formations: the Ga'ara Sandstone Formation (Boesch, *1938)* and the Nijili Formation (Dunnington, 1954). Antonets et al. (1963) argued that the two formations represent vertically and laterally interfingering lithofacies of the same lithostratigraphic unit. They introduced the name Ga'ara Formation for the whole unit; a definition accepted by Buday (1980).
The age of the Ga'ara and Nijili formations were preliminarily determined as Middle Triassic (without any palaeontological evidence) because of the slight lithological similarity of the Nijili Formation with the Beduh and Lower Geli Khana formations of N Iraq, and the Late Triassic age of the overlying Mulussa carbonates. However locally abundant plant remains indicate a Permocarboniferous age. The clays with *Lobatannularia, Plagiozamites* etc. at Wadi Duwaikhlah are of Early-Late Permian age. The sandstones with *Sigillaria* at Wadi al Sufi in the centre of the depression are of Permocarboniferous age (Ctyroky, 1973).

The Ga'ara Formation is also amended to include the section drilled in nearby water well K5-1. The thickness of the exposed Ga'ara Formation, after including the original type section at Tlul Afyef and the Nijili section at Wadi Duwaikhla is amended to 120 m.

The supplementary section in well K5-1 is 450 m thick and comprises cross-bedded sandstones overlying mottled mudstones with occasional thick cross-bedded sandstone beds. Both units contain red mudstones which are absent in the underlying Bir El Rah Formation.

Detailed geological mapping by GEOSURV and data from 50 shallow boreholes and tens of trenches indicates the Ga'ara Formation contains stacked sandstone channels (often with channel lags of ironstone pebbles) passing upwards into siltstone, green kaolinitic mudstone and mottled

red-green mudstones, overlain by purple to red (locally pisolitic) ironstone (Tamar-Agha et al., 1984). The stacked channels occur in the western part of the Ga'ara depression; flood plain-facies dominate the eastern part. Remnant flood plain sediments occur between the stacked channels (e.g. Nijili type section). Stacked channel contain sigmoidal cross bedding similar to point bar accretion structures. The orientations of these accretion structures and other cross bedding structures suggest that the rivers trended N-S; the rivers probably flowed from S to N (Tamar-Agha et al., 1984). Thin oxidized coal seams (a few cm thick) seen in both surface and subsurface sections probably represent marsh deposits possibly formed in oxbow lakes.

The palynomorphs of the Ga'ara Formation were studied by Kaiserova and Kalibova (1984) from outcrops and subsurface (water well *KS-2)* samples. Well preserved plant material was sampled at a locality 3.5 km east of Bir A1-Aqhari. The following species were identified: *Annularia sphenophylloides* (Zenk), *Lobatannularia heianensis* (Kodaira), *Pecopteris sp., Alethopteris? sp., Neuropteris? sp.* In addition, *Plagiozamites oblongifolius* Halle and *Protoblechnum sp.* were reported by Ctyroky (1973). Many silicified stem fragments of *Sigillaria sp.* (decorated stems of the *Sirigodendron* type) were also collected near Na'aja (on the NW rim of the Ga'ara depression). These forms belong to *Planolites;* cylindric forms (1-2 mm wide and 4-14 mm long) belong to the genus *Bifungites,* Four horizons in the Ga'ara Formation in well *KS-2* yielded palynomorphs. The deepest sample at 332 m, contained light yellow spores without trilete and monolete marks such as *Punctatisporites sp.* The following spores with trilete marks were observed: *Leiotriletes, Punctatisporites, Granulatisporites, Apiculatisporis Lophotriletes, Converrucosisporites, Convolutispora* and *Cirratriradites.* However, they do not correspond to species known from the European Carboniferous. The following species were also determined: *Laevigatosporites vulgaris, Latosporites fico ides, Punctatisporites cf. marattioides, Tuberculatosporites anicystoides, Spinosporites sp., Thymospora apaqua, Thymospora. sp., Torispora securis, T. verrucosa, Speciososporites sp., Sporonites sp., Cycadopites sp., Marsupipollenites sinuosus, Florinites sp., Cordaitina sp.* Some forms resembling the species *Bicolora gothanii* were also observed.

The sample at 319 m contains abundant spores of the genus *Cyclogranisporites,* monolete spores belonging to the genera *Torispora, Pectosporites* and *Pericutosporites,* and saccate spores (light coloured) which may belong to the genera *Florites* and *Protohaploxypinus.* The coal seam samples from 319 m also yielded abundant trilete spores similar to those found in the Upper Carboniferous of the Euramerician province. The coal seams at 258-259 m contain abundant cuticules of conifers and desiccated spores resembling the genus *lllinites* and *Cordaites Florinites* spores of probable late Early Permian age (Late Autunian and younger). The youngest assemblages in the borehole at 227 m mostly contain desiccated spores and the genera *Lueckkisporites '* and *Vesicaspora, Klausipollenites, Pityosporites, Gardenasaccites (G. Leonardi)* and *Falcisporites (F zapfei).* Other common spores are those of the genus *Punctatisporites (P. cf obesus). Paricutosporites. Leiotriletes, Bifurcatisporites, Lophotriletes, Acaruhoroniies, ?Calamospora, Cyclogranisporites, Granulatisporites,* ? *Apiculatisporis,* ? *Raistrickia, Punctatosporites, Pericutosporites, Pectosporites* and *Florinites* were also recorded.

The coal seam samples from 319 m yielded abundant trilete spores similar to those found in the Upper Carboniferous of the Euramerican province. The samples from the coal seam at 258-259 m are of late Early Permian age (Late Autunian and younger). The uppermost sample from 227-228 m contains abundant bisaccate spores suggesting a Late Permian (Zechstein) age. In a shallow, 100 m deep water well, in the Ga'ara depression (10 km NNE of Bir El Rah village) samples at 70-80 m provided assemblages of Early Permian (Autunian) age (Habba et al., 1994). The same authors dated a 50 m thick clastic section below the Chia Zairi Formation in well W Kifl-I in S Iraq (assigned to Ga'ara Formation) as Kungurian. The Ga'ara Formation is thus considered to be of Early Permian to early Late Permian age.

The Ga'ara Formation was deposited by large river systems. Prolonged periods of exposure of flood plains resulted in desiccation and formation of ferricrete soil. The abundance of red claystone and ironstones suggest frequent long periods of drought occurred. The Bir El Rah Formation, however, was deposited in a fluvio-lacustrine environment characterised by high water supply and abundant vegetation.

The Ga'ara Formation can be correlated with the Heil Formation of E Syria (680 m in well Doubayat-2) which consists of an upper 105 m thick sandy unit (equivalent to the Amanus Sandstone), a middle black silty shale unit (165 m thick), and a lower unit of mudstone, marl and sandstone (410 m thick). In Saudi Arabia, the Unayzah Formation is similar in age and facies to the Ga'ara Formation.

Chapter 9
Late Permian-Liassic Megasequence AP6

by

Saad Z. Jassim, Tibor Buday, Ivan Cicha and Vladimir Prouza

The Neo- Tethys Ocean opened in Late Permian time when one or more narrow blocks of continental crust drifted away from the NE margin of Gondwana (Chapter 3). The Late Permian-Liassic Megasequence (AP6) was deposited on the N and E facing passive margin of the Arabian Plate. The unconformity at the base of the megasequence is a break up unconformity. Renewed rifting occurred within this passive margin in Mid-Late Triassic time creating a broad and highly restricted intra-shelf basin in Mesopotamia separated from the open ocean by a narrow rift with alkali basalts and an outer ridge of thinned continental crust on which an open marine carbonate platform developed (Chapter 3). This phase of rifting was followed by slow thermal subsidence in Norian-Liassic time.

The Rutba Uplift developed in the area now representing W Iraq, NE Jordan, E Syria and NW Saudi Arabia. Upper Permian and Lower Triassic sediments were deposited on a broad platform. This platform underwent extension in Mid-Carnian time; up to 2000 m of Mid Triassic-Carnian carbonates and evaporites were deposited in the axis of the intra-shelf basin in North Iraq. An imbricate of nautiloid bearing red Upper Permian limestone and associated basic volcanics is the only recorded occurrence of deep water Permian Tethyan margin rocks in Iraq. The lower boundary of the megasequence is the base of the Chia Zairi Formation. Megasequence AP6 in N Arabia unconformably overlies sequences ranging from Precambrian to Early Permian age. It consists of three second order sequences: the Late Permian-Mid Triassic, Late Triassic, and Early Jurassic sequences. The stratigraphic correlation of the formations of Megasequence AP6 in Iraq and Jordan is shown in Fig. 9-1.

The megasequence is up to 3000 m thick (Fig. 9-2), distributed in a N-S trending belt, thinning to the east and west from a central basin coinciding with the Mesopotamian Zone. The thinning of the megasequence across W Iraq is due to both reduced subsidence and subsequent erosion over the Rutba Uplift.

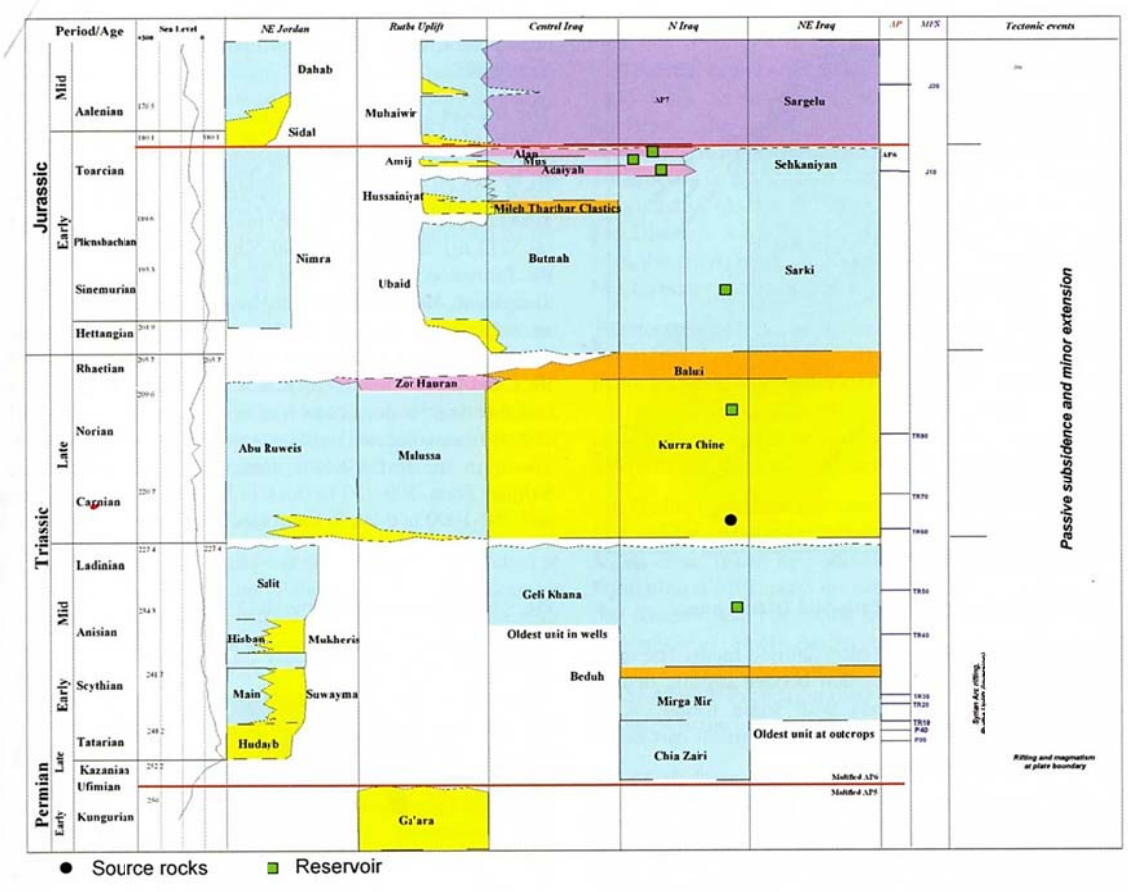


Fig. 9-1: Stratigraphic correlation of the Late Permian-Liassic Megasequence (AP6)

Fig. 9-2: Thickness of the Late Permian-Liassic Megasequence AP6

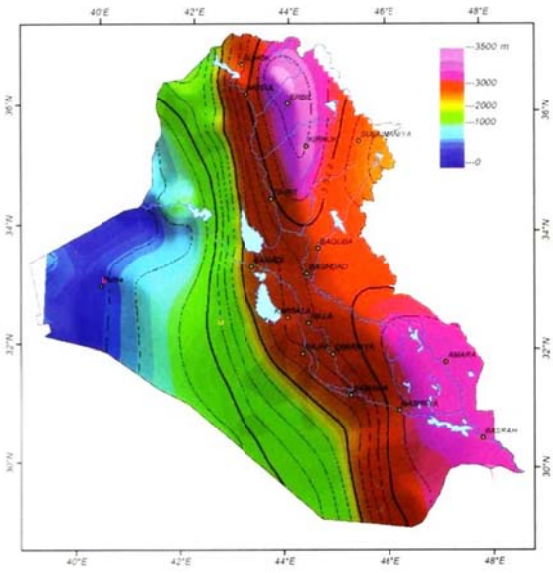
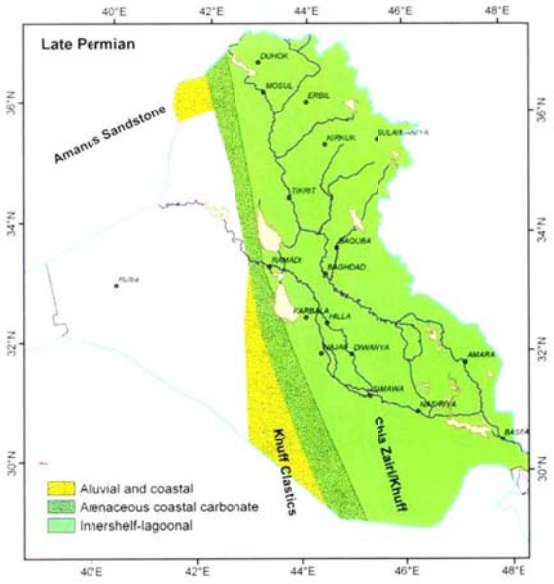


Fig. 9-3: Palaeogeography of Late Permian time



9.1 Late Permian-Mid Triassic Sequence

Following the Hercynian uplift during the Late Carboniferous and early Permian major changes' in basin' geometry occurred late' Permian time in Iraq The previously subsiding area of the' Stable Shelf (Rutba-Jezira Zone) was uplifted initiating the Rutba uplift, whereas the previously elevated Salman and the Mesopotamian zones subsided.

A shallow inner shelf lagoonal sea, whose western shore line lay along the western border of the Salman Zone, covered the Unstable Shelf, and the Mesopotamian and Salman zones. The elevated Rutba Uplift extended into Jordan and Syria. The photo Palmyride basin developed in central and E Syria as a depression of NE- SW- orientation Characterised by rivers flowing into the sea in N Iraq. Coastal clastics were deposited in the Salman Zone; the area further east and north was dominated by carbonate sedimentation of the Chia Zairi formation equivalent to the Khuff in Saudi Arabia (Powers et al, 1966; Al Jallal, 1294) and the Dalan Formation in –SW Iran. Along the Qulqula Khwakurk Zone of NE Iraq, some crinoid-ammonite bearing bioclastic limestones were deposited in a relatively deep water environment (Biyarah Limestone, see Chapter 16), probably separated from the lagoonal Chi a Zairi Formation by reef build-up facies similar to the limestones of the Dalan Formation of SW Iran (Edgell, 1977). The Biyarah Limestone facies was deposited on the shelf margin flanking the newly formed Neo- Tethys Ocean. The palaeogeography of the Late Permian is shown in Fig. 9-3.

During the Early and Middle Triassic, the Rutba Uplift was narrow ridge. The western shoreline of the Rutba Uplift was located in NE Jordan, E of the Azraq-Sirhan area; the eastern shoreline was located along the eastern boundary of the 'Rutba-Jezira Zone. Three main facies can be identified: clastics and carbonates" deposited-in an inner "shelf environment equivalent to the Jilh and Sudair formations of Saudi Arabia carbonate evaporite inner shelf facies, and restricted lagoonal Facies. The latter two facies are represented by the Mirga Mir, Beduh and Ge1i Khana formations (Fig.' 9-4).The - thickness of the Chia Zairi ~n and the combined thickness of the Lower-Middle Triassic formations are shown in Fig. 9-5 and Fig. 9-6 respectively.

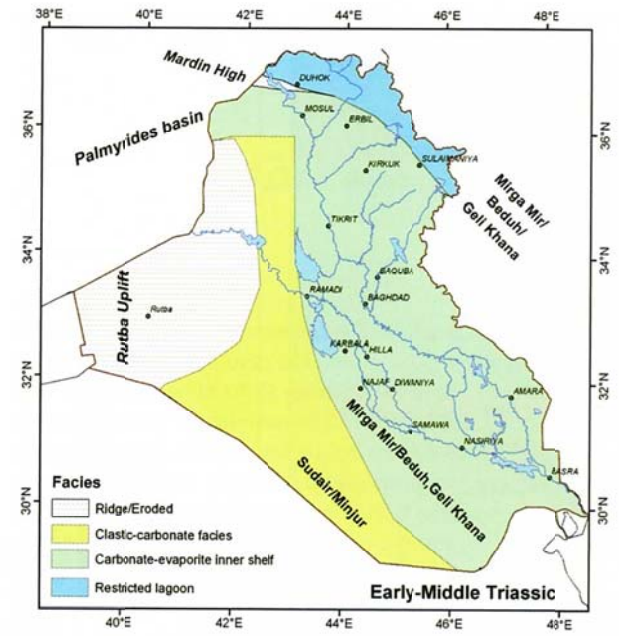


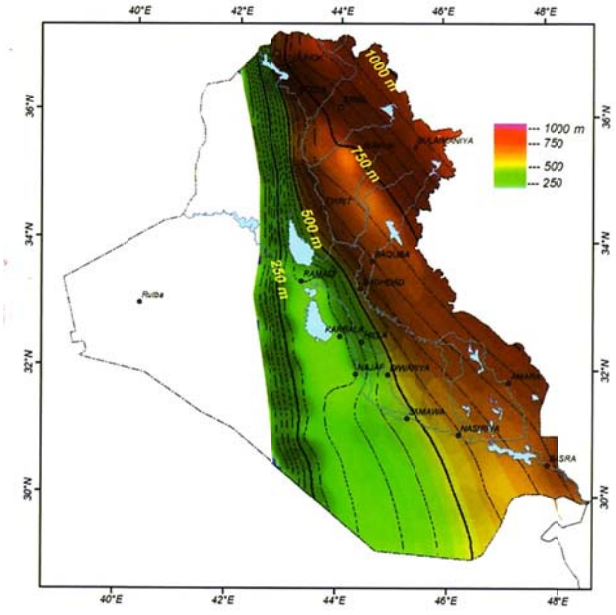
Fig. 9-4: Palaeogeography of Early-Mid Triassic times

9.1.1 Chia Zairi Formation

The Chia Zairi Formation was first described by Wetzel in 1950 in the Northern Thrust Zone (Bellen et al., 1959), and later subdivided by Hudson (1958) into three units referred to, from the base to the top, as the Darari, Satina Evaporite and Zinnar members. The lower member (Darari) consists of alternating thin bedded organic detrital limestone, dark blue limestone and massive, cliff-forming silicified limestone with black shale beds near the base. The Satina Evaporite Member, comprises dolomite, and solution and recrystallisation breccias formed by dissolution of anhydrite beds (present in wells), and recrystallised marls. The upper member (Zinnar) comprises thin bedded organic detrital, sometimes cherty, limestone with some harder, scarp- forming silicified limestone; in the uppermost part oolitic limestones with clastic beds occur.
In the Foothill Zone, where the formation was partly penetrated (299 m) in well Atshan 1 (west of Mosul), the lithology differs from the type section. Below the uppermost oolitic limestone, the formation here contains silty argillaceous limestone, silty dolomite, and some shale and, in the lowermost parts, sandstone interbeds. The sandy facies is probably the coastal facies of the formation, a continuation of the clastic belt (? Amanus Sandstone) of the Palmyrides.

The thickness in the type area is 750-810 m (340-390 m Darari Member, 60-80 m Satina Evaporite Member and 300-320 m Zinnar Member). It was also penetrated in wells Jabal Kand-l (5126-5757 m, thickness 631 m) and W Kifl1(5323-5823 m, thickness 500 m) and reached in Diwan-l (at 5211 m); it is absent in well Khlesia-l. In Jabal Kand-l , the formation, as in the type section, is underlain by the Tournasian Harur Formation. However, in W Kifl-l it is underlain by at least 50 m of Kungurian sandstone of the Ga'ara Formation (Haba et al., 1994). The isopach map of the Chia Zairi Formation (Fig. 9-5) based on three boreholes and the type section, combined with the data of AI Jallal (1994) from adjacent countries, shows that the formation is absent in the Rutba-Jezira Zone, 0-500 m thick in the Salman Zone, 500-750 m thick in the Mesopotamian Zone and 750-1000 m thick in the folded belts.

Fig. 9-5: Thickness of the Upper Permian Chia Zairi Formation



The Chia Zairi Formation was deposited in a transgressive neritic sea on a broad carbonate platform with locally developed lagoonal conditions and sabkhas. The Satina Evaporite Member may be equivalent to the five sedimentary cycles of carbonates and evaporites recognised in the Gulf region (Al Jallal, 1994; Douban and Al Sahlan, 2001) indicating recurrent periods of extensive lagoonal sedimentation and repeated desiccation. Coralline limestones in Iran (Dalan facies) were deposited in reefs along the Tethyan margin in Iran (Edgell, 1977). On the western side of the basin, coastal sandstone facies (as seen in well Atshan-l) are equivalent to the Khuff clastics facies of Saudi Arabia.

The formation is rich in fossils in both the type area and in well Atshan-l , listed in Bellen et al, (1959) and Hudson (1958). The coral and algal fauna indicates a "Mid"-Late Permian age. The uppermost beds of the formation contain some Early Triassic fauna. The lower boundary in N Iraq is associated with a ferruginous surface developed on top of the Harur Formation (Bellen et al., 1959). The age of the formation is therefore accepted to be Post-Kungurian Late Permian to Early Scythian. Outcrops are restricted to the Northern Thrust Zone of Iraq.

The formation is probably partly equivalent to the Biyarah Limestone (Kazanian), exposed as imbricates within the Qulqula-Khwakurk Zone where some ammonite-crinoid packstones were found (Chapter 16). The Chia Zairi Formation is equivalent in age and facies to part of Imbirik Formation of SE Turkey, the Khuff Formation of the Gulf region and the Dalan Formation of SW Iran.

9.1.2 Mirga Mir Formation

The Mirga Mir Formation was first described by Wetzel in 1950 from the Ora region of the Northern Thrust Zone. It comprises 200 m of thin bedded grey and yellow argillaceous limestone and shale with some recrystallised breccias. Oolitic limestone with rare sandy beds near the base of the formation (Bellen et al., 1959). In well Atshan-l of the Foothill Zone, the formation contains a higher proportion of clastics probably derived from the Rutba Uplift to the SW. Thicknesses in other wells are: Jabal Kand-I in N Iraq (165 m), W Kifl-1 in south central Iraq (134 m), and Diwan-l in S Iraq (99 m). The formation is always underlain by the Chia Zairi Formation and overlain by the Beduh Formation; both contacts are gradational (Hamza and Isaac, 1971). The formation is also present in the High Folded Zone in the Sirwan gorge in NE Iraq (Bellen et al., 1959; Bolton, 1958c). On the Stable Shelf, its most western occurrence is probably along the western boundary of the Salman Zone. Anhydrites in well Atshan-l and the presence of solution breccias in outcrops also indicate lagoonal conditions.

Fossils recorded from the type section confirm an Early Triassic (Werfenian) age (Bellen et al., 1959).

The formation correlates with part of the Goyan Formation (Altinli, 1966) of SE Turkey and is age correlative with part of the Upper Dubayyat Group (Dubertret 1966). The lower parts of Khaneh Kat Formation in SW Iran (Furst, 1970) and the Sudair Shale Formation of Saudi Arabia (Powers et al., 1966) are age equivalent to the Mirga Mir. The Amanus Sandstone in Syria is a continental equivalent of the Mirga Mir though this sandstone unit might be partly of Late Permian age.

9.1.3 Beduh Formation

The Beduh Shale was first described near Beduh village in the Northern Thrust Zone by Wetzel in 1950 (Bellen et al., 1959) as 60 m of shale and marl, sometimes silty, with subordinate thin limestone interbeds with sandstone streaks. Its red brown-purple colour makes it an excellent marker unit for field mapping. The characteristic purplish colour is also well developed in the subsurface (well Atshan-1). In well Atshan-1 and at outcrop in the Sirwan valley (Bolton, 1958c) the formation contains a higher proportion of sandstone. The formation is 84 m thick at Sirwan near Halabja. The formation appears to be widespread in Iraq. Thicknesses in other wells are: Jabal Kand-I in N Iraq (67 m), Atshan-1 (58 m), and W Kifl-1 in south central Iraq (65 m) and Diwan in S Iraq (26 m). The contacts of the formation with the overlying Geli Khana and the underlying Mirga Mir formations are conformable and gradational.

The conspicuous purple colour was thought to be related to volcanicity (Bolton, 1958c; Bellen et al., 1959). A more likely source for the red sediment might be lateritic soils on the exposed Arabian Shield and Rutba Uplift. The formation is of shallow marine origin. Fossils are reported from the type area and confirm a Werfenian age (Bellen et al., 1959).

The Beduh Formation has a similar distribution to the Mirga Mir and Geli Khana formations, being absent in the Rutba-Jezira Zone. It can be correlated with parts of the Goyan Formation of SE Turkey, the Amanus Shale in Syria, parts of the Khaneh Kat Formation of SW Iran and the Sudair Formation of Saudi Arabia and Kuwait. In Jordan, the Beduh Formation is correlatable in age with the upper part of the Mudeib Formation (200 m). However, this formation is absent in the NE part of Jordan (Shinaq, 1996).

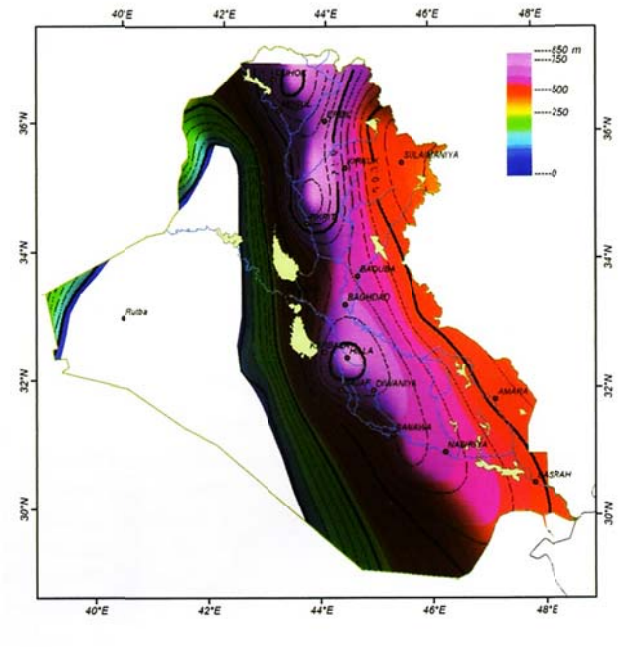
9.1.4 Geli Khana Formation

The Geli Khana Formation, originally described by Wetzel (1950) from the northern flanks of the Ora anticline, comprises two subdivisions (Hall, 1957). The upper division (200 m thick) comprises dark, massive dolomites overlying thick-bedded limestones with subordinate marl and shale with occasional chert nodules. The lower division (375 m thick) consists of bluish, greyish and yellowish shale and thin bedded limestone with some sandstone beds that increase in amount SW of the outcrops. The clastic increase is significant in the subsurface (in well Atshan-1). These subdivisions are applicable throughout N Iraq. Equivalent stratigraphic units in Kuwait (Douban and-Al-Sahlan: 2001)-and SE Iran (Setudehnia, 1978) comprise dolomite, anhydrite and local halite beds. The thickness of the formation is 575 m at Ora and 450 -575 m in Sirwan Gorge. It is penetrated in wells: Jabal Kand-l (781 m), Atshan-l (460 m), Alan-I (482 m), Mityaha-l (385 m), W Kifl-l (533 m) and Diwan-1 (510 m).

All outcrops in N and NE Iraq are of similar facies and include anhydrite in the lower parts of the formation. The facies of the Geli Khana Formation in well sections show an increased proportion of mudstone throughout, and anhydrite layers in the lower part. The upper division was deposited in a shallow marine basin while the lower division was deposited in a nearshore (locally lagoonal) environment [(Bellen et al., 1959).

Fossils reported by Bellen et al. (1959) indicate an Anisian age for the type section and a Ladinian age for the sections near Sirwan.

Fig. 9-6: Thickness of the Early-Mid Triassic Sequence



The absence of Middle Triassic deposits in the Rutba-Jezira zone, in the eastern Syria, and in extreme NE Jordan suggests that sedimentation was influence by the mega N-S tending Rutba Uplift. The Middle Triassic age originally assigned to the Nijili Formation (now considered part of the Ga'ara Formation - see Chapter 8) by Bellen et al. (1959) and accepted by Sadooni (2004) is inconsistent with survey results.

Bellen et al. (1959) suggested the Geli Khana Formation is equivalent in SE Turkey to the lower part of the Tanin Formation of Tasman (1949). However, accord in to Altinli (1966)- ,this formation is of Permian age. The equivalent stratigraphic unit in SE Turkey is probably the upper part of the Goyan Formation, or the lower part of the Cudi Group (Schmidt, 1964).

In Syria the lower arts of the Dolaa Group can be correlated with the Geli Khana Formation. The Geli Khan formation is partly equivalent to the Mulussa-B of the Palmyrides (absent in SE Syria). In Jordan, the formation may be equivalent to the Anisian-Ladinian units described by Shinaq (1996) which include the Hisban, Mukheiris, Iraq Al Amir and Umm Tina formations. In Saudi Arabia and Kuwait it is probably equivalent to' parts of the Jilh formation (Powers et al., 1966) and probably to parts of the Sudair (Douban and Al Sahlan, 2001) in SW Iran, it may
Correlate' with the lower evaporitic sequence of the Khaneh Kat Formation of Furst (1970).

9.2 Late Triassic Sequence

The Late Triassic Sequence is the most widespread Triassic sequence in the Arabian Peninsula. The sequence is best developed within a N-S belt along the Salman Zone in central and SW Iraq and in the fold belt of N Iraq. It is > 1000 m in the High Folded Zone (Fig. 9-7). In the Rutba subzone, the sequence is thinnest near the Iraq-Jordan border but thickens to 500 m in N Jordan. The sequence is represented by the Mulussa and Zor Hauran formations in the Rutba Subzone and by the Kurra Chine and Baluti formations in the rest of Iraq.

The palaeogeography of Late Triassic time differs from that 'of the Middle Triassic only by the extent of the Rutba Uplift. In W Iraq, most of the Stable Shelf was submerged (Fig. 9-7). Three

distinct facies are recognised, comprising inner shelf carbonates and clastics on the Stable Shelf (Mulussa and Zor Hauran formations), inner shelf carbonates and evaporites in the Foothill Zone, and restricted lagoonal facies in the High Folded Zone (Kurra Chine and Baluti formations) (Fig. 9-8).

The Late Triassic transgression reached far beyond the Mid Triassic shoreline. The whole Stable Shelf area of Iraq was submerged in the Late Triassic; its shoreline was located not far beyond Iraq in Saudi Arabia. Along the shoreline littoral-continental sediments were deposited (Minjur Sandstone Formation).

Fig. 9-7 Thickness of the Late Triassic Sequence

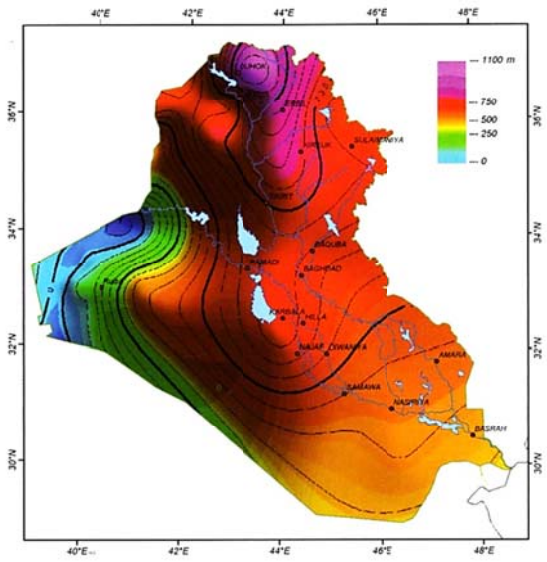
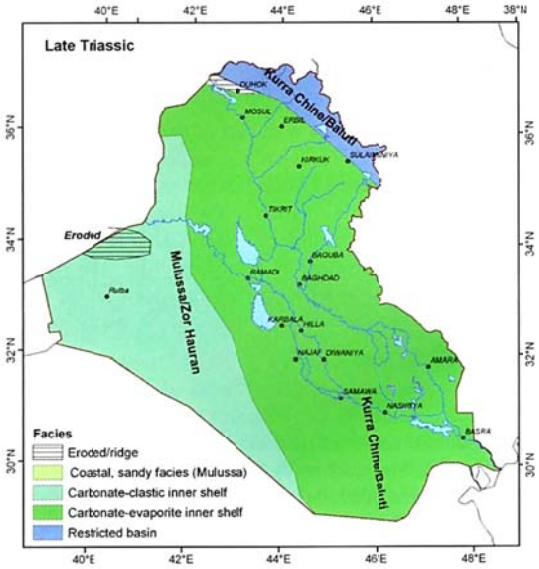


Fig. 9-8: Palaeogeography of Late Triassic time



9.2.1 Carbonate-clastic inner shelf

9.2.1.1 Mulussa Formation

The Mulussa Formation is exposed in the western parts of Iraq in the Rutba area and is widespread on the Rutba Subzone except in the area between the Ga'ara depression and the Euphrates River (Fig. 9-8) where it may have been eroded. It was first introduced by Williamson and Picles in 1931 and described in detail by Dunnington (Bellen, et al., 1959). The formation consists mainly of limestone, sometimes sandy and oolitic, often dolomitized with subordinate yellow marl, and marly limestone. An oolitic locally conglomeratic, fossiliferous limestone bed, designated as the "i" marker (Bellen et al., 1959) occurs in the middle of the formation. The lithology is relatively uniform in the area adjacent to Rutba town in W Iraq. The thickness of the formation is up to 150 m thick but wedges out by erosion towards the N and NW. It has been completely eroded in the central part of the Ga'ara depression. Many of the large limestone pebbles and boulders within the basal conglomerate of the Upper Cretaceous formations along the W and N rim of the depression were derived from the Mulussa Formation. Subsequent detailed mapping of the Ga'ara depression showed that individual subdivisions of the formation also pinch out towards the N and NW, suggesting depositional thinning in addition to erosional thinning.

The formation outcrops on the southern flank of the Ga'ara anticline from the area SW of Rutba in the SW to Wadi Horan in the NE. The thickness of the formation in water wells around Rutba is as follows: K5-2 (120 m), K5-4 (100 m), K5-5 (50 m), K5-3 (120 m), K5-6 (120 m), K5-7 (50 m) and K5-9 (158 m).
The lower contact of the Mulussa Formation, according to Bellen et al. (1959), appears conformable. However the recently recognized age gap between the Palaeozoic Ga'ara Formation and the Upper Triassic Mulussa Formation is large. The apparent conformity is due to reworking of the clastics of the underlying Ga'ara Formation into the overlying basal units of the Mulussa. The formation passes upwards gradationally into the marly Zor Hauran Formation However, around the rim of the Ga'ara depression, the formation is unconformably overlain by Cretaceous and Tertiary formations, (Cenomanian Rutbah Sandstone and late Campanian Hartha Formation along the western rim and by the Eocene Ratga Formation along the SE rim).

Bioglyphs, both burrows perpendicular to bedding planes and animal trails on bedding surfaces are common in the Mulussa Formation and are particularly abundant in the lower half which contains variable amount of sand and silt. This section, usually yellowish, light fawn or greenish, is sometimes reddish, variegated and mottled (violet to pink). These beds contain material derived from the Ga'ara Formation. Fossil plant stems and leaves occur (e.g., south of Bir Al Agharri) in calcareous siltstones and mudstones in the basal part of the unit. A layer of calcareous sandstone, about 12 m thick, outcrops approximately 13 m above the base of the formation, ESE of Bir Al Rah, containing numerous small fragments of phosphatic rocks, shark teeth and fragments of fossils. The stratigraphic position of these phosphates is doubtful.

Several beds with chert nodules and lenses, some of organic origin (stromatolitic algal texture), occur in the lower part of the formation south of Bir Al Rah and Bir Al Agharri. Pebbly layers near the base of the unit, and beds of calcareous sub-arkoses and dark grey mudstone with plant leaves were penetrated by borehole K5-2 E of Rutba, approximately 15 m above the base of the formation.
In well K5-9, 70 km east of Rutba, the Mulussa Formation (drilled from 421-579 m; thickness 158 m) comprises grey, well-bedded dolomite and dolomitic limestone with marl beds in the upper part. It overlies quartzitic sandstone (assumed to be the Ga'ara Formation) and is overlain by the anhydrite-bearing Zor Hauran Formation. The upper contact is taken at the base of the first gypsum layer.

Fossils are generally rare within the Mulussa Formation, particularly in the upper part. However, several fossiliferous horizons were found in the formation including the 'i' marker. Another fossil-rich horizon is a green-yellow calcareous mudstone bed (about 7 m above the base of the formation) which was found in the Duekhla valley of the Ga'ara depression. Silty dolomitic limestone and calcareous siltstone containing fossils are also recorded at Bir Al Agharri, about 9-12 m above the base of the formation. Palaeontological evaluation was carried out during the geological surveys of the region.

The locality at Bir Al-Agharri was selected as the new "paratype" of the Mulussa Formation. This section is about 55 m thick and contains: *Septihoersia joannisaustriae* (KIipstein), *Septihoernesia sp., Bakevellia (Neobakevellia sp.), Filopecten filosus* (Hauer). These assemblages locally form coquinas. Fossils tracks, belonging mostly to the genus *Rhizocorallium* Zencer and *Zoophycos? massalongo,* occur throughout the "paratype" section. Tracks belonging to the genus *Thalassinoides* (Ethenberg) and *Planolites* Nicholson were found in the basal layer (7 m above

base) with *Schafhaeutlina cf. mellingi* Hauer. Only one foraminiferal horizon was observed at the "paratype" locality. It contains:
Trocholina biconvexa Oberhauser, *"Trocholina" procera* (Liebus), *Duostomina cf alta* Kristan-Tollman, *Involutina (Arenovidalina) pragsoides* Oberhauser, *Involutina sinuosa* (Weynschenk), *Involutina sp., Glomospirella sp. and Nodosinella? sp.*

Grey sandy marls, argillaceous doloarenite, dolomitic marl and dolomite alternate in the higher part of the section. The first stromatolite (loferite) horizon, about 25 cm thick. occurs approximately 18 m above the base. Foraminifera occur in this layer and include *Glomospirella friedli* Kfistan and Tollman, *Agathammina sp., Endothyra sp.* Fragments of pelecypods, gastropods and crinoids, trace fossils, *Entolium sp.* and *Lyriomorphia?* occur in doloarenite beds. Some horizons of "loferites?" contain strongly recrystallised algae *(Dasycladaceae)* with crinoids in the uppermost part. A horizon with *"Nodosaria" sp. nov., Lenticulina sp.* and fragments of molluscs was found in the overlying massive dolomite.
The stratigraphic classification of the Mulussa Formation is based on molluscs (pelecypods) and foraminifera. The oldest mollusc assemblage consists of: *Septihoemesia joanni-saustriae, Filopecten filosus* (Jul- Tuval), *Homomya bittneri* (Jul), *Entolium cf hallense* (Cordevol-Jul). *Schafhaeutlina cf mellingi* which indicates a Carnian age. Foraminifera identified in the lower part of the Mulussa Formation: *Trocholina biconvexa, "Trocholina" procera. Involutina pragsoides, Involutina sinuosa sinuosa, Duostomina cf alta.* also indicate a Carnian age. The younger part of the Mulussa Formation is characterized by the occurrence of very rare *Semiinvoluta clari* and *Glomospirella friedli* of Norian age. The Mulussa Formation is thus of Carnian-Norian age.

The local occurrence of the genus *Involutina, (Involutina communis)* indicates lagoonal conditions. The Mulussa Formation was deposited in tropical to subtropical shallow water and supra-littoral environments. It is characterised by dolomicrosparite with dolomitised pelmicrite or pelsparite and laminated dolomite and lime mudstone suggesting a supratidal to intertidal and lagoonal environment. The upper part of the formation is gypsiferous indicating a sabkha depositional environment.

Towards the N and E, the formation passes laterally into the anhydrite-bearing Kurra Chine Formation. To the west it passes into the carbonates of the Lower Dolaa Group of Syria (Dubertret, 1966) or the Mulussa (units C, D and E only; Sharland et al., 2001). The formation passes into the Abu Ruweis Formation or the Zarqa Group of Jordan which is dominated by sand and shale. The passage of the Mulussa Formation into the Minjur Formation of Saudi Arabia and Kuwait is not well defined; the latter formation may be younger. The only known occurrence of the Minjur Formation in Iraq is in well Diwan-l in SSW Iraq where it was previously included in the Butmah Formation. The upper part of the Minjur Formation in Kuwait is considered to be of Liassic age (Douban and Al Sahlan, 2001).

9.2.1.2 Zor Hauran Formation

The Zor Hauran Formation was first defined by Dunnington in 1951 (Bellen et al., 1959) as 45 m of predominantly yellow and grey gypsiferous marl, interbedded with yellow green marly limestone, oolitic limestone and dolomitised limestone and tentatively assigned a Rhaetian age.

Later mapping of the Rutba region showed that the lower part of the formation comprises interbedded yellow green mudstone, gypsiferous marl and white laminated dolomite. Yellow and green oolitic and pseudo-oolitic limestones occur in several 0.5-2 m thick beds. The upper part of the formation starts with yellowish silty marl with beds of laminated, bioturbated calcareous, fine-grained sandstone, usually coarser upwards. This interval is followed by 3 m of yellowish, slightly bioturbated silty marl, 2 m of intraformational breccia and 3 m of greenish silicified marl. In well K5-9, the formation (309-421 m) is 112 m thick. The lower part comprises cycles of fine clastics, argillaceous dolomite and dolomite, ending with evaporites. The upper part consists of gypsiferous dolomite and dolomite with a 3 m gypsum bed at the top. The upper part of the Zor Hauran in K5-9 has no outcrop equivalent; it is truncated westwards below the Ubaid Formation.

The lower boundary with the underlying Mulussa Formation is gradation.al and placed at the base of the first continuous bed of yellowish or yellow-green marl. Sometimes the contact is marked by an emergent surface where a siltstone layer usually occurs at the base of the formation. The upper contact with the Ubaid Formation is disconformable. In many outcrops, the Ubaid Formation overlies the Zor Hauran with fluvial basal clastics (near Rutba town) or is associated with reddened underlying carbonates.

'Fossils are poorly preserved due to recrystallisation. They include: *Lingula, Myophoria, Glomospira, Trocholina* (Bellen et al., 1959). Subsequent mapping showed that the upper part of the sequence, with characteristic partly oolitic limestones, contains molluscs and brachiopods. The youngest unit of the Zor Hauran Formation consists mostly of dolomitic siltstones with fossil worm tracks, the sandstones and pseudoolitic limestones contain algae, ostracods, microgastropods, echinoids and forams including *Trocholina sp., Involutina sp., Nodosaria sp., Glomospirella cf friedli* Kristan- Tollman, *Lingula sp., Myophoria sp., Gervillia praecursor* Quenstaedt. This faunal association is of Late Triassic age. Stratigraphically the most valuable species appears to be *Gervillia praecursor*, found at the type locality in layers of sandy marl and marls tone. *Glomospirella friedli* has a broader stratigraphic span (Norian-Rhaetian). The Zor Hauran is assigned a NorianRhaetian? age based on the occurrence of the genus *Gervillia* and on the stratigraphic relationships between the Mulussa and Ubaid formations.
The oolitic facies was probably deposited in a shelf lagoon. The presence of gypsum and desiccation cracks indicates an evaporitic supratidal environment.
Towards the N and NE the formation has been assumed to pass into the Baluti Formation (Bellen et al., 1959). However in well Tharthar-l, the Baluti Formation is not recognised, and this lateral facies change cannot be confirmed. The Zor Hauran Formation, (present on the uplifted Rutba Block) may be older than the Baluti, and may pass into the Kurra Chine Formation. The Zor Hauran Formation may also be equivalent to the marly and shaly unit of the "Mulussa-F" of SE Syria (Sharland et al., 2001). Towards the S the formation may pass laterally into continental-littoral clastics of parts of the Minjur Formation (Douban and Al Sahlan, 2001).

9.2.2 Carbonate-evaporite inner shelf and restricted lagoons

9.2.2.1 Kurra Chine Formation

The Kurra Chine Formation is the most widespread formation of the Late Triassic Sequence. It was defined by Wetzel in 1950 (Bellen, et al., 1959) from the Northern Thrust Zone of N Iraq where it is up to 850 m thick and comprises monotonous dark brown and black limestones, thin and thick-bedded, with occasional beds of thick bedded fetid dolomite with slump structures, and papery shales. Recrystalllisation breccias also occur occasionally. In the subsurface the maximum thickness of 1150 m is in well Jabal Kand-l; in other wells the thickness is 548 m (Atshan1), 1784 m (Mityaha-l), 1443 m (Khlesia-l), 1636 m (W Kifl-l) and 406 m (Diwan-l). It is also reached in well Rumaila-172.

In the High Folded and the Balambo- Tanjero zones of NE Iraq, the Kurra Chine Formation contains evaporites. In the Sirwan gorge near Halabja, gypsum beds occur (Bellen et al., 1959). Evaporites are also present in well sections of the Foothill Zone (Tharthar well, Hay and Algawi, 1958), including some salt layers in the middle part of the formation. The absence of evaporites from the type section may be due to surface dissolution with formation of recrystallisation breccias. Basal sandstone beds occur in well Awasil-5 (Crank and Ritchie, 1955). Clastic beds also occur in the southern Mesopotamian Zone. The sandstones occur along the eastern shores of the Rutba Uplift.

The lower contact of the formation is marked by an erosional break indicated by haematitization, silicification and leaching of the underlying Geli Khana Formation. In some areas (Tharthar and Awasil), a thick basal sandstone occurs. The contact with the overlying Baluti Formation is conformable and taken at the base of the first green shale bed of the Baluti Shale Formation. However in some areas along the margin of the Stable Shelf the Kurra Chine Formation is unconformably overlain by the Liassic Butmah Formation (well Thartar-l).

The fauna from surface sections and wells (Bellen et al. 1959) suggest a Late Triassic age (Rhaetian) for the upper part of the formation.

The depositional environment of the Kurra Chine Formation is characterized by lagoonal, sometimes euxinic, conditions in the Foothill and Mesopotamian zones. Along the western margins of the Mesopotamian Zone (Tharthar and Awasil), terrigenous clastics were derived from the Rutba Uplift to the W-Sw.

The Kurra Chine Formation is correlatable with the Mulussa and probably the Zor Hauran formations of W Iraq and the Mulussa (units C, D and E) of SE Syria. Age correlatives of the formation might also be the Upper Khaneh Kat Formation of Iran (Furst, 1970) and the lower part of Minjur Formation of Saudi Arabia (Powers et al., 1966) and Kuwait (Douban and Al Sahlan, 200l).The Minjur Formation is the near-shore equivalent of the Kurra Chine Formation.

9.2.2.2 Baluti Formation

The Baluti Shale of supposed Rhaetic age is a poorly defined stratigraphic unit. It was introduced by Wetzel in 1950 and amended by Morton in 1951 (Bellen et al., 1959). It comprises 60 m of grey green and grey shales with decimetre beds of thin bedded dolomitic, silicified, and oolitic limestones, and recrystallisation breccias. The lithology of the formation is similar in the Balambo-Tanjero and High Folded zones. To the SE in NE Iraq it outcrops in the Ranya area (Bolton, 1958). In the Sirwan gorge two shale units resembling the Baluti Formation outcrop; it is 'unclear which shale unit belongs to the Baluti Formation. In other areas of Iraq a unit of limestone, anhydrite, and subordinate shale, is usually referred to as the Baluti Shale Formation (Bellen et al., 1959; Ditmar and the Iraqi-Soviet Team, 1971) but lacks the high proportion of shale seen in the outcrops. Its status as a separate formation is thus questionable.

The thickness of the formation is around 35-60 m at outcrop. It was identified in wells: Jabal Kand-l (61 m), Khlesia-l (22 m), Atshan-l (40 m) and W Kifl-l (46 m). In well Diwan-l, the unit was not identified, being either included within the Kurra Chine Formation or the Butmah Formation. The formation thins towards the west.
Both lower and upper contacts of the formation are reported to be conformable (Bellen et al., 1959) except in well Tharthar-l. However in view of the apparent stratigraphic break between the Triassic and Jurassic in Saudi Arabia and SW Iran, the upper contact of the formation in western Iraq needs further study.

Fossils are rare and not age diagnostic (Bellen et al. 1959). Therefore, the age of the formation is arbitrary and determined from its stratigraphic position between the proved Upper Triassic Kurra Chine Formation and the overlying Sarki Formation (Liassic). The formation was deposited in lagoonal/evaporitic and estuarine environments.

Equivalent formations in W Iraq may be eroded. Buday (1980) assumed that the Zor Hauran Formation is tentatively correlatable with the Baluti Formation. In Syria the formation may be equivalent to the "Mulussa-F" unit of Palmyride and SE Syria.

9.3 Liassic Sequence

The Liassic Sequence outcrops in numerous anticlines of the High Folded Zone of N and NE Iraq and in the Rutba subzone in W Iraq. It is penetrated by many wells within the Rutba-Jezira, Salman and Mesopotamian zones. The formations included in this sequence are, the clastic-carbonate inner shelf Ubaid, Hussainiyat and Amij formations in W Iraq, the carbonate-evaporite inner shelf Butmah, Adaiyah, Alan and Mus formations in well sections of central Iraq and the Foothill Zone, and the restricted lagoonal Sarki and Sehkaniyan formations in the High Folded and Balambo-Tanjero zones of N and NE Iraq.

After the Rhaetic emergence, a series of cyclic transgressive-regressive pulses occurred in the Liassic which are well developed along the edge of (and above) the Rutba Uplift. The Liassic sequence was deposited in a lagoonal evaporitic environment except in N and NE Iraq where evaporites are subordinate. The generalized palaeogeography of the Liassic is shown in Fig. 9-9.

The sequence in W Iraq contains three cycles; each cycle comprises fluvial to fluviomarine clastics overlain by inner shelf to coastal carbonates. Towards Mesopotamia the cyclicity is defined by alternating inner shelf carbonate and sabkha facies.

Fig. 9-9: Palaeogeography of Late Liassic time

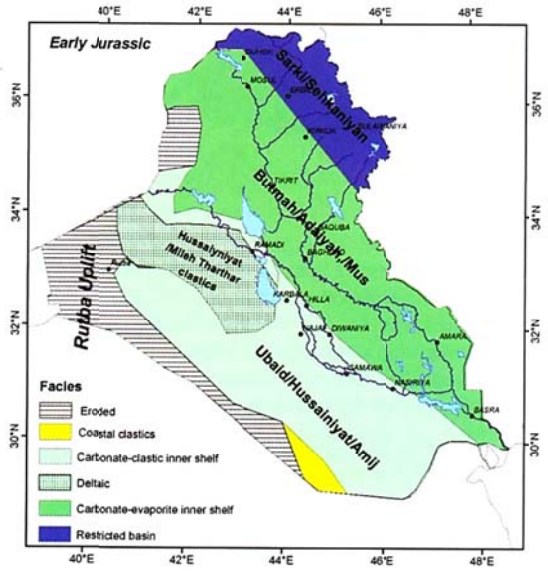
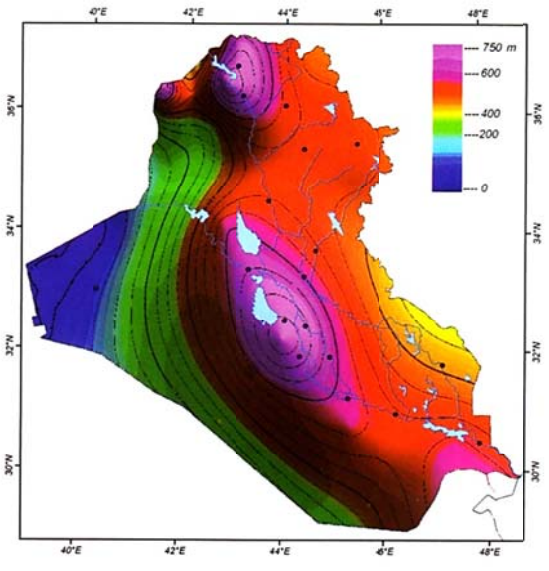


Fig. 9-10: Thickness of the Liassic Sequence



The Liassic sequence is thickest in the Unstable Shelf area and in the Mesopotamian Zone (Fig. 9-10) (up to 800 m thick). In W Iraq, the sequence is up to 200 m thick. The depocentre of the basin follows the boundary between Salman Zone and Mesopotamian Zone, trending N-S in N and Central Iraq and NW-SE towards the Iraq-Kuwait border.

9.3.1 The Clastic-carbonate inner shelf

9.3.1.1 Ubaid Formation

The Ubaid Formation was defined by Dunnington (in Bellen et al., 1959) in the Wadi Hauran area, NE of Rutba in W Iraq, as a 75 m thick stratigraphic unit comprising 37 m of pseudo-oolitic dolomitised limestone overlain by 38 m of similar limestones with abundant chert nodules. The age of the formation was assumed to be Liassic on the basis of its stratigraphic position between the underlying Upper Triassic Zor Hauran (assumed to be of Late Triassic age) and the overlying Muhaiwir formations (assumed to be of Middle Jurassic age). The Ubaid Formation outcrops in a SW-NE trending belt extending from 10 km E of Rutba town to Wadi Hauran (see the geological map in Chapters 1 and 5) in the NE.

The lower contact with the underlying Zor Hauran Formation is variable. A reddened carbonate layer usually exists at the top of the underlying formation and in Wadi Hauran the contact is marked by steep narrow channels filled with limestone conglomerates. Near Rutba laterally extensive fluvial sandstone with flaser structures occurs above the contact. The upper contact with the newly introduced Hussainiyat Formation is a disconformity. The uppermost part of the Ubaid Formation is highly karstified, with dolines ranging in diameter from a few metres to tens of metres and depths reaching 50 m. In addition, the top layer of the formation is always ferruginous. The karsts are often filled in with laterite, bauxite and clastics. The laterite formation may be the product of this hiatus or of subsequent exposure during the Cretaceous (see Chapter 20).

The Ubaid Formation was later described from Wadi Hauran (Jassim et al. 1984) as a 95 m thick section consisting, from the base upwards, of the following units: 1) 35 m of sandstone, sometimes pebbly, and red claystone with ironstone beds in the upper part; these clastics thin towards the SE as noted in wells *KS-9* where the Ubaid Formation overlies the Zor Hauran Formation with a thin basal bed of green silty marlstone. 2) 40 m of dolomite and recrystallised dolomitic limestone, yellowish to light grey with thick and thin bedded silicified horizons and chert nodules; with yellowish marly limestone in the upper part. 3) 20 m of gypsiferous marl and recrystallised shelly limestone often stained purple to red at the top. In water well *KS-9* 70 km E of Rutba, the formation was drilled from *184* to 310 m and is 126 m thick.
The most abundant fossils in thin sections are recrystallised ostracod shells. The foraminiferal genus *Involutina* (most probably *Involutina cf communis)* and fragments of unidentified micro gastropods and pelecypods also occur. The stratigraphically important brachiopods *Spiriferina cf. muensteri* Davidson and *Spiriferina walcotti* (Sowerby) indicate a Sinemurian to Late Pliensbachian-Dornerian age (Jassim et al., 1984). Ctyroky and Karim (1981; Jassim et al., 1984)) recorded poorly preserved assemblages of *Neomegaladon? sp., Grammatodon? sp., Mytilus? ssp., Modiolus? sp. and Cardita? sp.* which they assumed to be of possible Late Triassic age.

The Ubaid formation thins out both depositionally and by erosional truncation in the Rutba area. To the west of Rutba the formation is totally truncated by the Cenomanian Rutbah Formation. Across the N-S Rutba uplift in NE Jordan a similar unit is recorded in boreholes W of the Risha field, belonging to the Azab Group. According to publications of the Natural Resources Authority of Jordan the Liassic Sequence is represented by two formations: the Hihi Formation (latest Hettangian-early Sinemurian) and part of the Nimra Formation (Late Sinemurian-Toarcian). Based on the age of the Hihi Formation in Jordan, the age of the Ubaid Formation may also extend into the Late Hettangian. In SE Syria, the Liassic is missing.
Al Jumaily (1984; in Jassim et al., 1984) considered the basal clastics were deposited in a fluvial depositional environment. The carbonates were deposited in shallow hypersaline and supratidal ponds and subtidal lagoons (Skocek and Hussain, 1980). The succession in well K5-9 represents a transgressive-regressive cycle, the regressive supratidal part of the sequence is missing in the outcrop area NW of this well (probably due to truncation). The probable equivalent unit in the Unstable Shelf region is the lower part of the Butmah Formation.

9.3.1.2 Hussainiyat Formation

The Hussainiyat Formation was introduced by Al Mubarek et al, in 1981 (Jassim et al., 1984) for a sequence of clastics and carbonates that overlie the Ubaid Formation. Dunnington (in Bellen et al., 1959) probably included this unit in the Ubaid Formation. It outcrops in a NE-SW trending belt between Wadi Hauran in the NE and Rutba in the SW. It has a lower clastic unit and an upper carbonate unit, both thinning towards the SW. The thickness near Wadi Hauran exceeds 120 m (confirmed by drilling). Near Rutba the formation is totally truncated by a regional unconformity beneath younger Jurassic and Cretaceous sequences. In well K5-9 the formation is 84 m thick (100-184 m depth) and contains 9 m of pebbly sandstone at the base.
The clastic part of the formation is missing near Rutba. It is 54 m thick near Wadi Hauran. It was penetrated in well K59 at 175 m depth and probably in another well near K160 settlement which suggests that it passes laterally into the Mileh Tharthar clastics (seen in well Tharthar-l) towards the Mesopotamian Zone. The lithology of the clastic units varies laterally (Jassim, 1981b).

The outcrop of the formation between Rutba and Wadi Hauran is dominated by stacked river channels. The SW part of the outcrop is dominated by highly ferruginous flood plain mudstones truncated by minor channels with basal lags of ironstone pebbles. The NE part is dominated by deltaic facies with common silicified tree trunks in Wadi Hauran. Sandstones of the formation also contain silicified plant stems, prints of leaves and layers of Turritellaceae coquinas. The dolomites contain fragments of pelecypods and gastropods and are highly bioturbated and in places silicified. The carbonate member comprises heavily bioturbated dolosparites with ghosts of pellets and intraclasts, dolosparites with ghosts of bioclasts (mainly pelecypods and gastropods) and micritic limestone with detrital quartz and lacking fossils. The carbonates occasionally contain algal structures and were probably deposited in a lagoonal to supratidal environment. The specific character of the Turritellaceae coquinas suggests a partly freshwater deltaic environment with supply of terrigenous organic material (tree trunks). The uppermost part of the formation was deposited in the supratidal zone. The flora of the Hussainiyat clastic member is characterized by the genus Cycas indicating a tropical climate.

The flora and fauna of the formation are not age diagnostic. However a Late Liassic (Pliensbachian-Toarcian) age is inferred for the formation based on its stratigraphic position between the Ubaid and Amij formations. The Hussaiyniat Formation may be equivalent to the upper part of Butmah Formation, i.e. the section with the Mileh Tharthar Clastics at the base and the carbonates of the Upper Butmah above.

9.3.1.3 Amij Formation

The Amij Formation was introduced in W Iraq by Jassim et al, (1984). The formation was probably previously included in the Muhaiwir Formation. The type section in Wadi Amij (50 km ENE of Rutba Town) is 42 m thick. The formation is totally truncated towards Rutba in the WSW. It comprises a lower clastic unit and an upper carbonate unit. The lower clastic unit consists of 20-30 m of cross-bedded and cross-laminated (herring-bone), ripple-marked (oscillation ripples) fine-grained quartzitic sandstone and siltstone with lamination produced by concentration of heavy minerals such as zircon and ilmenite. The sands are associated with red and green mudstone and occasional thin beds of gypsum. The upper carbonate unit is composed of white to yellowish argillaceous dolomite and dolomitic limestone. Laminated and domal algal stromatolites were also recorded. The formation is also penetrated in well K5-9 between 20 m and 100 m depths.

The Amij Formation unconformably overlies the Hussainiyat Formation; the contact is taken at the base of a red claystone bed. The upper contact is variable. In the type area of Wadi Amij, the formation is overlain by a sandstone bed at the base of the Muhaiwir Formation. However, near the Baghdad-Rutba motorway, the Amij Formation is overlain unconformably by channel sandstones of the Upper Jurassic Saggar Formation.

The lowest part of Amij Formation is rich in molluscs, mostly pelecypods and fragments of gastropods; coquinas occur in marl beds. Strongly recrystallised algae and a fine pulp of plant remnants also occur, in addition to *Tancredia? sp., Pleuromya sp., Plagiostoma sp., Mytilus? sp.* On the basis of this fauna and that found in the overlying Muhaiwir Formation, the age of Amij Formation is older than Bathonian. Ctyroky and Karim (1981; in Jassim et al., 1984)) reported *Grammatodon sp., Oxytoma sp., Pinna sp., Corulomya sp.* and stromatolites.

They considered that this fauna is similar to the fauna recorded in the upper part of the Butmah Formation in well Tharthar-l. They therefore considered the formation to be of Liassic age. However the faunal assemblages found in the Amij Formation do not occur in the Ubaid and Muhaiwir formations; a Bajocian age cannot be excluded for the Amij Formation.

The Amij Formation was deposited in a marginal marine, coastal lagoon and marsh environment. The upper part of the formation contains brackish water molluscs. The ripple marks, herring-bone structures and black sands suggest coastal environments. The presence of laminated algal stromatolites and domes suggest the upper part of the formation was deposited in a supratidal environment.

The probable age-equivalent of the formation in NE Jordan is part of the Nimra Formation. Liassic formations are not recorded from SE Syria over the Rutba Uplift. Both the Mus Limestone and the overlying Alan Anhydrite in central Iraq may be the lateral equivalents of the Amij Formation.

9.3.2 Carbonate-evaporite inner shelf

9.3.2.1 Butmah Formation

The Butmah Formation does not outcrop but is penetrated in wells in the Foothill, Mesopotamian and Salman zones. It was first described by Dunnington in 1953 (Bellen et at, 1959) from well Butmah-2 in the Foothill Zone of N Iraq as a 500 m carbonate unit. Unfortunately, the type section was subsequently found to be strongly faulted. Further drilling elsewhere (Tharthar-1, Makhul-2 and Anah-2) indicates several thick mudstone beds are present in the formation. The thickness of the formation in wells is as follows: Butmah-2 (500 m), Jabal Kand-1 (481 m), Mityaha-l (285), Atshan-l (570), Ibrahim-1 (448 m), Khlesia-1 (162 m), Tharthar-l (494 m), W Kifl (460 m), Diwan-1 (295 m) and Rumaila-l72 (337 m). It was also reached in wells Tel Abtakh, Tel Hajar, Sasan2A, Anah-2 and Sufayah-2A. The formation is thickest along the W boundary of the Mesopotamian Zone in S Iraq and in the Foothill Zone of N Iraq.

The Butmah Formation is lithologically heterogeneous. The upper 200 m in the type section consists of oolitic, pseudooolitic and detrital limestone with beds of argillaceous limestone, shale and anhydrite. The middle part of the formation (180 m) is oolitic and pseudo-oolitic, argillaceous and dolomitic with sandstone and shale beds. The lower part (120 m) is composed of limestone with bedded anhydrite. The lithofacies and faunal assemblages indicate the Butmah Formation was deposited in a shallow water lagoonal and sabkha environment.

The name Butmah Formation was used in Syria but subsequently the name was unfortunately applied to rocks dated as Middle Triassic by Segal and Bach Imam (1975) and subsequent authors (Litak et at, 1996). Earlier workers Wolfart (1967) described the Liassic from the Jezira area of Syria (adjacent to NW Iraq) as 340 m of alternating dolomite, limestone and anhydrite (upper part of Dolaa Group), the lower parts of which are correlatable with the Butmah Formation.

In the Hezan area near Hazro in SE Turkey, the Liassic comprises 70 m of red conglomerate assumed to be of alluvial fan origin, followed by 150 m of limestone with *Glomospira* and occasional stromatolites belonging to the Liassic Nenyas Formation. The conglomerates were probably derived from the nearby Mardin uplift. In SW Iran (Setudahnia, 1978) the Neyriz Formation, composed of silty shale, limestone and dolomite deposited in a shallow marine and tidal flat environment, correlates with the Butmah Formation.

The Butmah Formation in S Iraq interfingers with sands assigned to the Minjur Formation and is also correlatable with the Marrat Formation of Saudi Arabia.

Beds of variegated and mottled green, red and purple shale associated with siltstone and ferruginous sandstones occur it the middle and upper parts of the Butmah Formation in well Tharthar-I (2409-2561 m). Dunnington (in Bellen et at, 1959) recommended the introduction of a separate name for these clastics (Mileh Tharthar Clastics). In Anah-2 the formation contains clastics, prominent in the depth range 3110-3476 m. In well Khlesia-l, a 15 m thick mudstone bed occurs below the Upper Cretaceous unconformity and might be correlated with the Mileh Tharthar Clastics. In well Makhul-2 the Butmah Formation is dominated by shale and anhydrite. Similar beds were also found in well Samawa-l (Halliwell, 1959).

The lower, highly ferruginous clastic unit of the Hussainiyat Formation has been traced for 100-140 km to the east of the outcrop; other Jurassic clastics of W Iraq pinch out a short distance from their outcrop area. This suggests that the basal clastics of the Hussainiyat Formation may be equivalent to the Mileh Tharthar Clastics. Therefore, the upper part of the Butmah Formation might be equivalent to the Hussainiyat Formation and the lower part with the Ubaid Formation.

9.3.2.2 Adaiyah Formation

The Adaiyah Formation is present in the Mesopotamian and Foothill zones and the Anah Graben. Its type section was first described by Dunnington in 1953 (Bellen et al., 1959) from well Adaiyah-I from the Foothill Zone of N Iraq (W of Mosu1) as 90 m of bedded anhydrites with subordinate beds of brownish limestones and of black calcareous shales and greenish marls, both with anhydrite nodules. In some wells, such as Makhul-2, salt beds occur (Ditmar and the Iraqi-Soviet Team, 1971; Thompson and Hart, 1957). The thickness in other wells is as follows:

Sufaya-2A (128 m), Jabal Kand (106 m), Mityaha-l (29 m), Tharthar-1 (29 m), Atshan-1 (72 m), Alan-l (52 m), Butmah-2 (52 m), Ibrahim-l (91 m), Tel Abtakh (108), W Kifl-1 (128) and Diwan-1 (104 m). The formation thus increases in thickness from Wand NW Iraq towards the Mesopotamian Zone and the Foothill Zone. The formation is absent in NW Iraq (well Khlesia-1) due to truncation below the Lower Senonian unconformity. Both lower and upper contacts of the formation are elsewhere gradational and conformable. Fossils are rare (Bellen et al., 1959) but support a Liassic (probably Late Liassic) age.

Throughout the High Folded, Imbricated and Northern Thrust Zones of the Unstable Shelf the formation is replaced by the lower part of the Sehkaniyan Formation. The boundary between these two formations may lie on a buried uplift along the Dohuk-Chemchemal line (Ditmar and the Iraqi-Soviet Team, 1971).

Age equivalent units are the argillaceous-anhydritic parts of the Upper Dolaa Group of Syria, part of the Marrat Formation of Saudi Arabia, and the upper parts of the Neyriz Formation of the Iranian Zagros. In W Iraq, the probable equivalent is the upper part of Hussainiyat Formation. The formation was deposited in sabkha environment in an inner shelf basin.

9.3.2.3 Mus Formation

The Mus (Limestone) Formation was described by Dunnington in 1953 (Bellen et al., 1959) in well Butmah-2 in the Foothill Zone of N Iraq. It is a 50 m thick limestone consisting, in the upper part of locally recrystallised, occasionally dolomitised, pseudo-oolitic limestone, with some organic detritus, and beds of argillaceous limestone. The lower part of the formation comprises recrystallised and dolomitised limestone, interbedded with hard argillaceous limestone and subordinate calcareous shale and rare anhydrite beds. The maximum recorded thickness is 92 m in well Diwan-l in the Salman Zone in SW Iraq. Elsewhere the formation varies in thickness from 20 m (Sasan-l) to 87 m (Jabal Kand-l). The formation is missing in NW Iraq (well Khlesia-l) due to truncation beneath the Lower Senonian unconformity.

The formation has conformable and gradational contacts with the underlying Adaiyah and overlying Alan Formations. However Bellen et al, (1959) noted a conglomerate layer at the base of the Alan Formation.

Fossils are relatively abundant, especially in the upper part of the formation, but the assemblage listed by Bellen et al, (1959) is insufficient for precise age determination. The formation has been correlated, based on the similarity of its microfacies and fossil content, with the Upper Liassic «*Lithiotis* Limestone» of the Sehkaniyan Formation of N and NE Iraq. Therefore a Late Liassic (probably Early Toarcian) age is assigned to the Mus Formation *(Lithiotis* appears to range from Pliensbachian-Toarcian). The formation was deposited in a transgressive marine environment of normal salinity (Bellen et al., 1959).

The formation has a similar distribution to the underlying Adaiyah Anhydrite Formation in the Foothill and Mesopotamian zones. Based on data from well Anah-2, some equivalents may occur in the Stable Shelf. The surface equivalent of the Mus Formation in W Iraq may be the lower part of the Amij Formation in the Rutba area (Fig. 9-1).

Outside Iraq the formation is equivalent to the lower part of Marrat Formation (Bellen et al., 1959). It may also be correlated with the limestone members of the Upper Dolaa Group that lie below *Haurania-Trocholina* bearing limestones (Dubertret, 1966). In Iran, some limestone members of the Surmeh Formation (James and Wynd, 1965) might be tentatively correlated with the Mus. However, Furst (1970) argued that the Lower Surmeh is Doggerian in age.

9.3.2.4 Alan Formation

The Alan Formation is the uppermost part of the Liassic Sequence in the western parts of the Unstable Shelf and on the Stable Shelf in Iraq. The formation was first described by Dunnington (1953a) from well Alan-l north of Mosul as 87 m of bedded anhydrites with subordinate pseudo-oolitic limestones. Lateral changes, i.e. the frequent wedging out by the anhydrites are typical for the formation and greatly affect its thickness. In well Makhul-2 halite is present. The maximum thickness is reached in well Makhul-2 (199 m). Thicknesses in other wells are: Diwan-l (76 m), Khidr Al Maa (102 m), Tel Abtakh-l (50 m), Sasan-2A (93 m), Tel Hajar-I (26 m), Jabal Kand-l (73 m), Alan-I (87 m), Butmah-2 (138 m), Najmah-29 (70 m), Atdhan-l (71 m), Ibrahim-I (100 m), Samawa-l (68 m), W Kifl-l (156 m), Anah-2 (134 m) and Rumaila-l72 (135 m). The equivalent formation on the surface in W Iraq may be the upper part of the Amij Formation (Fig. 9-1). The Alan Formation is best developed in the Foothill and Mesopotamian zones and parts of the Salman Zone.

Fossils are absent. Due to its position between the Middle Jurassic Sargelu Formation and the Liassic Mus Formation, a Liassic age has been presumed (Bellen et al., 1959). It has conformable and gradational contacts with both underlying and overlying formations. The formation was deposited in a basin-centred sabkha environment.

9.3.3 Restricted lagoons

9.3.3.1 Sarki Formation

The Sarki Formation was first described by Dunnington in 1952 (Bellen et al., 1959) from the Chia Gara range of N Iraq as a 300 m carbonate unit. It also outcrops in the Balambo- Tanjero Zone. The formation consists of a lower unit (120 m thick) comprising thin bedded, fine-grained, cherty and dolomitic limestone, alternating with cherty shale, occasional dark sugary dolomites, and bands of shell breccias, oolitic limestones, micro conglomerates and recrystallisation breccias. A dark brown massive-bedded dolomite marks the base of the unit. The upper unit (180 m thick) consists almost entirely of dolomites. They are mostly soft and highly cavernous, alternating with soft, friable cherty dolomites and some shale and marls. Boxwork structures and recrystallisation breccias occur throughout the formation and are assumed to be a result of dissolution of anhydrites.

The formation is 500 m thick in the Northern Thrust Zone (Hamza and Issac 1971) and 260 m thick in the Sirwan valley in NE Iraq (Bolton, 1958c) and comprises contorted dolomites with residual solution rubble and rare undissolved gypsum lenticles (Bellen et al., 1959). Near Ranya Town in NE Iraq the formation is predominantly dolomite, while near Barsarin village (Bolton, 1958d) it comprises thin bedded and partly bituminous limestone and marl. At Shiranish Islam in N Iraq, the middle part of the formation is shale-dominated (Bellen et al., 1959). In the area S of Sulaimaniya, the formation consists predominantly of thin bedded dark algal dolomite.

The fauna of the lower division, is dominated by the cyrenid *cf. Eomiodon indicus, Spongiostroma,* and foraminifera such as *Trocholina? sp., Glomospira sp.* The lower division is often referred to as the *"Cyrenia* Beds". **In** the upper division rare foraminifera such as *Archaediscus* and *Problematina,* minute gastropods, fish and algal debris occur (Bellen et al., 1959). This fauna is not age diagnostic. An Early Liassic age has been inferred based on the stratigraphic position of the formation between the well defined underlying Upper Triassic Kurra Chine Formation and the well-defined overlying Mid Jurassic beds of the Sargelu Formation.

The upper and lower contacts of the formation are conformable and gradational. The lower contact is at the top of the shales of the Baluti Formation. The upper boundary is often obscured by dolomitisation.

The Sarki formation was deposited in a restricted lagoonal environment between the Qamchuqa High in the SW and an elevated zone in the NE. The boundary between the Sarki Formation and the more evaporitic facies of the Butmah Formation may be located along the High Folded and Foothill zones (Qamchuqa palaeoridge) with the axis between Dohuk and Taq Taq (Ditmar and the Iraqi-Soviet Team, 1971).

The limestone-dolomite and anhydrite bearing units of the Upper Dolaa group in Central Syria (Dubertret, 1966) and the Ubaid Formation in W Iraq are age equivalent to the Sarki Formation. In SW Iran, parts of the Liassic Neyriz Formation (James and Wynd, 1965; Furst, 1970) are equivalent to the Sarki Formation.

9.3.3.2 Sehkaniyan Formation

The Sehkaniyan Formation was first described by Wetzel and Morton in 1950 (Hellen et al., 1959) from the Surdash anticline of the High Folded Zone of NE Iraq as a 180 m thick carbonate unit divided into three units. The lower unit (85 m) comprises dark saccharoidal dolomites and dolomitic limestones with some solution breccias. The middle unit (44 m) referred to as the *"Lithiotis* Limestone", consists of organic and pelletal fossiliferous limestone, often dolomitised with some chert bands that become thicker near the top. The upper unit (51 m) comprises dark, fetid, sachharoidal dolomites and dolomitic limestones, locally with chert.

In the Northern Thrust Zone the formation consists of dark, fetid dolomites comprising saccharoidal dolomite, bedded very bituminous (locally cherty) dolomite, and fossiliferous dolomitic limestones with *Posidonia,* ammonites and fish remains, overlain by thick bedded grey dolomitic limestone. It is likely that the section includes part of the Sargelu Formation. The boundary with the Sargelu Formation requires further study.

In the Avroman range within the Qulqula-Khwakurk Zone, a sequence of light and dark grey thin bedded arenaceous limestone and varicoloured clayey organodetrital limestone was correlated with Sehkaniyan Formation and yielded fossils characterized by a typical assemblage of the *"Lithiotis* limestone". In the Ranya area, where the formation is composed of dark dolomites only, the thickness reaches 300 m, (Bolton, 1958d). In the Qalat Dizeh area the thickness is 100 m and in the Sirwan area the formation reaches its maximum thickness of 360 m (Bolton, 1958c).
Fossils found in the middle *"Lithiotis* limestone" unit are: *Lithiotis sp., Spiriferina sp., cf., ampla, Spiriferina ssp., Zeilleria sp., Haurania sp., Lituola sp., Glomospira sp., Nubecularia sp., Boueina hochstetteri,* var. *liassica,* undeterminable gastropods, and echinoid and foraminiferal debris. In the Halabja area further studies confirmed the presence of thick-shelled filaments, fragments of gastropods, pelecypods and mainly brachiopods *(Spiriferina, Zelleria and Rhynchonella).* Based on this fauna and by correlation with Early Jurassic *Lithiotis* bearing units in Iran described by Kent et al, (1951), and on the Middle Liassic occurrence of the *Boueina hochstetteri* in Morocco, a Liassic age has been assigned to the formation (Bellen et al., 1959). *Lithiotis* appears to range from Pliensbachian-Toarcian.

Chapter 10

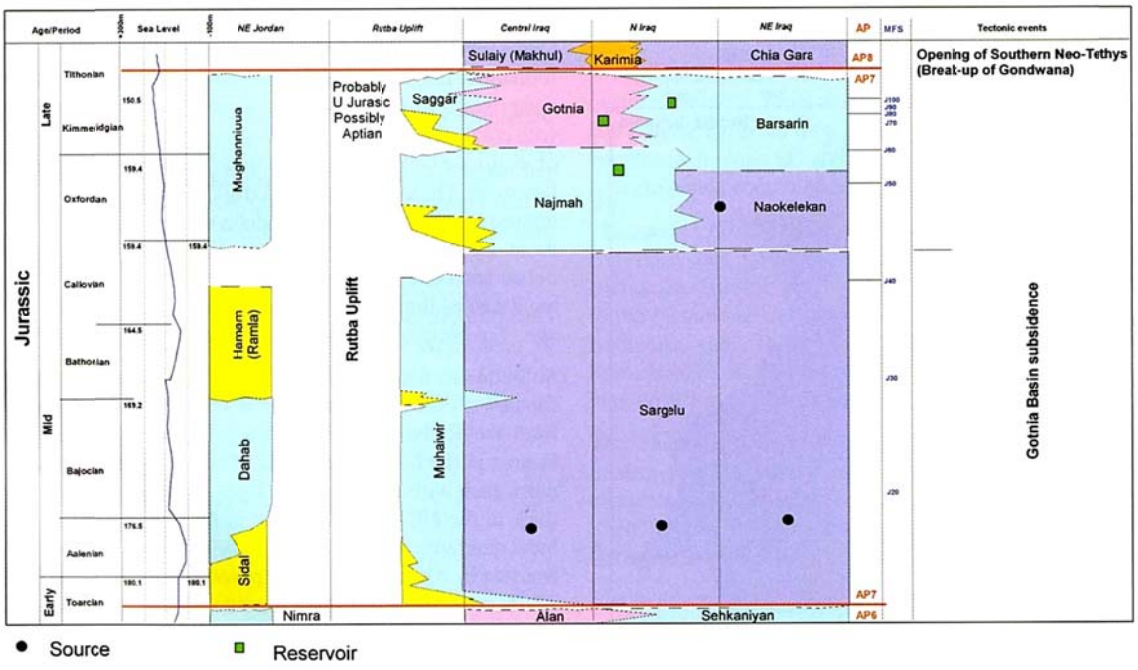
Late Toarcian-Early Tithonian (Mid-Late Jurassic) Megasequence AP7

by

Saad Z. Jassim and Tibor Buday

The Mid-Late Jurassic Megasequence was deposited during a period of isolation of the main intra-shelf basin of Mesopotamia from the Neo- Tethyan Ocean probably due to renewed rifting along the NE margin of the Arabian Plate (Chapter 3). The basin was bounded to the W by the N-S trending Rutba Uplift of W Iraq. Deposition within the basin occurred in a restricted, relatively deep water, environment during the Mid Jurassic. The basin became evaporitic during Late Kimmeridgian-Early Tithonian time. The base of the megasequence starts with the neritic Muhaiwir Formation in the Rutba Subzone and the basinal Sargelu Formation elsewhere in Iraq. The upper evaporitic part of the megasequence comprises the evaporites of the Gotnia Formation in Sand N Iraq, the Saggar Formation in W Iraq and the Barsarin Formation in NE Iraq (Fig. 10-1). The megasequence isopach (Fig 10-2) shows two main depocentres associated with the Mesopotamian and Salman zones in S Iraq and the area S of Mosul in N Iraq. These depocentres are separated by an area of reduced thickness coinciding with a transversal block lying between the Anah Qalat Dizeh Fault in the N and the Sirwan Fault in the S (i.e. the subsequent Kirkuk Embayment). The megasequence comprises two second order sequences: the Late Toarcian Callovian and Late Jurassic sequences.

Fig. 10-1: Stratigraphic correlation of Megasequence AP7



10.1 The Mid Jurassic (Late Toarcian-Callovian) Sequence

Late Toarcian time was marked by a transgression that partially covered the evaporitic platform sabkhas basins of the Liassic, creating a more uniform basin with relatively deep water and euxinic sedimentation. In NE Iraq the rim of this euxinic basin was probably separated from the Neo-

Tethys (Chapter 3) by a rifted area and an outer ridge on which shallow water carbonates were deposited. This ridge formed the NE boundary of the Arabian Plate. On the Stable Shelf, a shallow carbonate shelf covered the whole of the Rutba Subzone apart from the Rutba Uplift whose SE flank formed the shoreline of the basin. Along this shoreline coastal clastics and fringing shoals were deposited. The Jezira Subzone also emerged as the continuation of the Rutba Uplift towards the N. (Fig. 10-3). A submerged NW-SE trending Palaeo-high may have existed between N Iraq and the Stable Shelf. It was probably located between Mosul, Tikrit and Amara and is overlain by a thin development of the Mid Jurassic Sequence.

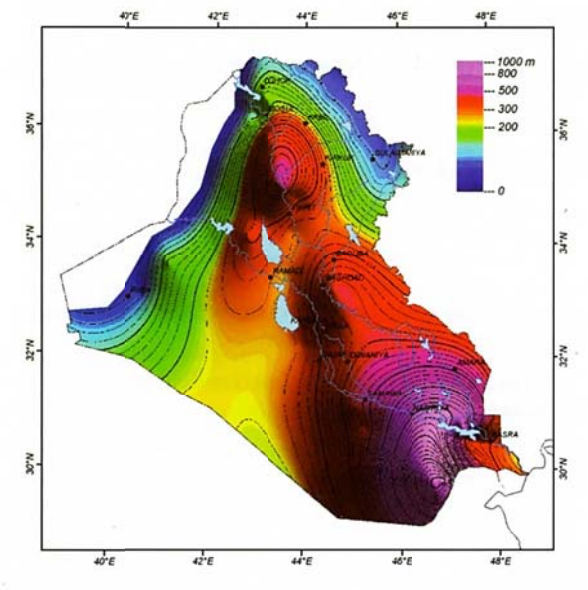


Fig. 10-2: Thickness of the Late Toarcian-Early Tithonian Megasequence AP7

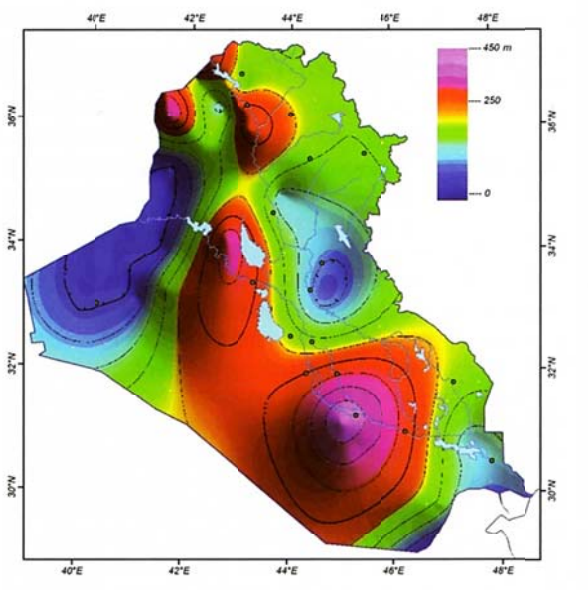
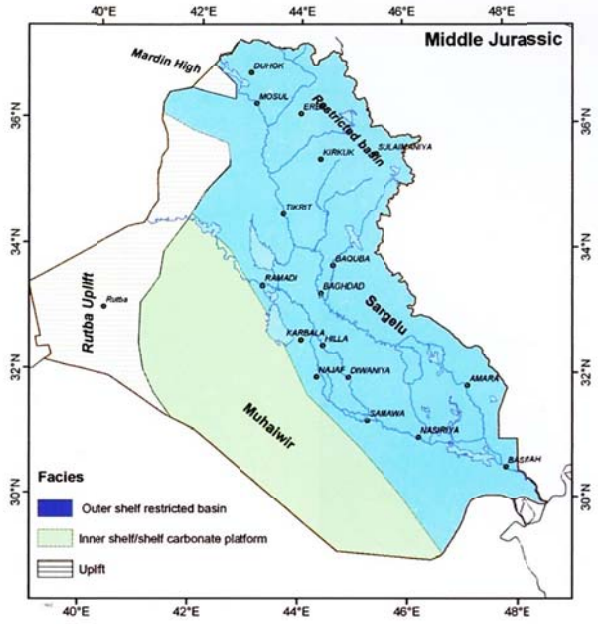


Fig. 10-4: Thickness of the Mid Jurassic Sequence

The sequence (Fig. 10-4) is thickest on the Salman and Mesopotamian zones of S Iraq and in isolated areas of the Foothill Zone of N Iraq. Three wells within the Mesopotamian Zone of S Iraq indicate the formation thins to the E. The sequence is absent in the W part of the Rutba Jezira Zone due to both depositional thinning and erosion below an unconformity at the base of the Late Jurassic Sequence. Thickness variations along the Mesopotamian and Foothill zones in E Iraq may have been influenced by transversal faults (Fig. 10-4).

The Mid Jurassic Sequence is represented by the sandy calcareous shallow water Muhaiwir Formation in the Rutba Subzone of W Iraq and the deeper water euxinic argillaceous-calcareous Sargelu Formation elsewhere. The boundary between these two facies lies on the W side of the Salman Zone.

Fig. 10-3: Mid Jurassic Palaeogeography



10.1.1 Inner shelf clastic-carbonate platform (Muhaiwir Formation)

The Muhaiwir Formation was first described by Wetzel in 1951 (Bellen et al., 1959) from four sections along Wadi Haman and Wadi Muhaiwir in W Iraq. It was revised by Dunnington in 1954. Dunnington divided the 48 m thick formation into two parts: The lower part (13 m thick) comprises 9 m of argillaceous, sandy and oolitic limestone with corals, brachiopods and sponge detritus overlain by 3 m of sandstone with lenses of limestone and 1 m of sandy oolitic limestone. The upper part (35 m thick) comprises 9 m of fine grained limestone with chert nodules overlain by soft marl, 12 m of sandstone and argillaceous limestone with beds of oolitic and coralline limestone, and 14 m of well-bedded and argillaceous limestones containing abundant *Rhynchonella spp., Terebratula sp.*, echinoids, gastropods and pelecypods.
Subsequent mapping by GEOSURV showed that the Muhaiwir Formation outcrops in a NE-SW belt extending from the Rutba Highway in the S (75 m thick) to Wadi Haman in the NW (96 m thick). It comprises two carbonate units, each with a basal clastic layer. The lower unit is 55 ill thick in the NE and 25 m thick in the Sw. It consists of a basal quartzitic sandstone and sandy limestone (5-6 m thick) overlain by 8 m of yellowish grey to pinkish hard limestone, 12-16 m of whitish to grey coralline limestone alternating with beds of marl, and 8-10 m of highly weathered recrystallised fossiliferous limestone with white chert nodules and beds of siltstone and fine-grained sandstone. The upper unit is up to 46 m thick and comprises a basal conglomerate and pebbly sandstones (up to 20 m thick), (or interbedded sandstone and reddish brown detrital dolomitic limestone rich in detrital corals and chert nodules) passing up into alternating marl and marly limestone and sandstone, overlain by fossiliferous limestone and marl.

Thicknesses of the formation in water wells are: K7-12 near Anah (>130 m), K7-9 (141 m) and K7-7 (>122 m). In the outcrop area, the lower 20 m of the formation was penetrated in well K5-9, 70 km E of Rutba.

The Muhaiwir Formation is overlain by the Saggar Formation throughout the outcrop area except near Wadi Hauran where it is overlain by Najmah Formation. This contact is generally unconformable and is taken at the base of a sandstone layer or reworked lateritic conglomerate. The lower contact with the underlying Amij Formation is at the base of a conglomeratic or sandy dolomite. The upper carbonates of the Amij Formation are often stained red, indicating a hiatus associated with leaching.

GEOSURV studies provided additional fauna (Ctyroky and Karim, 1981; in Jassim et al., 1984) which includes abundant corals, brachiopods *(Daghanirhynchia sp., Micromphalites sp.),* Ostracoda, macroforams *(Haurania amiji* Henson and *Nodosaria sp.)* from the lower cycle. In the upper cycle, the foraminiferal fauna includes *Haurania amiji* Henson, *Nautiloculina sp., Trocholina elongata* Henson, *T. alpinus* Henson, *Trocholina sp.,* rniliolids and textularids. The macrofauna includes *Lopha* g *rega rea, Exogyra nana, Nucleoites orbicularis, Arsosalenia cf hemicidarcides, Pholadomya cf compressa* (Sow), *Thamneasteria sp., Stylina sp., Burmirhynochia sp., Rugitella sp., Polyphylloseris sp., Amphiastria sp., Homomya sp., Inoperma sp., Ampulina? sp., Isastrea sp.* and *Zeillaria?* The fauna indicates the formation is of Bathonian age although *Haurania (Amijiella) amijii* appears to range from Sinemurian-Bajocian.

Skocek and Hussain (1980; in Jassim et al., 1984) suggested that the lower unit was deposited in a shallow water inner shelf environment comprising tidal flats, sandy shoals and lagoons. The carbonates of the upper unit were deposited in an inner shelf marine environment (Ctyroky and Karim, 1981; in Jassim et al., 1984).

In Syria, the Muhaiwir Formation passes laterally into parts of the D01aa Group (Dubertret, 1966). Age equivalents of the formation are the Middle and (partly) Upper Dhruma formations of Saudi Arabia (Powers et al., 1966) and possibly the lowermost Surmeh Formation of the eastern Zagros (Furst, 1970).

10.1.2 Restricted outer shelf and basinal (Sargelu Formation)

The Sargelu Formation was first described by Wetzel in 1948 (Bellen et al., 1959) from the Surdash anticline of the High Folded Zone of NE Iraq. It also outcrops in many structures of the High Folded, Balambo- Tanjero and Northern Thrust zones and in tectonic windows within the Qulqula- Khwakurk Zone. It is present throughout Iraq except in the Rutba Subzone where it passes .into the Muhaiwir Formation.

The Sargelu Formation in its type section comprises 115 m of thin-bedded, black, bituminous and dolomitic limestones, and black papery shales with streaks of thin black chert. A similar lithology is encountered in most outcrops (Plate 10-1). Subsurface sections contain a higher proportion of shale and occasional very fine grained sandstone beds. The thickness of the formation in the well sections is as follows:

W Kifl-1 (209 m), Rumaila-l72 (92 m), Diwan-l (367 m), Khidr Al Maa-l (141 m), Rumaila N-l (74 m), Samawa-1 (447 m), Tel Abtakh-1 (200 m), Tel Hajar-1 (378 m), Sufaya A-2 (225 m), Sasan A-2 (110 m), Jabal Kand-1 (150 m), Tharthar-1 (325 m), Makhul-2 (178 m), Alan-1 (223 m), Najmah-29 (201 m), Alan-1 (223 m), Butmah-2 (201 m), Adaiyah-I (166 m), Atshan-l (250 m) and Ibrahim-1 (88 m). In Kuwait the formation is thinner: 75 m in Burgan and 83 m in Umm Gudair.

Fossils are abundant in both outcrop and subsurface sections. In addition to the fossils listed by Bellen et al. (1959), subsequent work in the Halabja area identified a microfauna of pelagic character including radiolarians, Globochaeta, sponge spicules, calcispheres, ostracods,

echinoderms, fragments of pelecypods and gastropods, *Cadosina sp., Saccocoma,* minute aptychi, and the following foraminifera: Miliolids, *Orbitannia sp., Haurania sp.* and *Pfenderina sp.* Shallow water facies occur in the higher less fossiliferous beds which comprises micrite and microsparites which contain algae, and spores of Dasycladaceae and *Thaumatoporella vesiculifera* Rainieri. The upper part of the Sargelu Formation comprises a microfacies with thin-shelled juvenile pelecypods *(Bositra div. spp.* and *Posidonia).* An abundant ammonite fauna of *?Thaboceras sp.* (Upper Bajocian) and *Micromphalites* (Bathonian) occurs in this formation. Abundant *Bositra buchii* (Roemer), *Bositra cf buchii iraqensis, Bositra sp.* and *Astarte sp.* were also recorded from imbricates within the Avroman range SE of Sulaimaniya. Pelagic facies of the formation also contain radiolarians and echinoderms.
The species *Bositra buchii* has an age range of Toarcian to Callovian but is most abundant in the Bajocian and Bathonian. Biostratigraphically the formation corresponds to the Pfenderina-Haurania Zone of SW Iran (of Bajocian-Bathonian age). Based on the above fauna, the Sargelu Formation is of Bajocian-Bathonian age. The basal beds may be of Latest Toarcian age.

The Sargelu Formation was deposited in basinal euxinic marine environment; some beds were deposited in shallower or better aerated water (on the Salman Zone of the Stable Shelf). These shallow carbonates represent tongues of the Muhaiwir Formation.
The lower contact in the type area, and in N and NE Iraq, is usually gradational and conformable. In subsurface sections the boundary is defined by the last occurrence of anhydrite at the top of the Alan Formation. In the Jezira area (in wells Khlesia and Mityaha), the formation has been truncated at the Base Cretaceous unconformity.

The Sargelu Formation is equivalent to parts of the Cudi Group of SE Turkey (Altinli, 1966). It is present in wells in NE Syria, and in Central Syria it is equivalent to the black shale of the uppermost part of the Dolaa Group (Dubertret, 1966). Age equivalents of the Sargelu Formation are the Dhruma Formation of Saudi Arabia and the lower part of the Surmeh Formation of SW Iran.

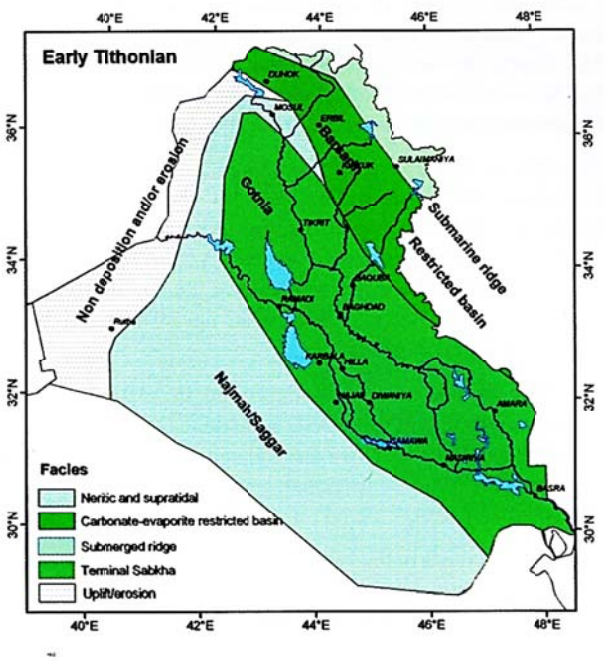
10.2 Late Jurassic Sequence

The palaeogeography during the Late Jurassic is controlled by the effects of Late Jurassic tectonic activity along the Arabian Plate margin prior to the opening of the Southern Neo- Tethys (Chapter 3). Differential subsidence led to periodic isolation of the intra-shelf basin from the NeoTethys.
Three distinct facies can be recognised (Fig. 10-5) these are: 1) A clastic-carbonate inner shelf represented by the Najmah and Saggar formations. 2) A carbonate-evaporite inner shelf represented by the Najmah and Gotnia formations. 3) A restricted basin represented by the Naokelekan, Barsarin and Gotnia formations.

The area of the High Folded, Balambo- Tanjero and Northern Thrust zones is characterized by a condensed sedimentary succession of euxinic character in the lower part (Naokelekan Formation) and lagoonal evaporitic character in the upper part (Barsarin Formation) which led Ditmar and the Iraqi-Soviet Team (1971) to assume the presence of a tectonic ridge in N Iraq isolating the basin to the south. The mapping results obtained during GEOSURV investigations in 1976 are consistent with this model.

The Upper Jurassic sediments were deposited following a break of Callovian age. They are thickest (700 m) in the Mesopotamian and Salman zones of the Stable Shelf near the Kuwait border (Fig. 10-6). In N Iraq, the sequence is about 400 m thick in the area along the Tigris River between Mosul and Tikrit. On the Rutba Subzone, the sequence is at least 38 m thick (Najmah Formation) in outcrops of Wadi Hauran and another 30 m (Saggar Formation) is tentatively included within this sequence.

Fig. 10-5 Palaeogeography of Late Jurassic time (Oxfordian-Early Tithonian)



10.2.1 Clastic-carbonate inner shelf (Najmah Formation)

The Najmah Formation represents the calcareous neritic and lagoonal facies of the Late Jurassic Sequence on the Stable Shelf. The only known outcrop of the formation is in Wadi Hauran, 80 km NE of Rutba in W Iraq. The type section of the formation was defined in NW Iraq by Dunnington in 1959 from well Najmah-29 from the Najmah anticline of the Foothill Zone. The formation is here 341 m thick and comprises from the base to the top: 1) Fine-grained recrystallised limestone with remnant shells and oolites, 2) oolitic limestone with macrofossil debris, 3) coarse granular dolomite with large zoned dolomite crystals and 4) thin anhydrites and fluffy limestone (Bell en et al., 1959).

In wells between Awasil and Makhul (Bellen et al., 1959) a thin unit of black shale, and oolitic and micritic limestone is placed in the lower part of the Najmah Formation. Argillaceous limestones and shales attributed to Najmah Formation also occur between Mosul and Samarra (Kadhim and Nasr, 1971). Dolomitised chalky limestone and pelletal anhydritic limestone were also reported in wells near Samawa in S Iraq (Kadhim and Nasr, 1971).

At Wadi Hauran in W Iraq, a 38 m outcrop succession was assigned to the Najmah Formation (Jassim et al., 1984). It comprises, from the base upwards: sandstone (base not exposed), 5 m of brown, very hard lithographic limestone with burrows and algal structures, 15 m of white to grey and buff fossiliferous lithographic limestone, 10 m of buff, very hard recrystallised limestone (argillaceous and sandy in part) and 8 m of greyish white to buff, recrystallised limestone with burrows, partly argillaceous and partly oolitic. This section probably correlates with units 1 and 2 of the type section.

The section is overlain by sandstones of the Saggar Formation (originally included in the Najmah Formation by Al Mubarek, 1978; and Jassim et al., 1984).

The thickness of subsurface sections of the Najmah Formation are as follows: W Kifl-I (205 m), Diwan-I (421 m), East Baghdad-I (64 m), Khidr Al Maa-I (485 m), Tharthar-I (49 m), Makhul-2 (14 m), Najmah-29 (341 m), Atshan-I (75 m), Samawa-I (403 m), and Rumaila-l72 (34 m). In Kuwait the formation is 81 m thick in Sabriyah field.

In addition to the fauna listed by Bellen et al. (1959), in . Wadi Hauran outcrops Ctyroky and Karim (1981; in Jassim et al., 1984) identified: *Pseudochrysalidina sp., Kilianina sp., Nodosaria sp., Choffatella sp., Bigenerina sp.,* alvulinds, *Nauiiloculina oolithica, Pfenderina salernitana, Protoglobigerina sp., Haurania amiji* Henson, *Haurania deserti* Henson, calcispheres, echinoid spines, textularids,

Nodosaria sp. and shell fragments. This faunal assemblage is of Mid-Late Jurassic age. Some of the fauna may belong to the overlying Saggar Formation. *Haurania (Amijiella) amijii* appears to range from Sinemurian-Bajocian; *H. deserta* from Sinernurian-Bathonian. *Pfenderina salernitana* appears to range from Bathonian-Tithonian. The formation was deposited in a neritic environment of oolitic shoals and restricted lagoons.

The presence of species of *Valvulinella, Pfenderina* and *Haurania* indicate a broad stratigraphic range of Mid-Late Jurassic as discussed by Bel1en et al. (1959). However based on regional correlation they inferred a Late Jurassic age for the formation.

The contacts of the formation in the type section and surrounding area are both unconformable. The hiatus above the formation occurs below the Gotnia Formation. However it is possible that the Najmah Formation may also interfinger with the Gotnia Formation. In S Iraq, the Najmah Formation is conformably overlain by the Gotnia Formation

The Najmah Formation passes to the N into the argillaceous and condensed basinal Naokelekan Formation. The location of the shelf edge of the Najmah Formation is currently poorly defined but may coincide with the Dohuk-Chemchemal Palaeo-uplift (Ditmar and the Iraqi-Soviet Team, 1971). This however is inconsistent with the presence of the presumed Naokelekan and Barsarin formations in well Kirkuk-109. The Kirkuk section may, therefore, represent interfingering between Najmah and Gotnia formations rather than between the Naokelekan and Barsarin (Buday, 1980).

The formation extends into Saudi Arabia and Kuwait (Arab and Jubaila formations; Powers et al., 1966), and most probably into the Eastern Zagros. The formation does not continue towards the Wand N into Syria and SE Turkey. Upper Jurassic formations are absent in the Iraq/Syria and Iraq/Turkey border areas. Its age equivalent in SW Iran is the lower and middle part of the Surmeh Formation (Furst, 1970).

10.2.2 Evaporite-carbonate lagoons and sabkha (Gotnia Formation)

10.2.2.1 Gotnia Formation

The Gotnia Formation comprises anhydrite with subordinate beds of brown calcareous shales, thin black bituminous shales, and recrystallised oolitic limestones (Bellen et al., 1959). In SE Iraq, beds of halite are ·also recorded by Kadhim and Nasr (1971). Well data show two main depocentres located mostly within the Mesopotamian Zone (Fig. 10-7). The southern depocentre extends into Kuwait (620 m), and the northern depocentre is near Tikrit (466 m). The maximum thickness of 700 m is reached in Kuwait. In N Iraq (Jabal Kand-I) the combined Barsarin and Gotnia Formation is 216 m thick. Fossils are very rare and not age diagnostic. According to Bellen et al. (1959) and Kadhim and Nasr, 1971), a Late Jurassic (Callovian to Early Tithonian) age is assigned to the formation. However in Kuwait and the Gulf region the Gotnia Formation has been assigned a Kimmeridgian to Early Tithonian age (Al-Sharhan and Kendall, 1986). The contacts of the formation in the type locality and in other subsurface sections usually appear conformable. The upper contact with the Makhul Formation is erosional.

Bellen et al. (1959) suggested that the Gotnia Formation was also deposited in the Foothill Zone area NE of Makhul but was subsequently removed by post Jurassic erosion. Ditmar and the Iraqi-Soviet Team (1971) however suggested that the Gotnia was restricted to the SW parts of the Foothill Zone (mainly to the SE of Makhul) and the Mesopotamia Zone in S Iraq. Ditmar and the Iraqi-Soviet Team (Op. Cit.) placed the W limit of the Gotnia basin along the RamadiMusaiyib palaeo-uplift, but subsequent drilling (wells W Kifl-l, Diwan-l and Khidr Al Maa-l) showed that the Gotnia Formation was deposited over the whole of the Salman Zone in Central and S Iraq.

In the Gulf area and E Saudi Arabia, the Gotnia Formation passes partly into the Hith Formation and partly into units A, Band C of the Arab Formation (Powers et al., 1966).

Fig. 10-6: Thickness of the pre-Late Tithonian (Late Jurassic) Sequence

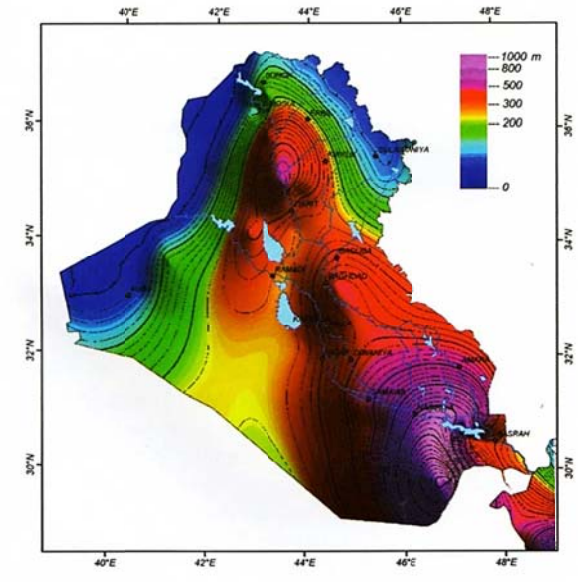
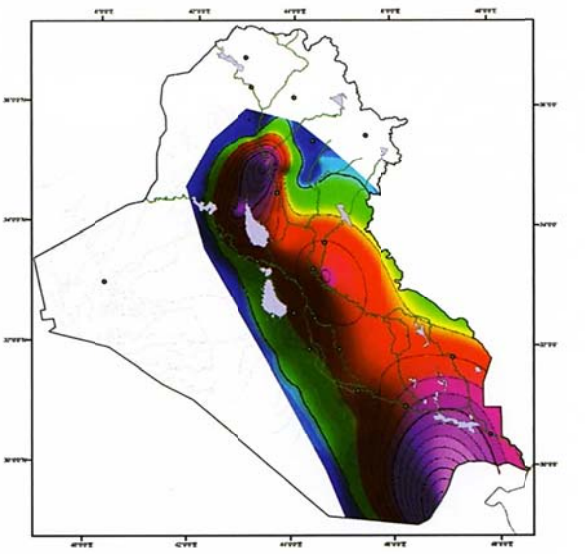


Fig. 10-7: Thickness of the Gotnia Formation



10.2.2.2 Saggar Formation

The Saggar Formation was introduced by Jassim et al. (1987) on the Geological Map of Iraq (1: 1,000,000 Scale) as an Upper Jurassic unit. The formation lies between the underlying Callovian Najmah Formation and the overlying Albian Nahr Umr Formation. The type section of the Saggar Formation was chosen along road cuts of the Rutba-Baghdad Motorway between Rutba and Wadi Saggar, 55 km E of Rutba. It is 30 m thick and comprises a lower clastic unit and an upper carbonate unit. The clastic unit consists of red pebbly sandstone with rootlets (sometimes very severely silicified) overlain by gypsiferous sandstone. The thickness of the clastic unit is variable. It is thickest in palaeo-depressions (>15 m). The carbonate unit is a very distinctive chocolate-brown sugary dolomite with characteristic white and brown zoned rhombs embedded in brown dolomitic micrite. The formation occasionally exhibits algal lamination. Algal domes up to 50 cm in diameter were recorded 70 km E of Rutba. The thickness of the carbonate unit varies from 10 m near Rutba in the SW to 25 m near Wadi Hauran in the NE. In some outcrops leaf prints occur.
The 70 km long outcrop E of Rutba is characterized by horsts and grabens (see geological map, Fig. 5-2) which were tectonically active in pre Campanian time. These structures may have been active during deposition of the Saggar Formation since in some grabens the fluvial clastic unit of the Saggar is thick relative to the surrounding horsts where the clastics are extremely thin or absent.

The formation may be equivalent to units 3 and 4 of the Najmah type section which contains similar zoned dolomites (Section 10.2.1). Similar dolomites are also described from outcrops of the Jubaila Formation in Saudi Arabia (Powers et al., 1966) passing laterally into sandstone or calcarenite. In 1963, samples collected from a mesa 55 km E of Rutba, along the Rutba-Baghdad old highway were studied by the Late Professor John F. Brand (Baghdad University 1962-1965) and thought to be of Jurassic age. This outcrop now mapped as Saggar Formation.

Mapping demonstrates that the Saggar Formation unconformably overlies Jurassic and Triassic formations. It overlies the Najmah Formation at Wadi Hauran, and the Muhaiwir Formation between Wadi Hauran and the Rutba highway. It overlies the Amij, Hussainiyat, Ubaid, and Zor Hauran formations near Rutba in the SW; the contact is sometimes associated with a lateritic bed. The Saggar Formation is generally overlain by sandstones of the Nahr Umr Formation in a broad belt extending from Wadi Hauran to the Rutba Highway. West of this area the Saggar, Nahr Umr and Mauddud formations are unconformably overlain by the Cenomanian Rutba Sandstone.

The stratigraphic position of the formation indicates a possible age range of Late Jurassic to Aptian. However, the unique lithology of the carbonate (with zoned dolomite) and the presence of abundant algal stromatolites suggest a supratidal depositional environment probably during a period of desiccation corresponding to the deposition of the Gotnia Formation. Additionally, the presence of similar dolomites in well Najmah-29 and in water well K7/12 near Anah and in the Jubaila Formation supports a Jurassic age. The authors provisionally accept a Late Jurassic age (Probably Late Kimmeridgian) for the formation until better age determination is provided.

The environment of deposition of the Saggar Formation is fluvial in the lower part and lagoonal and supratidal in the upper part. The formation may represent the near-shore equivalent of the Gotnia Formation.

10.2.3 Euxinic basin

10.2.3.1 Naokelekan Formation

The Naokelekan Formation was defined by Wetzel and Morton in 1950 from the Balambo-Tanjero Zone near Rowanduz. A better exposed supplementary type section from the Chia Gara fold of the High Folded Zone of N Iraq was later described by Bellen et al. (1959). The 20 m thick formation comprises three units: 1) a lower unit of laminated argillaceous bituminous limestone alternating with bituminous shale and fine-grained limestone, 2) a middle unit consisting of thin-bedded fossiliferous dolomitic limestone referred to as the "Mottled Beds" and 3) an upper unit (mostly obscured in the type section), of thin-bedded, highly bituminous dolomite and limestone with beds of black shale ("coal horizons") in the lower part. This lithology is consistent in all outcrops of N and NE Iraq (Plate 10-2).

In addition to the fossil list provided by Bellen et al. (1959) which support a Late Oxfordian-Early Kimmeridgian age, subsequent mapping in the Halabja area revealed that the formation contains: *Hibolites semihastatus* (Blainville), *Kurnubia palestiniensis* Henson, *Ammobaculites sp.*, Textulariidae div. spp., *Nautiloculina oolithica* Mohler, *Protoglobigerina sp.* The algae *Cladocoropsis Thaumatoporella sp., Cayeuxia doerflesiana, Cadosina sp.,* Dasycladaceae gen indent and the tromatoporoid *Shuqraia heybrocki* ocur. *Shuqraia* is characteristic of the Oxfordian elsewhere in the Middle East. *Hibolites semihastatus* (Balinville) has an age range of Callovian-Oxfordian. The age of the Naokelekan Formation may therefore extend into the Callovian. The assumption of Bellen et al. (1959) that a break exists between the Sargelu and Naokelekan formations has not been confirmed in NE Iraq. Spath (In Bellen et al., 1959) suspected that a break occurs within the formation at the top of the Mottled Bed. Hamza and Isaac (1971) identified a ferruginous horizon at the contact of the Naokelekan and Barsarin formations in the Northern Thrust Zone.

The formation was deposited in an euxinic environment in a very slightly subsiding or starved basin.

10.2.3.2 Barsarin Formation

The Barsarin Formation was defined by Wetzel in 1950 (Bellen et al., 1959) from the type area in the Balambo-Tanjero Zone near Rowanduz in NE Iraq. It is 20 m thick and comprises limestone and dolomitic limestone (laminated, some fluffy textured, locally cherty) and argillaceous, brecciated and contorted beds (Plate 10-2). The breccias may have formed by dissolution of anhydrite beds (observed in some outcrops in Ser Amadya and Kurrek Mountains). The formation is up to 60 m thick. It was deposited in a lagoonal often evaporitic environrtient. A 407 m thick dolomite unit in well Kirkuk-I09 was assigned to the Barsarin Formation by lPC geologists. Buday (1980) however, assumed that this section represents intercalations of the Najmah and Gotnia formations. A 216 m thick anhydrite and dolomite unit in well Jabal Kand-1 (referred to the Barsarin-Gotnia Formation) may also represent interdigitating Najmah and Gotnia formations.

Fossils are absent in both surface and subsurface sections due to strong dolornitisation and recrystallisation. A Kimmeridgian-Early Tithonian age for the formation is based on its stratigraphic position below the Chia Gara Formation of Late Tithonian age and above the Kimmeridgian-Oxfordian Naokelekan Formation.

The contacts of the formation appear conformable in the type area but the base of the formation in the Northern Thrust Zone is marked by a detrital, ferruginous bed (Hamza and Isaac, 1971). The upper boundary is lithologically sharp though no break was identified in the type area. However, in the Kirkuk wells a basal conglomerate has been identified at the contact of the Chi a Gara and Barsarin formations (Ditmar and the Iraqi-Soviet Team, 1971).

Plate 10-1: Sargelu Formation along the Rowanduz River at Barsarin village, E of Rowanduz (photo by S. Jassim)

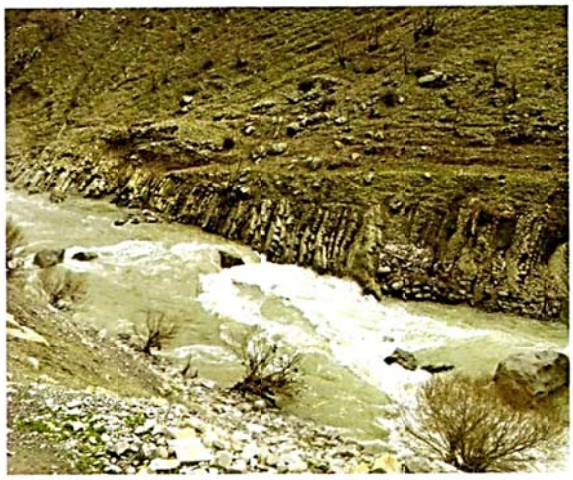


Plate 10-2: Type section of Barsarin Formation, Barsarin village, Rowanduz Valley, E of Rowanduz. Thin bedded sequence to the left belongs to Naokelekan Formation (photo by S. Jassim)



CHAPTER 11

Late Tithonian-Early Turonian Megasequence AP8

by

Saad Z. Jassim and Tibor Buday

The Late Tithonian-Early Turonian Megasequence was deposited in a large intra-shelf basin contemporaneous with a new phase of ocean floor spreading in the Southern NeoTethys (Chapter 3). Differential subsidence (and resultant thickness changes) occurred across transverse faults. The axis of the intra-shelf basin shifted towards the eastern Mesopotamian Zone into the Tigris Subzone from its previous position on the Salman Zone and western Mesopotamian Zone.

The opening of the Southern Neo- Tethys (Chapter 3) led to the drifting away of a narrow microcontinent; a new passive margin formed along the NE margin of the Arabian Plate. The Rutba Uplift formed the western margin of the Mesopotamian basin. The NE margin was formed by a carbonate ridge along the north facing passive margin of the Southern Neo- Tethys.

The stratigraphic correlation of formations in Megasequence AP8 is shown in Fig. 11-1.

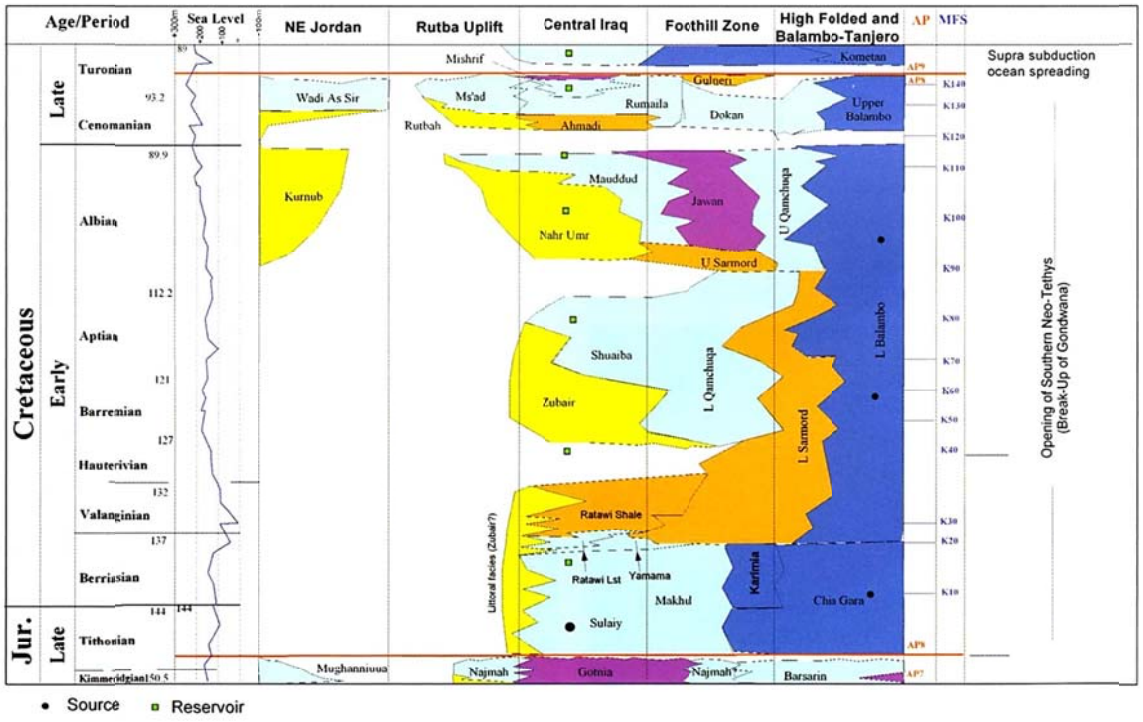


Fig. 11-1: Stratigraphic correlation of formation of Megasequence AP8

The megasequence is thickest in the Foothill Zone and in the Tigris Subzone of the Mesopotamian Zone; reaching 1200 m near Baghdad. It is up to 500 m thick near Sinjar, in NW Iraq. The megasequence is absent over part of the Mosul High, due to erosion and onlap. Formations of pre-Albian age are probably missing in the Rutba-Jezira Zone.

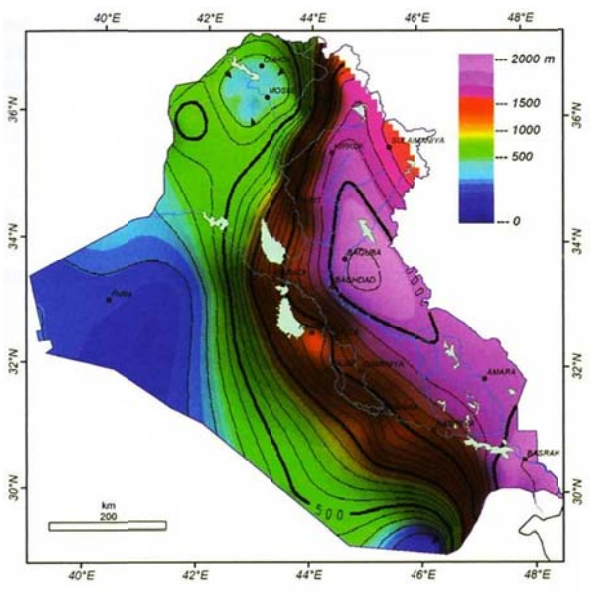
The megasequence comprises the Upper Tithonian-Aptian Thamama Group and the Albian-Lower Turonian Wasi'a Group. In Kuwalt (Douban 1999) recognised four sequences within the Late Tithonian-Early Turonian Megasequence, these are: the Late Tithonian-Hauterivian and Barremian-Aptian sequences (Thamama Group), and the Albian and Cenomanian-Early Turonian sequences (Wasi'a Group). The Thamama Group is absent in the Rutba-Jezira Zone; the Wasi'a Group is widely distributed over that zone.

11, 1 Upper Tithonian-Aptian Thamama Group

The Thamama Group is present throughout Iraq except in the Rutba Jezira Zone where it is missing due to nondeposition or truncation below the Albian unconformity. The depocentre of the Group (Fig. 11-3) is located in a N-S trending basin in the Mesopotamian Zone in S Iraq and in the Foothill and High Folded zones of NE Iraq.

In Late Tithonian-Valanginian time the Southern NeoTethys opened with the separation of the Bisitoun (Avroman) microplate from Arabia (Chapter 3). The Late Tithonian- Valanginian palaeogeography is summarized in Figs. 11-4 to 11-6. The intra-shelf basin comprised inner and outer shelf (basinal) areas. The western shoreline of the basin lay along the eastern side of the Rutba-Jezira Zone.

Fig. 11-2: Thickness of the Late Tithonian- Early Turonian Megasequence AP8



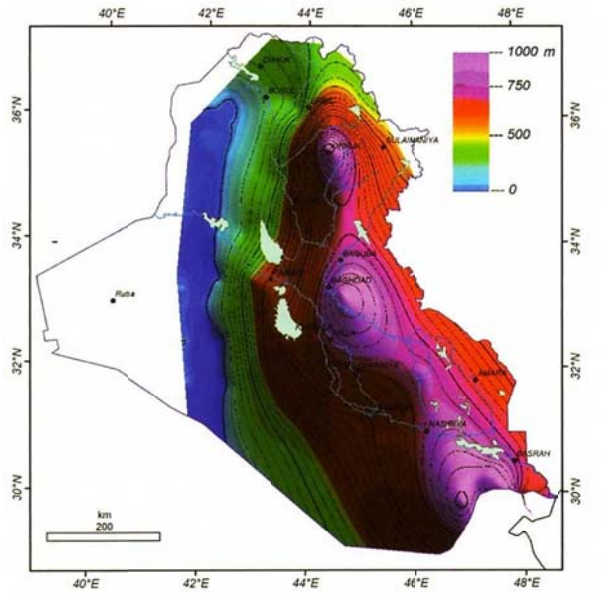
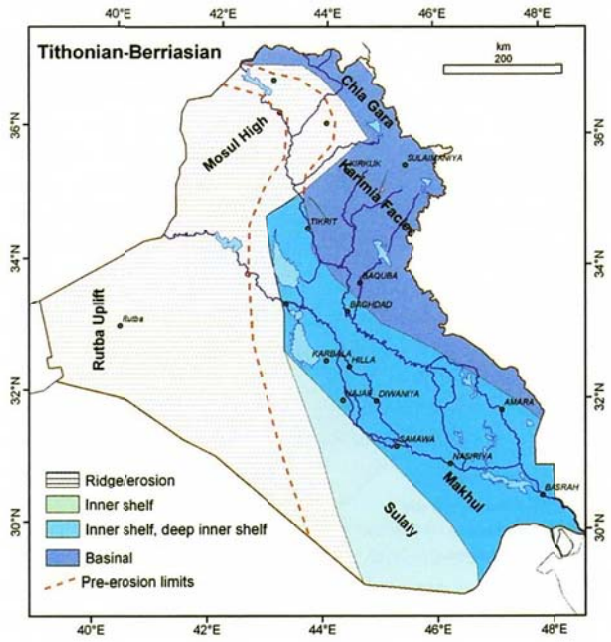


Fig. 11-3: Thickness of the Thamama Group

The eastern margin of the basin was probably formed by a carbonate ridge which bordered the continental margin along the southern Neo- Tethys. The Rutba Uplift dominated the Rutba-Jezira Zone of the Stable Shelf. The Salman Zone and some of the S parts of the Mesopotamian Zone were covered by a shallow inner shelf sea with coastal terrigenous influx and widespread deposition of neritic (often oolitic) carbonates of the Sulaiy Formation (Fig. 11-4). The Mesopotamian Zone witnessed repeated open marine incursions leading to deposition of alternating shallow water carbonates and outer shelf marls. Sedimentation began with deposition of the transgressive Sulaiy and Yamama formations and ended with deposition of the Ratawi Formation during a highstand (Douban and Medhadi, 1999). On the SW shoreline of the basin (W boundary of the Salman Zone) the sequences passes into fluvial, coastal and littoral clastics (Fig. 11-1) previously assigned to the Zubair Formation; such clastics should now be identified as a separate formation. The inner shelf formations pass to the NE into outer shelf and basinal sediments of the Sarmord and Balambo formations; the boundary between the two lithofacies was a submarine palaeoridge located at the NE boundary of the Mesopotamian Zone (the Tikrit-Amara palaeoridge).

Fig. 11-4: Late Tithonian-Early Berriasian Palaeogeography



The Barremian-Aptian time started with deposition of the Zubair Formation (Salman and Mesopotamian zones) during a low stand followed by deposition of the Shu'aiba Formation during a highstand. The Shu'aiba carbonate ramp was probably located along the Tikrit-Amara palaeoridge separating the clastic-carbonate inner shelf of the Stable Shelf from the outer shelf marls of the basinal sediments to the E (Fig.1l-7).

11.1.1. Late Tithonian-Hauterivian Sequence

The Late Tithonian- Hauterivian Sequence comprises the Sulaiy, Makhul, Chia Gara (including Karimia), Yamama (including Garagu and Zangura), Ratawi and Lower Sarmord formations. Although geologists in Iraq and Kuwalt dropped the Sulaiy Formation in favour of Makhul Formation (Abdulla and Kinghorn, 1996; Douban and Medhadi, 1999) the two formations

represent two distinct facies, The Sulaiy Formation is an inner shelf facies deposited on the Salman Zone; the Makhul Formation is a deep inner shelf facies deposited in the Mesopotamian Zone.

11.1.1.1 Inner shelf and deep inner shelf facies

11.1.1.1.1 Sulaiy and Makhul Formation

The Sulaiy Formation as defined in Saudi Arabia comprises chalky, massive bedded limestones, with some interbeds of calcarenite (Powers et al., 1968) and is of Early Valanginian age. A subsidiary section in Iraq described by Rabanit (Bellen et al., 1959) in well Ratawi-l in SE Iraq consists of over 331 m (base not reached) of detrital, oolitic limestone and hard recrystallised limestone with rare interbeds of shale.

The Makhul Formation was defined by Dunnington in 1955 (Bellen et al., 1959) in well Makhul-l near the SW margin of the Foothill Zone. It comprises argillaceous limestones and calcareous mudstones which are sometimes dolomitised with beds of pseudoolitic limestones near the top and base. Anhydrite nodules occur in the lower part of the formation in Makhul-1. In well Awasil-5 oolitic limestones are more frequent (Huber, 1940). In Samarra (Johnston, 1961) and Musalyib (Kasim, 1962) the formation contains a high proportion of marl. Siltstones and sandstone beds were reported from wells Falluja-l (Gaddo et al., 1958), Samarra-l (Johnson, 1961) and Mussalyib-l (Kasim, 1962) where the formation passes into the Sulaiy Formation,

In the subsurface the two formations have often not been differentiated. The Sulaiy/Makhul Formation was also drilled in wells Rumalla-l72 (262 m), Merjan-l (47 m), Diwan-l (31), Samawa-l (31 m), Kifl-I (35 m), Tharthar-l (18 m), Rumaila-N (252 m), and Khidr-al-Maa-l (337 m). In Kuwait the Makhul Formation is 285 m thick in the Burgan field thinning to <100 m in W Kuwait. The combined formations thicken from the Salman Zone towards SE Mesopotamia.

Ditmar and the Iraqi-Soviet Team (1971) showed that the name Sulaiy had often been applied to rock units of different age. They proposed that the name Sulaiy should be used more precisely as previously recommended by Chatton and Hart (1960) who applied the name to the neritic limestone lithofacies of Late Tithonian-Berriasian age. Sharland et al. (2001) located a Maximum Flooding Surface (MFS 1110, 147Ma) in a shale layer in the middle of the Makhul Formation. According to Douban and Medhadi (1999), the Makhul Formation represents a transgressive shelf margin wedge in Kuwalt.
Fossils listed by Bellen et al. (1959) indicate a Late Tithonian age for the Makhul Formation and a Tithonian-Berriasian age for the Sulaiy Formation.

The Sulaiy Formation is conformably overlain by the Ratawi or Yamama Formation except in some parts of the Salman Zone where it is unconformably overlain by the Zubair Formation (Buday, 1980). The Sulaiy Formation passe to the SW into a sandy unit. A basal sandstone or sandy limestone occurs at the contact with the Gotnia Formation in the W parts of the Salman Zone.
Towards the E and NE, the Makhul Formation passes laterally into the Chia Gara Formation as indicated in wells Samarra-I (Johnson, 1961) and Mussalyib-I (Kasim, 1962) and by the thick Chi a Gara Formation in Kirkuk-109 and in Qara Chauq. Bellen et al' (1959) considered that the Makhul Formation passes eastwards into the Karimia Formation and that the lower part of the Karimia Formation passes into the Chi a Gara Formation.

Fig. 11-5: Valanginian Palaeogeography

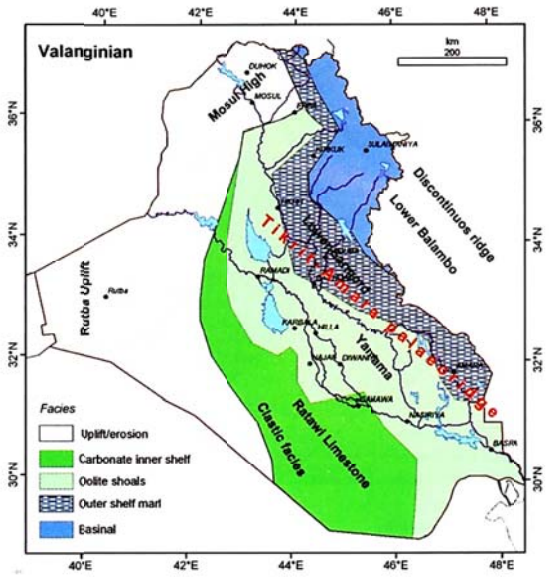
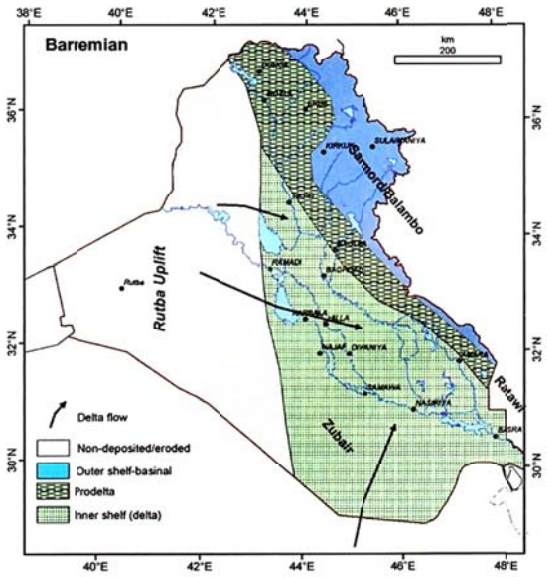


Fig. 11-6: Barremian Palaeogeography



11.1.1.1.2 Yamama Formation (including Garagu and Zangura)

The Yamama Formation was defined by Steinke and Bramkamp in 1952 (Powers et al., 1967) from outcrops in Saudi Arabia. Bellen at al. (1959) described a 257 m interval in Ratawi-1 as the "Yamama-Sulaiy" Formation. The upper 203 m, now assigned to the Yamama Formation (Sadooni 1993) comprises 12 m of spicular and brown detrital limestone with thin shale beds overlain by 191 m of micritic limestone and oolitic limestone. The isopach of the Yamama Formation (Fig. 11-7) indicates the formation thickens S of the Mosul High. Four isolated roughly N-S and NW-SE oriented depocentres occur in the Mesopotamian Zone and there is a small depocentre near Kirkuk. The formation is up to 400 m thick in the Euphrates area near Najaf and up to 360 m thick in SE Iraq.

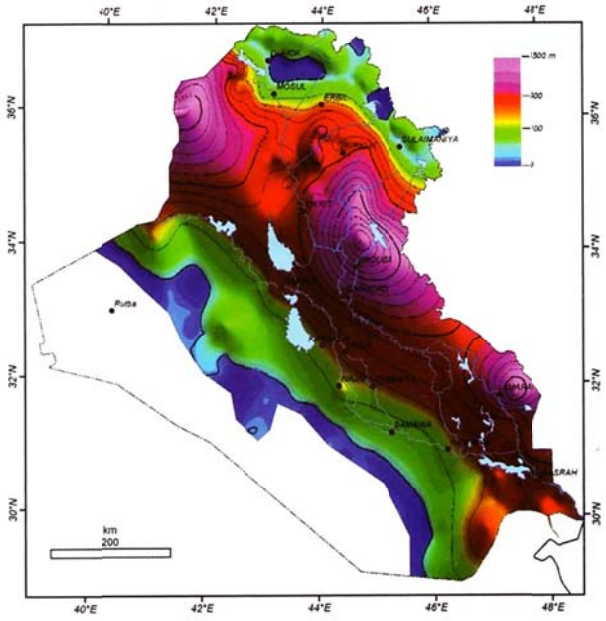
The Yamama Formation in S Iraq comprises outer shelf argillaceous limestones and oolitic, pelloidal, pelletal and pseudo-oolitic shoal limestones. Oolitic reservoir units are present in several NW-SE trending depocentres (Sadooni, 1994). The equivalent Minagish Formation in Kuwalt (Douban and Medhadi, 1999) was deposited as a transgressive unit in an inner shelf environment.

The formation is of Berriasian-Valanginian age (Bell en et a!., 1959). From its stratigraphic position an age range of Late Berriasian to Early Valanginian age is likely. In Kuwalt the Yamama Formation is assigned a Berriasian age (Douban and Medhadi, 1999).

Two variants of the Yamama Formation (originally described as separate formations) are the "Garagu" and "Zangura" formations. The "Garagu" Formation comprises oolitic sandy limestones with marls and sandstones in its upper and lower parts, with organic detrital limestones in the middle (Bellen et al., 1959). The "Zangura" Formation occurs in the Awasil-Makhul-Falluja areas. It comprises pseudoolitic limestones, argillaceous limestones and calcareous mudstones. Sandstones occur in the Falluja area.

The Yamama Formation was deposited in alternating oolitic shoal and deep inner shelf environments, probably controlled by subtle structural highs within a carbonate ramp (Sadooni, 1993).

Fig. 14-7: Thickness of the Early-Mid Miocene Sequence



11.1.1.1.3 Ratawi Formation

The Ratawi Formation was defined by Nasr in 1950 (Bellen et a!., 1950) from well Ratawi-I in S Iraq. The formation comprises dark, slightly pyritic, shales; beds of buff, pyritic, pseudoolitic, detrital fossiliferous limestones are present in the lower part of the formation. In some areas E and N of the type well, beds of sandy shale and sandstone occur. Towards the Wand N the formation contalns a higher proportion of sand. The thickness of the formation in S Iraq ranges from 23 to 629 m. Thickness in wells are: 28 m (K7 -7), 198 m (Tuba-2), 23 m (W Kifl-1), 147 m (Zubalr-47), 205 m (Ur-1), 80 m (Nasiriya-1), 44 m (Safawi-1), 110 m (Rumaila-North-1), 357 m (Ratawi-3), 470 m (Rachi-2), 88 m (Merjan-L), 95 m (Diwan-1), 629 m (E Bagdad-1), 167 m (Khidr Al Maa-1), 67 m (Ghalaisan-l), 73 m (Majnoon-11), 132 m (Abu-Amud-1), 224 m (Ratawi-6), 86 m (Samawa-1), and 118 m (Rumaila-l72). The formation is thickest in Central Iraq near Baghdad and in S Iraq.

The name Ratawi Formation has often been incorrectly applied to rock units of different age and lithology. Buday (1980) suggested that the term Ratawi Formation should be only applied to the shale lithofacies. In Kuwalt the Ratawi Formation has been divided into the Ratawi Limestone and Ratawi Shale Members; it is recommended that this practise is followed in Iraq.
The lower part of the Ratawi Formation was deposited during a highstand in an inner shelf environment; the Upper Ratawi Shale was deposited in a deep inner shelf to middle shelf environment (Douban and Medhadi, 1999).

Bellen et al. (1959) assigned a Hauterivian age to the upper shale-dominated part of the formation; the lower part of the formation was assumed to be of Valanginian age based on its stratigraphic position. Douban and Medhadi (1999) assigned an Early Valanginian age to the Ratawi Shale Member and a Late Berriasian age to the Ratawi Limestone Member.
The lower and upper contacts of the formation are conformable (Buday, 1980). However Douban and Medhadi (1999) identified a sequence boundary (3Ma hiatus) on the top of the formation in Kuwalt.

The lower part of the formation is equivalent to the Buwaib Formation of Saudi Arabia (Powers et al.. 1966) and the lower parts of the Gadvan Formation of SW Iran (Furst, 1970).

11.1.1.2 Outer shelf and basinal

11.1.1.2.1 Chia Gara Formation

The Chia Gara Formation was defined by Wetzel in 1950 (Bellen et al., 1959) in the Chia Gara anticline of the High Folded Zone of N Iraq. Throughout the outcrop area the formation comprises up to 230 m of thin bedded limestone and calcareous shale, with a consistent bullion zone and Phacoid beds at the base. Argillaceous limestone and marl, interbedded with shale prevail in the upper part of the formation (Plate 11-1). In the Northern Thrust Zone the uppermost beds of the formation are silty. In well Kirkuk109 conglomeratic beds occur at the base of the formation (Bellen et al., 1959). In some sections the limestones are dolomitised or silicified. The formation is 30-300 m thick.
610 m of monotonous dark-coloured calcareous mudstones and rare marl bands were described in well Kirkuk-109 by McGinty in 1953 (Bellen et al., 1959) and referred to as the Karimia Mudstone. It overlies the Chia Gara Formation. Chatton and Hart (1960) correlated this formation with the Lower Sarmord although fossils indicate a Tithonian age in the lower part and a Berriasian age for the upper part of the formation (Bellen et al., 1959); therefore its inclusion in the Sarmord is not acceptable. The "Karimia" Formation passes into the Chia Gara Formation towards the NE and into the Makhul Formation to the SW. It was deposited in a deep basin. The authors recommend that the Karimia Mudstone is included in the Chia Gara Formation.
Fossils in the Chia Gara Formation indicate a Mid Tithonian-Berriasian age (Bellen et al., 1959). Mapping in the Halabja area in 1976 showed that the formation comprises thick and thin bedded micritic limestone alternating with calcareous shales with ammonites. Thin bedded limestones at Kani Askan near Halabja contain representatives of the Haploceratidae family of Late Jurassic age and *Lamellaptychus cf didayi* (Coquand) of Tithonian to Early Hauterivian age. A locality near Goryana originally studied by Spath (1950) yielded *Leptoceras* sp. Ind., *Protancyloceras gracile* (Oppel) and *Protaconthodiscus? sp.* indicating a Berriasian age. A locality SSE of Biri Dalro, also originally described by Spath yielded *Nothostephanus cf. kurdistanensis* Spath and *Nothostephanus subcoronatus* Spath, and fossils belonging to the genus *Bochianites.* The foraminifera that occur in micritic carbonates and sparites include: Lagenidae div. spp. (indent.), Valvulinidae div. spp. (indent.), *Pseudocyclammina cf lituus* (Yok.), *Trocholina elongata* (Leupold), *Saracenania sp., Pseudochrysalidina? sp., Kilianina sp.,* Textulariidae div. spp., *Nautiloculina sp.* and *?Neoendothyra sp.* Algae are also common. These fossils confirm a latest Tithonian to Berriasian age.

The Chi a Gara Formation in the Halabja area is characterized by micritic limestones and was deposited in a mid-deep shelf environment.

The contact with the underlying Barsarin Formation is conformable. However Bellen et al. (1959) suggested that there is a stratigraphic break between the Barsarin and Chia Gara formations. The Chia Gara rests disconformably (with a basal conglomerate) on the underlying Late Jurassic Sequence in well Kirkuk-109 in the Foothill Zone (Ditmar and the Iraqi-Soviet Team, 1972).

In the type area in N Iraq the formation is conformably overlain by the Garagu Formation. However in the Northern Thrust Zone the upper contact is locally erosional; in this area either the Garagu or the Campanian Hadiena Formation overlies the Chia Gara Formation. To the SE of Sulalmaniya the Chia Gara Formation passes gradationally into the Balambo Formation: However, a slight break may be present between these two formations in the Ranya, Dalamar and Sirwan areas. Towards the Foothill Zone the upper contact is mostly erosional.

The Chia Gara Formation (along with the Karimia Formation) is generally restricted to the Unstable Shelf. In the Foothill Zone the formation gradually passes into the Makhul Formation SW of the Butmah-Chemchemal Subzone, and is absent west of the Tigris River. The Chia Gara passes into the Makhul Formation to the E of the Tikrit-Amara palaeoridge.

11.1.1.2.2 Lower Sarmord Formation

The Sarmord Formation was defined by Wetzel (1950) in the Surdash anticline of the High Folded Zone in the Sulalmaniya area of NE Iraq. It comprises 455 m of homogeneous brown and bluish marls, with beds of argillaceous limestones (Plate 11·2), and is dated as Valanginian-Aptian by Bellen et al. (1959). In Kirkuk wells the formation was assigned a Berriasian age by the same authors. Chatton and Hart (1960) divided the formation into the Lower, Middle and Upper Sarmord formations. Ditmar and the Iraqi-Soviet Team (1971) assigned a Tithonian Berriasian age to the Lower Sarmord, a Valanginian-Aptian age to the Middle Sarmord, and an Albian age to the Upper Sarmord. Buday (1980) combined the lower two divisions into the Lower Sarmord which is here considered to be of Berriasian-Aptian age. The Upper Sarmord is absent in High Folded Zone of NE Iraq and the Sarmord type section represents the Lower Sarmord only.
The formation was deposited in a deep inner shelf to outer shelf environment. The formation contalns a higher proportion of limestones towards the SW where it passes laterally into the Qamchuqa Formation.

In the Kirkuk area, the lower boundary of the Lower Sarmord Formation is gradational. In the Amadiya area, the basal beds of the formation, of Valanginian age, unconformably overlie the Chia Gara Formation. The upper contact with the Albian Mauddud (Upper Qamchuqa) Formation is conformable.

11.1.1.2.3 Lower Balambo Formation

The Balambo Formation was first described by Wetzel in 1947 (Bellen et al., *1959)* from the Sirwan valley near Halabja in NE Iraq. It can be divided into two units of Valanginian-Middle Albian and Late Albian-Turonian age, representing the Lower and Upper Balambo respectively. The formation as a whole was deposited in a deep water bathyal environment in an outer shelf basin near the margin of the Arabian Plate in NE Iraq.

The Lower Balambo Formation comprises 280 m of uniform thin bedded blue ammonite bearing limestones, with beds of olive green marl and dark blue shale (Bellen et al., 1959). The "Balambo Formation" in well Pulkhana-5 of the Kirkuk Embayment of the Foothill Zone (Humphreys et al., 1959) is composed of grey-brown micritic limestones, with beds of argillaceous limestone, marl and blue grey calcareous shales. The Lower Balambo Formation passes into the Qamchuqa (Mauddud and Shu'aiba) and Sarmord formations to the Wand SW.

Fossils are abundant. Bellen et al. (1959) recognised three faunal zones in the Hauterivian-Valanginian part of the formation. These comprise from the base upwards: ***1.*** *Crioceras* Zone with: *Crioceras plicatilis,* C. *raricostatum, Neocomites houdardi, Olcostephanus sp. Bochianites neocomiensis, Kilianella bochianenensis, K.ischnotera, Neocosmoceras cf sayni.* **2**. *Hoplites* Zone with? Criocera *plicatilis, Crioceras sp., Neocomites houdardi, Olcostephanus sp., Distoceras sp., Acanthodiscus sp., Thurmannites sp., Holcodiscus sp.,* and *Hoplites karakash.* **3**. *Duvalia* Zone with *Hibolites sp., Phylloceras tethys,* and Radiolaria. The AptianBarremian part of the formation contalns Radiolaria and *Pseudohoploceras* sp.

The Albian parts of the "Balarnbo Formation" in well Pulkhana-5 contalns a foraminiferal fauna with *Hastigerinella subcretacea* and *Schackoina eicheli;* ammonites are absent.

11.1.2 Barremian-Aptian Sequence

The Barremian-Aptian Sequence comprises the following facies: 1) A clastic inner shelf (Zubair), 2) a carbonate ramp (Shu'aiba) over the Tikrit-Amara palaeoridge in S Iraq and the Qamchuqa Ridge in NE Iraq and 3) an outer shelf basin facies (Sarmord and Lower Balambo) in the High Folded and Balambo-Tanjero zones and the Kirkuk Embayment of the Foothill Zone of the Unstable Shelf.

The Barremian sediments comprise the clastics of the Zubair and Upper Ratawi (Ratawi Shale) for the Stable shelf which represent a delta/pro delta facies. The pro delta facies of the Ratawi Shale passes both upwards and westwards into the sandy Zubair deltaic facies (Fig. 11-8). Beyond the Tigris Subzone, the Ratawi Shale passes into the upper part of the Lower Sarmord Formation.

In Aptian time transgression led to deposition on a broad carbonate shelf over the former Zubair delta, and in the Foothill, High Folded and Balambo-Tanjero zones.

The formations included in this sequence are: the upper part of the Ratawi (Ratawi Shale), and the Zubair, Shu'aiba (Lower Qamchuqa), Lower Sarmord and Lower Balambo formations. The sequence is absent on the flanks of the Rutba Uplift in W Iraq.

11.1.2.1 Clastic-carbonate inner shelf

11.1.2.1.1 Zubair Formation

The Zubair Formation was introduced by Glynn Jones in 1948 from the Zubair oil field and amended by Nasr and Hudson in 1953 (Bellen et al., 1959). The formation comprises 380-400 m of alternating shale, siltstone and sandstone. The type section was divided into five informal sand and shale units used for reservoir description in the Zubair oil field. To the SW the proportion of shale in the formation rapidly decreases. **In** the Salman Zone (Awasil Ghalalsan-Safawi areas) the formation consists only of sandstone. The proportion of sandstone in the formation also decreases to the NE; the formation consists almost entirely of shale near Dujalla in Central E Iraq. The

Zubair Formation passes laterally into the limestone-marl of the Shu'aiba or Sarmord formations in the Buzurgan area.

The formation is thickest in the type area in S Iraq; the depocentre is located at the boundary of the Salman and Mesopotamian zones (Fig. 11-9).

The Zubair Formation is assumed to represent a prograding delta originating from the Arabian Shield (Ali, 1985; Zeigler, 2000, etc.). The sand isolith of the formation in central and S Iraq suggest influx of clastics from the NW in Central Iraq and probably from the SW in S Iraq.

Bellen et al. (1959) assigned a Hauterivian to Early Aptian age to the formation. A Late Hauterivian to Early Aptian age is given by Douban and Medhadi (1999) for the formation in Kuwalt.

The contacts of the formation are gradational and conformable in the central part of the basin. Towards the W in the Salman Zone, the lower boundary is unconformable and the Zubair Formation represents the lowermost unit of the Thamama Group. The upper boundary with the overlying Albian Sequence in the Salman Zone is unconformable.

In some wells on the W side of the Mesopotamian Zone and the Salman Zone in S Iraq, the Zubair Formation passes laterally into Ratawi and Yamama formations (Buday, 1980); in such case these sands may be the coastal clastics of the Yamama Formation. The Riyadh Formation of Saudi Arabia (Powers et al., 1966) is equivalent to the Zubair Formation. A succession of sandstones interbedded with marls and limestones of Valanginian-Barremian age in Jabal Abdul Aziz in Syria (Ponikarov et al., 1967) is equivalent to the Zubair Formation.

Fig. 11-8: Aptian Palaeogeography

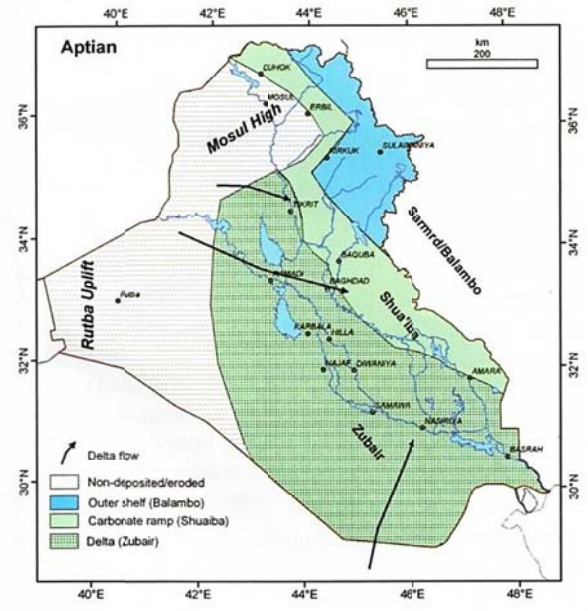
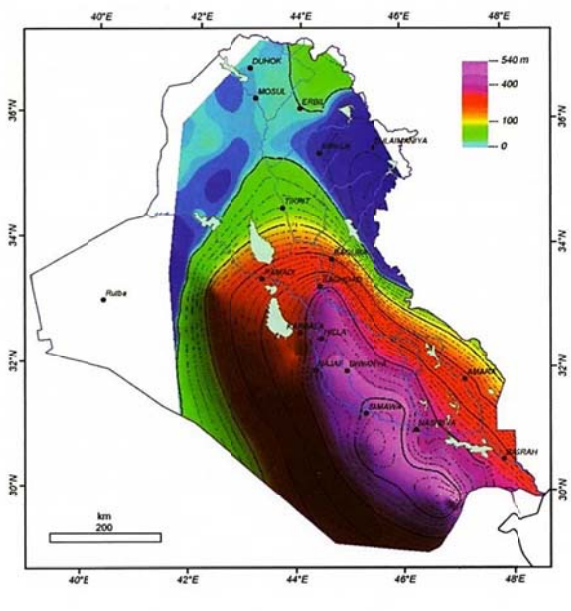


Fig. 11-9: Thickness of the Zubair Formation



11.1.2.1.2. Shu'aiba (including Lower Qamchuqa) Formation

The Shu'aiba Formation was first defined by Owen and Nasr in 1958 (Bellen et al., 1959) from well Zubalr-3 in S Iraq. It comprises 62 m of pseudo-oolitic limestone, sometimes sandy, fine-grained organodetrital limestone grading into chalky limestone and limestone with shale streaks near top. It contalns *Orbitolina cf. disco idea* Gras, *Choffatella decipiens* Schlumberger (at the base

only) and globogerinids which (together with the stratigraphic position of the formation) indicate an Aptian age. The formation overlies and passes laterally into the Zubair formation with a conformable and gradational contact. The upper contact is associated with a 6 Ma break in Kuwalt (Douban and Medhadi, 1999).

The Qamchuqa Formation was described from the Qamchuqa Gorge in the High Folded Zone in NE Iraq (Bellen et al., 1959). It comprises thick bedded limestones (often strongly dolomitised) of Hauterivian to Albian age. Subsequently, Chatton and Hart (1960) divided the Qamchuqa into a lower unit of Barremian-Aptian age and an upper unit of Albian age. The Shu'aiba and Mauddud formations of S Iraq are laterally extensive tongues of the Lower and Upper Qamchuqa formations respectively. It is proposed that Shu'aiba and Mauddud formations should replace the Lower and Upper Qamchuqa formations respectively and their ages should be amended. **In** outcrops in NE Iraq where the two units are difficult to differentiate, the term Qamchuqa Formation should be retained.

The thickness of the "Lower Qamchuqa Formation" in the High Folded Zone averages 250-300 m, exceptionally reaching 500 m. The thickness of Shu'aiba (including "Lower Qamchuqa") Formation in the subsurface is as follows: 19 m (K7 -7), 71 m (Tuba-1), 70 m (Tuba-1), 31 m (W Kifl-I), 53 m (Zubalr-47), 61 m (Ur-1), 63 m (Nasiriya-l), 189 m (Haifaya-l), 188 m (Noor-1), 69 m (Subba-5, 92 m (Rumaila-North-l), 96 m (Rifaei-1), 67 m (Ratawi-3), 70 m (Rachi-l), 31 m (Merjan-l), 35 m (Diwan-l), 108 m (E Bagdad-I), 57 m (Khidr-al-maa-1), 9 m (Ghalalsan-l), l35 m (Nahr-Umr-9), 164 m (Majnoon-11), 183 m (Halfaya-1), 135 m (Dujalla-l), 87 m (W-Qurna-148), 70 m (Rachi-1), 112 m (Abu-Amud-l), 79 m (Ratawi-o), l34 m (E-Abu Amud-l), 421 m (Abu-Khalma-1), 126 m (Siba-1), 167 m (Majnoon-l), 86 m (Ratawi-1), 91 m (Rumaila-L), 257 m (Tharthar-1), 234 m (Kirkuk-109), 298 m (Kirkuk-116), 214 m (Kirkuk-117), 153 m (Makhul-l), 50 m (Makhul-1), 34 m (Najmah-29), 64 m (Musayib-l), 150 m (Qara-Chauq-l), 36 m (Awasil-S), 55 m (Falluja-l), 38 m (Demir-Dagh-1), 163 m (Rachi-1), 113 m (Nahr-Umr-3), 33 m (Samawa-1), 41 m (Kifl-.l), 127 m (Dujalla-l), 3 m (Ash-Sharhan-1), 60 m (Samarra-1), 88 m (Rumalla-172). The formation is present in the Tigris Subzone and in the High Folded Zone and the Mosul High. **In** the Kirkuk Embayment, the formation passes into basinal sediments of Balambo Formation.

The lower contact is conformable except in the W parts of the Northern Thrust Zone near Banik where the "Qamchuqa" Formation unconformably overlies the Garagu Formation. The upper boundary of the formation is usually conformable in and NE Iraq. In the SW part of the Foothill Zone, in the • 1esopotamian Zone, and along the margins of the Salman Zone the upper contact is an unconformity.

To the NE the Lower Qamchuqa Formation passes into the Balambo Formation in the SW parts of the Balambo- Tanjero Zone. To the Wand SW the Shu'aiba Formation is present everywhere except on the Stable Shelf west of the Salman Zone.

The Shu'aiba Formation is widespread outside Iraq. It is present in NE Syria in the Suweidiyeh area (Dubertret, 1966). In central Syria and the Palmy rides pre Albian sediments are either absent or represented by the Rutbah Sandstone (Dubertret, 1966; Ponikarov et a1., 1967). In SE Turkey, adjacent to Iraq, the formation is included in the Cudi Group (Altinli 1966). In SW Iran, the Shu'aiba and Lower Qamchuqa formations are equivalent to the Dariyan and Neocomian Fahlyan formations respectively (Furst, 1970).

11.1.2.2. Outer shelf and Basinal

The outer shelf and basinal sediments of this sequence shelf are part of the Lower Sarmord Formation in the High Folded Zone area and the Lower Balambo Formation in the Balambo-Tanjero Zone. These two formations were discussed in sections 11.1.1.2.2 and 11.l.l.2.3.

11.2 Albian-Early Turonian Sequence (Wasi'a Group)

The Albian-Early Turonian Sequence is represented by the Wasi'a Group. It is present throughout Iraq, including the Rutba-Jezira Zone. It can be divided into two sequences: the Albian and the Cenomanian-Early Turonian sequences. The Wasi' a Group thickens (Fig. 11-10) towards the east in the Tigris Subzone and the Foothill Zone. Transversal faults strongly influence the thickness of the group especially along the Mosul High in N Iraq.

11.2.1 The Albian Sequence

The Albian sequence is separated from the underlying Aptian sequence by a major sequence boundary with a 6 Ma break in Kuwalt (Douban and Medhadi, 1999). This break is also evident throughout the Stable Shelf of Iraq but not within the Unstable Shelf area.

A carbonate ridge probably separated the pelagic Balambo basin in the Balambo-Tanjero Zone from the deep water continental margin on which the Qulqula radiolarites were deposited in Albian time (Chapter 3). At times silica-rich waters of the Southern Nee-Tethys flowed into the Balambo basin. To the SW, the basinal Balambo Formation passes laterally into the carbonate ramp of the Mauddud ("Upper Qamchuqa") located over the present day High Folded Zone and the NE part of the Foothill Zone (Fig. 11-11). The Qamchuqa ridge plunged towards the SE (across the Anah Qalat Dizeh Fault); basinal sedimentation continued within the Kirkuk Embayment to the SW. A change in facies can be observed in the Jambur structure; neritic carbonates occur in the NW, and basinal limestones occur in the SE of the Jambur anticline.

Clastic-carbonate inner shelf facies covered the Stable Shelf. A carbonate ramp developed within the Tigris Subzone over the Tikrit-Amara palaeoridge. The Mosul High subsided in Albian time with deposition of carbonates and evaporites of the lagoonal Jawan Formation and argillaceous lagoonal sediments of the Upper Sarmord Formation.

The Mesopotamian and Salman zones were characterised by a clastic inner shelf (Nahr Umr), which was later covered by a carbonate shelf (Mauddud Formation). During the Albian transgression almost the whole of the Stable shelf was submerged (apart from a small area on the Hauran Uplift in the Rutba Jezira Zone). The Nahr Umr clastics were partly derived from an uplifted area to the SW, partly from the Rutba Uplift in the Wand partly from the Mardin High in the N.

Originally the Nahr Umr, Mauddud, Jawan, Rim Siltstone, Qamchuqa and Balambo Formation were assigned to the Albian sequence. Chatton and Hart (1960) retained only the Nahr Umr Sands, Nahr Umr Shales and Qamchuqa formations. The Sarmord was included in the Nahr Umr Shale, the Mauddud and Jawan were considered as individual tongues of the Qamchuqa. The Rim Siltstone was considered to be equivalent to the Nahr Umr. However these recommendations were not followed by Ditmar and the Iraqi-Soviet Team (1971 and 1972).

The Nahr Umr and the Upper Sarmord are here recognized as independent units. The Upper Qamchuqa Formation is here replaced by Mauddud Formation. The undivided Hauterivian-Albian,

Qamchuqa Formation of N and NE Iraq should be retained as an independent unit (Qamchuqa Formation). The Rim Siltstone is here included within the Nahr Umr Formation.

The isopach of the Albian Sequence (Fig. 11-12) shows depocentres in the High Folded Zone of NE Iraq, the Foothill Zone of S Iraq, the SW boundary of the Mesopotamian Zone, and in the Sinjar area. An increase in thickness occurs in the Salman Zone, S of the Takhadid-Qurna Fault.

Fig.11-10: Thickness of the Wasi'a Group

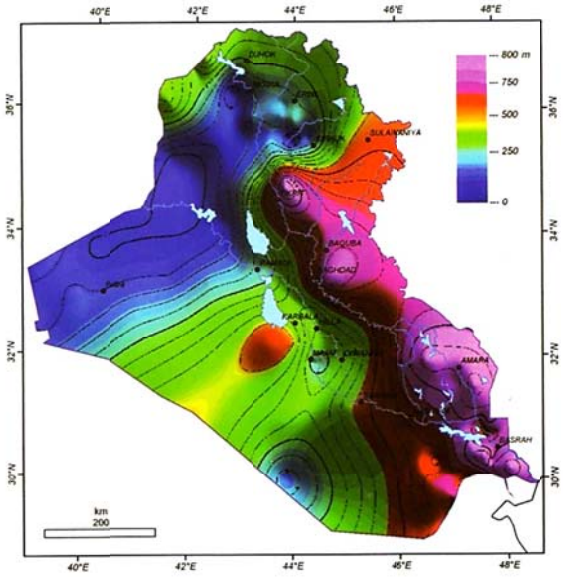
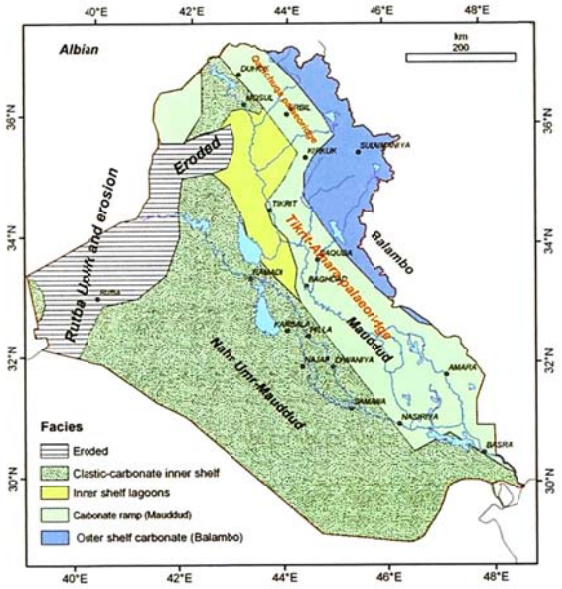


Fig. 11-11: Albian Palaeogeography



11.2.1.1 Clastic-carbonate inner shelf (Nahr Umr Formation, including Rim Siltstone)

The Nahr Umr Formation was defined by Glynn Jones in 1948 (Bellen et al., 1959) from the Nahr Umr structure in S Iraq. It is up to 360 m thick in the S parts of the Salman and Mesopotamian zones (Fig. 11-13). The formation is thickest in S Iraq and Kuwalt (around 400 m), south of Baghdad (160 m), and in NW Iraq (where the Rim Siltstone occurs). The two major depocentres in central and S Iraq correspond to areas which received clastics from the Rutba Uplift and the Arabian Shield.

In its type area in S Iraq, the Nahr Umr Formation comprises black shales interbedded with medium to fine grained sandstones with lignite, amber, and pyrite (Bellen et al., 1959). The proportion of sand in the formation increases towards the Salman Zone.

The "Rim Siltstone" of NW Iraq comprising 55-60 m of silty pyritic marls, marly siltstones, thin sandstones and anhydritic marls. It was derived from a different clastic source area to the Nahr Umr Formation.

The Nahr Umr Formation outcrops between Wadi Hauran in the NE and the Rutba-Baghdad motorway in the Sw. It is overlapped by Cenomanian clastics 50 km E or Rutba. The outcrop near Amij Oasis, N of the K160 settlement is 54 m thick and comprises a lower unit (43 m thick) of grey and yellow, cross-bedded ferruginous sandstone with a basal conglomerate, occasionally cemented by silica. The upper unit (11 m thick) comprises white and yellow sandstone with green sandy marl and reddish brown fossiliferous limestone. The formation is gradationally overlain by the Mauddud Formation; the contact is taken at the base of a 2 m thin bedded limestone bed. The

Nahr Umr Formation overlies the Saggar Formation. The formation thickens towards the east from 22 m 50 km E of Rutba to 54 m 140 km E of Rutba.

Ctyroky and Karim (1981; in Jassim et al., 1984) studied the outcrops of W Iraq and identified the foraminifera *Orbitolina cf. discoidea* Gras, *Haplaphragmoides sp.*, and *Cythereis sp.* Macrofossils include *Plicatula cf auressensis* Coquand, *Neithes cf dutrugi* Coquand, and *Exogyra cf. Dieneri* Blanckenhorn. The fauna from both surface and subsurface sections confirms an Albian age. In this context, the *Orbitolina cf. disco idea* is probably *O.ex gr. conca va.* The Rim Siltstone facies yielded no fossils (apart from some plant remains); it was assigned an Albian age based on its stratigraphic position.

The lower contact of the Nahr Umr Formation, according to Bellen et al. (1959) is conformable and gradational. However in Kuwalt, Douban and Medhadi (1999) recognized a 6 Ma age break at the base of the Burgan Formation (Nahr Umr-equivalent). The upper contact is generally conformable. However in the Butmah structure the Nahr Umr Formation is disconformably overlain by the basal conglomerate of the Mushorah Formation.

The Nahr Umr Formation is widespread throughout the Mesopotamian Zone. It passes to the NE into the Mauddud Formation and partly into the Upper Sarmord Formation.

The Nahr Umr Formation is a lateral equivalent of the Burgan Formation in Kuwalt (Douban and Medhadi, 1999; Sharland et al., 2001). In SW Iran the formation passes into the shales and limestones of the Kazdhumi Formation (Furst, 1970). It also correlates with the Rutbah Sandstone of the Palmyrides (Brew et al., 1999) and the Kurnub Sandstone penetrated in Risha wells of NE Jordan.

Fig. 11-12 Thickness of the Albian sequence

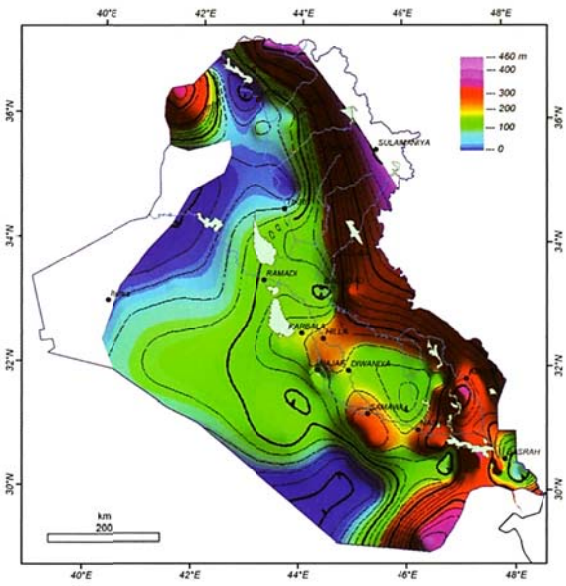
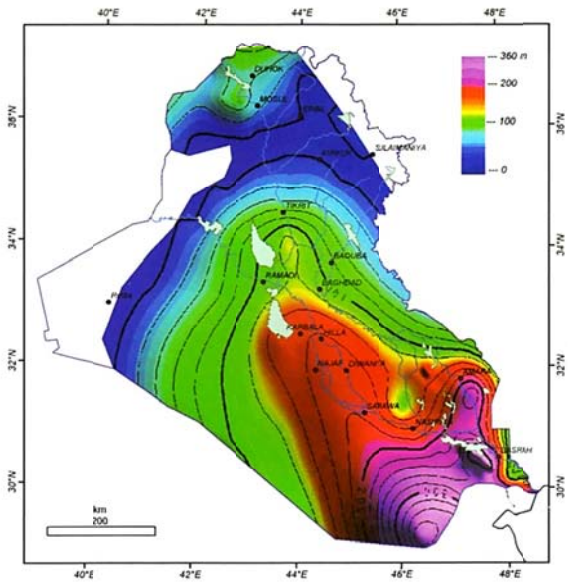


Fig. 11-13: Thickness of the Nahr Umr Formation (including Rim Siltstone)



11.2.1.2 Carbonate ramp (Mauddud Formation, including U Qamchuqa)

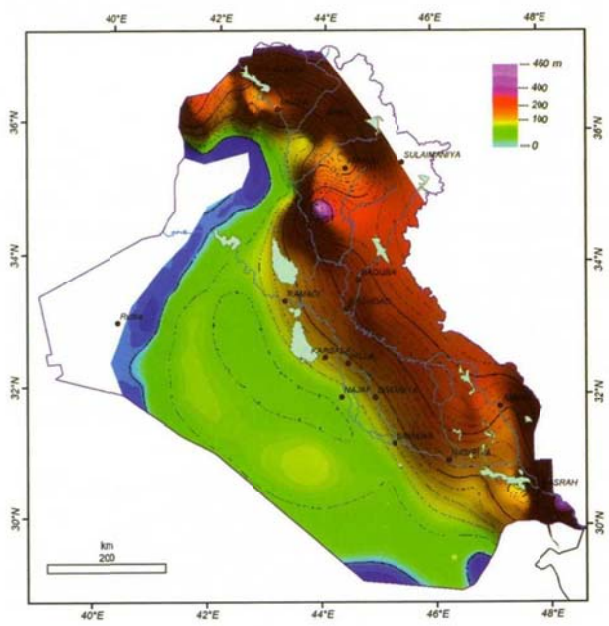
The Mauddud Formation includes the Upper Qamchuqa and is the most widespread Lower Cretaceous formation in Iraq. Its thickness varies due to lateral facies changes and erosional truncation (Fig. 11-14). The formation is present on the Stable Shelf (apart from the N part of the Rutba-Jezira Zone), and in the Foothill and High Folded zones. It is thickest on the Qamchuqa Ridge of the High Folded Zone. Two major depocentres are separated by the Mosul High. The northern depocentre is in the Foothill Zone, trending E- W, swinging to NW-SE in the High Folded Zone. The thickness of the formation decreases in the SE across the Anah-Qalat Dizeh Fault where the formation passes into basinal limestones of the Balambo Formation. The southern depocentre trends in a NW-SE direction along the NE boundary of the Mesopotamian Zone on the Tikrit-Amara palaeoridge of the Tigris Subzone. The Mauddud Formation also outcrops in W Iraq along the SE flank of the Hauran Anticlinorium.

At outcrop in NE Iraq (Plate 11-3) the Qamchuqa Formation comprises organodetrital and detrital and locally argillaceous limestones with variable degrees of dolomitisation (Bellen et al., 1959). In some areas fresh- or brackish-water limestone beds were reported (Bellen et al., op. cit.). In S Iraq, the Mauddud Formation comprises frequently dolomitised organodetrital limestone.
The thickness of the Albian carbonates in N Iraq reach 400 m. In the subsurface the formation is 50-250 m thick.
Abundant fossils (Bellen et al., 1959) support an Albian age. The formation was originally believed to extend into the Cenomanian because of the frequent occurrence of some species of the *Orbitolina concava* group (Bellen et al., 1959). In W Iraq the fauna of the formation is of Albian age only (Ctyroky and Karim, 1981; in Jassim et al., 1984).

The lower contact of the Mauddud ("Upper Qamchuqa") Formation is conformable and gradational with the Nahr Umr, Lower Balambo or Lower Sarmord formations. The upper contact is marked by a break and is either non sequential or unconformable; it is an unconformity in N Central, N and NE part of Iraq. The "Upper Qamchuqa" is here directly overlain by Turonian formations, for example in the Makhul and the Mileh Tharthar areas (Templeton et al., 1956; Hay and Algawi, 1958). The upper boundary of the formation is also marked by an unconformity in the Rutba Subzone (Jassim et al., 1984) and in Kuwalt (Douban and Medhadi, 1999).
In Kuwalt the Mauddud Formation was deposited during a highstand in a shallow inner shelf environment of Late Albian age developing from the transgressive Low Stand of the Burgan Formation (Douban and Medhadi, 1999).

The Mauddud ("Upper Qamchuqa") Formation passes into the Balambo Formation on the NE part of the High Folded Zone. On the Mosul High the formation passes into the Upper Sarmord or Jawan formations. In some uplifted areas the Mauddud Formation overlies pre Albian sediments, for example in Kirkuk and over most of the Northern Thrust Zone.
In Syria in the Palmyrides and central Syria, the neritic dolomitic limestones of the upper part of the Aasafir Formation are equivalent to the Mauddud Formation (Ponikarov et al., 1967). In SW Iran the Albian part of the Sarvak Formation is also equivalent to the Mauddud Formation (Furst, 1970).

Fig. 11-14: Thickness of the Albian carbonate unit (including Mauddud, "U Qamchuqa" and Jawan)



11.2.1.3 Inner shelf lagoons

11.2.1.3.1 Upper Sarmord Formation

The Upper Sarmord Formation occurs in the subsurface between Kirkuk in the E and Mosul in the W. This area was separated from the Balambo basin by the Qamchuqa carbonate ramp situated on the High Folded Zone. The association of the formation with the partly evaporitic Jawan Formation suggests that it was deposited in a lagoon developed to the SW of the Qamchuqa Ridge. Chatton and Hart (1960) replaced the name of formation by the term Nahr Umr Shale. The thickness of the Upper Sarmord is 169 min Kirkuk-109, 110 m in Kirkuk-116, 79 m in Kirkuk117, 73 m in Najmah-29, 94 m in Qara-Chauq-l and 62 m in Demir-Dagh-1. The formation thickens from SW to NE.

The Sarmord Formation, at its type locality, does not include Albian sediments. In the SE part of the Foothill Zone and the Mesopotamian Zone the Upper Sarmord passes into the Nahr Umr Formation.

The Upper Sarmord Formation in the Foothill Zone comprises marls with neritic limestone beds. Sediments previously assigned to the formation in the Kirkuk and Bai Hassan fields by Ditmar and the Iraqi-Soviet Team (1971) comprise dolomitic limestones and dolomites of probable Aptian age which would be better placed in the Shu'aiba Formation (Bellen et al., 1959).

Fossils reported by Bellen et al. (1959) confirm an Albian age.

The lower contact of the formation in the E is gradational and conformable. In the W, the Upper Sarmord Formation unconformably overlies the Najmah or Sargelu formations. The upper contact with the Mauddud Formation is usually conformable and gradational.

11.2.1.3.2 Jawan Formation

The Jawan Formation was defined by Dunnington in 1953 (Bellen et al., 1959) in well Jawan-2 (SW of Mosul) in the Foothill Zone. It was abolished by Chatton and Hart (1960). It comprises > 176 m of pseudoolitic, argillaceous and recrystallised limestones, argillaceous dolomite and anhydrite (Bellen et al., 1959). A prominent anhydrite unit was differentiated as the Hibbarah Anhydrite Member by Dunnington (1953). In the Makhul area a different facies of the formation was recognized, comprising thin siltstone beds and limestone with euhaline fossils.
The formation is also present in wells Kirkuk-117 (137 m), Makhul-l (222 m), Makhul-2 (276 m), Najmah-29 (150 m), Ibrahim-l (11 m), Awasil-5 (74 m) and Fallujah-l (129 m). In well K-116 (152 m) the formation is interbedded with the Mauddud Formation. This data suggests the formation occurs between the Mosul area in the NW, the Falluja area in the S and the Kirkuk area in the NE (Fig. 11-10).

The Jawan Formation unconformably overlies the Najmah Formation in well Qalian-l but in many wells SW of the Mosul High it unconformably overlies the Shu'aiba Formation. Near Kirkuk the formation conformably overlies the Upper Sarmord Formation. The upper contact is gradational and conformable in areas where the formation occurs as a tongue within other Albian formations at Qara Chauq and Makhul (Templeton et al., 1956). In all other areas the formation is unconformably overlain by the Turonian Kometan Formation.
The Jawan Formation was deposited in a restricted lagoonal environment. To the Sand SW the formation passes into the Mauddud Formation in Makhul-2 (Templeton et al., 1956). Homci (1975) traced the formation to the Falluja area in the northern Mesopotamian Zone.
The formation is equivalent in age and facies to the evaporitic Albian sediments in Syria which occur along the SE margin of the Palmyrides (Ponikarov et al., 1967).

11.2.2 The Cenomanian-Early Turonian Sequence

Deformation along the NE Tethyan margin of the Arabian Plate in Cenomanian-Early Turonian time (Chapter 3) led to the reactivation of longitudinal ridges and transversal blocks such as the Mosul High and the Kirkuk Embayment. The Cenomanian Sea transgressed onto the Rutba and Mosul Highs, which re-emerged during the Early Turonian. Deposition of the pelagic Balambo Formation (of globigerinal and partly oligosteginal facies) continued in the Balambo- Tanjero Zone.

On the Shelf (apart from the major Rutba and Mosul Highs) some NW-SE trending ridges divided the basin into smaller basins, causing facies variations. Major facies belts of the Cenomanian-Early Turonian Sequence comprise: 1) A western clastic-carbonate inner shelf on which clastics of the Rutba Formation, followed by coastal and supratidal carbonates of the M'sad Formation were deposited. 2) A deep inner-middle shelf sea in which deeper water limestones and marls of the Rumaila Formation were deposited. 3) A belt of shoals and rudist patch reefs of the Mishrif Formation which formed above actively growing structures within the Rumaila basin. 4) A deep water basin developed along the plate margin (Balambo- Tanjero Zone) in which the basinal limestones of the Upper Balambo Formation were deposited. This basin shifted towards the SW and encroached on the Foothill Zone in the Kirkuk Embayment. 5) An isolated deep basin, which formed between the Balambo basin in the NE and the Rumaila basin in the Sw. It occupied the area of the Foothill Zone, especially the Kirkuk Embayment, in which the euxinic shales of the

Gulneri Formation and the basinal oligosteginal limestones of the Dokan Formation were deposited (Fig. 1114). 6) The lagoonal inner shelf desiccation basin of the Kifl Formation which is the youngest unit of the sequence developed in the Mesopotamian Zone; it is not shown on the palaeogeographic map of Fig. 11-15.

In NW Iraq a relatively small basin (mainly in the Sinjar area) developed in which carbonates of the Gir Bir and Mergi formations were deposited; these facies are now included in the Mishrif Formation.

The stratigraphy of the Sequence was revised by Chatton and Hart (1961). They included the neritic, partly reef-forming limestones of the M'sad, Gir Bir, and Mergi formations in the Mishrif Formation. They included the Maotsi, Fahad, and Mahliban formations in the Rumaila Formation. They introduced the Kifl Formation as a new formation.

The recommendations of Chatton and Hart (1961) are mostly accepted here, but the M'sad Formation is retained as an independent unit. Regional mapping of W Iraq by GEOSURV showed that the M'sad Formation is partly of supratidal-coastal facies.

The isopach of the Cenomanian-Early Turonian Sequence (Fig. 11-16) shows two areas of significantly reduced thickness over the Rutba Uplift and along the Euphrates River near Najaf. The sequence is thickest in the N (including the Sinjar trough), in central Iraq near Ramadi, and in S Iraq in the southern part of the Mesopotamian and Salman zones.

11.2.2.1 Clastic-carbonate inner shelf facies

11.2.2.1.1 Rutbah Formation

The Rutbah Sandstone (as originally named) was deposited following the Cenomanian transgression on the Stable Shelf in Iraq. It is restricted mainly to the area west of the Salman Zone. The formation was defined by Foran and Keller in 1937 (Bellen et al, 1959) from the Rutba area of W Iraq. It comprises 30-40 m of white to varicoloured fine to coarse grained, cross-bedded quartz sands (sometimes ferruginous) which are locally calcareous or argillaceous. It varies in thickness from a few metres (Ga'ara area) to 30-40 m near Rutba. It thins to the E due to passage into the M'sad Formation.

The formation was deposited mostly in a continental to occasionally marginal marine environment. Antonets et al. (1962) reported marine fossils from the upper part of the formation. Subsequent mapping in W Iraq confirmed the presence of *Ceratostreon spinosum* Matheson, *Strombus incertus* d'Orbigny, gastropods and oysters. The age of the formation was assumed to be Cenomanian (Bellen et al., 1959; Antonets et al., 1962) since it passes laterally into the M'sad Formation. The presence of *Strombus incertus* d'Orbigny suggests a Cenomanian-Turonian age range. However the confirmed Late Cenomanian age of the basal part of the overlying M'sad near Rutba (Bellen et al., 1959) indicates the age of the Rutbah formation is restricted to the Cenomanian.

The lower contact of the formation is unconformable. In the type area the underlying formation is the Upper Triassic Mulussa Formation; 10 km E of Rutba it overlies the Upper Jurassic? Saggar Formation and 55 km E of Rutbah it overlies the Mauddud Formation. On the W rim of the Ga'ara depression it overlies the Permian Ga'ara Formation. The formation passes up into the M'sad Formation except on the western rim of the Ga'ara depression where it is unconformably overlain by the Upper Campanian Hartha Formation.

The Rutbah Formation is equivalent to the Sakakah Sandstone of the Wasi'a Group of Saudi Arabia (Powers et al., 1966). In NE Jordan it passes into the carbonates of the Wadi As Sir Formation. In Syria, the name Rutbah Sandstone has been applied to a different formation of Early Cretaceous age. The Cenomanian clastics disappear in SE Syria where they are overstepped by Maastrichtian sediments.

11.2.2.1.2 M'sad Formation

The M'sad Formation was described by Henson in 1940 (Bellen et al., 1959) from Wadi M'sad, a tributary of Wadi Hauran in its type section 30 km S of Rutba Town in W Iraq, as about 65 m of alternating shallow marine limestone, buff and white chalky limestone, with beds of marl and sand near the base. Later surveys of the region indicated that the type section of the formation included Campanian sediments (Jassim et al., 1984); the thickness of the formation has thus been reduced to 35 m.

The M'sad Formation is exposed in an E- W belt running from S of Rutba towards the E and just S of the main Baghdad-Rutba motorway. The outcrop can be followed from the area SW of Rutba to the western rim of the Ga'ara depression, where it is overstepped by the Campanian Hartha Formation. It conformably overlies the Rutbah Formation throughout its outcrop area and the Mauddud Formation in water wells on the Salman Zone.

The revised description of the type section is from the base: 1) 20 m of alternating siltstone, marl and sandstone with beds of organodetrital or shelly limestone. 2) 25 m of interbedded calcareous siltstone, dolomitic limestone, dolomite with fenestral porosity and birds eye texture, and subordinate marl and sandstone. The formation comprises several cycles; each cycle is 2-10 m thick and begins with sandstone (locally glauconitic) passing up into fine-grained silty sandstone and dolomite.

The thickness of the M'sad Formation varies from 45 m near Rutba to 97 m near Kl60 settlement (140 km E of Rutba) where it totally replaces the Rutbah Formation. It thins towards Ga'ara in the N.

The following macrofauna occurs in the M'sad Formation in the Rutba area: *Protocardita cf coquandi* Sequenza, *Cyprimeria deletteri* Coquand, *Barbatia sp., Pinna sp., Trigonia sp., Cardita cf forgemoli* Coquand, *Eoradiolites sp., Nerinea sp., Nerinea cochlaeformis* Conard and *Strombus incertus.* The microfauna includes *Dentalina sp., Spiroplectammina sp., Quinquelocuilina sp., Nezzazata sp., Nummoloculina sp., Marssonella sp., Dorothia sp., Pithonella sphaeritica* Kaufman and *P ovalis* Kaufman.

The macro fauna identified in the area 50 km E of Rutba includes: *Exogyra flabellata* Sowerby, *Rhynchostreon cf colombus* Noettling, *Lopha dichostoma* Bayle, *Trigonia pseudocrenulatus* Noettling, *Protocardium hillanum* Sowerby, *Pseudoptera sp., Neitheia cf quinquecostata* SAW, *Ceratostraeon cf flabellatum* Goldfus, *Ceratostreon sp., Terebratula sp., Micraster cf cortestudinarium* Goldfus, *Ceratostreon spinosum* Matheson and *Heteraster sp.* The microfauna includes: *Gavelinella sp., Cuneolina sp., Lituola sp.,* Alveolinids ?, textularids, miliolids, and rotaliids. Fragments of rudists, echinoids and bryozoans occur.

The faunas indicate the formation is of Cenomanian-Early Turonian age. *Exogyra flabellata* also occurs in the upper part of the Kazhdumi Formation of SW Iran.

The M'sad Formation contalns the following sedimentary structures: massive bedding, ball and flow structures, false bedding, cross bedding (trough and tabular) and trace fossils and fenestral porosity. Near Rutba the formation was deposited in a supratidal to intertidal environment with abundant clastic influx. East of Rutba, the formation is composed of dolomite with cryptalgal structures and nodular dolomicrite. Further to the east, near K 160 settlement, the formation consists of finely crystalline dolomite, sandy dolomite, laminated cryptalgal dolomite and nodular argillaceous dolomite. This lithofacies association indicates it was deposited on algal flats and in lagoons with restricted circulation and with occasional influx of clastic sediment.

Fig. 11-15: Cenomanian Palaeogeography

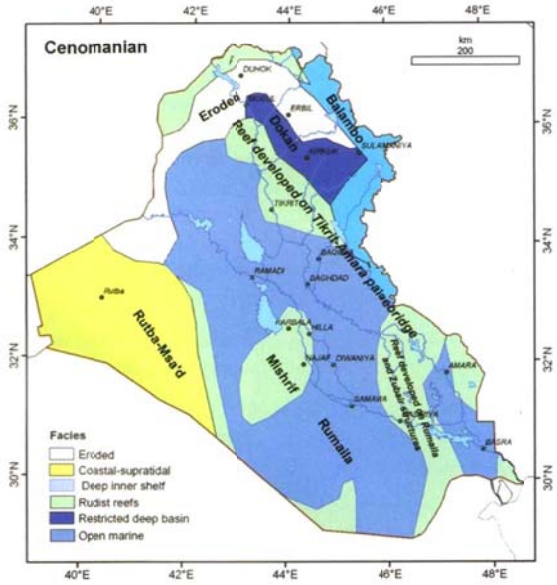
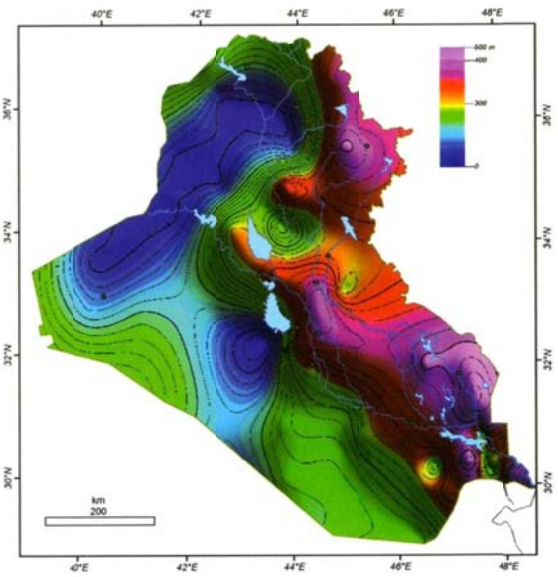


Fig. 11-16: Thickness of the Cenomanian-Lower Turonian Sequence



11.2.2.1.3 Ahmadi Formation

The Ahmadi Formation occurs in S Iraq. In the type section from the Burgan wells of Kuwalt, the formation is composed of grey shale passing up into green to greenish grey and chocolate brown shale. A limestone bed, characterized by the ostracod species *Cythereis bahralni* occurs the base of the formation (referred to as the *Cythereis bahralni* limestone, Bellen et al., 1959). The reference section for Iraq in Zubalr3 well comprises from the base upwards: grey detrital spicular limestone, unfossiliferous micritic limestone, and black silty shales (Bellen et al., 1959).

In Kuwalt the Ahmadi conformably overlies the Wara Formation which comprises fine-grained sandstones and siltstones, with interbedded grey shales. The Wara Formation has also been recorded in the Basra area (Owen and Nasr, 1958 and Bellen et al., 1959), where the unit is reduced in thickness and consists of black silty shales. However these shales are here placed in the basal part of the Ahmadi Formation.

The Ahmadi Formation is up to 160 m thick. The formation thins towards the north and east and passes into the Rumaila Formation. The Ahmadi formation occurs in most wells drilled in central and S Iraq. It is thickest in the Mesopotamian Zone in S Iraq and in the southern Salman Zone, to the N of the Takhadid-Qurna Fault and S of the Sirwan Fault. In central Iraq, the formation is restricted to the western Mesopotamian Zone (Fig. 11-17). To the east it passes into the Rumaila Formation; to the west it passes into the lower part of M'sad or Rutbah formations.

The Ahmadi Formation was deposited in a shallow marine basin with fine clastic sediment supply from the south.

Relatively abundant fossils in the formation in the Kuwalt (Bellen et al., 1959) prove a Cenomanian (probably Early Cenomanian) age.

The Ahmadi Formation overlies conformably the Wara Formation in Kuwalt. In Iraq the Ahmadi Formation unconformably overlies the Mauddud Formation. The formation is usually overlain conformably and gradationally y the Rumaila Formation.

11.2.2.2 Deep inner shelf facies (Rumaila Formation)

The Rumaila Formation is the most widespread Cenomanian formation in Sand SW Iraq and extends as far north as the Makhul area in the N. It was first described from the Zubair wells of the Mesopotamian Zone by Rabanit in 1952 (Bellen et al., 1959). Owen and Nasr (1958) assigned a Cenomanian-Turonian age to the formation. Bellen et al. (1959) and Chatton and Hart (1961) restricted the age of the formation to the Cenomanian.

In the type area the formation comprises fine-grained, marly, oligosteginal limestones with marls passing down into fine-grained, chalky limestones. Beds of dolomite, dolomitic limestones and subordinate shales occur in some wells.
The Mahliban, Fahad, and Maotsi formations of the Awasil- Samarra area are now all considered to be equivalents of the Rumaila Formation. The Mahliban "Formation" comprises oligosteginal, marly limestones, with oolitic and pseudoolitic, partly detrital, marly limestones at the base. The basal beds of the Mah1iban "Formation" are sandy and conglomeratic, similar to the facies of the M'sad Formation exposed to the west. The Fahad "Formation" (Bellen et al., 1959) comprises fine-grained, organic detrital, argillaceous, oligosteginal limestones. The basal beds of the Fahad Formation are glauconitic and conglomeratic. The Maotsi "Formation" comprises argillaceous oligosteginal limestones with beds of marl. It is exceptionally detrital, silty and glauconitic at the base (Bell en et al., 1959).

The Rumaila Formation is usually 100-120 m thick in the type area. In the Awasil-Falluja-Samarra area the thickness of the formation increases up to 240 m and is thickest in depocentres in the Salman Zone and in the eastern Mesopotamian Zone (Fig. 11-18).

The Rumaila formation was deposited in a relatively deeper basin which was locally restricted in the north (indicated by the dwarfed character of the fauna).

The age of Rumaila Formation ranges from Cenomanian to Early Turonian (Chatton and Hart, 1961).

In the type area and in S Iraq in general, the lower boundary of the formation with the Ahmadi Formation is conformable and gradational. Towards the N, the lower boundary is an unconformity; the basal beds of the formation are here locally conglomeratic. In the S, the formation is conformably overlain by the Mishrif or Kifl formations. In N part of the Mesopotamian Zone the formation is unconformably overlain by the Turonian (Kometan) or Senonian Sa'di formations.

The formation is widespread mainly on the Stable Shelf to the E of the Rutba-Jezira Zone and west of the Tikrit-Amara palaeoridge. In the E and NE parts of the Rumaila basin the formation is

progressively replaced by the Mishrif and finally wedges out along the NE margin of the Mesopotamian Zone. Towards N Mesopotamia, the Rumaila Formation extends as far as Samarra. Homci (1975) considered that the Rumal1a Formation was present in the Makhul area. It extends into Kuwalt where it passes further SE into the Magwa Formation (Owen and Nasr, 1958).

Fig. 11-15: Cenomanian Palaeogeography

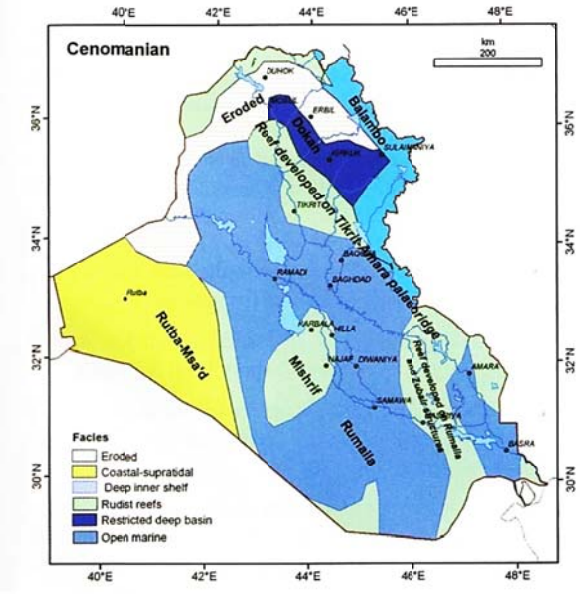
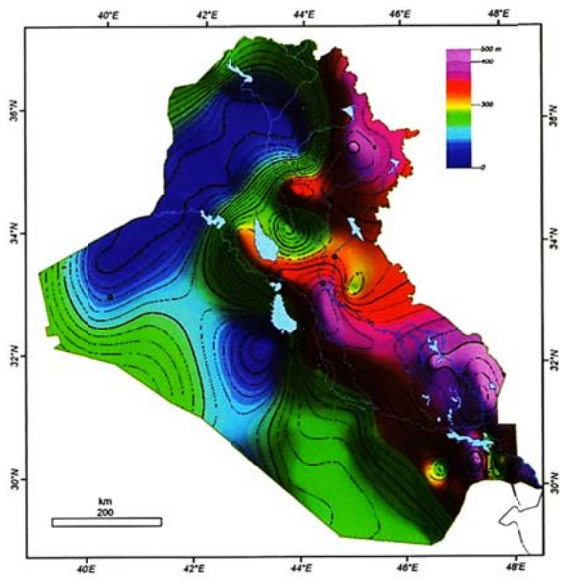


Fig. 11-16: Thickness of the Cenomanian-Lower Turonian Sequence



11.2.2.3 Rudist reefs (Mishrif Formation, including Gir Bir)

The Mishrif Formation represents a heterogeneous formation originally described as organic detrital limestones, with beds of algal, rudist, and coral-reef limestones, capped by limonitic fresh water limestones (Bellen et al., 1959).

Chatton and Hart (1961 and 1962) included all the organic detrital neritic limestone units of Cenomanian-Early Turonian age, such as the M'sad, Gir Bir, and Mergi formations in the Mishrif Formation. They placed the freshwater limestone in the newly introduced Kifl Formation. Ditmar and the Iraqi Soviet Team (1971) continued to recognize the Gir Bir and M'sad as separate formations. The Gir Bir and Mergi formations are here included in the Mishrif but the M'sad is retained as an independent unit because of its distinctive facies. Unlike the Mishrif Formation, the M'sad Formation was deposited in a coastal, locally supratidal environment.

The Mishrif Formation in its type area is composed of grey-white, dense, algal limestones with gastropods and shell fragments above, and of brown, detrital, porous, partly very shelly and foraminiferal limestones, with limestones with rudist debris below. The formation is variably dolomitised Wand NW of the type section. The Gir Bir Formation in NW Iraq consists of recrystallised and dolomitised limestone with ubiquitous organic detritus. The Mergi facies of N Iraq consists of massive, thick bedded recrystallised limestones which are conglomeratic and dolomitised at the base with abundant rudist debris. In the NW Foothill Zone the Mishrif is represented by recrystallised dolomitised limestones originally described by Dunnington (1956) as the Gir Bir Limestone Formation. The abundant fauna listed by Bellen et al. (1959) indicates the formation is of Cenomanian-Early Turonian age.

The Mergi facies in N Iraq is considered to be of Turonian age (Bellen et al., 1959).
The formation thins towards the Wand NW, passing laterally into the Rumaila Formation (for instance in the Kifl, Ghalalsan or Shawiya wells (Raleigh, 1960, 1961 and Halliwell, 1961) or into the Fahad facies of the Rumaila in the north (around Awasil and Falluja). In the Afaq, Dujalla and Samarra areas the Mishrif and Rumaila formations interfinger (Safar, 1961 and Johnson, 1961).

The Mishrif formation (Fig. 11-19) is thickest in the Rumaila and Zubair fields (270 m), in the Nahr Umr and Majnoon fields along the Iraq-Iran border (435 m), and in the A Amud field between Kut and Amara (380 m). Other isolated occurrences are situated near Kifl (255 m) and Samarra (25 m). In the western desert some rudist limestones of the M'sad Formation outcrop about 100 km ESE of Rutba (5 m). The formation was deposited as rudist shoals and pate reefs over growing subtle structural highs developing in an otherwise relatively deeper shelf on *which* open marine sediments of the Rumaila Formation were deposited.

The lower contact of the formation is usually conformable. The underlying unit is usually the Rumaila Formation in the S, and the M'sad Formation in the W. In the northern most area where the Mergi and Gir Bir facies occur, the lower boundary is unconformable and those units overly the Albian Mauddud (Upper Qamchuqa) Formation. The upper boundary is unconformable in the Awasil-Samarra area of central Iraq and in the Foothill and High Folded zones (Gir *Bir* and Mergi occurrences). In parts of S Iraq, where the Kifl Formation is present *(i.e.* in the basin roughly to the west of the Musalyib-Nahr Umr palaeoridge) the upper contact is conformable. Where the Kifl is absent the top of the Mishrif Formation is marked by an unconformity. The Kifl Formation progressively wedges out to the south (towards the Burgan Structure in Kuwalt) due to Intra Turonian erosion or because of non-deposition.

The Mishrif Formation passes *into* the M'sad Formation towards the Rutba Subzone. Rudist limestone lenses in the M'sad were mapped in an area about 100 km SE of Rutba. Towards the N and NE the formation passes laterally into the Fahad "Formation" in the Dujalla, Falluja, Samarra wells (Safar, 1951, Gaddo et al., 1958, Johnson, 1961), and partly into the Dokan and Maotsi Formation in the Bai Hassan, Sasan, Samarra wells (Ditmar and the Iraqi-Soviet Team, 1971). The formation is absent over most of the Mosul High. West of the Mosul High on the Foothill and High Folded zones, the Mergi and Gir Bir facies of the Mishrif are locally preserved, for instance in the Gullar, Mushorah, and Shiranish areas.

The formation is equivalent to the Mishrif Formation and the upper part of the Magwa Formation in Kuwalt (Owen and Nasr, 1958), to the Sarvak Formation in the Zagros (Furst, 1970), to the lower part of the Judea Formation in central and NE Syria (Ponikarov, 1967; Dubertret, 1966), and to the Mardin Formation in SE Turkey (Beer, 1966 and Weber, 1963).

Fig. 11-17: Thickness of the Ahmadi Formation

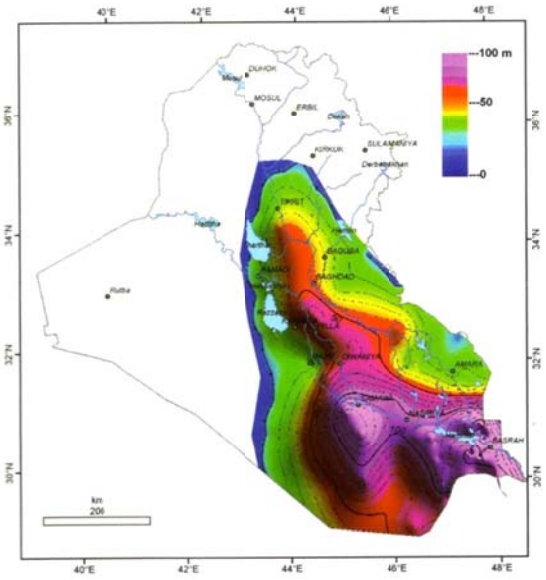


Fig. 11-18: Thickness of Rumaila Formation

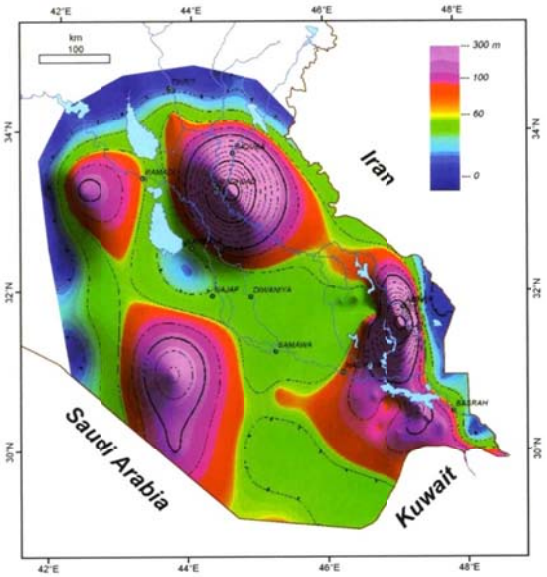
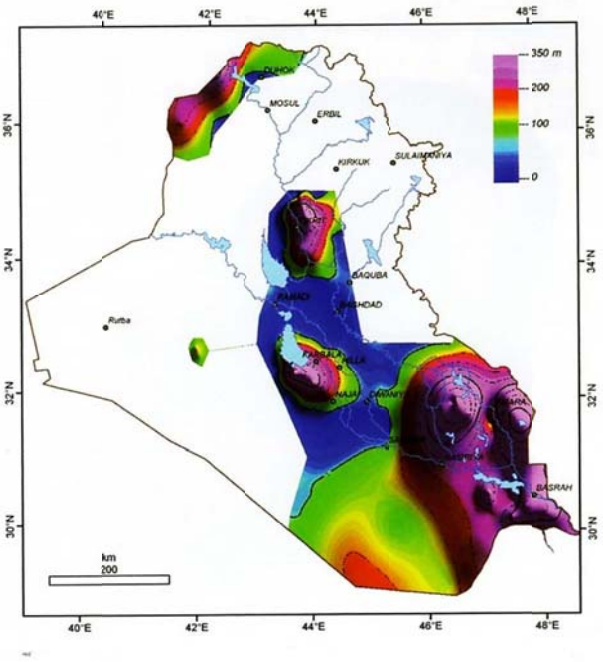


Fig. 11-19: Thickness of the Mishrif Formation and Gir Bir formations



11.2.2.4 Evaporitic inner shelf lagoonal facies (Kifl Formation)

The Kifl Formation was first introduced by Chatton and Hart (1961) in well Kifl-l in central Iraq. Previously it was included in the Rumaila, Mishrif or Fahad formations. It comprises anhydrite and oolitic and pseudo-oolitic limestone. The thickness of the formation in the type well is 19 m increasing to 45 m towards Baghdad. It Occurs in numerous wells in central and S Iraq, including Nasiriya-I (20 m), Merjan-l (17 m), E Bagdad-I (45 m), Ghalalsan-l (10 m), Samawa-l (26 m), Shawiyah-l (5 m), Ubaid-l (15 m), Kifl-2 (20 m) and Afaq-l (13 m).

The depocentre of the formation lies in S Central Iraq.

No fossil list was given by Chatton and Hart (1961) but a Turonian age was assumed based on its stratigraphic position. A Cenomanian age is unlikely but cannot be excluded. The formation is probably equivalent to the supratidal upper part of the M'sad Formation in W Iraq.

11.2.2.5 Restricted deep basin facies (Dokan and Gulneri formations)

The Dokan Limestone was formerly included in the Kometan Formation. It was first described as a separate formation by Lancaster and Jones in 1957 (Bellen et al., 1959). The type locality is on the site of the Dokan Dam in the High Folded Zone of NE Iraq. It comprises 4 m of light coloured grey and white oligosteginal limestone, locally rubbly, with glauconitic coatings of the pebble-like masses (Bellen et al., 1959, p. 92). In the subsurface the limestones are dark grey and often argillaceous. The formation thickens to the SW reaching 150 m in the Chemchemal wells. Further W it is 5-30 m thick in the Kirkuk, Bai Hassan, Demir Dagh, Qara Chauq areas.

The presence of ammonites indicates the formation was deposited in an open marine environment. The fauna in the type locality and in Bai Hassan (Ditmar and the Iraqi-Soviet Team, 1971) confirm the formation is of Cenomanian age.

Both the lower and upper contacts of the formation in the type area are unconformable. In the Bai Hassan area the basal beds of the Dokan Formation are conglomeratic (Ditmar and the Iraqi-Soviet Team, 1971) In Chemchemal the base of the Dokan Formation is glauconitic. The overlying formations are of Turonian age, mostly represented by the Kometan Formation. To the NW the formation is cut out by the intra Turonian unconformity; to the NE the formation passes into the Balambo Formation.
The Dokan Formation occurs in a restricted area in the High Folded and Foothill zones, SE of the Mosul High.

The Gulneri Shale Formation is a thin, highly condensed, unit which is locally preserved at the top of the Cenomanian-Early Turonian Sequence. Stratigraphic breaks occur at the base and top of the formation. The formation was first described by Lancaster Jones in 1957 from the site of the Dokan Dam in the High Folded Zone, NNW of Sulalmaniya, where it consists of about 2 m of black, bituminous, finely laminated, calcareous, shale with some glauconite and collophane in the lower part (Bellen et al., 1959).
The high bitumen content and dwarfed fossils indicate the formation was deposited in an euxinic environment. The fauna of *Rotalipora* cf. *apenninica, Globotruncana helvetica*, minute globigerinids, gumbelinids, fish detritus, small bicarinate *Globotruncana*, etc. (Bellen et al., 1959) indicates an Early-Mid Turonian age. *Globotruncana (Helvetoglobotruncana) Helvetica* is restricted in range to 'the *Helvetica* Zone of the late Early-early Mid Turonian. The formation is separated by unconformities from both the underlying Dokan and the overlying Kometan formations.

The distribution of the formation in the subsurface is poorly understood. It was only penetrated in well Kirkuk-116 on the Avanah dome.

11.2.2.6 Open marine facies
(Upper Balambo Formation)

The Balambo Formation of Valanginian- Turonian age is divided into the Lower Balambo Formation of Valanginian Albian age and Upper Balambo Formation of Cenomanian Turonian age. The Upper Balambo Formation is homogeneous and consists of thin bedded globigerinal limestone, passing down into radiolarian limestones (Bellen et al., 1959). In the type area between the Sirwan and Rowanduz rivers the Upper Balambo Formation comprises mostly thin bedded, (rarely thick bedded) light coloured limestones with a pelagic globigerinal -radiolaria oligosteginal fauna. In well Injana-5 the Upper Balambo consists of shale only. In Naft Khaneh oil field in central E Iraq it is composed of marl with a few thin limestone beds.

The Cenomanian part of the formation in the type area is 170-200 m thick and the Turonian part is 315-350 m thick. The undifferentiated "Balambo Formation" of the Naft Khaneh wells is >900 m thick but probably includes part of the Lower Balambo Formation.
The Upper Balambo Formation was deposited in an outer shelf to bathyal environment. The formation was deposited in a relatively deep basin situated along the NE boundary of the Arabian Plate, separated from the Southern NeoTethys by an intermittently submerged ridge. This ridge has been overthrust by the Zagros Suture units. To the W, the Balambo basin was separated from the main shelf basin by the Qamchuqa Ridge situated along the High Folded Zone.

Bellen et al. (1959) listed an abundant fauna in the Upper Balambo of Cenomanian-Turonian age.

The lowermost beds of Upper Balambo Formation comprise grey globigerinal limestones of Latest Albian age which conformably overlie blue ammonite bearing limestones. In the High Folded Zone, the Balambo passes into the Dokan Formation. The formation is overlain by the Upper Campanian Shiranish Formation (Bellen et al., 1959) or the Upper Turonian Kometan Formation (Bolton, 1958d).

The Upper Balambo Formation outcrops extensively in the Imbricated Zone of NE Iraq. In the High Folded Zone, the formation passes laterally into the Kometan, Gulneri, and Dokan formations. The depocentre extends into SW Iran where it is referred to as the "Massive Limestone Group" (Kent et al., 1951). In North Iraq, the Balambo-Tanjero Zone is either overridden by the Northern Thrust Zone or completely missing. In this region the Balambo Formation is replaced by neritic limestones of the Herki, Rikan and Zibar areas (Hall, 1957).



Plate 11-1: Chia Gara Formation, Rowanduz River near Barsarin village, W of Rowanduz (photo by S. Jassim)



Plate 11-2: Sarmord Formation overlain by terrace gravel along Geli Ali Beg gorge, W of Rowanduz (photo by S. Jassim)

Plate 11-3: The Maudduđ (Qamchuqa) Formation exposures along the Geli Ali Beg gorge of the Rowanduz River W of Rowanduz (photo by S. Jassim)



CHAPTER 12

Late Turonian-Danian Megasequence AP9

by

Saad Z. Jassim and Tibor Buday

12.1 Introduction

The Late Turonian-Danian Megasequence is the most widespread megasequence in Iraq. It is present throughout Iraq (except in the inner zones of the Zagros Suture and over parts of the ENE-WSW oriented Hauran Uplift in W Iraq). It was deposited following the onset of ophiolite obduction in the southern part of the Neo-Tethys (Chapter 3). Large N-S trending structures formed in SE Iraq due to inversion. NW-SE trending (extensional) and E-W trending (transextensional) basins formed in the Stable Shelf. Turonian-Early Campanian sediments are restricted to the Mesopotamian Zone and the Jezira Subzone but may have been more extensively distributed prior to the Intra Senonian erosion. The lower part of the megasequence is represented by the Khasib, Tanuma, Sa'di and Kometan formations. The upper part of the megasequence is represented by the Hartha, Tayarat, Digma, Aqra, Bekhme, Shiranish, Tanjero and Hadiena formations (Fig. 12-1).

The megasequence is thickest on the Salman Zone (Fig. 12-2), S of the Takhadid-Qurna Fault (1050 m) and also in NE Iraq. **It** is exceptionally thick in fault controlled extensional basins. **It** is >1500 m thick in the Anah Trough and >2000 m thick in the Sinjar-Abdul Aziz basin. **It** is locally >2000 m thick in a NW/SE trending foredeep basin that formed due to Late Cretaceous-Early Maastrichtian thrusting and ophiolite obduction along the Southern Neotethys suture zone (Chapter 3). Longitudinal and transversal structural features affected the palaeogeography of the megasequence. Inner shelf neritic carbonates were deposited on elevated blocks; basinal marls were deposited in grabens and in open marine basins.

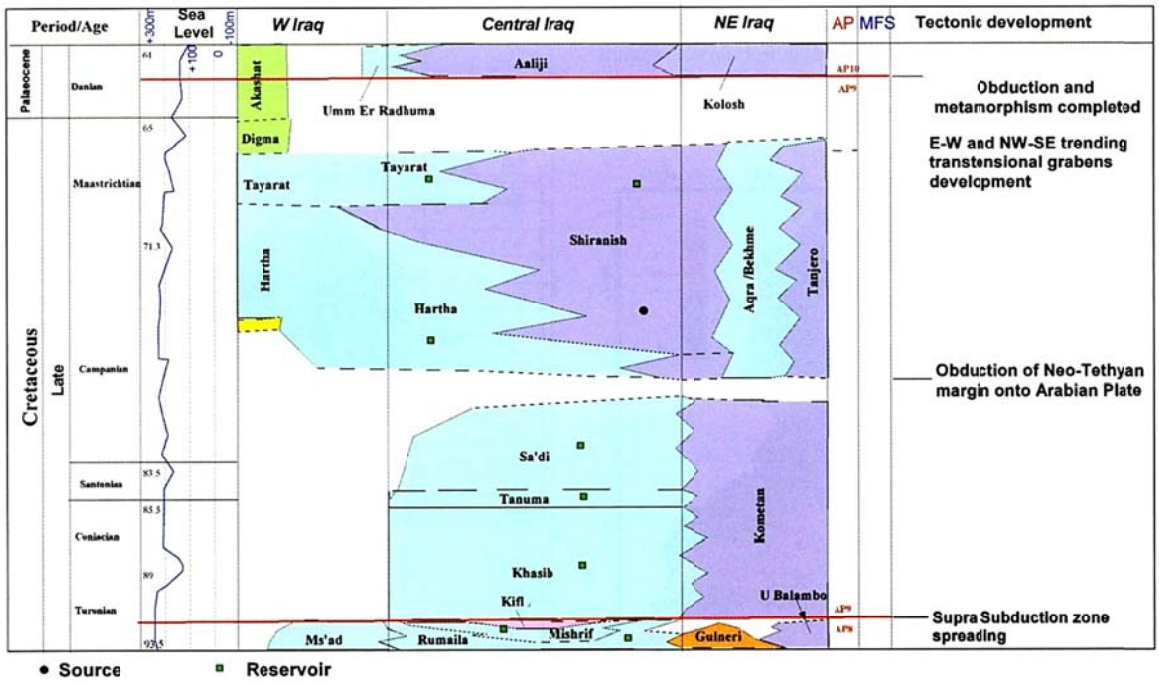


Fig. 12-1: Stratigraphic correlation of formations of the Late Early Turonian-Darian Megasequence

12.2 Late 'Turonian-Early Campanian Sequence

The Late Turonian-Early Campanian Sequence was deposited in a relatively narrow seaway occupying the area of the Salman, Mesopotamian, Foothill and High Folded zones. The Rutba-Jezira Zone of the Stable Shelf was emergent. In the Northern Thrust Zone, Turonian sediments are absent suggesting that this zone was part of a ridge separating the Southern Neo- Tethys from the Balambo Tanjero Zone (Fig. 12-3). Turonian sediments were fully deposited in the Balambo-Tanjero Zone.

After the Early Turonian movements, the Qamchuqa ridge became less expressive and broad and occupied the area of what is known today as the High Folded Zone and the Chemchemal-Butmah subzones of the Foothill Zone. The broad ridge was more uplifted in its NW side (Mosul High). This largely shallow water area extended N towards the Northern Thrust Zone and SW towards the Khlesia High. It formed an uplift that extends from the Rutba area into the Jezira area, and swings north and northeastwards towards the plate margin. The area of the submerged Mosul High was dominated by neritic to deep water carbonates, flanked on the Wand E by deep water basins in which oligosteginal basinal limestones were deposited (Mushorah facies).

At the end of the Turonian the NW-SE trending Qamchuqa Ridge was flanked by deep water basins. The SW basin formed in a previously uplifted area: the Hemrin-Makhul Subzone of the Foothill Zone. In the Jezira Subzone, deep water carbonates were deposited in E- W trending grabens; deep shelf sediments were deposited on the flanks of the grabens. However, intra Senonian uplift led to widespread erosion of these shelf sediments.
Upper Turonian-Lower Campanian sediments are absent in the Rutba Subzone (Fig. 12-3) due to non-deposition, and erosion in the eastern part of the subzone. Ditmar and the
Iraqi-Soviet Team (1971 and 1972) suggested that a fringing, partly terrigenous, clastic facies belt covered parts of the slopes of the Rutba and Khlesia highs.

In Late Campanian time ophiolites were obducted further across the NE margin of the Arabian Plate. The compression associated with this obduction initially caused uplift of the Balambo-Tanjero Zone and the immediately adjacent parts of the Unstable Shelf. During this uplift considerable thickness of Upper Turonian-Lower Campanian sediments were eroded (Dunnington, 1958); locally these sediments were completely removed on the Mosul High and over large areas of the Rutba-Jezira Zone.
The sequence is represented by the Khasib, Tanuma, Sa'di and Kometan formations. The Mushorah Formation is included in the Kometan Formation. The lower part of the Pilsner Formation in some of the wells in NW Iraq is included in the Sa'di Formation and locally in the Tanuma and Khasib formations.
The isopach of the Late Turonian-Early Campanian sequence (Fig. 12-4) shows three depocentres, in S Iraq where the sequence is >500 m thick, near Baghdad, and in the Sinjar area in NW Iraq. The sequence comprises two main facies, the deep inner shelf and lagoonal Khasib, Tanuma and Sa'di formations, and the outer shelf and basinal facies of the Kometan Formation. The thickness of the Khasib, Tanuma and Sa'di formations is given in Table 12-1.

Fig. 12-2: Thickness of the Late Turonian-Danian Sequence in meters

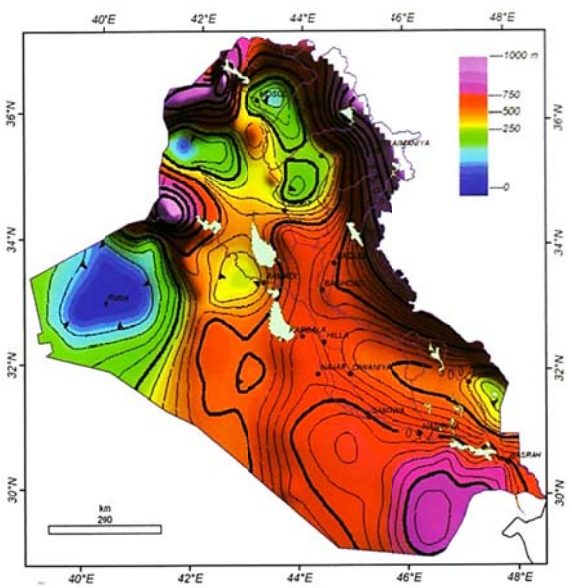
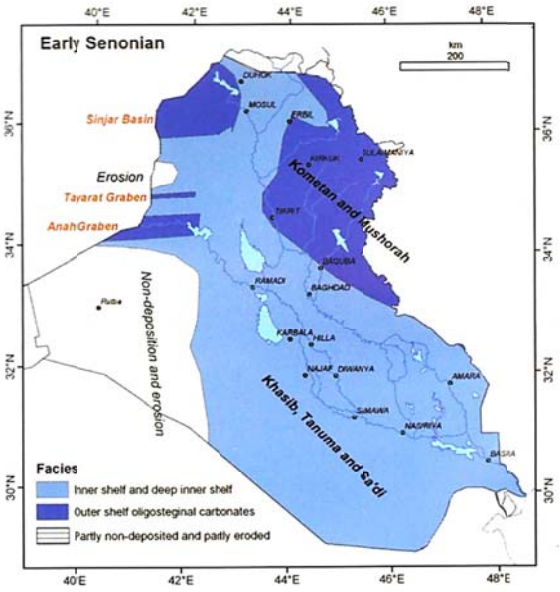


Fig. 12-3 Late Turonian-Early Campanian palaeogeography



12.2.1 Deep inner shelf and lagoons 12.2.1.1 Khasib Formation

The Khasib Formation (Chatton and Hart, 1961) is the most proximal unit of the Late Turonian-Early Campanian Sequence. It was defined by Owen and Nasr in 1958 from Zubair 3 well of the Mesopotamian Zone. The lower part (20 m) of the formation consists of dark grey and greenish grey shales, and grey, fine grained, argillaceous limestones. The upper part (30 m) comprises grey, fine grained argillaceous limestones (Bellen et al., 1959). In many wells the formation consists entirely of chalky and oligosteginal limestones, lithologically similar to the Sa'di Formation but of different biofacies. The thickness of the Khasib Formation (Table 12-1) is highest in S Iraq (225 m in the Zubair oil field). In general, the Khasib Formation is thickest in the Tigris Subzone of the Mesopotamian Zone.

Fossils are relatively rare in the type section. In other wells relatively rich assemblages occur (Darmoian, 1975). Oligostegina are abundant throughout. Bellen et al. (1959) suggested the formation is of Late Campanian age. However Chatton and Hart (1961) argued that the formation is of Turonian-Early Campanian age. The presence of planktonic foraminifera of the species *Globotruncana lapparenti* is consistent with a Turonian age. According to Darmoian (1975) the formation is of Late Turonian to Coniacian age.

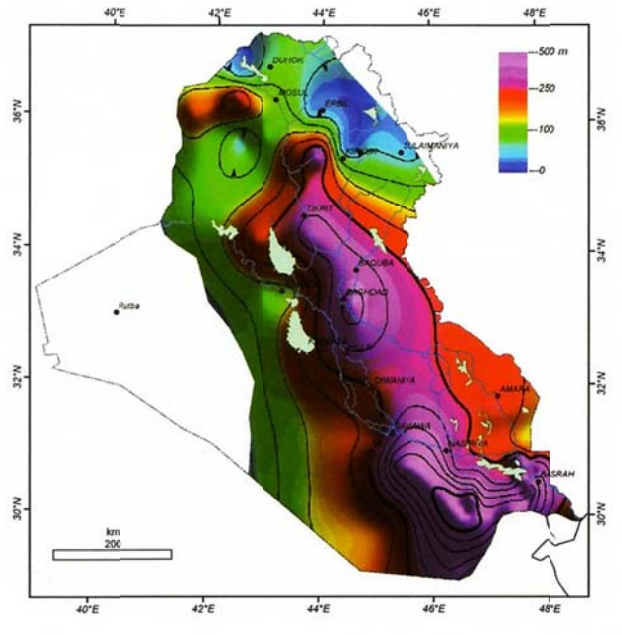
The oligosteginal fauna and the dwarfed character of the fossils indicate the Khasib Formation was deposited in a restricted basin. Open marine *Globotruncana* assemblages are also present.

According to Bellen et al. (1959) the lower boundary of the formation is disconformable. The upper boundary with the Tanuma Formation is gradational. The Khasib Formation is equivalent in both age and facies with the lower part of the Mutriba Formation of Kuwalt (Douban and Medhadi, 1999). In Saudi Arabia the middle shale-chalky limestone part of the Aruma Formation (Powers et al., 1966) might be partly equivalent to the Khasib Formation.

Table 12-1: Thickness in metres of the Khasib, Tanuma and Sa'di formations

Well	Khasib	Tanuma	Sa'di
Abu Amud-1			149
Abu Khaima-1			261
Afaq-1	75		155
Diwan-1	29		376
Dujaila-1			152
Dujaila-2	65		118
E Abu Amud-1			128
E Bagdad-1	108		159
Fallujah-1			154
Ghalaisan-1	24		121
Halfaya-1	81	15	124
Huwaiza-1	67		97
Khidr Al Maa-1	30		406
Kifl-1			142
Kifl-2			139
Luhais-1			260
Luhais-4	164		450
Majnoon-1			103
Majnoon-11			118
Makhul-2			171
Merjan-1	35	171	
M Tharthar-1			249
Mityaha-1			23
Naffatah-1			131
Nahr Umr-3			106
Nahr Umr-9	267		218
Nahrawan-1	11	95	107
Nasiriya-1	48	59	231
Noor-1	84	5	131
Qaiyarah A-5			42
Rachi-1			237
Rachi-2	36	57	322
Ratawi-1			175
Ratawi-3	44	46	183
Ratawi-6			187
Rifae-1	83	11	158
Rumaila-2			377
Rumaila N-1	54	24	176
Safawi-1		25	125
Samarra-1			40
Samawa-1			159
Sasan A-2			190
Shawiya-1			178
Siba-1			221
Sindabad-1			245
Subba-1			236
Subba-8	39	64	202
Tuba-2	59	47	262
Ubaid-1			172
Umm Qasr-1	64	19	340
Ur-1	40	65	195
W Kifl-1	104		132
W`Qurna-148			126
Zubair-1			287
Zubair-38			375
Zubair-47	225	120	245

Fig. 12-4: Thickness of the Late Turonian-Early Campanian Sequence



12.2.1.2 Tanuma Formation

The Tanuma formation was defined by Owen and Nasr (1958) in well Zubalr-3 in S Iraq. It comprises 30 m of black, fissile (locally pyritic) shale with streaks of grey, macrocrystalline, argillaceous and detrital limestones (sometimes glauconitic), with an oolitic limestone layer at the top. In the Musalyib, Afaq, Dujalla and Buzurgan wells the formation consists predominantly of marl and chalky limestone (Kasim, 1962; Macleod, 1961; Safar, 1961; Ditmar and the Iraqi-Soviet Team, 1972).

The thickness of the Tanuma Formation in SE Iraq reaches 60 m but wedges out in all directions. The subsurface thickness is provided in Table 12-1.

The Tanuma Formation was deposited in a restricted shallow basin, in a partly euxinic environment.

Rare fossils are not age diagnostic. According to Owen and Nasr (1958) the formation is Late Senonian in age and according to Bellen et a1. (Op. Cit.) the fauna appears to justify a Late Campanian age. Chatton and Hart (1961) and Ditmar and the Iraqi-Soviet Team (1971) claimed a Turonian-Early Campanian age. Darmoian (1975) determined the age of the formation as Coniacian. The Tanuma Formation usually conformably overlies the Khasib Formation. However, in the Salman Zone, the Tanuma Formation oversteps the Khasib Formation and transgressively overlies Cenomanian sediments (in the Samawa, Safawi and Ghalalsan wells; Johnson, 1961 and Rolleigh, 1960, 1961).
The Tanuma Formation wedges out towards the NW. To the NE, beyond an uplift located between Musalyib, Dujalla and Amara, the formation consists predominantly of shale. It is relatively thin at Awasil, Samarra and in Mileh Tharthar (Huber, 1940; Johnson, 1961; Hay and Algawi, 1958).

12.2.1.3 Sa'di Formation

The Sa'di Formation is the youngest, thickest, and most widespread formation of the Late Turonian-Early Campanian Sequence. The type section was defined by Owen and Nasr (1958) from well Zubalr-3. The definition and age of the formation was modified by Chatton and Hart (1961) and Ditmar and the Iraqi-Soviet Team (1971 and 1972). They included parts of the Pilsner Formation in the Sa'di Formation. The formation comprises 300 m of white, chalky, argillaceous and globigerinal limestones with a well-developed 60 m thick marl bed at the top. Outside the type area the upper part of the formation also includes organodetrital limestone (Bellen et al., 1959).

Argillaceous limestones predominate in the E and NE in the Nahr Umr, Siba and Dujalla wells (Kasim, 1962a; Safar, 1961). West of the type area, the formation comprises argillaceous limestone overlain by chalky limestones. The subsurface thickness is provided in Table 12-1. Additionally, the Sa'di Formation can be identified in some wells where it was originally included within the Pilsner Formation, these include: Fallujah-l, Mileh Tharthar-I, Makhul-2 and Naffatah-l (see Table 12-1). The Sa'di Formation is thickest (> 450 m) along the boundary of the Mesopotamian and Salman Zones (same as Hartha Formation).

Fossils are abundant. Owen and Nasr (1958) assigned a Late Senonian age to the formation. Bellen et a1, (1959) suggested it was of Late Campanian age. Chatton and Hart (1961) and Ditmar and the Iraqi-Soviet Team (1971) suggested a wider age range from Turonian to Early Campanian. Darmonian (1975) gave a Santonian-Early Campanian age, which is accepted in this book.

The Tanuma Formation is transgressive unit; its lower contact is conformable and gradational only where it is in contact with the Tanuma Formation. Elsewhere it unconformably overlies different units, especially in uplifted areas towards the Rutba-Jezira Zone. The upper boundary of the Sa'di Formation is usually unconformable and overlain by Hartha Formation.

Outside Iraq, the Gudair Formation is almost fully equivalent to the Sa'di. It correlates with parts of the Aruma Group in Saudi Arabia (Powers et al., 1966). Towards the W and NW, in Turkey and Syria units of Campanian age and of similar lithology similar were reported from the Soukhne Formation (Dubertret, 1966). In SE Turkey the Campanian Karabogaz Formation and parts of the Turonian-Santonian Karbaba Formation closely resemble the Sa'di Formation (Beer, 1966).

12.2.2 Outer shelf and basinal (Kometan Formation)

The Kometan Formation was defined by Dunnington, in 1953 from the Kometan village near Endezah in NE Iraq. The formation comprises 120 m of light grey, thin bedded, globigerinal-oligosteginal limestone, locally silicified (with chert concretions in some beds), with a glauconitic bed at the base (Bellen et al., 1959). The formation has a similar lithology throughout the Balambo- Tanjero Zone. However to the Wand SW it becomes increasingly argillaceous. The formation also contalns varying proportions of globigerinal and oligosteginal and oligosteginal limestones. The Mushorah Formation, now included in the Kometan, has a very similar lithology. It was described by Dunnington, in 1953 from well Mushorah-l of the Foothill zone and consists of partly silicified oligosteginal limestone (Bellen et al., 1959). However in at Ain Zalah the Mushorah Formation contalns abundant bedded and nodular chert and dolomite. In Makhul and Samarra wells (Templeton et al .. 1959 and Johnson, 1961) the formation contalns anhydrite.

During mapping of NE Iraq, Lower Campanian limestones were found in the under thrust block of the Avroman range Gukab area near Halabja). They are considered to represent of the Kometan Formation which is absent at the type section. This section could be used as a supplementary type section of the Kometan in the future.

The Kometan Formation is widespread in central, N and NE Iraq. Following Ditmar and the Iraqi-Soviet Team (1971) e Mushorah Formation is now considered to be a facies of e Kometan Formation, which was deposited during the later stages of the Turonian transgression. In some areas, such as Kirkuk, Makhul and Najmah, the Mushorah facies overlies the Kometan Formation. The thicknesses of the combined Kometan and Mushorah formations are as follows: Tel Abtakh-1 (97 m), Tel Hajar (204 m), Kirkuk109 (41 m), Kirkuk-116 (184 m), Makhul-l (60 m), Makhul-Z (52 m), Najmah-29 (53 m), Chemchemal-2 (58 m) and Demir Dgah-1 (32 m). The thickness of the Mushorah facies in wells is as follows: Anah-2 (88 m), Butmah-2 (58 m), Qara Chauq-I (282 m), Sasan-2A (160 m), Gullar-1 (39 m) and Sufaya-A-2 (33 m). Homci (1975) suggested the Kometan Formation reaches a maximum thickness of 300 m between Qara Chauq and Hemrin structures.

Abundant fossils in the Kometan Formation (Bellen et al., 1959) indicate the basal beds of the formation are of Turonian age (based on the presence of *Globotruncana renzi*, and that the overlying beds are of Santonian age. The Mushorah facies was dated as Early Senonian to Early Campanian age (Bellen et al., 1959).

Sediments of the Kometan Formation were deposited in different environments ranging from shallow shelf, restricted (oligosteginal facies) to open marine (globigerinal facies). The oligosteginal facies of the Mushorah was deposited in a partly isolated basin, which at times became hypersaline.

The lower contact of the formation with Albian Cenomanian formations is an unconformity. The upper boundary is a disconformity.

The Turonian upper part of the Balambo Formation is almost identical with the Kometan. In Syria, the Santonian Campanian Soukhne Formation of Syria (Dubertret, 1966) is of similar facies to the Mushorah. The Turonian Coniacian Upper Judea Formation of Syria is similar to the Kometan Formation. In SE Turkey, the Karbaba Formation (Beer, 1966) is of similar age and facies to the Mushorah Formation.

12.3 Late Campanian-Maastrichtian Sequence

The climax of the obduction and closure of the Southern Neo- Tethys occurred during the Late Campanian and Maastrichtian. This contributed to a major transgression across the whole of Iraq. The same stress regime in the NE Arabian Plate led to the formation of intraplate extensional and transextensional basins of NW-SE and E- W trend respectively. The palaeogeography is presented for two time slices, Late Campanian-Early Maastrichtian (Fig. 12-5), and Middle-Late Maastrichtian (Fig. 12-6). Strong subsidence of the Balambo-Tanjero Zone created a foredeep filled with flysch derived from erosion of the flanking thrust belt.

The palaeogeographic map of Late Campanian-Early Maastrichtian time shows five facies belts (Fig. 12-5). Lagoonal facies of the Hartha Formation are restricted to the Rutba Jezira Zone; supratidal facies locally occur especially on the elevated Hauran High in W Iraq and in a N-S basin extending from Mosul in the N to the Salman Zone in S Iraq. The Hartha Formation carbonate shoals were deposited on a carbonate platform bordering the open sea to the E. The Shiranish Formation was deposited in outer shelf to basinal environment. The Bekhme Formation was

deposited on a carbonate platform developed over the Qamchuqa ridge of the High Folded Zone; this ridge plunged to the SE across the Anah-Qalat Dizeh Fault. The Tanjero Formation is a flysch facies developed within the Balambo- Tanjero Zone as turbidites derived from uplifted thrust sheets.

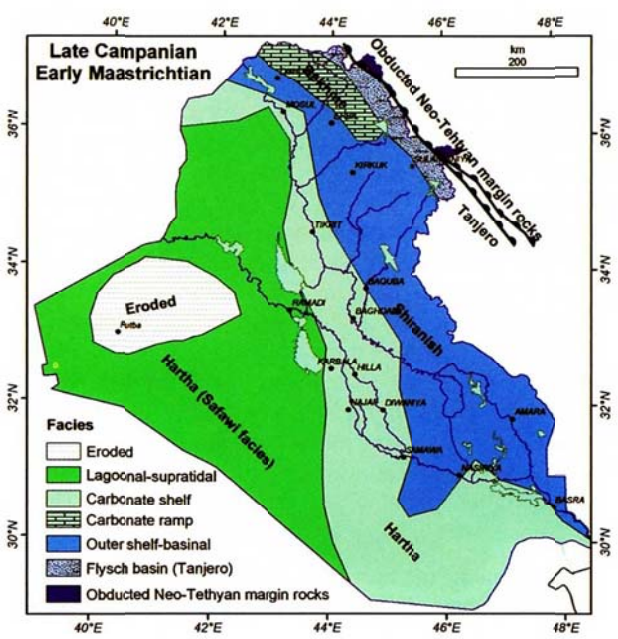
The palaeogeography of Mid-Late Maastrichtian time is shown in Fig. 12-6. Ophiolite obduction had now ceased; the front of the allochthonous thrust sheets had reached the Qulqula-Khwakurk Zone. The flysch deposition waned; shallow water *Loftusia* limestones (Aqra Formation) were deposited in the former flysch basin. This basin was bounded to the SW by the Qamchuqa ridge. Over 800 m of reef limestone of the Aqra Formation were deposited on this submerged ridge. To the SW of the Qamchuqa ridge, a wide open marine basin covered the whole of the Mesopotamian Zone and intermittently the Salman Zone. On the Rutba Subzone, a broad carbonate shelf developed, on which carbonates of the Tayarat Formation were deposited.

The Anah and Tayarat grabens were filled with thick deep water sediments. Extensional faulting in the Mesopotamian Zone (for example along the Tikrit-Balad-Baghdad structural trend) led to differential subsidence with deposition of thick Shiranish Formation. In the Anah and Tayarat grabens, the Maastrichtian sediments of the Shiranish Formation are >1500 m thick. The Anah Graben and a N-S embayment W of Rutba formed a semi-isolated basin in which upwelling of currents rich in phosphates and silica occurred, leading to deposition of phosphorites and silicified carbonates (Digma Formation). The Digma Formation both overlies and passes into Tayarat Formation towards the E and S.

The following formations are recognized in the Late Campanian-Maastrichtian Sequence: 1) The Upper Campanian-Lower Maastrichtian Hartha Formation deposited in an inner shelf to lagoonal environment 2) The Middle-Upper Maastrichtian inner shelf and shoal Tayarat Formation deposited in a inner shelf and shoal environment. 3) The Middle-Upper Maastrichtian phosphatic Digma Formation deposited in a lagoonal-outer shelf and basinal environment in the Rutba basin. 4) The Upper Campanian-Maastrichtian outer shelf to basinal marls and limestones of the Shiranish Formation. 5) The Upper-Campanian-Maastrichtian ramp carbonates of the Bekhme Formation deposited on the Qamchuqa Ridge. 6) The Maastrichtian ramp carbonates of the Aqra Formation deposited on the Qamchuqa Ridge. 7) The Upper Campanian-? Maastrichtian sediments of the Hadiena Formation deposited on the Ora Ridge. 8) The Upper Campanian-Maastrichtian flysch of the Tanjero Formation.

The thickness of the Late Campanian-Maastrichtian Sequence is shown in Fig. 12-7. Depocentres are associated with the Anah Trough in W Iraq, and the Tanjero trough in NE Iraq. Within the Stable Shelf, the thickness of the sequence is affected by the transversal Sirwan and Takhadid-Quma Faults.

Fig. 12-5: Late Campanian-Early Maastrichtian palaeogeography



12.3.1 Carbonate inner shelf (Hartha and Tayarat formations)

The carbonate inner shelf facies is represented by the Hartha and the overlying Tayarat formations. In S Iraq, they are separated by a tongue of basinal limestone previously referred to as the Qurna Formation which extends northwards to the Rutba area in W Iraq. This basinal limestone tongue is now included in the basinal Shiranish Formation.

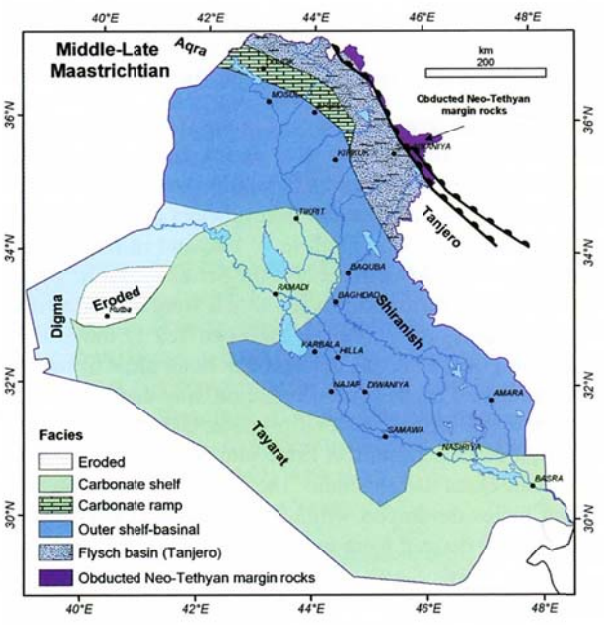
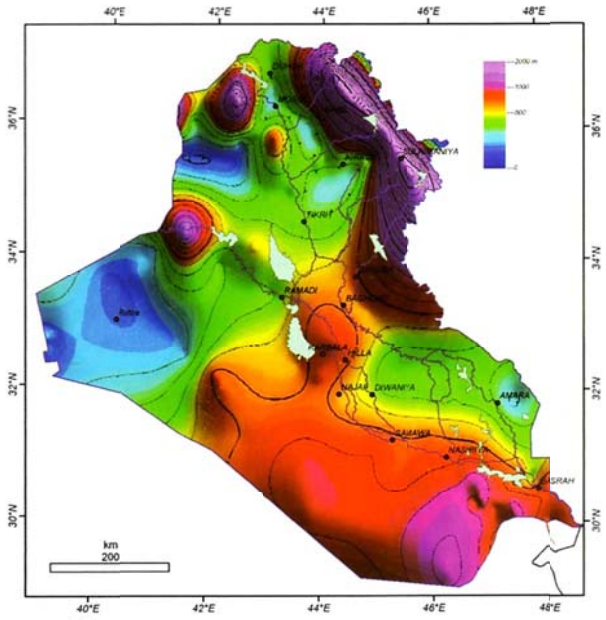


Fig. 12-6: Mid-Late Maastrichtian palaeogeography

12.3.1.1 Hartha Formation

The Hartha Formation was defined by Rabanit in 1952 from well Zubalr-3 in the Mesopotamian Zone of S Iraq (Owen and Nasr, 1958). It comprises organic detrital and glauconitic limestones with beds of grey and green shale; the limestones are locally strongly dolomitised. Beds of chalky limestone occur frequently (for example in the following wells: Buzurgan. Ghalalsan, Dujalla, Kifl, Musalyib, Siba, Ubaid). Oolitic limestone beds were found in the Luhais and Rachi wells. Nodules, lenses and beds of anhydrite often occur in the formation along the SW side of the Mesopotamian Zone, in the Salman Zone for example in well Safawi-l (referred to as Safawi Facies). Argillaceous limestones occur more frequently in the E parts of the Mesopotamian Zone where the formation passes into the Shiranish Formation (for instance in the Abu Ghirab well). In N Iraq, the Hartha Formation now includes parts of the Pilsner Formation. According to Bellen et al. (1959), the Pilsner facies comprises organic detrital limestones with beds of argillaceous limestones with fossil debris, and medium-grained dolomites.

Fig. 12-7: Thickness of the Late Campanian-Maastrichtian Sequence



Anhydrite and oolitic limestone beds and lenses are recorded in the Hartha Formation between Ramadi and Makhul. These beds are 50 m thick (Dibs Anhydrite and Mushak members) in well Makhul-2. In NW Iraq oolitic limestones occur in the Alan well (Ditmar and the Iraqi Soviet Team, 1971). These facies were deposited in lagoons in the interior of the Hartha carbonate platform to the west of a belt of carbonate shoals located on the W side of the Mesopotamian Zone.

In the Rutba area, in W Iraq, the Hartha Formation consists of beds of marl and dolomite with well developed fenestral porosity and "Birds Eye" texture indicating a supratidal subtidal depositional environment. South of Rutba, the upper 35 m of the original type section of M'sad Formation was reassigned to the Hartha Formation. A supplementary surface section (160 m thick) was chosen 40 km SE of Rutba between Wadi Mutedela and Wadi Ghadaf (Jassim et al., 1984). The section comprises a basal clastic unit (30 m) consisting of brownish grey, cross-bedded calcareous

sandstone, interbedded with green highly fossiliferous limestone with *Hippurites.* The clastic unit is overlain by 70 m of grey dolomite and pale grey argillaceous dolomite. The upper 60 m of the formation consists of light grey fossiliferous dolomite and yellowish grey fossiliferous marl and argillaceous limestone. Chert nodules are present throughout but are most abundant in the upper part of the section. The formation thins to 75 m to the east of the supplementary section and to 35 m to the S of Rutba. The formation thins to the north of Rutba until it is totally truncated below an unconformity at the base of the Tayarat Formation on the NW rim of the Ga'ara depression. The formation consists predominantly of carbonates in the west near Rutba, and marl in the east.

In the Rutba area the Hartha Formation comprises stacked 10-15 m thick cycles. Each cycle consists of cross-bedded calcareous sandstone, locally ferruginous, passing up into siltstone and silty mudstone or shale capped by coarse grained dolomite and dolomitic limestone. The sandstone beds wedge out to the SE of Rutba.

The lower contact of the formation is usually an unconformity, often marked by a basal conglomerate. The upper boundary in S Iraq is conformable and the formation is often overlain by pelagic sediments of the Shiranish Formation.

The thickness of the Hartha and Bekhme formations is shown in Fig. 12-8. The Hartha Formation is thickest within the Salman Zone, S of Ramadi (400 m). Near Mosul the thickness is 100-200 m.

The Hartha Formation was deposited in forereef to shoal environment. Locally lagoonal back reef facies occur around the margins of the Stable Shelf. Reef facies may be present around the Khlesia High, as indicated by the reef limestone debris in the detrital limestone beds in the formation in some wells.

A rich Late Campanian-Maastrichtian fauna was reported by Bellen et al. (1959). Karim and Ctyroky (1981; in Jassim et al., 1984) identified the following fauna from the basal clastics of the surface supplementary section to the ESE of Rutba, they include: *Vautrina syriaca* Vautrin, *Vautrina sp., Praeradiolites sp., Eoradiolarites sp., Hexacorals* (indent) and *Neithea sp.* The carbonate units contaln *Vautrina cf syriaca* Vautrin, *Radiolarites cf sequanosus, Eoradiolarites sp., Tylostoma sp., Nerinea cf bronni, Hexacorallatrochus sp., Tylostoma aff syriaca* Conard and *Micraster spp.*

The Aruma Formation (Powers et al., 1966) of Saudi Arabia partly correlates with the Hartha Formation. The Hartha Formation is recognized in Kuwalt (Owen and Nasr, 1958). In Syria some parts of the Soukhne Formation (Dubertret, 1966) are equivalent to the Hartha. Facies similar to the Hartha Formation are present in eastern Syria (Dubertret, 1966). In SE Turkey, the Karabogaz Formation (Beer, 1966) is of similar facies.

12.3.1.2 Tayarat Formation

The Tayarat Formation was defined by Henson in 1940 (Bellen et al., 1959) 30 km S of Rutba town in W Iraq. It comprises 48 m of rubbly, porous, chalky limestone which is locally dolomitised and sandy. The upper part of Tayarat Formation to the W of the type section is replaced by the phosphatic Digma Formation. The formation also outcrops along the W rim of the Ga'ara depression where it is 25 m thick, and comprises oyster-bearing limestone, *Loftusia* limestone and chalky limestone. The basal unit of this section comprises limestone conglomerates which were deposited in channels and oyster bearing limestones. On the N and NW rim of the Ga'ara depression, the basal beds of the formation are charophyte-bearing limestones which were

deposited in a fresh water environment. The uplift and emergence of the Ga'ara anticline in Maastrichtian time strongly influenced the distribution and facies of the Tayarat ' Formation.
The lower unit of the Tayarat Formation comprises conglomerate or coarse-grained calcareous sandstone, passing upwards into dolomitic limestone, dolomite, siltstone, silty marl and calcareous shale, locally containing shark teeth and thin-shelled gastropods. The upper unit comprises coarse grained limestone, locally sandy, overlain by mudstone and dolomitic conglomerate. Geodes and chert concretions are common in the carbonates of the upper unit. The clastics in the lower unit pass into carbonates to the east. The type section of the Tayarat Formation includes some phosphatic beds.

The formation thickens in S Iraq (Fig. 12-9) S of the Takhadid-Qurna Fault, and in Central Iraq between the Anah Qalat Dizeh and the Sirwan faults. It is absent in the Jezira area. The Tayarat Formation is reported to be 426 m thick in water well K7-12 near Anah but this thickness probably includes parts of the Hartha and Shiranish formations. In S Iraq, the formation is up to 370 m in the S part of Salman and Mesopotamian zones. The formation is thinner in the Euphrates and Tigris subzones of the Mesopotamian Zone where it passes into Shiranish Formation.
The formation overlies the Shiranish Formation in S and SW Iraq and the Hartha Formation in all other areas. The upper contact with the Umm Er Radhuma Formation in S and SW Iraq is disconformable; Danian beds are absent. W of Rutba, the Tayarat Formation is conformably overlain by the Digma Formation.
In addition to the fossils recorded by Bellen et al. (1959), Amer (1975; in Jassim et al., 1984) documented the following fauna from the Nukhalb area: *Praealveolina sp, Rugoglobigerina sp., Rotalia sp., Spiroloculina sp., Loftusia minor* Cox, *Loftusia coxi* Henson, *Loftusia elongata* Cox and rare *Globotruncana sp.* Karim and Ctyroky (1981; in Jassim et al., 1984) studied the area S of the Kl60 settlement and recorded the following fauna: *Orbitoides cf media* Darciac, *Dicyclina sp., Lepidorbitoides sp., Omphalocyclus macroporus Lamarck, Globotruncana sp., Loftusia elongata* Cox, *Nezzazata sp., Vaccuinites sp., Radiolarites, Orbitoides sp., Cardita sp., Caprinitodea sp., Rostellaria sp., ?Septifer sp., Modiolus sp.* and miliolids. From the area S of Rutba, Buday and Hak (1980) reported a microfauna of *Loftusia elongata* Cox, *Loftusia persica* Brady, *Loftusia minor* Cox, *Loftusia morgani* Douville, *Loftusia sp., Omphalocyclus macroporus, Orbitoides sp.* and macrofauna of *Actostrea bomilcaris* Coquand, *Ceratostreon cf lanciniatum* Nilsson, *Lopha villei* Coquand, *Trigonoarca schweinfurthi* Nilsson and *Turritella*
sp.
The above fauna indicates the age of the Tayarat Formation is Maastrichtian.

Fig. 12-8: Thickness of the Hartha and Bekhme formations

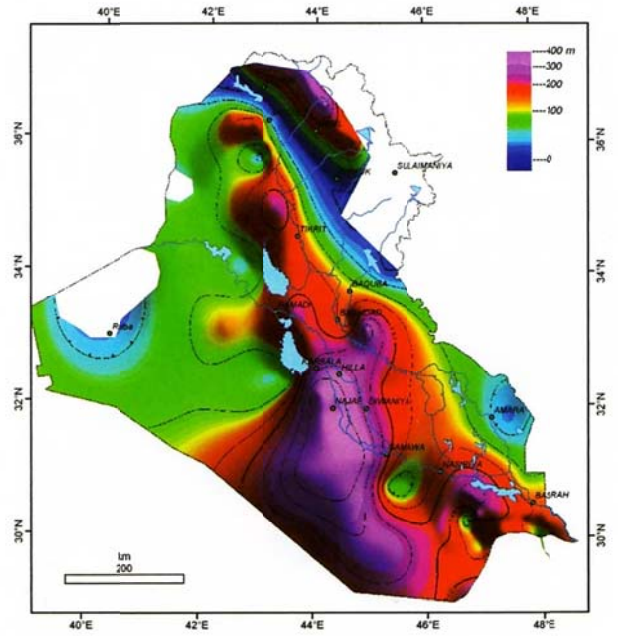
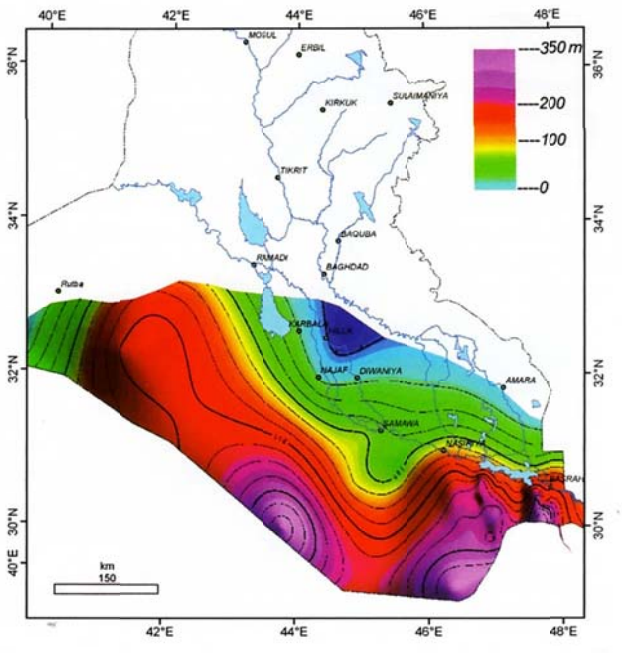


Fig. 12-9: Thickness of Tayarat Formation



12.3.2 Phosphatic inner and outer shelf (Digma Formation)

The Digma Formation is lithologically a very distinct formation of Maastrichtian age in Iraq which extends into Syria, Jordan and Saudi Arabia. The Digma Formation was first defined as an independent stratigraphic unit by Dunnington in 1953, in well Anah-I in W Iraq. It comprises 50 m of phosphatic, glauconitic, locally silicified marls. The use of term Digma Formation was abolished by both Chatton and Hart (1961) and Ditmar and the Iraqi-Soviet Team (1971), who

considered that it, did not warrant recognition as a separate formation.
However when the Digma Formation was defined the phosphate occurrences near Rutba Uplift had not been studied. The lower part of these phosphatic beds (Maastrichtian-Eocene Belqa Series) was included in the Tayarat Formation. These beds, described in detail by Cobbet (1956) and Antonets et al. (1963), are identical with the Digma Formation in age and comprise highly phosphatic and siliceous limestones and marls.
The Digma Formation outcrops near Rutba Town and in the Ga'ara depression. In the Tayarat type section (see above) significant phosphatic beds occur in the upper part of the section. Wand NW of Rutba, these phosphatic facies overlie the Tayarat Formation.

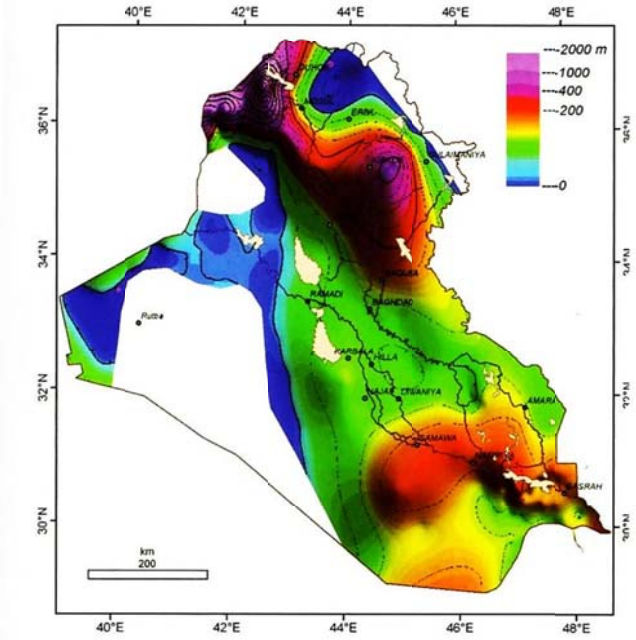
Jassim et al. (1984) described the formation from Wadi Jeed, 30 km W of Rutba Town. This section is located on the NW flank of the Hauran anticlinorium, 6 km S of the Rutba Amman and Rutba-Damascus road junction. It is 35 m thick and comprises, from the base upwards: Coarse pelletal phosphorite with conchoidal fractures (2 m), porous white chalk (2 m), white chalk with brown chert lenses (2 m), grey lithographic limestone with beds of marl, argillaceous limestone with oyster beds (9 m), hard recrystallised rubbly limestone with oysters often containing large geodes up to 0.5 m in diameter (6 m), thin-bedded hard limestone with chert concretions (0.5 m), pelletal phosphorite (2 m) topped by chert laminae, flaky marl with thin beds of white recrystallised limestone (0.7 m) and coarse recrystallised limestone with bands of chert and chert concretions capped by very dense lithographic limestone (5 m). This phosphatic sequence lies conformably on *Loftusia* limestones of the Tayarat Formation. It is overlain conformably by Danian shale. Along the northern and western rim of the Ga'ara depression, the Digma Formation comprises soft yellow marl (black in subsurface sections) with lenticular beds of *Lopha-bearing* limestones which are especially abundant near the top of the formation often overlying yellow marl with occasional phosphate interbeds. A good example is the butte of Radhuma Safra north of the Ga'ara depression (plate 12-1).
Fossils include benthonic foraminifera, with some planktonic foraminifera indicating communication with the open sea. The lower part of the formation in the Ga'ara depression contalns *Inoceramus regularis* Dorb., *Lopha diachotoma* Bayle, *Natica sp., Cryptorhytis sp., Lucina sp., Turritella sp., Lopha villei* Conard, *Nautilus sp.,* miliolids, echinoid spines, spicules and ostracods. The equivalent section from the area S of the Amman highway contalns *Loftusia elongate* Cox, *Pseudolituonella sp., Quinqueloculina sp.,* rare *Globotruncana sp.,* planktonics, miliolids, *Exogyra flabellatum* Sowerby, *Hippurites, Phaldomya sp.,* echinoid spines, coral fragments and ostracods.

In subsurface sections from the area W of the Akashat mine, Amer (1977) identified *Globotruncana aegyptiaca* Nakkady, *Globotuncana havanesis* Vocrwijk, *Pseudo textularia elongata* Rzehak, *Heterohelix striata* Ehrenberg, *Gabonella multituberculata* Deklsz-MarieMeijer, *Valvulineria koeingswaldi* Drooger, *Siphogerinoides cretacea, Gavelinella sp., Pyramidinia crassa* Brotzen. In water well near Nihaldaln at the Iraq-Jordan-Saudi triple border point the formation contalns the following fauna:
Heterohelix sp., Globigerinelloides sp., Globotruncana sp., Hippurites, Lenticulina sp., small planktonics, biserial benthonics, *Exogyra flabellatum* Sowerby, *Loftusia sp.* and shell fragments. This fauna indicates the Digma Formation is of Maastrichtian age.

At its type locality the Digma Formation overlies marl of the Jib'ab facies of the Shiranish Formation. The lower contact of the formation was assumed to be gradational and conformable (Bellen et al., 1959). In the Rutba area the formation conformably overlies the Tayarat Formation. The upper contact with the Akashat Formation is apparently conformable but is probably associated with a slight break in sedimentation.
The Digma Formation is present on the Stable Shelf, in the Anah Trough and on the NW slopes of the Hauran Anticlinorium. According to Jassim et al. (1984), the formation also outcrops in (and to the west of) the Nukaib ' Graben. The formation is probably present on the southern flank of the Khlesia High.

The Digma Formation is equivalent in facies to the phosphatic-siliceous Upper Cretaceous formations of Syria (Soukhne Formation; Dubertret, 1966), W Jordan (Belqa Series; Daniel, 1968) and NE Jordan (Muwaqqar Formation).

Fig. 12-10: Thickness of the Shiranish Formation (excluding the the Jibab facies of the Anah Graben which, along with Hartha Formation exceeds 2000 m)



12.3.3 Carbonate ramp (Bekhme and Aqra Formation)

The Aqra Formation was defined by Bennett in 1945 (Bellen et al., 1959) from the Aqra anticline of the High Folded Zone of N Iraq as a reef limestone complex with massive rudists, shoal facies, and detrital forereef limestone. It is locally dolomitised, siliceous, and impregnated with bitumen. The Bekhme Formation was defined by Wetzel in 1950 from the Bekhme Gorge of the Greater Zab River in the High Folded Zone as bituminous secondary dolomite, replacing organic detrital limestones in its upper part, and reef detrital limestones, alternating with reef shoal limestones in the middle part, with basal breccia conglomerate in the lower part. The formations form the cores of numerous anticlines in the S and SW parts of the High Folded Zone (Plate 12-2) and often overlie the Mauddud (Qamchuqa) Formation (Plate 12-3).

The Aqra and Bekhme formations comprise reef limestones, forereef and shoal limestones, and associated facies (Bellen et al., Op. Cit.). It is difficult to separate the two formations where an intervening tongue of the Shiranish or Tanjero formations is absent. The name Aqra-Bekhme has been suggested by Buday (1980) where these intervening formations are absent. Both formations were deposited over the Qamchuqa ridge of the High Folded Zone.

The thickness of the Aqra and Bekhme formations is typically 300-500 m in the type area (1050 m maximum) and between Bekhme Gorge (NE Erbil) and Dohuk. The formations wedge out relatively rapidly to the NE and SW, passing into the Tanjero and Shiranish formations respectively. To the SE, the formations pass into basinal facies across the Anah-Qalat Dizeh Fault into the Kirkuk Embayment. The formations were deposited mostly in a reef-forereef environment. The Aqra Formation also transgressively overlies the Tanjero Formation.

Abundant fossils confirm a Late Campanian age for the Bekhme Formation and a Maastrichtian age for the Aqra Formation.

The Bekhme Formation unconformably overlies the Mauddud (Qamchuqa) Formation with a basal conglomerate. The upper contact of the Aqra Formation is marked by an erosional break at the Cretaceous-Tertiary boundary.

The Aqra and Bekhme formations are equivalent to the upper part of the so-called "Massive Limestone" of NE Syria in Qamishlie, Bowab and Barde (Dubertret, 1966). In SE Turkey, limestone beds and limestone lenses in the Kermav Formation are equivalent to the Aqra and Bekhme formations. The correlation of the Aqra and Bekhme formations with the Mardin Formation, suggested by Bellen et a1. (1959), is unlikely because the Mardin Formation is of pre Campanian (mostly Cenomanian-Turonian) age (Beer, 1966; Schmidt, 1964). In SW Iran, N of Shiraz, reef limestones overlying Campanian-Maastrichtian flysch (Furst, 1970), are equivalent to the Aqra Formation.

12.3.4 Outer shelf-basinal (Shiranish Formation)

The Shiranish Formation was defined by Henson (1940) from the High Folded Zone of N Iraq near the village of Shiranish Islam, NE of Zakho. In S Iraq an almost identical unit, the Qurna Formation, was introduced by Rabanit in 1952. Following Chatton and Hart (1961), the Qurna Formation is here included in the Shiranish Formation. The Shiranish Formation, in its type area, comprises thin bedded argillaceous limestones (locally dolomitic) overlain by blue pelagic marls (Owen and Nasr, 1958; Bellen et al., 1959).

Limestone conglomerates (probably resulting from slumping) occur locally in the formation in the Sinjar area of NW Iraq (Bellen et al., 1959) and in the Jabal Abdul Aziz area of Syria (Ponikarov et al., 1967). The formation gradually passes into the Tanjero Formation to the NE.

Chatton and Hart (1961), and also Ditmar and the Iraqi Soviet Team (1971), included another lithologically almost identical unit (the "Jib’ab Marl Formation" of well Anah-l) within the Shiranish Formation. The Jib'ab facies comprises argillaceous limestones and marls, with occasional calcareous shales, locally anhydritic or glauconitic, with occasional beds of sandstone and thin beds conglomerates (Bellen et.al, 1959).

In the type area, the Shiranish Formation is 225 m thick. In other outcrop areas it varies in thickness from 100 to 400 m. The thickest drilled section (1500 m) of the formation is in well Sasan-1 the formation has a similar thickness between Hemrin and Mandali (Homci, 1975). The thickness of the Jib'ab facies reaches 1300 m (Hay and Hart, 1959). The thickness of the Shiranish

Formation is shown in Fig. 12-10; the figure does not include the thickness of the Jib'ab facies in the Anah Graben.
Fossils are very abundant in the Shiranish Formation and its Qurna tongue but rare in the Jib'ab facies. They confirm that the formation is of Late Campanian-Maastrichtian age. Sediments of latest Maastrichtian age are absent (Kassab 1972 and 1973).
In the type section the Shiranish Formation conformably overlies the Bekhme Formation. Elsewhere the Shiranish unconformably overlies older Cretaceous formations. The upper boundary is erosional or nonsequential where the Shiranish Formation is overlain by Palaeogene sediments.

The Shiranish Formation is also recognised in NE Syria (Dubertret, 1966 and Brew et al., 2002). Maastrichtian foraminiferal limestones and marls in central Syria can be party correlated with the Shiranish (Ponikarov et al., 1967). In SE Turkey the Shiranish is equivalent to the Kermav marls of the Mardin area (Beer, 1966). Towards the SE in Iran, the formation is equivalent to the upper part of the pelagic Gurpi Formation (Furst, 1970) and the "Upper Cretaceous Marl Group" of Kent et a1,. (1951).
The Anah Graben is a remarkable tectonic element which contalns over 2000 m of Shiranish Formation; thin carbonate turbidite beds are probably present derived from erosion of the adjacent platform areas.

12.3.5 Isolated basin of the Balambo-Tanjero Zone (Tanjero Formation)

The Tanjero Clastic Formation (Plate 12-3) is present in the Balambo-Tanjero Zone of NE Iraq. The formation was defined by Dunnington, in 1952. The type section of the formation in the Sirwan valley (SE of Sulalmaniya comprises two divisions. The lower division comprises pelagic marl, and occasional beds of argillaceous limestone with siltstone beds in the upper part (Bellen et al., 1959). The upper division comprises silty marl, sandstone conglomerates, and sandy or silty organic detrital limestones; it interfingers with the Aqra Limestone. The sandstones are composed predominantly of grains of chert and green igneous and metamorphic rocks. The conglomerates contain pebbles of Mesozoic limestones, dolomites, recrystallised limestones, and radiolarian chert. The thickness of the formation is very variable. The maximum thickness of the formation is about 2000 m between Rowanduz and Chuwarta.

The Tanjero Formation becomes finer grained and more thinly bedded towards the SW. In well Chemchemal-2 the flysch facies is absent. Bolton (1958d), reported Tanjero flysch between the Rowanduz and the Lesser Zab valley at Ganav.

The formation was deposited as flysch in a rapidly subsiding foredeep basin immediately in front of the thrust sheets of the obducted margin of the Southern Neo- Tethys. The onset of flysch deposition occurred when these thrust sheets were elevated above sea level and rapidly eroded.

Fossils (mostly planktonic fauna) are abundant in the Tanjero Formation and indicate a Late Campanian Maastrichtian age. The coarse grained flysch in the upper part of the formation is of Maastrichtian age; the lower part of the formation is of Late Campanian-Maastrichtian age. The uppermost part of the Tanjero Formation contalns the youngest Maastrichtian sediments in Iraq, based on the occurrence of the planktonic foraminifera *Globotruncana falsocalcarata* (Kassab, 1972, 1975b) in the Chalki and Sirwan valley sections.

The formation usually conformably and gradationally overlies the Shiranish Formation. An unconformable lower contact was reported in the Ranya area (Bolton, 1958d); however the Upper Cretaceous clastics here may belong to the basal unit of the Suwais Red Beds. The formation is usually unconformably overlain by Palaeogene formations except where it passes into the Shiranish Formation or is overlain by the Aqra Formation.

The formation mainly occurs in the Balambo- Tanjero Zone. It also occurs in the High Folded Zone, SE of the Greater Zab where it interfingers with the Shiranish Formation. The Tanjero Formation of the Foothill Zone (Chemchemal) comprises marl, limestone and mudstone, with some siltstone beds. The Tanjero Formation is absent in the Northern Thrust Zone.
The Tanjero Formation outcrop extends into SW Iran where it was referred to as the Maastrichtian Flysch by Kent et al. (1952) and described as chert conglomerates by James and Wynd (1965). In Turkey, the Cretaceous parts of the Kermav Formation are equivalent to the Tanjero Formation (Altinli. 1966).

12.3.6 Isolated basin of the Northern Thrust Zone (Hadiena Formation)

The Hadiena Formation occurs in the Northern Thrust Zone of N Iraq. It was defined by Wetzel in 1950 from the Hadiena area NW of Amadiya (Bellen et al., 1959). The formation (750 m thick) comprises three divisions: The lower division comprises dolomitised limestone. The middle division consists of silty marl, and argillaceous, sandy limestone with detrital hematite, phosphatic and chert grains, and thin beds of conglomerate and breccias. The upper division comprises conglomerates and breccias with angular fragments of hematite set in a matrix of ferruginous limestone and terrigenous quartz grains (Bellen et al., 1959). In some areas the lower and middle divisions are absent and the haematitic, brecciated, and conglomeratic beds unconformably overlie the Chi a Gara or Barsarin formations (Hamza and Isaac, 1971). The formation thins rapidly to the E and W, partly due to tectonic complications. The lithology of the formation suggests it was deposited on a platform that was periodically exposed.

An abundant planktonic and benthonic fauna in the middle and upper divisions is of Late Campanian age. The age of the lower division is uncertain; this unit (which has a similar lithology to the "Mergi" facies of the Mishrif Formation) may belong to an older sequence.

The lower contact of the formation is an unconformity. The formation usually overlies the Chia Gara, Barsarin or Naokelekan formations. The upper contact of the formation is conformable; the formation is gradationally overlain by a unit of limestone and dolomitic limestone unit assumed to be the Aqra Formation (Bellen et al., 1959), confirmed by the discovery of rudist reefs (Hamza and Isaac, 1971).

12.4 Danian sequence

The presence of Danian sediments is confirmed locally in Syria (Ponikarov et al., 1967) and in N Iraq (in wells Ain Zalah and Butmah; Dr Farouq AlOmari-oral communication). Jassim et al. (1984) and Jassim and Karim (1986) confirmed the presence of Danian strata in W Iraq (in the lower part of the Palaeocene Akashat Formation exposed W and NW of Rutba Town). Kassab (1972, 1975b, 1976) had earlier considered that Danian sediments were absent in Iraq. The lack of evidence of basinal Danian sediments in central Iraq may be due to insufficient sampling of the Cretaceous/Tertiary boundary sections in wells and/or to condensed sedimentation in Danian time.

12.4.1 Phosphatic outer shelf (Tarfawi Member of Akashat Formation)

Danian sediments occur to the west of Rutba in W Iraq. They are included in the Palaeocene Akashat Formation (Jassim et al., 1984). Five outcrop sections were investigated to the SW, Wand NW of Rutba Town (Karim and Jassim, 1986). The thickest section of the Akashat Formation was described from Wadi Tarfawi 40 km WSW of Rutba; it has been referred to as the Tarfawi Member. GEOSURV investigated the outcrops in detail with trenches and shallow boreholes.

The lowest unit of the formation comprises 7 m of buff to grey shale and white chalk. The shale contalns ribs of intraclastic and bone bearing phosphates; the lowest phosphate bed overlies a layer of chalk with a contact marked by load casts and pseudonodules. The shales contain montmorillonite and palygorskite (Kassim, 1985; Al Bassam and Al Saadi, 1985). The unit overlies Upper Cretaceous oyster bearing *(Lopha)* limestones; the contact is marked by a few centimetres of intraclastic phosphorite. Beds with abundant phosphate intraclasts may have been deposited by turbidity currents.

The chalk beds contain abundant siliceous spicules and are sometimes totally silicified; they contain a rich in planktonic fauna which is often silicified. X-ray diffraction indicates the spicules have a tridymite structure (see Chapter 20).
The shale beds contain the following fauna: *Globigerina daubjergensis, Chilogumbelina sp., Eoglobigerina cf. danica, Guembelitria spp., Globorotalia pseudobulloides, Globorotalia compressa, Globobulimina sp., Bulimina sp., Siphogenerinoides elegantus, Cibicides sp., Yalvulinaria ravani* and *Gaudryina sp.* The chalk beds contaln G. *daubjergensis* and *Guembelitria spp.* In a borehole at the Jordanian border the shale unit is 30 m thick and contalns fauna of the G. *daubjergensis* zone including *Eoglobigerina cf danica.*

The middle unit of the formation consists of 7 m of sandstone which outcrops locally S of the Rutba-Amman highway. It is yellowish, quartzitic and often phosphatic with occasional beds of silicified shelly limestone. It passes laterally into argillaceous phosphatic limestones towards the N. A benthonic marine fauna of *Cibicides sp.* is recorded from this unit. The unit may have been deposited as sand bars which passed laterally into bivalve shoals.

The upper unit consists of micrite limestone and chert (II m thick) comprises foraminiferal biomicrite and micrite with recrystallised planktonic tests often alternating with sparite, with broken bivalve shell fragments, including large *Lenticulina sp.* Black, white and grey chert occurs. Laterally the unit passes into extremely recrystallised limestone with calcite crystals up to one centimetre in size. This particular unit is well defined on the satellite images by its black tone caused by the desert varnished chert fragments. The biomicrites were probably deposited in a bathyal to outer shelf environment as indicated by the alternation of planktonic and planktonic-benthonic assemblages with bivalve fragments.

The Danian section thins towards the N. 28 km along the road to Akashat (from the junction of Rutba-Amman highway) the Danian sediments are 7 m thick, thinning to 3 m along the NW rim of the Ga'ara depression (Tel Semhat). The Danian section is thicker in boreholes to the W, NW and N of the Ga'ara depression. In borehole BH9, 28 km N of the Akashat mine the Danian section is 20 m thick. It comprises from the base upwards: marl and biomicrite with fauna of the G. *daubjergensis* Zone (6 m), sandstone with *Cibicides* (2 m), and marl (13 m). The upper marl unit contalns limestone beds with a benthic fauna of *Siphogenerinoides elegantus, Lenticulina sp., Bulimina sp.* and *Gaudryina sp.* 32 km to the NW of Akashat mine, the Danian section is up to

110m thick, comprising marl with benthic and planktonic fauna of the G. *daubjergensis* Zone and shelly limestone. The fauna is of Danian age in accordance with the global planktonic foraminiferal zonation for the Palaeogene established by Loeblich and Tappan (1957), EI-Naggar (1966), Berggren (l969a and b, 1970, 1972a and b), Kureshy (1979) and others.

The Late Maastrichtian-Early Palaeocene boundary is placed at the first occurrence of the Danian datum *Globigerina daubjergensis* which defines the *Globigerina daubjergensis* Zone also characterized by the first appearance of *Globorotalids* and *Chiloguembelina* and the extinction of *Globotruncana* and *Heterohelix.* The index species is associated with *Chiloguembelina sp., Guembelitria spp., Globorotalia compressa, Globorotalia pseudobulloides,* and *Eoglobigerina cf danica* (present in the basal Danian in the Tralbeel borehole at 278 m depth) and *Chiloguembelina spp.* The benthonic foraminiferal assemblage of this zone is characterized by *Bulimina sp., Globobulimina sp., Siphogenerinoides sp., valvulineria sp., Cibicides sp., Gabonella spp.* and *Gaudryina sp.* The zone was first established in Iraq by Karim and Jassim (1986).

Plate 12-1: Radhuma Safra butte, north of the Ga'ara depression, showing Lopha-bearing limestone overlying the yellow marls of the Digma Formation (photo by Jiří Rudolský)

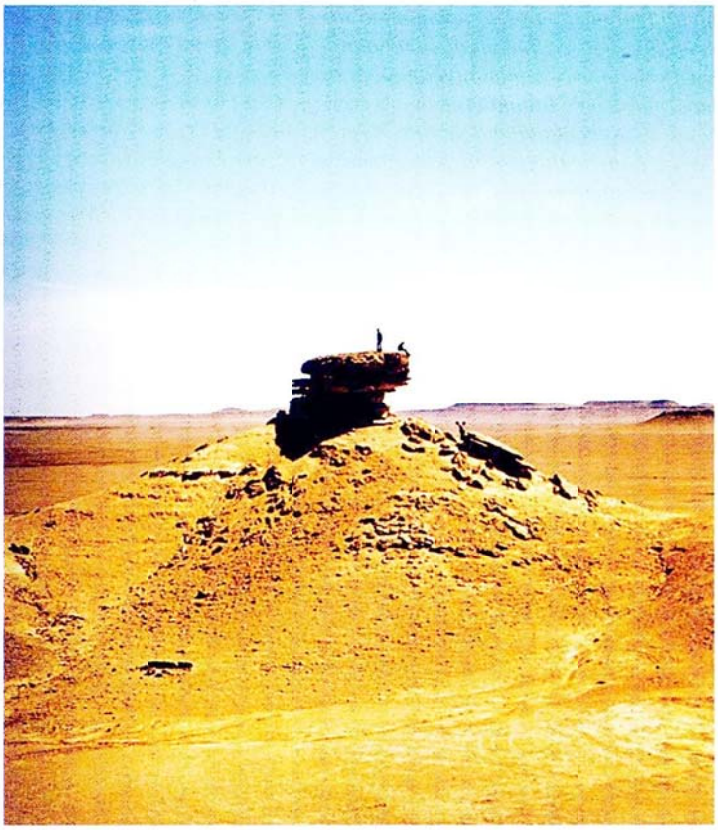


Plate 12-2: Bekhme Formation in core of the Hair Dagh anticline, 10 km NE of Shaqlawa Town in NE Iraq (photo by S. Jassim)





Plate 12-3: Bekhme Formation (massive limestone in top view) overlying the thick bedded Mauddud (Qamchuqa) Formation, Geli Ali Beg gorge, W of Rowanduz (photo by S. Jassim)

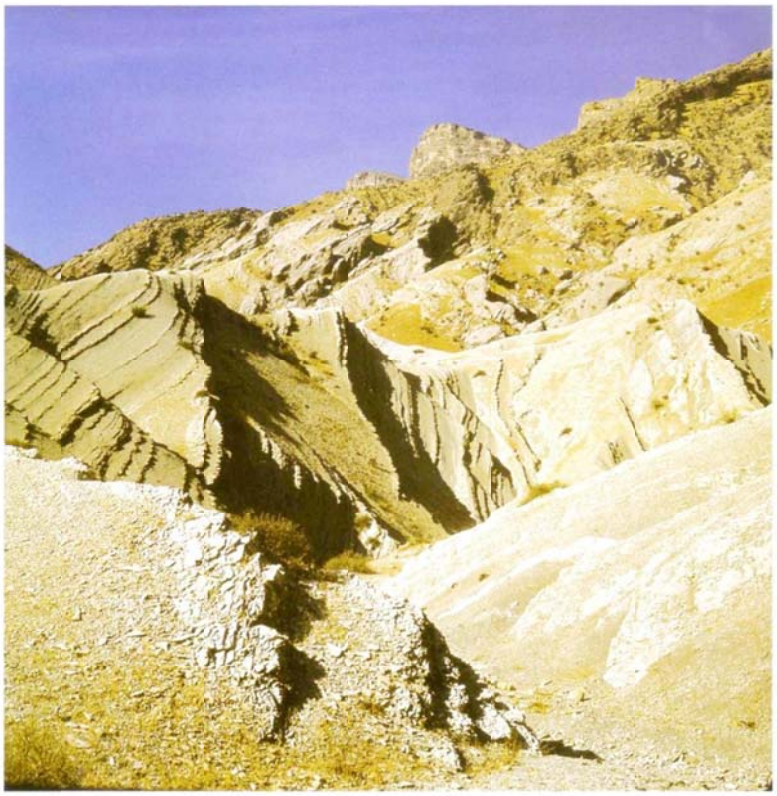


Plate 12-4: Tanjero Formation overlying Shiranish Formation along the NE flank of Azmur anticline, E of Sulaimaniya (photo by Jiří Rudolský)

Chapter 13

Middle Palaeocene-Eocene Megasequence AP10

by

Saad Z. Jassim and Tibor Buday

The Middle Palaeocene-Eocene Megasequence AP l0 was deposited during a period of renewed subduction and volcanic arc activity associated with final closure of the Neo-Tethys (Chapter 3). This led to uplift along the NE margin of the Arabian Plate with the formation of ridges and basins, generally of NW-SE trend in N and Central Iraq and E- W trend in W Iraq. Significant lateral facies changes occurred across these tectonic features. Uplift of the E margin of the Arabian Plate during the Early Palaeocene explains the absence of the Danian from most of the High Folded Zone and the Foothill Zone.

Ditmar and the Iraqi-Soviet Team (1971) recognized an important regional unconformity at the base of the Middle Eocene. However this unconformity is here recognized as a sequence boundary; the megasequence boundary is placed in the Latest Eocene following Sharland et al. (2001). The Middle Palaeocene-Eocene Megasequence (AP 10) is divided into two sequences: The Palaeocene-Early Eocene and Middle-Late Eocene sequences. The stratigraphic column of Megasequence AP 10 is shown in Fig. 13-1. The two sequences of Megasequence AP 10 require further study; with further work they could be subdivided.

The thickness of Megasequence AP 10 (Fig. 13-2) increases from 500 m along the boundary of the Foothill and Mesopotamian zones to over 2000 m within the Balambo Tanjero Zone. The megasequence is also thick in the Sinjar Trough. The megasequence is absent or thin on the crest of the Hauran anticlinorium, the Jezira Subzone and the Mosul High. In the Mesopotamian and Salman zones the thickness of the megasequence increases to the south across the Sirwan transversal fault zone from < 1 00 m to 500 m. The megasequence thickens progressively to the SSE to 900 m at the Iraq-Kuwalt border. West of the Rutba Uplift another basin developed in W Iraq and Jordan.

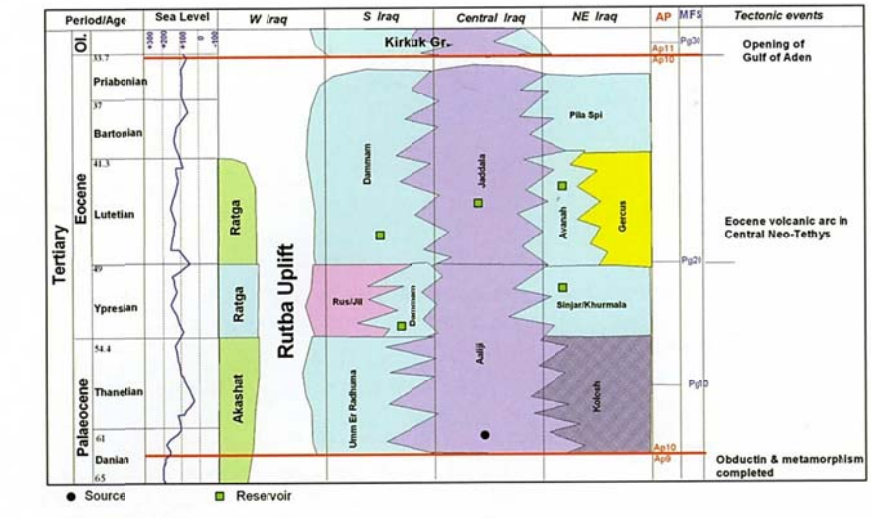


Fig. 13-1: Stratigraphic correlation of the formations of Megasequence AP10

Fig. 13-2: Thickness of the Palaeocene-Eocene Megasequence

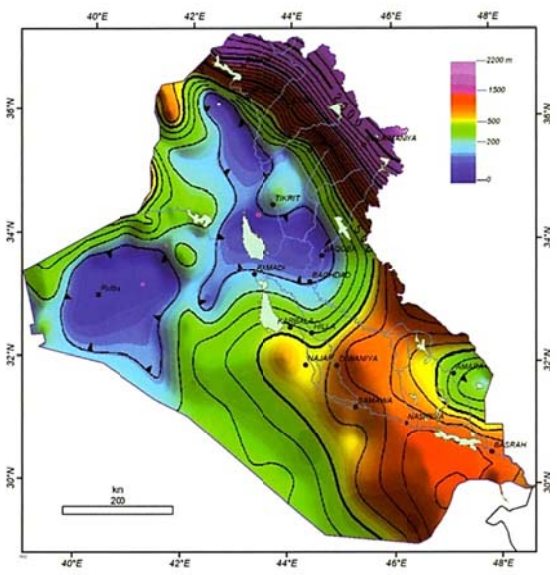
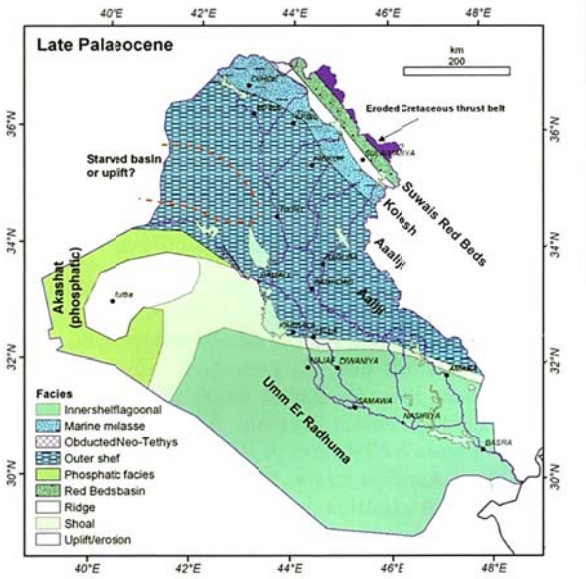


Fig. 13-3: Late Palaeocene Palaeogeography



13.1 Mid Palaeocene-Early Eocene Sequence

Within the Unstable Shelf area two separate longitudinal basins developed in Mid Palaeocene time. An intermontane basin (Red beds basin) flanked the SW and NE sides of the eroded thrust belt that has formed in Late Campanian Maastrichtian time. The Kolosh basin which occupied the area of the High Folded Zone was partly isolated from the Red Beds basin in NE by a ridge along the Balambo- Tanjero Zone from Amadiya in the NW through Rowanduz and Ranya towards Halabja in the SE (Dunnington, 1953; Bolton, 1958b, c, d; Ditmar and the Iraqi-Soviet Team, 1971). Both the NW and SE continuations of this ridge can be traced to Dohuk (Ditmar and the Iraqi-Soviet Team, 1971) and probably to Mardin (Weber, 1963).

Immediately SW of the marginal ridge a relatively narrow foredeep developed during the Early Palaeogene which was filled in with the Palaeogene clastics of the Kolosh Formation (Fig. 13-3). The foredeep progressively migrated towards the SW; its SW boundary is situated approximately along a line connecting Mushorah, Mosul, Kirkuk, and Chia Surkh (i.e. occupying the Butmah-Chemchemal Subzone of the Foothill Zone). Further to the SW, the Kolosh trough passed into a basin that covered most of the Foothill and the NE parts of the Mesopotamian zone where open marine marls of the Aaliji Formation were deposited.

The area to the SW of the Butmah-Chemchemal Subzone was an open marine sea with two subsiding sub-basins separated by a stable but submerged structural high. This high comprised the Mosul High, the Khlesia High of the Jezira Subzone and the Rawdah Uplift in Syria; it extended SE to the Ramadi area (Fig. 13-2). It is unclear whether this ridge was emergent or whether it was submerged and starved of sediment supply. Evidence of erosion has not been observed. To the N and NW of this ridge the Jezira basin developed and extended into the Jezira and Palmyra basins of Syria (Weber, 1963; Ponikarov et al., 1967). It was bordered in the N by an uplifted area between Sinjar, Atshan and Ibrahim in Iraq and Jabel Abd El Aziz in Syria.

Another basin extended from the Mosul High in the NW to the Eastern Zagros in the SE where the Aaliji and Pabdeh formations were deposited. The Khlesia-Mosul Highs formed an important bioprovincial boundary; the NW basin clearly belonged to the Mediterranean bioprovince

(Ponikarov et al., 1967; and Powers et al., 1967) whereas the SE basin belonged to the eastern Indopacific bioprovince.

A facies change occurred along a possible ridge between Falluja in the NW and Amara in the SE. To the SW of this ridge, the Aaliji Formation of SE and central Iraq was replaced by the neritic-shoal facies of the Umm Er Radhuma Formation, followed during the Early Eocene by the evaporites of Rus Formation.

The Danian deep water basin W of Rutba shallowed during Middle-Late Palaeocene time with deposition of phosphatic oolites in an inner shelf environment. The phosphatic facies formed as a result of upwelling of cold, nutrient rich, waters from the narrow closing Neo-Tethys Ocean to the NE (Al Bassam, 1976 and Sheldon, 1981). The Rutba area was partially isolated from the main basin to the E which allowed concentration of phosphogenic water.

In Early Eocene time a local NW-SE trending basin developed within the Umm Er Radhuma belt extending from Kifl in the NW to the Dammam structure in eastern Saudi Arabia in the S. This basin was filled by lagoonal evaporitic sediments of the Rus Formation (Fig. 13-4). To the east, these evaporitic sediments passed into nummulitic shoals which in turn passed into the open marine Pabdeh marls. The nummulitic shoals were probably formed on the Ramadi-Musalyib palaeoridge.

The break between the Maastrichtian and Palaeocene (Bellen et al., 1959) was studied by Kassab (1972 and 1976). Kassab showed that sediments of latest Maastrichtian and Early Palaeocene (Danian) age are absent in the shelf areas of Iraq. However, as discussed in Chapter 12, the presence of Danian is now proven in W Iraq (Karim and Jassim, 1986).

The formations of the Palaeocene-Early Eocene sequence comprise: the phosphatic facies of the Akashat Formation and Swab member of the Ratga Formation, the carbonate evaporite facies of the Umm Er Radhuma and Rus formations, the outer shelf facies of the Aaliji, the molasse of the Kolosh, the carbonate ramp facies of the Sinjar, and the inner shelf lagoonal carbonates of the Khurmala. The lithofacies of the phosphatic cherty and partly argillaceous sediments of W Iraq greatly differs from that of the type Umm Er Radhuma and is almost identical with the phosphatic Syrian Palaeocene (Ponikarov et al., 1967), and with the Upper Cretaceous-Palaeogene phosphatic Belqa Series (Daniel, 1963) of Jordan. Jassim et al. (1984) included the Palaeocene phosphatic rocks in the Akashat Formation and the nummulitic Lower Eocene limestones in the Eocene Ratga Formation. The correlation of units of Megasequence APIO in W and SE Iraq is shown in Fig. 13-5.

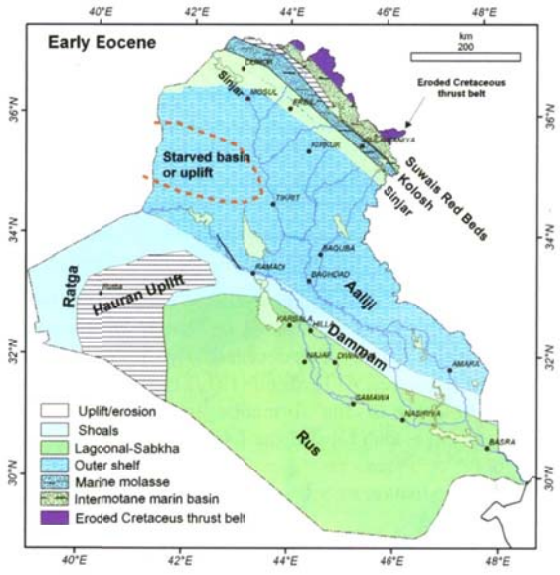


Fig. 13-4: Early Eocene Palaeogeography

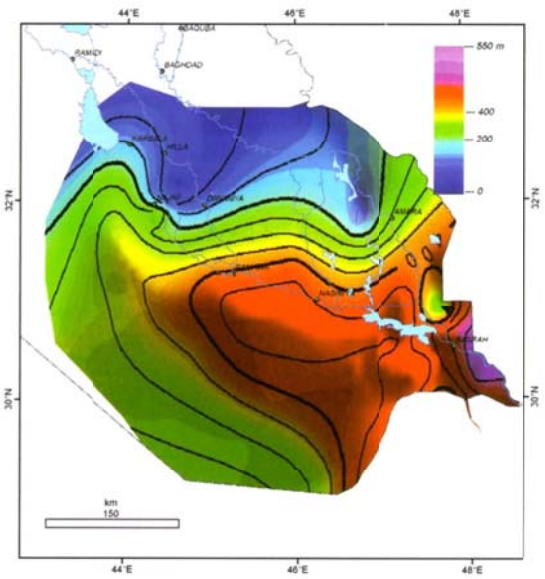
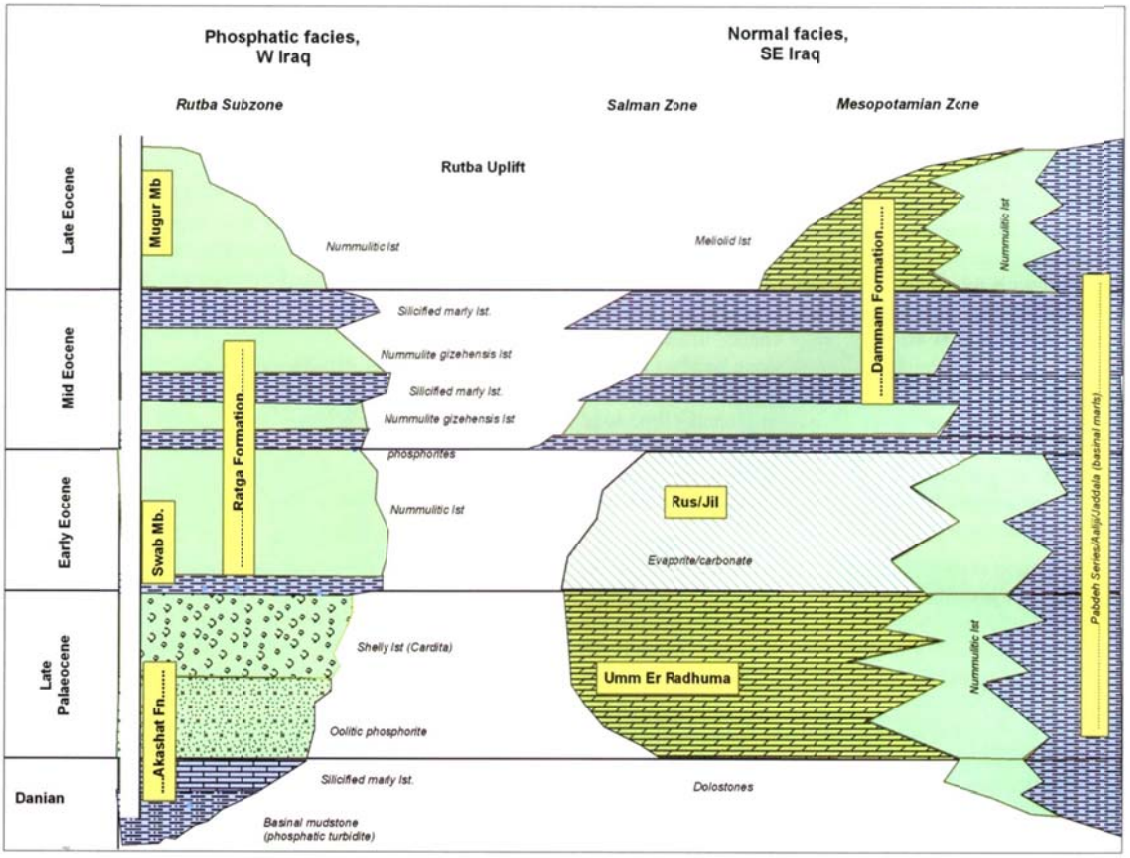


Fig. 13-6: Thickness of the Umm Er Radhuma Formation

Fig. 13-5: Stratigraphic correlation of the phosphatic and non-phosphatic units of Megasequence AP10 in W and SE Iraq



13.1.1 Carbonate-Evaporite inner shelf

13.1.1.1 Umm Er Radhuma Formation

The Umm Er Radhuma Formation was described by Steineke and Brarnkamp in 1952 (Bellen et al., 1959) from the type locality at the Umm Er Radhuma wells in Saudi Arabia. The reference section is in Wadi al Batin, in Saudi Arabia. A supplementary type section for Iraq introduced by Owen and Nasr (1958) in well Zubair 3 in S Iraq comprises anhydrite and white to buff dolomitic microcrystalline porous limestone; chert occurs in the upper part.

The Umm Er Radhuma Formation in Iraq outcrops in the eastern parts of the Rutba Subzone, south of Wadi Al Kharr, along the Iraq-Saudi border and on the shoulders of the Nukhaib Graben. N and NW of Wadi Al Kharr the lagoonal facies of the formation passes into a phosphatic facies.

In the Tekhadid area of S Iraq in water borehole KH-4 (from 50 to 356 m) the Umm Er Radhuma Formation comprises from the base upwards: 92 m of pale grey dolomitic marl and argillaceous dolomite with anhydrite nodules, 67 m of anhydrite and argillaceous dolomite with anhydrite nodules, 56 m of pale grey dolomitic marl and argillaceous dolomite with frequent anhydrite nodules, and 91 m of dolomitic limestone and coarsely crystalline dolomite, with rare phosphatic grains.

Near Nukhaib, the formation is 240 m thick and comprises from the base upwards: 1) 40 m of white fossiliferous chalky limestone and yellow recrystallised shelly calcareous dolomite with thin beds and lenses of chert with geodes. 2) 40 m of grey recrystallised shelly calcareous dolomite with chert lenses. 3) 40 m of white chalky limestone and grey calcareous dolomite (with chert along bedding planes) containing a 5 m varicoloured calcareous sandy limestone at the base. 4) 50 m of white argillaceous and chalky limestone and grey shelly calcareous dolomite with black chert lenses 40 m of white chalky limestones with chert bands.
5)30 m of recrystallised shelly and dolomitic limestones, phosphatic at the top, with red mudstone beds.

The formation is up to 570 m thick in wells near the Shat Al Arab River within the Mesopotamian Zone. The formation thins to the W and NW; on the Sand SE slopes of the Hauran anticlinorium it wedges out completely. Towards the E and NE it passes laterally into the open marine Aaliji Formation. It also passes into the phosphatic Akash.at Formation to the W of the Nukhaib Graben where the thickness decreases to around 200 m. The thickness of the Umm Er Radhuma Formation in S Iraq is shown in Fig. 13-6. The formation sharply increases in thickness largely S of the Kut Dezful Fault.

. Shakir (1983; in Jassim et al., 1984) studied outcrops in SW Iraq and identified the following fauna: *Saudia labyrinthica* Grimsdale, *Alveolina primaeva* Reichel, A *globosa* Leymerie, *Coskinolina sp., Cibicides sp., Valvulina sp., Spiroloculina sp., Nodosaria sp., Orbitolites sp., Dentalina sp., Idalina sp., Pyrgo sp., Globorotalia cf aequa* Cushman and Renz. Small nummulites were also recorded in the upper part of the section. *Saudia labyrinthica* and *Alveolina primaeva* appear to be restricted to the Late Palaeocene, and *Alveolina globosa* to the Late Palaeocene-Early Eocene.

Based on fossil evidence and correlation with Saudi Arabia (Bellen et al., 1959) the age of the Umm Er Radhuma Formation in Iraq is Palaeocene-Early Eocene (Early Ypresian). However, Al Hashimi (1972) concluded that the uppermost beds of the formation in Zubalr-3 are of Palaeocene age. Outcrops of the formation in SW Iraq are also only of Palaeocene age. Therefore, the Umm Er

Radhuma Formation in S Iraq is likely restricted in age to the Palaeocene.

The lower contact of the formation in both S Iraq and Saudi Arabia (Powers et al., 1967; Bellen et al., 1959) is marked by the appearance of black and dark brown chert horizons or geodes. In the west the contact is marked by sandstone and gypsiferous mudstone. The upper contact with the Rus Formation is gradational and conformable in the type area. Bellen et al. (1959) indicate this contact is disconformable in S Iraq. According to Al-Hashimi (1973) the upper contact is marked by a break.

The Umm Er Radhuma Formation was deposited in a supratidal sabkha environment similar to that of the younger Rus Formation (Basi, 1984; in Jassim et al., 1984). Near Nukhaib where the formation passes into a phosphatic facies, Skocek and Hussein (1980; in Jassim et al., 1984) concluded that the basal part was deposited in subtidal marine environment with areas to the west being closer to the shoreline. In the east the formation was deposited in the more distal parts of the carbonate platform. Faunal evidence indicates an inner shelf depositional environment with water depths up to 50 m; alternating shelly horizons suggest a shallower depth of about 20 m. To the NE and N, the formation passes laterally into the more basinal Aaliji Formation.

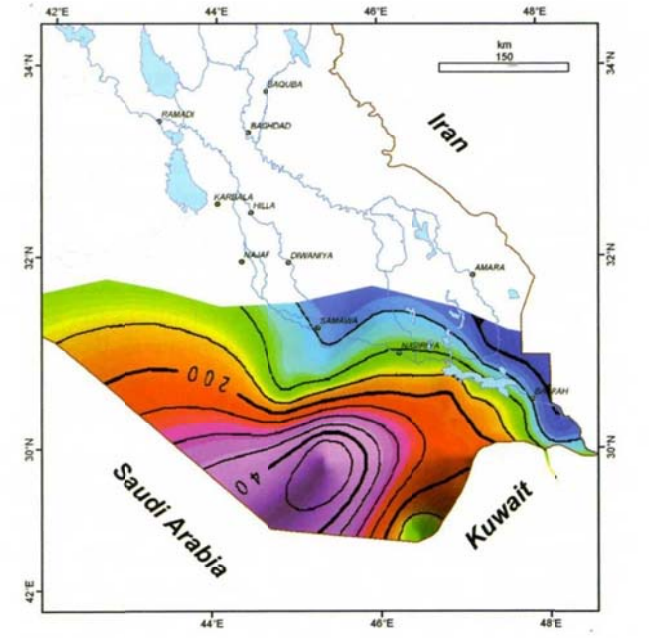


Fig. 13-7: Thickness of the Rus (Jil) Formation in S Iraq

13.1.1.2 Rus (Jil) Formation

The Rus Formation was first defined by Bramkamp in 1964 (Bellen et al., 1959) from the type section on the SE flank of the Darnmam dome in E Saudi Arabia. A supplementary type section was introduced by Owen and Nasr (1958) in well Zubalr-3 in the Mesopotamian Zone of S Iraq where the formation consists predominantly of anhydrite with some unfossiliferous limestone, blue shale, and marl. In some areas the formation has been combined with the Umm Er Radhuma Formation, for instance in Dujalla, Ghalalsan, Kifl, Shawiya, Ubaid (Safar, 1961; Rolleigh, 1960; Kasim, 1960, 1961; Halliwell, 1960). In Afaq the formation had been included in the Dammam Formation (MacLeod, 1961).

The formation is well defined in a very restricted area in Iraq in the southern Salman and Mesopotamian zones especially between the transversal Kut-Dezful and AL Batin Faults (Fig. 13-7). Outcrops along the Saudi-Iraq border lack anhydrite (due to dissolution). Jassim et al. (1984) suggested the use of the name Jil Formation for the Rus equivalent at outcrop where the anhydrite has been dissolved. The Jil Formation corresponds to beds previously assigned to the Dammam Formation (the Wagsa, Sharaf, Schbicha Members and the lower chalky part of Huweimi beds introduced by Owen and Nasr in 1958).

At outcrop the Rus (Jil) Formation can be divided into two members: The Lower member (equivalent of Wags a) is 20 m thick and consists of flaky yellowish marl with thin beds of nummulitic limestone with gastropods towards the top. Fossils include *Nummulites deserti* Delharpe, *N. fraasi* Delharpe, *N. globulus* Leymeri, *N. sp., Operculina libyca* Schwager, echinoid spines and pelecypods (Shakir, 1984 and Abdulmunim and Yacob, 1984; in Jassim et al., 1984). *Nummulites deserti* and *N. fraasi* appear to range in age from latest Palaeocene to earliest Eocene; *N. globulus*, appears to be restricted to the Early Ypresian. The age of this unit is thus interpreted as Early Eocene (Early Ypresian). The Upper member (equivalent to the Sharaf, Schbicha and lower Huweimi units) is 62 m thick. Its best exposures are near Schbicha Town. It comprises recrystallised limestone, partly silicified, overlain by fossiliferous limestone with thin beds of recrystallised limestones. Chert nodules are common throughout. Fossils include abundant shell fragments, echinoid spines and recrystallised miliolids. The Upper Member correlates with the milioloid limestone beds described by Al Hashirni (1973) from well Zubalr-3 of Late Ypresian age. In water wells in the S desert of Iraq thick anhydrites occur. Dissolution of the anhydrites has created karst topography.

According to Powers et al. (1967) the age of Rus Formation is Early Eocene (Ypresian). The same age is also accepted by Bellen et al. (1959), and Naqib (1967). Fossils from outcrops also indicate an Early Eocene (Ypresian) age.
The lower contact of the formation is conformable in Iraq and Saudi Arabia. The upper contact is disconformable, marked by a breccia. The thickness of the formation in S Iraq is around 200 m. The very high thickness of 513 m in well Ubaid-I (Fig. 13-7) may be due to inclusion of part of the Umm Er Radhuma Formation within the Rus. To the NE, the Rus Formation may be replaced by the nummulitic limestone of the Dammam Formation. The formation was deposited in a lagoonal-sabkha environment on the Stable Shelf.

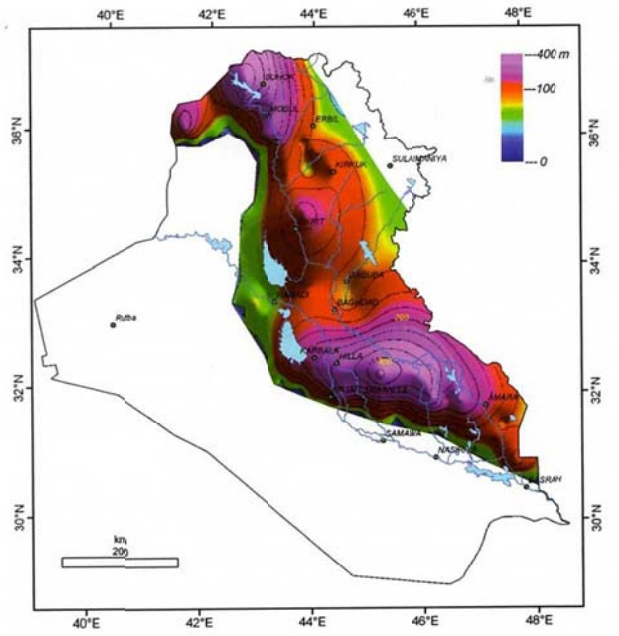


Fig. 13-8: Thickness of the Aaliji Formation

13.1.2. Phosphatic inner shelf

13.1.2.1 Akashat Formation (M-U Palaeocene part only)

Phosphorites are restricted to the N, W and S flanks of the Hauran anticlinorium. They outcrop in W Iraq in a narrow belt near Rutba, extending from the Iraq-Saudi border to the Ga'ara depression in the N. They were deposited in shoreline, shoal and open marine environments. Jassim et al. (1984) introduced the name Akashat Formation for these phosphorites. The type section at Tel Semhat on the NW rim of the Ga'ara depression, 7.5 km SE of the Akashat mine, is 12 m thick.
The Akashat Formation overlies the phosphatic Digma Formation of Maastrichtian age. It is overlain by the phosphatic Ratga Formation of Eocene age (Jassim et al., 1984). The Akashat Formation overlies the Digma Formation disconformably or gradationally with a short hiatus. The Akashat Formation is conformably overlain by Lower Eocene nummulitic limestones except near the eastern rim of the Ga'ara depression and eastward along Wadi Hauran, where the formation is overstepped by the Lower Eocene limestones.

The Akashat Formation near Rutba is 12 m thick at Tel Semhat (the type section). Thicknesses at other localities are as follows: 28 m at the Akashat mine, 44 m in the H3 area west of Rutba, 190 m in borehole BHI north of the Akashat mine, and >200 m at the Iraq-Jordan border near Traibeel. The Middle-Late Palaeocene part of the sequence decreases in thickness towards the N; Southwest of Rutba the unit is 19 m thick, 17 m thick 28 km N of the Rutba-Amman highway, and 12 m thick on the NW rim of the Ga'ara depression. It increases in thickness to 81 m in BH I, NW of the Akashat mine.

At outcrop the thickest section (19 m) of the Akashat Formation is located WSW of Rutba. It comprises the following units from base to top:

1. Shelly limestones with phosphatic intraclasts (4 m thick) passing upwards into micritic limestone (4 m thick), containing both planktonic and benthonic faunas, mainly: *Globorotalia angulata* White, *Globorotalia uncinata* Bolli and *Vavulineria ravni* Brotzen.

2.Oolitic phosphorite (2 m thick) composed of phosphatic oolites, intraclasts and shark teeth embedded in a calcareous matrix; planktonic foraminifera often form the nuclei of the oolites.

3. Brown mudstone (0.3 m thick), containing isolated dolomite rhombs and a rich fauna of dwarfed planktonic foraminifera indicating a stressed depositional environment.
4. Bone-intraclastic phosphorite (0.3 m thick) containing bone and intraclastic fragments and pellets exceeding 50% of the rock, embedded in a fine micritic matrix with heavily-spinosed planktonic foraminifera shells. It is overlain by a thin radiolarian chert. This assemblage and lithology indicate an outer shelf to bathyal depositional environment.
5. Intraclastic micrite and calcareous mudstone (6 m thick).
   The associated fauna is: *Globorotalia velascoensis* (Cushman), *Globorotalia acuta* Toulmin, *Globigerina triloculinoides* Plummer and benthonic fauna like *Astacolus gladius* (Philips), *Nodosaria macneili* Cushman, *Lenticulina wilcoxensis* Cushman and Ponton, *Dentalina sp.* and *Bulimina sp.* This unit was deposited in a bathyal-deep shelf environment.
   6.Coarse, pelletal phosphorite with intraclasts passing up into and phosphatic limestone (2.5 m thick).
7. Bone intraclastic limestone (2 m thick)

Units 1-4 above belong to the *Globorotalia angulata* Zone of Middle Palaeocene age. Units 5 to 7 belong to the *Globorotalia velascoensis* Zone (of Late Palaeocene Earliest Eocene age) and were deposited in outer shelf to bathyal environments.

A laterally persistent coprolite phosphorite bed about 0.5 m thick containing coarse-grained coprolites in a calcareous matrix locally rich in shell fragments occurs at the top of the formation. It passes gradually into the overlying nummulitic limestone of the Ratga Formation.

The section in the Akashat mine is 27 m thick. It comprises from the base upwards:

1. Marl passing up into biomicrite (8 m thick) with planktonic fauna of the *Globorotalia angulata* Zone, occasionally with recrystallised macroforams.

2. Phosphatic biomicrite (6 m thick) with phosphatic intraclasts containing planktonic foraminifera of the *Globorotalia velascoensis* Zone.
3. Green marl (13 m thick) rich in planktonic foraminifera of the *Globorotalia velascoensis* Zone and benthonic foraminifera.
   Evidently sediments of this section were deposited in a bathyal-deep shelf environment.

The Akashat Formation can be correlated with the glauconitic, phosphatic, shark teeth bearing facies of the Lower Pabdeh Formation of Iran (Furst, 1970), and the Taqiye Marl Formation of Jordan (Daniel, 1963). It is .equivalent to the lower part of the Hibr Formation in Saudi Arabia.

13.1.2.2 Ratga Formation (Swab Member)

The Ratga Formation was introduced for the phosphatic facies representing the whole of the Eocene in W Iraq (Jassim et al., 1984). The formation comprises open marine chalk, nummulitic limestone and phosphorites. It was divided into the Lower Eocene Swab, Middle Eocene Damlouk and Upper Eocene Mugur Members.

The type locality of the Swab Member is at Wadi Swab along the Syrian border NW of the Ga'ara depression. The Swab Member outcrops to the Wand N of the Ga'ara anticline. In the NE corner of the Ga'ara depression it unconformably overlies the Triassic Mulussa Formation. On the N and W rim of the depression it overlies the Palaeocene Akashat Formation. The outcrop continues into Saudi Arabia as a long N-S belt. It outcrops immediately E of the Nukhaib Graben, and passes laterally into the Rus Formation S of Wadi Al Kharr. The thickness of the Swab Member is 65 m at Wadi Swab, 46 m in Nihidain area near the Iraq-Jordan-Saudi triple border point and 35 m near Nukhaib.

The lower part of the member is composed of thick to massive white recrystallised limestone with abundant patches of centimetric honey coloured calcite. This unit overlies a coprolite phosphorite throughout W Iraq. The upper part of the member comprises thick nummulitic limestone, silicified in places, followed by thick-bedded soft fossiliferous limestone with silicified horizon containin$_g$ phosphatic pellets and shells.
The fauna determined by Al Hashimi (1972; in Jassim et al .. 1984), Shakir (1979; in Jassim et al., 1984), Ctyroky and Karim and Ctyroky (1971b) and Buday and Hak (1980) for the lower part of the member comprises: *Nummulites fraassi* Delharpe, *N deserti* Delharpe, *Assilina sp., Rotali trochidiformis* Deshayes, *Operculina libyca* Schwager, N *deserti akashensis* Al-Hashimi, Bryozoa and alage. The upper part contains *Nummulites planulatus* Lamarck, N *lucasanus, N. globulus,* algae, shark teeth and Nautilu *Nummulites globulus, N. planatus* and *Operculina libyca* appear to be restricted to the early Eocene; *N. lucasanus* to the Mid Eocene. The age of the Swab Member is in the range Early-Mid Eocene.
The Swab Member was deposited as a belt of nummulite shoals along the margin of the Rutba Uplift, between the near-shore and shoreline deposits of the Rutba uplift and the outer shelf which lay to the N and W of the Ga'ara anticline and Hauran anticlinorium.

13.1.3 Outer shelf-basinal
13.1.3.1 Aaliji Formation

The Aliji Formation is widespread in the Foothill Mesopotamian zones (Fig. 13-4). It was introduced b. Bellen in 1950 (Bellen et al., 1959) from the type locality' NW Syria. The supplementary type section for Iraq in we Kirkuk-l09 of the Foothill zone comprises grey and light brown argillaceous marl, argillaceous limestone, and shale with occasional microscopic fragments of chert and rare scattered glauconite. Silty and sandy beds occur towards the N and NE where the

formation gradually passes into the clastic Kolosh Formation. Towards the SE and W, the formation is composed predominantly of limy globigerinal mud. Chalky and argillaceous limestone beds occur where the formation passes laterally into the Umm Er Radhuma Formation.
The thickness of the formation in the type area is about 100 m. Greater thicknesses were recorded in SE Iraq (350 m) and NW Iraq (470 m). In S Iraq (Fig. 13-8) the formation thickens in the western extension of the E- W trending Dezful Embayment of SW Iran S of the Kut Dezful Fault. This suggests that the Kut-Dezul Fault affected subsidence in the Mesopotamian Zone during Late Palaeocene-Early Eocene time. In NW Iraq a depocentre is located in the Sinjar area in the E-W Sinjar-Abdul Aziz basin of the Foothill Zone. A N-S trending depocentre formed along the E boundary of the Salman Zone, extending from N Iraq to Najaf swinging eastwards across the Mesopotamian Zone into SE Iraq. On the Stable Shelf, N and W of the Ga'ara and Hauran anticlines, the Aaliji Formation passes into the phosphatic pelagic facies of the Akashat Formation.

The formation was deposited in an off-shore, open marine environment lying between two belts of platform margin carbonate shoals in the SW and NE. The Aaliji Formation is absent in the Jezira Subzone. Dunnington (1968) and Buday (1980) suggested that this area formed an uplift where Palaeocene-Lower Eocene sediments were not deposited; the offshore Eocene Jaddala Formation overlies basinal Upper Cretaceous sediments of similar basinal facies. Jassim et al. (1984) proposed that this hiatus was due to deposition in a starved basin.
Fossils, especially the globorotalids are abundant. The assemblages are composed of: *Alabamina wilcoxensis, Ammodiscus incertus, Anomaloides granosa, Cibicides beaumontianus, Dorothia gibbosa, Gaudryina soldadoens is, Globigerina triloculinoides, Globorotalia angulata,* G. *aragonensis,* G. *membranacea,* G. *spinulosa,* G. *velascoensis, Gyroidina naranjeensis, Karreria fallax, Parrella, Pullenia coryelli, Quadrimorphina allomomorphinoides, Valvulina pectinata* etc. (Bellen et al., 1959). These fossils indicate a Palaeocene-Early Eocene age. Ditmar and the Iraqi-Soviet Team (1971) noted that where the formation is thin, it only contalns Late Palaeocene-Early Eocene fossils. This is due to the later transgression of the sea in the west. Kassab's (1972 and 1975b) detailed studies confirmed that the base of the Aaliji Formation is of Late Palaeocene age. *Globigerina triloculinoides* is restricted to the Early Palaeocene; *Globorotalia angulata* to the Mid Palaeocene; G. *velascoensis* to the Late Palaeocene Earliest Eocene; and G. *aragonensis and* G. *spinulosa* to the Early-Mid Eocene.
The lower contact of the formation in the type area is unconformable except where the Aaliji occurs as tongues within the Kolosh Formation. The upper boundary in the type area is also unconformable.
The formation correlates with the Aaliji of Syria (Dubertret, 1966; Ponikarov et al., 1967), the Germav marl (Beer, 1966) of SE Turkey, and the Lower Pabdeh Formation of the Iranian Zagros (Furst, 1970).

13.1.3.2 Kolosh Formation

The Kolosh Formation was first described by Dunnington in 1952 from Kolosh village, N of Koi Sanjak, in the High Folded Zone. According to Ditmar and the Iraqi-Soviet Team (1971), the type section of the formation includes part of the Sinjar Limestone Formation. The type section comprises from the top:
1) 144 m of limestones and marls with *Miscellanea miscella,* ostracods and miliolids, **2**) 30 m of

limestones with *Dictyokathina simplex, Lockhartia sp.,* valvulinids, miliolids and ostracods, **3**) 114 m of limestones and shales, red shales and sandstones with the same fossils but without *Dictyokathina simplex*, **4**) 6 m of limestones with *Saudia labyrinthica*, miliolids and rotalids, and **5**) 410 m of blue shales and green sand. *Saudia labyrinthica* appears to be restricted to the Late Palaeocene, and *Dictyokathina simplex* and *Miscellanea miscella* to the Late Palaeocene-Early Eocene.

The sand grains in the Kolosh Formation are composed of green rock, chert and radiolarite. Units 1) and 2) were reassigned by Ditmar and the Iraqi-Soviet Team (1971) to the Sinjar Limestone Formation. The lithology of Units 3) and 4) indicates that interdigitating of the Kolosh and Sinjar formations occurs. Interfingering of the Kolosh and Sinjar formations has also been observed in the Taq Taq well (Ditmar and the Iraqi-Soviet Team, 1971), in wells in the N part of the Kirkuk structure (Bellen et al., 1959), and in Derbendikhan area (Jassim et al., 1975).

Towards the west the formation comprises mudstones, siltstones, and argillaceous limestones and detrital limestone beds in wells in the Chemchemal, Taq Taq and Mushorah.

The Kolosh Formation is about 400 m in the type area. It reaches a thickness of up to 1000 m in the Derbendikhan area (Jassim et al., 1975). In N Iraq the formation is 230 m thick in well Jabal Kand-l and 318 m thick in Kirkuk-1l7.

The formation was deposited in a marginal marine depositional environment in a narrow rapidly subsiding trough. Ditmar et al (1971) considered that the Kolosh clastics were flysch. However Seilacher (1963) considered that they have the characteristics of molasse.

Fossils are rare in the Kolosh Formation, but a faunal list by Ditmar and the Iraqi-Soviet Team (1971) indicates the formation is of Palaeocene age. Limestone beds which occur near the top of the formation may be of Early Eocene age (Jassim et al., 1975). Kassab (1972 and 1976) confirmed that the base of the formation is of Middle Palaeocene age. The Early Palaeocene (Danian) is absent.

The formation unconformably overlies Upper Cretaceous beds. In the type area it overlies the Tanjero Clastic Formation; elsewhere it overlies the Shiranish Formation or Upper Cretaceous limestones. The clastics of the Kolosh were derived from erosion of the Tanjero, Qulqula and other Cretaceous-Jurassic formations. Bellen et al. (1959) suggested that the upper boundary of the Kolosh Formation was unconformable. However, where the Kolosh is overlain by Palaeocene-Lower Eocene limestones (as in the type section) the upper boundary is conformable and gradational.

The formation was deposited in a relatively narrow NW-SE trending trough extending from Mushorah in the NW through Koi Sanjak to Kashti in the SE. The trough was bordered to the N and NE, by a narrow, probably discontinuous ridge separating it from the Balambo- Tanjero Zone where the Suwais Red Beds were deposited in a separate basin. According to Bolton (1958d) and Dunnington (1953) the ridge passed through the Dohuk, Ranya, Sulalmaniya, and Ha1abja areas. In areas where there was communication between the two basins, the Kolosh clastics pass to the NE into the Suwais Red Beds.

The formation extends into Turkey, where it is represented by the clastic facies of the Kermav Formation (Altinli, 1966). In SE Iran the upper part the Amiran Formation of James and Wynd (1965) and the purple shales of the Lower Pabdeh Formation (Furst, 1970) can be correlated with the Kolosh Formation.

13.1.4 Carbonate ramp (Sinjar Formation)

The Sinjar Limestone Formation was first described from the Jabal Sinjar area (near Mantissa village) by Keller in 1941. It comprises 176m of limestone of algal reef, lagoonal mi1iolid, and nummulitic shoal nummulitic shoal facies (Bellen et al., 1959). Elsewhere the limestones are often dolomitised. The Sinjar Formation interfingers with the Kolosh Formation in well Taq Taq-I (Ditmar and the Iraqi-Soviet Team, 1971), and in the type area of the Kolosh Formation (Bellen et al., 1959; Ditmar and the Iraqi-Soviet Team, 1971). The Sinjar Formation is present in the Foothill Zone and on the SW margin of the High Folded zones. The SW limit of the formation lies along a line crossing the Foothill Zone from the S limit of the Sinjar Trough to the Alan structure, and passing through Demir Dagh, the NW end of Kirkuk, and the SW margin of the High Folded Zone around Bawanur.

The thickness of the formation in its type area reaches 176 m. In the Derbendikhan area of NE Iraq the formation is 120 m thick (Jassim et al., 1975). In the Foothill Zone of N Iraq the thickness of the formation is 213 m in well Alan-I, 541 m in Mushorah-l and 126 m in Demir Dagh-1. In some wells the formation interfingers with the Aaliji Formation, for example in Tel Hajar (158 m) and Sufaya-A2 (337 m). The formation is probably thickest near the Iraq -Syria Turkey triple border point.

The formation was deposited predominantly in shallow water reef, forereef and lagoonal environments.

Abundant fossils (Bellen et al., 1959, p. 279 and Ditmar and the Iraqi-Soviet Team, 1971) comprise: *Alveolina sp., A. elliptica; A. oblonga. A. primaeva, Dictyoconus arabicus, Dictyokathina simplex, Idalina sinjarica, Miscellanea miscella, Nummulites atacicus, N. discorbinus, N. bolcensis, N. globulus, N. lucasanus, N. carpathica, N. fraesi, Assilina placentula, Operculina salsa, Operculina herberti, Orbitolites complanatus, Daviesina ghilizarda, Rotalia trochidiformis, Discocyclina sp., Saudia labyrintica, Taberina daviesi,* and *Parachaetetes asvapatii.* Several algae were found and described by Elliot in 1955 and 1956 (Bellen et al., 1959). *Alveolina primaeva* and *Saudia labyrinthica* appear to be restricted to the Late Palaeocene; *Daviesina, Dictyokathina simplex, Idalina sinjarica, Miscellanea miscella, Nummulites fraasi* and *Operculina salsa* to the Late Palaeocene-Early Eocene; and *Alveolina oblonga* and *Assilina placentula* to the Early-Mid Eocene.

The age of the formation, according to Bellen (1959), is Palaeocene-Early Eocene. Ditmar and the Iraqi-Soviet Team (1971) considered the formation to be of Early Eocene age because it overlies the Kolosh Formation. However its lateral passage into the Aaliji and Kolosh Formation indicates its age extends into the Late Palaeocene. An Early Eocene age is confirmed for the Sinjar Formation of the Derbendikhan area of NE Iraq (Jassim et al., 1975).

In the type area in Sinjar the formation unconformably overlies the Shiranish Formation. However in NE Iraq it passes down gradationally into the Kolosh Formation. It is conformably overlain by (or passes laterally) into the Khurmala Formation. It is locally unconformably overlain by the Jaddala Formation (Bellen et al., 1959).

The Sinjar Formation also extends into Syria (Sinjar Limestone; Weber, 1963; Dubertret, 1966). It is developed in similar facies in SE Turkey (Becirman Formation; Altinli, 1966). In Iran the formation is equivalent to the lower part of Jarum Formation (Furst, 1970) and to the Taleh Zang Formation (James and Wynd, 1965).

13.1.5 Carbonate inner shelf (Khurmala Formation)

The Khurmala Formation was described by Bellen in 1953 in the Kirkuk-114 well (Bellen et al., 1959) where it is 185 m thick and comprises dolomite (pseudoolitic in parts) and finely recrystallised limestone. The calcareous beds interfinger with clastics of the Kolosh Formation. It is locally anhydritic. The formation has a restricted distribution in a belt between Jabal Maqlub in the NW and the Chemchemal-Qizil Dagh area in the SE. It was most probably deposited in a relict basin corresponding to the SE part of the Kolosh trough. This basin was separated from the off-shore Aaliji basin by a partly disconnected submarine ridge on which shoals of the Sinjar Formation were deposited.

10 well Chemchemal-2 (Ditmar and the Iraqi-Soviet Team, 1971; Melville and Fothergill, 1956) the formation is composed of recrystallised limestones, with occasional argillaceous beds, and beds of anhydrite and gypsum. In some outcrops, argillaceous limestones and marls (Koi Sanjak, Surdash and Sirwan) formerly referred to as the 'Hanjir Backreef Complex' (Bellen et a!., 1959), pass laterally to the NE into terrigenous clastics.

The thickness of the formation is 185 m in the type area, 173m in (Kirkuk -117), 115 m Taq Taq-l and 262 m in Atshan1. The recorded thickness in well Jabal Kand-l of 606 m is probably too high because of inclusion of sediments of the overlying sequence.

The facies of the carbonates, the high pyrite content, and the presence of beds of gypsum and anhydrite indicate the formation was deposited in a restricted lagoonal environment. Fossils, mostly dwarfed and obliterated by recrystallisation, comprise miliolids, small valvulinids, clavulinids and alveolinids. Some small gastropods and fragments of algae also occur. The formation was assigned a Palaeocene-Early Eocene age (Bellen et al., 1959) based on its stratigraphic relationship to other dated formations.

The lower contact of the formation is usually gradational; the underlying formation is usually the Kolosh Formation, with which the formation interfingers. However, in well Jabal Kand-l the formation disconformably overlies the Upper Cretaceous Shiranish Formation.

13.2 Mid-Late Eocene Sequence

The Mid-Late Eocene sequence was deposited to the SW of an emergent uplift during the final phase of subduction and closure of the remnant Neo- Tethys ocean. Red beds were deposited in the basin to the NE of the uplifted area. Red beds clastics were also deposited in a narrow intermontane basin, between the uplifted area in the NE and a ridge located along the NE side of the Balambo- Tanjero Zone, running from Amadiya in the NW through Ranya, Sulalmaniya and Halabja in the SE (Fig. 13-9).

Fig. 13-9: Mid Eocene Palaeogeography

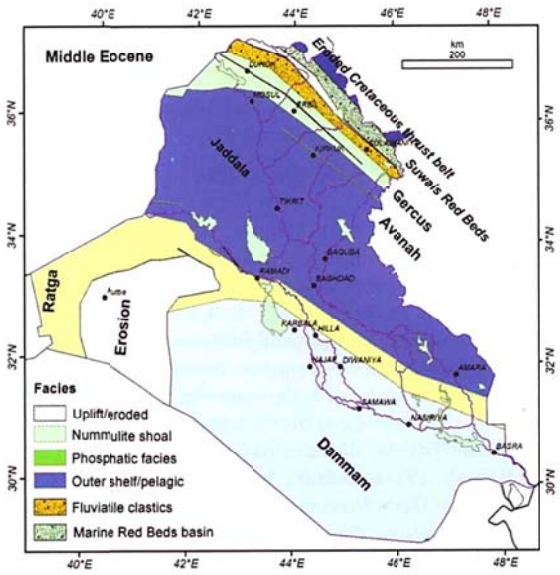
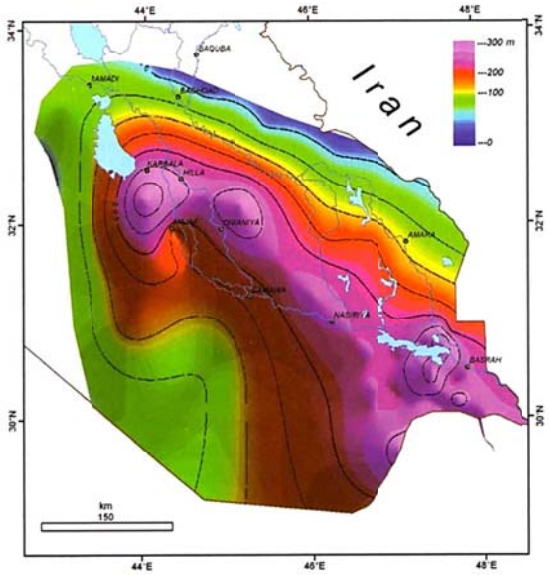


Fig. 13-10: Thickness of the Dammam Formation (not including the Nummulitic limestones of W Iraq)



A strongly subsiding trough, in which the molasse of the Gercus Red Beds was deposited, formed southwest of the Balambo- Tanjero Zone ridge. At the end of the Mid Eocene, the clastic sediment supply from the uplifted area to the NE ceased and the basin was filled with lagoonal carbonates of the Pila Spi Formation.

The foredeep basin of the mid and partly Late Eocene was separated from the basin to the SW by a belt of nummulitic shoals (Avanah Formation). The foredeep basin was located in the present day Butmah-Chemchemal Subzone of the Foothill Zone and extended into Syria and SE Turkey in the NW (Ponikarov et al., 1967) and into SW Iran in the SE.

The central open marine basin was located in the Mesopotamian Zone, parts of the Mosul High and the Jezira Subzone (Jaddala Formation), extending to the area of Rutba. The Rutba basin on the N and W shores of the Ga'ara anticline contained phosphate and silica rich waters resulting in the deposition of phosphorites, in addition to open marine carbonates and nummulitic shoals (Fig. 13-10).

The Mid-Late Eocene sequence is represented by the Dammam, Ratga, Avanah, Jaddala Pila Spi and Gercus formations.

13.2.1 Carbonate inner shelf lagoons and shoals

13.2.1.1 Dammam Formation

The Dammam Formation was first described by Bramkamp in 1941 from the Dammam dome in E Saudi Arabia (Bellen et al., 1959) where it comprises limestones (chalky, organodetrital or dolomitic), dolomites, marls, and shales; it was divided into five informal members. In the supplementary type section in well Zubalr-3 of the Mesopotamian Zone (Owen and Nasr, 1958), the formation comprises whitish grey, porous, dolomitised, locally chalky limestone. A grey green waxy shale layer often occurs near the base of the formation in S Iraq. The Dammam Formation consists mainly of neritic shoal limestones often recrystallised and/or dolomitised, nummulitic in the lower part and miliolids-bearing in the upper part.

In the outcrop area Huber and Ramsden (1945) introduced 10 informal lithological units for mapping purposes as described by Bellen et al. (1959). Ramsden and Andre (1953) recognised only four informal units. These informal units comprise from the base upwards:

1) Wagsa unit composed of chalky, moderately fossiliferous, limestones. **2**) Huweimi Schbicha-Sharaf unit composed of chalks and chalky limestones. **3**) Chabad-Shawiya-Huweimi unit consisting of nummulitic-alveolinid limestones. **4**) Tuqiyid-Ghanimi-Barbak-Radhuma unit, composed of Bryozoan-peneroplid limestones and shelf limestones. During regional geological mapping of SW Iraq (Jassim et al., 1984) two members of the Dammam Formation were defined which could be recognised throughout the Southern Desert of Iraq.

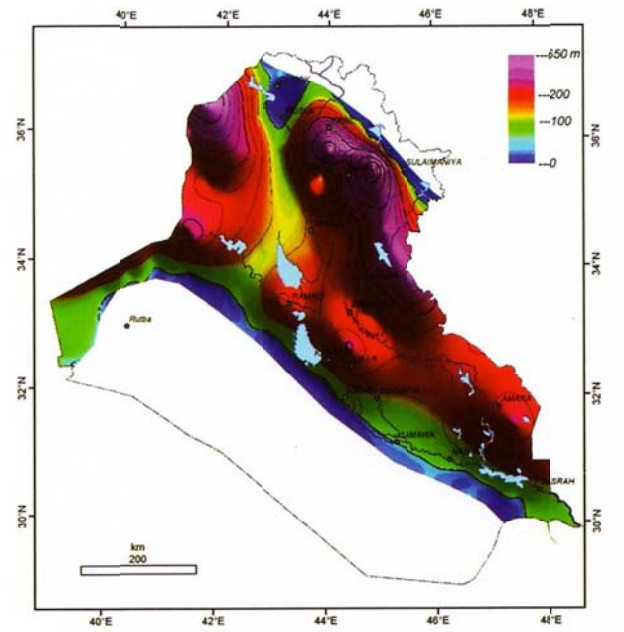
The lower, Gleb Member is the most widely exposed unit of the Dammam Formation. The maximum thickness of the member is 110 m. It comprises from the base upwards:

1. 20-25 m of breccia with fossiliferous limestone fragments of highly recrystallised phosphatic limestone, argillaceous calcareous dolomite and very hard fossiliferous limestone with chert nodules. The Fossils recorded by Shaker (1983 and 1984; in Jassim et al., 1984), Mahmoud and Abdulmunim (1984; in Jassim et al., 1984) include: *Nummulites atacicus* Leymerei, *N. globulus* Leymere, *Lockhartia sp., Peneroplis sp., Pyrgo sp., Valvulina sp.* This assemblage, correlated with the zonation of Al Hashimi (1972; in Jassim et al., 1984), is of Early Mid Eocene (Lutetian) age. This section is equivalent to the upper part of the Huweimi unit.
2. 20-44 m of yellowish recrystallised limestone and shelly limestone with occasional chert nodules and red mudstone lenses. Fossils recorded (AL Hashimi,1972; Al Hashimi and Amer, 1974; Amer, 1980; Yousif et al., 1981; and Shakir,1983 and 1984; all in Jassim et al., 1984) comprise: *Nummulites gizehensis* Montfort, *N. discorbinus* Schlothien, *N. perforatus* Montfort, *N. perforatus* var *bayhariensis* Cheshea-Rispoll, *N. irregularis* Deshayes, *Coskinolina balsilliei* Daves, *Linderina brugesi* Schlumberger, *Alveolina elliptica* Sowerby, *A. lepidula* Schwager, *A. palemitana* Hottinger, *A. oblonga* var bassanii Checchia-Rispoll, *Assilina spira* Deroidy, *Assilina exponens* Sowerby, *Dictyoconoides cooki* Carter, *Lockhartia alveolata* Silvestri, *Coskinolina sp., Orbitolites sp.,* miliolids, gastropods, pelecypods, oysters, ostracods, algae and echinoid spines. The age of this unit is Lutetian. This section is equivalent to the Shawiya unit.
3. 35-50 m of yellowish saccharoidal limestone with thin beds of nummulitic limestone. Thin (20 cm thick) beds of silicified limestone occur in the upper part. Fossils include: *Nummulites sp., Alveolina elliptica* Sowerby, *Coskinolina sp., Linderina sp., Lockhartia alveolata* Silvestri, miliolids, gastropods and pelecypod fragments. This age of this unit is also interpreted as early Mid Eocene (Lutetian). This section is equivalent to the Chabad unit. This unit is of Lutetian age. This section is equivalent to the Chabad unit.
4. 35-40 m of shelly dolomitic limestone and light grey burrowed limestone with chert nodules, passing up into marl and argillaceous limestone with beds of fossiliferous chalky limestone with some horizons of brown chert. Fossils include: *Dictyoconoides cooki* Carter, *Coskinolina balsilliei* Davies, *Lockhartia sp., Spirolina sp., Pyrgo sp., Rhapydionina sp., Peneroplis sp., Valvulina sp.* and pelecypods. The age of the unit is also interpreted as Mid Eocene. It is equivalent to both the Radhuma and Barbak units.

   The upper, lagoonal Umm Bir Member is equivalent to the Ghanimi and Takalyid units. The section near Faidhat Umm Bir in the Southern Desert comprises a basal conglomerate (5 m), brecciated limestone rich in silicified limestone fragments (2 m), alternation of thick-beds of

recrystallised limestone and thin beds of chalky and argillaceous limestone and pink saccharoidal limestone. The uppermost part of the section is composed of yellowish soft marl and argillaceous limestone with abundant chert nodules. The top of the unit is erosional and the thickness thus varies from 15 m to 40 m. Fossils, as recorded by Al Hashimi (1972; in Jassim et al., 1984), include: *Spirolina sp., Peneroplis sp., Valvulina sp., Textularia sp., Articulina sp.* and *Valvulina kitchini.* The age of the unit is interpreted as Late Eocene (Priabonian).

Fig. 13-11: Thickness of the Jaddala Formation



The lower part of the Gleb Member was deposited on a shallow marine shelf with high energy nummulitic shoals. The upper part of the Gleb Member was deposited in more restricted conditions with higher salinity as indicated by the abundant miliolids and alveolinids. The Umm Bir Member was deposited in a lagoonal environment «20 m depth) in a subtropical sea. Abundant *Peneroplis* indicate a relatively high salinity.

The thickness of the formation, in the Iraqi supplementary type area, reaches 250 m. The maximum known thickness is 298 m in water well K7-17 SW of Anah. However, in that well, Lower Eocene limestones (Swab Member of Ratga Formation) and chalks of the Jaddala Formation were included in the Dammam Formation. The formation is restricted to the S part of the Mesopotamian Zone (the Euphrates and Zubair subzones) and to the southern part of the Salman Zone (Fig. 13-10). The nummulitic limestones of W Iraq which are up to 100 m thick in NW and SW of Ga'ara are not included within the Dammam Formation.

According to Bellen et al. (1959), the nummu1itic limestones, encountered in well sections, correspond to the upper two biozones of the surface section. The lower two units of the surface sections may be equivalent to the Rus Formation penetrated in boreholes. Al-Hashimi (1973) divided the Dammam Formation into 11 biostratigraphic units, comprising five larger foraminiferal assemblage zones, three planktonic foraminiferal concurrent range zones, and three benthonic foraminiferal local zones.

The age of the Dammam Formation in the supplementary subsurface type section in Iraq is Mid Eocene (Bellen et al. 1959). Al-Hashimi (1973) showed that part of the Dammam Formation is of Late Eocene age on the northern flank of the Rutba Uplift; he suggested that the lower beds of the formation are of Middle Eocene (Lutetian) age. Based on the work of Al Hashimi in 1973, Jassim et al. (1984) confirmed that the Dammam Formation is also partly of Late Eocene (early Priabonian) age in SW Iraq.

A correlation with the type section in Saudi Arabia, described by Powers et al. (1966) suggest that the lower part of the formation, corresponding to the Huweimi, Schbicha, Sharaf and Wagsa units, is of Early Eocene age. The apparent variation in age of the lowest beds of the formation suggests that the onset of deposition of the formation was diachronous.
The lower contact of the formation in the Saudi type area is conformable (Powers et al. 1966). In Iraq, Bellen et al. (1959), and Al-Hashimi (1973) suggested that the lower contact with the Rus Formation may be unconformable. The formation is unconformably overlain by the Ghar Formation.
The formation passes towards the NE into the deeper water sediments of the Jaddala Formation. To the SW the formation passes into the phosphatic Ratga Formation. The distribution and thickness of the Dammam Formation is shown in Fig. 13-10. In Jordan the Ma'an Nummulitic Limestone Formation correlates with the higher nummulitic zones of the Dammam.

13.2.1.2 Avanah Formation

The Avanah Formation was first described by McGinty in 1953 from well Kirkuk 116 (Bellen et al., 1959) located on the Avanah dome of the Kirkuk anticline of the Foothill Zone. It comprises 210 m of limestones, generally dolomitised and recrystallised, of shoal facies with occasional beds of lagoonal dolomitised limestones. Thicknesses in other wells in N Iraq are as follows: Kirkuk-117 (159 m), Butmah-I (503 m), Alan-l (154 m), Atshan-1 (138 m) and Mushorah-l (550 m). Interfingering of the Avanah and Jaddala formations occurs in wells Sufaya-A2 (238 m), Najmah-30 (11 m). The Avanah Formation was deposited in a belt along the boundary of the Foothill and High Folded Zones and is especially thick in the area of Foothill Zone of N Iraq.

The formation contalns *Alveolina elliptica* var. *flosculina, Asterigerina rotula, Asterocyclina sp., Baculogypsinoides sp., Dictyoconus aegyptiensis, Discoyclina sp.* and *Nummulites* (Bellen et al., 1959). *Alveolina elliptica* and *Dictyoconus aegyptiensis* apper to be restricted to the Mid Eocene. The Avanah Formation was deposited as an isolated carbonate shoal associated with a palaeoridge along the NE shoreline of the basin during a highstand of sea level. This barrier separated the molasse basin of the Gercus Formation in the N and NE from the open sea basin of the Jaddala Formation to the Sand SW.
The lower contact of the formation is probably unconformable. The abrupt change from the lagoonal facies of the Khurmala Formation to the shoal facies of the *Avanah* Formation is probably associated with a transgression (Bellen et al., 1959). Middle Miocene sediments usually unconformably overlie the Avanah Formation, except where Oligocene or Lower Miocene sediments are locally preserved.

The Eocene limestones of the Midiyat Formation of N Syria (Dubertret, 1966) and Weber (1963) which locally are of reefal facies (Ponikarov et al,. 1967) may be partly equivalent to the Avanah Formation. In the Mardin area of SE Turkey, the Midiyat Limestone Formation, which overlies the

Lower Eocene Kermav Formation (Beer, 1966), is probably equivalent to the Avanah Formation. In SW Iran, the Shah basin and Jahrum formations of the Zagros can be correlated with the Avanah Formation (James and Wynd, 1965; Furst, 1970).

13.2.1.3 Pila Spi Formation

The Pila Spi Formation was first described by Lees in 1930 from the Pila Spi area of the High Folded Zone. It was redefined by Wetzel (1947) and amended by Bellen (1957). The original type section was submerged under the waters of the Derbendikhan Dam. A supplementary type section was thus described at Kashti, on the Barand Dagh. The resistant Pila Spi Formation forms a conspicuous ridge between the recessive weathering Gercus and Fars formations throughout the High Folded Zone.

The Pila Spi Formation is 100-200 m thick. The upper part of the formation comprises well bedded, bituminous, chalky, and crystalline limestones, with bands of white, chalky marl and with chert nodules towards the top. The lower part comprises well bedded hard, porous or vitreous, bituminous, white, poorly fossiliferous, limestones, with algal or shell sections. In the supplementary type section it consists of dolomitic and chalky limestone with chert nodules. The limestones are sometimes oolitic with rare layers of gastropod debris (Bellen et al., 1959). Tongues of the nummulitic Avanah Formation occur within the basal part of the formation near Dohuk and in some Kirkuk wells.
The formation was deposited in a shallow lagoon.

Fossils are abundant and indicate a Late Eocene age. In N Iraq the formation may be partly of Middle Eocene age.

The lower boundary of the Pila Spi Formation appears to be conformable and gradational in the original type section in NE Iraq and near Amadiya in N Iraq, where interfingering of the Gercus and Pila was observed (Hall, 1957). However, conglomerates occur at the base of the formation in the Derbendikhan area (Jassim et al., 1975). To the NE the Pila Spi Formation oversteps the Gercus Formation; small outliers of Pila Spi Formation (containing beds of red shale) unconformably overlie older Tertiary sediments in the Zibar area (Hall, 1958). The Upper boundary is unconformable throughout. The overlying sediments are mostly of Miocene age.

Part of the Midiyat Limestone Formation of NE Syria (Weber, 1963) and SE Turkey (Altinli, 1966) is equivalent to the Pila Spi Formation. In SW Iran, the Jarum Formation (Furst, 1970) can be correlated with the Pila Spi.

13.2.2 Phosphatic deep inner shelf-inner shelf (Damlouk and Mugur members of Ratga Formation)

The Ratga Formation was introduced to represent the phosphatic facies of the Eocene in W Iraq, largely W of the Rutba Uplift. Jassim et al. (1984) divided the Ratga formation into three members. The lower member is of Early Eocene age and was described in Section 13.1.2.2. The Middle Eocene Damluk and the Upper Eocene Mugur Members are described below:
The Damlouk Member outcrops Wand N of the Ga'ara anticline and along the Iraq-Jordan border.

It comprises 30 m of thin-bedded argillaceous limestone with loaf-like chert nodules and laterally continuous chert beds. Fossils include:
Globorotalia bullbrooki Bolli, *Glt. Aspensis* Colom, *Glt. Broedermanni* Cushman & Bermudez, *Glt. spp*, sponge spicules, radiolarites and ostracods. The fauna belongs to the *Globorotalia bullbrooki* zone and is of Early Lutetian age. A Late Lutetian fauna was also recorded (Sahira Karim, oral communication, 1983) which includes: *Globorotalia lehneri* Cushman & Jarvis, *Globigerina Boweri* Bolli, *Glt. aspens is* Colom, G. *spp, Globigerapsis sp., Globobulimina sp., Bolivina sp., Nodosaria sp.* and *Lenticulina sp.* Two beds of limestone with *Nummulites gizehensis* (indicating a Late Lutetian age) are recorded NW of the Ga'ara depression.

The passage between the nummulitic facies to the offshore facies is often associated either with intraclastic or oolitic phosphorites. The Damlouk Member passes laterally and vertically into highly phosphatic facies in the direction of the Jordanian border where it consists of alternation of three phosphatic horizons (2-4 m thick) and thick- and thin bedded limestone. The phosphorites are very coarse grained, pelletal, with large coprolites and shark teeth. Fossils within in this section include: *Nummulites gizehensis* Forskal, *N. perforatus* Montfort, *N. millecaput* Boubee, *N. atacicus* Leymerie, *N. discorbinus* Scholthiem, *N. cf batchisaralensis* Rozcozsnik, *Operculina seminvoluta* Nernkov & Barkhaton and O. *cf exiliformis* Qavioves. This assemblage is of Late Lutetian to Bartonian age. The phosphatic section along the Jordanian border represents the upper part of the Damluk Member.

The Mugur Member outcrops in only one area near the Iraq Syrian border NW of Ga'ara in the Wadi Akash-Mugur El Dhib area. It consists of 159 m of alternating fine- to medium-grained nummulitic limestone and white chalky limestone (tongues of Jaddala Formation). Benthonic fauna include: *Nummulites bouillei* Delharpe, *N. praejabianii* Avsrentsou & Manner, *N. incrassatus* Delharpe, *N. sp.* Planktonic fauna include: *Globorotalia cerroazulensis* Cole, *Glt. centralis* Cushman, *Globigerina ampliapertura* Bolli, G. *officinalis* Subbotina, G. *venezuelana* Hedberg and *Globanomalina micra* Cole (Jassim et al., 1984). *Operculina sp., Bolivina sp., Truncorotalites rohri* Bronimann and *Hantkenina alabamensis* Cushman occur in a separate section (Sahira Karim, personal communication). The overall age-range represented by the above fauna is Late Middle Eocene-Late Eocene.

13.2.3 Outer shelf-basinal (Jaddala Formation)

The formation represents the off-shore facies of the late Early Eocene-Late Eocene Sequence in the western and central areas of Iraq. It was first described by Henson in 1940 from the type locality near Jaddala village in Jabal Sinjar of the Foothill Zone. It comprises 350 m of argillaceous and chalky limestones and marls, with occasional thin tongues of Avanah Limestone shoals (Bell en et al., 1959). The Jaddala Formation was deposited in a basin lying between two belts of carbonate shoals on the SW and NE margins of the basin. The NE shoals were deposited on a ridge separating the basin from the platform in which the Gercus Formation and Pila Spi formations were deposited.

The formation also outcrops in the Qara Chauq South structure, SE of Mosul, where it overlies the Shiranish Formation. It is unconformably overlain by the Tarjil Formation; the contact is marked by 1.5 m of breccia.

Ditmar and the Iraqi-Soviet Team (1973) suggested that the formation may be up to 750 m thick in the basin to the south of 1abal Sinjar which is the easterly extension of a basin recognized in Syria Weber (1963). The thickness of the 1addala Formation in Fig. 13-11 shows two major depocentres. The Kirkuk basin is associated with the Butmah-Chemchemal Subzone of the Foothill Zone; the formation is 1131 m thick in well Chemchemal-2. The Sinjar depocentre extends into NE Syria where the 1addala is 446 m in well Afendi-1. A north-south trending high developed along the Tharthar line in central and N Iraq separating the 1ezira basin to the W from the Mesopotamian basin the E. To the N of the Ga'ara anticline, the 1addala Formation interfingers with the phosphatic Ratga Formation. A minor depocentre is located along the W margin of the Mesopotamian Zone in Central Iraq.

The rich fauna of foraminifera includes: *Bulimina jacksonensis, Dentalina sp., Globigerina bulloides,* G. *mexicana,* G. *triloba, Globorotalia centra lis, Gl. wilcoxensis, Hantkenina alabamensis, H. dumblei, Nodosaria sp., Uvigerina eocaenica, Valvulina pectinata* (?) and small gumbelids (Bellen et al., 1959). The base of the formation contalns: *Anomalinoides granosa, Bulimina quadrata. Globorotalia aragonensis, Globorotalia cf velascoensis, Marsonella oxycona* and *Quadrimorphina allomorphinoides.*

In the Qara Chauq South structure, the fauna includes:
Globigerina linaperta Finlay, G. *boweri* Bolli, G. *venezuelana* Hedberg, G. *ouachitaensis* How & Wallace, G. *pileata* Chalilov, G. *veguaensis* Weinzierl & Appline, G. *trilocularis* D'Orbigny, G. *rohri* Bolli, *Globorotalia aspensis* Colom, *Globorotalia cf cocoanensis* Cushman, *Globorotalia. bullbrooki* Bolli, *Globorotalia spinulosa* Cushman, *Globigerapsis index* Finlay, *Hantkenina alabamensis, Truncorotaloides topilensis* Cushman, *Catapsydrax dissimilis* Cushman, *Chilogumbelian cubensis* Palmer, *Heterolepa*
costata Franzena, *Robulus indenodablis* Israelsky, *Lenticulina sp., Bulimina midwayensis* Cushman, *Eponides megastoma* Crzybowski, *Spiroplectamina sp.* and *Nodosaria sp.* of Mid-Late Eocene age.

Bellen et al. (1959) considered that the formation is of Mid Late Eocene age, and that it contalns reworked fossils of Early Eocene age. However the formation may be partly of latest Early Eocene age since it contalns *Globorotalia aragonensis,* which is the index fossil for the upper faunal zone of the Early Eocene (Ponikarov et a!., 1967). The stratigraphic relations of the 1addala Formation with the Dammam and Avanah formations indicate a late Early Eocene-Late Eocene age.

The lower contact of the formation in the type area is unconformable (Bell en et al., 1959) and is marked by the occurrence of glauconite. The formation often transgressively overlies pre Tertiary formations, for example N of the Euphrates River, where the Palaeocene-Early Eocene beds are either very thin (10-20 m only) or absent. The upper contact of the formation in the type area is unconformable; the overlying sediments are of Miocene age, except in a narrow belt passing through the Qara Chauq structure of the Foothill Zone where the formation is overlain by the Oligocene sediments.

The SW limit of the formation lies along the N and NE slopes of the Ga'ara anticline where it interfingers with the Middle Eocene part of the Ratga Formation. The SW limit is along the Euphrates Boundary Fault. The NE limit of the formation approximately follows the boundary of the Foothill and High Folded zones in N Iraq.

Part of the Pabdeh Formation, of the Buzurgan area (Ditmar and the Iraqi-Soviet Team, 1972), is here included in the 1addala Formation.
The formation is recognized outside Iraq in Syria (Dubertret, 1966), mainly in the 1ezira area (Ponikarov et al., 1967). In the Palmyrides and other areas of central Syria, the 1addala passes into phosphatic limestones or other neritic limestone formations. The upper parts of the Hibr Formation in NW Saudi Arabia are very similar to the 1addala (Powers et al., 1966) but lie within the phosphatic basin W of the Rutba Uplift. In Iran the Middle Pabdeh Formation (Furst, 1970) is equivalent to the 1addala Formation.

13.2.4 Fluvial and fluviomarine (Gercus Formation)

The Gercus Formation consists of molasse deposited following Mid Eocene uplift. The formation was first described by Maxon in 1936 in the Gercus region of SE Turkey, which extends into the Iraqi High Folded Zone (Bellen et al., 1959). A supplementary type section for Iraq was described by Wetzel from the Dohuk area of N Iraq (originally referred to as the Dohuk Red Beds). It comprises 850 m of red and purple shales, mudstones, sandy and gritty marls, pebbly sandstones and conglomerates. Gypsum lenses and halite occur near the top of the formation. Rare lignite and sandstones are present near the base. The formation consists of brown clastics and limestones in the Demir Dagh area (Ditmar and the Iraqi-Soviet Team (1971). The proportion and grain size of the clastics increase towards the N and NE.
The formation is present in the High Folded and Foothill zones of the Unstable Shelf. The SW limit of the formation follows a line from Mushorah Dagh in the NW to Demir Dagh and Chemchemal in the SE. The NE boundary is located at the boundary of the Balambo-Tanjero Zone. In N Iraq, the formation is overthrust along the Northern Thrust Zone; the original depositional limit lay further to the N.

The thickness of the formation decreases towards the SE; near the Iranian border along the Sirwan (Diyala) River, it is usually <100 m thick. In the Derbendikhan anticline (Jassim et al., 1975) the Gercus Formation is 300 m thick on the NE limb and only 50 m along the SW limb, indicating growth of the structure in Middle Eocene time. Regionally the formation thins to the NE due to depositional thinning and erosion, and to the SW due to facies changes. The Gercus Formation is present in the Taq Taq (66 m thick) and Demir Dagh wells (117 m thick).
The formation was deposited in a relatively broad trough (foredeep) along the NE margin of the Middle Eocene basin. It is a typical red molasse sequence derived from uplifted areas in the N and NE.
Fossils are very rare and probably mostly reworked. The age of the formation cannot be determined from the fauna. Bellen et al. (1959) and Ditmar and the Iraqi-Soviet Team (1971) considered the formation was of Middle Eocene age. In the Derbendikhan area (Jassim et al., 1975), the Gercus Formation unconformably overlies Lower Eocene limestones of the Sinjar Formation. In the Dohuk area the Gercus Formation overlies the Lower Eocene Khurmala Formation and interfingers with the Avanah Formation. In both these localities the Gercus is overlain by the Pila Spi Formation. These stratigraphic relationships indicate that the Gercus Formation is of late Early Eocene to Middle Eocene age.
Bellen et al. (1959) recognised an unconformity between the Gercus and Kolosh formations. In the subsurface in NE Iraq, the formation unconformably overlies different Palaeocene Lower Eocene formations. Basal conglomerates of the Gercus Formation often contain pebbles of the underlying units. The Gercus Formation near the Derbendikhan Dam contalns pebbles of Sinjar Limestone

(Jassim et al., 1975). Where the formation is overlain by Miocene deposits, the upper boundary is marked by an unconformity; elsewhere it is conformably and gradationally overlain by the Pila Spi Formation (Plate 13-1).

The formation correlates with Kashkan Formation of SW Iran (James and Wynd, 1965).

Plate 13-1: Gercus Formation overlain by Pila Spi Formation along the NE flank of Sefin Dagh anticline, Shaqlawa Town, NE of Erbil (photo by S. Jassim)



Chapter 14
Latest Eocene-Recent Megasequence AP11

by

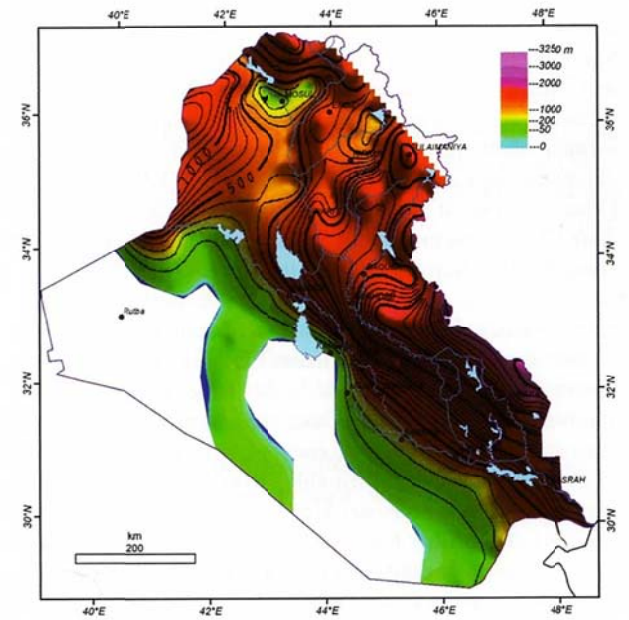
Saad Z. Jassim and Tibor Buday

The Latest Eocene-Recent Megasequence is associated with the collision of Neo-Tethyan terrains along the N and E sides of the Arabian Plate, and the opening of the Gulf of Aden and the Red Sea on the Sand W sides of the Plate. The opening of the Red Sea and Gulf of Aden was associated with thermal uplift, flood basalt, and rifting. The Gulf of Aden opened first in Oligocene time followed by the Red Sea in the Early Miocene (Makris and Henke, 1992 and Hughes and Beydoun, 1992). The N and NE drift of Arabia and the closure of the Neo- Tethys resulted in folding and thrusting of the Neo- Tethyan terranes along the NE margin of the Arabian Plate.

The Latest Eocene-Recent Megasequence is >3000 m thick in the Foothill Zone in SE Iraq (Fig. 14-1). To the SE in the Dezful Embayment of SW Iran, it is locally >6000 m thick. It is <500 m thick in an area extending from Mosul southwards along the Tharthar valley towards the Euphrates River. This area separated the Kirkuk basin in the SE from the Sinjar basin in the NW. Smaller, isolated basins developed on the Rutba Subzone in grabens along the E boundary of the subzone (the Nukhaib and Ghadaf grabens). In N and NE Iraq in the Foothill and High Folded zones the megasequence is dominated by Mio-Pliocene molasse up to 3000 m thick in the foredeep basin located to the SW of the Zagros Suture.

Megasequence APII is here subdivided into three sequences of latest Eocene-Oligocene, Early-Middle Miocene, and the Late Miocene-Recent age. The Quaternary part of the Late Miocene-Recent Sequence is described separately in Chapter 15. The megasequence contalns many formations (Bellen et al., 1959), which are shown on the stratigraphic correlation chart of Fig. 14-2. Some of the earlier formation names (which were first used in Iran) have been replaced with new names from localities in Iraq.

Fig. 14-1: Thickness of Megasequence AP11 (including the Quaternary thickness)



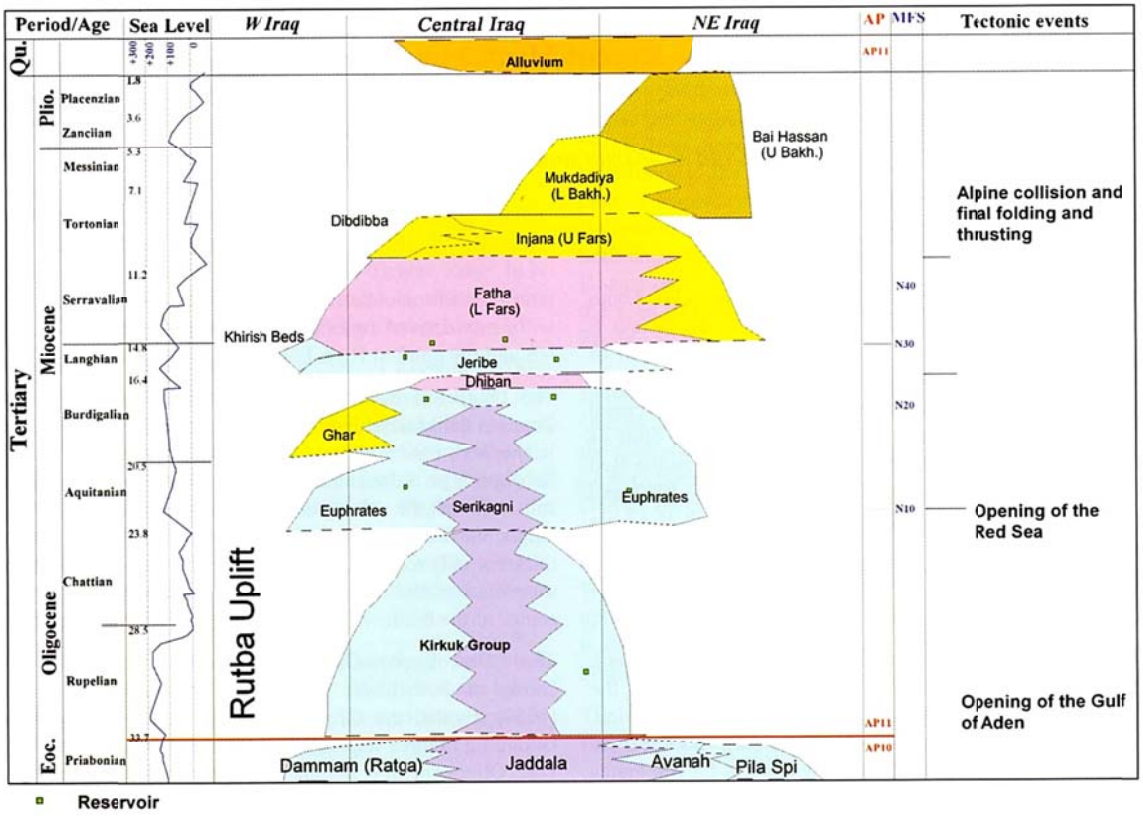


Fig. 14-2: Stratigraphic correlation of formations of Megasequence AP11 (excluding the Quaternary)

14.1 Latest Eocene-Oligocene Sequence

At the end of the Eocene the main intraplate basin became narrower due to the tilting of W Arabia on one side and uplift of the High Folded Zone on the other. The western shoreline receded towards the area of the present day Euphrates River. The eastern shoreline receded to the SW boundary of the Butmah-Chemchemal Subzone of the Foothill Zone. The closed Neo-Tethys was a narrow seaway in which clastics and carbonates were deposited. The remnant Cretaceous thrust belt contained a narrow intermontane molasse basin and was filled with the sediments derived from the Cretaceous thrust zone in the NE and the uplifted High Folded Zone in the Sw.

The Oligocene basin was located in the Mesopotamian Zone, in the Makhul-Hemrin Subzone of the Foothill Zone, in the Jezira Subzone and on the N margin of the Rutba Subzone. The Salman Zone and the Euphrates and Zubair subzones of the Mesopotamian Zone were uplifted in Oligocene time (Fig. 14-3). The basin was relatively narrow; thick fringing reefs developed along the western and eastern shorelines of the basin. Thin marls were deposited in the centre of the basin which was starved of sediment supply.

The Latest Eocene-Oligocene Sequence is bounded by breaks on both lower and upper contacts. Bellen et al. (1959) divided the Oligocene section into 9 formations belonging to three sequences of assumed Early, Middle and Late Oligocene age (based on their relative stratigraphic position rather than age diagnostic fossils). These sequences show lateral facies variations from basinal to reef and backreef facies. Ditmar and the Iraqi-Soviet Team (1971) modified Bellen's divisions recognizing only two sequences rather than three based on lithological and well log correlation. They arranged the formations into two cycles: a lower cycle comprising the Palani, Sheikh Alas,

Shurau and Tarjil formations and, an upper cycle comprising the Anah, Azkand, Bajawan and Baba formations.

Outcrops of the Oligocene formations are restricted mainly to the exceptionally elevated Qara Chauq structure of the Foothill Zone and to the Euphrates valley between Haditha and Anah. Al Hashimi (1974; in Jassim et al., 1984) recorded the Lower Oligocene Sheikh Alas and Shurau formations along the Iraq-Syria border NW of the Ga'ara depression and along Wadi Hauran, 200 km ENE of Rutba. Other outcrops of Oligocene sediments in Iraq include the Qara Chauq structure, Jabal Sinjar, and Jabal Bamu located along the Iraq-Iran border, S of the Sirwan River.
Some clastics, included within the Maisan Group, which overlie the Oligocene carbonates (Ditmar and the Iraqi Soviet Team, 1971) in wells in SE Iraq, were originally assigned an Oligocene age and correlated with the Ghar Formation. Similar clastics, encountered in well Dujalla-l (Safar, 1961), disconformably overlie the Oligocene carbonates. However detailed mapping indicates the outcrops of the Ghar Formation along the Euphrates valley from S Iraq to the Syrian border are of Early Miocene age throughout (Jassim et al., 1984).
The lower contact of the sequence with the underlying megasequence is generally disconformable especially on the margins of the basin. However in the central part of the basin this contact is conformable. The upper boundary of the sequence is generally unconformable.

Two NW-SE trending belts of high thickness (Fig. 14-4) are present, one in the SW between the Iraq-Syria border SW of Al Qaim and Amara, the other extending from Mushorah in the NW to the Iraq-Iran border in the SE and passing through the Baba dome of the Kirkuk structure. They are associated with fringing or barrier reefs that developed along the shorelines of the basin.

The intervening basinal sediments are thin. Oligocene sediments are absent on the Butmah-Chemchemal Subzone of NE Iraq, on the High Folded, over most of the SW part of the Balambo-Tanjero Zone and in the Northern Thrust Zone. This large uplifted area separated the basin to the west from the Red Beds basin to the NE. **In** W Iraq Oligocene sediments are absent over most of the Rutba Subzone, the Salman Zone and on the Zubair and Euphrates subzones of the Mesopotamian Zone. The highest thickness of the Oligocene Sequence is 160 m near Anah on the Euphrates River representing the western shoreline reef zone. The eastern shoreline reef zone is >370 m thick between the Kirkuk and Kor Mor structures in NE Iraq (Fig. 14-4).

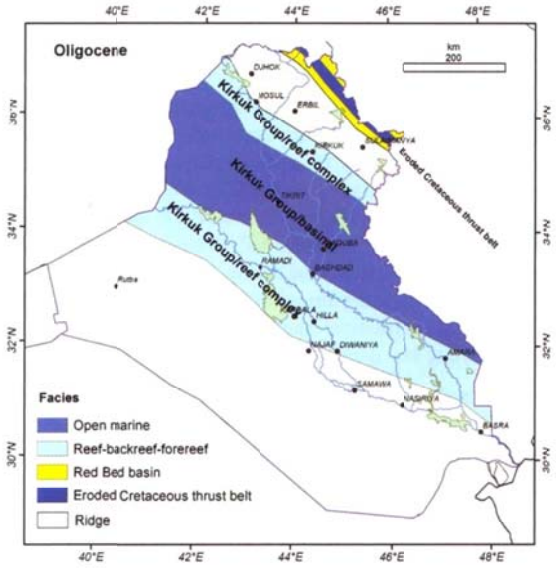


Fig. 14-3: Oligocene Palaeogeography

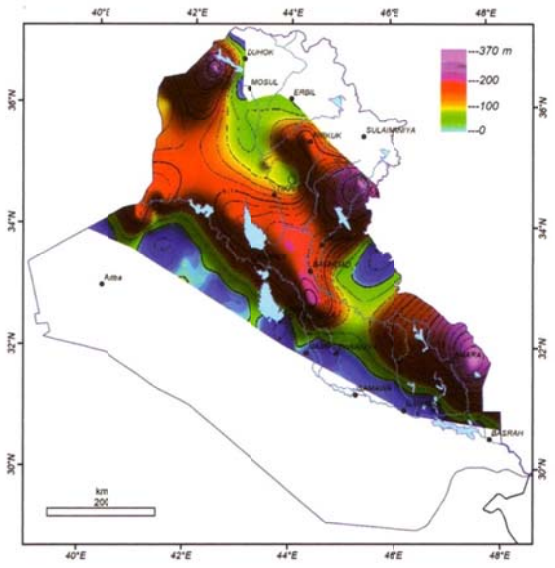


Fig. 14-4: Thickness of the Latest Eocene-Oligocene Sequence

Following the recommendations of Ditmar and the Iraqi Soviet Team (1971) the Oligocene is divided into a Lower and an Upper sequence.

14.1.1 Lower Sequence

The Lower Sequence comprises the reefal Sheikh Alas and Shurau formations and the basinal Palani and Tarjil formations.

14.1.1.1 Basinal (Palani and Tarjil formations)

14.1. 1.1.1 Palani Formation

The Palani Formation was defined by Bellen in 1956 (Bellen et al., 1959) from well Kirkuk-85 located on the plunge of the Tarjil dome of the Kirkuk structure. It consists of 64 m of dolomitised globigerinal limestone. The age of the formation was assumed to be Early Oligocene, based on its stratigraphic position between the underlying Eocene Jaddala Formation and the overlying and interfingering Lower Oligocene Sheikh Alas Formation. Ditmar and the Iraqi-Soviet Team (1971) considered the Palani Formation to be of Late Eocene age. The formation may thus range in age from latest Eocene to Early Oligocene. The Palani Formation rests unconformably over the Jaddala Formation (Bellen et al., 1959) and is conformably overlain by the Sheikh Alas Formation. In the Kirkuk structure, the Palani Formation is only present in the Baba dome in the SE of-the anticline, and overlies the Avanah Formation. In the SE and NW parts of the Baba dome, it is overlain by the Tarjil and Sheikh Alas formations respectively. In the Nahrawan structure SE of Baghdad, the Palani Formation is 80 m thick.

The only surface occurrence of the Palani Formation is in the Qara Chauq structure. It is encountered in many wells including: Qalian-l, Gusair-l, Mileh Tharthar-I, Abu Jir-1, and Hit- 1.

The globigerinal limestones of the Palani Formation in Kirkuk were deposited in an outer shelf basinal environment passing up into a slope environment (Majid and Vizer, 1986).

14.1.1.1.2 Tarjil Formation

The Tarjil Formation was defined by Bellen in 1956 from well Kirkuk-85. It consists of 100 m of slightly dolomitised globigerinal marly limestone. It has a relatively constant thickness in wells of the Kirkuk structure (Bellen et al., 1959). The Tarjil Formation has been drilled along the NE margin of the Oligocene basin in the Tarjil dome of Kirkuk, and in Bai Hassan and Kor Mor. Oligocene marls in well Dujalla-l were assigned to the Tarjil Formation (Safar, 1961). In Injana, Naft Khaneh and Chia Surkh, Oligocene marls and marly limestones, may form part of the Tarjil Formation.

The formation contalns a rich fauna of foraminifera including *Nummulites intermedius* and *Lepidocyclina* (Bellen et al., 1959). These fossils indicate the formation was deposited in an outer shelf environment. *Nummulites intermedius* appears restricted to the Early Oligocene.

The Tarjil Formation unconformably overlies the Palani Formation. The upper contact with Baba Formation is gradational.

At outcrop in Qara Chauq the formation comprises 20 m of hard yellowish grey limestone overlain by thick bedded limestone with fossils including: *Nummulites sp., Lepidocyclina sp., Rhapydionina sp., Rotalia viennoti, Lenticulina sp.,* gastropods, echinoids, algae, Bryozoa and pelecypods, deposited in a relatively shallow water environment. According to Hamid and Vizer (1986) the lower part of the Tarjil Formation in Kirkuk was deposited in an open marine environment, and the upper part in a shallower toe of slope environment.

14.1.1.2 Reef-backreef and forereef

14.1.1.2.1 Reef-forereef (Sheikh Alas Formation)

The Sheikh Alas Formation represents the oldest reef and forereef facies of the Oligocene. The formation was defined by Bellen in 1956 from an outcrop in the N dome of the Qara Chauq structure near Sheikh Alas village, 50 km SSE of Mosul. The formation comprises 26 m of porous, occasionally rubbly dolomitic and recrystallised limestones (Bellen et al., 1959). In wells Anah-l and Anah-2, the formation contalns some marly limestones and organic detrital limestones with a basal conglomerate (Keller, 1939 b; Hay and Hart, 1959). The thickness increases to 50 m in the Kirkuk area. In well Anah-2 the Sheikh Alas Formation is 18 m thick (Hay and Hart (1959). In outcrops in W Iraq, 6m of limestone were assigned to the Sheikh Alas Formation (Jassim et al., 1984).40 m of limestone exposed in Wadi Swab near the Syrian border were included in this formation (AL Hashini, 1974; in Jassim et al., 1984).

The lower contact of the formation in the type area is unconformable; the underlying formation is the Upper Eocene Palani Formation (Ditmar and the Iraqi-Soviet Team, 1971). In W Iraq the formation comformably overlies the Upper Eocene Mugur Member of the Ratga Formation. The upper contact with the overlying Shurau Formation in the type area is conformable. In W Iraq the upper contact is either unconformable where the formation is overlain by the Lower Miocene Ghar Formation or conformable where it is overlain by the Lower Oligocene Shurau Formation (Jassim et al., 1984).

The Sheikh Alas Formation (in the type locality) contalns only rare poorly preserved *Nummulites fichteli* (Bellen et al., 1959, p. 268). In the Kirkuk area *Nummulites intermedius, N. incrassatus, Operculina cf. complanata,* and *Rotalia viennoti* occur. *Lepidocyclina sp.,* is reported in well Anah1 (Keller, 1939). In W Iraq, Al Hashimi recorded *Nummulites intermedius, N. vascus* Joly &

Leymerie, *N. bulloidei* Del Harpe, *Rotalia viennoti,* few shell fragments, Bryozoa and rare miliolids.

The age of the formation, where *Lepidocyclina (Eulepidina)* occurs is Oligocene. Where *Lepidocyclina (Eulepidina)* is absent the formation may be of Late Eocene age. In W Iraq, Al Hashimi (1974) restricted the age to the Early Oligocene.

The lower part of the Sheikh Alas Formation was deposited in a fore slope environment, and the upper part in a lagoonal environment (Majid and Vizer, 1986). It passes vertically and laterally into the reefal facies of the Shurau Formation.

14.1.1.2.2 Reef (Shurau Formation)

The Shurau Formation was defined by Bellen in 1956 in well K-109 of the Kirkuk structure (Bellen et al., 1959). It consists of 18 m of coralline limestone in the lower (thickest) part and grey dense limestones in the upper part. In well Awasil-5 W of Ramadi, about 60 m of dolomitic limestones were assigned to the Shurau Formation though Ditmar and the Iraqi-Soviet Team (1971) correlated this succession with the Bajawan and Baba formations. In W Iraq (Mughr Al Dhib, NW of the Ga'ara depression near the Iraq-Syria border) the formation conformably overlies the Sheikh Alas Formation and comprises 30 m of thick bedded, white and dense limestone (Jassim et al., 1984).

The contact of the formation with the underlying Sheikh Alas Formation is conformable. The upper contact with the Baba Formation is unconformable.
Fossils in the type locality are relatively rare (Bellen et al., 1959). In W Iraq, Al Hashimi (1974; in Jassim et al., 1984) recorded miliolids, *Austrotrillina howchini* Schlumberger, *A. paucialveolina* Grimsdale, *Peneroplis thomasi* Henson, *P. planulatus var laevigatus* Karr, *Praerhapydionina delicata* Henson, *Spiralina sp., Borelis pygmaenus* Henzawa, *Rotalia viennoti* Grigg, rare *Nummulites fichteli* Michellotti, algae, corals, Bryozoa, pelecypods and gastropods. The age of this assemblage is Early Oligocene.

The Shurau Formation of W Iraq was deposited in a reef and partly backreef environment (Jassim et al., 1984). In the Kirkuk the lower part of the formation was deposited in a reefal environment, and the upper part in a tidal flat environment (Majid and Vizer, 1986).

14.1.2 Upper Sequence

The Upper Sequence comprises the reef complex of Baba, Bajawan, Azkand and Anah formations and the basinal Ibrahim and Tarjil formations. These formations pass both vertically and laterally into each other.

14.1.2.1 Basinal (Ibrahim Formation)

The formation was defined by Bellen in 1957 (Bellen et al., 1959) from well Ibrahim-l in the Sheikh Ibrahim structure of the Foothill Zone, NW of Mosul, It comprises 56 m of globigerinal marly limestones with specks of pyrite and occasional glauconite, and a fauna of planktonic foraminifera. It was deposited in a basinal environment and has been provisionally assigned a Late Oligocene age. The Ibrahim Formation also occurs in the Qasab and Najmah structures. Ditmar and the Iraqi-Soviet Team (1971) considered the formation was present in wells Hibbarah-l and Khleisia-l, Injana-5, Chi a Surkh-l and Buzurghan-1. Jassim et al. (1984) recorded Upper

Oligocene basinal sediments below the Anah Formation in shallow boreholes drilled near the Haditha dam near Anah. The formation in its type section unconformably overlies the Eocene Jaddala Formation, and is unconformably overlain by the Lower Miocene Euphrates Formation.

14.1.2.2 Reef, backreef and forereef

14.1.2.2.1 Reef-forereef (Baba and Azkand Formation)

The Baba Formation was defined by Bellen in 1956 from well Kirkuk -109. It comprises 20 m of porous and dolomitised limestones. At outcrop the limestones are massive and appear chalky. Jassim et al. (1984) described exposures from the Euphrates valley, along Wadi Khazga, Wadi Fuhalmi and Wadi Kheshkhesh near Anah where 20 metres of porous dolomitised limestones were attributed to the Baba Formation (Ctyroky and Karim 1971a). The formation is >60 m in well Anah-2.

The formation is rich in fossils (Bellen et al., 1959). Ctyroky and Karim (1971 a) studied the outcrops of the Anah area of W Iraq and identified the following fauna: *Rotalia viennoti, Lepidocyclina cf elephantina, L. cf dilatata, L. cf morgani, Archalas sp., Triloculina sp., Quinqueloculina sp., Robulus sp., Peneroplis sp., Praerhapydionina sp.* (?), *Spiroclypeus cf marginatus,* Ostracoda sp., Gastropoda juv. indet., *Spirorbis sp.* (?), *Chlamys sp.* (?), corals and fish teeth. This fauna indicates a Mid Oligocene age. Bellen et al. (1959) dated the upper part of the formation in the Anah area as early Late Oligocene.

The Baba Formation unconformably overlies the Lower Oligocene Shurau Formation in the type area. In the Anah area, it unconformably overlies the Sheikh Alas Formation (Hart and Hay, 1959). The formation is conformably overlain by the Bajawan Formation in the type area. In the Anah area, the Baba Formation is conformably overlain by the Anah Formation.

The Baba formation was deposited in a forereef environment along both the NE and SW margins of the Oligocene basin. The formation is equivalent to reef-detrital and dolomitised limestones which outcrop along the Euphrates valley in Syria (Ponikarov et al., 1967).

14.1.2.2.2 Reef- Backreef (Bajawan Formation)

The Bajawan Formation was defined by Bellen in 1956 from well Kirkuk-109. It comprises 40 m of tight backreef miliolid limestones alternating with porous, partly dolomitised, rotalid-algal reef limestones, with fairly abundant coral fragments and thin argillaceous limestone beds. The formation outcrops in the Qara Chauq, Baski Zanur Dagh, Aj Dagh, and Darband-i-Sagirrma areas. The lithology of the formation is relatively uniform except in SE Qara Chauq structure where it consists mostly of conglomerate (Bellen et al., 1959). Subsurface sections include: Kirkuk, Bai Hassan, and Ain Zalah wells in the NE and Falluja, Dujalla and Afaq in the S (Gaddo et al., 1958; Macleod 1961).

The Bajawan Formation in its type locality is conformably underlain by the Baba Formation. Towards the shoreline area in the NE and SW the formation transgressively oversteps older pre Oligocene formations. In the type area the formation is unconformably overlain by the Middle Miocene Fatha (Lower Fars) Formation.

Two faunal zones were identified within the Bajawan Formation (Bellen et al., 1959): a lower *Delicata* Zone characterized by *Praerhapydionina delicata* and an upper *Kirkukensis* Zone characterised by *Archals kirkukensis,* indicating the formation is probably of Late Oligocene age.

Ditmar and the Iraqi-Soviet Team (1971) claimed that there is no age difference between the Bajawan and Baba, Anah and Azkand formations and that these four formations belong to one sequence.
The lower part of the Bajawan Formation was deposited in a reef and partly backreef environment; the upper part was deposited on mud flats (Hamid and Vizer, 1986).

14.1.2.3.3 Reef-forereef (Azkand Formation)

The Azkand Formation was defined by Bellen in 1956 in the Azkand cirque of the Qara Chauq structure. It comprises 100 m of thick massive, dolomitic and recrystallised, generally porous limestones (Bellen et al., 1959). It was also encountered in the following wells: Mileh Tharthar, Qalyarah, Gussair, Ibrahim, Najmah, Makhul, and Samarra (Ditmar and the Iraqi-Soviet Team, 1971). The formation is of forereef facies.
Fossils include *Heterostegina cf assilinoides, Miogypsinoides complanata,* and (in the lower part) *Lepidocyclina spp.* (Bellen et al., 1959) belonging to the lower *Miogypsinoides-Lepidocyclina* Zone and a higher *Miogypsinoides* Zone. The presence of *Heterostegina cf assilinoides* indicates a Late Oligocene age.
The lower contact of Azkand Formation with the Baba Formation is unconformable in the type area. The upper boundary with Anah Formation is conformable and gradational. Ditmar and the Iraqi-Soviet Team (1971) showed that the Anah-Azkand and Bajawan-Baba formations are partly contemporaneous. Ctyroky and Karim (197la) proved that Baba Formation underlies the Anah Formation. The contact of the Anah and Baba formations in the Euphrates area is conformable and gradational. Thus, the unconformity reported from the type locality of the Azkand is probably only locally developed.

14.1.2.2.4 Reef (Anah Formation)

The Anah Formation was defined by Bellen in 1956 from the Euphrates valley about 15 kms west of Al Nahiyah village near Anah. The type section comprises grey, brecciated recrystallised, detrital, and coralline limestones. A supplementary type section in the Qara Chauq anticline comprises 40-60 m of white or grey dolomitised and recrystallised limestones, massive in the lower part and becoming thinner bedded upwards. The formation also outcrops in the Euphrates valley near Anah and near Shiranish in the High Folded Zone of N Iraq. It is drilled in wells on the Bai Hassan and Alan structures.
The lower contact of the formation in the type area is conformable. The upper contact is always unconformable.
Outcrops from the Euphrates valley were studied by Ctyroky and Karim (1971a) who reported: *Subterranopyllum thomasi, Archalas kirkukensis, Austrotrillina howchini, Rotalia viennoti,* miliolids, *Robulus sp., Bolivina sp., Textularia sp., Trioculina cf gibba, Triloculina sp., Quinqueloculina sp., Peneroplis thomasi, P. evolutus, Operculina cf complanata, Lepidocyclina sp., Miogypsinoides complanata, Hydrobia sp.* indet., *Cons sp. juv., Scaphander sp., Acteonia sp., Nassa sp., Natica. sp., Mitra sp., Cerithium sp., Pyramidella sp., juv., Tympanotomus margaritaceus, Oliva sp., Chlamys sp., Euchilus sp. juv.,* Bryozoa remalns indet, *Heliastrea defrancei,* fish bones. These fossils prove a Late Oligocene age. According to Ctyroky and Karim (l971a) the presence of *Miogypsinoides complanata* indicates a latest Oligocene age.

The formation is mostly a reef deposit, alternating with backreef, mi1ioloid facies.

14.2 Early-Mid Miocene Sequence

The Oligocene-Early Miocene "Savian" movement which affected the Zagros Suture was marked by the uplift of the Balambo- Tanjero Trough. It is possible, however, that some more internal parts of this zone (now overthrust), might have been invaded by a shallow sea during the Early Miocene. The palaeogeographic evolution of the shelf during the Early and Middle Miocene is marked by the development of a broad but relatively shallow basin.

During the Early Miocene the basin was bordered by a relatively broad ridge in the present day Northern Thrust, Ba1ambo- Tanjero, High Folded, and in the Butmah Chemchemal Subzone of the Foothill Zone. The axis of the basin passed through the Foothill Zone, the Jezira Subzone (submerged Khlesia High) and the Mesopotamian Zone (Fig. 14-5). The Stable Shelf immediately SW of the Euphrates Boundary Fault and S of the Anah Qalat-Dizeh Fault was covered by a very shallow sea. Basinal carbonates and marls were deposited in the deeper parts of the basin in the N and NE (Serikagni Formation) overlain by lagoonal evaporites (Dhiban Formation). The lagoons were separated by the elevated N-S trending Abu Jir block over which detrital carbonates (Euphrates Formation) were deposited. The Abu Jir block separated the saline Kirkuk-Hemrin-Naft Khaneh basin in the SE from the saline Jezira basin in the NW (Fig. 14-15). The saline basins extended into both Syria and SE Iran.

The new transgression in the Middle Miocene reached the area of the Balambo- Tanjero Zone. In the Qulqula- Khwakurk Zone shallow water conglomerates and oyster-bearing carbonates (Govanda Limestones) were deposited on a peneplaned surface (Fig. 14-6). In the SW the Middle Miocene transgression did not reach the Stable Shelf area S and SW of the Euphrates River. In the NE the Middle Miocene Sea transgressed over the whole of the Foothill Zone and, in N Iraq only, over large parts of the High Folded Zone.

In early Middle Miocene time widespread shallow water lagoonal and reefal carbonates (Jeri be Formation) were deposited on a broad carbonate platform. The Abu Jir block was re-activated and separated two lagoonal basins in which the Fatha Formation was deposited. Carbonates and thin evaporites were deposited over this high.

The Early-Mid Miocene Sequence can be divided into two second order sequences, each with shallow water carbonates passing up into evaporites. They are the Early Miocene and the Mid Miocene sequences. The formations previously included in the Early-Mid Miocene Sequence include the Asmari, Euphrates, Serikagni, Dhiban, Kaihur Gypsum, Ghar, Jeribe and Lower Fars formations. Ditmar and the Iraqi-Soviet Team (1971 and 1972) claimed that Jeribe Formation is equivalent to the basal limestone members of the Lower Fars (Fatha) Formation marked by conglomeratic limestones at the base (Fig. 14-2).

The Lower Miocene formations are mainly of late Early Miocene age sequence deposited after a break representing the Aquitanian and the early Burdigalian. Clastic formations almost identical with the Ghar Formation occur in many areas of the Stable Shelf. These clastics pass laterally into the Euphrates Formation (Jassim et al., 1984). The Oligocene age of the Ghar (Ditmar and the Iraqi-Soviet Team, 1971) is thus rejected. The Ghar Formation represents the littoral and coastal equivalent of the Euphrates Formation.

Fig. 14-5: Early Miocene Palaeogeography

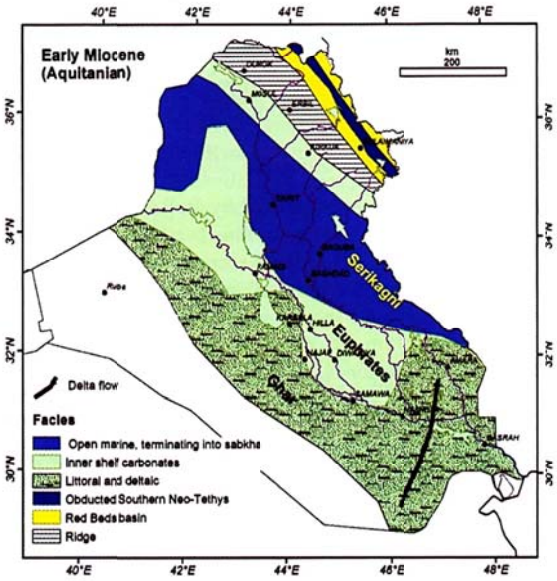
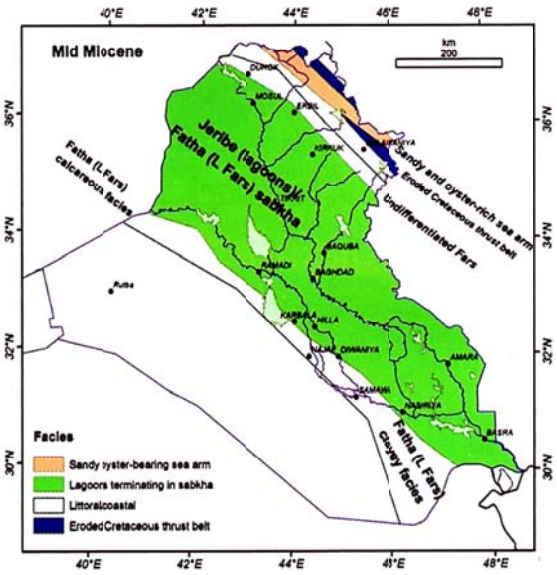


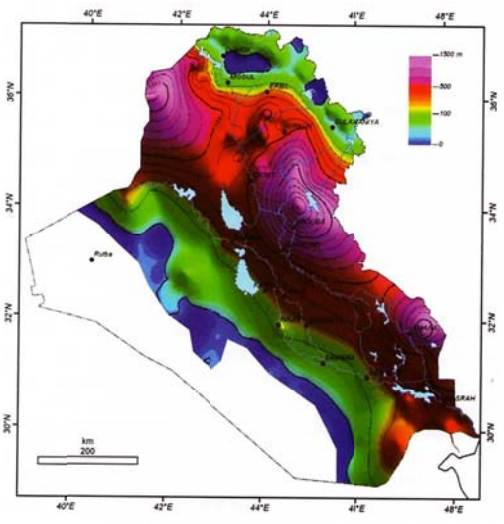
Fig. 14-6: Mid Miocene Palaeogeography



The Early Miocene Sequence in this book includes the Ghar, Euphrates, Serikagni and Dhiban formations; the Mid Miocene Sequence includes the Jeribe and the Fatha (Lower Fars) formations (Fig. 14-3). In the eastern Balambo Tanjero Zone and in the Qulqula-Khwakurk Zone the Early Miocene sequence is probably missing. The Mid Miocene Sequence is represented there by the Govanda Limestone of early Middle Miocene age.

The Early-Mid Miocene Sequence is thickest in the central parts of the basin between Sinjar, Baghdad and Amara (Fig. 14-7). A N-S trending area of low thickness roughly coincides with the eastern part of Salman Zone (Abu Jir High). The maximum thicknesses of the sequence are 1100 m in the Sinjar area, >1400 m near Baghdad and 1000 m near Amara. The sequence is absent in the High Folded Zone; it is locally present in a small belt along the Balambo Tanjero Zone and in front of the Northern Thrust Zone.

Fig. 14-7: Thickness of the Early-Mid Miocene Sequence



14.2.1 Early Miocene Sequence

The Early Miocene Sequence comprises the Ghar, Euphrates, Serikagni and Dhiban formations. The sequence outcrops in a broad area across the Stable Shelf to the Sand SW of the Euphrates River (Fig. 14-5). It also outcrops in the cores of some anticlines on the Mosul High and along the SW limits of the High Folded Zone.

14.2.1.1 Clastic inner shelf (Ghar Formation)

The formation was defined by Owen and Nasr (1958) from well Zubalr-3 of the Mesopotamian Zone of S Iraq. It comprises 100-150 m of thick sandstone and conglomerate with rare anhydrite, clay, and sandy limestone beds (Bellen et al., 1959). More silty beds and an increasing number of limestone and marl beds occur towards the NE. Anhydritic beds occur in Siba, Buzurgan, etc. (Ditmar and the Iraqi Soviet Team, 1972).

The formation was originally assigned an Oligocene Miocene age. Bellen et al. (1959) assigned a Middle Miocene age but later Naqib (1967), considered the beds to be of Early Miocene age. Ditmar and the Iraqi-Soviet Team (1972) considered the formation was of Oligocene-Early Miocene age. Surface mapping confirmed an Early Miocene age (Jassim et al., 1984).

The Ghar Formation was mapped by GEOSURV (Jassim et al., 1984) in three areas. At Busaya and near Abu Ghar, SW of Nasiriya it comprises 32 m of calcareous sandstone and marly and sandy limestone. Between Wadi Ubayidh and Wadi Ghadaf, W of Karbala, it comprises 45 m of thin bedded burrowed limestone with 12 m of red mudstone at the base, overlain by 32 m of varicoloured, cross-bedded calcareous sandstone with a few red silty mudstone beds. Between Wadi Hauran and the Syrian border it comprises 40 m of calcarenite sandstone with an 8 m thick limestone bed in the middle.

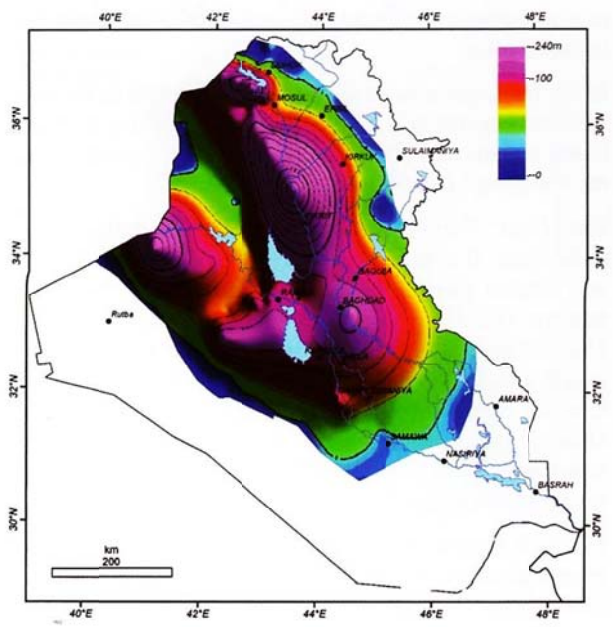
In the Buzurgan area along the Iraq-Iran border in SE Iraq, the Ghar Formation is reported to be up to 200 m thick but it may include part of the underlying Pabdeh Formation and the overlying Lower Miocene carbonates.

The Ghar Formation unconformably overlies older formations. It overlies the Lower Oligocene Sheikh Alas and Shurau formations in Wadi Akash near the Syrian border, the Umm Er Radhuma Formation in Wadi Ubayidh and the Dammam Formation near Busaya. In the Akash area the formation is gradationally overlain by Unit C of the Euphrates Formation (Section 14.2.1.2). In Wadi Ghadaf, the Ghar Formation is overlain by the basal conglomerate of the Ghadaf Beds. Near Busaya it is unconformably overlain by the Dibdibba Formation.

Fossils in surface sections include abundant shell fragments, fragments of *Peneroplis* and *Ammonia beccarii,* rniliolids, charophytes, and reworked planktonics (Jassim et al., 1984); organic matter also occurs. The Ghar Formation was deposited in a marginal marine (possibly partly deltaic environment). It passes gradationally into the Euphrates Formation.

At outcrop the Ghar Formation has been observed to pass laterally into the Euphrates Formation. This stratigraphic relationship indicates the Ghar Formation is of Early Miocene age.

Fig. 14-8: Thickness of the Euphrates Formation



The Ghar Formation can be correlated with the Hadrukh Formation of Saudi Arabia (Powers, et al., 1967) and with Lower Miocene sandstones in Syria which outcrop along the SW bank of the Euphrates, between Albu Kamal and Jebel Bishri (Ponikarov et al., 1967).

14.2.1.2 Carbonate inner shelf (Euphrates Formation)

The Euphrates Formation is the most widespread formation of the sequence. It was originally described by De Boeckh in 1929 and later amended by Bellen in 1957. The type locality near Wadi Fuhalmi near Anah on the Stable Shelf comprises 8 m of shelly, chalky and well bedded recrystallised limestone; however it represents only a small part of the formation and does not include the basal conglomerate. Sands and anhydrites also occur in some subsurface sections (Bellen et al., 1959) and are possibly tongues of the Ghar and Dhiban formations respectively.
Field surveys performed by GEOSURV (Al-Mubarek, 1971 and Al-Jumaily, 1974; in Jassim et al., 1984; Prazak, 1974; Tyracek and Youbert, 1975) indicate that the Euphrates Formation is heterogeneous. The formation consists mainly of limestones with textures ranging from oolitic to chalky, which locally contain corals and shell coquinas; they are often recrystallised and siliceous. Beds of green marls, argillaceous sandstones, breccias, conglomerates, and conglomeratic limestones also occur.

In Well Anah-Z, the Euphrates Formation is 94 m thick and comprises five units. These comprise from the base upwards: 1) Cream to buff dolomite with basal conglomerate. 2) Dolomite. 3) Soft white limestone with macrofossils. 4) Oolitic and chalky limestone. 5) Brownish dolomite. This section is not representative of the whole formation and it lacks the marly limestone and marl which outcrop near the well (Hopkins, 1958).

Two supplementary type sections were described in Wadi Chabbab, 39 km W of Anah, and in Wadi Rabi, 20 km E of Husaiba. The first section is 110 m thick and represents the lower and middle units of the formation. The second is 25 m thick and represent the upper unit of the formation. The combined section comprises:

1. Lower unit: 20 m thick basal conglomerate with subrounded boulders and cobbles of limestone derived from the underlying Oligocene Anah Formation, followed by 10 m of recrystallised fossiliferous limestone, grading into coralline limestone (Unit A).
2. Middle unit: 90 m of hard, fossiliferous limestone and pseudo-oolitic limestone beds (Unit B). Along the Euphrates River, between Al Qaim and Busaya, this unit interfingers with the Ghar Formation.
3. Upper Unit: 25 m thick soft, fossiliferous bluish green marl, interbedded with thin beds of shelly, recrystallised limestone or shelly oolitic limestone (Unit C). This is the most widespread Miocene unit occurring along, and west of, the Euphrates. The bedding in the limestones is often contorted especially along the Abu Jir Fault. This contorted bedding may have formed soon after sedimentation due to fluid movement (for example gas escape) or mud thixotropy due to earthquakes along the fault.

The thickness of the Euphrates Formation is shown in Fig. 14-8; two thick belts coincide with the margins of the Early Miocene basin. The formation thins rapidly towards the centre of the basin where the Serikagni Formation was deposited. In Sand W Iraq, the formation is replaced by the Ghar Formation.

Fossils in units A and B include: *Peneroplis evolutus* Henson, *P. farsensis* Henson, *Arehias sp., Robulus sp., Quinqueloeulina aknariana* Dorbigny, *Triloeulina sp.,* ostracods *(Cythereis sp, ?Cyprideis sp.,)* and pelecypods *(Hydrobia sp., Macoma sp.)* (Ctyroky and Karim, 1971a). Fossils in unit C include: *Quinqueloeulina akneriana* Dorbigny, *Arehalas sp., Robulus sp., Nodosaria sp., Sigmoilina sp., Miogypsina globulina* Michelotti, *Borelis melo melo* Fitchel & Moll, *Peneroplis farsensis* Henson, ostracods and rotaliids. The macrofauna includes: Gastropods *(Troehus sp., Pirenella sp., Turritella ef vermieularis, T. ef angulata* Brocchi, *?Mures sp, Fissurella sp., Aeteonina sp., Conus sp., Capulus sp., Fusus sp., Aeaphander sp., Ficus eonditus* Brongniart, *Bittium sp.* and *Aneilla sp.).* Pelecypods *(Glyeymeris pilosus* Linnaes, *Area turoniea* Dujardian, *Area sp., Phacoides cf columbella* Lamarck, *Veneridae sp., Chione sp., Cordiopsis sp., Divaricella cf ornate* Agassiz, Milyah sp., Donax sp., Timoclea sp., Thracia sp., *Macoma sp., Tellina sp., Solecurtus sp., Corbula gibba cf curta* Olivi, *Lucinom sp., Cardita sp., Pinna cf pectinata brocchi* d'Orbigny, *Cardium aff pseudomulticostatum* Zhischenko, *Cardium sp., Modiolus cf incrassatus* d'Orbigny, *Modiolus sp., Chlamys sp., Ostrea cochlea* Poli, *Chama gryphoides* Linnaeus, Brachipods *(Discinisea sp.),* echnoids *(Clypeaster sp.* and *Brissopsis sp.).*

Additional fossils recorded from unit C near Hit include:

Deniritina sp., Triloculina subinflata, T. asymmetrica Sald, *T. asperula* Cushman, *Quinqueloculina acuta* Hussey, *Spiroloculina terquemiana, Elphidium advenum* Cushman, *Bolivina shukrii* Soaya, *Bulimina ovata* Dorbigny, *Textularia sp., Eiphidium crispum* Linne, *E. enccrotum* Williamson, *E. gunteri* Cole, *Borelis melo melo* Fitchel & Molm, *Cibicides lobatulus* Walker & Jacob, *E. enccrotum* Williamson, *Nonion sp., Triloculina cf austriaca* d'Orbigny, *Spiroculina sp.,* S. *terquemiana* Fornasisni, *Ammonia beccarii* Linne, *Peneroplis [arsensis* Henson, *Miogypsina cf cushmani* Vaughan, M. *sp., Ostrea latimarginata* Vrebenburg, *Ostrea verieti* Deshayes, *Chlamys cf varia* Linne, *Clausinella sp, Cute/us sp.,* echinoid spines and plates, bryozoans, ostracods and algae.

In S Iraq, near Samawa, Al Hashimi and Amer (1974; in Jassim et al., 1984) recorded the following fauna in the subsurface: Rare *Miogypsina intermedia, Quinqueloculina angularis* Dorbigny, Q. *carinata* d'Orbigny, Q. *seminulum* Linne, Q. *collumesa* Cushman, Q. *quadrata* Noraung, *Triloculina schreibersiana* d'Orbigny, *T. cf trigonula* Lamarck, *Spiroloculina limbata* d'Orbigny, S. *platulata, Spirolina cylindracea* Lamarck, *Peneroplis planatus* Fitchell & Moll, *Ammonia beccarii globula* Colom, A. *beccarii koeboensis* Leroy, *Rotalia convexa* Leroy, *R. punctatogranosa* Sequenzs, *R. umbonata* Leroy, *Elphidium articulatum* d'Orbigny, *E. alvarezianum* d'Orbigny, *E. chipolense* Cushman, *E. decipiens* Costa, *E. indicum* Cushman, *E. minitum* Reuss, *E. talwanum* Nakamura, *Nonion densepunctatum* Egger, *Discorbis sp., Heterolepa dutemplei* d'Orbigny. The fauna also included pelecypods *(Barbatia varvata* Linne, *Cardium faeetum* Zhizchenko, C. *multieostatum* Brocchi, *Cultellus produs* Merklin, and *Nueula nucleus* Lamarck.

Further macrofauna was determined from the Euphrates Formation in the western desert by Prazak (1974). This fauna includes: *Modiolus incrassatus* Dorbigny, *Tapes vetulus* Bast, *Troculus nefas* Kolesnikov, *Corbula gibba* Olivi, *Diveraeella ornata* Agassiz, *Tomatina sp., Cardium faeetum* Zhizchenko, *Modiolus eonditum* Mayer, *Turritella angulata* Sowerby, *Barbatia ef barbata* Linne, *Glyeymeris cf pilosus* Linnaeus, *Lima ef subaurieulata* Montacu, *Venerupsis irus* Linnaeus, *Dosinia lupinus* Linnaeus, *Area turomiea* Duijardin, *Cardium kubanieum* Zhizchenko, c., *mulliertatum* Brocchi, *Cutellus probus* Merklin, and *Nueulana nucleus* Lamarck.

The age of the Euphrates Formation is late Early Miocene (Burdigalian), proved by the presence of *Miogypsina globulina* and *Miogypsina intermedia* (Ctyroky and Karim, 1971a). *Miogypsina globulina* appears to be restricted to the Early Miocene (early-mid Burdigalian); M. *intermedia* to the Early-Mid Miocene (Burdigalian-early Langlhan). Prazak (1974) argued that only *pre-Orbulina* beds are present (pre-Middle Miocene).

The formation usually unconformably overlies Oligocene and Eocene formations. In the type area the basal beds of the formation comprise conglomerates and residual clays which infill an uneven surface at the top of the Oligocene Anah Formation. In areas where, the underlying unit is the Serikagni Formation, the lower boundary is conformable. The upper boundary at the type locality is not exposed. The investigations of GEOSURV revealed, that the upper members of the formation are overlain by a brecciated or conglomeratic horizon above which the *Orbulina* datum with the index fossil *Borelis melo eurdiea* of the Middle Miocene Jeribe Formation limestones occurs (Prazak,1974).

Lower Miocene limestones in Syria were referred to the Euphrates Formation by Dubertret (1966). The formation is equivalent to part of the Asmari Limestone of SE Iran. The Euphrates Formation passes laterally into continental clastics in Saudi Arabia, represented by the Hadrukh Formation (Powers et al., 1966).

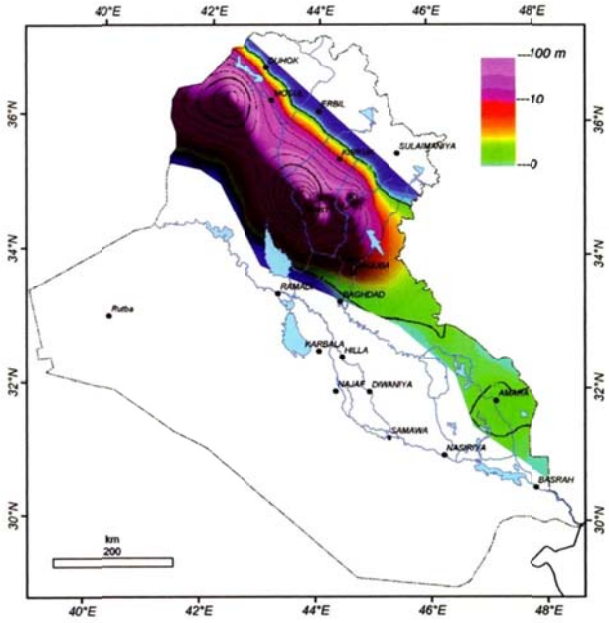
14.2.1.3 Basinal (Serikagni Formation)

The Serikagni Formation represents the basinal facies of the Sequence which has a restricted distribution. It was first described by Bellen in 1955 from the type area at Bara village in Jabal Sinjar of the Foothill Zone of NW Iraq where it comprises 150 m of globigerinal chalky limestone.

The thickness of the formation is shown in Fig. 14-6. The Serikagni Formation was deposited in a restricted marine environment in the central parts of the latest Early Miocene basin. Fossils in the Serikagni Formation are abundant and prove a late Early Miocene age (Bellen et al. (1959).

The Serikagni Formation in the type area unconformably overlies the Eocene Jaddala Formation or basinal Oligocene formations. The formation is conformably overlain by the Dhiban Formation. In Syria, the formation is equivalent to a Lower Miocene marl unit which interfingers with evaporites (Ponikarov et al., 1967) which Dubertret (1966) referred to the Serikagni Formation.

Fig. 14-9: Thickness of the Serikagni Formation



14.2.1.4 Evaporite lagoons (Dhiban Formation)

The Dhiban Formation was defined by Henson in 1940 and amended by Bellen in 1957 (Bellen et al., 1959) from the type area near Dhiban village in the Sinjar area of the Foothill Zone of NW Iraq. The formation comprises 72 m of gypsum, thin beds of marl and brecciated recrystallised limestone. Salt occurs in well Injana-5 (Bray, 1960). Salt exploration wells drilled S of Sinjar, as in NE Syria (Ponikarov, et al., 1967) discovered halite beds in the formation. Between Mosul and Qaiyarah the anhydrites are replaced by "chemical" limestones (Bellen et al., 1959) due to bacterial reduction and sulphur formation. Gaddo and Parker (1959) recorded sandstone in well Khleisia-l.

The thickness of the formation is up to 150 m but it averages 70 m. The isopach of the formation (Fig. 14-10) shows two depocentres separated by the Abu Jir High. The formation was deposited in basin-centred sabkhas and salinas.

The age of the Dhiban Formation has been defined on the basis of stratigraphic relationships with other formations. The
Dhiban overlies the Serikagni Formation, interfingers with the Euphrates Formation and is overlain by the Jeribe Formation. Therefore its age has been established as Early Miocene.

The Dhiban Formation occurs in NE Syria (Dubertret (1966). The Kalhur Gypsum of SW Iran (sometimes recorded in Iraq) is equivalent to the Dhiban Formation.

Fig. 14-10: Thickness of the Dhiban Formation

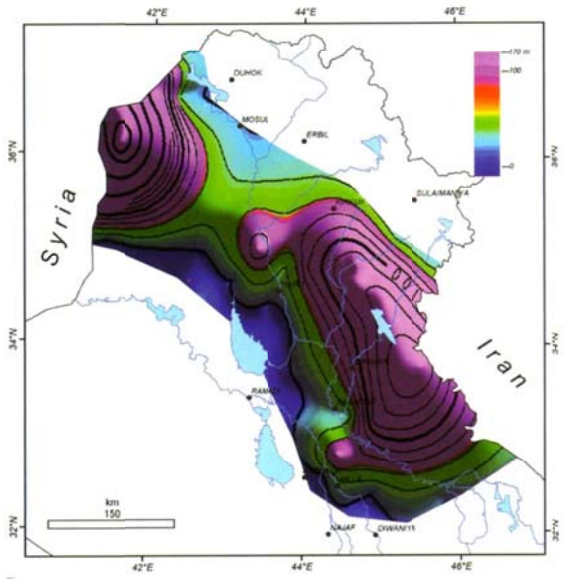
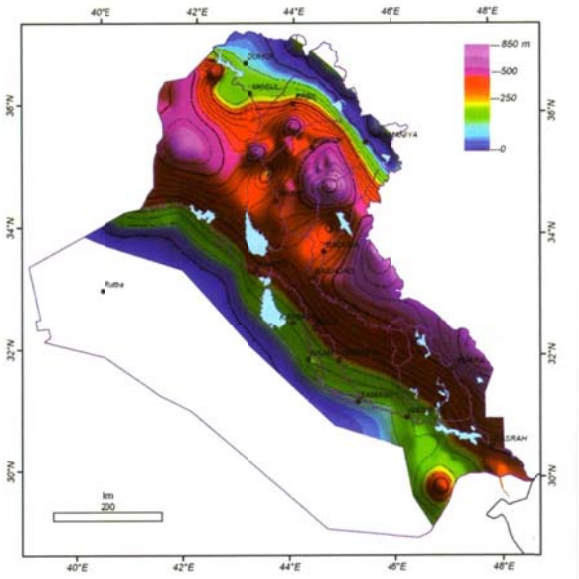


Fig. 14-11: Thickness of the Mid Miocene Sequence



14.2.2 Middle Miocene Sequence

The Middle Miocene Sequence was deposited in broad basin following a marine transgression during a phase of strong subsidence that overlapped the margins of the former Oligocene-Early Miocene basin, especially in NE Iraq. The sequence was also deposited in the Red Beds basin of the Zagros Suture. Within the intra-shelf area the sequence comprises a shallow water carbonate (Jeri be Formation) overlain by thick evaporites, carbonate and marls of the Fatha (Lower Fars) Formation. In the Zagros Suture the sequence comprises a conglomerate-carbonate unit (Govanda Limestone) overlain by continental clastics (Merga Red Beds). The Govanda Formation is discussed in Chapter 15 (along with the Red Beds Series).
The sequence is thicker (> 1 000 m) in the Foothill Zone (Fig. 14-11) than in the Mesopotamian Zone. The sequence is missing in the Rutba-Jezira Zone and in the southern part of the Salman Zone. It is relatively thin on the Abu Jir High.

14.2.2.1 Carbonate inner shelf and shaols (Jeribe Formation)

The Jeribe Limestone was defined by Bellen in 1957 (Bellen et al., 1959) from the type locality near Jaddala village in the Sinjar anticline, and assumed to be of Early Miocene age. However the formation was later included within the Middle Miocene Sequence. A Middle Miocene age is indicated by the presence of the Orbulina datum near the base of the Jeribe Formation (Prazak, 1974).

The Jeribe Formation comprises 70 m of recrystallised, dolomitised, generally massive limestones; in beds 1-2 m thick. **In** well sections, argillaceous limestones (Ain Zalah, Mushorah, Najmah, Samarra, Khlesia, Awasil) and anhydrites (Khlesia, Ain Zalah, Mushorah, Samarra) were recorded by Huber (1940), Melville (1949), Gaddo and Parker (1959) and Johnson (1961). **In** the Euphrates valley the formation comprises disharmonic ally folded conglomerates, sandy recrystallised limestones, silicified limestones, chalky limestones and some marl (Tyracek and Youbert, 1975). Unfortunately the Jeribe and Euphrates formation were not differentiated during field mapping when the intervening Dhiban Formation anhydrites are absent.

In the western desert of Iraq a unit of carbonates and clastics referred to as the Khirish Beds was introduced by Jassim et al. (1984). These beds pass laterally into the Fatha (Lower Fars) Formation, They outcrop in a wide area S of the Euphrates River (25 km S of Al Qaim). They comprise two units:

1. A Lower unit comprising from the base upwards: A) Grey, well sorted sandstone with clay balls, cemented by calcareous and argillaceous material, exposed on the right bank of Wadi Ratga along the main road between Khirish and Tl pumping station. B) Large lenses of conglomerate with pebbles and cobbles of limestone and chert; boulders up to 50 cm in size are sometimes present. C) Pink arenaceous limestone or calcareous sandstone exposed in many areas including Wadi Akash, Ratga and Al Maani; this is the most extensively exposed unit. D) Massive grey breccia, with angular and subangular limestone fragments, outcropping to the NE of the Tl pumping station.

2. An Upper unit comprising massive splintery limestone with sandy limestone and calcareous sandstone with beds of marl and local lenses of gypsum. This unit is best exposed in the Khirish area; the marls outcrop along the Al Qaim-Akashat road.

The Khirish Beds overlie unit C of the Euphrates Formation (Section 14.2.1.2) and pass laterally into the Fatha Formation to the north near Al Qaim.

In the Hit area (60 km NNW of Ramadi) thick recrystallised shelly limestones are probably equivalent to the Jeribe Formation. They overlie the Euphrates Formation and are overlain by gypsum and marl beds of the Fatha Formation. Large blocks of these limestones (4 m x 2 m x and 0.5 m in size) were excavated and used to construct the little known historic settlement of "Maqluba".

The isopach of the Jeribe Formation and Govanda Limestone is shown in Fig. 14-12. The main basin trends NW-SE and contalns four separate depocentres. The thickness of the Jeribe Formation is about 200 m in the area along Tigris River in N Iraq, 180m near Kirkuk, >500 m in the Badra area, and 50-150 m near the Zagros Suture Zone. The Jeribe Formation is thickest in the Makhul-Hemrin Subzone and the Tigris Subzone.

Bellen et al. (1959) suggested that the Jeribe Formation was deposited in lagoonal (backreef) and reef environments. Backreef-reef facies are predominant.

The conspicuous index fossil *Borelis melo curdica* (Karim and Prazak, 1973) and *Orbulina* occur in the lower part of the formation. **In** addition to the fossil list provided by Bellen et al. (1959), Prazak (1974) provided a fossil list which supports a Middle Miocene age.

The lower contact with Serikagni Formation in the type area is unconformable. **In** many areas conglomeratic beds occur at the base of the Jeribe Formation. The Jeribe Formation passes gradationally into the overlying Fatha (Lower Fars) Formation.

The Jeribe Formation has a similar distribution to the underlying Euphrates Formation. The Jeribe Formation is absent in the southern desert. **In** NE Iraq, the Jeribe oversteps the Euphrates Formation in the Kirkuk Embayment. The Jeribe Formation is equivalent in age to the Govanda Limestone Formation in NE Iraq. It is also recognised in the Jezira basin of Syria (Ponikarov et al., 1967); it unconformably overlies older formations with a basal conglomerate. **In** SW Iran, the formation is equivalent to the Kaihur Limestones and part of the Upper Asmari.

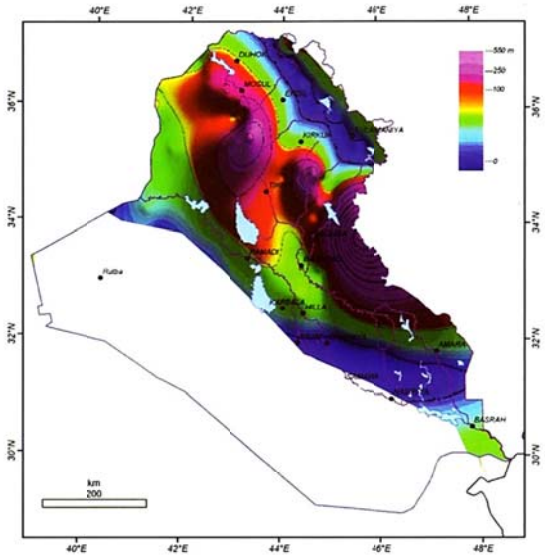


Fig. 14-12: Thickness of the Jeribe and Govanda formations

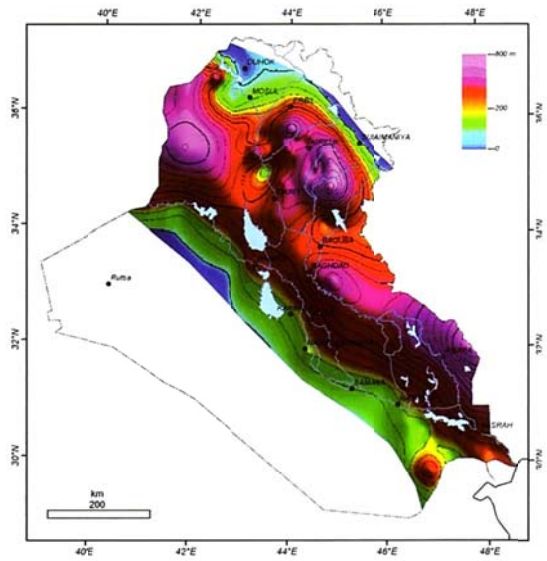


Fig. 14-13: Thickness of the Fatha (Lower Fars) Formation

14.2.2.2 Evaporite lagoons (Fatha Lower Farsi Formation)

The Fatha (Lower Fars) Formation is one of the most aerially widespread and economically important formations in Iraq.

The "Lower Fars" Formation was defined from the Fars Province in SW Iran and introduced to Iraq by Busk and Mayo in 1918 (Bellen et al., 1959). **In** Iran its name was changed to the "Gachsaran Formation". A new type section has been established in Iraq in the Al Fatha gorge where the Tigris River crosses the Makhul-Hemrin range, 10 km N of Baiji town; the name of the formation has been changed to the Fatha Formation (Jassim et al., 1984).

The Lower Fars Formation of Iraq was subdivided by oil geologists in the early years of exploration into informal units. It comprises anhydrite, gypsum and salt, interbedded with limestone and marl. The informal units (Bellen et al., 1959) comprise from bottom to top:

a) Transition Beds normally comprising beds of anhydrite, mudstone and thin limestones. The transition beds usually overlie the so-called "Basal Fars Conglomerate", which is now included in the Jeribe Formation. This division is dominated by carbonates on the Mosul High.

b) Saliferous Beds comprise anhydrite and halite with beds of siltstone, mudstone, and less frequent limestone beds.

c) Seepage Beds comprising anhydrites with beds of siltstone, mudstone and limestone.
d)Upper Red Beds comprises red mudstones, siltstones and relatively frequent beds of limestone and anhydrite.

These units are easily recognized in the Kirkuk basin (the Kirkuk Embayment). In the Jezira basin and the Mesopotamian Zone these informal units cannot easily be identified. In the Buzurgan, Abu

Ghirab, Nahr Umr, and Dujalla areas of the Mesopotamian Zone in S Iraq (Ditmar and the Iraqi-Soviet Team, 1972; Karim 1962; Safar, 1961) the evaporites are interbedded with marls, mudstones and siltstones; limestones are rare. Along the margins of the basin, the formation is dominated by marl and clastics.

Regionally the formation can be divided into two members. The Lower Member lack red mud tone. In the new type section at AL Fatha, the Lower and upper ember are 220 m and 400 m thick respectively. The Lower Member comprises a 40 m thick basal unit of organodetrital limestone and anhydrite (or gyp urn) with minor amounts of green dolomitic marl (probably equivalent to the Transition Beds) followed by 100 m of cyclically interbedded gyp urn, green marl and thin limestones. On the Mosul High carbonates comprise >50% of the Lower Member compared to <20% in the Sinjar area the NW (Jassim et. al., 1998).
The Upper Member comprises a cyclic succession of green and red mudstone and gypsum and a few thin oolitic or recrystallised shelly limestone beds; beds of calcarenite occur near the top.

A typical section of the Lower Member of the formation near the Euphrates valley comprises a basal conglomerate, and cycles of gypsum, marl and limestone. The conglomerate consists of rounded and sub-rounded, poorly sorted fragments of white chalky limestone and grey crystalline limestone and lenses of green marls. The gypsum beds are white massive or nodular, and are interbedded with thin chalky and crystalline shelly limestone beds. The Upper Member comprises cycles of red silty mudstone, green silty mudstone, marl, nodular gypsum and limestone.
In the Hit area, the formation comprises cycles of mudstone, limestone and gypsum. South of Ramadi (near Razzaza Lake) the formation comprises a lower unit of green marl (Shithatha Marl) with mudstone and fossiliferous limestone beds, a middle unit of calcareous and argillaceous sandstone and sandy limestone, and an upper unit of red mudstones and gyp urn capped by a limestone bed.

Along the Najaf escarpment (Tar Al Najf) the formation comprise mudstone and limestone with the following fauna: *Ammonia beccarii* Linne, *Parkinsonia sp., Ammonia sp.,* miliolids *(Quinqueloculina sp., Pyrgo sp., Spiroloculina sp.)* 0 tracods *(Paracypris sp., Loxoconcha sp.* etc.), *Clausinella sp., Modiolus sp., Balanus sp.,* echinoid fragments and shell fragments.

Important contemporaneous travertine and bitumen lenses, interbedded with the basal green marls of the Fatha Formation, occur near Hit town. An isolated hill (Murgeb Jerin) on the left bank of the Euphrates River, 30 km N of Hit is very spectacular. It towers above the surrounding Mesa of the Fatha Formation. The hill comprises five lenticular travertine beds, each a few metres thick, interbedded with green marl and sometimes with fossiliferous limestones. These travertine beds wedge out and dip radially away from the hill. The travertine has large voids (occasionally containing sulphur crystals).

The travertine beds interfingers with the surrounding evaporites of the Fatha Formation and overlie unit C of the Euphrates Formation. The travertine cones may have formed in very shallow lagoons as a result of asphalt seepage and bacterial reduction of the basal gypsum beds of the formation producing fluids that deposited sinters. Numerous bitumen beds with aragonite and celestite are also present in the basal marl of the Fatha Formation near Hit Town and probably have the same origin. These deposits occur along the *N-S* Abu Jir Fault zone which is also characterised by active asphalt seepages (at Ain Jabha, Ain Abu Jir, Ain Atalt and Ain Hit).

The thickness of the formation is very variable (Fig. 14-13). The formation is >900 m in a depocentre in the Kirkuk basin and >600 m in a depocentre in the Sinjar basin. The formation thins over the Abu Jir High.

The Fatha Formation was deposited in a rapidly subsiding sag basin which periodically became evaporitic with formation of sabkhas and salinas.

Fossils are rare. Limestones in N Iraq contain mostly minute foraminifera, mainly miliolids; ostracods are also common. The fauna includes: *Clausinella* (?) *amidei, Clausinella ssp., Ostrea latimarginata* (considered to be an index fossil of the formation), *Rotalia beccarii,* and *Elphidium sp.* (Bellen et al., 1959). Ctyroky and Karim (197 I a) recorded: *Sigmoilina sp.,* S. *tschokrakensis, Quinqueloculina akneriana,* Q. *sp., Plectofrondicularia sp., Cytheriedeis sp.* and *Cardium sp.* The age of the formation is Middle Miocene. According to Ponikarov et al. (1967), the Fatha Formation is of Tortonian age; this is confirmed by its position above the Orbulina Datum (Prazak, 1974).

The lower contact of the Fatha Formation with the underlying Jeribe Formation is conformable. In some areas, however, the formation overlies older rock units, especially near the shoreline of the basin. The upper contact with the Injana (Upper Fars) is gradational and diachronous (Bellen et al., 1959).

The formation is present in the Foothill and Mesopotamian zones. In the High Folded Zone, the formation is generally missing or replaced by clastics facies ("Undifferentiated Fars"). The presence of volcanics in the High Folded Zone (the Sinia Volcanics of Mitchell. 1960) has not been confirmed. To the SE of the Anah-Qalat Dizeh Fault, the Fatha Formation thickens and the proportion of gypsum increases as seen for example in the Taq Taq and Chemchemal wells (Melville and Fothergill, 1954 and Jameson, 1961).

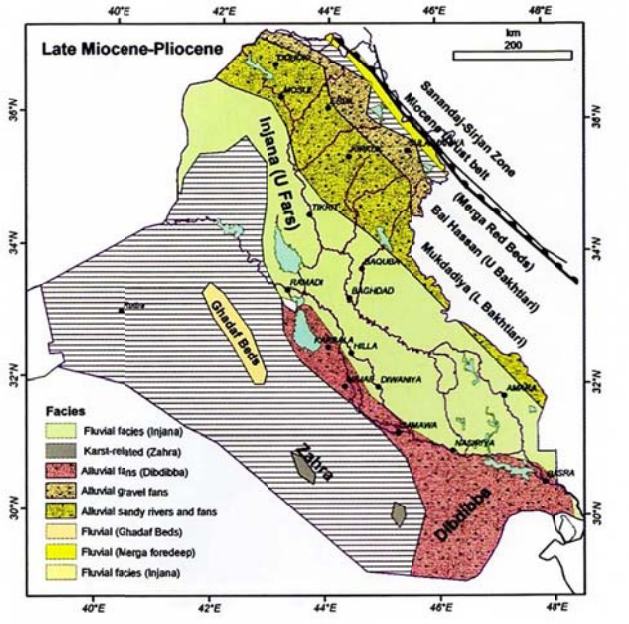
In the High Folded Zone a limestone, sandstone and mudstone succession (equivalent to the Fatha Formation) is occasionally preserved in synclines. Further to the NE the basal clastics of the Merga Red Beds (Chapter 16), comprising sandstone and red and green mudstone, are equivalent in age to the Fatha Formation.

The Fatha (Lower Fars) Formation is also widely distributed in the Jezira area of Syria and along the Syrian-Turkish border (Weber, 1963). Towards the SE in Iran, the formation passes partly into the Gachsaran Formation. In Kuwalt and Saudi Arabia the formation is age equivalent to the Dam Formation which includes marine interbeds with a fauna identical to that of the Fatha Formation (Powers et al., 1967).

14.3 Late Miocene-Pliocene Sequence

In Late Miocene-Pliocene time major thrusting occurred during collision of the Neo- Tethyan terranes and the Sanandaj-Sirjan Zone with the Arabian Plate. This event resulted in the uplift of the High Folded, Northern Thrust zones and the NE parts of the Balambo- Tanjero zones and Mesopotamian zones. A major foredeep formed in the Foothill Zone. On the SW side of the basin, the whole of the Rutba-Jezira and Salman zones were uplifted (Fig. 14-14).

Fig. 14-14: Late Miocene-Pliocene Palaeogeography



During the Late Miocene and especially the Pliocene, the High Folded Zone was uplifted with increasing intensity. The products of erosion were deposited in the nearby molasse basin characterised by the conglomerates of the Bai Hassan (Upper Bakhtiari) Formation. In the SW the uplifted Stable Shelf was the source of the terrigenous clastics deposited to the NE of the Euphrates Boundary Fault (Dibdibba Formation).

At the end of the Pliocene the Foothill Zone was uplifted and deformed; molasse was deposited in synclines between strongly uplifted long anticlines. Synclines received sediments of polygenetic origin (See chapter *15).* The Mesopotamian Zone became the new molasse foredeep.

Bellen et al. (1959) recognised the Middle Fars, Upper Fars, Lower Bakhtiari, Upper Bakhtiari, Dibdibba and Zahra formations in the Mio-Pliocene sequence. The Merga Red Beds also belong to this sequence (see Chapter 16). The Middle Fars Formation is now included in the Injana (Upper Fars) Formation. The Bakhtiari Formation comprises two separate formations now referred to as the Mukdadiya and Bai Hassan formations (Jassim et al., 1984).

Since the Zahra Formation locally overlies the proved Fatha (Lower Fars) Formation, it is here included in the Late Miocene-Pliocene Sequence.

Sandstones deposited in a graben 15 km E of Kl60 settlement in the western desert described by Jassim et al. (1984) are referred to as the Ghadaf Beds.

The following units are included in the Late Miocene Pliocene Sequence: the Dibdibba, Zahra, Injana (Upper Fars), Mukdadiya, Bai Hassan (L and U Bakhtiari) formations and the Ghadaf Beds. The Merga Group is also included in the sequence and is discussed in Chapter 16.

The formations of the sequence are strongly diachronous due to facies changes resulting from deposition synchronous with folding and thrusting.

The thickness of the Late Miocene-Pliocene Sequence (including Quaternary) is shown in Fig. 14-15; note the main depocentre in the Foothill and Mesopotamian zones. The sequence is relatively

thin on the N-S Abu Jir High. The thickness also includes the Quaternary flood plain deposits of Mesopotamia (-300 m thick). The Zahra Formation clastics of the Salman Zone are not included in Fig. 14-15 due to their patchy distribution.

Fig. 14-15: Thickness of the Late Miocene-Pliocene Sequence (including Quaternary)

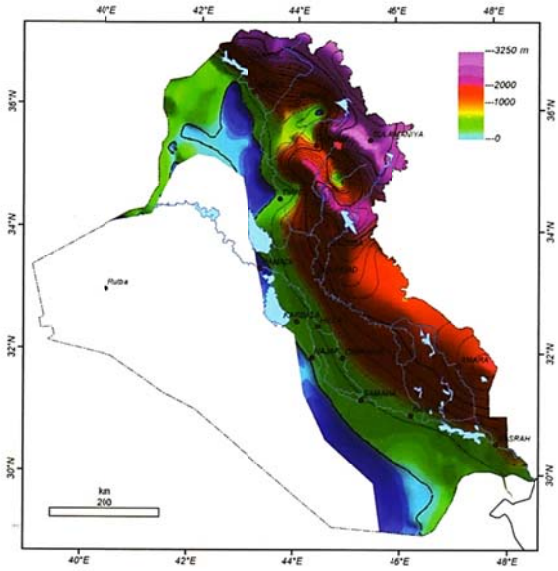
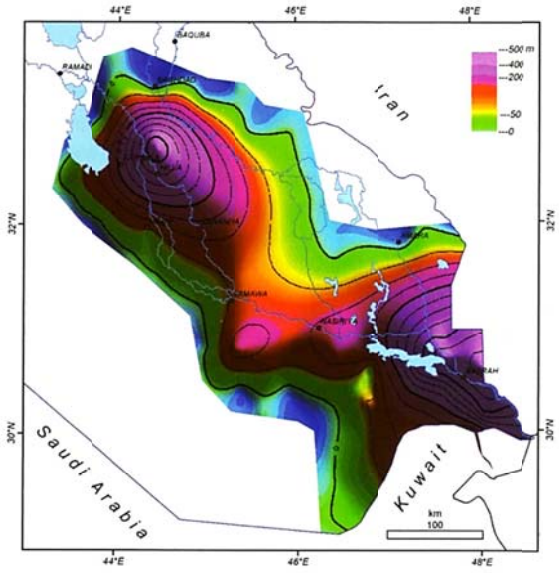


Fig. 14-16: Thickness of the Dibdibba Formation



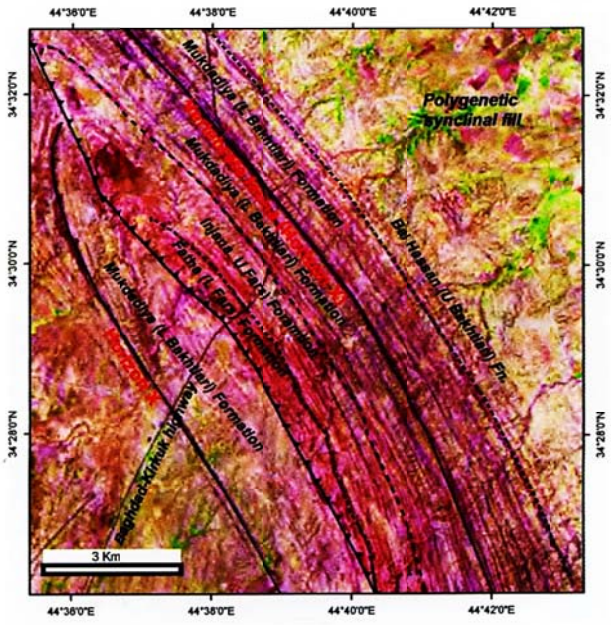
14.3.1 Fluvio-lacustrine and karst fill facies (Zahra Formation)

The Zahra Formation occurs locally in the Salman Zone and along the margins of the Rutba Subzone. It was defined by Williamson in 1941 (Bellen et al., 1959) from the Busaya- Schbicha area. It consists of 30 m of limestones (subsequently found to be reed-bearing fresh water limestone), marls, and sandy marls. Locally sandstone occurs at the base of the formation. The Zahra Formation lies in karst depressions formed on the Rus (Jil) Formation due to dissolution of the anhydrites of the formation (Maala, 1983; in Jassim et al., 1984). The presence of limestone beds similar to those found in the Dibdibba Formation suggests that Zahra Formation may pass laterally into the Dibdibba Formation.

Based on the age determinations of Williams (1941) and Rogers (1939), Mitchell suggested an Oligocene age for the Zahra Formation. However a Mio-Pliocene age is accepted by Jassim et al. (1984).

The presence of *Chara sp., Melanoides tuberculata, Planorbis sp., Vivipara sp.* indicates the Zahra Formation was deposited in a fresh water environment. Near Samawa the recorded fossils include: *Planorbis sp.*, charophytes, pelecypods and gastropods (Jassim et al., 1984). Bellen et al. (1959) favour a Mid Miocene age for the formation. However a Late Miocene-Pliocene age is more likely because of its stratigraphic position above the Middle Miocene Fatha Formation and its possible correlation with the Dibdibba Formation.

Fig. 14-17: Satellite image for the Injana area, Hemrin South, 120 km NE of Baghdad. A thrust (thick black ornamented line) separates the NE flank from the SW flank. The NE flank exposes the Fatha Formation in the core followed by Injana Formation (type section of Injana Formation) and the Mukdadiya Formation (L Bakhtiari). In the NE the conglomerates of the Bai Hassan (U Bakhtiari) Formation appear as dark belts. The linear dark tones in the Mukdadiya Formation represent layers with gravel-rich sandstone. The layer containing vertebrate fauna is indicated.



14.3.2 Alluvial Fans of the Stable Shelf (Dibdibba Formation)

The Dibdibba Formation was defined by Macfadyen in 1938 (Bellen et al., 1959) and amended by Owen and Nasr (1958). The type locality is in the Burjisiya area of the Zubair oil field in S Iraq. Owen and Nasr (1958) described the formation from wells of the Zubair field. It comprises sand and gravel containing pebbles of igneous rocks, (including pink granite) and white quartz, often cemented into a hard grit. Beds of limestone, marl and silt were reported from wells in Nahr Umr field (Elliot et al., 1954; Rutgers, 1950), Kifl (Kasim, 1960) and at Musalyib (Kasim, 1962). In the latter two areas anhydrite beds also occur. Elliot et al' (1954) divided the formation into four units. From the base up these comprise: 1) Green sand and soft green marly sands. 2) Conglomerate with pebbles of limestones, chert, and igneous rocks (porphyries) in a calcareous matrix. 3) Grey and pink Lower Sandstone followed by limestones. 4) Sandstone and grit. In a water well SW of Busaya, the formation comprises from the base upwards: 21 m of gravely sandstone, 60 m of medium-grained pink sandstone, and 18 m of calcareous sandstone. Limestone beds occur sporadically throughout. The formation was deposited in a fresh water environment becoming deltaic to the NE. It is of post Middle Miocene age based on its stratigraphic position.

In wells of S Iraq and the N Gulf the Dibdibba Formation is up to 500 m thick (Fig. 14-16). Two depocentres of the Dibdibba Formation are located along the Euphrates Boundary Fault near Busaya and Karbala.

The main depocentres of the formation is in SE Iraq in the Zubair Subzone of the Mesopotamian Zone. Other depocentres are near Samawa and Hilla and seems to have been sourced from the NW.
The contact of the formation with the underlying Fatha Formation is conformable in SE Iraq (Bellen et al., 1959). At outcrop to the west the formation unconformably overlies Lower Miocene and Palaeogene units. The formation is often covered by sand sheets or by the alluvial fan sands of Wadi Al Batin.

The Dibdibba Formation is also recognised in Kuwalt; in Saudi Arabia similar facies are included within the Hofuf Formation and partly in the Kharj Formation (Powers et al., 1967).

14.3.3 Fluvial system

14.3.3.1 1njana (Upper Fars Formation)
The Injana (Upper Fars) Formation (including the Middle Fars) comprises fine grained pre-molasse sediments deposited initially in coastal areas, and later in a fluvio lacustrine system. It was described by Busk and Mayo in Iran in 1918 and subsequently recognized widely in Iraq.
The formation was later abandoned in Iran (James and Wynd, 1968) and was renamed the Injana Formation in Iraq (Jassim et al., 1984). A subsidiary type section was measured near Injana, at Jabal Hemrin South (near the old police station along Baghdad-Kirkuk Highway, 120 km NE of Baghdad). It is 620 m thick. The basal unit comprises thin-bedded calcareous sandstone, and red and green mudstones with one thin gypsum bed (20 cm thick) and a purple siltstone horizon with glass shards. The calcareous sandstones contain miliolids and oscillation ripple marks; they are overlain by fining upwards cycles of sandstone siltstone and red mudstone The thickness of individual sandstone beds increase upwards from I m to several metres. The formation as a whole coarsens upwards.
The thickness of the formation is very variable, due to subsequent erosion over major folds. A maximum thickness of 2000 m in the central depositional area in the Foothill Zone (Naqib, 1960) was not confirmed during later mapping. The maximum thickness of the formation is 900 m was measured near Kirkuk (Jassim et a!., 1984).
The lower contact of the Injana Formation with the Fatha Formation is gradational. The upper contact with the Mukdadiya Formation is gradational marked by appearance of gravely sandstone.
In the central parts of the basin the formation consists predominantly of uniform silty claystones or marls with anhydrite. In the NE side of the basin the sands were derived from the rising Zagros and Taurus mountains. On the SW margin of the basin the sands contain Dibdibba-type components such as rounded coarse quartz and stable heavy minerals such as rutile and Zircon. In this marginal area along the Euphrates Boundary Fault, the formation was deposited by anastomising rivers (Salah Maaroof, personal communication) and passes gradually upwards into the Dibdibba Formation.
Fossils occur mainly in the lower part of the formation but are poorly studied. In the Habaniya area an assemblage of charophytes was recorded by Salah Maroof (personal communication). The age of the formation is usually accepted as Late Miocene. Vertebrate fossils from sandstones 600 m above the contact with the overlying Mukdadiya (L Bakhtiari) Formation were dated as 8Ma old (Thomas et al., 1978). The Injana Formation must be older than this age.

14.3.3.2 Mukdadiya and Bai Hassan (Lower and Upper Bakhtiari) formations

The Bakhtiari Formation was first described from Iran by Busk and Mayo in 1918 and later introduced in Iraq where it was divided into the Lower and Upper Bakhtiari formations (Bellen et al., 1959). The two formations are strongly diachronous but can be recognised throughout the Foothill and High Folded zones. The names Mukdadiya and Bai Hassan formations were used by Jassim et al. (1984) to replace the Lower and Upper Bakhtiari formations respectively.

The Mukdadiya (Lower Bakhtiari) Formation comprises up to 2000 m of fining upwards cycles of gravely sandstone, sandstone and red mudstone. The sandstones are often strongly cross-bedded and associated with channel lags and clay balls. Basi and Jassim (1973) noted that in the Injana area the whole formation comprises stacked fining up depositional cycles. Individual sandstone beds extend laterally for several kilometres.

The formation is distributed mostly in the Foothill Zone where it is >2000 m thick in the Kirkuk Embayment. It is replaced almost totally by the Bai Hassan (Upper Bakhtiari) conglomeratic facies in the High Folded Zone of NE but not in N Iraq; for instance, in the Derbendikhan area S of Sulalmaniya the Mukdadiya Formation is almost totally replaced by -3000 m of conglomerates of the Bai Hassan Formation (Plate 14-1). The formation is thin or absent over the Mosul High. In the Rabia'a plain N of Sinjar, 258 m of clastics are assigned to the Mukdadiya Formation (well Tel Abtakh-l) but to the S of Sinjar the formation is absent (well Tel Hajar-l).

An interval about 600 m above the base of the formation (Fig. 14-17) consists of sandstones with rounded and rod-like calcite-cemented concretions. It has yielded a vertebrate fauna of mastodons and others mammals (Thomas et al., 1978). A similar lithological unit was observed by the authors in many areas in NE and N Iraq (for example near Kirkuk and Amadiya). This unit may indicate a climate when indurated calcareous crusts formed in river channels were reworked during subsequent flooding. These conditions of desiccation and flooding may have caused mass drowning and transportation of the carcases of large mammals.

The Mukdadiya (Lower Bakhtiari) Formation was deposited in fluvial environment in a rapidly subsiding foredeep basin. The conglomeratic Upper Bakhtiari was deposited in alluvial fans originated from the High Folded Zone and the Zagros Suture.

Bellen et al. (1959) recorded the horse *Hipparion sp.* Based on the vertebrate fauna a Late Miocene age (8 Ma) for the lower part of the Bakhtiari Formation is accepted (Thomas et al., 1978).

The Mukdadiya and Bai Hassan (Bakhtiari) formations are equivalent to the Pliocene clastics of N and NE Syria (Dubertret, 1966). Ponikarov et al. (1967) noted a major unconformity at the base of the Pliocene clastics in the N Jezira area where the Pliocene sequence coarsens upwards. The Bakhtiari Formation conglomerates can be followed into SE Turkey (Altinli, 1966). In SW Iran (the type area for the formation), the formation is widespread. However the Lower Bakhtiari Formation was later included in the Agha Jari Formation (James and Wynd, 1965).

Plate 14-1: The Bai Hassan Formation in the middle ground on the W shores of Derbendikhan Lake in NE Iraq. See text for explanation (photo by J. Radolský)



Plate 14-2: Bai Hassan (Upper Bakhtiari) Formation, SW flank of Taq Taq anticline, 20 km SW of Erbil (photo by S. Jassim)



Chapter 15

Quaternary Deposits

by

Adnan A. M. Aqrawi, Jaroslav Domas and Saad Z. Jassim

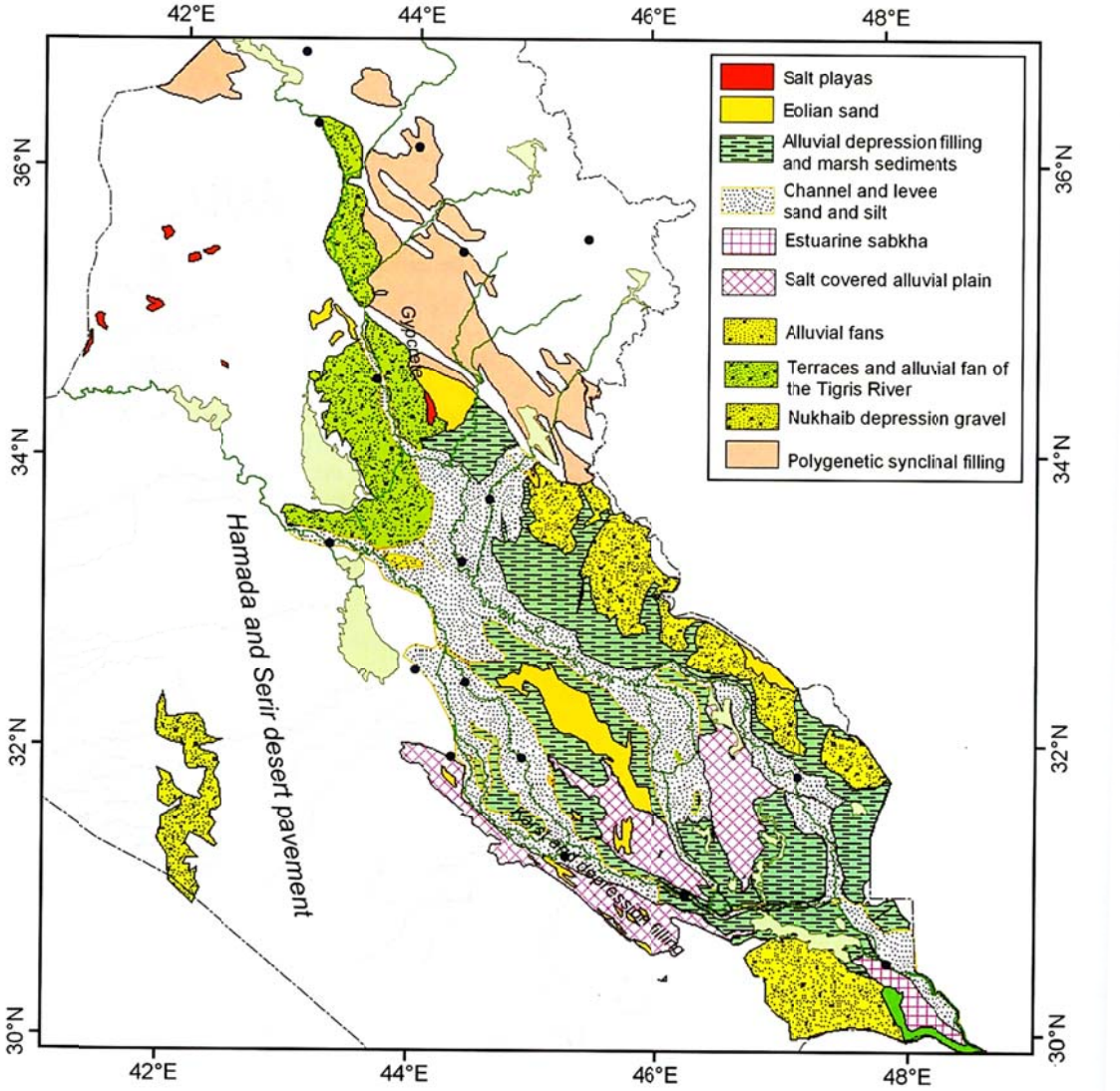
Detailed stratigraphic and sedimentological studies of the Quaternary were neglected until the start of the regional geological survey program, conducted by GEOSURV during the 1970's and completed in 1982. Quaternary sediments cover more than one third of the surface area of Iraq, mostly within the Mesopotamian Plain, where they comprise fluviatile, lacustrine, deltaic, and aeolian sediments that replace each other both horizontally and vertically. Outside the Mesopotamian Plain, a Quaternary sedimentary veneer of polygene tic origin covers large areas in the synclines of the Foothill Zone. Terraces of the Euphrates and the Tigris Rivers and their tributaries are present along river courses, generally in narrow belts that usually do not extend more than two kilometres on either side of the rivers, occasionally expanding to cover areas over 10 km wide, often preferentially on one side of the river. Aeolian deposits are restricted to three belts associated with the Mesopotamian Zone. Alluvial fans also occur along the flanks of the Mesopotamian Zone (Ya'acoub et al. 1981; Baitzer and Purser, 1990). Over half of the territory of Iraq belongs to the deserts of W Iraq in which Quaternary sediments form a thin veneer of desert pavement, or fill local depressions.

This chapter is mainly concerned with the Upper Quaternary sediments of the Mesopotamian plains since they constitute the main aquifer for shallow ground-water reserves and the hypersaline ground water that affects the salinity of the plain. The clays of Mesopotamia are also important for both agriculture and the brick building industry. Valuable archaeological sites of ancient Mesopotamian civilisations are mainly concentrated in this belt.

The Quaternary sediments, most of which are represented in Fig. 15-1 are divided into three categories influenced by the neotectonic development of Iraq. These are:

1. Quaternary deposits of the Stable Shelf which include wadi fills, playas, depression fill, desert pavement, aeolian deposits, salt playas, gypcrete, and karst depression fill.
2. The Mesopotamian flood plain sediments and the associated alluvial fans and aeolian sediments which are the most extensive.
3. Quaternary sediments of the Unstable Shelf which include largely polygenetic fills in wide synclines of the Foothill Zone and river terraces and some depression fill in the High Folded Zone.

Fig. 15-1: Distribution of major Quaternary units



15.1 Quaternary sediments of the Rutba-Jezira and Salman zones

Quaternary sediments of the Rutba Subzone are generally restricted to depressions and wadis. However, a thin veneer of loam with rock fragments covers large areas of the subzone which are not severely dissected by drainage. This veneer forms the Serir plain which represents remnant surfaces affected by deflation.

Wadi fill sediments in large drainage systems such as Wadi Hauran reach thicknesses of several metres and consist mainly of boulders, cobbles and pebbles of limestone. The wadi beds are often partly covered by aeolian sand, trapped by bushes. Large wadis often have terraces. Wadis to the W of Rutba are generally broad and very shallow. They have very low, poorly defined shoulders with remnant ergs. The erg slope sediments pass into the wadi deposits through a zone of gentle pediment. The drainage courses in these wadis are strongly meandering (see Chapter 5, Fig. 5-14).

Playas are mostly restricted to depressions associated with the eastern side of the subzone especially within the Nukhaib Graben. A playa was also described from the Umm Chaimin depression (Chapter 5) near the Jordanian border associated with an explosion-related depression

(see Chapter 5, Fig. 5-6). **In** SW Iraq playas and depressions occur especially at the border of the Rutba Subzone where they are related to karst depressions formed by dissolution of the underlying anhydrites of the Lower Eocene Rus Formation; the largest of these depressions is the 60 km long and 15 km wide Salman depression. Satellite images revealed that some buried meandering rivers exist in the Salman Zone, W of the Salman depression. Numerous channels may also be noted elsewhere within the zone (see Chapter 5, Fig. 5-14).

The Ga'ara depression, 70 km N of Rutba, is an E-W trending feature, about 40 km long and 20 km wide with numerous inlet wadis in the Wand S and one exit wadi in the NE. Inlet wadis terminate in an inclined bajada produced by coalescing fans consisting of boulders and cobbles in the proximal parts. Towards the centre of the depression, some elevated terraces and fresh water carbonates of Pleistocene age are present. Another important depression is the N-S trending Nukhaib Graben where about 18 m of conglomerates (Nukhaib Gravel) were deposited by fans where wadis enter the graben from the W. The exit from this depression is through one valley to the E (Wadi Ubayidh). Aeolian deposits within the Rutba-Jezira Zone are uncommon. 15 km E of settlement K160 (140 km E of Rutba) is a NW-SE trending dune field overlying MioPliocene graben-fill sediments (Ghadaf clastics). In the Salman Zone very wide sand sheets associated with active dunes are common over the Dibdibba plain. They are mostly restricted to NW-SE or N-S trending depressions associated with neotectonic movements along the Euphrates Boundary Fault or the N-S boundary of the Salman Zone with the Mesopotamian Zone near the Kuwalt border.
In the Jezira area of NW Iraq (Jezira Subzone of the Rutba Jezira Zone) thick gypcrete soil and large numbers of salt playas occur. The gypcrete soil varies in thickness from 30 cm in the most elevated parts to over 8 m in depressed areas. Mass wasting of palaeo relief played an important role in the soil development. Gypsum content is usually high in the soil cover of the depressions, averaging 30% and locally exceeding 80%. Salt playas are numerous; some are small and restricted to local depressions. However there are several major salt playas in the Jezira region, these are: 1) The Sunailsla playa which is the largest and controlled by a topographic depression; no detailed work on the sediments of this depression has been carried out. 2) The Bowara playa (which was evaluated for salt production) is located at the Iraq-Syria border and is tectonically controlled by the ENE-WSW trending Khlesia Graben; two further playas are also present along this tectonic trend. 3) The Tawila playa which trends N-S and is located along a flexure in the dip of the strata at the contact of the Fatha and Injana formations; a broad depression in E Syria lies to the W of this flexure.

15.2 Quaternary sediments of the Mesopotamian Zone

The Mesopotamian Plain begins NW of Baiji as a narrow area between the Makhul range in the NE and Wadi Tharthar in the W. It gradually broadens to the SE where it is bounded by the Hemrin anticline in the NE, and by the Salman Zone in the Wand SW (along the Abu Jir and the Euphrates Boundary faults). It stretches to the Arabian Gulf, covering an area of about 110,000 km^2. It is a vast lowland with a relatively flat surface sloping from 155 m ASL near Baiji to 30 m ASL near Baghdad to sea level at the head of the Arabian Gulf about 700 km S of Baghdad.
The climate of Mesopotamia is semi-arid with maximum temperatures up to +53°C in July-August and a minimum temperature of - *T'C* in January. Average annual precipitation is 150 mm/year (mostly occurring from November to March) and can reach 250 mm/year near Jabal Hemrin in the NE. It falls to <100 mm/year towards the desert in the SW causing generally semi-desert to desert climatic conditions.

The prevailing wind is generally northwesterly and dry for about 300 days of the year turning to southeasterly and humid for about 60 days.

The Mesopotamian Plain was historically lush but is now generally barren; palm trees and bushes densely cover narrow belts of natural levees rimming the Euphrates and Tigris Rivers courses and artificially irrigated areas. The discharge of the Euphrates and Tigris varies from several hundred m^3/sec to about 80000 m^3/sec in spate. Within the Mesopotamian Plain, the Euphrates River has no tributaries whereas the Tigris has left bank perennial tributaries (Adhaim and Diyala, and the periodic Badra, Djangalah and Tib Rivers). All these rivers are major agents in the development of the plain. A dense network of irrigation canals has significantly affected the natural primary sedimentation. The micro-relief of the generally flat plain controls the recent development of the region. The variation in amplitude of the land surface of only a few metres can cause devastating floods.

The Mesopotamian Plain also comprises a lake/marsh complex (Ahwar in Arabic) in S Iraq comprising the ancient Tigris-Euphrates-Karun Delta, and modem tidal flats and the Shatt Al-Arab/Karun estuary/delta. At the present time, most of the Lower Mesopotamian Plain is a flat broad area covered by shallow fresh-brackish water lakes (usually <3 m deep) which are surrounded by extensive vegetated marshes. The low and flat nature of the area, which is sometimes below sea-level, makes it prone to extensive flooding in spring time.

The thickness of the Quaternary deposits in the Mesopotamian Plain exceeds 250 m (Fig. 15-2). The upper part of the sequence (mostly of Holocene age) comprises fluviatile flood silts and aeolian silts (Philip, 1969; Kukal and Sa'adalla, 1973) which are palaeontologically difficult to differentiate from Pre-Quaternary deposits (Raji and Salman, 1983). However, the Quaternary sediments are unconsolidated and usually finer grained than the

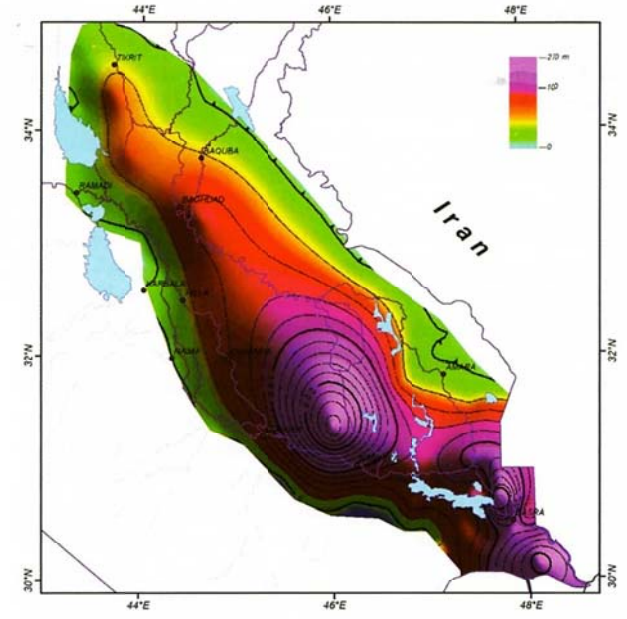


Fig. 15-2: Thickness of the Quaternary alluvial fill of the Mesopotamian Zone derived from oil wells and deep survey wells

Underlying pebbly sandstones of the Dibdibba or the Mukdadiya and Bai Hassan (L and U Bakhtiari) or Injana (Upper Fars) formations (Bellen et al. 1959; Naqib, 1967; Al-Siddiki, 1978). Holocene marine and brackish sediments occur only south of the line between Amara and Nasiriya (Lees and Falcon, 1952, Hudson et al. 1957, Ya'aroub et al, 1981, Al-Azzawi, 1986, Aqrawi,

1993a, 2001). Surface sediments of Mesopotamia are of Recent age; older sediments were penetrated in numerous boreholes (> 100 m deep) sunk by GEOSURV to study the Mesopotamian Plain. The sediments of the Plain can be divided into Plio Pleistocene, Pleistocene and Holocene deposits, largely on the basis of heavy mineral corrosion.

15.2.1 Plio-Pleistocene (Mahmudiya Formation)

The Mahmudiya Formation, introduced by Domas et al. (1983) comprises the Plio-Pleistocene deposits of the Mesopotamian Zone. The formation has been drilled in many boreholes in a large area stretching from the N part of Upper Mesopotamia near Mukdadiya to Baghdad and as far S as Kut and Diwaniya. The formation lies at an average depth of around 20 m in the area near Mukdadiya, 30 m near Baghdad and at about 140 m near Diwaniya. The Plio Pleistocene deposits were differentiated by their heavy minerals assemblages and the degree of heavy mineral corrosion (Minarikova, 1979).

Some fine-grained beds are rich in microfossils, especially ostracods such as: *Candona, Cyprideis, Cyprinotus, Ilyocypris, Darwinula* and *Limnocythere.* Pleistocene ostracods include: *Candona cf Baiatonica* (Daday), *Darwinula dadayi* Nemes and *Candona cf elegans* Nemes.

Quaternary ostracods includes: *Candona cf neglegta* Sars, *Candona cf such* Hartwig and *Candona cf angulata* MUller. The beds contaln freshwater gastropods, *Planorbis, Lymnea, Melania* and *Viviparus.*

15.2.2 Pleistocene

15.2.2.1 River terraces

River terraces occur within the upper reaches of the Mesopotamian Plain. They extend into the Foothill Zone and the Jezira Subzone in the valleys of the two main rivers, the Tigris and Euphrates and their tributaries. Four main terrace levels are associated with the Euphrates River at about 10-13 m, 17-25 m, 30-36 ***m*** and 60 m above river level. They extend into the Mesopotamian Plain as pebbly deposits forming the mesa caps near Falluja and Iskandariya. Deposition of these terraces is attributed to Pleistocene climatic oscillations when periods of vertical erosion by rivers alternated with periods of aggradation. Gypcrete formed on terrace surfaces as a result of pre Holocene soil-forming processes, due to Pleistocene climatic fluctuations. The lowermost terrace level may have formed during the WUrm stage of the Alpine stratigraphic scale. The higher terraces could be equivalent to the Middle and Early Pleistocene periods. The relative altitudes of the terrace stages correspond with groups **I,** IVa, IVc and V of the Euphrates in the stretch between the Iraqi-Syrian border and Khan AL Baghdadi which has been attributed to the Plio Pleistocene, Middle Pleistocene and Late Pleistocene periods (Tyracek, 1987).

In the Tigris River valley, terraces are more prominent. Four Pleistocene terraces were described by Jassim et al. (1997,

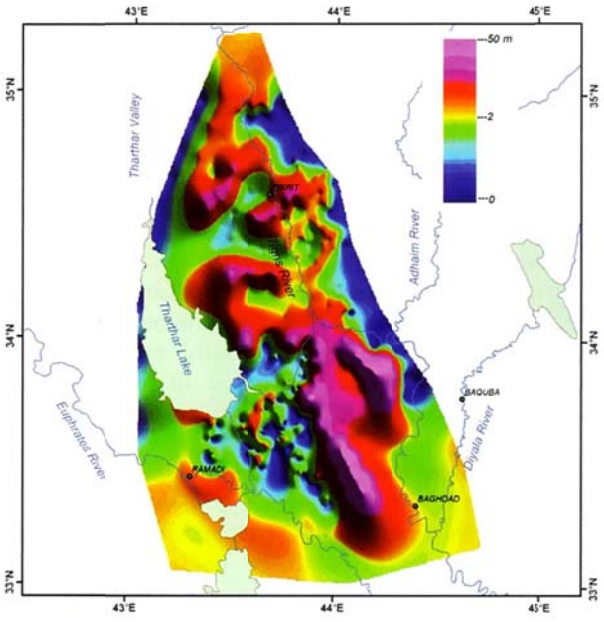
1999) at elevations of 95 m, 65 m, 35 m and 12 m above the present river level. These levels are well established between Mosul in the N and Fatha in the S. Jassim (1981) correlated the gravel fan between Baiji and Baghdad with the highest and oldest of the terraces. The terraces S of Mosul occur almost exclusively on the left (eastern) bank of the Tigris River in a zone up to 10 km wide. On the right bank, the river has been incised into the bedrock of numerous anticlines that plunge towards the river restricting the river flood plain to the east. A similar number of terrace levels can also be identified along the Greater and the Lesser Zab Rivers.

The composition of the terraces of the Tigris River in N Iraq is dominated by quartzite derived from the Palaeozoic Cambro-Ordovician formations exposed in the Ora Zone and SE Turkey and by carbonates derived from Mesozoic formations. **In** NE Iraq significant proportions of chert pebbles occur. **In** both the river terraces and the flood plain of the Tigris River in N Iraq, the sediments are very coarse (up to cobble size) indicating the Tigris was a high capacity river in N Iraq during Quaternary time.

In NE Iraq, the terraces of the Rowanduz and Sirwan rivers are often restricted to narrow valleys. However the highest river terrace usually extends for a significant distance from the present day river course and could be confused with the conglomerates of the Bai Hassan (D Bakhtiari Formation). However, the conglomerate beds of the Bai Hassan Formation are usually folded. The terrace conglomerates have a high content of carbonate pebbles (>70% of the rock) whilst the Bai Hassan conglomerates have <30% carbonate pebbles. The Pleistocene fluvial deposits comprise sand and silt with varying amounts of gravel and clayey silt. The gravels are generally of pebble size, derived from the Zagros Mountains. The gravels are composed of abundant chert, carbonates, basic, ultrabasic and metamorphic rock pebbles; frequent clay balls with a diameter of 20-30 cm occur.

Gypcrete horizons within fluvial layered sequences may indicate a hiatus in fluvial deposition. The basal part of a uniform terrace body was probably deposited at the end of a pluvial period and the upper part during the beginning of the following pluvial period. The gypcrete horizons would have formed during an intervening warmer inter-pluvial period (Sibrava, 1964).

Fig. 15-3: Thickness of the Fatha-Baghdad alluvial fan after Jassim (1981a)



15.2.2.2 Alluvial fans

15.2.2.2.1 Tigris River Alluvial fan of Northern Mesopotamia

Tilted terraces locally occur where rivers enter the Mesopotamian Plain from the east (due to folding) for example at Fatha where a terrace dips at 11^0 SW towards the Mesopotamian Plain. These tilted conglomerates can be traced into the highest terrace level N of the point of entry into

the plain. Jassim (1981) suggested that the gravel body between Fatha and Baghdad represents an Early Pleistocene fan produced by the Tigris River where it enters the Mesopotamian Plain. The fan is generally well exposed along the Tigris valley from Fatha to Samarra and along the eastern cliffs of the Tharthar depression. The fan is usually covered by a veneer of gypcrete, <1 m thick. The fan disappears below the Quaternary deposits of the river which produce a wide plain south of Balad. It is encountered in boreholes at depths of 18-25 m near Baghdad.

The fan was mapped using data from hundreds of seismic shot holes and hand-dug wells (Jassim, 1981). The thickness of the fan in the N part of Mesopotamia (Fig. 15-3) shows that it extended to Falluja on the Euphrates River, suggesting that branches of the Tigris and Euphrates rivers met in that region during the Early Pleistocene. The isopach maps (except in the west) show channels of N-S and E-W orientation in the N part of the fan and N-S orientation in the S part. Channels thicker than 40 m are present N and NW of Baghdad. In the W part of the fan south of the Tharthar Lake, the channels are truncated by a younger channel system (up to 10 m thick) probably of Middle to Late Pleistocene age, forming isolated shallow gravel bodies. This younger system is rich in gypsum and is often described as gypcrete.

Gravel bodies are common in Upper Mesopotamia. They occur within three major sedimentary cycles identified in boreholes based on heavy minerals assemblages and the degree of heavy mineral corrosion (Minarikova, 1979). Each cycle is 20-30 m truck consisting of gravel, sand, fine sand, silt, silty clay and clayey silt; gravels disappear towards Lower Mesopotamia. Correlation of heavy mineral assemblages indicates two tectonic phases of deformation that slightly tilted the Pleistocene sedimentary infill.

15.2.2.2.2 Alluvial fan of Eastern Mesopotamia

Alluvial fans on the eastern side of Mesopotamia developed along the boundary of the Foothill Zone with the Mesopotamian Zone from Mandali in the NW to Amara in the SE. They were deposited by ephemeral streams draining the Foothill Zone to the NE. The alluvial fans coalesce to form morphologically impressive bajada up to 15 km wide and 100 m truck. Some individual fans cover areas > 1 00 km-. Older fan bodies are often truncated by younger ones. Poorly sorted coarse deposits of cobbles and sometimes boulders occur in apical parts passing into finer grained, better sorted, layered fluvial sediments. The outer rims of the fans consist of sand and silt. The clastics generally contalns pebbles of siliceous, carbonate, basic and ultrabasic rocks.
The alluvial fans are the product of several cycles of sedimentation. The oldest fans were deposited near stream outlets from Jabal Hemrin, and the younger fans lie further downstream. The surface of the older fans is generally weathered (due to a warmer and more humid climate in the past) and consists of a veneer of red clay and coarse particles coated by desert varnish. Gypcrete also developed on the surfaces of some fans. Based on the mutual position of the individual fans, their superposition and the degree of weathering of their surfaces, four stages of deposition can be differentiated. These can be correlated with major Plio Pleistocene climatic oscillations.

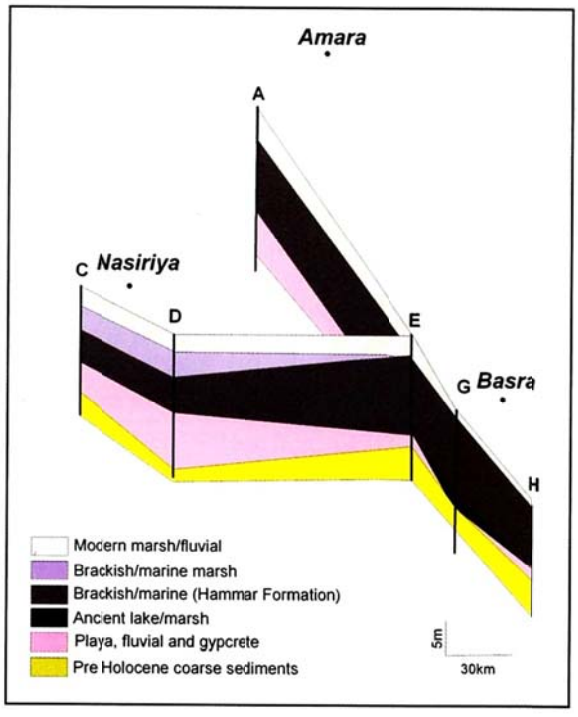
15.2.2.2.3 Alluvial fan of Western Mesopotamia

Alluvial fans in W Mesopotamia are supplied by desert drainage that reaches the Mesopotamian plain. They are located along the Euphrates Boundary Fault where a sudden drop in gradient occurs. A fan near Najaf, originates from Wadi Ubayidh in the NW and another near Zubair, from the Wadi Al Batin in the SE. along the SW side of the Mesopotamian flood plain, three sandy areas and exposed sand terraces occur near Nasiriya in the S, and near Karbala and Falluja in the N. These fans comprise quartz sands with a heavy mineral assemblage of mostly rutile and zircon; these heavy minerals are common in Palaeozoic and Mesozoic clastics exposed to the Wand SW.

15.2.3 Holocene

Sediments of Holocene age cover the Mesopotamian Plain. They comprise fluvial and lacustrine deposits. The natural processes forming the Mesopotamian Plain have been modified by human activities for several thousand years. Many artificial irrigation canals have behaved as rivers, eroding the original sedimentary cover of the plain. The boundary between the Pleistocene and Holocene deposits is based on lithological criteria since age diagnostic fossils are absent. Pleistocene sediments are generally coarser since they were deposited during a more severe climate during alternating pluvial and inter pluvial cycles. The correlation of the Holocene units in the S part of Mesopotamia is shown

Fig. 15-4: Correlation of the Holocene units of Lower Mesopotamia after Aqrawi (2001)



15.2.3.1 Sedimentary environments

15.2.3.1.1 Fluvial, fluvio-lacustrine and lacustrine deposits The Holocene deposits of the N part of the Mesopotamian Plain occur in valleys of the Euphrates and Tigris Rivers in the Falluja and Balad areas in the NW and N respectively, building up a flood plain which progressively widens to the S. Typical flood plain sediments consist of "loam": a mixture of clayey silts and silty clays. **In** the flood plains of both rivers several morphological flood plain stages are developed due to cycles of aggradation and erosion. Morphologically two stages are most prominent. **In** the Euphrates River these stages are 4-6 m and 7-8 m above the river level; in the Tigris River they are 3-4 m and 5-6 m above the river level. At the base of the 5-6 m stage of the Tigris flood plain near Balad a remnant of an ancient brick wall was found which confirms a Holocene age. The elevations of these stages gradually reduce to the SE; south of Baghdad they disappear below ground level. Cyclic deposition of Holocene sediments is indicated by up to four fossil soil horizons in outcrops of flood plain sediments.

These pale red soil horizons are 0.3-0.5 m thick and formed of relatively well aggregated loamy sediment.

The most typical depositional model for Upper Mesopotamia from Falluja and Balad southwards involves interfingering natural levee, flood plain and flood basin environments. River floods have controlled the geological development of the plain. Natural levees form by fluvial deposition on river banks and comprise fine sand and silt. Crevasse splays participate in aggradations of levees; water streams running through breaches in the levee walls deposit fine sand and silt in fan-like accumulations which can extend for several kilometres.

Depth slicing was used to analyse the architecture of the Holocene sediments. Four metre depth spans (in the upper 20 m) were studied from tens of wells in the Mesopotamian Plain. However in the central parts of the basin, the 4 m interval represents a much shorter time span than in areas at the margin of the plain; the depth spans thus *should not* be assumed to be time spans. The sand isoliths of these depth spans is shown in Fig. 15-5; areas of high sand isolith values correspond to stacked channels. The supposed channel trends for all intervals are summarized in Fig. 15-6. The channels of the Tigris and Euphrates migrated through time, at times approaching each other S of Baghdad. The Diyala River did not join the Tigris at its present position but at a distance of about 60 km to the S. The high sand isolith values on both margins of Mesopotamia are related to flanking alluvial fans.

Fig. 15-5: Sand isolith maps for five 4 m intervals within the upper 20 m of the alluvial fill of the Mesopotamian Zone based on data of GEOSURV for tens of shallow wells (located in Fig. 15-4) in Mesopotamia

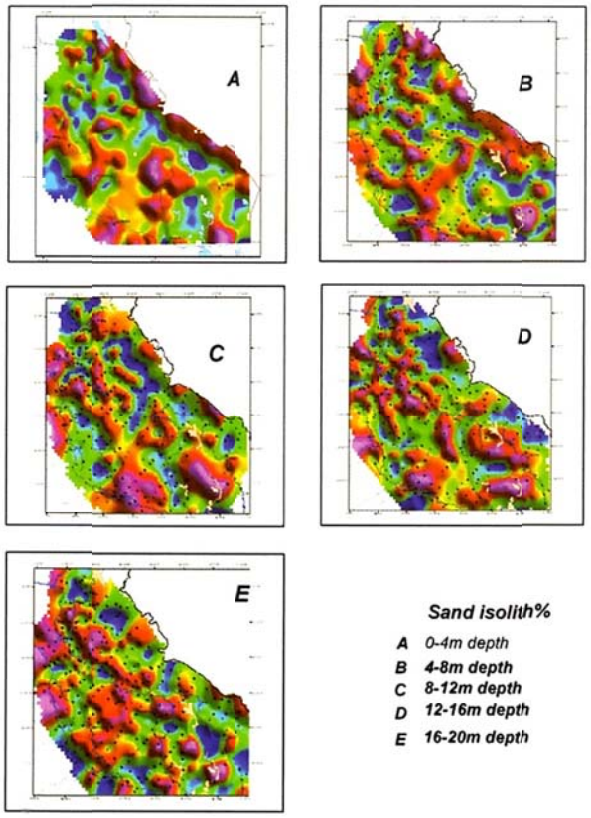


Fig. 15-6: Summary of the assumed buried channels in Mesopotamia based on sand stacking of Fig. 15-5

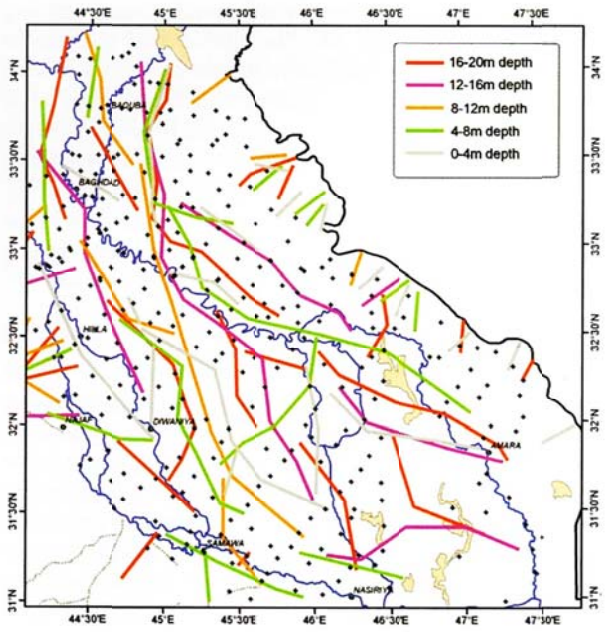


Table 15-1: Heavy minerals in samples of: Diyala River (1), Tigris River (2), Euphrates River (3), Adhaim River (4), Fluvial terraces, Falluja Mesa (5) and fluvial terrace, Iskandariya Mesa (6)

Sample No.	1	2	3	4	5	6
Number of samples	8	26	12	10	1	1
Heavy fraction%	0.87	7.42	7.66	3.55	----	----
Magnetic fraction	23.63	12.68	16.4	9.11	----	----
Opaque minerals	13.64	15.50	15.26	19.21	35.7	16.9
Alterite minerals	8.85	11.35	20.07	15.65	11.0	10.4
Fragments of rocks	17.91	11.33	7.74	20.12	6.3	16.7
Zoisite-epidote gr.	19.99	18.87	17.03	31.72	8.8	20.4
Hornblende common	9.73	14.22	10.82	3.12	7.1	8.6
Hornblende brownish	2.71	2.39	2.52	0.90	1.9	3.2
Tremolite-actinolite	0.44	1.27	0.86	0.12	0.6	----
Ortho-pyroxene	2.80	1.62	1.18	0.09	1.0	2.7
Augite, diopsid-augite	11.40	11.82	14.60	0.9	16.2	16.7
Titan-augite	3.71	1.61	1.13	0.14	0.3	3.2
Whitish pyroxene	0.34	0.78	0.78	0.18	0.3	2.3
Rutile	0.087	0.18	0.12	0.23	0.3	----
Zircon	0.037	0.24	0.21	0.33	0.6	----
Tourmaline	0.11	0.22	0.06	0.13	0.3	0.5
Titanite	0.90	0.53	0.31	0.48	0.3	----
Garnet	1.35	6.19	5.12	3.52	6.2	2.7
Andalusite	----	0.054	0.092	----	----	----
Sillimanite	----	0.10	0.22	0.05	----	----
Kyanite	0.075	0.15	0.28	0.11	0.3	0.4
Staurolite	----	0.12	0.26	0.11	----	0.4
Chromite	0.24	0.44	0.33	0.47	----	----
Chlorite	1.60	0.88	0.76	1.81	----	----
Barite-celestite	3.70	0.088	0.19	0.43	----	----

Flood plain sediments gradually pass into flood basins containing lacustrine to fluvio-lacustrine silty clays and clays. Dark-coloured (dark grey to black) marsh deposits also occur in this sedimentary environment. They comprise layers of silty clay and clay, typically 10-20 cm thick but sometimes up to I m thick. The lacustrine sediments often have a greyish tint due to increased contents of organic matter and traces of biological activity. The upper parts of the thicker layers are sometimes weathered. Near Falluja and Balad some of these horizons represent fossil soils. Organic rich deposits (sub-aquatic marsh soils) also occur in ox-bow lakes along both major rivers. The thickness of the flood basin sediments can reach several metres but in buried ox-bow lakes dark marshy deposits are up to 30 m thick as proven by a borehole near Baghdad. These ox-bow lakes may represent abandoned over-deepened channels of the Tigris River. Lacustrine sediments bounded by irrigation channels also occur in shallow depressions away from the rivers. They extend for considerable distances from the canals and may have been deposited by tall waters of the canals. These sediments are generally coarser grained than the sediments of river flood basins and have a higher silt content.

Salt crusts (Marnlaha in Arabic) frequently form in some river flood basins and shallow depressions with shallow saline groundwater (see Chapter 19) due to capillary action. Salt efflorescence appears in the morning but is usually blown away by winds during the day. Salt efflorescence is a precursor of a saline soil formation. Basins and depressions filled by deeper water during the rainy season dry out in summer and leave behind salt crusts which contain a mixture of chlorides but consisting predominantly of rock salt.

Flood basins are developed on both sides of the Tigris for most of its length in contrast to the Euphrates. This is because the former trough of the Euphrates was located further to the NE near the ancient settlement of Nippur. It did not shift to the Shatt al-Hilla until later. Another change in the course of the Euphrates River to its present day position occurred during construction of an irrigation canal bringing water from the Euphrates to Karbala; due to lack of knowledge of the river gradient the canal was over-deepened and it tapped the Euphrates.

The sediments of the different rivers that flow into the Mesopotamian Plain can be differentiated using heavy mineral assemblages (Minarikova, 1979) (Table 15-1). The Diyala River sediments have a significantly higher content of the magnetic fraction and rock fragments. The zoisite content is highest in the Adhaim River. Both the Tigris and Euphrates rivers have high contents of metamorphic minerals such as garnet (common in the Anatolian massifs); as do the Falluja terraces which are probably related to the Euphrates River.

15.2.3.1.2 Run-off and ephemeral/periodic deltas (fan) deposits

The NE Upper Mesopotamian Plain lies between the peripheral parts of alluvial fans and the left bank flood basins of Tigris. The foothill of Jabal Hemrin is drained by many periodic and ephemeral streams that flow across the run-off plain with anastomising branches, forming intricate patterns of shallow rills. Bigger streams may reach the Tigris left bank whereas smaller ones spill their tall water within the run-off plain. During the rainy season, these streams flood considerable parts of the run-off plain forming a thin sheet of water transporting sediment (eroded from the foothills and alluvial fans) down the plain to the Tigris flood basins. These sediments are generally reddish-brown fine sand, silt and clayey silt. The tall waters create morphologically unimpressive low relief deltas (fans) on the run-off plain. Deltaic sediments deposited by streams reaching flood basins have a higher content of clays and are interbedded with lacustrine sediments.

The depressions also contain playa deposits. In Lower Mesopotamia, dolomite samples from playa sediments, based on their oxygen and carbon isotope values (-0.731 to -17.693% PDB of $\delta^{13}C$ and from 6.491 to +4.452 % PDB of $\delta^{18}o$), were formed in brackish water or evaporitic environments (Aqrawi, 1995b). The low carbon isotope values may be due to organic enrichment of CO_2 or methane oxidation by sulphate reducing bacteria during the formation of dolomite. The lower oxygen isotopic values have apparently been caused either by water depleted in $^{18}0$ or by the influence of meteoric water. The dolomites have relatively high calcium content (Ca 54-61 % and Mg 44-39%). Microcrystalline low-Mg calcite associated with calcic dolomite and high-magnesian-calcite is restricted to a brackish environment with limited supply of Mg"" and a high input of freshwater. The last phase of authigenic carbonate mineral formation, which begins with dolomite and continues with low-Mg calcite, via high-Mg calcite is probably related to marine incursion into Lower Mesopotamia. In some ancient playas the Magnesium ions were probably supplied either by groundwater infiltration or by enrichment due to evaporation of ponds (or lakes) during periods of drought or hot summer seasons. The water of both Lake Hammar and the Tigris and Euphrates rivers has a relatively high content of Mg+ Z, SO-z and HCO-3 compared to world standards (Aqrawi, 1993a).

15.2.3.1.3 The Ahwar (i.e. lacustrine and marsh) sediments

The marshes (Ahwar in Arabic) contain a complicated network of channels passing through reed beds forming open lakes and reed islands. These marshes are dominated by sediments rich in *Phragmites sp.* and *Typha sp.,* especially in the relatively fresher waters towards Amara in the NE. The salinity and temperature of the lakes fluctuate seasonally. The water of the freshwater lakes (such as Lake Zechri and Lake Baghdadi) have salinities of <I $‰_0$ in winter rising to <10$‰_0$ in summer. In the brackish-water lakes (such as Lake Hammar) the salinity is not < 5$‰_0$ in winter and is up to 20$‰_0$ in summer. The pH fluctuates between 7 and 8 in the freshwater lakes and from 8 to >9 in the brackish-water lakes. The Lower Mesopotamian plain is dominated by fresh, brackish and relatively saline lakes with surrounding marshes traversed by fluvial channels with associated levees and crevasse-splays, which pass into an estuarine sabkha and intertidal belt along the coast. Draining and reclamation of parts of the area (for oil industry and irrigation purposes) has strongly affected the environment of the marshes. These marshes/lakes are a natural habitat for many species of fauna and flora.

The marshes of the Mesopotamian plains can be subdivided into three major types (Al-Khattab, 1967). The Suziana marshes are located in brackish water or evaporitic environments such as Hor Al-Huwaiza E of the Tigris River and SE of Amara. The Middle marshes are located between the Tigris and Euphrates rivers Sand SE of Baghdad. The Chaledonian marshes such as Hor Al-Hammar occur along, and to the S of, the Euphrates River ESE of Nasiriya.

Peaty horizons which formed in freshwater lakes and marshes mainly occur below brackish/marine sediments. The peat thus accumulated prior to the middle Holocene transgression. Higher sedimentation rates and anoxic conditions may have enhanced peat preservation. Climatic changes in the Early Holocene may also have led to the preservation of the organic matter older than 8000 years (Aqrawi, 2001). Organic rich sediments occur at depth of 20-30 m in wells near the modem shoreline of the Arabian Gulf (Godwin et al., 1958 and AlZamel, 1983). Organic-rich coastal marshes sediments with TOC > 1 % have been dated as about 500 years old in the W marginal parts of Lower Mesopotamia.

The surface sediments of the marshes consist mainly of sandy or clayey silt (Aqrawi and Evans, 1994). The sandy fraction is derived from shell fragments, or from aeolian dune and mobile sands in the SW (Aqrawi, 1993c). Marsh sediments rich in organic matter are generally black to grey to olive green in colour. They overlie yellowish grey and olive-coloured sediments down to I m depth. However in the E parts of Lake Hammar and Lake Shafi, 20-30 cm of grey marsh/lacustrine sediment overlies brownish red alluvial mud (Aqrawi and Evans, Op. Cit.). This mud was probably deposited on ancient levees of the Shatt AL-Arab estuary or in the ancient Karkha River delta. The Karkha River formerly flowed from the Iranian plateau into the marshes NE of Basra like the present day Karon river further S, which joins the Shatt Al-Arab S of Basra, i.e. at Siba.

The following sedimentary units can be distinguished in the near-surface studied sections of the area (Aqrawi, 1993a, Aqrawi and Evans, 1994): an upper organic-rich silty unit (0-15 cm depth), a shelly silty unit (15-45 cm depth) dominated by molluscs shell-fragments, and a lower unit of grey silty-clay or clay found at depths >45 cm. The lower unit passes laterally into reddish-brown alluvial clay. The middle and lower units are exposed in the western uplifted margins and in some dredged channels in the east near Lake Hammar and its marshes. Most parts of the marshes (except in the NE) appear to contain <0.5 m of modern lacustrine/marsh sediments; the fine clastic

components of these sediments are supplied by aeolian dust fall-out and from fluvial suspended fluvial loads.

In the modern environments of the marshes predominantly organic matter is deposited (remains of reeds and other plants). In some sections of the NE parts of the area, especially in Lake Zechri and the surrounding marshes, deposition of alternating organic-rich and shelly layers indicates periodic supply of fluvial sediment. The main source of sediments for the NE area is the Tigris channel system while the Euphrates River and its associated crevasse-splay channels are the main source of sediment supply for the rest of marshes.

The marsh sediments are usually laminated. Bioturbation characterises the sedimentary units and is most dominant in the lacustrine part. Plant roots, especially reed roots, penetrate to depths of> 30 cm. Clastic sediments in the lakes and marshes consist of clayey silt, clayey-sandy silt, silty sand and sandy clay. Silt generally comprises 50-60% of the total analysed samples, sand 20-27%, and clay 17-22%.
The Total Organic Carbon (TOC) content of the marsh sediments varies from <1 to 15% in both surface and subsurface samples (Aqrawi, 1997). However values of >20% were recorded in modem, extensively vegetated freshwater marshes: A TOC content of >5% is mainly restricted to surface organic-rich layers in freshwater lakes and marshes. In most of the brackish-water lakes and marshes, the TOC of the organic-rich layer is <5%. It is only slightly > 1 % in the more saline surface deposits. Older deltaic sediments penetrated in boreholes have TOC contents of 1-5% (occasionally up to 15%), mainly in organic-rich (peaty) horizons. The preservation of organic matter in surface sediments occurs only in the NE parts of the Lower Mesopotamian Plain (in Lake Zechri and surrounding marshes). Degradation of organic matter has occurred in all areas which have become covered as clearly observed in the reclaimed and dried up lakes and marshes in brackish and saline areas.

15.2.3.1.4 The ancient Tigris-Euphrates-Karun Delta

The regional tectonics of the Mesopotamian foreland basin have influenced the evolution of the delta plain, and continue to do so; sediments are exposed on the W margin of the basin due to uplift and local growth of some subsurface anticlines. However, sea-level and climate changes during the Holocene and differential sedimentation in Lower Mesopotamia are believed to be the main factors that controlled the evolution of the Mesopotamian delta. Neotectonic movements caused local river channel diversions affecting the Euphrates near Medaina and for the Shatt AL-Arab near Siba town (just south of the junction with the Karun). This assessment of the Holocene history of the area is consistent with archaeological findings and historical events, which occurred in the Lower Mesopotamia, since the first ancient civilisations of Sumer evolved (Aqrawi, 1993b, 1995a, 2001).

The ancient Tigris-Euphrates-Karun Rivers delta is located in the SE Mesopotamian Plain. It extends NW as far as Amara and Nasiriya, 200 km from the present shoreline of the Arabian Gulf. It occupied most of the Lower Mesopotamian Plain (Larsen and Evans, 1978; Ya'acoub et al., 1981; Sanlaville, 1989; Aqrawi, 1995a and 1995b).

Syn-sedimentary tectonic movements affected the delta region (Lees and Falcon, 1952; Mitchell, 1957) and neotectonic movements caused river channel diversion (AlSakini, 1986) above oil-field anticlines (Aqrawi, 1993b). The arid delta of the Tigris, Euphrates and Karun Rivers is an

important depositional complex in the Mesopotamian foreland basin (Baltzer and Purser, 1990; Aqrawi and Evans, 1994). It is probably the only modem delta opening into a hypersaline, semi-closed marine basin bordered by a desert (Gunatilaka, 1986). There is very limited published research on the Tigris- Euphrates- Kurun Rivers delta. De Morgan (1900) and Lloyd (1949) suggested that a marine transgression from the Arabian Gulf occurred across the hinterland of the Mesopotamian Plain for a distance at least 200 km N of today's shorelines.
Lees and Falcon (1952) concluded, based on geomorphological and geological studies, that the TigrisEuphrates Delta had grown very little during the previous 85 years. They also related the creation of the lakes and marshes to tectonic movements and floods during the last few thousand years. The presence of brackish/marine deposits (i.e. Hammar Formation) in the Holocene succession of Lower Mesopotamia (Hudson et al. 1957; MacFadyen and Vita-Finzi, 1978) was attributed to tectonic subsidence of the plain. However compaction of fluviodeltaic sediments can locally lead to subsidence similar to the tectonic subsidence which occurs when river mouths alter their points of debauchment (Evans, 1989).

De Morgan's (Op. Cit.) early suggestion of the transgression of the Gulf northwards was revived in the 1970's and later (Larsen, 1975; Larsen and Evans, 1978; Ya'acoub et al., 1981; Purser et al., 1982; Al-Zamel, 1983; Al-Azzawi, 1986; Sanlaville, 1989; Baltzer and Purser, 1990; Aqrawi, 1993a, b and c, 1995a and b, 1997, 2001). These workers assessed the marine transgression in Lower Mesopotamia using geological and sedimentological data. However, more sedimentological and palaeontological chemostratigraphy studies are required to determine the evolution of the Lower Mesopotamian Plain. Radiometric dates of both surface and Holocene sediments of the delta region and Mesopotamian plains are required to support these studies. The offshore and SW areas of the Gulf have been the main subjects of research over the last three decades (e.g. Evans et al. 1969; Purser, 1973; Stoffers and Ross, 1979).

15.2.3.1.5 Marine sediments

Macfadyen (Lees and Falcon, 1952) and Hudson et al (1957) described sediments and marine fauna at levels of 1-11 m below the bed of the Tigris near Amara and at 12 m below sea level near Basra (Hammar Formation-Hudson et al., 1957; Bellen et al. 1959; Naqib, 1967; Macfadyen and Vita-Finzi, 1978). During the last two decades the Hammar Formation has been recorded elsewhere in N Arabian Gulf (AL-Zamel, 1983) and Lower Mesopotamia (Ya'acoub et al., 1981; Raji and Salman, 1983; Al-Azzawi, 1986; Baltzer and Purser, 1990).
The Hammar Formation overlies ancient fluvial, marsh or playa units, (Fig. 15-3) within the main foreland basin. The brackish/marine Hammar and underlying sediments were included in the Hammar Formation by Hudson et al (1957). A Sabkha unit 0.5-1 m thick covers the brackish/marine unit of the Hammar Formation in the western margins (Aqrawi, 1995b), which is equivalent to recent estuarine sediments of the N Gulf, particularly in the western Khor AL-Zubair tidal channel (Aqrawi and Sadooni, 1988).

15.2.3.1.6 Aeolian deposits

Wind blown deposits of the Mesopotamian Plain are confined to three belts. These belts trend NW-SE (Fig. 15-1) and form the recent cover of the upper part of the Plain. The NE belt is the most extensive, extending from Baiji in the NW to Al Tib E of Amara in the SE. It is restricted to a

foredeep in front of Jabal Makhul, Hemrin and Pesht-i-Kuh ranges. The aeolian deposits in the Baladruz and Al Tib areas were derived from alluvial fans; they are often rich in grains which occur in the older Mio-Pliocene molasse. The central belt lies between the Tigris and Euphrates Rivers and is generally rich in gypsum and clayey-crusted grains derived from the sabkhas and depression deposits on which they are often located. The SW belt is located along the SW margin of the Mesopotamian plain at the contact with rocky desert outcrops (along the Euphrates Boundary Fault Zone). The belt comprises narrow longitudinal dune fields, often controlled tectonically by the numerous splays of the Euphrates Boundary Fault. Many of the dunes are active but in places they are fixed by vegetation due to seepage of relatively saline ground water. The sand in this belt consists of quartz and limestone grains derived from outcrops of Eocene and Miocene formations. The belt extends from the Najaf area in the NW to Nasiriya in the SE, swinging S along the tectonic boundary of the Mesopotamian Zone towards Kuwalt. The width of the belt is variable but is usually about 20 km.

Aeolian sediments were and still are one of the main sediment sources for the Quaternary deposits of the Mesopotamian plain, particularly during the latest Holocene, when the climate was more arid and hotter than today. Three types of aeolian sediment are currently found in the southern part of the Mesopotamian plain: dust fall-out, mobile sand without clear forms and dune sand. Dust and its subsequent fall-out is one of the striking features of the whole area of Mesopotamia and N Arabian Gulf, particularly in the summer (Kukal and Saadalla, 1973; Al-Bakri et al. 1985; Foda et al., 1985; Aqrawi and Sadooni, 1988).

The dust is silty, reddish brown and calcareous (Khalaf et al. 1985). It commonly blows all year except during the three months of winter. The transport of the wind-blown dust peaks during the summer, usually in July and August. The concentration of summer dust is related to other climatic conditions such as the absence of precipitation, and higher air temperature that can exceed 50°e. About 10 days per month in summer are considered dusty in S Mesopotamia. The dust fall-out from Basra and Qurna during June-July 1990 (Aqrawi, 1993a) has a clayey sandy silt texture. Sand fractions form <22% of the dust. Microscopic analysis of the sand fractions indicates they are composed predominantly of moderately rounded quartz with calcareous and feldspar grains.

Aeolian sediments are important contributors to the western sides of the Mesopotamian Plain. Storms moving from the SW in the desert often drop their sandy fraction within the depressions along the Euphrates Boundary Fault. Their silty and clayey fractions are then transported further into Mesopotamia with finer fractions forming the dust storms that can travel hundreds of kilometres into SW Iran and Kuwalt.

15.2.3.1.7 Anthropogenic deposits

The central and most inhabited part of the Mesopotamian Plain were periodically flooded. Settlements thus had to provide protection for their inhabitants. They were thus constructed in the form of hillocks and mounds several metres high, locally called "tell". Remnants of those settlements, which became ancient administrative centres, are more than one kilometre across and over 10 m in height. Some of them are still inhabited, for example at Badra. They are built with "loamy" material from the surrounding plain. An enormous quantity of pottery fragments occur in these mounds. **In** many mounds (especially in large ones). remnants of ancient brick walls are often found such as in Babylon, Nippur, Wasit, UruklWarka, Ur, Salman Pak, and Agarguf.

15.2.3.1.8 Irrigation canals deposits

The extensive civilisation of the Mesopotamian Plain was based on intensive agriculture. Irrigations canals, ditches and their walls form prominent micro-morphological features. The plain is criss-crossed by ancient and modem canal systems hundreds of kilometres in length. Most of the ancient canals were abandoned; a few are still in use. Older canals systems are partly eroded; remains of long canal walls are scattered all over the plain. The biggest known historical systems were the Nahrawan and Kharidge canals. The former originated from the left bank of Tigris near Tigris-Adhaim confluence and extended to an area NE of Numaniya (80 km SSE of Baghdad) nearly 300 km away from its inlet. It was hundreds of metres wide with many branches which were used to irrigate the vast flood plain east of the Tigris. The capacity of the Nahrawan Canal proved insufficient, so the parallel Kharidge canal was constructed. The Kharidge canal was up to 2 km wide. Both canals acted as artificial rivers flowing from the Tigris. They were known to flood like the Tigris River with even more catastrophic results. The Kharidge Canal was abandoned soon after its construction; and the Nahrawan Canal was abandoned at a later date. They were used as irrigation canals to spread flood water rapidly over the flood plain and adjacent flood basins far from the main rivers causing catastrophic deluge. Rapid flowing canal streams transported fine sand, silt and clay. Sediments deposited around canals near breaches in the canal walls are generally coarser than the surrounding flood plain sediments. The main canal bodies had many distributaries which were used to irrigate fields. The long-lasting irrigation, and related sediment deposition from the canal water, created small depressions between individual canal branches in which lacustrine clays and silts were deposited. Some depressions became sabkhas through long and repeated irrigation.

15.2.3.2 Fauna

Macrofauna species identified in Lower Mesopotamia (Aqrawi, 1993a) mainly include Thiaridae, Viviparidae and Corbiculidae species. *Bellamya sp., Corbicula sp .. Mellanoids sp., Melanopsis sp., Unio sp.* and *Lymnea sp.* also occur. The same macrofaunal assemblage and other species were reported by Ya'acoub et al. (1981) in Upper Mesopotamia. Harris (1964) also described some fauna of rivers and lakes in central and N Iraq. He found that the concentrations of magnesium, nitrate and bicarbonate in the water appear to exert more control on the molluscan distribution than salinity and temperature. Aqrawi (1993al also reported microfauna usually restricted to foraminifera. ostracods and micro-molluscan shells.

The fauna is mainly limited to the fine and very find sand sizes and is rarely found in the silt fractions. The same species also occur in the surface sediments of the marshes (Aqrawi, 1993b) and in the older Holocene sequences (Aqrawi, 1995a).

Foraminifera which are very common in many borehole sections are usually restricted to a dominant calcareous species of rotaliid: *Ammonia beccarii* (Aqrawi, 1993a). This species indicates brackish environments with marine influence such as brackish lagoons and wide intertidal flats (Murray, 1991). It occurs very frequently in cores of sampling points in the Hammar, Shafi and Luqalt lakes and their surrounding marshes. It also occurs in the lower samples of the other stations in modem fresh water areas. **In** several boreholes this species was found within a shelly biozone with shell fragments and ostracods at different depths intervals within the Holocene Hammar Formation. Other foraminifera associated with the *Ammonia beccarri* are *Elphidum,* rotalids and agglutinated forams; the latter mainly occur in surface sediments of Baghdadi Lake in the S and within the lower parts of core samples of crevasse splay of the Euphrates River.

Agglutinated foraminifera are good indicators of coastal marshes of relatively high salinity. Coastal marshes existed here until very recently but later changed into freshwater marshes and crevasse splays after the elimination of marine influence from Lower Mesopotamia about 6000 years ago.

Miliolids found in only one borehole (E) at depths >15 m shown in Fig. 15-3 are probably reworked. They are associated with other sandy bioclasts in a silty sand facies. This facies is probably of fluvial origin deposited in an ancient Karun River delta. Miliolids were also reported in the modem NW parts of the Arabian Gulf (Aqrawi and Darmoian, 1988, Aqrawi, 1994).

Ostracods are the other common microfauna (Aqrawi (1993a). They are restricted to a few genera of which *Cyprideis* is the most dominant, usually associated with *Ammonia.* C. *torosa* is the most common of the *Cyprideis* species. This species indicates a wide range of brackish estuarine environments (Athersuch et al. 1989). There are also some different types of *Cyprideis torosa* indicating brackish water conditions.

15.2.3.3 Palaeogeographic history of the Mesopotamian Plain

The Mesopotamian Plain was, from the Plio-Pleistocene to the present, a vast subsiding sedimentary basin in which relatively thick Quaternary sediments accumulated. The major rivers, the Euphrates and Tigris, transported the bulk of the sedimentary load although the contribution by the Diyala and Adhaim Rivers in Central Iraq and the Karun River in SE Iraq is also significant. Perennial rivers emanating from the Foothill Zone (dispersing in the plain or reaching the Tigris River from the NE), and wadis reaching the Euphrates River from the W, also contribute to sediment supply. These perennial rivers have produced a series of individual or coalescing fans on both sides of the plain. Aeolian deposition has also contributed to the sediments of the plain, especially at its margins. Human activity has also been a significant factor in the development of the plain in the last 3000 years.

During the Early Pleistocene in the northernmost part of Mesopotamia the River Tigris, after passing the Fatha gorge between Hemrin and Makhul ranges, lost energy in the subsiding foredeep of the N part of the Mesopotamian Plain. This resulted in the formation of a vast gravel fan which extended from Fatha in the N to south of Baghdad. Its eastern limit was the eastern side of the Shari Lake in the E and western limit was probably the Tharthar Fault Zone (Jassim, 1981). Numerous braided river channels have been identified within this fan. The most western of these channels met the Euphrates River near Falluja. These two rivers then flowed through the central part of Mesopotamia where finer grained deposits of the Mahmudiya Formation were deposited.

One of the branches of the Tigris River was located several tens of kilometres to the NE in Early Pleistocene time as indicated by assemblages of heavy mineral in boreholes and also by the sand isoliths. The Euphrates River may have also been located to the NE of its present course. Both rivers meandered and shifted across the Mesopotamian plain. Pleistocene uplift in the Tigris Subzone shifted the plain to the SW. Pleistocene fluvial and fluvio-lacustrine deposits are coarser grained than equivalent Recent deposits. They were deposited by powerful rivers during the pluvial periods. Deposition was controlled by climatic oscillations; periods of aggradation alternated with periods of weathering in a warm and moist climate with local development of sub aquatic marshes. Alluvial fans were deposited along the SW flank of the Jabal Hemrin. Run-off

plains continuously widened to the SW due to the shift of the Tigris in the same direction. Older terrace deposits and higher stages of alluvial fans were eroded. Two tectonic phases slightly tilted the Pleistocene sedimentary infill.

Pleistocene erosion of pre-Quaternary rocks took place in the peripheral parts of the plain forming mesas, erosional valleys and pediments. Wind and run-off erosion of Pleistocene river terraces and alluvial fans also occurred in Holocene time, providing sediment for fluvial, run-off and aeolian deposits.

Folding began in the Foothill Zone during the Pliocene and continued into the Pleistocene. The boundary of the Foothill Zone with the Mesopotamian zone is defined by one of the longest anticlinal structures in the region (Makhul, Hemrin and Pesht-i-Kuh) which is >700 km long. The anticline was segmented by structural cols (plunges) that were exploited by major rivers, including the Tigris and its tributaries. As these rivers exited the anticlines they passed into a subsiding foredeep; some of the rivers then branched forming alluvial fans which locally coalesced to create bajada plains.

The Pleistocene clastic deposits in Lower Mesopotamia wedge out toward the W margin, where Holocene sediments overlie the Mio-Pliocene Dibdibba Formation. The delineation of the boundary between Holocene and Pleistocene sediments is difficult (Ya'acoub et al 1981; Raji and Salman, 1983).
About 18000 years ago, when the Weichsel-Wisconsin glaciation was at a maximum (Mathews, 1990), sea level was > 1 00 m lower than at present. During the last glacial stage the mouths of the Mesopotamian Rivers may have been located at the shelf margin in the Gulf of Oman (Sarnthein, 1971) with a consequent increase of 800 km in their length (Kassler, 1973). A true delta is not thought to have existed in the Gulf at that time but some lakes and marshes (similar to the modern marshes of S Mesopotamia) may have been formed (Sarnthein, Op. Cit.).

The sea reached the northern end of the present day Gulf about 8500 years ago (Stoffers and Ross, 1979) or 6000 years (Sarnthein, 1971; Al Zamel, 1983). However, Aqrawi (1993a, 1995a and 2001), based on stratigraphic evidence, suggested that 6000 years ago the Gulf shoreline was located near Amara and Nasiriya, 200 km N of the present day shoreline. Melting of the glaciers began 15000 years ago and continued for 8000 years causing sea levels to rise (Falrbridge, 1958) resulting in a warmer and wetter climate. This climatic change affected both the morphology and ecology of the whole region and resulted in deposition of organic-rich sediments in swamps and marshes (Godwin et al., 1958; Al Zamel, 1983). A sample from near Basra (i.e. in borehole G of Fig. 15-4) was dated as 8350 ± 230 years (Aqrawi, 1993a). The end of the last glaciation (about 11000 years ago) was a period of transition and fluctuation, which lasted several thousand years.

Historically, reed marshes occupied extensive areas in S Mesopotamia; reeds were used in building (Oates, 1969) before bricks were made by the Sumerians (i.e. 6000 years ago; Thesiger, 1967). Human habitations around depressions even in W Iraq are believed to have flourished around 8000 years ago (Glushko, 1990). Analysis of available borehole sections (Aqrawi, 1993a) indicates the central and eastern areas of Lower Mesopotamia were dominated by river channels and associated lakes/marshes, particularly along the depositional axis of the foreland basin. Freshwater mud and sands have been described by Godwin et al (1959) from Fao and by Al-Zamel (1983) from Bubiyan Island in the N part of the modern Gulf. Similar deposits occur near Basra (i.e. boreholes F, G and E of Fig. 15-3) and Amara (borehole A of Fig. 15-3). These fluvial deposits contain a

higher proportion of aeolian material towards the W (Aqrawi, 1995b).
A wetter climate in the Early Holocene is indicated by peat (or carbonaceous mud) preserved at depths of about 14 m in Basra (Aqrawi, 1993a and 1997),20-24 m in N Bubiyan (AlZamel, 1983) and at about 30 m in Fao (Godwin et al, 1959). During the wet climate period about 9000 years ago (COHMAP, 1988) locally fluctuating environmental conditions led to the preservation of three levels of peat in Bubiyan Island (Al-Zamel (1983). The same fluctuations for this period have also been reported based on palynological evidence in Iran. Unfortunately, in Iraq, these fluctuations cannot be determined because of the incomplete borehole sections (F & G Fig. 15-3). **In** the Early Holocene different sedimentary environments existed in S Mesopotamia before the marine incursion. **In** the N fluvial environments were dominant. To the S marshes and lakes became increasingly important (Aqrawi, 1995a). The proximity of the desert in the W led to invasion by dunes and mobile sands (Aqrawi, 2001).
A specific geomorphological/hydrological event in the Holocene was the passage of the Euphrates River into the Gulf as an individual channel crossing through the areas of Khor Al-Zubalr and Khor Al-Subiyah (Wilson, 1925). The joining of the Tigris and the Euphrates Rivers in the Early Holocene has not been documented (Aqrawi, 1995a). However the presence of a river, extending along the Gulf axis in Late Pleistocene / Early Holocene time appears well established (Sarnthein, 1971; Kassler, 1973). Most previous workers agree that the Late Pleistocene-Early Holocene rise of sea level slowed down about 7000 years ago (e.g. Godwin, et al. 1958; Falrbridge, 1958; Evans et al. 1969). **In** the last 7000 years, sea-level rose, with oscillations of I-3m (e.g. Falrbridge, 1958).

Aqrawi (1993a) stated that the deposits of the Hammar Formation were the first Holocene brackish/marine sediments to be deposited in Lower Mesopotamia, overlying older fluvial deposits in the east, playa deposits along the W margins, and marsh/lake or ancient marsh deposits along the depositional axis of the basin. The Hammar Formation contains distinctive brackish/marine microfauna of foraminifera and ostracods with marine macro shells (Aqrawi, 1995b). These brackish/marine deposits were then covered by fluvio-lacustrine marsh sediments (0.5-2.4 m thick), with interbedded aeolian sediments in the west, and fluvial deltaic sediments towards the E (Karon & Karkha deltas), NE (Tigris delta) and NW (Euphrates delta). This sedimentary cover is usually thickest along the E and W margins and within the deltas and crevasse-splays of the Tigris (near Amara) and Euphrates (near Nasiriya). It thins within the central parts of the basin at Hammar, Baghdadi and Zechri lakes and marshes where it is <0.5 m thick. The deepest sediments of the studied surface cores and pit sections of the marshes are probably part of the Hammar Formation. They are exposed locally along the SW margins as ancient shelly shorelines (Aqrawi, 1993b).

The limit of marine influence on the Mesopotamian plain is well defined in the west where coastal sabkha sediments occur at a depth of about 2.5 m in boreholes C and D of Fig. 15-3. The peaty intertidal mud beneath the gypsum bearing sabkha beds are dated as approximately 5500 years old. They were deposited with fluvial-aeolian silty sediments in a freshwater marsh/lake, presumably on the deltaic plain of the Euphrates River after the retreat of the sea (Aqrawi, 1995a).
About 5500 years ago the area around Nasiriya was then the heartland of Sumer (Ubaid Period, Whyte, 1961). Soils became saline after 2400 BC when sabkhas formed in S Iraq (Jacobsen and Adams, 1958) and later migrated N (Aqrawi, 1995a).
The best preserved organic-rich layers were deposited just before the deposition of the brackish/marine Hammar Formation, especially within the central areas of S Mesopotamia. The

best preserved peaty horizon in borehole B of Fig. 15-3 was dated as 6500 years old (Aqrawi, 1995b). The present conditions of the Arabian Gulf region became established about 5500 years ago (Stoffers and Ross, 1979). The marine transgression did not extend inland further than Amara and Nasiriya. However, the sediments of the Khors (sea arms) may have been deposited along the Euphrates Boundary Fault in estuaries extending as far NW as Najaf accounting for the historical references to the "Bahr AL Najf' or Najaf Sea.

The rate of sedimentation in Lower Mesopotamia from 8000-4000 years ago was probably higher than at present (Aqrawi 1995b), particularly in the area S of Amara and Nasiriya. The Tigris and the Euphrates here deposited a sequence of deltaic brackish/marine deposits 4-8 m thick. After the retreat of the sea, nearly 4000 years ago, the coastlines of the deltas of the Tigris and the Euphrates were located at Amara and Nasiriya. The salt contaminated land needed desalinisation before it could be used for agricultural purposes. Rulers of Lagash thus dug the world's first canal (the AL-Gharraf canal) in the third mi11ennium BC (Lloyd, 1949). Aqrawi (1993b) concluded that regression of the sea was probably more rapid in the last 5000 years in the higher areas further inland than in the areas in the S. The ages of some exposed shelly sediments of the area indicate that a marine-brackish lagoonal environment dominated the site of Lake Hammar and the surrounding marshes until about 3000 years ago or even later until the Abbasid Era (Aqrawi, 1993b). Most previous studies indicate that sea level reached approximately its present level around 4000 years ago (e.g. Evans et al. 1969). Other authors consider that the present sea level was not reached until 1000 to 2000 ago (e.g. Shepard, 1963; Scholl et al' 1969).

The exposed brackish/marine sediments in Hammar Lake are dated as 3000 years old. They are overlain by a very thin overburden of modem lacustrine sediments (about 0.5 m thick). The modern morphology of Lower Mesopotamia area is thus much younger than 3000 years old (Ya'acoub et a!., 1981; Baltzer and Purser, 1990).

Southern Mesopotamia was probably a wide lagoon or embayment prior to 3000 years ago. Low energy depositional conditions are indicated by laminated mud units in the basal parts of most pit-sections and of cores in the surface marshes (Aqrawi and Evans, 1994). The connection of this embayment to the sea is proven by the occurrence of foraminifera and brackish water ostracods (Aqrawi, 1993b, 1995a and b). The fluvial influence of the Tigris and Euphrates was apparently negligible since most

of their sediments were deposited further N. Sedimentation from the Karun and Karkha rivers to the E of Shatt AL-Arab and from the W alluvial fan of Wadi AL-Batin, created a lateral barrier across the alluvial plains of Mesopotamia in the S. This barrier isolated S Mesopotamia from the open Gulf (Aqrawi, 1993a). The joining of the Euphrates River with the Tigris River at Quma, after the retreat of the sea and then the creation of the Shatt AL-Arab channel, has been attributed to local neotectonic effects (Lees and Falcon, 1952), but it could also have been caused by normal deltaic sediment compaction (Evans, 1988).

15.3 Quaternary sediments of the Foothill and High Folded zones

15.3.1. Polygenetic synclinal fill and depression fill of the Unstable Shelf

The Foothill Zone, especially in the Kirkuk Embayment is characterised by long anticlines with Miocene cores flanked by very broad and shallow synclines exposing Mio-Pliocene molasse along their flanks. The inner parts of the synclines contain Quaternary deposits, referred to here as the Polygenetic Synclinal Fill. The thickness of this Quaternary veneer is variable but is >120 m in some water wells.

These synclines often have a central river system that cuts across, or flows parallel to, their axes. These rivers join the main tributaries of the Tigris (Fig. 15-7). In some synclines, the rivers are braided (often shallow and dry) and periodically flood. The beds of these rivers are often gravel-dominated. Some synclines contain meandering rivers with finer sediments. The catchment of the synclinal rivers is from the flanking anticlines but the main river catchments may extend far beyond the Foothill Zone.

Slope sediments have formed along the flanks of the structures, usually in narrow belts; along high mountains thick accumulations of limestone scree occur. The sediments filling the synclines consist mainly of a mixture of gravel and clay. They form pediment deposits, developed on the flanks of anticlines, passing laterally into river deposits towards the centre of the depressions. Some rivers breaking out from the anticlines produce alluvial fans locally merge to form bajada.

Accumulation terraces occur at three levels along large rivers. They consist of boulders, gravels, sands and clays that are often poorly cemented. Sheet run-off sediments cover flat areas between anticlines and comprise clay, silt and sand, sometimes covered by scattered gravels. Locally developed valley fill deposits, flood plain and sabkha sediments, and sand dunes are also common within the synclinal areas of the Foothi11 Zone.

In the High Folded Zone, Quaternary deposits are restricted to depressions such as the Halabja and Qalat Dizeh depressions where the present day Dokan and Derbendikhan lakes are situated. The deposits in these depressions range from coarse conglomerates on the flanks to sands and silts

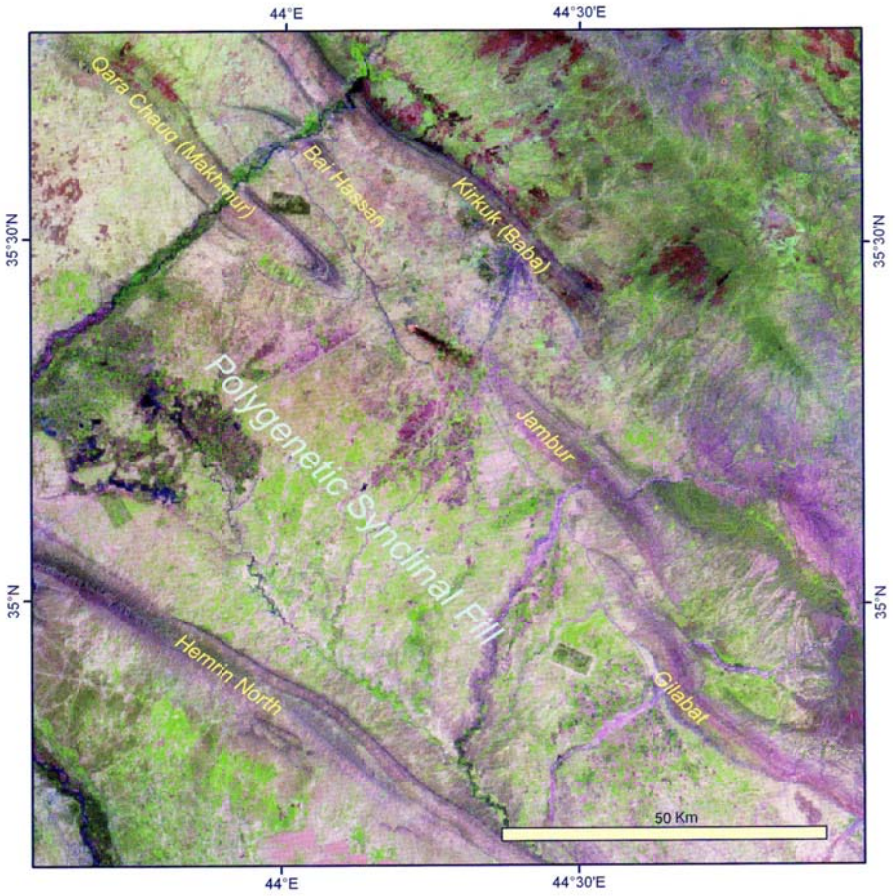


Fig. 15-7: Polygenetic Synclinal Fill sediments of the Foothill Zone

Chapter 16
Tectonostratigraphy of the Zagros Suture

by

Saad Z. Jassim, Tibor Buday, Ivan Cicha and Mojmir Opletal

The tectonic units of the Zagros Suture Zone comprise thrust sheets, which outcrop in a 5-70 km wide belt along the Iraq-Iran border. The widest outcrop of these units is in the Shalair Valley. They were emplaced during Late Cretaceous and Late Tertiary thrusting. Three tectonic zones are recognised in the suture zone each with a characteristic tectonostratigraphy. The tectonostratigraphic units are the product of the complex geodynamic evolution along the Arabian Plate Tethyan margin, which is summarised in Chapter 3. The tectonic zones comprise from the outer part of the suture zone inwards:

1. Qulqula-Khwakurk Zone: This zone comprises deep water passive margin sediments (radiolarian chert and limestone) and volcanics of the Southern Neo-Tethys which opened in Late Tithonian-Cenomanian time; it includes a huge allochthonous block of carbonate interpreted as the sheared off cover of a micro continent. The whole complex was obducted and sutured to the Arabian Plate during the Late Cretaceous. It can be divided into the Qulqula Subzone (deep water passive margin rocks) and the Avroman subzone which represents the allochthonous carbonate unit.

2. Penjween- Walsh Zone: This zone represents the oceanic domain of the central part of the Neo-Tethys and comprises metamorphosed volcanics and sediments of Cretaceous age, and unmetamorphosed Palaeogene fore-arc and volcanic arc rocks that formed during the final closure of the Neo- Tethys.

3. Shalair Zone: This zone is part of the Sanandaj-Sirjan Zone of SW Iran, consisting of a pre-Cretaceous metamorphic basement of largely Palaeozoic pre-Hercynian age, overlain by Triassic rocks (deposited on the Triassic crust of the Central Neo- Tethys) and metamorphosed volcanic arc and fore-arc sequences, of probable Jurassic Cretaceous age. A "Red Beds Basin" formed along the suture zone in Late Maastrichtian-Neogene time.

The stratigraphy of the Zagros Suture units needs further study before formation names can be introduced. The units need to be mapped on a scale of 1: 100,000 and in many areas more detailed mapping is required. Age determinations, both palaeontological and isotopic, and detailed geochemical studies are also necessary to better understand the evolution of the Neo- Tethyan margin. The authors wish to stress that the current stratigraphic terminology of the Zagros Suture units does not comply with the rules of stratigraphic nomenclature. Where the units are very complex and wide ranging in age the term Series is re-used. However, the term "Group" is used for most units. In some cases unspecified terminology based on lithology has been applied (e.g. Darokhan Limestone). The tectonostratigraphic correlation column and chart are shown in Figs. 16-3 and 16-4.

Fig. 16-1: Geological map of the southern part of the Zagros Suture

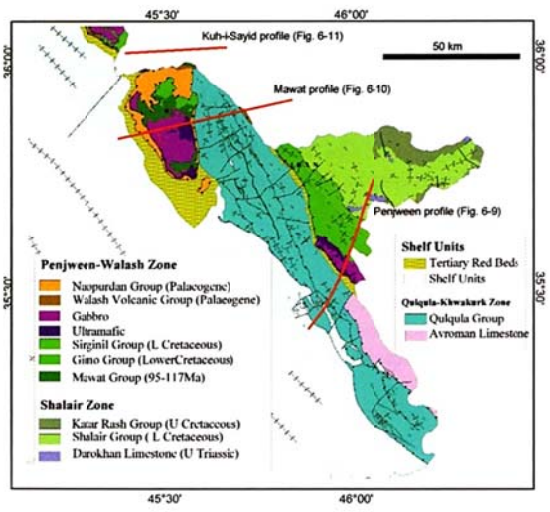
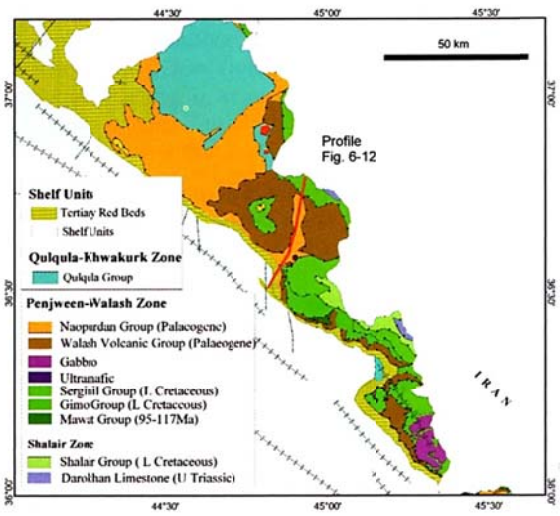


Fig. 16-2: Geological map of the northern part of the Zagros Suture



16.1 Tectonostratigraphy of the Red Beds basin

A thick sequence of clastics unconformably overlies the obducted Neo- Tethyan units and the shelf carbonates of the Balambo- Tanjero Zone. These clastics are generally referred to as the Red Beds Series. They were deposited in a shallow narrow embayment at the plate margin during the Palaeogene and in a strongly subsiding intermontane basin during the Neogene.

16.1.1. Red Beds Series

The Red Beds Series was introduced by Bolton (l958d) for a sequence of clastics with occasional limestone beds, ranging in age from Late Maastrichtian (?) to Pliocene. He divided the Series into the lower Suwais Red Beds, the middle Lailuk Limestone (later called the Govanda Limestone) and the upper Merga Red Beds.

16.1.1.1 Marine and continental foredeep (Suwais Red Beds Group)

The Upper Maastrichtian-Palaeogene clastic deposits of the Balambo-Tanjero and Qulqula-Khwakurk zones have been assigned to the Suwais Red Beds Group. In Iraq, the outcrop of the Suwais Red Beds is narrow due to overthrusting by the Naopurdan Group. The Suwais Red beds were deposited in two basins on either side of the Lower Maastrichtian thrust belt; the north eastern basin is overridden by Miocene thrusts. However an outcrop in the Khwakurk area assigned to the Naopurdan Formation, which unconformably overlies radiolarian chert may be a unit of the Suwais Red Beds. The Suwais Group is up to 1000 m thick in its outcrop area along the base of Qandil range.

The basal conglomerate of the Suwais Red Beds overlies well-dated Upper Maastrichtian *Loftusia* and rudist-bearing limestones identical to those of the Aqra Formation. The Suwais Red Beds are overlain with angular unconformity by the Govanda Limestone (Lailuk) of Miocene age.
The group comprises both flysch- and molasse-type clastics alternating with neritic nummulitic limestones deposited in a trough. The clastics were derived from erosion of the Upper Cretaceous thrust belt and the uplifted Balambo Tanjero Zone. Nummulites occur throughout the group. In the lower part of the group very abundant macrofossils such as large foraminifera, sponges, echinoids,

corals, rudists, large gastropods, and pelecypods occur. Unfortunately no fossil list has been published. The basal beds are similar to the limestones of the Aqra Formation, which contain Maastrichtian fossils that may be ' reworked. The highest beds contain Oligocene fossils. The conglomerates of the middle part of the Suwais may be of Early Eocene and Mid Eocene age.

Within Iraq the Suwais Red Beds correspond in age, and partly in composition, to the Naopurdan Group of the Penjween-Walash Zone into which it they may pass laterally.

The **Suwais I** Red Beds unit comprises lenticular fossiliferous, detrital, and massive conglomeratic limestone beds with red ferruginous shales in the upper part. The Suwais I Red Beds (usually 50-100 m but locally up to 600 m thick) are well developed near Chuwarta and Mawat. They contain numerous indigenous Cretaceous fossils, such as rudists and larger foraminifera of Late Maastrichtian age. The rudist bearing limestones in the Chuwarta area are probably lenses of the Aqra Formation. The fossils collected in the type area also indicate a Palaeocene-Eocene age for the Suwais I unit. In the inner thrust belt units in Iraq, such as the Penjween-Walash Zone, the Piran Limestone (Maastrichtian-Palaeocene age) may correlate with the Suwais I unit.

The **Suwais II** unit consists of flysch with rhythmically interbedded dark red, ferruginous-siliceous silty shales and blue grey siltstones. These sediments locally contain beds and lenticular bodies of conglomerate and very fossiliferous limestones (with abundant redeposited Cretaceous fossils). The indigenous fossils are of Palaeocene-Early Eocene age. Outside the type area, near Chuwarta, the Suwais II unit limestone conglomerates pass into sandy limestones of Palaeocene age. Irregular lenses and beds of polymictic conglomerates are often present (Vejlupek, 1972). The thickness of the Suwais II in the type area is about 300 m. Similar thicknesses were reported from other areas.

The conspicuous dark red colour of the beds may indicate contemporaneous volcanic activity (Bolton, 1958d). Volcanics occur in the Walash and Naopurdan groups to the E with which the Suwais might have an interfingering relationship.

The **Suwais III** unit consists of coarse, partly block-sized conglomerates with abundant chert boulders derived from the Qulqula Radiolarian Formation. Numerous boulders of volcanic and sedimentary rocks of unknown derivation also occur. This conspicuous conglomeratic unit also occurs outside the type area. The thickness reaches 400 m, averaging 200 m in the type area. It unconformably or conformably overlies the Suwais II unit (Ranya area; Bolton, 1958d; Chuwarta area; Vejlupek, 1973; and Mehaldi, 1974). It represents talus sediments or gravel fans (Bolton, 1958d).

Bolton (1958d) assumed the age of Suwais ill to be late Middle Eocene. However, subsequent mapping of the Chuwarta area (Prazak, 1973) showed that the overlying beds are of Late Palaeocene or earliest Eocene age indicating a possible Late Palaeocene age for the Suwais ill unit. However it is possible that the Suwais II beds in Chuwarta are overlain tectonically by the Naopurdan Formation as claImed by Bolton (1958b and Srnirnov and Nelidov, 1962). At this stage the interpretation of Bolton is accepted.

The **Suwais IV** unit in the type area at Merdka and Daruma (Bolton, 1958d) comprises red calcareous shales and sandstones, with layers of reddish or grey nummulitic limestones and conglomerates. The proportion of limestone varies. The lithology is similar in the Herki and Govanda areas (Hall, 1957). In the Chuwarta area, the presence of the Suwais IV is uncertain; the Suwais ill conglomerates are here overlain by red flysch-like clastics containing nummulitic limestones of Late Palaeocene and mainly Early Eocene age which may be part of the tectonically overlying Naopurdan Group (Bolton, 1958b) or Walash Group (Srnirnov and Nelidov, 1962). The

thickness of Suwais IV in the type area is up to 800 m. In the Herki-Govanda area of N Iraq the Suwais IV is up to 220 m thick.

The age of Suwais IV is Eocene-Oligocene; Eocene nummulites (no list of fossils is avallable) were found near Endezah, and Oligocene nummulites were recorded at Mazna (Bolton, 1958d). In the Herki-Govanda area, parts of the Suwais IV were dated as Eocene (Hall, 1958).

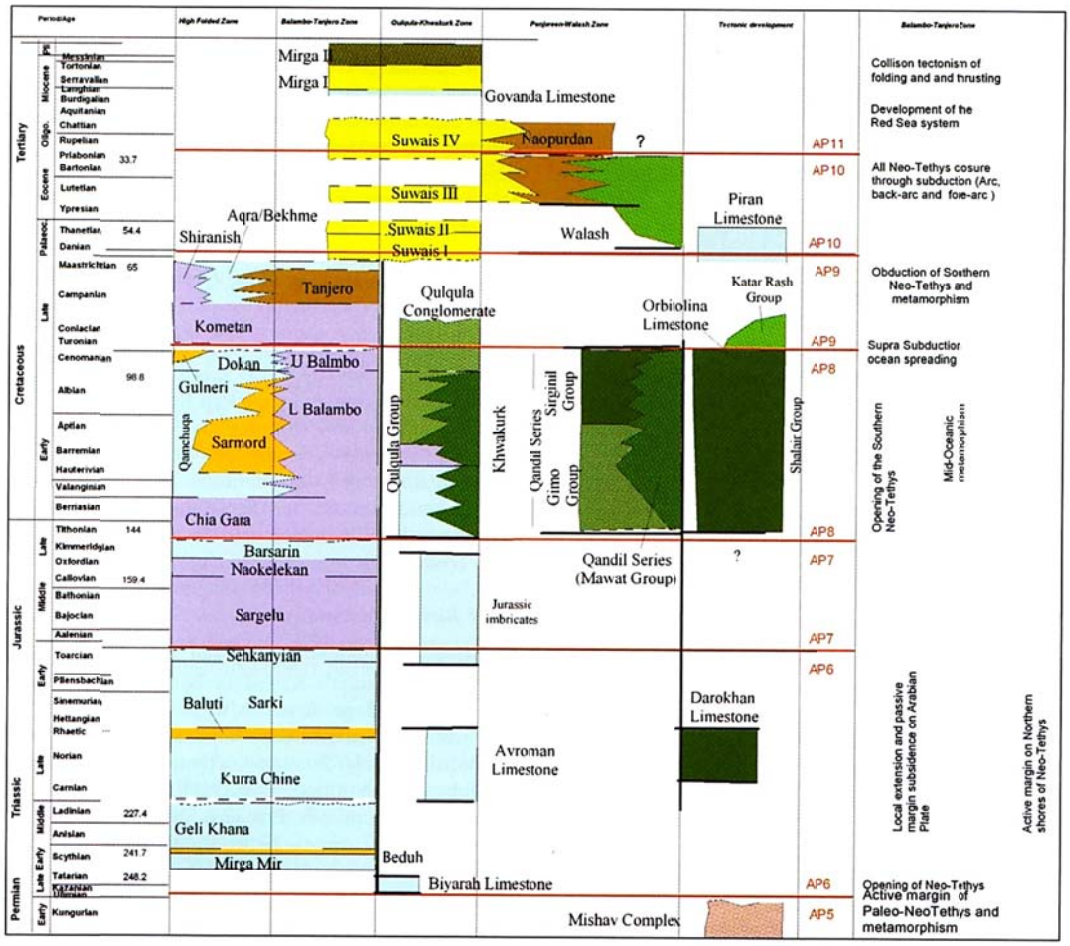


Fig. 16-3: Tectonostratigraphic column for the Zagros Suture zones. Thick lines represent tectonic contact

16.1.1.2 Marine-continental marginal basin (Govanda Limestone)

The Govanda Limestone Formation was first described by Dunnington, Naqib and Morton in 1957 (Bellen et al., 1959). These authors included the Lailuk and Chama Limestone formations (Morton, 1951; Dunnington, 1956) in the Govanda. The type locality of the formation is on the NW slopes of the Govanda Plateau in the Balambo- Tanjero Zone of N Iraq. It comprises a 6 m thick polygenic basal conglomerate with red pebbly sandstone and siltstone, overlain by 20 m of silty and sandy detrital limestones with abundant derived Cretaceous fossils, and 80-90 m of limestone of reef-fore to reef facies. Outside the type area the limestone members are less well developed and vary in thickness. Bolton (1958d) described three to four conglomerate beds capped by foraminiferal and! Or reef limestones with some red shales. The formation is up to 150 m thick in the type area (Bolton, 1958d; Hall 1958) but decreases in thickness towards the SE. In the Ranya area it is less than 10 m thick.

In the Shalair Valley it is up to 100 m thick and composed of a basal conglomerate (containing pebbles of chert derived from the Qulqula Radiolarian Formation) which passes upwards and

laterally into sandy limestone capped by a thick oyster-bearing limestone. The conglomerate is 4-6 m thick, lacks fossils and fills erosion furrows. The sandy limestone contains a rich fauna including: *Chlamys (Aequipecten) scabrella* (Lam.), *Chlamys sardoa* Ug., *Chlamys cf latissima* (De Serr), *Chlamys calaritana* (Men), *Chlamys cf solarium* (Lam.), *Chlamys opercularis* (L.), *Spondylus crassicostata* Lam., *Ostrea sp.*, Veneridae indent., *Cardita cf crassa* Bast, Cypraeidae indent., Lucinidae indent., *Clypeaster latirostris* Hoern, The microfauna includes: *Neoalveolina melo curdica* Reichel, *Meandropsina cf anahensis* Henson, *Amphistegina cf lessonii* d'Orb., *Gypsina globulus* (Rss.), *Ammonia beccarii* (L.), *Nonion pompilioides* (Ficht. et Moll.), *Heterostegina calcarata* d'Orb., *Orbulina suturalis* (Bronnirnann), Recrystallised ostracods and the algae *Archaeolithothamnium, Mesophyllum sp.* are also present. *(Neoalveolina [Borelis] melo curdica* appears to range from late Early-early Middle Miocene lBurdigalian-Langhiani. *Orbulina* ranges no older than Middle Miocene (Langhian). This association is mostly of a bioherm character and is of early Middle Miocene (Langhian) age.

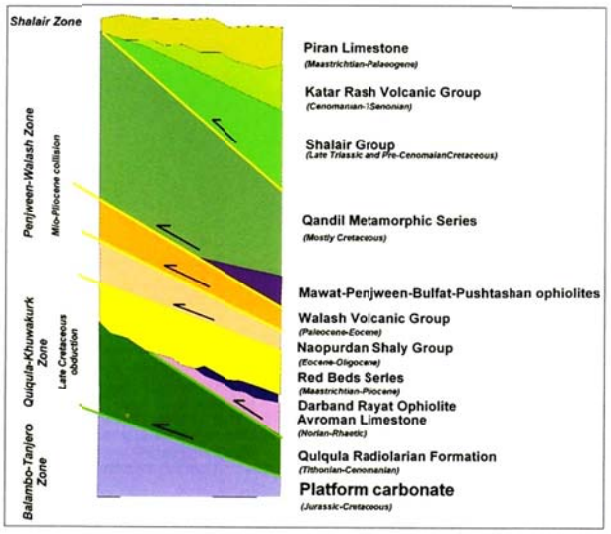
The formation was deposited in shallow marine reef forereef environment, strongly affected by clastic supply from a nearby landmass. The formation unconformably overlies the Tanjero Formation, the Suwais Group and locally the Qulqula Group. The upper contact, at the type locality, is not visible. In other areas the formation passes up gradationally into red shales and sandstones of the Merga Red Beds of Bolton, 1958d). The formation is equivalent to the Jeribe Formation.

16.1.1.3 Intermontane molasse basin (Merga Red Beds Group)

The Merga Red Beds were first described by Bolton in 1958 in the Balambo- Tanjero Zone at the foot of the Qandil Range in NE Iraq, between the Ranya area in the SE and the Rowanduz River valley in the NW. The lower or Merga I unit (Lower Merga Beds) comprises red calcareous silty shales, interbedded with gritty, and locally pebbly, sandstones, which occasionally pass into conglomerates. The overlying Merga II unit consists of massive conglomerates composed of pebbles and boulders of metamorphic and igneous rocks derived from the adjacent Penjween-Walsh Zone. Bolton (1958d) described red shales in Merga II unit. The Merga Group is up to 500 thick. The Merga I unit varies in thickness and is locally absent; the Merga II is usually 200-250 m thick. The formation is only present in the Balambo-Tanjero and Qulqula-Khwakurk zones mainly between the Rikan and Zibar areas in the NW and the Lesser Zab River in the SE, and in the Penjween area where the unit unconformably overlies the Qulqula Group in Iraq and the Avroman-Bisitoun Limestone in Iran.

The Merga I unit conformably overlies the Govanda Formation. The Merga II unit unconformably overlies the Merga I unit (Bolton 1958d). The Merga Group is often overridden by thrust sheets, or covered by high terrace or boulder deposits of Quaternary age.

Fig. 16-4: Tectonostratigraphic position of the Suture Zone units; thrust faults are coloured either in green for those active in the Cretaceous obduction or in yellow for those active in the Mio-Pliocene collision.



The Merga I unit was deposited on littoral tidal flats and in channels (Bolton, 1958d), probably in an estuarine environment. The Merga II unit was probably deposited in alluvial fans. Fossils have not been found in the Merga Group. Bolton (1958d) noted that the Merga I unit is lithologically similar to the Injana (Upper Fars) Formation and to the clastics of the Lower Fars (Fatha) Formation. He assumed a Late Miocene age for the Merga I unit. The Merga II unit is also undated but its resemblance to the Bakhtiari Formation led Bolton (1958d) to assume a Pliocene age.

16.2 Tectonostratigraphy of the Qulqula-Khwakurk Zone

The Qulqula-Khwakurk Zone forms disconnected outcrops overlain tectonically by thrust sheets of the inner thrust zone, or unconformably by the Red Beds Series. The most extensive outcrop area (forming the Naorbab Plain SE of Sulalmaniya) consists mainly of Cretaceous radiolarian chert and limestone with imbricates of Permian, Triassic and Jurassic limestones. These include the Biyarah Limestone (Late Permian) and the Avroman Limestone (Late Triassic).

16.2.1 Biyarah Limestone

The Biyarah Limestone (Buday and Suk, 1978) is known only from the Qulqula-Khwakurk Zone, E of Halabja and near Biyarah village. It occurs as imbricates up to 20 m thick within the Qulqula Radiolarian Formation. It consists of reddish, muddy limestone, crammed with ammonite shells, partly with orthocone shells of Nautiloidea and with rare remains of crinoids. Fractures, cavities and shells are often filled with white calcite. Brown to reddish layers alternate with whitish coarse grained or crystalline limestone. The limestone is micritic, associated with fragments of crinoids, corals, conodonts, ammonites, ostracods and coprolites. It was deposited in an open marine (probably deep water) environment.

The fauna includes: *Boesites sp.* (Moscovian- Sakrnarian), *Neoproorites sp.* (Late Carboniferous-Artinskian), *Synartinskia sp.* (Sakmarian), *Artinskia sp.* (OrenburgianArtinskian), *Eumedlicottia sp.* (Artinskian- Tatarian), *Agathiceras sp.* (Moscovian-Kazanian), *Paragastrioceras sp.* (Asselian-

Artinskian), *Neocrimites sp.* (ArtinskianKazanian), *Stacheoceras sp.* (Artinskian- Tatarian) *Waagenoceras sp.* (Kazan ian) and *Popanoceras sp.* (Artinskian). The age of the formation is thus late Early early Middle Permian, correlatable with the Sakmarian Kazanian of Europe.

The Biyarah Limestone may be equivalent to the imbricates of deep water Permian limestones which occur in the Ba'id area of Oman in the Hawasina nappes. They contain a similar fauna to the Biyarah Limestone including *Eumedlicottia, Neocrimites, Stacheoceras* and *Waagenoceras* (Blendiger et al 1990).

The Biyarah Limestone is possibly also equivalent to the Permian limestone described in thrust units of SE Khuzestan of SW Iran (Sampo, 1969).

16.2.2 Avroman Limestone

The Avroman Limestone was introduced by Bolton (\ 958) for the massive carbonate sequence forming the high grounds of Jabal Avroman (Hauraman) in the area ENE of Halabja. It forms a NW-SE trending mountain range following the state border between Iraq and Iran, between Sayid Sadiq and Tawila (SE of Halabja) with a highest peak of 2670 m. The Avroman Limestone outcrops in the Avroman Subzone of the Qulqula-Khwakurk Zone which was obducted and sutured to the Arabian Plate during the Late Cretaceous. The subzone extends into adjacent areas of Iran, where the outcrop area is much wider. The Avroman Subzone is thrust over the Qulqula Subzone. In adjacent areas of Iran to the E, the Avroman Formation is unconformably overlain by clastics of the Red Beds Series.

The Avroman Limestone comprises 800 m of light grey, brownish, sometimes milky white, thick-bedded to massive, hard limestone. The carbonates of the formation are very clean, with minimum clastic content and are very rarely dolomitised. Microscopically, they contain a very wide range of shallow water microfacies including: bioclastic, organic, barren, nodular, oolitic, laminated, algal with fenestrae, and bioturbated facies. Alkali olivine basalt dykes and trachyte occur in the formation (Chapter 17).

The biostratigraphy of the Avroman Limestone was evaluated in outcrops in the Zulam Valley, Bani Shar and Kani Seif areas. The oldest beds of the Triassic of the Avroman area are light grey, hard, massive, locally dolomitised limestones similar to the Dachstein facies of the Alpine-Carpathian mountaln ranges. They yielded tlie following fossils: In the Banishar area: *Neomegalodon (Gemmelarodus) cf. saccoi* (Parone, 1988), *?Seisia sp., Promathilda sp.,* Megalodontidae indent., *Dicerocardium sp., Neoschizedus? sp.* In the Zulam area: *Neomegalodon (Neomegalodon) sp.* In the Kani Seif area: *Dicerocardium sp.* The species of *Neomegalodon* is a new form of the genus. It was identified in the Zulam Valley in grey, massive limestones with *Involutina gaschei, Involutina [riedli* and *lnvolutina oberhauseri,* thus proving the Norian age of these beds. Reworked clasts of Permian age were recorded in some thin sections.

The following list of microfossils were found in all the studied localities: *Reophax sp., "Tetrataxis" cf. inflata* Kristan, *Ophthalmidium sp., Ophthalmidium triasicum* (Kristan), *lnvolutina communis* (Kristan- Tollmann), *Angulodiscus pokornyi* (Salaj), *lnvolutina gaschei* (KoehnZaninetti and Bronnirnann), *Involutina cf. liassica* (Jones), *Involutina oberhauseri* (Salaj), *lnvolutina pragsoides* (Oberhauser), *lnvolutina tumida* (Kristan- Tollmann), *lnvolutina sinuosa* (Weynschenk), *Semiinvolutina clari* Kristan, *Triassina hantkeni* Majzon, *Coronipora austriaca* (Kristan), *Agathammina austroalpina* Kristan- Tollmann and Tollmann, *Trocholina crassa* Kristan, *Trocholina cf. acuta Oberhauser, Involutina friedli* Kristan- Tollmann, *Duostomina sp.* (Names of

individual taxa are given mostly according to Zaninetti, 1976). *(Agathammina austroalpina* appears to be characteristic of the Latest Triassic (Rhaetian» .
Ostracods are common in the uppermost Triassic beds. Recrystallised algae (Dasycladaceae) are often present. The genera *Physoporella, Diplopora* and *Macroporella* occur.

Organic limestones of the uppermost Triassic contain gastropods and pelecypods, brachiopod remnants (rhynchonellids and terebratulids), crinoid columnals corals of the genus *Thecosmilia* and coprolites of *Thoronetia quinaria* (Bronnimann, Caron and Zeninetti).

The range of macrofossils and microfossils is extremely large. The most typical Avroman limestone fauna comprises megalodons *(Neomegalodon cf. Saccoi,* Parone) accompanied by encrusted forams and algae, gastropods and brachipods. Other microfacies contain a sessile coral fauna *(Thecosmilia sp.),* algae *(Cayeuxia),* green algae *(Dasycladaceae-Diplopora sp., Physoporella sp.* and *Macroporella sp.).* Clasts of pelecypods, gastropods and brachiopods are locally abundant. They are accompanied by crinoids, echinoids, foraminifers and coproliths. The Avroman limestone is thus of Late Triassic age (NorianRhaetian).

The formation was deposited on a shallow carbonate platform. The pure carbonate indicates the formation was deposited far from continental clastic influence. The presence of Permian limestone clasts is extremely significant. They suggest that the Avroman Limestone was deposited on a block of continental crust containing Permian carbonates.
The Avroman Limestone is equivalent to the lower part of the Bisitoun Limestone exposed a short distance to the SE in Iran. The Bisitoun Limestone is a carbonate unit ranging in age from Triassic to Cenomanian. The significance of the Avroman and Bisitoun Limestones for the plate tectonic evolution of the NE margin of the Arabian Plate is discussed in Chapter 3.

16.2.3 Jurassic imbricates

Imbricates of Jurassic sequences are common within the Qulqula-Khwakurk Zone in the Naorbab area, SE of Sulalmaniya. They belong to the platform unit, which forms the tectonic substrate below the Qulqula-Khwakurk Zone which was imbricated within the overlying thrust sheets during Late Miocene-Pliocene deformation. The imbricates represent carbonates of the Sehkaniyan, Sargelu, Naokelekan and possibly Barsarin formations. These formations were described in the chapters dealing with the stratigraphy of the shelf (Chapters 9 and 10).

16.2.4 Qulqula Group

This stratigraphic unit was first described by Bolton in 1955 and 1956 and in more detail in 1958. He described two units: the Qulqula Radiolarian Formation and the Qulqula Conglomerate Formation. Subsequent investigations in the Naorbab-Halabja area indicate that the radiolarian and conglomerate lithofacies occur at different positions in the Group. The type locality of the Qulqula Group is in the Qulqula gorge along the Marado River in the partly buried Qulqula-Khwakurk Zone, E of Merga Sur and to the N of Qalat Dizeh in NE Iraq.
The Qulqula Group is divided into four divisions. The lowest division consists predominantly of moderately thick bedded, oolitic and detrital limestones, and thick beds of white chert, both interbedded with grey marly shale. The overlying division comprises thin bedded, red, grey and green chert, with beds of cherty radiolarian limestones and dark red ferruginous shales and occasional beds of massive oolitic and detrital limestones. The next division is dominated by a thick sequence of dark red ferruginous-siliceous, shaly, rubbly mudstones, with occasional beds of oolitic and detrital limestone (Bolton, 1958d). The highest division consists of limestone and chert

conglomerate with beds of radiolarian chert. These divisions can be identified in other outcrop areas. However the proportion of the different lithofacies is very variable. In the Halabja-Avroman area the limestone beds are very frequent but in the Naorbab-Surkev area chert and shale predominate. Mapping of the Halabja region of NE Iraq revealed that the Qulqula Group also consists of four units which mayor may not be exactly equivalent to those described in the type section.

Plate 16-1: Highly contorted limestones of the lower, Tithonian-Berriasian, part of the Qulqula Radiolarian Formation, ENE of Halabja, NE Iraq (photo by Jiří Rudolský)



16.2.4.1 Shallow water carbonate sequence (Tithonian-Berriasian)

The lower unit (of Tithonian-Berriasian age) is 120 m thick and exposed near Tawila village in the SE part of the Iraqi Avroman Range. It comprises light grey, locally nodular and oolitic limestones with pyritised coprolites of *Favreina sp.* The limestones contain green algae, hydrozoans and very rich foraminiferal assemblages. This microfacies comprise outer shelf and calciturbidite facies. The basinal micritic limestones of the lower part of the Qulqula Group contain clasts of pelagic crinoids *(Sacco coma sp.),* calcified Radiolaria and sponge spicules. This facies was deposited in a starved basin. The unit contains frequent chert beds and nodules of chert (Plate 16-1).

This division contains Miliolids, Langenidae *(Saracenaria, Lenticulina),* Valvulindae, *Pfenderina?, Trocholina elongata* (Leupold), *Ammobaculites sp.,* Textulariidae, *Salpingoporella sp., Cladocoropsis sp., Faverina sp.*

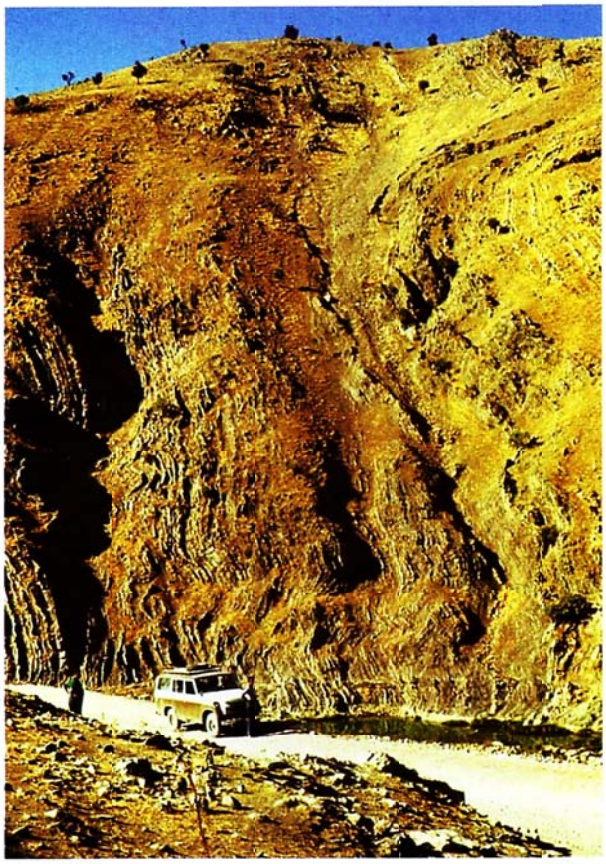
16.2.4.2 Carbonate-chert sequence (Valanginian-Lower Aptian)

The middle unit (Valanginian-Early Aptian) comprises white-grey limestones rich in bioclasts and often containing stylolites. Coarse bioclastic, oolitic and nodular limestones are interbedded with chert and are interpreted as proximal calciturbidites. They were deposited on a deep shelf with open circulation. The limestones contain varied foraminiferal assemblages, clasts of crinoids, gastropods and ostracods, rare clasts of Tintinninidae, abundant Radiolaria, and spicules of sponges and ostracods. The division contains *Pseudocyclammina cf hedbergi* Mayne,

Pseudocyclammina cf lituus (Yokoyama), *Cyclammina greigi* Henson, *Nummuloculina sp., Nautiloculina sp.,* Rotaliidae, Textulariidae, Miliolidae, Valvulinidae, *Lenticulina sp., Nezzazata? sp., Pseudoglandulina sp., Actinoporella? sp., Faverina sp. and Hensonella? sp.,* echinoid spines, crinoid fragments, sponge spicules. Very rarely fragments of pelagic gastropods were also recorded. The assemblage is characterized by the representative of the genus *Pseudocyclammina* and *Cyclammina;* pelagic fauna are rare. *(Pseudocyclammina lituus s.s.* appears

restricted to the Berriasian-Valanginian; *Cyclammina [Everticyclammina] greigi* to the Berriasian-Aptian).

Plate 16-2: Isoclinally folded radiolarian chert succession of the Qulqula Radiolarian Formation from Nal Pariz, on the road between Sayed Sadiq and Penjween (photo by Jiří Rudolský)



16.2.4.3 Offshore Southern Neo-Tethys radiolarian chert (Aptian-Albian)

The upper and thickest unit of the formation is of Aptian Albian age and was deposited in a deep water environment. The basinal limestones are mostly monotonous, micritic and bioclastic sediments. The fauna consists entirely of pelagic foraminifers, radiolarians, spicules of sponges and pelagic crinoids. The sediments may have been deposited close to the calcite compensation depth (CCD). The sequence is complicated by isoclinal folding (Plate 16-2). The thickness of 1500 m suggested by Bolton (l958d) can not be confirmed and may be due to tectonic repetition; only 500 m can be confirmed in the Naorbab region. This sequence is characterized by planktonic fauna belonging to three microfacies:

1. *Stomiosphera,* radiolarian and sponge facies

2. *Stomiosphera, Hedbergella* and radiolarians facies, containing *Hedbergella div. spp.* and *Hedbergella cf washitensis* (Carsey). This assemblage is interpreted as Aptian to Early Albian in age (note though, that
   Plate 16-2: Isoclinally folded radiolarian chert succession of the Qulqula Radiolarian Formation from NaJ Pariz, on the road between Sayed Sadiq and Penjween (photo by Jil'i Rudolsky)
   Hedbergella [Favusella] washitensis s.s. is restricted to the Albian-Cenomanian). This facies always interfingers with Facies I.
3. *Stomiospahera, Thalmanniella* and *Heterohelix* facies, containing *Hedbergella div. spp., Hedbergella cf washitensis* (Carsey), *Hedbergella trochoidea* Gandolfi, *Heterohelix globulosa* Ehrenberg, *Heterohelix div. spp., Thalmanninella ticinensis* Gandolfi, *Thalmanninella roberti* (Gandolfi), *Ovalveolina reicheli* Marie with rare *Orbitolina. Stromiosphaera* and radiolarians of the Spumellaria type are abundant. The Nasellaria type of radiolarians are rare. This assemblage is of Albian to Cenomanian age. *(Hedbergella trochoidea* is restricted to the Aptian-Albian; *Thalmanninella roberti* and *T ticinensis* to the Albian; and *Hedbergella [Favusella] washitensis s.s.* and *Ovalveolina* to the AlbianCenomanian).

16.2.4.4 Qulqula Conglomerate Formation (Cenomanian-Early Senonian?)

The Qulqula Conglomerate was described as a separate formation by Bolton in 1955 and in more detail in 1958. The type area of the formation is the same as the Qulqula Radiolarian Formation. The Qulqula Conglomerate Formation consists of thick lenticular beds of conglomerates, composed of pebbles and small boulders of limestone, and to a lesser extent of chert. Both the limestone and chert boulders and pebbles were derived from the underlying Qulqula Radiolarian Formation. The conglomerates are interbedded with grey shale and beds of oolitic detrital limestone and white chert. **In** the western part of the type locality the formation includes breccias with angular fragments of detrital limestone and green silty shale. The formation may represent wild flysch or an olistostrome unit associated with the initial phase of obduction of the Southern Neo- Tethys. Volcanics mentioned in the Halabja area by Bolton (l958c) are diabase bodies localized along thrust contacts; they may not be part of the Qulqula Group.

In the Naorab area near Chuwarta the formation comprises sheets of limestone conglomerate and gritty limestone in the east, and conglomerates (with pebbles of oolitic limestone and chert) embedded in a yellow calcareous or red/grey argillaceous matrix (Bolton, 1958b). In the Halabja area, conglomerates and breccia conglomerates occur (Bolton, 1958e; Buday and Suk, 1978). The amount of the conglomerates in the Naorbab-Avroman-Halabja area is relatively restricted; the conglomerates form isolated bodies bounded by faults.

The thickness of the Qulqula Conglomerate Formation is about 1200 m in the type *area,* 1400 m in the Naorbab area 'and 500 m in the Halabja area (Bolton, 1958a, b and c).
Subsequent mapping in the Naorbab and Halabja areas indicates that the thickness has been overestimated.

The age of the formation was not determined by Bolton (l958c) but was assumed to be Albian-Cenomanian. It may correlate with the upper part of the Karadut Group of SE Turkey. The youngest part the Qulqula Conglomerate Formation may be of Santonian or even Early Campanian age. Fossils from the Halabja area belong to the *OvaLveolina* and *ThaLmannineLLa* facies. They include *OvaLveoLina sp., Hemicyclammina sigali* Mayne, *HedbergeLLa washitensis* (Carsey), *HedbergeLLa sp., Thalmanninella ticinensis* Gandolfi, *Thalmanninella apenninica* Renz,

Praealveolina sp., Dicyclina sp., fragments of molluscs and pelagic crinoids. *tHemicyclammina sigali* appears restricted to the Albian; *Ovalveolina, HedbergeLLa [FavuseLLa] washitensis s.s.* and *Thalmanninella apenninica* to the AlbianCenomanian). The age of this assemblage is Albian-Cenomanian.

16.2.5 Chert, volcanic and ultramafic rocks of the Southern Neo-Tethys (Khwakurk Series)

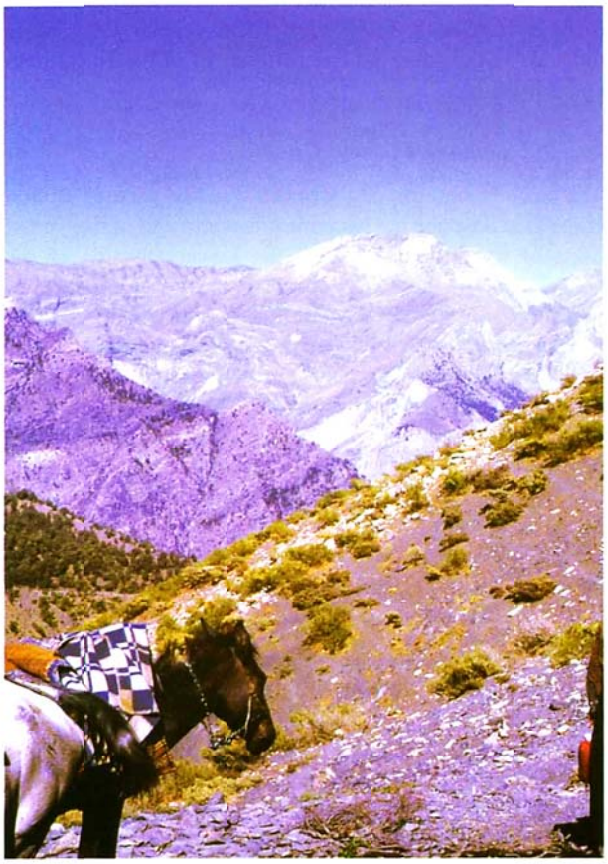
The Khwakurk Series outcrops near the Iraq-Iran- Turkey border junction. It was originally described by Cobbett (1957) from the Sidekan area of the Zagros Thrust Zone. It was traced on the 1: 1 ,000,000 Geological map of Iraq by Bolton et al. (1960) as an equivalent unit of the Qulqula Group. The series is poorly described. According to Cobbett (1957) it consists of acid and basic lavas and associated agglomerates, chert, jaspers, and purple slates with some pelagic limestones. Subsequent mineral investigations in the same region identified chromite bearing ultramafic rocks. The series outcrops in a relatively large area between Kani Rash, Sidekan and the Turkish-Iranian borders north of the Rowanduz river valley. The thickness of the series has not been estimated but is probably several hundred metres.

The ultramafic rocks of the Darband Rayat, exposed in the Rowanduz valley in NE Iraq may be a tectonic window of the Khwakurk Series beneath the tectonically overriding Naopurdan Group.

The Khwakurk Series requires further study. It may represent imbricates and melange derived from the floor of the Southern Neo- Tethys ocean (Chapter 3). The series may be equivalent to the Qulqula Group. It can be correlated with the ophiolitic sequence exposed in Iran, N of the Greater Zab River and directly N of the Mawat Complex. It is also equivalent to the radiolarian and volcanic sequence of the Kermanshah region of SW Iran.

The lower boundary of the series is not exposed. The upper contact is tectonic (the Naopurdan Rock Group is usually thrust over the Khwakurk) but in the NE parts of the outcrop the isoclinally folded and faulted Khwakurk Series is unconformably overlain by slightly folded shales and nummulitic limestones of Eocene age.

Plate 16-3: Qandil range viewed from Marado village. The foreground is built by the Eocene volcanics of the Walash Group. The bulk of the Qandil range is built by :he Qandil metamorphics, (domal structure), capped by Triassic limestone forming distant ridge (photo by Tibor Buday)



16.3 Tectonostratigraphy of the Penjween- Walash Zone

16.3.1 Pre-Tertiary Qandil Metamorphic Series

The Qandil Metamorphic Series was first used by Bolton (l958d) for a sequence of mostly slightly metamorphosed limestones and schists building the frontier thrust ranges of
NE Iraq. He unfortunately included some nonmetamorphosed Palaeogene limestones within the series. He considered the series to be of Palaeogene age and the metamorphosed equivalent of the Naopurdan and Walash groups. Subsequent mapping showed the series is very complex. Traverses by the authors in the Marapasta area and the investigations of Sattran et al (1973) and Buday et al., (1977) indicate that the units of the series originally described by Bolton are of structural, rather than stratigraphic character.
Based on fieldwork in the Qalat Dizeh and Halabja areas the Qandil Metamorphic Series is here divided into three major groups:

1. The oldest Group is the Mawat Group which consists mainly of pillow basalts and keratophyres and includes the purely volcanic sequence of the Pushtashan Group.
2. The overlying Gimo Group (formerly called the Gimo Sequence) comprises marbles, calcschists and metavolcanics. It includes the following obsolete units (lower part of the Bulfat Group, the lower part of Penjween Group or Series, and part of the Qandil Series).

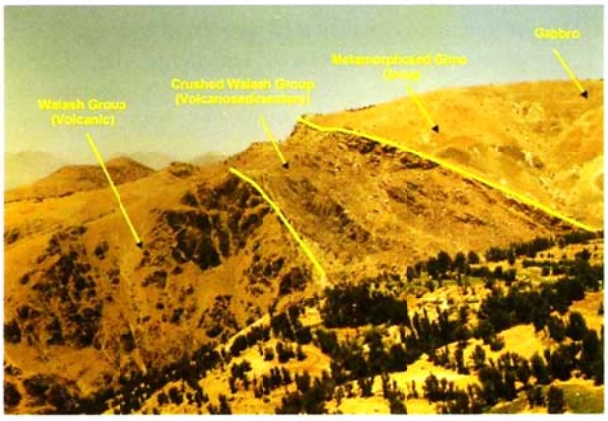
3. The youngest unit is the Sirginil Group which consists of metapelites, calcschists, marbles and rare metavolcanics. It includes the upper part of the obsolete Penjween Group or Series, and part of the Qandil Series.

16.3.1.1 Mawat Volcanic Group

The Mawat Volcanic Group outcrops on the northern slopes of Gimo Mountain and in the SW and S areas of the Mawat nappe complex. It comprises 600-1000 m of pillow basalt, amygdaloidal basalt, spilite and keratophyres, metamorphosed into the greenschist facies (see Chapter 17) and is intruded by gabbro and ultramafic rocks. K-Ar dating of the volcanics indicate an age range from 97 to 105 Ma (Aswad, 1986). They are thus of Albian-Cenomanian age. Details of the lithology and geochemistry of the Mawat Group is provided in Chapter 17. A similar unit, exposed in the Pushtashan valley of the Qandil Range is over 1000 m thick. It forms a separate thrust sheet and is lithologically similar to the Mawat Group. It is intruded by norite and plagiogranite bodies. Bolton (1959d) suggested that the Pushtashan Group is equivalent to the Eocene volcanics of the Walash. However, the absence of intermediate volcanics in this group and the regional metamorphism associated with it makes this correlation improbable. It is suggested that the name Pushtashan Group or Series should be abandoned. These rocks are here included in the Mawat Group.

The volcanic sequences of Mawat and Pushtashan represent basalts formed either at a Mid-Oceanic ridge or at a supra subduction zone spreading centre within the Neo- Tethys (Chapter 3).

Plate 16-4: The Walash Volcanic Group allochthon, overlain by the Qandil series of the Gimo Group allochthon Bulfat Range SE of Qalat Dizeh, NE Iraq (photo by Jiří Rudolský)



16.3.1.2 Gimo Calcareous Group

The Gimo Calcareous Group forms the highest unit above the intrusives of the Mawat Complex. A similar unit extends into the Bulfat range and the Rowanduz valley in the NW and into the Penjween area in the SE. In the Gimo Mountain in the Mawat Massif the group comprises 600 m of massive and thick-bedded marble and calcschist, interbedded with basaltic flows. In the Qandil range it forms a monocline or massive domes (Plate 16-3). In the Bulfat massif the equivalents of the Gimo are strongly altered by contact metamorphism by basic and intermediate intrusions. The calcareous lower part of the Penjween Group, exposed around Penjween Town, can be correlated with the Gimo Calcareous Group. This part consists of alternating calcschist, marble, meta-tuffites and amphibolite, intruded by mafic-ultramafic rocks of the Penjween Complex. For details of the magmatism and metamorphism of the group see Chapter 17.

The lower part of the Bulfat unit, which is equivalent to the Gimo Group, was studied in detail by Buday and Suk (1978). It consists of regionally and contact metamorphosed carbonates, alternating with rnetavolcanics, intruded by basic and intermediate plutons and associated alkaline syenite differentiates. A cooling age of 45 Ma for the gabbro intrusions suggest that they were emplaced during Palaeogene time. The lower part of the Bulfat Group is exposed in the middle slopes of the Bulfat range and tectonically overlies Eocene volcanics (Plate 16-4).

The carbonates of the Gimo group may have been deposited on sea mounts within the Neo-Tethys.

16.3.1.3 Sirginil Phyllite Group

The Sirginil Phyllite Group was described from the northern parts of the Bulfat Massif, and extends from the Rowanduz River Valley in the NW to the Penjween area in the SE. North of the Rowanduz River; only disconnected outcrops occur on the Hasar i Rust Mountain and along the Iranian border.

The Sirginil Group consists of > 1000 m of pelitic and arenaceous rocks with volcanic flows, and is regionally and thermally metamorphosed (Buday and Suk 1978). It forms the highest part of the Bulfat range. The upper part of the Penjween Group, which comprises schist and phyllite with occasional lenses of massive slightly marblized limestone, is probably equivalent of the Sirginil Group. The Sirginil Group, probably represent the upper part of an oceanic sequence of the Neo-Tethys with sediments being derived from island arcs contemporaneous with initial subduction and deformation of the Neo- Tethys during the Albian Cenomanian.

The Qandil Metamorphic Series can be traced into the Mordag Metamorphics of SE Turkey which comprise metamorphic rocks, peridotite, gabbro, diabase, amphibolite and serpentine of Late Jurassic-Early Cretaceous age and granite intrusions. The Mordag rnetamorphics also include Upper Permian carbonates but the main body consists of metashale, metasandstone and calcschist (Dogan Perincek, personal communication), and may at least be partly equivalent to the Shalalr Group.

16.3.2 Non metamorphosed Tertiary volcanosedimentary units

The Penjween- Walash Tectonic Zone was part of the deformed oceanic domain of the Neo-Tethys. During the Palaeogene subduction occurred within the remnant of the Neo- Tethys which resulted in the formation of volcanic arc associated with a fore-arc basin to its SW (Chapter 3). Two tectonostratigraphic units are recognized within this tectonic zone: the Walash Volcanic Group which consists predominantly of intermediate (occasionally basic) volcanics of arc origin, and the Naopurdan Shaly Group which consists *predominantly* of flysch with volcanic units and nummulitic limestone lenses deposited in a fore-arc region.

16.3.2.1 Walash (Volcanic) Group

The Walash (Volcanic) Group was first described as the Walash Volcanic Series by Bolton in 1958. The type locality at Walash village in the Rowanduz River valley of NE Iraq is composed of 1000 m of mainly volcanic rocks. According to Bolton (1958d), the Group contains a volcanic cone enclosed in sedimentary rocks. Unfortunately only part of the Group is exposed at the type locality. Outside the type area 3500 m of volcanics and sediments were reported by Bolton (l958d). The type locality is thus not very representative of the Walash (Volcanic) Group. The authors have tried to reconstruct the stratigraphic succession of the Group by comparing different sections. From the base the Walash Group comprises the following units:

a) Basal Red Beds consisting of red mudstone, cherty siltstone and shale

b) Lower Volcanics consisting mainly of basic, less frequently acid, lavas, frequent pillow lavas, and associated pyroclastics. The volcanics occur frequently in the form of volcanic cones around the type area and at Pushtashan. They pass laterally into volcano sedimentary sequences with tuffs, tuffaceous rocks, red mudstones, radiolarites and white limestones.

c) Middle Red Beds consisting of a lithologically very variable sequence which passes into tuffaceous rocks. The unit consists of red mudstone, red and grey shale, sandstone, conglomerate, and lenticular, often brown limestone; the latter containing Palaeocene and Eocene fossils (Bolton, 1958d).

d) Upper Volcanics consisting of basalt and andesite flows, pyroclastics, and associated sediments. The Upper Volcanics also form volcanic cones which pass laterally into marine sedimentary sequences with limestones containing Eocene fossils.

e) Upper Red Beds consisting of red mudstone and conglomerate near the base and brown red siltstone and grey wacke higher up. Bolton correlates these beds with the Choman clastics.

The succession is rarely completely developed in one traverse or outcrop because of thrusting. Correlation of units within the group is therefore difficult. Volcanic cones, passing laterally into sediments, cause frequent problems in correlation and make the thickness of the formation difficult to estimate. The maximum thickness determined by Bolton (1958d) in the Darband area is around 3700 m. This may be an overestimate due to tectonic repetition. A thickness of 2000 m was measured by Polnikov and Nikolajev (1962) from the Kewrta area. Along the SW slopes of the Bulfat massif (Fig. 16-4) a thickness of 2500 m was reported by Bolton.

Sediments of the Walash Group are texturally immature. The mudstones are slightly calcareous. Nodular limestones occur within the mudstone beds. Siltstones are less common than mudstones; saridstone bed up to a few metres thick occurs within the mudstone. Conglomerates occur only rarely within the group except in the basal unit. Volcanics of the Walash are classified into basic dykes and lava flows (usually spilitic diabase and pyroxene-bearing spilitic basalt and spilite) and intennediate volcanics (pyroxene andesite, pyroxene-amphibole andesite, amphibole andesite and altered andesites). The plate tectonic setting of the Walash volcanics is discussed in Chapter 3.

Fossils are abundant mainly in the limestones. *Nummulites*and *Alveolina-bearing* limestones are reported by many authors, but no species list has been published. The age of the Group is probably of Palaeocene-Eocene and may extend into the Oligocene based on its lateral passage into the Naopurdan Group (Bolton, 1958d).

The Iranian Zagros, adjacent to the Iraqi area contains thrust sheets of Palaeogene age that include volcanics (geological maps of Iran, scale 1:250,000). These volcanosedimentary units are both facies and age correlatives of the Naopurdan and Walash.

16.3.2.2 Naopurdan (shaly) Group

The name Naopurdan Shaly Series was first used by Bolton (1958d) to describe the lowermost tectonic unit of the Thrust Zone of Iraq, formerly called the Lower Division of the Nappe Zone or the Shaly Rock Group of Heron and Lees (1943). The type locality at Naopurdan village in the Rowanduz River Valley contains relatively abundant lavas and pyroclastics; elsewhere volcanic rocks are rare. The type locality is thus unfortunately not very representative of the group. The lithology of the Naopurdan Group varies considerably. The proportion of volcanic rocks decreases

towards the SW. The volcanic rocks occur mainly in two divisions separated by sedimentary rocks. The thickness of the Naopurdan Group is difficult to estimate because of structural complications. A value of 2500-3000 m is indicated. The age was determined as Palaeocene-Oligocene.

Buday (1980) divided the group into two subgroups: the Naopurdan- Type Subgroup which comprises intercalated sedimentary and volcanic units and the Sidekan Type Subgroup composed only of sedimentary rocks.

The Naopurdan Type Subgroup of the type locality is divided into six units (Bolton, 1958d), in ascending order:

a) 500 m of grey shales with thin beds of green greywacke, lenticular conglomerates (with pebbles of basic volcanics), lenticular limestones and sills of basic volcanics, associated with red mudstones, jaspers, limestones and radiolarites
b) 150 m of coralline limestone overlain by massive lenticular nummulitic limestones capped by red shales; the nummulites indicate a Palaeocene-Early Eocene age
c) 250 m of tuffaceous slates and shales with occasional basic pillow lavas
d) 200 m of andesite volcanics comprising lavas, agglomerates and tuffaceous beds; this unit is laterally discontinuous
e) 400 m of thin-bedded argillaceous conglomerates and grit, the pebbles and grains of which consist almost entirely of basic volcanic rocks
f) An upper unit (thickness not measured) of thin bedded, grey gritty greywacke, alternating with sandy shale referred to as the Choman Clastics. The pebbles are mostly of volcanic origin. This unit is dated as Late Palaeogene-Miocene? Age by Bolton (l958d) but he did not provide a fossil list.

The Sidekan Type Subgroup was described by Cobbett (1957) on the N slopes of Jabal Hasr-i-Rust near Sidekan Town. This subgroup consists from the base upwards of the following units:

a) Multi-coloured grit and sandstone
b) Purple and green silty shales and marls with subordinate sandstone beds with nummulites of Palaeocene-Eocene age. This unit may be equivalent to the Grey Shaly Beds (a) of the Naopurdan type locality.
c) Black bituminous limestones with Palaeocene-Early Eocene fossils (Stevenson, 1957) which may correlate with the coralline limestone horizon (b) of the Naopurdan type area.
d) Reddish and greenish grits and slate with limestone and limestone breccias. These beds may correlate partly with the coralline limestone horizon and partly with the transitional horizon between units (a) and (b) of the type locality.
e) Naopurdan Needle Slate which may be equivalent to the slates of unit (c) of the Naopurdan type locality.
f) A Conglomerate, grit and limestone unit. This unit is probably equivalent to the Choman clastics and of the Avdele Conglomerates.

The clastic sediments include turbidites.

The Naopurdan Group was deposited in marine environment on the SW margin of the Palaeogene volcanic arc (Walash Group) that probably developed before the total closure of the Neo- Tethys (Chapter 3). The Group passed laterally into the volcano-sedimentary Walash Group.

Nummulitic limestones were deposited as shoals. The clastic beds include turbidites and shales with planktonic foraminifera.

The limestone beds contain large forms of *Pecten sp., Ostrea multicostata* Deshayes, and *Ostrea brongniarti* Deshayes. Large forams are abundant and include:

Alveolina sp., Alveolina oblonga (d'Orbigny), *Discocyclina roberti* (Douville), *Assilina sp., Nummulites atacicus* Leymerie, *Nummulites aturicus* Joley et Leymerie, *Nummulites cf striatus* (Brugeuire), *Orbitolites complanatus* Lamarck, *Peneroplis sp.* and miliolids. Further fragments of *Globigerina sp., Globorotalia sp., Globorotalia lehneri Cushman, Globorotalia cf crassata* Cushman, *Porticulasphera mexicana* (Cushman) and *Bulimina cf jacksoniensis* Cushman. *(Nummulites atacicus* and *N. aturicus* appear restricted to the Early Eocene; *Alveolina oblonga* to the Early-Middle Eocene; *Globorotalia [Morozovella] lehneri* to the Middle Eocene; and *Porticulasphaera mexicana* to the Middle-earliest Late Eocene).

The outcrops of the Group extend into Iran where they are mapped as thrust sheets of an un-named unit of shale and limestone with volcanics of Eocene age. In SE Turkey, the group can be correlated with parts of the 2000 m Urse Formation of the Hakkari Complex (Dogan Perincek personal communication). The Hakkari Complex consists of, from the top: 50 m of green shale and silty shale, 400 m of dark red and greenish metamorphosed limestone, 1445 m of partly metamorphosed sandstone and shale (Middle Eocene), 165 m grey dark limestone and clayey limestone and 115 m of greenish black shale with sandstone intercalations. It may also correlate with Cungus Formation which consists of: turbidite sandstone with sole marks and graded bedding, grey/green shale to marl, blocks of limestone with Middle Eocene fauna, and blocks of serpentinite derived from the Guleman Ophiolite. Similarly the Durankaya Formation which consists of grey, dark grey, yellowish grey phyllite and dense pelagic limestone and green limestone lenses and exotic blocks with olistostrome conglomerate with serpentinite pebbles may be equivalent to parts of Naopurdan Group.

16.4 Tectonostratigraphy of the Shalair Zone

The Shalair Zone is an integral part of the Sanandaj-Sirjan Zone of Iran. It comprises metamorphosed Triassic Cretaceous sediments that were deposited on the SW margin of the Sanandaj-Sirjan microplate. The older crystalline rocks of the Sanandaj-Sirjan Zone are exposed to the N, E and S of the Shalair valley, mainly in Iran. They are represented by the Mishav Complex in Iraq which consists largely of granite intrusions. Upper Triassic recrystallised limestones (Darokhan Limestone) are exposed in the core of the Shalair anticline, often imbricated with phyllites of the Shalair Group. Andesites and rhyolites of the Katar Rash Group are the product of Cenomanian arc volcanicity. Maastrichtian-Palaeocene carbonates (Piran Limestone) form either isolated thrust sheets or unconformably overlie units of the zone. Units of the Shalair Zone are mostly exposed in the Shalair valley. Thrust sheets occur NE of Qalat-Dizeh town; the highest thrust sheets within the Qandil range (Marapasta area).

16.4.1 Mishav Complex

The axis of the E- W trending Shalair anticline is exposed in the Shalair valley. Pre Permian metamorphic rocks and granites are exposed in the core of the anticline in the east adjacent to the Iraq-Iran border. A plagiogranite intrusion was originally considered as part of the Katar Rash Group by Villiers (1957). Subsequent mapping of the region (Buday and Suk, 1978) and dating of the granite body proved it is of Late Carboniferous age (305 Ma). Granites and metamorphic rocks of similar (or older) age form large parts of the Sanandaj-Sirjan Zone in Iran (Iran 1 :250,000 map

Series). Their outcrop area in Iraq is very limited and it was difficult to map the host rocks of the intrusion as they are mainly within Iran. These rocks represent the continental basement of the Sanandaj-Sirjan Zone.

Late Carboniferous (324-323 Ma) granitoid bodies were identified from the pre-Alpine basement of the Hellenides (Xypolias et al., 2006), interpreted as remnants a Cimmerian terrane tectonised along a southerly dipping subduction zone along the southern side of the Palaeo-Tethys. They are probably similar in tectonic setting to the granitoid bodies of the Mishav Complex.

16.4.2 Darokhan Limestone

The Darokhan Limestone is introduced in this book to describe the Triassic carbonates and phyllites, differentiated by Buday and Suk (1978) as the "Triassic of the Shalair". It comprises massive, slightly metamorphosed and recrystallised limestone with occasional phyllite intercalations, exposed in a few localities in the Shalair Valley. The type section, which is few hundred meters thick, is exposed in the core of a minor faulted anticline located near Darokhan village on the northern flank of the Shalair anticline. It is embedded in isoclinally folded phyllites of the Shalair Group. Other localities include Gokhlan on the southern flank of the Shalair anticline. Most outcrops are located adjacent to the main thrust separating the Shalair and the Penjween groups.

Fossils in this slightly metamorphosed unit include:

Textularia sp., Involutina friedli Kristan- Tollmann, *I. communis* (Kristan), *I. pragsoides* (Oberhauser), *I. tumida* (Kristan- Tollmann), *I. sinousa* (Weynschenk), *Ophthalmidium cf chianlingense* (Ho), *Duostomina sp., Variostoma? sp.,* Polymorphinidae and Lagenidae. The assemblage indicates a Late Triassic (Norian-Rhaetian) age. It is similar to the assemblage in the Avroman Limestone but lacks the megaladons.

The contacts of the Darokhan Limestone with the phyllites of the Shalair Group are tectonic. It was probably deposited in an outer shelf environment on a carbonate platform on the Sanandaj-Sirjan Zone.

A possible equivalent unit comprises calcschists and phyllites that outcrop on the highest part of the Qandil range near Marapasta in NE Iraq along the Iraq-Iran border. It contains Lead-Zinc ores. The galena has been dated at 180-200 Ma by the Lead-Lead model age method (Chapter 20).

16.4.3 Shalair Group

The regionally metamorphosed pelitic rocks that form the lower slopes of the Shalair valley were originally described by Villiers in 1957. He introduced two series: the Penjween Series and Shalair Phyllitic Series. The Penjween Series is included in the Qandil Series (Gimo and Sirginil groups, see section 16.3.1.2-3). The Shalair Phyllitic Series is here placed in the Shalair Group.

The Shalair Group comprises quartz-sericite schists, sericite schists, and silty-clayey schists (Plate 16-5) with slightly metamorphosed limestones, tuffaceous slates and relatively rare recrystallised limestones. The thickness of the combined Penjween and Shalair Phyllite Series was originally estimated to be 4500 m (Smirnov and Nelidov, 1962). The newly defined Shalair Group is estimated to be 2000 m thick.

The original stratigraphic relationship of the Shalair Group to other units is unclear. The Group may pass upwards gradationally into the overlying Katar Rash (Volcanic) Group. Bolton (1958 c) claimed the presence of *Alveolina* with Late Cretaceous palaeontological affinities. However no *Alveolina* bearing limestones were found during mapping by the GEOSURV team. They identified:

a) Facies with *Orbitolina s.l.* of Aptian to Cenomanian age

b) Organodetrital facies with crinoids, echinoids, gastropod fragments of uncertain Mesozoic age

c) Facies with algae and rare foraminifera of the genera
Glomospira and *Vidalina* probably Mesozoic in age

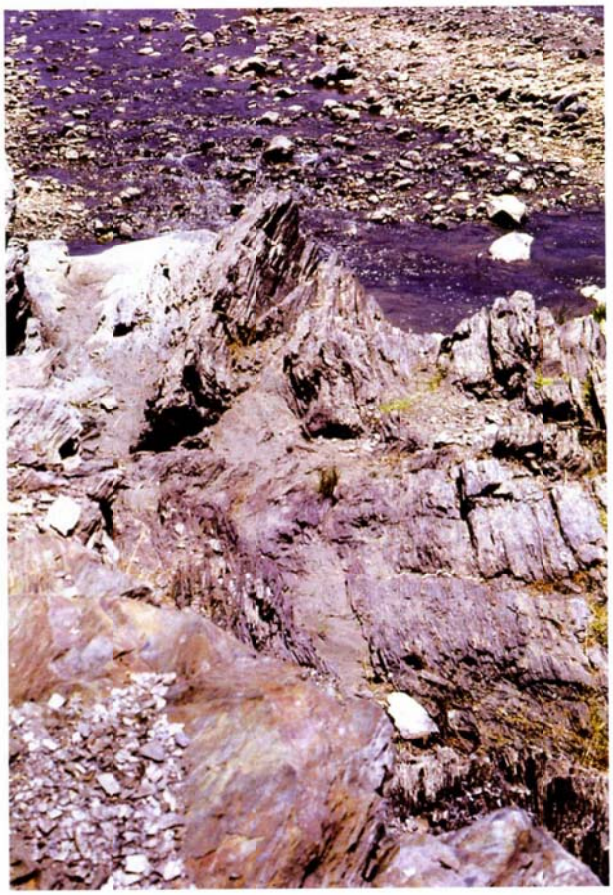
The microfacies with Orbitolina were found in limestones in the higher parts of the group, underlying the Katar Rash Volcanics. Facies (b) and (c) are the most widespread and occur in many limestone beds throughout the area. The upper part of the Shalair Metamorphic Group is of Aptian Cenomanian age. The underlying beds are likely of Triassic Early Cretaceous age.

The distinctive composition of the phyllites and schists of the Shalair Group (inclusing metagreywackes with abundant plagicoclase grains and lithic rock fragments) indicates they were derived by the rapid erosion of a volcanic sequence, probably corresponding to the calc-alkaline Jurassic volcanics (of arc origin) which occur in the Sanandaj-Sirjan Zone in Iran. Tuffaceous interlayers and rare intermediate volcanic flows occur in the Shalair Group. Stocklin and Nabavi (1973) described similar rocks to the Shalair Group in SW Iran as flysch. The carbonate-rich lower and upper parts of the group however were deposited in relatively shallow water environments. The Shalair Group is interpreted to have been deposited in a fore-arc basin in front of a subduction zone dipping underneath the Sanandaj Sirjan Zone (Chapter 3).

The Shalair Group continues into the Sanandaj-Sirjan Zone of Iran (Stocklin, 1960; Stocklin et al., 1973). A widespread Jurassic-Cretaceous boundary break, occurs throughout the Sanandaj-Sirjan Zone.

The lower contact of the group is at least in part being with the Darokhan Limestone and in part with the Mishav Complex of Early Palaeozoic metamorphics intruded by syntectonic granite bodies of Carboniferous age. The nature of the upper contact with the overlying Katar Rash Volcanic Group is unclear; the boundary may be a low angle unconformity or it may be a gradational contact.

Plate 16-5: View of phyllites of Shalair Group at Nazarna, Shalair valley (photo by Jiří Rudolský)



16.4.4 Cretaceous volcanic arc (Katar Rash Group)

The Katar Rash Group was introduced by Villiers in 1957 but later included in the Walash (Volcanic) Rock Group (Bolton, 1958d). The group is here treated as a separate tectonostratigraphic unit belonging to the Shalair Zone. The Katar Rash Group consists predominantly of calc-alkaline volcanics of the andesite-rhyolite association. The most common are andesites (normal, acidic, and basaltoid). dacites and rhyolites (all associated with pyroclastics). Rhyodacites are less common (Chapter 17). Phyllites occur near the base of the group. The Katar Rash Group has been metamorphosed to a similar grade as the underlying Shalair Group. The Katar Rash Group is distributed on the high grounds forming the flanks of the E- W Shalair anticline. Its thickness reaches 1800 m (Polnikov and Nikolajev, 1962). The volcanics have not been dated. They are interpreted as the products of a volcanic arc of early Late Cretaceous age that formed on the SW margin of the Sanandaj-Sirjan Zone (Chapter 3).

The Katar Rash Group is intruded by granodiorite, granites, and quartz diorites. Some of these "granitoid bodies" may actually be very thick rhyolite flows which are coarse grained because of slow cooling. The Group is undated. However it is younger than the Albian limestones in the upper part of the underlying Shalair Metamorphic Group. It is probably of Late Cretaceous age (Cenomanian and younger) based on correlation with the widespread Upper Cretaceous volcanics in the neighbouring Sanandaj-Sirjan Zone in Iran (Stocklin, 1968).

16.4.5 Carbonate shelf of the Sanandaj-Sirjan Zone (Piran Limestone)

The Piran Limestone was described by Cobbett (1957) from the Piran Mountain between Kani Rash and Mirga Sur. He incorrectly included this unit in the Naopurdan Shaly Rock Group. It consists of massive, reddish or pinkish argillaceous fossiliferous limestones. According to Cobbett the lower beds contain Palaeogene-Early Eocene fossils and in the upper beds contain Maastrichtian fossils indicating that the unit has been imbricated or overturned. The unit tectonically overlies dark coloured flysch of the Eocene Naopurdan Group.

Maastrichtian limestones, shown on the Geological maps of Iran of 1 :250,000 and 1: 1 00,000 scales S of the Shalair valley, unconformably overlie metamorphosed rock units of similar lithology to the Penjween, Shalair and Katar Rash groups. These are likely equivalent to the Piran Limestone.

CHAPTER 17
Magmatism and metamorphism in the Zagros Suture

by

Saad Z. Jassim, Milos Suk and Jarmila Waldhausrova

Ophiolite suites are usually interpreted as fragments of oceanic lithosphere. A completely developed ophiolite, as defined by the Penrose Conference in 1972, contalns, from the bottom: ultramafic rocks, gabbro (3-5 km thick), mafic sheeted dyke complex (1-2 km thick); mafic volcanic complex (commonly pillowed, 1-2 km thick), and a sedimentary succession with chert and shale and minor limestone beds (1-2 km thick). They may also contain sodic-felsic intrusive and extrusive rocks. However, many ophiolites suites are dismembered and may not contain all the above components.

The lowest members of the ophiolite complexes are the peridotites and are of three types. The first type consists of sub-continental or orogenic Alpine ultramafic rocks, comprised of dispersed ultramafic bodies (metric to thousands of metres thick), aligned along thrust faults and embedded in metamorphic rocks; these ultramafic rocks may not necessarily represent oceanic crust (Menzies and Dupuy, 1991). The second type comprises slivers of ancient oceanic lithosphere obducted on to continental or oceanic crust (Beccaluva et al. 1984, Nicolas and Boudier 2003). The third type is of oceanic origin and represents mantle rocks that were exhumed by normal faults associated with rifting or along transform faults (Zabargad peridotite in the Red Sea; Bonatti et al. 1981). All abyssal peridotites generally comprise serpentinized harzburgites and, less commonly, lherzolite, dunite, wehrlites, and pyroxenite (Snow and Dick 1995).

The second component of ophiolites is the igneous oceanic crust (Klein, 2004) which includes pillow basalts, sheeted dolerite dykes and gabbros. This oceanic crust is created at divergent plate boundaries (ocean ridges or spreading centers). The oceanic crust usually contains a basal gabbroic unit comprised of large cumulate basaltic intrusions usually with igneous layering (Klein 2004; Dilek and Thy, 1998; Irvine, 1987).

Ophiolites may contain arc volcanics. In intra-oceanic island arcs the arc volcanics are dominated by low Aluminum olivine-tholeiitic basalts. At active plate margins the volcanics contain lower values of Ti, Zr and Hf. Volcanics erupted in mature oceanic island arcs usually comprise calc-alkalic basalt, andesite and dacite with increased silica content; their bulk and isotopic compositions reflect the thickness and age of the preexisting crust (Hamilton 1995). Volcanic arcs sometimes contain boninites which are typically high magnesia andesite volcanics with $Si0_2$>52%, MgO>8% and $Ti0_2$<0.5 % (Le Bas, 2000). They are common in the intraoceanic island arc environment, particularly in forearcs, and originate from a primitive melt generated by partial melting of a shallow, considerably hydrated, mantle wedge (Crawford et al. 1989).

There is little doubt that ophiolite suites of orogenic belts represent remnants of oceanic crust-mantle sequences but their tectonic setting has been actively debated particularly whether they formed in a mid ocean ridge or in a Supra Subduction Zone (SSZ) setting. Sheeted dyke complexes in ophiolites have been assumed to form through a process of lateral spreading at spreading centres. The stratigraphic position and geochemical composition of ophiolites frequently point to a close spatial association with island arcs (Upadhyay and Neale 1979) and formation in marginal ocean basins adjacent to island arcs of major oceans (Hart et al., 1972). Upadhyay and Neale (1979) concluded that the most likely site of formation of many ophiolites around the world may

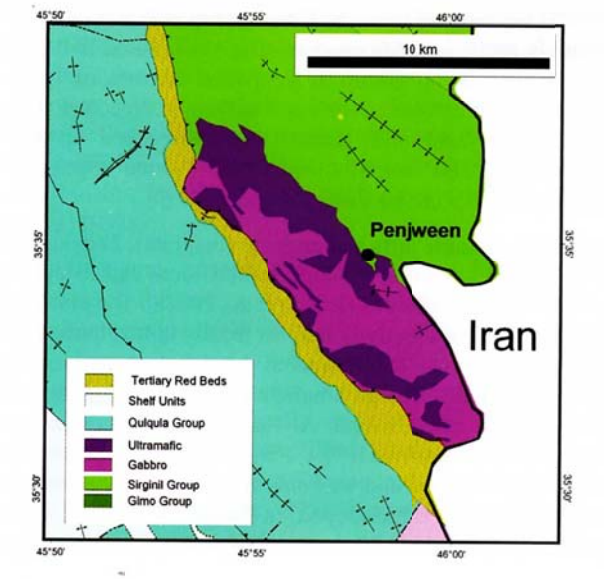
be similar to that of the Western Pacific-type marginal seas bordered by island arcs on one side and continental margins on the other.

A general overview of the geological setting of the Eastern Mediterranean ophiolites (Robertson, 2002) indicate that the widespread occurrence of depleted basalts, andesites and boninitic lavas favors the formation of most of the large, relatively intact ophiolites in the Tethyan region above subduction zones rather than at mid-oceanic ridges. The various models of formation of the Tethyan ophiolites can be summarized below:

1. Ophiolites formed at Mid-ocean ridges, comprising mainly lherzolite bearing ophiolites formed at slow spreading ridges and harzburgite bearing ophiolites formed at fast spreading ridges.
2. Ophiolites formed at spreading ridges between microcontinents (very narrow basins) where melts were contaminated by partial melting of neighbouring lower continental crust (Hall 1984; Dilek et al., 1999) or even old subducted mantle (Moores and Kellog, 1999).
3. Ophiolites formed in back arc Supra Subduction Zone (SSZ) settings in intra-oceanic environments which often give rise to high-magnesia andesite (boninite). The evidence for such origin comes from their position at active plate margins, their association with tectonic melanges and arc-type volcano-clastic deposits and the subduction- type signature of their extrusive rocks (e.g. Miyashiro 1973 for Troodos and Pearce et al. 1981 for Oman). Supra-subduction settings include back-arc basins (Pearce et al., 1981), juvenile island arcs (Maheo et al., 2000), and fore-arc settings. It is presently argued that harzburgite-type ophiolites are formed at intermediate- to fast-spreading ridges. The variations in the refractory character of the harzburgite mantle sequences are ascribed to differences in spreading rate (Boudier and Nicolas, 1985). To account for the conflicting indications for a supra-subduction setting in some ophiolites, notably in Oman, Moores et al. (2000) suggested that the geochemical signatures of the lavas might reflect contamination of their mantle sources by ancient subducted slabs.
4. Ophiolites formed in fore-arc regions characterized by high-Mg Andesite (boninite). The occurrence of fractionated, as well as primitive magma in fore-arcs provides an alternative interpretation for the tectonic setting of some ophiolitic masses.
5. A Mantle diapirism model has been suggested for the Oman ophiolites (Rabinowicz et al., 1984, 1987; lldefonse et al., 1995).

   For further information on the origin of ophiolites and on supra subuction zone spreading the reader is referred to Special Publications 218 and 219 of the Geological Society of London edited by Dilek and Robinson (2003) and Larter and Leat (2003) respectively.

Fig. 17-1: Geological map of the Penjween igneous complex



17.1 Magmatism

In NE Iraq igneous rocks occur in the Qulqula-Khwakurk Zone, the Penjween-Walash Zone, and the Shalair Zone. The Penjween- Walash Zone and locally the Qulqula Khwakurk Zone contain ophiolites. Arc volcanics of Palaeogene and Late Cretaceous age occur in the Penjween Walash and Shalair Zones respectively.

17.1.1 Magmatism of the Southern Neo-Tethys (Qulqula-Khwakurk Zone)

The Qulqula-Khwakurk Zone contains volcanics interbedded with radiolarian chert of Early Cretaceous to Cenomanian age. A thrust sheet of Upper Triassic limestones is thrust over the chert sequence. It contains the Avroman volcanics comprising olivine-bearing basalt, diabase, trachyte and tuffs, forming small lava flows. Potassium-Argon dating of a diabase flow gave an age of 220 Ma ± 20 (Norian) consistent with the age of the limestones (Chapter 16). The Triassic volcanics are of alkali olivine basalt type, probably associated with rifting at the margin of the Arabian Plate (Chapter 3). The radiolarian cherts were deposited in a deep water environment in the Southern Neo- Tethys along the eastern margin of the Arabian Plate during the Late Tithonian-Cenomanian. The associated volcanics comprise glassy devitrified basalt and trachybasalt in addition to volcanics of unknown origin, found near thrust faults within the zone; they are generally devitrified basalts. There are also some small intrusive bodies of ophitic olivine gabbro.

The chemical analyses of the volcanics of the Qulqula Khwakurk Zone are given in Table 17-1. The plots on the Mullen (1983) differentiation diagram indicate that the basalt sample of the Qulqula lies within the Calc Alkaline Basalt (CAB) and near the Arc Tholeiite (IAT) field whereas the Triassic trachyte samples lie within the field of Oceanic Islands Alkali Basalt (OlA).

The ultrabasic rocks of Darband Rayat outcrop in a tectonic window within the Naopurdan thrust sheet. These ultrabasic bodies, were described by Bolton (1958a), Stevenson and Cobbet (1958) and Vasiliev and Pentelikov (1962). The largest of these is the NW-SE oriented Bard-i-Zard body which is 1.5-5 km long and 0.5 km wide. It comprises serpentinite with associated yellow recrystallised limestone and phyllite, interrupted by faults bringing slices of the overlying Naopurdan Eocene carbonates into contact with the ultrabasic rocks. Bolton (l955a) assumed that

the ultrabasic body was a phacolith intruded into the Eocene sediments. However the position of the serpentinites below the Naopurdan Group suggests a tectonic position within the Qulqula-Khwakurk Zone.

17.1.2 Cretaceous Magmatism of the Neo-Tethys (Penjween- Walash Zone)

The three intrusive complexes of Penjween, Mawat and Pushtashan are associated with volcanics and are most likely of Cretaceous age. The Bulfat intrusive complex was intruded into Cretaceous volcanics and sediments but its origin and age may be different from the former three; its age is probably Palaeogene.

17.1.2.1 Penjween ophiolites

The Penjween ophiolitic sequence is incomplete. It comprises dunite, pyroxenite, layered gabbro and diorite that are in contact with a volcano sedimentary sequence referred to in literature as the Penjween Group (Jassim et al., 1982a) but referred to as the Gimo Group in this book. The group is thrust over Miocene molasse (Mirga Red Beds) in the W. The Gimo Group at Penjween consists of basic volcanics and associated tuffs and tuffites, interbedded with calcareous shale and lutites, metamorphosed in the greenschist and amphibolite facies. Three types of magmatic rocks can be distinguished:

1) Basalts, basaltic tuffs and andesite (boninite); 2) dykes of fine-grained gabbro of tholeiite composition; and 3) dykes and sills of microdiorites (Jassim et al., 1982a). The plutonic complex outcrops partly in Iraq but mostly in Iran to the SE. It comprises two main igneous bodies with numerous pyroxenite dykes. The ultramafic body consists of relatively fresh dunite (Jassim and Al-Hassan, 1977) comprised almost totally of olivine (F084-F092). Pyroxene is present in very small amounts and was only found in a few samples; while chromite is developed in bands throughout. The gabbro body (18 km^2 in extent in Iraq) sharply overlies the ultrabasic body with a gently-dipping contact (20^0 dip towards W). Highly inclined and vertical serpentinite offshoots penetrate the gabbro in this contact area and are believed to have formed by subsequent mobilization along shear zones. The gabbro is layered and laminated (Jassim and Al Hassan, 1977).

Irregular pegmatitic gabbro and dyke-like sheets or dykes of pyroxenite occur in the dunite member of the Penjween ophiolite complex. These gabbros are interpreted as segregations of gabbro schlieren and bodies of trapped partial melt in the dunite restite; the pyroxenites are interpreted as crystal cumulates that segregated from the rising melt that fed the layered gabbros *(AL* Hassan and Hubbard, 1985). They formed by partial melting of depleted upper mantle creating gabbro magma and residual dunite. The concentration of Rare Earth Elements (REE) in the Penjween layered gabbro is low (AL Hassan, 1987).

The sub-alkali basalts (Table 17-3a) are low in MgO, and high in K_20, $Ti0_2$ and P_20_S' They differ markedly in composition from the Penjween gabbros. The mugearite (Table 17-3a) has higher K_20, Na20, P_20_S and $Ti0_2$ values than the gabbro. The andesite (Table 17-3a) is rich in Fe and poor in MgO. The P_20_S and $Ti0_2$ contents are highest in the intrusive rocks of the Penjween igneous complex. The boninites (Table 17-3a) have higher contents of MgO and very low contents of $Ti0_2$, P_20_S' and K_20 (Table 17-3a). Table 17-3b and Fig. 17-11 show the composition of rocks from the Mariana trench (Jakes and Miyake 1984), Bonin Islands and Oman (Ishikawa et al. 2002) for comparison.

17.1.2.2 Mawat

The Mawat ophiolite complex is more complete than the Penjween Complex but also does not contain a complete ophiolite sequence. The ophiolite comprises the upper thrust sheet of the Mawat Nappe (Fig. 17-2) and consists of 6001000 m of basalt (Mawat Group) intruded by a plutonic complex of ultrabasics, pyroxenite, layered and coarse gabbros, diorites, dolerite dykes and, late stage plagiogranite differentiates (Jassim, 1973) overlain by a "roof unit" of 600 m of interbedded marble and basalt (Gimo Group).

The Mawat Group comprises amygdaloidal, occasionally pillowed and spilitic, lava flows (3-10 m thick), rich in actinolite and albite. They belong to the basalt- spilitekeratophyre association and are metamorphosed into the greenschist and amphibolite facies. Their average chemical composition shows them to be slightly under saturated tholeiites with low normative olivine (3%).

The Mawat Intrusive Complex (about 250 km^2 in area; Fig 17-2) is emplaced within the metavolcanics (Jassim (1972 and 1973; AL-Mehaldi, 1974). Petrographic details are provided by Jassim (1973), Masek and Etabi (1973), Al Hassan (1975), Jassim and Al Hassan (1977) and Jassim et al. (1982a). Gabbro is the main component of the complex followed by ultramafic rocks and minor diorite and dolerite intrusions. Acidic and intermediate plagiogranite dykes occur in the western part of the complex (Fig. 17-3).

The dunite-peridotite (harzburgite and wehrlite) body consists of magnesia-rich olivine, variably serpentinized, with subordinate orthopyroxene and chromite. Tremolite and talc are common. Serpentinization of the olivine occurs mostly around grains or along cracks; it is most prominent in shear zones and at contacts. Chromite laminae are common; chromite pods occur locally.

The largest body is the banded gabbro which is layered or laminated. Cryptic variations occur away from the contact with the ultrabasic body in the E (AL Hassan, 1975). **It** is intruded by a coarse gabbro body in the E which outcrops near the eastern thrust contact. The coarse gabbro contains crystals up to five centimetres in size; coarse pegmatitic gabbro patches are also common.

The western contact of the banded gabbro body with the metavolcanics is a N-S trending shear zone (20-200 m wide) along which the gabbro is highly deformed and crushed, and is intruded by small basic and acidic intrusions (diorite, quartz dolerite and plagiogranite). Within these shear zones, the gabbro contains highly granulated, clouded plagioclase; its pyroxene is totally altered to hornblende and ultimately to chlorite. Epidote and quartz occur in epidosite veins. Plagiogranites are the most striking minor intrusions forming small boss-like bodies within the sheared gabbro. Jassim (1973) described the rock as mottled whitish grey and fine-grained, containing mainly albite and quartz with a strong mermykitic texture. He assumed the gabbro was emplaced upwards into the metavolcanics during the final stages of solidification resulting in marginal shearing along the contact. The differentiation products of the gabbro were then squeezed and probably emplaced in shear zones at high temperatures.

The intrusive and extrusive members of the Mawat Complex (Tables 17-4 and 17-5) have a low content of $Ti0_2$ and K_20, and a high content of MgO, except for the spilites which have a high content of $Ti0_2$ and K_20, and a low content of MgO. Both gabbros belong to the high-Al basalt group; the layered gabbro differs from the coarse gabbro by a slightly higher content of $Ti0_2$ and FeO (tot). The AFM plots indicate the Mawat intrusive rocks are similar to those of Penjween and that they are of tholeiitic affinity. The extrusives rocks comprise alkaline basic and intermediate rocks of hawalite, basanite, and mugearite (Fig. 17-5). They have a high content of Na20, high contents of $Ti0_2$ and $A1_20_3$, and low contents of K_20 and Zr (70-104 ppm). According to the

available major and trace elements analyses (Table 17-5), these rocks may have originated from a mantle source (As wad and Elias, 1988). They could represent island arc or oceanic island basalts. On the Mullen plot (Fig. 19-9) the volcanics of Mawat lie in the fields of Mid-Oceanic Basalt (MORB) and Oceanic Island Alkali Basalt (OIA).

17.1.2.3 Bulfat

The Bulfat Complex (100 km^2 in extent in Iraq) outcrops in Jabal Bulfat near Qalat Dizeh (Fig. 17-3). It is an incomplete ophiolite sequence comprising a volcanosedimentary unit originally referred to as the Bulfat Group (Jassim et al., 1982a) and here as the Gimo and Sirginil groups. The intrusive complex comprises gabbro-diorite intrusions and late stage differentiates of syenite and nepheline syenite. Ultramafic rocks are rare.

The Gimo Group at Bulfat comprises regionally metamorphosed basalt, diabase, andesite, acid volcanics and tuffs and calcareous and argillaceous sediments (Jassim et al., 1982b) which have been locally thermally metamorphosed by basic intrusions with the formation of hornfels in contact metamorphic aureoles. The metabasalts are porphyritic and sometimes amygdaloidal. The metadiabases are fine- to medium-gralned, and locally porphyritic. The metandesites (or microdiorites) are foliated. They contain white porphyritic plagioclase (An28An42) and albite with amphibole, epidote, zoisite, prehnite, chlorite and biotite. The Gimo Group also contains some acid volcanics and tuffs.

Serpentinites occur as slivers along the base of the nappe, and in an isolated peridotite body near Pouza (Fig. 17-3). They are serpentinized lherzolites or harzburgites with remnant olivine, orthopyroxene and tremolite. Pyroxenites are rare in the Bulfat Complex. They occur mainly at the contacts of basic rocks and marble, and probably formed by assimilation of carbonates.

Basic intrusions in the Bulfat Group have caused contact metamorphism of the surrounding country rocks (see Section 17-2). The pyroxene gabbros are mostly developed in the NE part of the complex forming the high ground of the Bulfat range along the Iraq-Iran border. They form a considerable part of the complex and generally contain calcschist xenoliths, often as screens a few hundreds of metres in length. They comprise pyroxene (rich in salite Ca49 Mg32 FeI9), plagioclase (An52 to An77) and minor amounts of ilmenite and apatite. The gabbros contain lighter-coloured diorites with pyroxene and amphibole with a distinct structure and texture of mono-mineral bands and augens with pronounced micro-folding and foliation. The mineral grains of the diorite are strongly granulated due to deformation prior to total solidification of the rock. The diorite consists mainly of plagioclase (andesine An28 An45), pyroxene (diopside) and brown hornblende; minor amounts of chlorite, biotite, apatite, magnetite, sphene and epidote occur.

The olivine gabbro and diorite form separate bodies with variable amounts of olivine and pronounced igneous layering produced by alternating olivine-rich and plagioclase-rich rock bands. They consist of plagioclase (67% of the mode, An57-An72), brown hornblende (kaersutite), pyroxene (1-27% of the mode, Ca 45 Mg 39 Fe16) and olivine (12% of the mode, Fo64) with minor amounts of apatite, chlorite, bowlingite, calcite, biotite and iron oxides. Olivine diorites often occur within the main body of olivine gabbro with slightly different plagioclase and pyroxene compositions (An45 and Ca44 Mg40 Fe16 respectively). Biotite is more frequent in the diorites. K-Ar dating indicates a cooling age of 45Ma which suggests that the intrusions formed in Palaeogene time; the intrusions are therefore much younger than the Cretaceous country rocks.

The Bulfat Complex is intruded by minor intrusions and pegmatite. The high intrusion temperature

and assimilation of the calcareous and pelitic host rocks resulted in strongly alkaline magmatic residues which led to the formation of pegmatite and nepheline syenite. The pegmatites usually occur as offshoots from the amphibole pyroxene diorite. They are white, coarse-grained feldspar-rich dykes cutting both the intrusive and the surrounding rocks with dominant plagioclase (An32) and minor nepheline. Dykes related to the olivine gabbro and diorites contain calcic plagioclase (An56) and are often altered to prehnite and zoisite. Severely deformed small syenite dykes with clouded albite crystals are abundant near Hero. Nepheline syenites are medium-grained and grey with black prismatic crystals of amphibole (ferrohastingsite) surrounded by plagioclase with secondary twinning lamellae (An28), tabular crystals of orthoclase (Or68 Ab30 An2) and nepheline; microcline is rare. The nepheline syenite contains 55% Si02, 7% Na20, and 2.7% K20.

Analyses of the Bulfat Complex (Table 17-6) confirm that sub-alkali gabbros are predominant, except for sample 37 which has a composition approaching an alkali gabbro. The sub-alkali gabbros are high-alumina rocks with low contents of$Ti0_2$, K_20, P_20_S' and usually also of MgO. Only samples 17 and 24 have high contents of MgO; they have compositions similar to the gabbros of Penjween. The low content of Zr in the sub-alkali gabbros indicates that most of them belong to a geochemically primitive magma. Sample 37 (transitional to the alkali gabbro) is geochemically one of the most mature rocks as indicated by the high Zr content and the high contents of $Ti0_2$, K_20, and P_20_S' Sample 30 shows a higher Zr content indicating it is of more mature composition than other Bulfat gabbros. The Mullen Plot for the intrusive rocks shows a scattered distribution in almost all fields probably due to the alteration of their chemical composition by assimilation of the country rocks. Variations in the Zr content (5-204 ppm) in the Bulfat intrusive rocks may be due to assimilation of the country rocks. The samples with low Zr (27 and 28) have high $A1_20_3$, low FeO (tot) and very low P_20_S contents; they may represent geochemically primitive magmas of immature island arcs. The higher values of Zr in other samples may be related to assimilation of the surrounding host rocks. Basaltic andesites represent sub-alkali rocks with high contents of MgO, K_20 and low contents of $A1_20_3$ and $Ti0_2$.

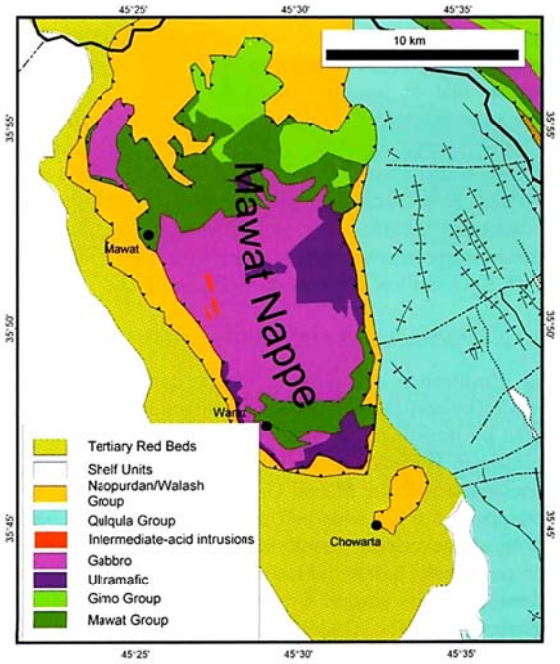


Fig. 17-2: Geological map of the Mawat Complex

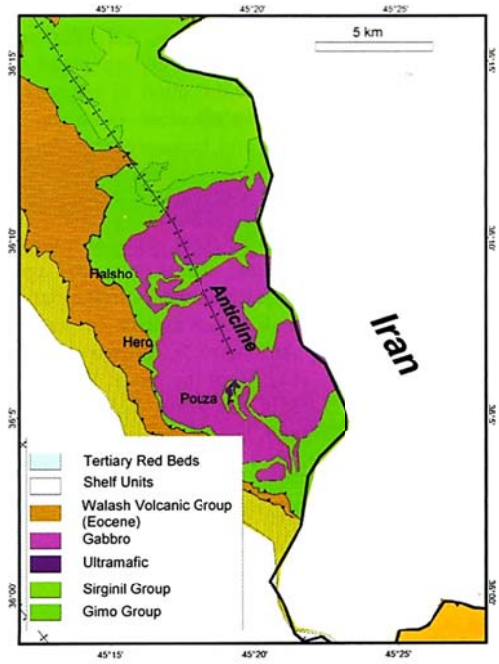


Fig. 17-3: Geological map of the Bulfat Complex

17.1.2.4 Pushtashan

The Pushtashan ophiolitic complex comprises basalts intruded by norites and last stage plagiogranite differentiates sliced by thrusting. The volcanic sequence belongs to the Pushtashan Volcanic Series (Bolton, 1956) and is probably correlatable with the Mawat Group of Cenomanian age. It outcrops in a 6 km wide belt at the base of a thrust sheet tectonically overlying grey flysch of the Naopurdan Group. It is overlain by 3500 m of tuffaceous phyllites and sheared limestone of the Sirginil Group of the Qandil Series (see Chapter 16). The Qandil Series (Roulkovsky, 1962) comprises basalt flows (50 m thick) at the base, overlain by porphyritic andesite (30 m), dark green and red shale (100 m), basalt porphyry-basalt-shale intercalations (70 m), weathered laminated tuff (6 m), basalt porphyry, red limestone, mottled calcareous shale, amygdaloidal basalt (8 m), limestone (60 m) and dark red shale (50 m). Serpentinites form lenses at the base of the complex and along thrust faults (Fig. 17-4).

The norite body (about 100 m thick, dipping 25°-30° N), which is intruded into the volcanics, is often irregularly altered to uralitized norite (odenite) containing calcic plagioclase, hornblende, and relics of pyroxene (Roulkovsky, 1962). Hornblendite lenses (0.2-0.5 m thick) are associated with the norite. Pegmatitic gabbro veins (0.5 m thick) are common and extend for hundreds of metres, generally parallel to the root of the norite body. They are medium- to-coarse grained, generally fresh-looking with labradorite, hornblende and augite. Anorthosite is often developed from norite. The plagiogranites form minor intrusions (5-40 m thick) at the top of the norite, containing plagioclase (65%) and quartz (35%). The intrusive complex appears to have been sliced from a larger complex probably lying under the thrust, some unknown distance to the E.

17.1.3 Tertiary volcanic arc of the Neo-Tethys (Penjween- Walash Zone)

Palaeogene volcanics of the Penjween- Walsh Zone occur in thrust sheets which lie tectonically between metamorphosed Cretaceous sequences above and a Cretaceous obducted unit (Qulqula-Khwakurk) below. The volcanics occur in the Walash Group and comprise intermediate volcanics, basic lavas and dykes. The basic volcanic flows are submarine basalts that pass upwards into andesites and include spilitic diabase, pyroxene-bearing spilitic basalt and spilite and associated tuffs. In the Qalat Dizeh area, the basic rocks form small dykes or minor lava flows enclosed in sediments. However, andesites and tuffs predominate; they are pyroxene and pyroxene-amphibole-bearing.

Chemical data (Table 17-7) indicates the volcanics of the Walash Group comprise sub-alkaline and alkaline suites. The TAS diagram (Fig. 17-5) can be used to recognize calcalkaline (sub-alkaline) andesite, dacite and alkaline rocks: alkali basalt, mugearite and benmoreite. The alkali basalt, mugearite and andesite are high-Al volcanics of low-K type and enriched in Iron. The chemical characteristics of the Walash volcanics (Table 17-7), especially of the andesites, are similar to those of island arcs. Most samples of the Walash volcanics fall within the Calc Alkaline Basalt (CAB) and Arc Tholeiite (IAT) fields on the plot of Mullen (1983).

17.1.4 Upper Cretaceous volcanic arc of the Shalair Zone (Sanandaj-Sirjan Zone)

The Katar Rash Group comprises over 1000 m of volcanics with minor sedimentary interbeds especially near the base. The volcanics overlie Albian *Orbitolina* bearing limestones of the Shalair Group. The group comprises three volcanic sequences; an andesite-dacite sequence at the base, followed by a rhyodacite-rhyolite-acidic andesite-Na rhyolite sequence, overlain by a dacite-andesite-basaltic andesite-K rhyolite sequence. Most of the volcanics are sodic in character though some rhyolites and basaltic andesites may be potassic (Jassim et al., 1982a).

Basaltic andesites are uncommon; pyroxene-hornblende and hornblende-biotite types occur and contain the mineral assemblage: albite-chlorite-epidote-carbonate-titanite- Ti magnetite ? apatite with relict phenocrysts of augite or augite-diopside. Andesites usually occur as thick lava flows (separated by pyroclastic beds) consisting of albite-chlorite (pycnochlorite)-epidote-zoisite-carbonate with minor titanite, magnetite, ilmenite, leucoxene, ? hematite .and quartz. Their pyroclastic equivalents are mainly litho-clastic and litho-crystalline clastic tuffs, and vitro-clastic tuffs and agglomerate. Dacites and rhyodacites are not widespread and comprise small flows and pyroclastic sheets. Rhyolites form thick lenticular flows with strong flow structures associated with thick pyroclastic accumulations. The mineral assemblage in the rhyolites is albite-chlorite-quartz-epidote with accessory calcite-opaque (hematite, Timagnetite, ilmenite)-titanite. Sericte occurs in shear zones. The groundmass of the rhyolites is often formed of devitrified glass. Their pyroclastic equivalents are crystal or lithic tuffs and agglomerate. The lithic fragments often consist of rhyolite and andesite. Some exceptionally thick rhyolite flows are coarse-grained and porphyritic in texture and resemble granitoid bodies or sills.

The plot of the Katar Rash volcanics on the TAS diagram (Fig. 17-5) and their chemical analyses (Table 17-8) indicate they belong to the calc-alkaline and alkaline suites. The calc-alkaline suite comprises sub-alkali basalt, basaltic andesite, andesite, dacite and rhyolite. The alkaline suite comprises trachybasalt (hawalite and potassic trachybasalt), basaltic trachyandesite (mugearites), and trachyandesites (benmoreites). Both suites have high Alumina contents except for two samples of the sub-alkali basalts that have higher Fe, MgO and Ti02 contents. The volcanics of the Katar Rash fall within the Calc Alkaline Basalt (CAB) and Arc Tholeiite (IAT) fields of Mullen's discrimination plot (Fig. 17-9), confirming that they formed in a volcanic arc.

The Katar Rash volcanics are predominantly of calcalkaline composition, transitional to Na-type alkaline rocks; a similar compositional distribution is seen in the Aleutians where basic rocks of calc-alkaline series show a trend to alkaline rocks (Irvine and Baragar 1971). The geochemical features of the Katar Rash volcanic sequence confirm the primitive mantle character of the magma (e.g. the low contents of Ti, Zr and Y) and indicate that these volcanics formed in an island arc. According to Hamilton (1995), volcanic rocks erupted in mature oceanic island arcs typically comprise alkaline basalt, high Al basalt, andesite and dacite. However, the presence of rhyolites with high contents of Si02, K20 and Zr suggest that the parent magma was influenced by melting of continental crust which suggests that the volcanic arc was located along an active margin on the SW side of the Sanandaj-Sirjan Zone.

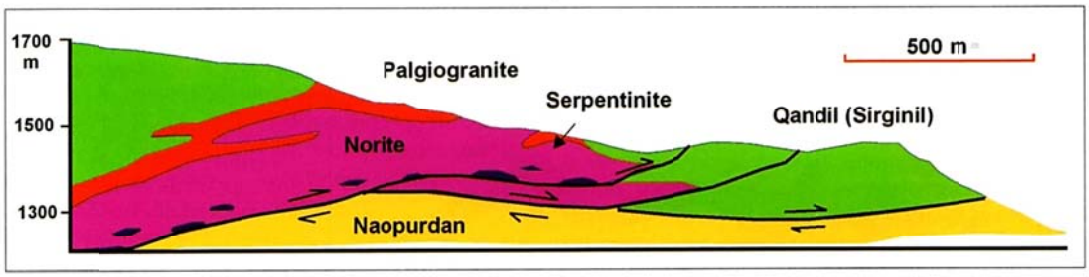


Fig. 17-4: Cross section through the Pushtashan Complex

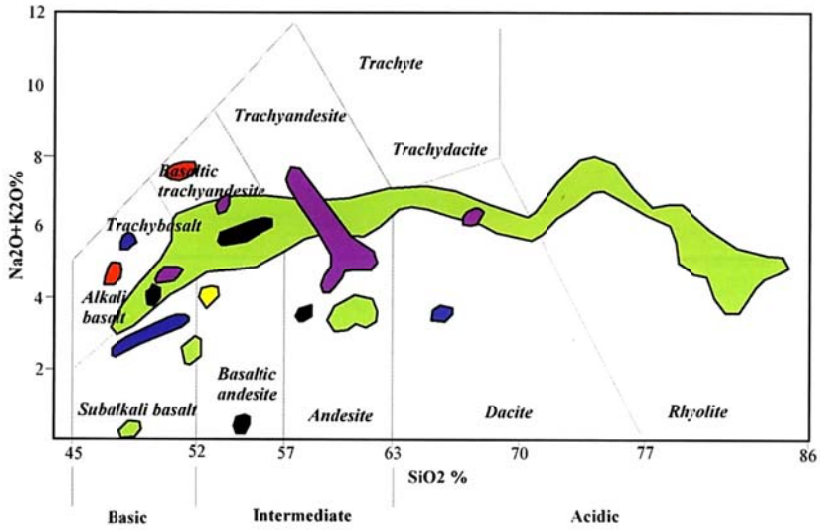


Fig. 17-5: TAS (alkali-silica) plot of volcanics (Le Maitre, 1989) of the volcanics of the Zagros ophiolites which include the Katar Rash Cretaceous arc volcanics (light green), volcanics of the Qulqula-Khwakurk Zone (red), Eocene volcanics of the Walash (purple), Mawat volcarics (blue), Bulfat (yellow), Penjween (black). The plots are from analyses of Buday and Jassim (1987)

17.1.5 Origin of the Iraqi Ophiolites

The plots of the Iraqi ophiolites on the Mullen discrimination diagram (Mullen, 1983) show that the volcanics of the Qulqula-Khwakurk Zone lie within the Oceanic Islands Basalt Association (OIA). The Penjween volcanics fall with the fields of Island Arc tholeiite (IAT) and Calc Alkaline Basalt (CAB). The Mawat volcanics are of Mid-oceanic Ridge Basalt type (MORB), metamorphosed at ridge position soon after crystallization and at low pressure (-1 Kb) and Temperature (-500°C) soon after crystallization at around 105±5 Ma (Aswad and Elias, 1988). The Penjween gabbros were formed from partial melting of the upper mantle leaving behind a dunite restite (AL Hassan and Hubbard, 1985; Al Hassan, 1987). Their REE compositions of (1.5 to 7 times those for chondrite) indicate a mantle origin for the magma *(AL* Hassan (1987). The similar petrography and chemical composition of the gabbroic rocks of both Penjween and Mawat (Jassim and Al Hassan, 1977) suggests that both these complexes had the same origin. The pyroxenites were probably derived from the gabbro magma at the anatectic equilibrium (AL Hassan, 1987). Further fractionation occurred during emplacement of the gabbros by squeezing of the residual plagiogranite liquid into shear zones (Jassim, 1973 and Jassim and Al Hassan, 1977). Pyroxenites and pegmatoid coarse grained gabbros are probable differentiates of the original, probably picritic, tholeiite magma. The norites of the Pushtashan complex are probably comparable in origin to the Mawat and Penjween coarse pegmatitic gabbros.

The gabbros intruding the Bulfat ophiolitic complex are of different origin. A wide thermal aureole is developed around them with temperatures of metamorphism ranging from anatexis (around

850°C) at the immediate contact to low temperature Albite-Epidote-Hornfels facies away from it (Section 17.2.3). The Bulfat gabbro magma suffered contamination by assimilation of limestone and pelitic country rocks, with formation of late stage alkaline nepheline syenite of contrasting composition to the late stage calc-alkaline plagiogranite of the Mawat and Penjween Complexes. The age of the gabbro in the Bulfat range is 45 Ma (cooling age) which suggest that it was probably emplaced any time between the Danian to Middle Eocene whereas the gabbros of Mawat and Penjween were intruded during the ocean spreading process in Albian Cenomanian time. The Bulfat gabbros may be syn-tectonic intrusions associated with the Eocene Walash volcanic arc, intruded into the deformed Nee-Tethyan ocean floor above a subduction zone during the final closure of the Neo- Tethys (Chapter 3). Ophiolites associated with radiolarian chert and coloured melange are represented by the ultramafic rocks of Darband Rayat; they require further study.

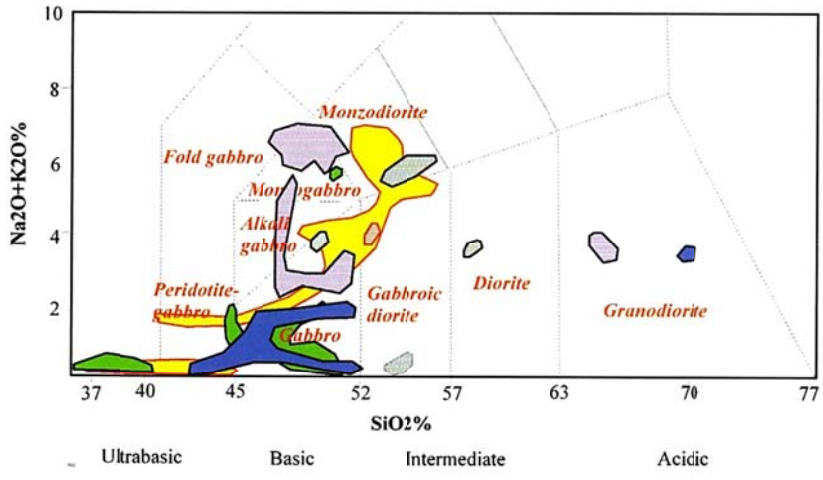


Fig. 17-6: TAS (alkali-silica) plot of the Plutonic rocks (Middlemost, 1994) of the intrusive rocks of the Zagros ophiolites which includes: Bulfat (yellow), Mawat (Blue), Penjween (green) and sub-volcanics and metavolcanics (hatched) from data of Buday and Jassim (1987), Buda and Al Hashimi (1977) and Aswad and Elias (1988)

17.2 Metamorphism of the Zagros Suture units

17.2.1 Serpentinite imbricates

The ophiolite suites of Penjween, Mawat and Bulfat (Figs. 17 -1 to 3) contain serpentinized ultramafic rocks which were mobilised along thrust faults. Bolton, 1958) first referred to the association of serpentinites with thrust faults in NE Iraq.

Serpentinite imbricates occur in the Penjween- Walash Zone where large ultramafic bodies are also present. They mostly occur along thrust faults which juxtapose the metamorphosed Cretaceous volcanosedimentary successions with the underlying unmetamorphosed Tertiary volcanosedimentary successions (Walash and Naopurdan), particularly in the Bulfat area of NE Iraq. The serpentinite imbricates vary in width from a few metres to tens of metres and in places pass into major ultrabasic bodies in Bulfat and Mawat. The serpentinites often contain exotic blocks, generally small, derived from the red limestones of the Walash Group or from the phyllites and calc schist of the Qandil Series.

The Mawat range comprises two thrust sheets, a lower thrust sheet of Palaeogene volcanosedimentary rocks belonging to the Walash Naopurdan Group and an upper sheet of metavolcanic and metasedimentary rocks of Cretaceous age with large mafic and ultramafic bodies. The serpentinites are localised at the base of the higher thrust sheet. In the eastern part of the complex the serpentinite imbricates can be traced to a large ultramafic mass. Since no ultrabasic body was found on the W side of the complex, the serpentinite imbricate in that region

must have originated from 10 km away in the E.

In the Bulfat range, between Hero and Halsho villages, narrow, discontinuous serpentinite imbricates occur along the main thrust fault and in three imbricated sections of Palaeogene volcanics and Gimo Group metamorphic rocks; the serpentinites locally contain exotic blocks of calcschist.

In the Qandil range, serpentinite imbricates occur in the Pushtashan valley (Bolton, 1958) and along the main thrust separating the metavolcanic sequence from the underlying unmetamorphosed Tertiary metavolcanites of the Walash Group. Chromite bearing ultrabasic imbricates were mapped in detail in the Darband Rayat area (Bolton, 1958a; Stevenson and Cobbet, 1958; Vasiliev and Pentilikov, 1962). At least two imbricates were mapped within the Naopurdan Group, separated by a wide zone of phyllites of unknown origin. The ultramafic mass forms a tectonic window of the Khwakurk Group beneath the Naopurdan sequence. Similar ultramafic bodies were also recognised in the Khwakurk area to the North.

Serpentinite imbricates are clearly restricted to thrust faults within the Penjween- Walash zones; larger ultramafic bodies may be hidden by the thrust faults. Jassim (1973) assumed that serpentinization occurred at various stages: during initial emplacement in the Late Cretaceous and during Late Miocene thrusting.

Fig. 17-7: TAS Diagram with plots of island arc basalt (IAB), average mid-oceanic ridge basalt (MORB), average boninite, Oman volcanics, Chichijima island arc and Penjween boninites

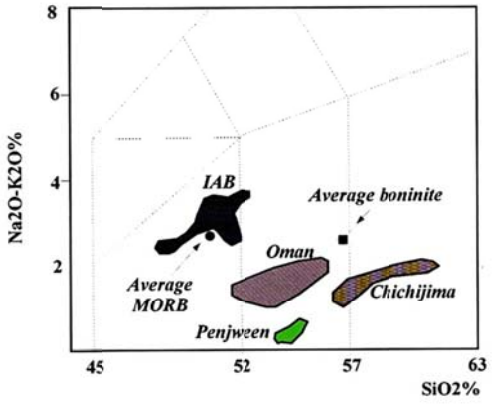
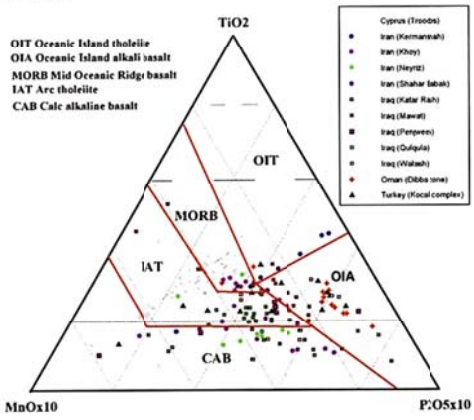


Fig. 17-8: Mn-Ti-P discrimination diagram of Mullen (1983) with plots of some of the Zagros-Taurus ophiolites and those of Cyprus and Oman



17.2.2 Regional metamorphism

17.2.2.1 Metamorphism of the Shalair and Katar Rash groups

The Shalair Group consists of regionally metamorphosed lutites in the greenschist facies (slate, phyllitic schists and phyllite), meta-carbonates and meta-igneous rocks (basalts and basic dykes). Lutites and their metamorphic equivalents consist largely of chlorite, sericite, quartz and extensively chloritized fragments of volcanic rocks and pyroclastic material with volcanic glass. Phyllitic schists and phyllites locally contain numerous vein or lenses of secretion quartz. These veins occur only rarely in the slates. Interbedded quartzite, and metamorphosed subgreywacke and grey wacke occur in the N side of the Shalair Valley in the Shalair Group. Both the Shalair and Katar-Rash groups contain interbedded tuffaceous rocks. Chlorite schists and chlorite bearing shales and tuffaceous schists with pumpellyite formed during dynamo-metamorphism.

The phyllites and slates of the Shalair valley are relatively poor in potassic feldspar and calcite (Fig. 17-9). A typical phyllite of the Shalair Group is often highly dipping and contorted (Plate 16-5) and has schistose texture in shear and crush zones.

Crystalline limestones (marbles) occur in the northern and central Shalair Valley. They have a granoblastic texture and are fine to coarsely crystalline. **In** the crystalline limestones strongly recrystallised organic remains can be distinguished. The limestones contain detrital quartz. Secondary quartz fills pores and torsion micro-joints. Most of the metacarbonates of the Shalair Group were either originally pure limestone or sandy limestones (Fig. 17-10).

The volcanics in the Shalair and Katar Rash groups have suffered low-grade regional metamorphism. The metamorphic grade of the Katar Rash volcanic complex ranges from the prehnite-pumpellyite facies to the greenschist facies. The original textures of volcanic rocks are still preserved in the greenschist. They contain albite +chlorite +epidote ±titanite ±carbonate ±quartz. Only small relics of original phenocrysts of plagioclase and coloured minerals are oreserved. Rocks containing pumpellyite and prehnite (prehnite-pumpellyite facies) were mostly pyroclastics of andesite and basaltic andesite composition.

Fig. 17-9: ACF, A'KF diagrams of the Shalair phyllitic and slate rocks

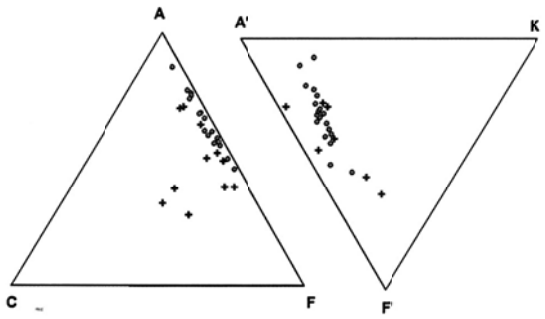
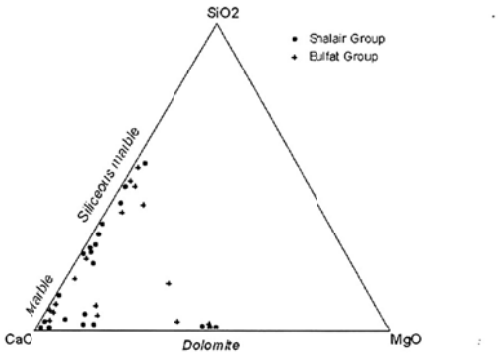


Fig. 17-10: Si-Ca-Mg ternary representation of the carbonate sedimentary rocks of the Shalair and Bulfat groups



17.2.2.2 Metamorphism at the Gimo Group

The metamorphosed Gimo (Penjween) Group outcrops in the western part of the Shalair valley to the N and NE of Penjween town. The group comprises schist, phyllitic schist and phyllite, commonly associated with lenticular recrystallised limestone, calc-schist, meta-tuffites, basic quartz-actinolite-chlorite-stilpnomelane schist and amphibolite. They were metamorphosed to the Biotite Zone (albite-epidote-amphibolite facies). Actinolite and common hornblende formed in mixed sequences of volcanic and sedimentary rocks.

In the lower part of the group (near Penjween town) crystalline limestones predominate; they grade into calcareous schists and amphibolite. The metacarbonates contain granoblastic calcite; other minerals include amphibole, epidote (near Penjween) and rare phlogopite, biotite and chondrodite (east of Penjween) and belong to the biotite zone. Amphibole is absent in the eastern part within the marginal part of the biotite zone.

Most amphibolites were derived from volcanics (spilites and olivine tholeiite); they contain minute lath-shaped plagioclase crystals and strongly corroded prismatic crystals of actinolite and ore. They often contain chlorite and epidote and are affected by secondary carbonitization and silicification. Amphibolites were also derived from the gabbros of the Penjween igneous complex during subsequent amphibolitization (uralitization), by metamorphism at gabbro-peridotite contacts, and by dynamic metamorphism during thrusting. Uralitization of the gabbro occurred during emplacement of the semisolidified gabbro into the overlying metasedimentary sequence (Jassim and Al Hassan, 1977). Amphibolites also formed within the serpentinized peridotite especially at contacts with pyroxenite dykes, and in shear zones in the middle of the peridotite. These amphibolites contain amphibole, epidote, (zoisite, chlorite, quartz, titanite, chromite) and? prehnite.

The amphibolites derived from the gabbro contain epidote, plagioclase, hornblende and pyroxene. They are usually strongly prehnitized with millimetre-thick prehnite veinlets that occasionally protrude into the country rocks (Ojha, 1978). Strongly folded chlorite schists (95% chlorite) occur in thrust zones. Hornblende schists occur in the crushed zones within the gabbro. Actinolite schists occur within the peridotite and zoisite-epidote-hornblende schist at the gabbro-peridotite boundary. All these rocks have very strong schistosity.

17.2.2.3 Metamorphism of the Mawat Group

The Mawat Complex was mapped in detail by GEOSURV (Jassim, 1972 and 1973; Masek and Etabi, 1973 and ALMehaldi, 1974). These surveys were accompanied by detailed petrographic and geochemical studies (Jassirn, 1973; Jassim and Al Hassan, 1977 and Buda and A-Hashimi, 1977). Aswad (1986) presented the results of isotopic age determination and Rare Earth element analysis of the metavolcanics of the Mawat Group.

The metamorphic rocks in the Mawat area comprise: 1) metavolcanics which comprise metabasalts, spilites, and keratophyres, and the related metasediments (metapelites and marbles) of the Mawat and Gimo groups, 2) basic intrusive igneous rocks and differentiates and, 3) ultramafic rocks.

The metasediments occur in the upper part of the Mawat nappe, forming the 600 m high cliff of carbonate and basalt of Gimo Mountain. Rafts of these metasediments occur in the underlying gabbro. Buday (1975) argued that the "Gimo Series" forms the mantle of the basic massif. The Group comprises mostly greyish siliceous marble and dark calc schist with tremolite, diopside, phlogopite, and forsterite. Isolated decimetre-to-metre-thick layers of phyllitic schists and metavolcanites are petrographically undistinguishable from the rocks of the metavolcanics of the Mawat Group.

Metavolcanics of the Mawat Group are exposed along the NW, SW and S margins of the Mawat nappe. Near Konjrin village, these metavolcanics contain garnets. Buda and AL-Hashimi (1977) argued that the volcanics were altered by regional metamorphism into the greenschist facies; they include numerous relics of pillow lavas and amygdales. The metamorphic rocks include chlorite-actinolite-quartz schist (with relict amphibole and plagioclase) and a blueschist that contains the glaucophane-crossite alkaline amphibole; this however cannnot be considered as a blueschist facies. The metabasalts contain relict ophitic textures and the metaspilites contain relict of pillows. Relict amphibole in the greenschists (with chlorite, calcite and epidote) and in the metavolcanites cannot be easily distinguished from amphibole of metamorphic origin. The chemical compositions of the metavolcanites are slightly undersaturated and close to oceanic tholeiite. They have identical *Na20/K20* ratios. The Mawat metavolcanics, however, are higher in Fe203 (possibly due to oxidation during metamorphism) and have a higher content of $Ti0_2$. Their content of trace elements, notably Ni (140ppm) and Cr (380ppm) are very similar to oceanic tholeiite. The Cu content is increased (due to secondary mineralisation) in the metavolcanics, due to mineralisation possibly associated with black smokers. The metabasalts are often associated with keratophyres that are poor in potassium (K_20-O.13} and rich in sodium (Na20-3.87), which formed by differentiation of tholeiitic magma.

17.2.2.4 Metamorphism of the Bulfat area (Gimo and Sirginil groups)

The Bulfat block consists of a volcano sedimentary regionally metamorphosed sequence (Gimo Sequence), which has been intruded and contact-metamorphosed by basic and intermediate rocks. The sedimentary parent rocks of the Gimo Group comprise pelites and tuffs with minor amounts of quartzite and carbonates (Fig. 17-11); they are similar to those of the Penjween area.

The Gimo (Bulfat) Group was tectonically emplaced during late Miocene thrusting. Both the basic and ultrabasic intrusive rocks were affected by cataclastic metamorphism (indicated by crushing, undulatory extinction of minerals, secondary schistosity) which increases in intensity towards thrust faults.

The volcanosedimentary succession in the Bulfat Group is regionally metamorphosed. The regional metamorphism is of relatively low-grade and corresponds to the greenschist facies or to the onset of the amphibolite facies. The chemical properties and the textures of the initial rocks have thus been mostly preserved. The original textures of the igneous rocks (metabasalts, metadiabases, meta-andesites and acidic volcanic tuffs) have been preserved (porphyritic, amygdaloidal) despite extensive crystallization of new minerals such as chlorite, actinolite, albite, epidote, zoisite, and hornblende.

The characteristic minerals of the greenschist facies vary; in marble they comprise tremolite, Mg-chlorite and mica, in pelitic rocks chlorite and mica, and in basic igneous rocks actinolite, zoisite, albite and chlorite. The metamorphic grade increase towards the base of the nappe where diopside

and tremolite formed in marbles, biotite formed in pelitic rocks and, green hornblende formed from actinolite in basic meta-volcanics. Albite disappears downwards and is replaced by oligoclase. The mineral associations suggest that regional metamorphism is of low- to medium-pressure type. Regionally metamorphosed rocks of the Bulfat block have been contact metamorphosed by basic intrusions up to 2.5 km from the contact.

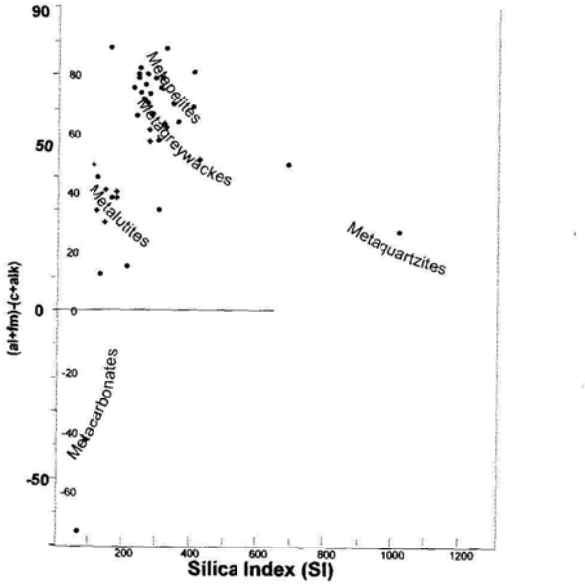


Fig 17-11: Simon's diagram for the rocks of the Bulfat Group metasedimentary rocks

17.2.3 Contact Metamorphism

Contact metamorphism occurs in the Bulfat Complex and to lesser extent in the Penjween and Mawat Complexes. Contact metamorphic rocks, mainly metasediments, are located in the NE part of the Penjween Complex. The characteristic mineral assemblage of the contact aureole includes amphibole, pyroxene, epidote, mica, feldspar and quartz. Near the contact, the rocks show preferred orientation and form bands enriched in amphibole and pyroxene. Cordierite is sometimes present but is strongly altered to sericite. Further from the contact the content of pyroxene and amphibole varies irregularly depending on the composition of the parent rock (metagreywacke). Jassim and Al Hassan (1977) described thermally metamorphosed tuffs, from an inclusion within the gabbro, near the main thrust in the western part of the Penjween Complex. This inclusion contains plagioclase, pyroxene and scapolite. Similar rocks also occur in the metasomatic iron-rich contact zone of Asnawa, at the Iraq-Iran border S of Penjween town. In this area, some rocks contain garnet, ferrohedenbergite, scapolite and magnetite. Magnetite locally exceeds 50% of the rock and may have formed during metasomatic alteration of iron-rich tuffs.

In contrast to the Penjween Complex, only very limited contact metamorphism is associated with the gabbros of the Mawat Complex. The contact of the gabbros is observed to be tectonic (Al-Mehaldi, 1974). However, Jassim and Al Hassan (1977) identified a roof pendant of spotted slate near the top of the gabbro body S of Gimo.

The gabbro and diorite intrusions of the Bu1fat Complex have complex relationships with the surrounding country rocks. Large screens of country rocks often occur at the intrusive contacts. These screens are a few metres to tens of metres thick and sometimes extend for over one kilometer along the boundary of the gabbro. Small xenoliths near Beklo are relics of initially continuous beds that were affected by plastic deformation during the intrusion of the gabbro.
Contamination of the basic magma due to assimilation of host rocks is indicated by the chemical and mineral composition of the gabbros (Section 17.1.1.3). Screens of carbonate rocks SW of Hero and near Beklo are surrounded by reaction rims and metre-size coronate structures containing high-temperature mineral associations. Pelites, which melted at lower temperature, have been completely assimilated; only some streaks of biotite and relics of the initial texture remain. Basic metavolcanics preserved as xenoliths also often have streaky boundaries due to partial assimilation by the magma.

Where the gabbro intrusions contain numerous xenoliths, it is very difficult to define the boundary between the hybrid oriented gabbros and the recrystallised partially melted amphibolites (metavolcanites). In such cases (for instance between Hero and Beklo) the boundary is a wide zone and approximate. The xenoliths occur almost exclusively in the pyroxene-hornblende gabbro and diorites. They are very rare in the olivine-pyroxene-hornblende gabbros which are the least contaminated intrusions in the Bulfat basic complex.

The composition and the mineral assemblages of the xenoliths vary depending on the chemical composition and structure of the parent rocks and on the degree of assimilation by the gabbroic magma. The most frequently occurring xenoliths consist of siliceous Mg-rich (dolomitic) marble (Ca-skarns). Definable xenoliths of anthophyllitehornfels and amphibolites are less frequent. The textures of the siliceous dolomitic marbles are very variable; schistose, granoblastic, mosalc and suture textures occur.
Calcite is usually the main constituent of the skarn. The major mineral assemblages of marble xenoliths are as follows: 1) Calcite, accessory diopside, phlogopite, 2) Calcite (dolomite), forsterite (serpentine), spinel, perovskite, 3) Calcite (dolomite), periclase (brucite), spinel, forsterite (serpentine), 4) Calcite, diopside, wollastonite, plagioclase, garnet. 5) Calcite, melilite, wollastonite, garnet, 6) Diopside, plagioclase, calcite and, 7) Anthophyllite, garnet, melilite (vesuvianite).

The temperature of the metamorphism of the xenoliths is estimated to be 60o-800°C corresponding to the pyroxenehornfels facies. Most of the reactions occurred under extremely water-deficient conditions. The reaction products of the gabbro magma and the carbonate inclusions indicate recrystallisation occurred at very low water pressures (100MPa) under sub volcanic conditions (Buday and Suk, 1980). Secondary minerals were formed during retrograde metamorphism by hydration. Vesuvianite formed from melilite, and brucite formed from periclase. Serpentinization of olivine and scapolite occurred at the expense of plagioclase.

The mineral assemblage and texture of the contact metamorphic rocks changes with decreasing distance and temperature away from the contact with the intrusions (Fig. 17-12). Spotted slates are

the lowest grade contact metamorphic rocks. The thermal aureole around the gabbro intrusion extends for 2.5 m from the contact with the country rocks. The thickness of the high-grade thermal metamorphic aureole is <150 m; medium grade contact metamorphic rocks extend up to 1.6 km from the contact (Fig. 17-12).

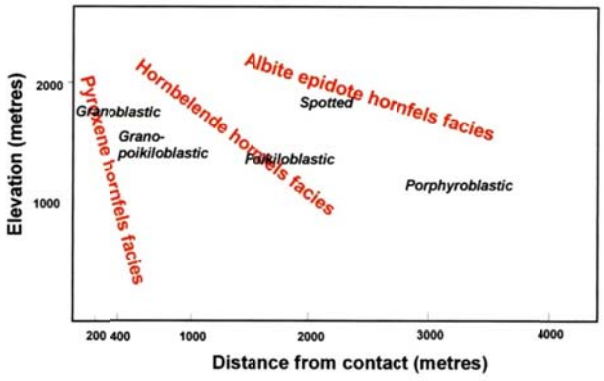


Fig. 17-12: Distribution of mineral association and textures of pelitic hornfelses based on estimated distance from intrusive contact and elevation above sea level

17.2.3.1 Contact metamorphism of pelitic rocks of Bulfat

The mineral assemblages of metapelites comprise: hornfels (pyroxene, hornblende, cordierite, andalusite), spotted schist (andalusite, chiastolite), and phyllite (which formed during regional metamorphism). The metamorphic facies of the hornfels comprise: pyroxene-hornfels, hornblende-hornfels and albite-epidote hornfels facies. The albiteepidote hornfels facies passes into the regional metamorphic rocks of the Bulfat Group (Fig. 17-13).

The bulk chemical composition of the contact metamorphosed pelitic rocks is very similar. The (FeO + Mn)/(FeO + MnO + MgO) ratio ranges between 0.76 to 0.77 and the variation is, therefore, related to reactions caused by the variable PT conditions. Facies of the high grade pyroxene hornfels comprise Fe-rich pyroxene, biotite, orthoclase (microperthite), andesine, ± sillimanite, accessory tourmaline and garnet. This mineral association is estimated to have formed at temperatures of 560-580°C and a pressure of 1 Kb. The highest grade pyroxene hornfels contain hypersthene and formed at an estimated temperature of 650-850°C and a pressure of l Kb (Fediukova, 2004).

Further mineral association with cordierite minerals can be found in rocks of medium metamorphic grade, composed of cordierite, biotite, andalusite, plagioclase, ± sillimanite, garnet, muscovite, and tourmaline. The estimated temperature of origin of this mineral association is 400520°e. Cordierite minerals are also present in rocks ,of transitional facies characterized by andalusite schists. Analyses of the cordierite minerals, at different grades of contact metamorphism studied are shown in Table 17-9. The "mg" index decreases with increasing metamorphic grade. The Fe-content increases with metamorphic grade in cordierite minerals from Mg-cordierite up to sekaninalte (Fig. 17-14).

The garnets in the andalusite schists are of almandinespessartine composition but with significant pyrope content. The microprobe composition of garnet is: 37.90% $Si0_2$, 0.10% $Ti0_2$, 19.35% $A1_20_3$, 19.98% FeO, 13.40% MnO, 2.90% MgO, 2.10% CaO and 0.05% Na20. Recalculation on the basis of 12 Oxygen indicates a garnet composition of 50.63% almandine, 6.20% grossularite,

11.90% pyrope and 31.27% of spessartine components. The garnet composition and related cordierites and biotites are plotted in a ternary diagram (Fig. 17-15).

The binary relation among all three minerals with regard to the FeO versus MgO ratio is presented in Fig. 17-16. Biotite and garnet approximately contain similar amounts of FeO.

The garnet is impoverished in MgO. Biotite and cordierite have higher amounts of MgO. Cordierites are impoverished in MgO. Decomposition of the minerals of the cordieritesekaninalte series occurs in hornfelses of the Bulfat massif, dependent on the distance from the intrusive contacts. In low- and medium-grade hornfelses, rocks rich in Mg component (cordierite) occur; in higher grade rocks, varieties with Fe>Mg (sekaninalte) occur.

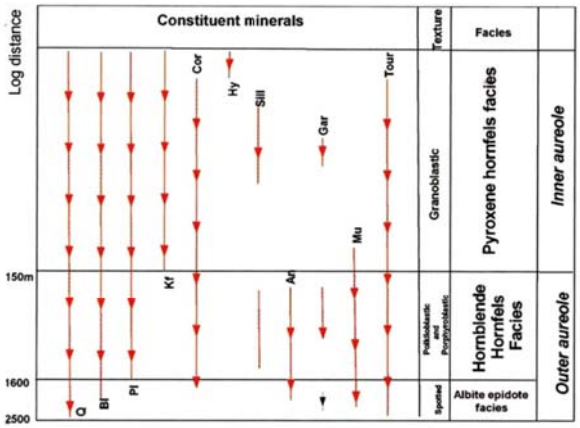


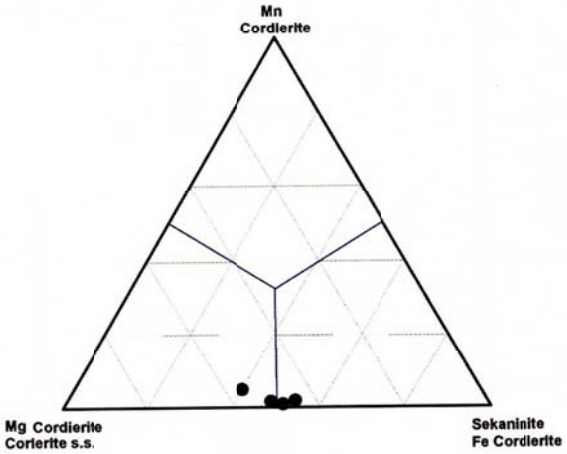
Fig. 17-13: Simplified mineralogical and textural scheme of contact metamorphosed pelitic rocks in the aureole of the gabbroic intrusions of the Bulfat Complex

17.2.3.2 Contact metamorphism of calcareous and basic rocks of Bulfat

Contact metamorphic calcareous and basic rocks were metamorphosed under the conditions of pyroxenehornblende- hornfels and albite-epidote-hornfels facies. The high-temperature mineral assemblage diopside wollastonite occurs near the contact with the gabbro. Diopside without wollastonite indicates lower temperatures; this assemblage is recorded twice in a N-S profile between the diopside-wollastonite and diopsidetremolite bearing rocks (about 600 and 400 m from the contact), and between the diopside-tremolite and tremolitebearing rocks (2200 to 2900 m from the surface contact). This latter occurrence indicates the contact with the underlying intrusion lies at shallow depth.

A rare rock type (anthophyllite hornfels) formed by contact metamorphism of silica-rich calcareous rocks by diorite. This hornfels is fine-grained and spotted: the white part consists of calcite, garnet, diopside, plagioclase, sphene, altered melilite (vesuvianite) and prehnite; the dark part contains anthophyllite, garnet, phlogopite, calcite and sometimes plagioclase (andesine). It occurs at Halsho and Hero villages.

Fig. 17-14: Ternary classification of minerals of the cordierite-sekaninaite series. Two cordierites and two sekaninaite minerals are plotted



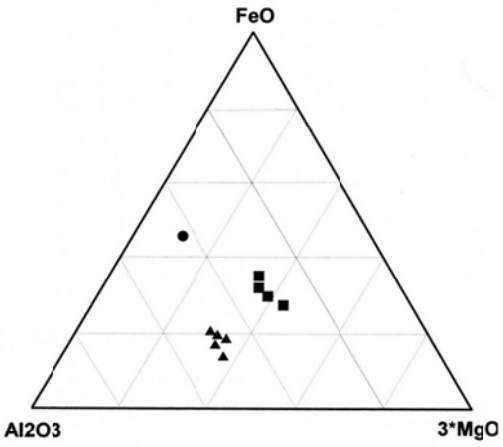
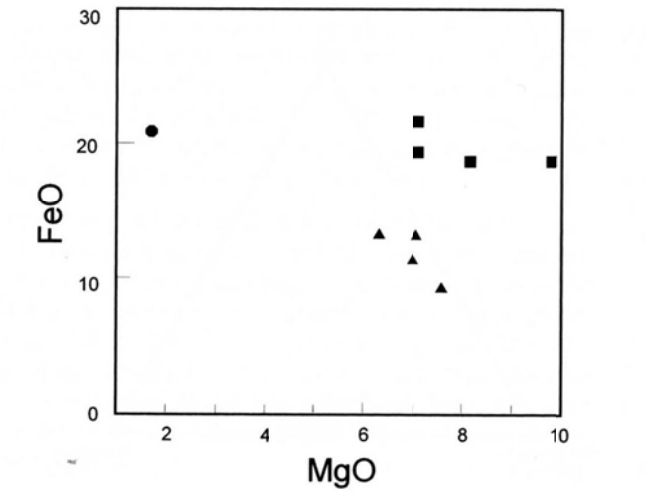


Fig. 17-15: Ternary diagram (FeoTot: 3MgO: Al2O3) with plots of four minerals of the cordierite sekaninaite series (triangles), four coexisting biotites (square) and garnet (circle)

Fig. 17-16: Binary diagram of FeO versus MgO of three minerals as in Fig. 17-14



17.2.4 The development of the metamorphism of the Zagros Suture

The metamorphic pattern of the Zagros Suture was first studied by Bolton (1956 and 1958). He considered that dynamic metamorphism occurred during deep burial in a geosyncline. Polnikov and Nikolayev (1962) subsequently reported the occurrence of high-temperature minerals in the Bulfat massif indicating that contact metamorphism had locally occurred. Masek and Etabi (1973) considered that high temperature metamorphism was controlled by "thermal domes" affecting individual blocks. Buday (1975) and Buday and Jassim (1987) considered that both regional dynamothermal and contact metamorphism had occurred. Differences determined in regional metamorphic grade from phyllite schists in Penjween to cordierite- and sillimanitebearing schists in the Bulfat were noted. Buda and Al-Hashimi (1977) identified hydrothermal, dynamic, and contact metamorphism in the Mawat Massif. The hydrothermal metamorphism occurred during sea water movement through ocean floor basalt volcanics. Dynamometamorphism (mylonitization) occurred during thrusting under greenschist to albite-epidote amphibolite facies conditions. Jassim and Al Hassan (1977) noted that the dynamic metamorphism postdates the contact metamorphism.

17.2.5 History of metamorphic events

1. Hydrothermal metamorphism of oceanic volcanic rocks occurred in Early-Late Cretaceous time. It was caused by the interaction between basalts, seawater and hot magmatic fluids. Spilitization of basalts in the Mawat, Bulfat and Penjween complexes resulted in an increase in their Sodium content. The age of this event has been dated from the Mawat Volcanics (Aswad et al., 1986) as Late Albian-Cenomanian (95-107 Ma).

2. Regional metamorphism occurred during Late Cretaceous deformation in the Neo- Tethys and in the Sanandaj-Sirjan Zone. Intra-oceanic compression resulted in the deformation and metamorphism of the Mawat, Gimo and Sirginil groups. During regional metamorphism the original textures of the rocks and their initial chemical properties have mostly been preserved.

The newly formed mineral assemblages are of the andalusite-staurolite type (Dalradian type). Widespread high-pressure/low temperature metamorphic rocks do not occur in NE Iraq. However pumpellyite and stilpnomelane occur in the Penjween Group. These minerals are common in rocks of suitable chemical composition even in the andalusite-staurolite metamorphic facies. An isolated occurrence of blueschist is recorded in the Mawat Massif. In the Bulfat Group an increase in metamorphic grade occurs from greenschist facies present in the uppermost frontal parts of the nappe, to the upper part of the albite-epidote amphibolite facies in the structurally lowest parts of the nappe. In the Mawat Group the albite-epidote amphibolite facies is predominant. In the Shalair anticline the phyllites of the greenschist facies increase in metamorphic grade towards the fold axis.

3. Contact metamorphism of country rocks of the Bulfat group by syn- to post-tectonic gabbros occurred in Palaeogene time. Intrusions of similar Eocene age occur in the thrust belt in adjacent SW Iran. Age determination of the Bulfat gabbro indicates a cooling age of 45 Ma consistent with intrusion in Palaeocene-Mid Eocene time. The mineral assemblages of the contact zone formed at low pressures; intrusion of the gabbros occurred under subvolcanic conditions. A short cooling period is therefore likely. A contact metamorphic aureole 2.5 km wide is present around the gabbro intrusions of Bulfat. The contact metamorphic facies in the country rocks comprise sanadinite facies, pyroxene hornfels facies, hornblende hornfels facies and albite epidote hornfels facies with increasing distance from the contact with the gabbro. The temperature of contact metamorphism of the Bulfat skam, inferred from the associations of carbonate rocks was 700-750°C, reaching 850°C in xenoliths and at the contact of the gabbros with the country rocks. In Penjween and Mawat, the Cretaceous basic intrusions are associated with skams that formed at much lower temperatures; a temperature of 300-400°C is estimated for the skams of Penjween.
4. Cataclastic metamorphism affected the rocks of the Zagros Suture during the collision of the Sanandaj Sirjan Zone with the Arabian Plate during Late Miocene Pliocene time. Jassim (1973) and Jassim and Al Hassan (1977) described cataclastic deformation of both the intrusive and volcanic host rocks of the Mawat and Penjween area along thrust faults and shear zones. This metamorphic event also affected the Naopurdan and Walash groups of the Penjween- Walash Zone.

Oxide	Basalt	Trachyte	
SiO_2	43.71	49.29	47.97
TiO_2	2.41	2.53	2.39
Al_2O_3	16.88	15.15	14.85
Fe_2O_3	8.15	13.68	1.05
FeO	3.6	1.05	1.25
MnO	0.51	0.11	0.12
MgO	4.01	1.37	1.54
CaO	8.21	4.9	6.1
Na_2O	3.48	7	6.8
K_2O	0.76	0.22	0.26
P_2O_5	0.69	0.59	0.54
H_2O^+	3.54	1.51	1.93
H_2O^-	1.25	0.19	0.37
S	0.06	0.02	0.01
F	0.09	0.05	0.05
Total	**99.7**	**99.57**	**99.78**

Table 17-1: Chemical analyses (wt%) of volcanic rocks from the Naorbab Plain, SE of Sulaimaniya; the basalt belongs to the Cretaceous Qulqula Radiolarian Chert Formation and trachytes to the Triassic Avroman Limestone Formation

Table 17-2 Chemical analyses (wt%) of the Penjween intrusive rocks

	Gabbros												
Sample	**103**	**97**	**88**	**108**	**99**	**109**	**87**	**98**	**100**	**104**	**101**	**107**	**105**
$Si0_2$	43.14	43.57	44.08	44.76	44.84	45.45	46.71	47.09	47.14	47.73	48.16	48.61	48.71
TiO_2	1.52	1.09	0.45	0.13	0.1	0.17	0.11	0.2	0.09	0.2	0.14	0.62	0.21
Al_2O_3	16.01	14.5	16	18	18.57	17.74	16.34	16.37	16.01	17.34	14.43	7.22	12.79
Fe_2O_3	2.21	7.58	4.58	0.95	2.26	0.8	3.28	1.1	3.86	1.19	3.73	4.38	1.17
FeO	10.72	10.58	4.27	3.94	3.39	3.59	3.5	6.39	2.1	5.14	5.01	5.04	6.75
MnO	0.23	0.2	0.02	0.1	0.02	0.09	0.02	0.15	0.01	0.14	0.03	0.04	0.17
MgO	9.01	6.15	12.67	10.72	9.92	12.39	11.46	11.36	13.16	10.17	11.29	17.12	12.49
CaO	11.01	11.84	13.86	14.89	17.51	14.24	15.92	12.74	14.83	13.78	15.41	12.76	13.32
Na_2O	1.65	0.61	0.89	0.92	0.81	1.06	0.52	0.4	0.37	0.63	0.37	1.52	0.41
K_20	0.14	0.06	0.04	0.03	0.04	0.09	0.03	0.16	0.04	0.02	0.02	0.2	0.03
P_20_5	0.15	0.08		0.03		0.04		0.03		0.03			0.03
H_20^+	3.25	2.47		4.44		3.62		3.12		2.98			3.09
H_20^-	0.21	0.23		0.33		0.37		0.24		0.26			0.21
H_2O (tot)			3.12		2.51		2.08		2.36		1.39	2.55	
$C0_2$	0.01	0.01		0.01		0.03		0.04		0.01			0.01
C	0.02	0.02		0.02		0.01		0.02		0.03			0.02
S	0.04	0.17		0.04		0.04		0.06		0.05			0.05
F	0.02	0.01		0.01		0.01		0.01		0.01			0.01
Total	**99.37**	**99.16**	**99.98**	**99.31**	**99.97**	**99.73**	**99.91**	**99.48**	**99.97**	**99.7**	**99.98**	**99.96**	**99.46**

Table 17-2 (continued)

	Monzo-gabbro	Pyroxenite	Ultramaflcs		
	96	89	112	90	111
SiO_2	49.26	48.75	33.56	35.42	37.28
$Ti0_2$	1.17	0.1	0.02	0.03	0.03
AI_2O_3	16.57	1.3	1.68	1.47	1.25
Fe_20_3	2.39	4.86	2.76	3.41	4.05
FeO	8.37	3.18	4.26	3.96	3.66
MnO	0.16	0.05	0.06	0.1	0.13
MgO	5.01	24.3	49.51	47.43	45.35
CaO	8.56	14.02	0.8	0.75	0.69
Na_aO	5.28	0.18	0.06	0.08	0.09
K_2O	0.22	0.03	0.01	0.01	0.01
P_20_S	0.13				
H_2O^+	1.81				
H_2O^-	0.19				
H_2O (tot)		3.08	7.25	7.79	7.44
CO_2	0.04				
C	0.04				
S	0.43				
F	0.02				
Total	**99.65**	**99.85**	**99.97**	**100.45**	**99.09**

Table 17-3a: Chemical analyses (wt%) of the volcanic rocks of the Penjween Group

Oxides	Subalkali-basalt	Mugearite		Moreite	Andesite	Boninites
	92	94	91	95	110	93
SiO_2	47.55	52.49	53.51	54.68	51.82	52.81
TiO_2	0.73	0.92	0.8	1.96	0.22	0.25
Al_2O_3	16.73	18.18	14.4	13.12	4.56	5.2
Fe_2O_3	2.68	1.88	2.37	5.54	1.59	2.02
FeO	5.89	4.05	5.42	4.6	6	6.54
MnO	0.09	0.1	0.16	0.08	0.17	0.2
MgO	7.58	6.08	7.11	3.53	18.02	16.76
CaO	10.94	8.51	6.1	6.66	13.55	12.47
Na_2O	2.89	5.1	4.99	3.23	0.22	0.37
K_2O	0.86	0.38	0.8	0.07	0.02	0.03
P_2O_5	0.15	0.17	0.19	0.61	0.03	0.03
H_2O'	2.84	1.58	2.84	3.88	3.04	2.46
H_2Q-	0.21	0.34	0.4	0.63	0.29	0.15
CO_2	0.11	0.07	0.68	1.03	0.02	0.02
C	0.04	0.02		0.03	0.02	0.02
S	0.04	0.01	0.02	0.33	0.03	0.06
F	0.03	0.03	0.03	0.06	0.02	0.01
Total	**99.29**	**99.94**	**99.82**	**100.01**	**99.64**	**99.4**

Table 17-3b: Chemical analyses (wt%) of Boninites from Oman and other oceanic localities

	Oman	Bonin Islands		Mariana Trench
Sample	**OM2-73P**	**EK-03**	**EK-08a**	**4**
$Si0_2$	52.9	56.33	55.86	55.56
TiO_2	0.26	0.09	0.1	0.21
Al_2O_3	12.44	7.47	10.19	10.25
Fe_2O_3	8.75	10.36	9.36	2.85
FeO				5.86
MnO	0.15	0.19	0.16	0.18
MgO	10.91	17.13	11.68	13.57
CaO	13.03	5.95	10.61	5.91
Na_2O	0.9	1.04	0.28	1.51
K_2O	0.19	0.4	0.41	0.69
P_2O_5	0.04	0.04	0.04	0.03
H_2O				3.65
Total	**99.58**	**99**	**98.69**	**100.29**

Table 17-4: Chemical analyses (wt%) of intrusive rocks of the Mawat igneous complex

	Gabbro		Pyroxenite	Ultramafic	Plagiogranite
Sample	**75**	**76**	**81**	**82**	**80**
SiO_2	45.75	50.03	48.31	39.11	70.05
$Ti0_2$	0.31	0.4	0.12	0.04	0.34
Al_2O_3	17.9	15.37	2.87	2.43	12.64
Fe_2O_3	4.38	3.73	4.2	3.67	3.75
FeO	3.35	3.74	4.47	3.91	1.49
MnO	0.03	0.07	0.05	0.08	0.05
MgO	10.35	9.35	23.53	41.57	0.58
CaO	14.45	12.56	13.13	1.43	6.12
Na_2O	1.43	1.81	0.22	0.1	3.26
K_2O	0.2	0.1	0.03	0.02	0.31
H_2O (tot)	1.93	1.54	2.79	7.32	1.17
Total	**100.08**	**98.57**	**99.72**	**100.01**	**99.74**

Table 17-5: Chemical analyses (wt%) of the volcanic rocks of the Mawat igneous complex

	Alkali basalt	Mugearite	Benmoreite	Andesite				Dacite	
Sample No.	**122**	**125**	**123**	**124**	**113**	**114**	**116**	**115**	**126**
$Si0_2$	46.96	46.96	50.49	55.16	56.77	57.21	58	59.61	64.75
$Ti0_2$	1	1	1.78	0.94	0.39	0.37	0.46	0.4	0.27
Al_2O_3	15.06	15.98	15.48	14.35	15.56	19.55	15.52	16.01	14.75
Fe_2O_3	4.52	4.52	4.46	4.19	5.08	3.93	4.59	2.93	2.24
FeO	5.25	5.25	4.92	5.86	3.5	1.34	2.74	1.85	1.27
MnO	0.13		0.09	0.13	0.12	0.09		0.06	0.05
MgO	6.45	6.45	4.96	2.96	2.42	3.18	2.89	4.83	1.78
CaO	8.54	8.54	5.86	4.96	7.44	5.88	5.75	5.67	4.77
Na_20	3.42	3.41	5.03	7.04	4.04	5.13	5.05	3.98	5.13
K_2O	0.84	0.84	1.14	0.1	0.1	0.84	0.54	0.77	0.84
P_20_5	0.14	0.92	0.3	0.14	0.08	0.13	0.92	0.21	0.11
H_2O*	4.01		3.03	1.44	1.98	2.91		2.62	1.56
H_2O	0.22		0.64	0.16	0.16			0.53	0.25
H_2O (tot)	4.55				2.39				
$C0_2$			0.95		0.05				
S			0.02		0.01				
F			0.03		0.03				
Total	**99.26**	**98.16**	**99.26**	**98.13**	**98.6**	**98.33**	**99.47**	**99.62**	**99.44**

Table 17-6: Chemical analyses (wt%) of intrusive rocks of the Bulfat Complex and one basaltic andesite

	Gabbro										Gabbro-diorite		
Sample	**30**	**37**	**25**	**17**	**18**	**3**	**29**	**2**	**19**	**24**		**15**	**4**
SiO_2	46.55	47.88	49.17	49.47	49.5	49.85	49.99	50.08	50.08	50.47	51.45	53.09	55.37
TiO_2	1.44	2.36	0.89	0.43	0.64	2.69	1.01	0.59	0.19	0.48	1.3	0.74	0.45
AI_2O_3	12.39	13.96	17.26	18.1	18.57	16.95	17.87	18.55	23.08	17.22	15.5	18.7	17.89
Fe_2O_3	3.51	3.28	1.79	1.56	1.8	1.41	2.09	1.64	0.93	1.37	2.51	0.93	1.29
FeO	4.72	7.37	2.99	4.16	5.66	8	3.07	5.5	3.3	5.39	3.5	5.05	3.45
MnO	0.15	0.2	0.1	0.1	0.14	0.17	0.08	0.13	0.06	0.12	0.11	0.13	0.09
MgO	7.1	2.78	6.53	8.85	6.03	5.46	4.94	5.77	6.81	9.17	5.83	5.64	3.23
CaO	19.26	14.92	17.14	9.16	10.54	9.86	15.4	10.42	9.58	10.86	12.99	9.75	11.34
Na_2O	1.58	3.58	2.27	3.62	3.32	3.81	2.84	3.6	3.6	3.34	3.54	4.57	4.51
K_2O	0.41	0.57	0.3	0.15	0.13	0.26	0.37	0.15	0.08	0.08	0.3	0.39	0.83
P_2O_5	0.61	0.94	0.07	0.08	0.1	0.43	0.08	0.19	0.03	0.03	0.11	0.1	0.08
H_20*	1.02	1.49	1.16	1.48	0.7	0.55	1.47	0.81	0.97	0.72	1.6	0.8	0.89
H_20'	0.12	0.1	0.14	0.15	0.13	0.35	0.15	0.15	0.09	0.14	0.25	0.12	0.19
CO_2	0.49	0.06	0.05	0.07	0.03	0.05	0.07	0.04	0.1	0.14	0.04	0.05	0.09
C	0.02	0.03	0.03	0.05	0.02		0.02			0.02	0.03	0.03	0.03
S	0.09	0.06	0.05	0.06	0.12	0.09	0.05	0.01	0.07	0.12	0.03	0.1	0.03
F	0.06	0.04	0.02	0.02	0.02	0.03	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Total	99.69	99.77	100.41	99.75	99.53	100.03	99.7	99.7	99.28	99.97	99.25	100.26	99.93
Sr	436	411	628	319	422		525		371	281	299	335	376
Zr	115	193	20	5	5		21		5	5	5	5	28
Y	24	52	15	5	5		21		5	15	5	5	26

Table 17-6 (continued)

	Monzodiorjtes						Serpentinites								Pyroxenite		Basaltic andesite
Sample No.	26	34	35	28	1	27	20	9	10	12	11	22	21	8	36	23	14
SiO_2	50.34	50.74	52.52	52.81	53.1	53.47	31.56	32.31	38.51	38.71	40.14	41.48	41.59	41.92	40.16	44.45	50,96
$Ti O_2$	2.26	1.87	1.45	1.43	1.17	1.05	0.03	0.27	0.09	0.14	0.06	0.02	0.03	0.04	4,22	2,58	0,85
Al_2O_3	14.92	15.99	16.44	21.82	16.58	22.76	0.58	11.6	1.27	0.5	0.6	0.6	0.87	0.21	8,18	9,81	13.97
Fe_2O_3	3.58	2.47	1.82	1.3	1.57	1.19	5.18	5.73	7.1	6.78	3.6	2.68	2.98	2.58	5,29	4,07	2,24
FeO	7.26	6.37	5.7	2	4.39	2.01	1.62	7.5	2	1.84	4.03	5.38	4.92	5.15	8,92	6,47	6,13
MnO	0.18	0.17	0.15	0.05	0.09	0.04	0.08	0.2	0.13	0.09	0.1	0.12	0.11	0.1	0,22	0,16	0,15
MgO	4.08	5.37	5.34	1.73	7.02	2.08	29.49	24.76	35.56	382	42.86	42.98	40	43.64	5,38	7,89	8,95
CaO	7.77	8.09	7.25	11.05	7.84	10.47	11.41	5.06	1.32	1.4	1.75	0.39	1.34	0.43	23,94	20,64	9,56
Na_2O	5.35	6.05	5.95	5.12	5.2	5.38	0.05	0.03	0.1	0.15	0.1	0.04	0.18	0.06	0,62	1,3	3,32
K_2O	0.45	0.76	0.73	0.54	0.18	0.46	0.01	0.01	0.03	0.04	0.04	0.01	0.07	0.02	0,1	0,3	0,49
P_2O_5	0.54	0.31	0.27	0.11	0.1	0.03	0.03	0.11	0.09	0.1	0.07	0.05	0.05	0.09	1,16	0,24	
H_2O^+	1.22	1.41	1.89	1.46	1.51	1.39	9.39	11	11.93	10.69	5	4.78	6.83	4.6	0,69	1,46	
H_2O^-	0.16	0.14	0.38	0.41	0.15	0.09	0.69	0.4	0.88	0.43	0.21	0.53	0.26	0.38	0,26	0,15	
CO_2	0.36	0.2	0.04	0.1	0.14	0.05	9.05	0.16				9.05	0.36	0.2	0,23	0,03	
C	0.03	0.04	0.02			0.04	0.06					0.02	0.03		0,07	0,03	
S	0.15	0.05	0.04	0.02	0.04	0.06	0.05	0.03				0.04	0.04	0.02	0,06	0,05	
F	0.07	0.04	0.02	0.02	0.04	0.02	0.03	0.01				0.01	0.03	0.01	0,01	0,01	
Total	99.85	100.22	100.06	100.08	99.62	99.8	100.09	99.24	99.34	95.61	98.64	100.14	99.7	99.78	99,61	100,01	
Sr	246	239	297	803		803	42					5	28		171	75	
Zr	58	180	183	5		5	5					5	5		76	204	
Y	17	39	39	17		17	5					10	5		47	14	

Table 17-7: Chemical analyses (wt%) of the volcanic rocks of the Walash Group

	Alkali basalts		Mugearite	Benmoreite	Andesites				Dacite
Sample No.	**122**	**125**	**123**	**124**	**113**	**114**	**116**	**115**	**126**
SiO_2	46.96	46.96	50.49	55.16	56.77	57.21	58	59.61	64.76
TiO_2	1	1	1.78	0.94	0.39	0.37	0.46	0.4	0.27
Al_2O_3	15.06	15.98	15.48	14.35	15.56	19.55	15.52	16.01	14.76
Fe_2O_3	4.52	4.52	4.46	4.19	5.08	3.93	4.59	2.93	2.24
FeO	5.25	5.25	4.92	5.86	3.5	1.34	2.74	1.85	1.27
MnO	0.13		0.09	0.13	0.12	0.09		0.06	0.05
MgO	6.45	6.45	4.96	2.96	2.42	3.18	2.89	4.83	1.78
CaO	8.54	8.54	5.86	4.96	7.44	5.88	5.75	5.67	4.77
Na_2O	3.42	3.41	5.03	7.04	4.04	5.13	5.05	3.98	5.13
K_2O	0.84	0.84	1.14	0.1	0.1	0.84	0.54	0.77	0.84
P_2O_5	0.14	0.92	0.3	0.14	0.08	0.13	0.92	0.21	0.11
H_2O*	4.01		3.03	1.44	1.98	2.91		2.62	1.56
H_2O	0.22		0.64	0.16	0.16			0.53	0.25
H_2O (tot)	4.55				2.39				
CO_2			0.95		0.05				
S			0.02		0.01				
F			0.03		0.03				
Total	**99.26**	**98.16**	**99.26**	**98.13**	**98.6**	**98.33**	**99.47**	**99.62**	**99.44**

Table 17-8: Chemical analyses (wt%) of volcanic rocks of the Katar Rash Group

	Sub-alkali basalt						Trachybasalt		Basaltic andesite		High-K Mugearite
Sample No.	**44**	**46**	**45**	**65**	**40**	**59**	**68**	**39**	**41**	**62**	**38**
SiO_2	43.33	45.26	47.81	48.33	48.44	48.65	47.77	48.83	53.17	53.29	48.07
TiO_2	2.47	1.5	1.29	1.94	0.77	1.52	1.01	0.83	1.01	0.75	0.53
Al_2O_3	16	14.23	16.68	16	18.15	15.13	16.85	16.91	17.73	17.3	19.51
Fe_2O_3	7.57	8.05	5.15	2.64	3.51	10.48	4.22	5.98	4.51	3.33	3.8
FeO	6.6	5.5	7.5	6.5	5.63	3.15	7.92	1.8	3.6	4.95	4.78
MnO	0.39	0.22	0.21	0.17	0.19	0.16	0.17	0.13	0.13	0.14	0.21
MgO	8.81	8.95	5.39	7.19	3.5	5.69	7.29	3.34	3.81	4.65	3.86
CaO	2.65	9.63	5.61	7.98	10.81	6.23	2.75	11.61	7.38	6.2	6.48
Na_2O	2.24	0.13	1.74	3.27	1.65	4.5	4.8	3.06	4.5	4.36	4.18
K_2O	0.62	0.03	0.67	0.72	0.58	0.22	0.81	1.71	0.16	0.37	1.68
P_2O_5	0.62	0.26	0.4	0.47	0.14	0.23	0.21	0.16	0.19	0.11	0.07
H_2O*	6.17	5.75	5.53	3.67	5.25	3.01	5.04	3.11	3.21	3.97	4.56
H_{17}	0.5	0.22	0.69	0.17	0.63	0.23	0.2	0.17	0.27	0.38	0.78
CO_2	1.72	0.04	1.1	0.28	0.63	0.02	0.04	5.16	0.65	0.12	1.33
S	0.01	0.02	0.01	0.04	0.02	0.04	0.06	0.05	0.02	0.02	0.01
F	0.14	0.04	0.02	0.05	0.02	0.02	0.04	0.04	0.04	0.04	0.03
Total	99.93	100	99.8	99.43	99.96	99.38	99.22	99.96	100.44	99.99	100.09
Sr				275		1161	60			140	
Zr				60		30	36			56	
Y				25		21	28			24	

Table 17-8 (continued)

	Mugearite				Andesite							Benmoreite
Sample No.	**67**	**64**	**43**	**58**	**42**	**71**	**70**	**66**	**69**	**50**	**47**	**60**
SiO_2	49.78	49.85	51.59	51.71	56.18	57.67	57.69	58.3	58.91	60.18	60.59	53.96
TiO_2	1	0.88	0.96	0.85	1	0.84	0.7	0.67	0.8	0.85	0.84	0.77
Al_2O_3	16.88	19.06	17.41	17.89	17.05	15.31	15.78	16.79	14.52	15.38	16.12	16.6
Fe_2O_3	4.62	4.5	3.32	3.28	2.99	3.51	4.05	1.83	3.42	3.19	2.77	3.25
FeO	3.7	3.88	4.77	5.47	4.65	5.35	3.2	4.05	5.18	4.1	3.78	6.42
MnO	0.18	0.16	0.13	0.14	0.13	0.41	0.11	0.1	0.4	0.16	0.14	0.15
MgO	3.7	2.79	5.9	6.16	3.47	4.59	3.45	2.66	4.73	2.56	2.67	5.76
CaO	6.1	8.38	4.09	2.5	5.27	4.05	7.62	5.68	3.97	2.94	3.03	2.56
Na_2O	4.45	5.1	5.55	5.75	5.4	3.3	2.4	5.3	3.02	5.5	5.85	5.95
K_2O	1.19	0.37	0.72	0.62	0.14	0.33	0.73	0.24	0.24	1.09	0.42	0.18
P_2O_5	0.2	0.2	0.26	0.16	0.22	0.2	0.17	0.12	0.19	0.19	0.25	0.13
H_2O^+	4	3.42	3.81	4.36	3.11	3.82	3.61	2.78	3.68	2.56	2.55	3.82
H_{17}-	0.37	0.15	0.69	0.2	0.13	0.16	0.11	0.09	0.14	0.14	0.38	0.22
$C0_2$	2.94	0.88	0.12	0.34	0.65	0.07	0.02	1.02	0.03	1.06	0.14	0.55
S	0	0	0.02	0.01	0.01	0.01	0	0.03	0.02	0.01	0	0
F	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.02	0.05	0.02	0.03	0.04
I	99.3	99.73	99.43	99.54	100.5	99.74	99.78	99.52	99.52	99.93	99.56	99.36
Sr	159	199		220		214	322	199	215			350
Zr	30	28		44		43	98	28	35			68
Y	28	25		19		33	32	27	29			21

Table 17-8 (continued)

	Dacite		Na-rhyolites								Potassic rhyolite		Granite
Sample No.	**48**	**49**	**52**	**72**	**53**	**61**	**57**	**54**	**63**	**55**	**56**	**73**	**51**
SiO_2	64.57	64.73	68.61	70.46	71.21	73.38	74	78.25	78.6	83.21	71.62	79.7	66.65
$Ti0_2$	0.48	0.68	0.43	0.59	0.33	0.28	0.24	0.21	0.19	0.14	0.26	0.2	0.45
Al_2O_3	15.55	14.07	13.03	13.36	14.23	14	13.02	12	11.38	7.98	13.46	11.9	15.11
Fe_2O_3	2.63	2.74	3.28	1.55	1.4	1.69	1.13	1.19	0.99	0.98	1.41	1.14	2.33
FeO	2.35	3.33	0.8	2.1	1.8	0.9	1.03	0.75	0.53	0.6	0.78	0.25	2.3
MnO	0.1	0.17	0.08	0.09	0.08	0.04	0.06	0.1	0.04	0.01	0.04	0.01	0.07
MgO	2.76	2.6	1.33	1.1	1.15	0.51	0.53	0.58	0.21	0.36	1.77	0.54	2.1
CaO	2.09	1.69	2.69	1.81	0.83	0.46	0.87	0.62	1.08	0.37	1.43	0.08	1.05
Na_2O	5.1	5.75	4.05	6.3	6.6	6.9	4.75	3.1	5.4	4.62	2.24	0.18	7.25
K_2O	1.06	0.73	1.61	0.22	0.39	0.8	2.35	1.74	0.87	0.09	4.45	3.25	0.61
P_2O_5	0.12	0.28	0.18	0.2	0.11	0.06	0.15	0.12	0.1	0.06	0.15	0.1	0.18
H_20*	2.63	1.88	1.86	1.51	1.31	0.53	1.25	1.46	0.28	0.47	1.83	2.26	1.32
H_20'	0.61	0.68	0.49	0.05	0.24	0.05	0.15	0.09		0.16	0.11	0.15	0.48
$C0_2$	0.01	0.27	1.89	0.32	0.07	0.02	0.07			0.04	0.02	0.02	0.01
S		0.02	0.01		0.01			0.02	0.02		0.02	0.02	
F	0.04	0.04	0.04	0.05	0.02	0.03	0.02	0.02	0.01	0.01	0.02	0.04	0.03
Total	100.15	99.69	100.48	99.75	99.8	99.69	99.74	100.3	99.76	99.38	99.7	99.99	99.98
Sr				172		88	126		154		135	17	
Zr				57		128	74		76		101	94	
Y				34		21	18		24		12	87	

Table 17-9: Microprobe analyses (wt%) of minerals of the cordierite-sekaninaite series from contact rocks of the Bulfat gabbros and their crystallochemical recalculations on basis of 18 (O). Samples from: (1) cordierite (400 m SE of Halsho) from andalusite schist, (2) cordierite (N of Norsta) from cordierite-andalusite-sillimanite hornfels of medium grade facies, (3) sekaninaite (1.5 km W of Beklo) from sekaninaite hornfels of high grade facies and, (4) sekaninaite (Karsh peak) from sekaninaite hornfels, high-grade facies

Sample	1	2	3	4
SiO_2	47.30	46.97	46.70	46.92
Al_2O_3	31.09	31.70	31.10	30.90
FeO Tot	9.76	11.89	13.30	13.60
MnO	1.20	0.42	0.27	0.45
MgO	7.60	7.03	7.01	6.35
Na_2O	1.40	0.35	0.30	0.35
Total	98.35	98.36	98.68	98.57
Si^{IV}	4.966	4.942	4.926	4.967
Al^{IV}	1.034	1.059	1.074	1.0333
Al^{VI}	2.810	2.868	2.789	2.819
Fe^{2+}	0.857	1.046	1.173	1.204
Mn	0.107	0.037	0.024	0.040
Mg	1.190	1.102	1.102	1.002
Na	0.285	0.071	0.061	0.072
O	18.000	18.000	18.000	18.000
fe	39.79	47.87	51.02	53.61
mn	4.97	1.69	1.05	1.78
mg	55.24	50.44	47.93	44.61

Table 17-10 Microprobe biotite analyses (wt%) (as in samples of Table 17-9). Biotites have relatively low contents of tetrahedral AL and only moderate values of the ratio Fe/ (Fe+Mg) ratios; they have a high share of the annite component (Fig 17-13)

Sample	1	2	3	4
SiO_2	39.95	35.75	36.59	36.65
TiO_2	1.95	3.51	4.30	3.35
Al_2O_3	19.80	19.17	19.60	19.80
FeO Tot	18.60	19.52	19.20	18.80
MnO	0.40	0.12	n.d	0.17
MgO	9.85	7.10	7.10	8.20
Na_2O	0.60	0.27	0.28	0.40
Total	97.06	96.50	96.34	96.47
Si	5.716	5.648	5.720	5.710
Al^{IV}	2.284	2.352	2.280	2.290
Al^{VI}	1.137	1.215	1.428	1.343
Fe^{2+}	0.857	1.046	1.173	1.204
Mn	0.052	0.016	---	0.022
Mg	2.271	1.672	1.655	1.904
Na	0.180	0.083	0.085	0.121
O	24.000	24.000	24.000	24.000
fe	50.88	82.75	60.26	55.98
mn	1.10	0.35	---	0.50
mg	48.02	36.90	39.74	43.52

Chapter 18
Hydrocarbons
by
Saad Z. Jassim and Mohammad Al-Gailani

18.1 Introduction

Bitumen has been used in boat building and in building mortar since the Sumerian times around 4000 BC. The bitumen was probably obtained from bitumen seepages along the Upper Euphrates in central W Iraq and along the upper reaches of the Tigris River in N Iraq. The first oil and gas exploration drilling in Iraq began in 1902 when a well was drilled on the Chia Surkh anticline structure. In 1919, appraisal drilling started in the Naft Khana area resulting in the discovery of the first oil field in 1923.

The first commercial well struck oil in the Kirkuk structure of NE Iraq in 1927. Application of potential field data led to the discovery of the buried oil field trend of Mesopotamia in S Iraq in the late 1940s. Exploration drilling for surface anticlines in Iraq and buried structures in S Iraq and acquisition of regional seismic surveys continued until 1961 when the Iraqi Government introduced Law No.80 restricting exploration, both vertically and horizontally.
The establishment of the Iraqi National Oil Company (INOC) meant that control of exploration was passed to the young national establishment which immediately, especially after nationalization in 1972, started a program of more detailed seismic exploration, the aim of which was to cover the whole of Iraq (apart from the High Folded Zone). This task was interrupted in the 1980s. At the same time drilling on many structures delineated by seismic started through service contracts with Russian, French, Brazilian and other companies. Many oil fields were delineated and their reserves established. Several supergiant oil fields were discovered in the 1970's.

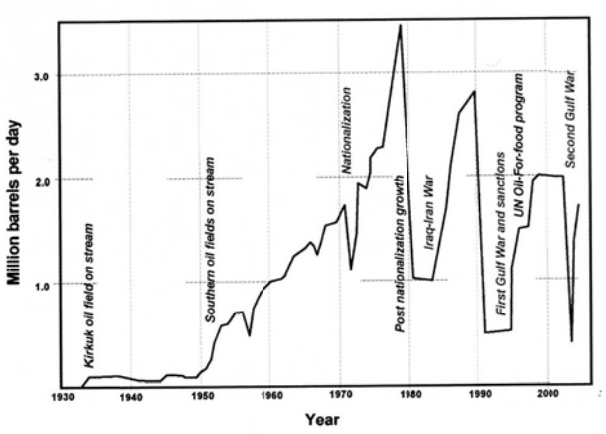
Oil and gas is produced mostly from Tertiary and Cretaceous reservoirs; older petroleum systems are yet to be evaluated in detail.

18.2 Oil and gas reserves

At the World Petroleum Congress in Washington (USA) in 1989 Hashim Al-Khirsan and Ahmad Al-Siddiki of the Oil Exploration Company of Iraq reported an increase in Iraq's oil reserves to 100 billion barrels in 73 oil fields. They noted that drilling of 62 structures from 1927 to the 1960's had resulted in the discovery of 35 fields with a total oil reserve of 34 billion barrels. In the period from 1968-1988 a further 52 structures were drilled with the discovery of 38 new fields; oil was also discovered in new reservoirs in 30 of the 35 'Previously discovered fields.
Al- Khirsan and Al-Siddiki (1989) also indicated that of the 73 field discovered in Iraq by 1988, six fields were super giants (each with reserves >5 billion barrels), and 23 were giant fields. They indicated that the volume of oil reserves in Tertiary and Cretaceous reservoirs was about 24 and 76 billion barrels respectively, with a very small contribution from Jurassic and Triassic reservoirs (100 million barrels). The distribution of oil and gas fields in Iraq is shown in (Fig. 18-1.)

Official estimates of the reserves of individual oil fields in Iraq have not been published. However estimates of the remaining recoverable reserves and oil in place of many individual fields are provided by Al-Chalabi (2001), Verma et al (2004) and by the Arab Oil and Gas Directory (2005). The interested reader is directed to these publications for further information. It is important to note that the reserve estimates of individual fields are likely to change in the future following acquisition of 3D seismic to better define many of the oil bearing structures, and assessment of the potential of secondary recovery techniques and enhanced oil recovery (EaR). The increase in Iraq's official oil reserves through time from 1969-2004 is reported in the OPEC Annual Statistical Bulletin for 2004. Iraq's official oil reserves stood at 115 billion barrels at the end of 2004.

Fig. 18-1: Iraq's oil production in million barrels per day



Iraqi oil reserves vary widely in quality. API gravity is in the range 20-42°. 90% of Iraq's historical production has come from just two super-giant fields: Rumaila in the South and Kirkuk in the North. These fields still dominate today, making up over 80% of the country's production capacity.

The Rumaila field produces three streams: Basra light (34° API, 2.1 % sulphur); Basra Medium (30° API, 2.6% sulphur); and Basra Heavy (22°_24° API, 3.4% sulphur). The Kirkuk field produces 36° API, 2% sulphur crude. Additional export crude, known as "Fao Blend", is heavier and sourer, with a 27° API and 2.9% sulphur.

Iraq's official gas reserves stood at 3170 billion cubic metres at the end of 2004 (112 trillion cubic feet) as reported in the OPEC Annual Statistical Bulletin 2004. About 70% of Iraq's gas reserve is associated gas (dissolved in oil under reservoir conditions); the remainder is non-associated gas (about 20%) and gas cap gas (10%). Until 1990, all of Iraq's natural gas production was from oil-associated fields. In 1996, Iraq produced slightly more than 128 billion cubic feet of gas, down drastically from peak output levels of 700 billion cubic feet in 1979.

The primary sources of associated gas are the Kirkuk, Ain Zalah, Butmah, and Bai Hassan oil fields in the North, and the Rumaila and Zubair fields in the South. At present about 70% of Iraq's associated gas production capacity is located in the Southern fields. The only non-associated gas production is from the Kor Mor field in the North. It was brought online in 1990 with output of 200 mmscf/d. The production from this field is routed to the Jambur gas processing station 30 km from Kirkuk.

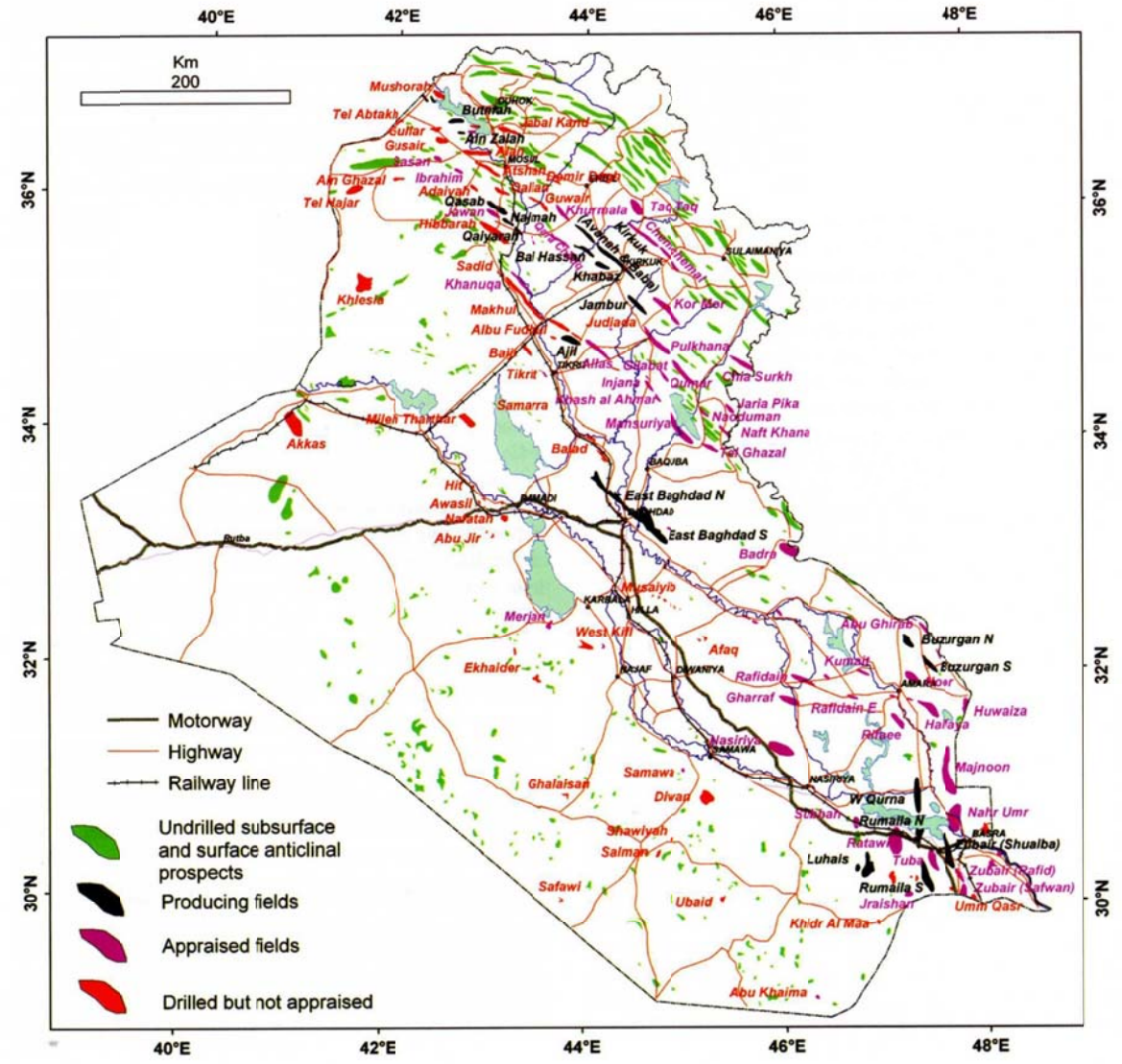
18.3 **Oil Production**

By July 1990, Iraqi crude oil output had reached 3.5 million barrels per day, with production capacity at 4.5 million barrels per day, the highest levels since 1979. Through the first 8 months of 1998, Iraqi crude oil production was averaging 2 million barrels per day, up from 1.2 MbIVd in 1997 (in October 1998, production reached approximately 2.4 million barrels per day). About 550,000-600,000 bbl/d of Iraq's oil output is for domestic consumption, either for refining or for direct burning by industrial customers or utilities. A further 90,000-100,000 bbl/d used to be delivered to Jordan via trucks. The main reasons for the cyclic nature of Iraq's oil production shown in Fig. 18-2 are:

- The Iraq-Iran war from 1980 to 1984
- The first Gulf war and sanctions from 1990 to 1996
- The second Gulf war in 2003 and the unrest that followed.

Historically four major fields, Kirkuk, Rumaila, Zubair and Bai Hassan, account for most of Iraq's oil production. Kirkuk field went on stream in 1933 with an initial production of around 2000 bbl/d increasing to 100,000 bbl/d in 1934, and gradually increasing to reach a maximum production of around 1.2 million barrels per day in 1980, generally averaging 1 million barrels per day but falling to 0.5 million barrels per day in 1991. Rumaila field went on stream in 1954 at a rate of 20,000 bbl/d; peak production of 1.6 million barrels per day was reached in 1980-1990. Zubair field went on line in 1950 with an initial production of 20,000 bbl/d; production steadily increased to a peak of 180,000 bbl/d in 1980. Bai Hassan field went on stream in 1960 with an initial production of 20,000 bbl/d; production increased to 50,000 bbl/d in 1961 and peaked at 60,000 bbl/d in 1967, dropping sharply to less than 30,000 bbl/d in 1974.

Fig. 18-2: Location of producing fields, drilled structures and un-drilled prospects (after Al-Gailani, 2003)



18.4 Oil Production System

The facilities at each field include the production wells together with one or more processing complexes, known as degassing stations, which process oil for shipment. Individual production well rates are in the range of 100010,000 barrels per day; 10 to 100 wells feed each degassing station. Their capacity will range from 20,000 barrels per day at a small field, to 150,000 to 200,000 barrels per day at a larger field, which will have several of these degassing stations. The primary role of these centers is to gather the incoming well fluids and to "de-gas" it to allow loading onto ships. To reduce the salt and water content of the oil, water is removed and simple "washing" of the oil is done with fresh water. Most gathering centers have booster pumps to allow transfer of oil to strategic tank farms and major pump stations. The gas gathered from the de-gassing stations is further processed at the strategic gas processing centers or, if equipment is unavailable, it is sent to a flare system and burned. These gas processing centers are installed to extract the valuable components such as propane, butane and natural gasoline. These plants normally dry and finally condition the gas to a "sales gas" specification.

The IPC and its sister companies, the MPC and BPC, built the nucleus of Iraq's production system.

Oil production in the North and Central areas comes from fields such as Kirkuk, Bai Hassan, Jambur, Aji, East Baghdad, Naft Khaneh, Khabaz, Ain Zalah, Butmah, Sufaya and Qalyarah. The Kirkuk area is the principal field and processing center in the North. It has eight degassing stations and has been producing oil since the 1930s. The crude oil is degassed in one stage to atmospheric pressure, sweetened at the Process Plant through cold stripping and stabilisation process and stored at a Kl tank farm then pumped to any of the export terminals via a major pipeline carrier. Each central degassing station gets its crude oil from three to ten wells which are spread over some 15 square kilometres. The gas is used to fuel the Process Plant, Pumping Stations and also to feed the Sulphur Recovery Plant; the rest of the gas was flared. A water injection system was established in 1961 at the Amsha Saddle between Baba and Avanah domes where the Lesser Zab River passes through Kirkuk structure. However, the high dally production of most of the wells meant that one injection well was needed for every four producing wells. Gas injection is also used in Kirkuk to re-inject surplus gas into the structure.
The near-by Jambur and Bai Hassan field are integrated with the Kirkuk system. The crude oil produced from the Bai Hassan field is degassed in one main station and in a remote separator using a two stage separation system. The gas from the first stage is dehydrated and then passed into a twelve inch gas line for transmission to Kl and then into a sixteen inch main pipeline to fuel the turbines of the pumping stations along the lines to T-4 pumping station. The second stage gas and the tanks associated gas are flared.

The production system for Jambur oil field is similar to that of Bai Hassan where the crude oil is degassed in two stages at the appropriate pressures. The oil is then pumped to join Bai Hassan crude for export. The sweet gas off the first stage separators is piped in a twenty-inch pipeline to the Process Plant for cold stripping. The remaining gas is piped with Bai Hassan sour gas in a sixteen-inch main gas pipeline. The second stage separator gas and the tank's associated gas are flared.
Ain Zalah and the near-by Butmah fields were developed jointly and their combined crude oil flows south to join the
Kirkuk transfer system. The Ain Zalah and Butmah oil fields each have one central degassing station. The crude oil from the first and second pay wells is degassed in two stages. The crude oil from Butmah first pay wells is degassed in one stage while the crude oil from the second pay wells is degassed in two stages. The gas from the first stage separators is injected into Butmah-6 well to pressurise the first pay reservoir. The degassed crude from the second pay wells of Ain Zalah and the second pay wells of Butmah are passed into two separate stripping columns to reduce their hydrogen-sulphide content. The degassed crude is then pumped via a twelve-inch 216 kilometre long pipeline to K2 pumping station to join the Kirkuk, Bai Hassan and Jambur crude for export.
Qaiyarah field contalns heavy oil *(15.5* API) with a low GOR (160 cubic feet per barrel). It is degassed and stored in tanks of 5000 barrels capacity and then gravitated through a 10-inch pipeline to storage tanks at the near-by Government bitumen plant.

The small production from the East Baghdad and Naft Khaneh fields has local destinations such as Doura Refinery.

The Basrah Petroleum Company (BPC) built the original oil production facilities for the Zubair and South Rumaila fields. The North Rumaila and other producing fields in SE Iraq were developed by the Iraq National Oil Company.

18.5 Oil Pipelines and Export Facilities

Before 1970's the Northern production centered on Kirkuk was exported predominantly through Syria to the Mediterranean ports. In the South, Zubair and Rumania's production systems were integrated and their crude oil production pumped from a centralized location to the oil terminals on the Shatt al-Arab waterway at Fao. To accommodate larger ships, the offshore loading points in deeper water of Mina al Bakr and Khor al Amaya were developed. In the early 1970s, Syria and Lebanon more than doubled the transit fee. This caused Iraq to build the first line across Turkey, as well as the "strategic line" between North and South Iraq. Shortly after this the trans Saudi Arabia line was inaugurated.

The major transportation systems include the substantial South and North intra-regional infrastructure, the interregional Strategic pipeline system and the international oil export systems. These systems may be summarized as:

- South Oil area transportation- Onshore gathering, pumping and storage
- North area transportation
- Central area transportation
- Inter-Regional transportation-the "strategic line" which runs from Basra to join the Rumaila/Zubair fields with the Banias/Tripoli pipeline network at Haditha and reversibly the Kirkuk and northern fields with the southern export terminals. The northern flow capacity is around 1.5 Mbll/d while, due to the bottleneck at the Rumaila-Fao sector, the southern flow capacity is limited to around 0.8 Mbll/d.
- Tanker export via Mina al Bakr
- Tanker export via Khor Al Amaya
- Pipeline export to Turkey which runs from Kirkuk, through Baiji to Ceyhan terminal on the Mediterranean with a capacity of 1.5 Mbll/d. This 900 km pipeline is Iraq's largest operable crude export pipeline comprised of two parallel lines built in 1977 and 1987. A 40-inch line has a fully-operational capacity of 1.1 Mbll/d. A second, parallel 46-inch line has an optimal capacity of 500,000 bbl/d and was designed to carry Basra Regular exports, for a combined capacity of 1.6 Mbll/d.
- Pipeline export to Red Sea via Saudi Arabia (Iraqi Pipeline through Saudi Arabia IPSA) which runs from Basra through Saudi Arabia to Yanbu'a Terminal on the Red Sea, joining Rumaila/Zubair and other southern fields. It has a capacity of 1.65 Mbll/d.
- Pipeline export to Syria (Kirkuk-Banias/Tripoli) with 1.4 Mbll/d capacity
- Pipeline export to Jordan (Haditha-Haifa) with a capacity of 100,000 bll/d, not used since 1948

When operational, between 450,000-600,000 bbl/d of Iraqi crude was exported to European markets through the Banias line, with the rest feeding Syria's Banias and Hums refineries and Lebanon's smaller Tripoli refinery. Since its closure in 1982, Syria has used the line to transport 360,000bbl/d of its own crude output from the Dair Al Zor area to the Banias export terminal. In addition, a 90 km stretch of the line has been converted by Syria to carry natural gas (to the fertilizer complex and refinery at Hums). Other constraints on using this line for Iraqi exports include: limited oil storage facilities at Banias; corrosion damage to unused portions of the pipeline in Syria. Following the 1982 Banias line closure, Saudi Arabia agreed to allow Iraq to export 500,000 bbl/d of crude through the Saudi Petro line to the Red Sea. Then, between 1983 and 1988,

two Iraqi pipelines across Saudi Arabia (IPSA-l and IPSA-2) were built. The first phase from Rumaila to the Petroline's PS3 pumping station was completed in 1985, when the second phase IPSA-2 project was begun. IPSA-2 included construction of a 1.65 Mbll/d capacity line running parallel to the Petro line, an additional pumping station to boost IPSA-l's capacity to 1.65 Mbll/d, storage facilities, and a new Red Sea terminal. Iraqi crude began flowing through the IPSA lines in January 1990. Following Iraq's invasion of Kuwalt in August 1990, Saudi Arabia closed the IPSA link, which now apparently has been emptied of oil and filled with water for maintenance.

In order to optimize export capabilities, Iraq constructed a reversible, 1.4 MBLL/d "Strategic Pipeline" in 1975. This pipeline comprises two parallel 700,000 bbl/d lines. The system allows for export of the northern Kirkuk crude to the Arabian Gulf and for southern Rumaila crude to be shipped through Turkey.

Iraq's southern oil production capacity before 1991 reached 2.25 Mbll/d (75000 bbl/d in mid 1991), particularly from the largest producing oil field in this region (Rumaila field). The production facilities, includes a storage capacity of 1.6 Mbll/d and export through Mina al-Bakr terminal, as well as pumping stations along the 1.4 Mbll/d Iraqi Strategic Pipeline. The southern oil capacity also has seven other sizable fields, which remain partially mothballed. These include Zubair, Luhais, Subba, Buzurgan, Abu Ghirab, Majnoon and Fauqi.

Normally the oil from the southern fields is exported from the Gulf terminals. It could be diverted northwards, when necessary, through the "Strategic Pipeline" to Haditha. Iraq has three tankers terminals in the Arabian Gulf; these are Mina al-Bakr, Khor Al-Arnaya, and Khor AL-Zubair. 1) Mina al-Bakr is Iraq's largest oil terminal, with four 400,000 bbl/d capacity berths capable of handling very large crude carriers (VLCCs). The terminal's capacity may reach 1.2 Mbll/d. 2) Khor Al-Amaya terminal could load 600,000 bbl/d and upon full completion of repairs its projected capacity can reach 1.2 Mbll/d. 3) Khor Al-Zubair, Iraq's third terminal, is linked to the Umm Qasr port by a 30-mile long canal. While Khor Al-Zubair terminal generally handles dry goods, it has the capability to service small quantities of liquefied petroleum gas (LPG) and refined products.

18.6 Gas processing and Transportation

Gas production in Iraq to date has been associated gas, either directly as a result of oil production or production from the gas caps in the North of the country. The gas arising from de-gassing stations may contain components that could condense liquids en-route which is unacceptable for long distance transmission to users that cannot accommodate liquids in their feed. Therefore the strategic gas processing centers were installed to extract the valuable liquids such as propane, butane and condensate. These plants dry and condition the gas to an agreed specification. At the degassing centers, over half of the associated gas is liberated at pressure suitable for entering a transmission system without compression. The remaining gas has to be flared if the compression machinery is not available. In the majority of installations in Iraq, flaring is likely either because gas recovery machinery was not installed as part of the original design scheme, or because the machinery has been subsequently damaged or not maintained for operation. There are other reasons why gas is not transported, such as non-availability of power stations and other consumers, damage to the gas transmission lines between the production sources and the end users, or inadequate function in the gas processing plants.

Gas flaring was reduced from roughly 50% in 1989 to less than 5% in 1994. This was accomplished mainly through increased use of Iraq's two gas gathering systems, which were built in the late 1980's. The "Northern Area Gas Project" which started operation in 1983 is able to recover and process up to 550 million cubic feet per day *(MCF/d)* of sour gas, with a resulting maximum output capacity of 300 *MCF/d* of dry gas as well as a mix of propane, butane, natural gasoline, and pure sulphur. The "Southern Area Gas Project" was completed in 1985, but was not brought online until February 1990. It has nine gathering stations and a larger processing capacity of 1.5 *BCF/d.* Gas gathered from the North and South Rumaila and Zubair fields is carried via pipeline to a 575 *MCF/d* natural gas liquids (NGL) fractionation plant in Zubair and a *100-MCF/d* processing plant in Basra. At Khor al-Zubair, a 17.5 MCF LPG storage tank farm and loading terminals were added to the southern gas system in 1990. LPG export capacity was 4 million tons per yeas in 1990. In addition, Iraq built another system in
1985 to recover up to 20 *MCF/d* of gas from the Jambur field.
The North gas plant near Kirkuk and the three Southern plants of North Rumaila, Khor al Zubair and South Gas produce a dry gas into the major transmission system, the principal components of which are summarized as follows.

• The 18" gas line follows the strategic oil line and delivers gas to the pump stations along the route.

- The 42" gas line is installed from the North Rumaila area up to the power plants at Mussalyib, via Nasiriyah. The eventual plan for the gas line is to run north to Baghdad from Mussalyib, and then up towards Kirkuk and possibly Turkey.
- The North gas plant delivers conditioned gas; this gas may be routed south to the Baghdadi Doura Refinery area. A connection to Mosul is indicated.
- The Gas Pipeline to Kuwalt delivered Southern Iraqi North Rumaila area to Kuwalt. With flow rates of 200400 mmscfd
- The Gas Pipeline from the Kirkuk area towards the Syrian may be partially used for natural gas service.
  The principal users of gas are:
  • Power stations and refineries
- Oil field users such as the pump stations on the strategic line
- Miscellaneous industrial and chemical users where pipelines run close by.

18.7 Petroleum Systems

18.7.1 Introduction

The most important petroleum systems in Iraq are the Jurassic, Cretaceous and Tertiary Petroleum Systems. The Palaeozoic Petroleum System is important in the Rutba Jezira Zone of W Iraq. The known extent of the Triassic Petroleum System is confined to a small area in N Iraq (extending into part of NE Syria and SE Turkey). The petroleum systems are discussed in term of their source rock richness, maturation, time of maturation and migration, reservoirs, cap rocks and the possible traps that might be associated with them.
Source rock data in Iraq are still scarce. For the Palaeozoic the data of Habba et al. (1994) for the Rutba area is most important and is complimented by the data from the Risha area of NE Jordan, the Tanf region of Syria and the Jauf graben of NW Saudi Arabia. Data for the Triassic source rocks in Iraq are not available; data from the Palmyrides of Syria (Serreya, 1990) were used to

estimate the Triassic source rock potential. Jurassic-Lower Cretaceous source rocks were studied by Al Habba and Abdulla (1989) and (Odishu, 1989) in the Kirkuk Embayment and NE Iraq and by PGA (2000; in Pitman et al., 2004). For the Lower Cretaceous source rocks in SE Iraq, data from Kuwalt (Abdulla and Kinghorn, 1994) and from SW Iran (Versvelt, 2001: in Downey et al. eds.) was used to estimate source rock properties. Data for Upper Cretaceous and Palaeogene source rocks is available in the Euphrates graben in Syria and the Dezful Embayment of SW Iran (Bordenave and Burwood, 1990).

18.7.1.1 Thermal gradient and heat flow

The relation between heat flow and temperature gradient is represented in the following formula:
$Q = (dt/dz) * \lambda$
Where Q= Heat flow (kwm^{-2}), (dt/dz) = Temperature Gradient (OC/km) and l = Thermal Conductivity (wm^{-1} k^{-1}). The temperature gradient derived from bottom-hole temperatures of numerous oil wells in Iraq and the surrounding countries is presented in Fig. 18-3. The highest temperature gradient is recorded in W Iraq and NE Jordan where it reaches 40°C/km. It is around 12-18°C/km along the Salman Zone and along the Tharthar and Tigris *tines in* N Iraq. The gradient increases to 20°C/km in the eastern side of the Mesopotamian Zone. The gradient along some of the structures of the Foothill is variable; some structures such as Kirkuk have a low thermal gradient, other like Hemrin have high thermal gradients exceeding 33°C/km.
The thermal conductivity of the sedimentary cover was estimated from the average conductivity of 14 layers as a weighted average (Fig. 18-4). A uniform heat flow of 58 kwm-2 from the crust was used in conjunction with the averaged thermal conductivity to recalculate the temperature gradient. The calculated gradient differs little from the actual gradient in most of Iraq except in the W parts of the Rutba Subzone where the former is about 10°C less than the latter. This is attributed either to higher heat flow from the crust in that region or to the Neogene volcanicity associated with the opening of the Red Sea which affected the W parts of the Arabian Plate with eruption of flood basalts in NE Jordan and SE Syria. Some buried volcanic bodies in W Iraq can also be determined from the aeromagnetic surveys of W Iraq.

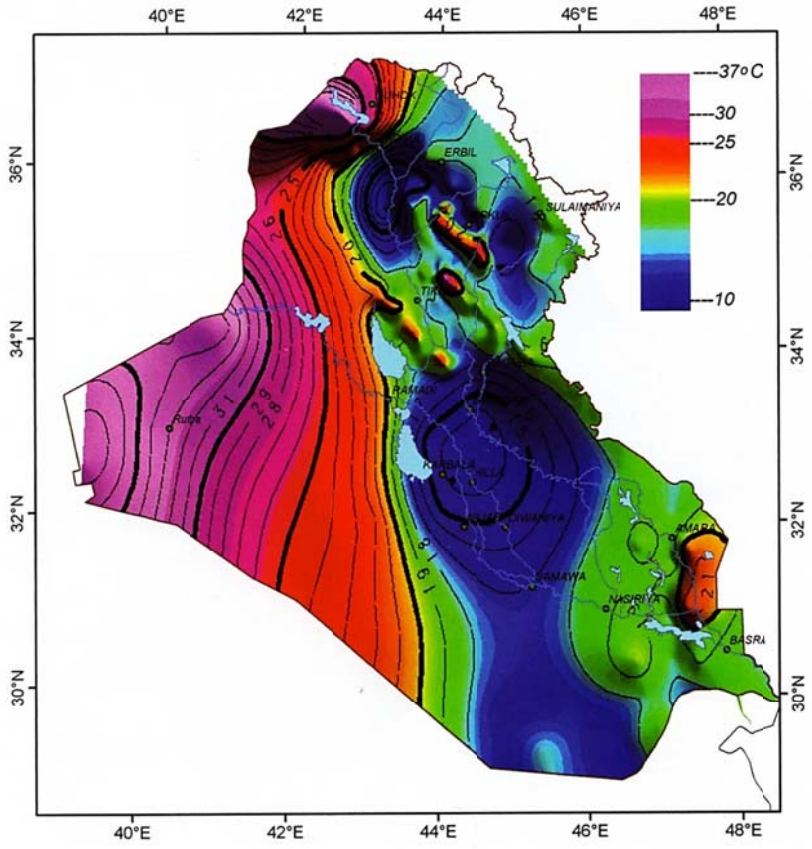
18.7.1.2 Maturity of organic matter

The Time Temperature Index (TTI) procedure of Lopatin (in Waples, 1980) was used for the modeling, using grid thickness files for 14 sequences ranging in age from Infracambrian to Recent and compared with modeling .of wells. A surface temperature of 20°C and a laterally variable temperature gradient were used. The effects of erosion and compaction were not considered. The calculated maturation levels compared favorably with measured maturities in Iraq and surrounding countries. The TTI values were converted to equivalent Ro values using Waples calibration in the following equation:
Ln (Ro) = (Ln (TTI) - 4.168) / 4.144
Where TTI is the Time-Temperature-Index of Lopatin and Ro is the Vitrinite reflectance in %.
The Ro values ranges were used to indicate different stages, of hydrocarbon generation using the scheme of Milner (1998) for Southern Arabia. These stages comprise: 1. early mature (0.5-0.7 Ro), 2. Middle mature (main oil generation 0.7 -1.0 Ro). 3. Late mature oil-Early mature gas (1.0-1.3 Ro). 4. Main gas generation (1.3-2.6 Ro). 5. Overmature (>2.6 Ro). There is little published information on oil typing in Iraq apart from some preliminary conclusions by Dunnington (1958).

The API-Sulphur plot for Iraqi oils (Fig. 18-5a and 18-5b) shows that there is great variation in the API Gravity (8-64°) and sulphur contents (0.05-6.5%) in most reservoirs. The plot of oil API versus depth shows that oils from the Mesopotamian and Salman zones cluster in a field showing a direct relation between API and depth. Within the same structure in these zones API increases with depth of reservoir; some deviations occur at the margins of the Mesopotamian Zone, particularly near the boundary of the Foothill Zone. Furthermore, there seems to be two sub clusters (Fig. 18-5a), an upper one (possibly related to Jurassic source) and a lower cluster (possibly related to Cretaceous sources). However, single structures in the Foothill Zone often show an indirect relationship between API and depth; oil from deeper reservoirs is usually heavier. This could be explained by seepage of lighter oil into higher reservoirs through fractures. Overall, the oil of the Foothill Zone overlap with the plot of oils from the Mesopotamian and Salman Zone but spreads over much bigger field and shows erratic correlation with depth. These deviations are especially evident in the Tertiary reservoirs oils.

The plot of oil API gravity versus S indicates that the Sulphur content decreases with increasing API gravity as a result of maturation. There is a sharp decrease from 7% S at I 0° API to 2%S at 30° API. After this the variation is smaller where sulphur drops from 2% at 30° API to <1 % at 50° API. A plot of API versus S was made for each reservoir (Fig. 185b) whereas the API versus depth plot was made for different reservoir ages (Fig. 18-5a).

Fig. 18-3: Temperature gradient in °C/km derived from uncorrected bottom-hole temperatures



18.7.2 Hydrocarbon seepages

Hydrocarbon seepages and seepage-related features occur in two main belts. One belt is located along the western boundary of the Mesopotamian Zone (Euphrates Boundary Fault), often at

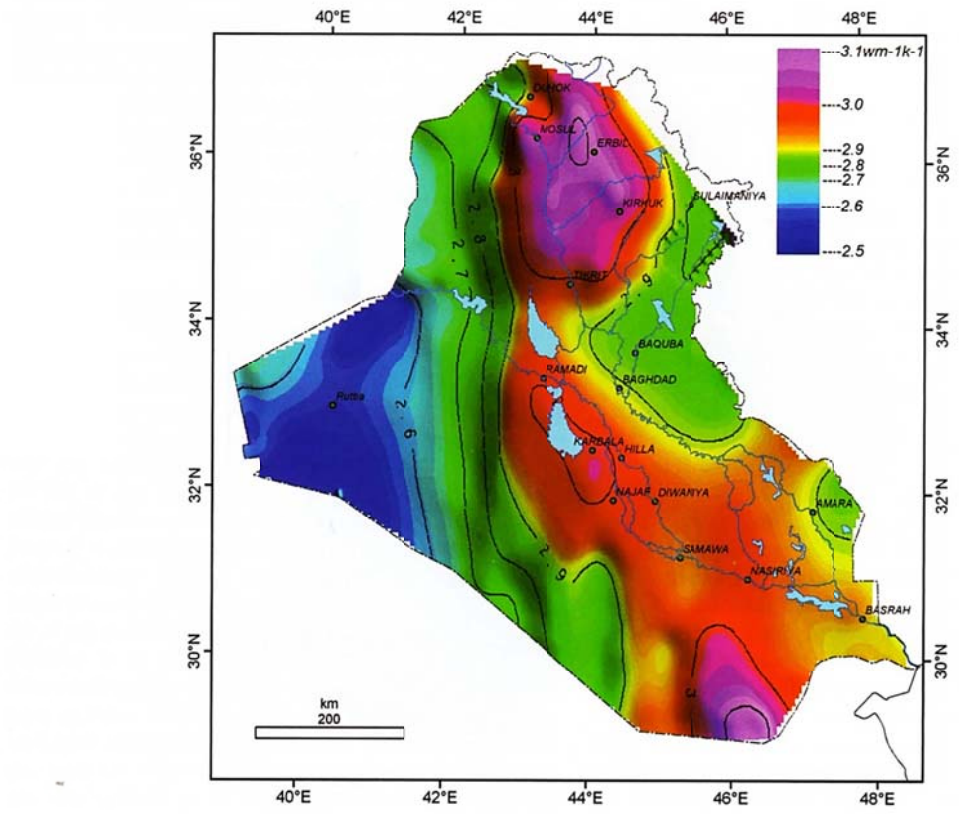
intersections with transversal faults; it extends further north along the Abu Jir Fault and along the Tigris River in N Iraq. The location of these seepages is clearly tectonically controlled but it is also apparently related to the western limit of the Upper Jurassic Gotnia anhydrite caprock. The two important areas of seeps are the Tigris in N Iraq and the Abu Jir Fault in W central Iraq.

The other belt of seepages is related to some long anticlinal structures in the Foothill Zone, for example the Kirkuk, Gilabat, and Hemrin anticlines in the Kirkuk Embayment. These anticlines have a detachment level at the base of the Fatha (L. Fars) Formation. The "Eternal Fires" of Kirkuk structure and the numerous bitumen seepages and fused rocks produced by gas combustion in Hemrin South structure (Basi and Jassim, 1972) are prominent seepage phenomena.

Seepage activity along the Tigris in the Mosul area includes bitumen seepages (Mosul and Qalyarah) and four centres of native sulphur deposits (Jassim et al., 1999) related to oil seepage in the Fatha (L. Fars) Formation and the reduction of its sulphate (gypsum and anhydrite) beds. Additionally some "gachiturush" (acid) soil, porcellanite and associated K and Fe sulphates are the product of leaching by sulphuric acid formed by oxidation of hydrogen sulphide by vadose water (Jassim and Al Naqib, 1989). It is estimated that one billion tons of possible sulphur reserves formed in the four mineralization centres in N Iraq requiring a feedstock of about 5-10 billion barrels of oil for their formation.

The Abu Jir seepage zone is situated on the N-S trending Abu Jir Fault, straddling the Abu Jir Basement High. It is dominated by large bitumen seepages forming crater lakes more than 2 km wide or small conduits; the most famous of which are at Abu Jir, Ain Jabha, Ain Hit and Ata'it. Thick bitumen beds are interbedded with the marls and carbonates of the Fatha (L. Fars) Formation. Travertine sinters of Miocene age are common to the S and N of Hit town. Saliferous water springs occur along this fault zone especially near Shithatha. Seepage activity clearly began in the Middle Miocene. A substantial volume of oil has probably been lost in this seepage belt. Much of the oil expelled from Jurassic and Lower Cretaceous source rocks in the area to the east may have been dissipated along this line of seeps.

Fig. 18-4: Mean thermal conductivity of the sedimentary cover in ($wm^{-1}k^{-1}$), calculated from the weighted average of thermal conductivity of 13 sedimentary layers (Infracambrian to Tertiary)



Sulphur deposits occur locally in some large karsts in the Southern Desert (Ain Kibritia) and are probably related to the sulphate reduction of the Lower Eocene evaporites of the Rus Formation possibly in the presence of hydrocarbons which had migrated through faults from deeper (probably Jurassic or older) source rocks.

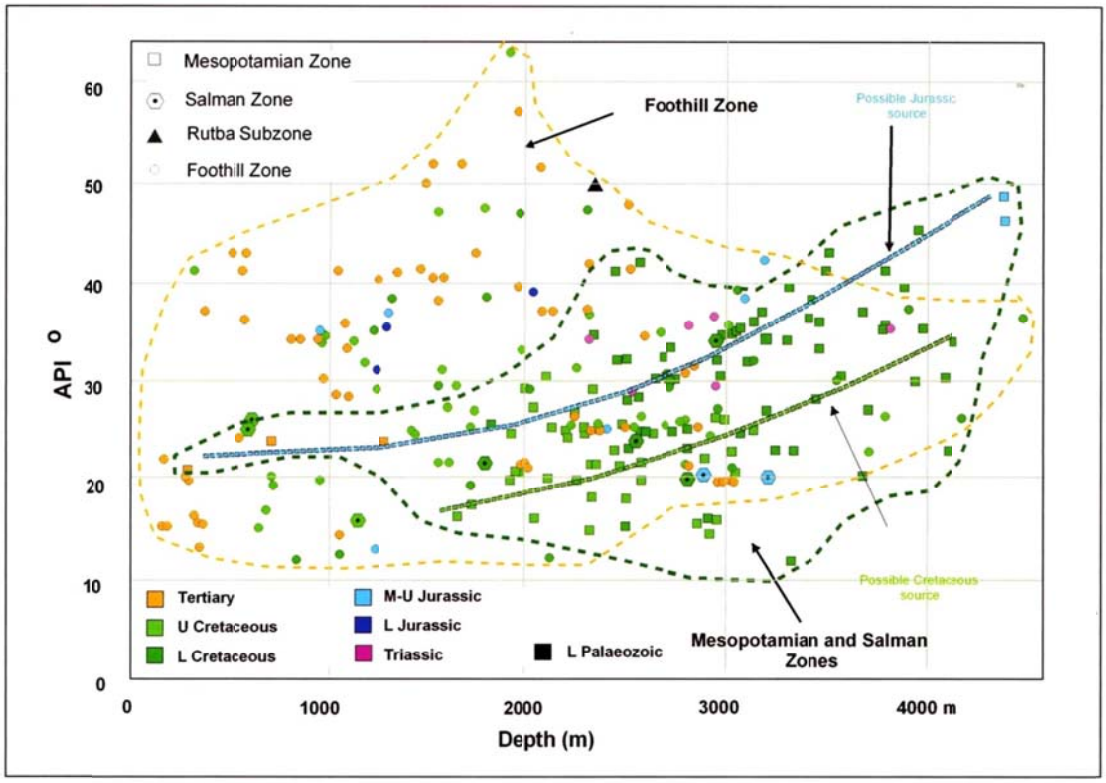
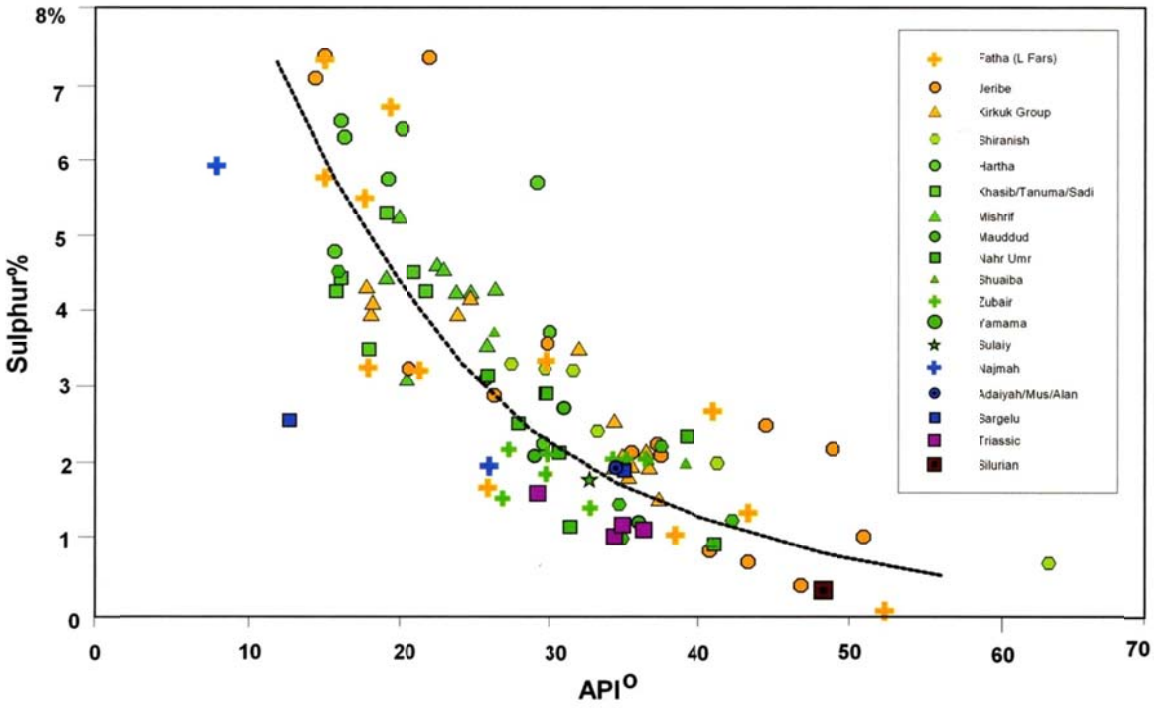


Fig. 18-5a: API-Depth plot of oils contained in reservoir formations ranging in age from the Triassic to Miocene

Fig. 18-5b: API-Sulphur plot of oil contained in reservoir formations ranging in age from the Silurian to Miocene



18.7.3 Palaeozoic petroleum system

18.7.3.1 Source rocks

Ordovician shales, Silurian shales, Lower Carboniferous shales are potential source rocks in Iraq and were investigated by Habba et al. (1994). A regionally extensive source rock unit is present in the Lower Silurian shale of the Qusaiba of central and NWW */N* Saudi Arabia and its correlatives in NE Jordan (Batra Formation), eastern Syria (Tanf Formation), Wand S Iraq (Akkas Formation) and SE Turkey (Hand of/Bedinan Formation). After the Saharan deglaciation at the close of the Ordovician a major transgression affected Gondwana that resulted in the deposition of outer shelf shales rich in graptolites.

Late Palaeozoic erosion led to widespread erosion of the Silurian section. This is the case in E Saudi Arabia and Kuwalt where the Silurian section was eroded over some of the major N-S trending structures such as Ghawar, Summan and Burgan. In Iraq, the Silurian section was probably deeply eroded in the Salman Zone. Oil-bearing Palaeozoic sandstones in central Saudi Arabia where charged by Silurian source rocks (Abu Ali et al., 1991; Husseini, 1992; McGillivray and Husseini, 1992). Silurian source rocks occur in the Nafud basin of NW Saudi Arabia (Cole et al., 1994; Aoudeh and AL-Hajri, 1994).

The following Palaeozoic source rocks can be recognized:

1. Ordovician shales within the Khabour Formation
2. The Basal shale of the Akkas Formation, equivalent to the Qusaiba "hot shale" of the Qalibah Formation of Saudi Arabia and the Batra Formation of Jordan.
3. Lower Carboniferous shales within the Ora Formation
4. Upper Permian carbonates of Chia Zairi (Khuff) Formation and shales of Ga'ara Formation

18.7.3.2 Ordovician

Black shales, with moderate total organic carbon content (TOC) of 0.9% to 5% wt were found in wells Akkas-l and Khlesia-I (Habba et al., 1994). In Jordan, Ordovician shale from the Risha boreholes, with TOC values of 0.54-0.84% wt, were found to be mainly over-mature, with low petroleum yields of <0.12 kg/tonne (NRA reports). In Syria, the Ordovician Khanaser Formations (well Khanaser-l) contain shales with TOC values of 0.08-0.81 % wt, and the Swab Formation contalns shales with 0.351.01% wt TOC (Serreya, 1990).

Maturity calculations indicate that the top of the Khabour Formation in the Akkas well is within the gas window, and that the lower part of the formation is overmature. The Khabour Formation is predicted to be in the gas window in the northern part of the Rutba and the Jezira Subzones but S of the well Akkas-1 it is probably over-mature. It is also over-mature within the Anah Graben area. The Ordovician source rocks in Iraq are of relatively poor quality and mostly over-mature. The sandstones of the Ordovician formations, in adjacent NE Jordan, are generally of poor reservoir quality, with porosities not exceeding 10%.

18.7.3.3 Silurian

Silurian shales source rocks are important plate-wide, in Arabia and N Africa. In Iraq the Silurian source rock is about 80 m thick; it is located at the base of the Akkas Formation and is directly underlain by a clastic bed of glacial origin. An equivalent unit occurs in Jordan at the base of the Batra Formation, and in Syria at the base of Tanf Formation.

The quality of the Silurian source is variable. In NE Jordan and Syria, the hot shale is generally poor in TOC. The highest TOC contents and petroleum yields are recorded from W Iraq (Habba et al., 1994) and NW Saudi Arabia (Oueda and Al Hajri, 1994). The TOC content in NE Jordan varies from 0.7% to 4.32%. In Syria, (well Tanf-I), the TOC content ranges from 0.4 to 1.2%. In well Akkas-I (Habba et al. (1994), the TOC ranges from 0.96 to 16.62% averaging around 6%, with a petroleum yield of up to 49 kg/tonne. In well Khlesia-l the TOC ranges from I % to 9.94%. The base of the Silurian section in Akkas-I contalns oil of 42-49° API and wet gas. The condensate fraction of the oil is rich in saturates and aromatics; the oil contalns 3.9% asphaltenes (Habba et al., 1994).

Maturity calculations (Fig. 18-6) indicate that the basal Silurian is within the oil window only in the northern part of the Rutba subzone, between the Ga'ara anticline in the south and the Anah Graben area in the north; to the south the basal Silurian is within the gas window. Further east, in places where it is still preserved within the Salman Zone, it is mostly within the gas window. It is estimated that the Silurian oil kitchen is restricted to the E and N boundaries of the Rutba Subzone and to the Jezira Subzone. The gas kitchen may be restricted to the southern parts of the Rutba Subzone, the Anah Graben and the Salman Zone. In the Mesopotamian, Foothill and High Folded zones, the source is overmature (Fig. 18-6).

In areas where the source is within the oil or gas windows it reached peak oil generation during the Jurassic and Cretaceous; locally it is still at peak oil generation. In the southern parts of the Rutba Subzone to the S of Rutba, oil generation peaked during the Late Silurian and Devonian and those areas are therefore probably un-prospective.

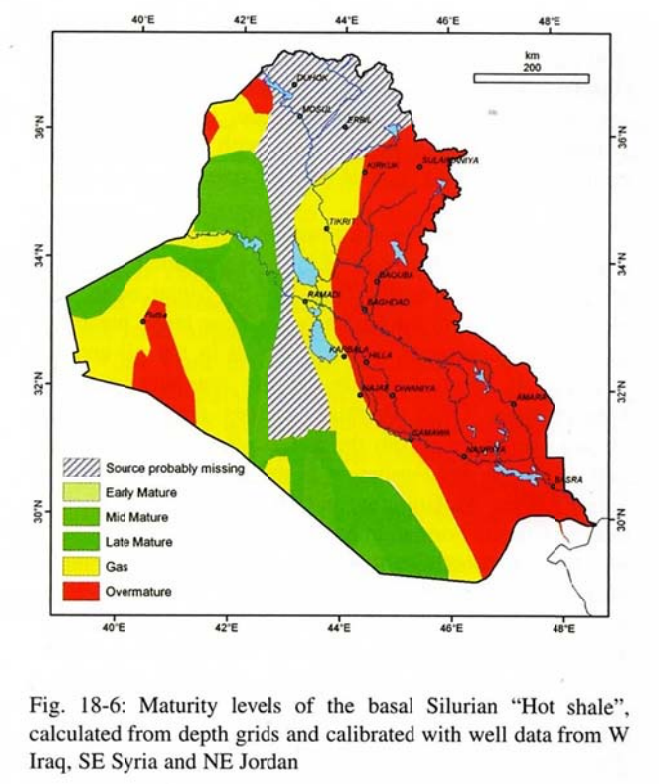
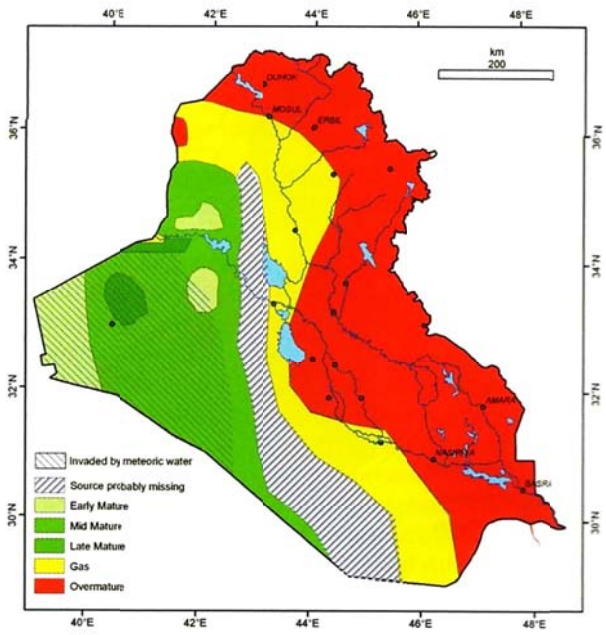


Fig. 18-6: Maturity levels of the basal Silurian "Hot shale", calculated from depth grids and calibrated with well data from W Iraq, SE Syria and NE Jordan

18.7.3.4 Lower Carboniferous

Lower Carboniferous black shales from Akkas-l , and the K5-1 and K5-6 boreholes in the Rutba subzone, have been recognized by Habba et al. (1994) as possible source rocks in W Iraq with 3.42% TOC in Khlesia, 1.48% in Akkas-l and 7.62% in K5-1. The organic matter is lignitic and chitinous and is of continental origin; it is gas-prone. Maturity calculations (Fig. 18-7) suggest that the unit is within the oil window in most parts of the Rutba-Jezira Zone.
The Lower Carboniferous source rocks could charge structures on the Hauran Uplift and Ga'ara Traibeel anticlines which may contain sandstone reservoirs in the Bir El Rah and Ga'ara formations (Upper Carboniferous-Lower Permian). However, meteoric water has been encountered in the Harur Formation of borehole K5-1.

Fig. 18-7: Maturity of the Lower Carboniferous source rocks



18.7.3.5 Upper Permian

The Upper Permian Khuff (Chia Zairi in Iraq) carbonate is considered as one of the main gas reservoirs in the Arabian Peninsula and its organic matter is humic and gas-prone.
In well W Kifl-I the Chia Zairi Formation contalns 20 m of lean net source rock with an average TOC content of 1 % (Habba et al., 1994); its organic matter is humic. Al Sharhan and Kendall (1986) described the equivalent Khuff Formation as a poor source level with an average TOC content of 0.6% and yield of 0.5 kg/tonne.

The Chia Zairi Formation maturation level is within the gas window in the northern part of the Mesopotamian Zone and over most of the Foothill Zone and the Sinjar basin. It is absent over most of the Rutba-Jezira Zone but is present in the Salman Zone area where it is still in the oil and gas window. It is over-mature in the southern parts of Mesopotamia. Other Permian sources may include the Ga'ara Formation within the Salman Zone. An equivalent unit of the Ga'ara Formation

is the Unayza Formation of Saudi Arabia. McGillivray and Husseini (1992) indicated that the Unayza Formation has a TOC content of about 1.5% wt TOC but concluded that its contribution to the total oil charge of Saudi Arabia is insignificant.

18.7.3.6 Reservoirs and seals

The reservoir properties of Ordovician reservoirs in Jordan are poor. The Silurian hydrocarbons may be trapped in the directly underlying Khabour (Traibeel) sandstone unit as seen in the Risha wells and Akkas-I and in sandstones of the Silurian sequence. The traps are most likely to be stratigraphic and stratigraphic-structural formed along N-S trending horst structures during the Late Carboniferous and Early Permian uplift. Within the Salman Zone, as in Saudi Arabia, the Silurian oil may be trapped within the Ga'ara Formation (basal Khuff clastics) below the Chia Zairi Formation. The Upper Permian Chi a Zairi (Khuff) Formation may be a prospective gas reservoir in Iraq, for example in the Salman Zone. The Chia Zairi Formation also has an intraformational seal formed by the middle section of Satina Evaporite Member or below other evaporite beds which may occur in the formation. The main prospective areas for the Upper Permian Chia Zairi Formation are the Salman Zone and the Mosul High. It could be charged by the Silurian or Lower Carboniferous source rocks.

18.7.4 Triassic petroleum system

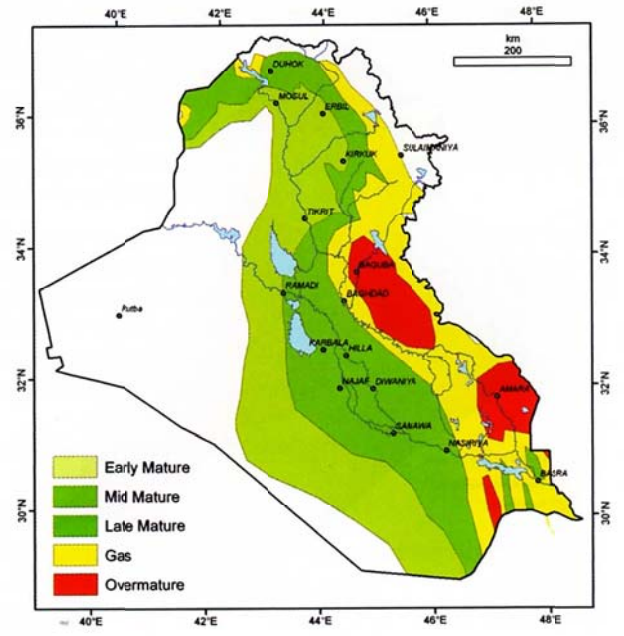
18.7.4.1 Source rocks

Triassic source rocks are relatively poorly studied in Iraq. Thin shale beds occur in the Upper Triassic Kurra Chine Formation in eastern Syria and have sourced light oils and condensates as well as heavy oils trapped in Triassic carbonate reservoirs depending on the level of maturation reached (Serreya, 1990). Source rocks in the Triassic of Syria are also recognized in the Lower Triassic (Amanus Shale). The Amanus source layer is 19-50 m thick with an average TOC of 3.9% wt; the Kurra Chine source beds are 15-40 m thick with a TOC of 3.1 % wt TOC (Serreya, 1990).

The calculated maturity for the Upper Triassic source level is shown Fig. 18-8. Triassic source rocks are probably in the oil window in the Sinjar basin in N Iraq and in the Jezira Subzone with higher levels of maturation in the Tayarat and Anah grabens. The Salman Zone is almost totally within the oil window while the Mesopotamian Zone is in the gas window and' in its eastern part the source rocks are overmature. The Foothill Zone is largely within the gas window while the High Folded Zone is within the oil window. This is due to prominence of the Qamchuqa ridge throughout the Cretaceous and Palaeogene.

In the Mesopotamian and Foothill zones, the Triassic source rocks reached peak oil generation during the Late Cretaceous. In the Salman Zone oil generation in potential Triassic source rocks peaked during the Neogene. Known Triassic oil can be proved only in Butmah oil field where the oil is contained in Upper Triassic dolomites.

Fig. 18-8: Maturity of the Upper Triassic source rocks



18.7.4.2 Reservoirs and seals

Triassic carbonate reservoir rocks occur in the Geli Khana and Kurra Chine Formations. They contain oil in seven oil fields of the Foothill Zone of N and NW Iraq. The Kurra Chine reservoir produces oil in the Butmah oil field. Triassic reservoirs contain oil ranging in API from 28° to 45° (averaging 34°). The sulphur content in the Triassic oil is generally low, ranging from 0.04% to 1.5% and averaging 1.2%. The reservoir properties of the Triassic reservoirs are variable due to irregular dolomitization of the carbonates. Increased permeability might also be due to fractures (Fig. 18-9). Triassic seal rocks are generally the anhydrites which alternate with the carbonate reservoirs.

The area for Triassic reservoirs may be linked to NW Iran (proven) and S Iraq (yet to be proved). The Folded belt might be prospective for the Triassic due to prevalence of fractures in the structures. However, the fractures encountered in some of these structures might be sealed at depth as is the case in many oil fields in SW Iran. The structures on the border of the Mosul High however have proven oil trapped within the Triassic (Butmah, Ain Zalah etc.). In S Iraq, the Triassic has been reached or penetrated by a few wells such as Rumaila-I72, Khidr Al Maa, Diwan, West Kifl and Marjan. The pressure data are: 0.11 atm/m for N Iraq, 0.126 atm/m for, central Iraq and 0.195 in S Iraq. The latter relatively high pressure gradient is due to the generally high pressure gradient within and below the Jurassic Gotnia Formation.

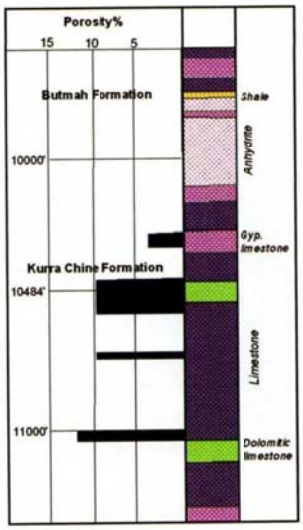


Fig. 18-9: The Upper Triassic Kurra Chine reservoir in the Butmah oil field of North Iraq

18.7.5 Jurassic petroleum system

18.7.5.1 Source rocks

Middle Jurassic source rocks are very important source rocks throughout S, NE and N Iraq due to the high TOC of the Sargelu and Naokelekan formations that were deposited throughout the Jurassic basin. Pitman et al. (2004) concluded that most of the oil of Iraq was sourced from Jurassic source rocks. Study of the Upper Jurassic-Lower Cretaceous source rocks and oil samples from six oil fields in the Kirkuk embayment of NE Iraq (Habba and Abdulla, 1989) confirm the organic richness and high petroleum potential of the Jurassic Sargelu and Naokelekan source rocks and also of the Lower Cretaceous Lower Balambo Formation.

The Sargelu Formation is up to 400 m thick with a TOC content of 1.7-7.6% wt%; the lowermost 40 m of the formation has the highest TOC content (Pitman et al., 2004). The Naokelekan Formation is up to 45 m thick in the E part of the Foothill Zone and in the High Folded Zone. Its TOC content is up to 13.2% and averages 5%. According to Habba and Abdulla (1989) the Sargelu and Naokelekan formations in the Kirkuk Embayment entered the oil window at the end of the Eocene (35 Ma) and are presently in the condensate and gas generating maturation levels. Odishu and Othman (1992) evaluated the source rock potential of the Sargelu, Naokelekan, Chia Gara and Sarmord Formations in N Iraq, over the Mosul block, in both well samples and outcrops. They showed that the Sargelu, Naokelekan and Chia Gara Formations are good source rocks although with variable hydrocarbon potential. The Chia Gara Formation was found to be the richest potential source rock in this region of Iraq with a TOC of up to 20.91 %. The Kimmeridgian Barsarin Formation had a TOC of up to 7.79% The Jurassic source rocks were buried to relatively shallow depths over the Mosul High; they are thus mostly early mature to immature in this region.

The maturation of the Middle Jurassic source rocks was studied in detail by Pitman et al. (2004). They modelled the present day maturity, the maturation history of the source rocks and migration pathways of oil expelled from them. They calculated that oil generation started in S Iraq and the

Kirkuk Embayment during the Oligocene, and that oil then migrated towards the Salman Zone in S Iraq and towards the Mosul High and the Euphrates River in the N. During the Late Miocene to present, the source rocks became almost totally mature; oil migrated from the central part of Mesopotamia towards the Euphrates River, and from the Foothill Zone towards the central Mesopotamia. In N Iraq, oil migrated into the Mosul High.

The calculated maturity of the Sargelu source rock (Fig. 18-10) indicates it is mostly immature to early mature within the Salman Zone and early mature on the Mosul High. The source rocks are mid mature to late mature within the western Mesopotamian zone and within the gas window in the eastern Mesopotamian zone. In the foothill zone, the maturity increases from early mature in the SW to mid mature in the east. In the high folded zone, the Jurassic source is within the late maturity window.

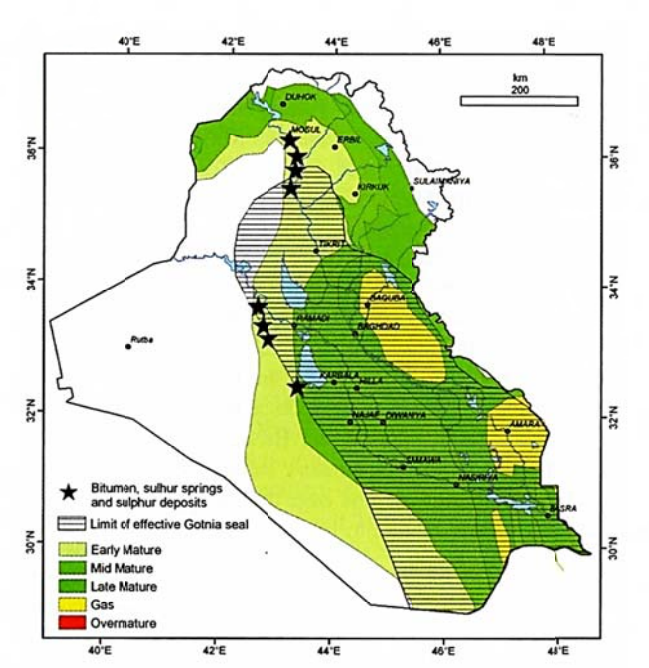


Fig. 18-10: Maturity of the middle part of the Middle Jurassic

18.7.5.2 Reservoirs and seals

The Sargelu-Najmah-Gotnia triplet (source-reservoir-seal) is an important potential petroleum system in Iraq. The reservoir potential of the Najmah Formation has yet to be properly evaluated in Iraq. In the North Rumaila and West Qurna fields the Najmah Formation flowed 48° API oil at a rate of over 3500 bbll /d. In S Iraq high pressures have been encountered within and below the Gotnia Formation which resulted in drilling problems. It is possible that the prolific Arab-Hith reservoir/seal system of Saudi Arabia extends in to parts of southern Iraq. In N Iraq, the prospectively of the Jurassic reservoirs is limited because of the frequent absence of the Jurassic evaporite caprock. Oil shows are also known in other Jurassic formations (see Appendix 2). These include the Butmah, Sargelu and Adaiyah-Mus-Alan formations.

18.7.5.2.1 Sarge1u, Adaiyah, Mus and Alan

The Sarge1u Formation contalns oil in fractures in some structures in N Iraq and in the Salman Zone. The oil trapped in the Sarge1u is often heavy and bituminous, because of the low maturity of this source rock in these areas and the lack of a seal where the evaporites of the Gotnia Formation are absent, allowing escape of the oil to the shallower Tertiary reservoirs and to the surface (Fig. 18-10). The Sargelu reservoir contalns oil with a wide range of oil gravities (13.3-42° API) and sulphur contents (1.8-2.5%).

The Adaiyah-Mus-Alan Formations comprising locally fractured carbonates and anhydrite are poor reservoirs in 'N Iraq. The formations contain oil in Ain Za1ah field with an API ranging of 28-34° and sulphur content of about 1.9%.

18.7.5.2.2 Najmah-Gotnia

The most important Jurassic reservoir is the Najmah Formation. It acts as a reservoir in 19 structures within the Foothill, Salman and the Mesopotamian zones (Appendix2). The Najmah (and locally carbonate beds in the overlying Gotnia Formation contain oil of API ranging from 8° to 46°, dependant on the maturation level of the underlying Jurassic source rocks. The sulphur content of the oils is 1.9-5.9%. The maximum reservoir porosity is 20%-30% while the permeability varies greatly due to dolomitization. The lowest recorded oil gravities (8 and 12° API) are in wells Fallujah-1 and Demir Dagh-I respectively. Both the Falluja and Demir Dagh structures are in a zone of early maturation of the Sargelu source. The Falluja structure is adjacent to the bitumen seepages of the Abu Jir and Hit (Fig. 18-10). The range in oil properties of the oil in the Najmah Formation indicates the oils were derived from Jurassic source rocks of different maturation levels.

In N Iraq, the Gotnia seal is missing, resulting in the leakage of oil into the overlying Hartha (Pilsner) and Jeribe reservoirs in the Qalyarah, Qasab, Najmah and Jawan fields. In the Qara Chauq structure SE of Mosul, the API Gravity of the oil in the Gotnia Formation is 39° and the pressure within the formation is generally normal (0.12 atm/m). This is probably due to the low thickness of the evaporite in the formation. In central Iraq around Tikrit (Tikrit-I) and in the S near Najaf (Kifl-I), the Najmah Formation is very poorly developed or absent. In S Iraq, the sequence below the top of the Gotnia Formation has an abnormally high pressure gradient (0.2 atm/m) compared to the normal hydrostatic pressure gradient of 0.12 atm/m above.

18.7.6 Cretaceous petroleum system

18.7.6.1 Source rocks

Cretaceous source rocks occur in Iraq but are poorly studied especially in S Iraq. Habba and Abdulla (1989) analyzed some Cretaceous source rocks in N Iraq (Section 18.7.5.1). Abdulla and Kinghorn (1996) analyzed Cretaceous source rocks in Kuwalt. They concluded that the Sulaiy Formation is the most productive source formation due to its TOC content and favorable burial history. Its TOC content ranges from 0.5-3.2% (Abdulla and Kinghorn, 1996). The formation is up to 300 m thick in S Iraq, thinning to <50 m in central Iraq.

In SW Iran (Dezful Embayment), Bordenave (1993) identified four main Cretaceous source rocks: the Garau, Kazdhumi, Shalaif and Gurpi Formations. These are respectively equivalent to the Balambo, Nahr Umr, Rumaila, and Shiranish Formations of Iraq. The Kazdhumi is the most important oil source of oil in SW Iran and, therefore, the Nahr Umr shales might be important source rocks in SE Iraq.

The Chia Gara Formation (of Tithonian-Berriasian age) has a TOC content of up to 6.91 % wt. The Lower Balambo is regarded as the major source of oil in the Kirkuk Embayment, entering the oil window in the Early Miocene (15 Ma), and are currently at peak oil generation (Habba and Abdulla, 1989). The average TOC content of the formation is lower than that of the Upper Jurassic source at 0.9% wt, but the effective thickness is much greater ranging from 100 m to 700 m.
The shales within the Ratawi and Zubair formations are considered as modest source rocks; they are in the oil window in the Mesopotamian Zone. The calculated maturity of the base of the Ratawi Formation (Fig. 18-11) indicates it has just entered the oil window in the Salman Zone, and i within the oil window in the Zubair and Euphrates sub zones and within the wet gas window in the Tigris Subzone.
Upper Cretaceous formations (Shiranish marls or the equivalent Jib'ab Marl and phosphatic Digma Formation are potential source rocks in the Anah and Tayarat grabens in W Iraq where they are partly within the oil window (Fig. 18-12). Areas within the Anah Graben and the Sinjar Trough are expected to contain mature Upper Cretaceous source rocks. Upper Cretaceous source rocks are also mature in E Iraq (Fig. 18-12). In Syria the net thickness of the Upper Cretaceous source rocks is 30-40 m with an average TOC of 2.6% (Serreya, 1990).

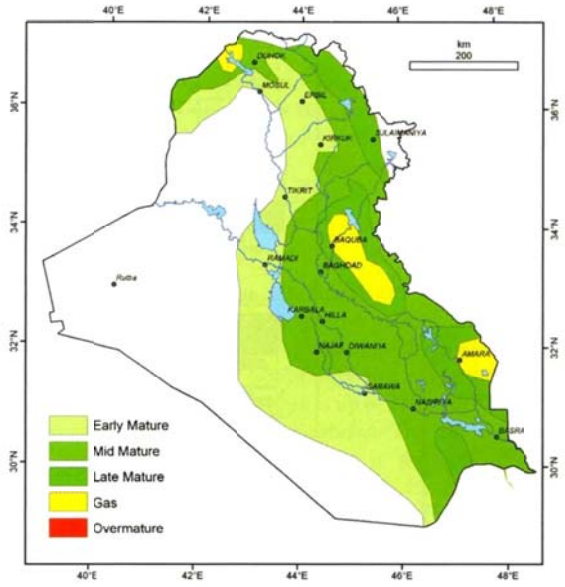


Fig. 18-11: Maturity of the middle part of the Lower Cretaceous source rocks

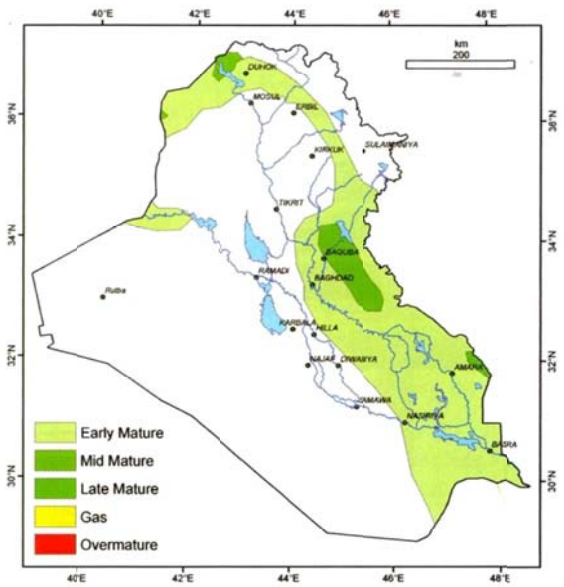


Fig. 18-12: Maturity of the Upper Cretaceous source rocks

18.7.6.2 Reservoirs and seals

Cretaceous reservoir rocks are abundant, especially in S Iraq. However, four reservoir units contain most of the oil of the region; the Yamama, Zubair, Nahr Umr and Mishrif. Other formations are locally important and include the:
Sulaiy, Ratawi, Shu'aiba, Mauddud, Rumaila, Khasib Tanuma-Sa'di, Hartha and Tayarat. In N Iraq the Qamchuqa Formation (equivalent to the Mauddud and Shu'aiba) is a reservoir in the oil bearing structures of the Kirkuk Embayment and in the Mosul High. The Shiranish, Hartha and Kometan Formations are important fractured carbonate reservoirs in N Iraq.

18.7.6.2.1 Yamama

The Yamama Formation contalns oil and gas in 26 structures of S Iraq (Appendix 2). The formation comprises two carbonate units each with basal reservoir oolitic limestones overlain by lime mudstone seals (Sadooni, 1994). Its porosity varies greatly from 5-20%. Permeability ranges from 3-180 md; highest porosities occur in the Rumaila and West Qurna structures. The formation has been tested at rates of up to 9000 bbl/day in West Quma, 10,800 bbl/day in Zubair, up to 19,000 bbl/day in Ratawi, 1,350 bbl/day in
North Rumaila and 4000 bbl/day in Halfaya. It contalns oil of 16-43° API gravity and a sulphur content of 0.9-4.5%. It is an important reservoir in the southern Mesopotamian Zone, especially in the West Quma, North Rumaila and Majnoon fields.

18.7.6.2.2 Zubair

The Zubair Formation is the most prolific reservoir in S Iraq especially in the Zubair and Rumal1a oil fields where it is known as the Third and Fourth Pays of S Iraq (Fig. 18-13). It is an oil reservoir in some 30 structures in the Mesopotamian Zone, including the fields of East Baghdad and Balad. The formation extends from the Tharthar region in central Iraq southwards towards the Iraqi-Kuwalt border; it is >500 m in the area S of Baghdad. The formation consists of sandstone and shale. Limestone beds occur in the formation in eastern SE Iraq. The net sand content of the formation generally increases towards the west, from zero near the Iraq Iran border to over 200 m near Zubair in the south and near Karba1a to the north. Between Nasiriya and Amara the net sand thickness is about 100m; carbonates comprise about 15% of the formation near Nasiriya and 35% near Amara. In East Baghdad field, oil of 32° API gravity is produced from the Zubair Formation; oil is also encountered in the Zubair Formation in the Balad oil field. Strong oil shows in the formation are also recorded from wells bordering the Euphrates River; Kifl-I tested 5,600 bll/d from the Zubair Formation.
Its porosity exceeds 30% in the Salman zone and diminishes to 15% along the Iraq-Iran border in S Iraq. The permeability ranges from 20 to 1800 md (averaging 700 md). It contalns oil with API gravity values ranging from 160 to 39° (averaging 34°) and a sulphur content of 1.5% to 2.18% (averaging 1.8%). The API varies from an average of around 34° in the western parts of Mesopotamian to around 16-27° in the east. The API gravity of the Zubair oil in Khidr Al Mal structure is 20°. The maturities of the underlying Jurassic and Cretaceous source rocks are shown in Fig. 1810 and Fig. 18-11 respectively.

The most important occurrences of oil in the Zubair Formation are in the S Iraq oil fields of

Zubair, Rumaila, Ratawi, Tuba and Luhais. Oil has also been discovered in the Zubair Formation further east in the Majnoon, Halfaya and Huwaiza fields.

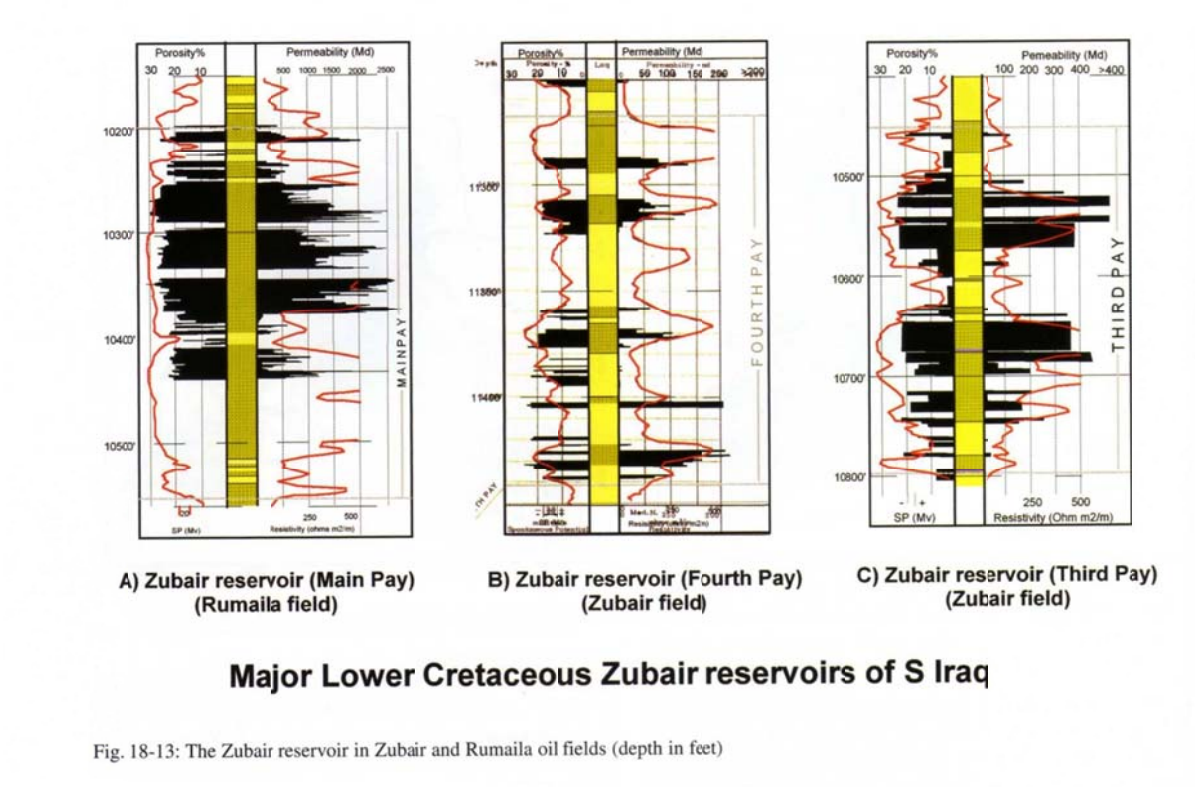


Fig. 18-13: The Zubair reservoir in Zubair and Rumaila oil fields (depth in feet)

18.7.6.2.3 Ratawi

The Ratawi Formation, which underlies and partly interfingers with the Zubair Formation, may have contributed to the oil charge of the Zubair Formation, especially in the eastern part of the Mesopotamian Zone. The formation is locally oil bearing but has very poor reservoir quality. The limestones of the formation are very tight with a primary porosity of 5 to 15% and low permeability (Tuba).

18.7.6.2.4 Shu'aiba

The Shu'aiba Formation and the equivalent Lower Qamchuqa Formation form a carbonate ramp trending NNW-SSE and extending from the Iraq Iran border in S Iraq, to the Kirkuk area in N Iraq. The Shu'aiba Formation consists of strongly recrystallized and dolomitized carbonates. The formation contalns oil in the Kirkuk (Baba Dome), Bai Hassan, Khabaz, Khurmala, Makhul and Qara Chauq structures in N Iraq and in the Ahdeb, Jraishan, Majnoon, North Rumaila, Samawa and Zubair structures of S Iraq. The Shu'aiba reservoir varies in porosity from 8 to 30% (averaging 18%), while the permeability varies from 80 to 1000 md (av. -150 md). Its API oil gravity varies from 12.6 to 42° (usually 21-42° in N Iraq) with a sulphur content of 0.92-3.7% (averaging 2%).

18.7.6.2.5 Nahr Umr

The Nahr Umr Formation is a significant oil reservoir in S Iraq. The Nahr Umr Formation is a sand-dominated clastic unit in the W and SW and shale-dominated in the E; it passes laterally into the Upper Sarmord Formation in N Iraq and the Kazdhumi Formation in SW Iran. It is equivalent to the important Burgan Formation of Kuwalt. The formation has a gradational contact with the overlying Mauddud Formation; in the Majnoon field 40% of the Nahr Umr Formation comprises carbonate beds. Its distribution is similar to that of the Zubair Formation; it extends into the Stable Shelf Zone along the southern side of the Rutba Uplift. The maximum thickness of the formation is around 250 m in S Iraq.

Most of the oil found in the Nahr Umr reservoir is located in S Iraq though numerous other structures in central Iraq were found to have oil within the formation. 37 structures contain oil in the Nahr Umr Formation (see Appendix 2).

The porosity of the formation ranges from 16 to 23.3% (averaging 21 %); permeability ranges from 20 to 3000 md (averaging about 200 md). The API oil gravity ranges from 20 to 35° (averaging about 28°) and sulphur ranges from 0.92 to 3.7% (averaging about 2%).

18.7.6.2.6 Mauddud

The Mauddud Formation was deposited on an Albian carbonate ramp developed along the eastern side of the Mesopotamian Zone of S Iraq, shifting to the E side of the Foothill and High Folded zones in N Iraq along the Anah Qalat Dizeh Fault. The formation is up to 240 m thick in two depocentres near Amara and Baghdad. The net reservoir thickness in S Iraq reaches 150 m in the Amara area, decreasing to 50 m towards the SW near the Zubair area. The Mauddud Formation contalns oil in 19 structures in N, central and S Iraq (Appendix 2).

The porosity of Mauddud Formation is generally <15%. The permeability is usually <10 md. The oil in the Mauddud varies from 12-38° (averaging 25°). The heaviest oil in the Mauddud is found in Amara field and the lightest is found in the Kirkuk structure. The sulphur content ranges from 1.2 to 3%; the lowest sulphur content is 1.2% is found in the Badra structure where the API gravity is 36°.

18.7.6.2.7 Mishrif

The Mishrif Formation is best developed as thick rudist buildups over structural highs in S Iraq, specifically in the eastern Mesopotamian Zone. The formation comprises repeated cycles of backreef/lagoonal sediments and rudist banks (AL Khersan, 1975). Other banks also developed along the W side of the Mesopotamian Zone, especially near Kifl (Chapter 12). Oil in the Mishrif Formation reservoir is confirmed in 32 structures in northern, central and S Iraq (see Appendix-2).

High net reservoir thickness is best developed within the rudist banks of E Mesopotamia. Porosity is up to 22% and averages 15%. Permeability ranges from 23 to 775 md and is generally good. The API gravity of the oil in the Mishrif is typically 23-36.6°, averaging around 25°.

18.7.6.2.8 Khasib- Tanuma-Sa'di

The three formations Khasib, Tanuma and Sa'di are present over much of S and Central Iraq and generally characterised by chalky sediments interbedded with marls and shale (especially in the Tanuma Formation). They were deposited in a NW-SE trending basin extending from NW Iraq to Kuwalt. They thin towards the east (125 m), west (150 m) and northwest (100 m).

The reservoir units in the Khasib- Tanuma-Sa'di have porosities of 18-23% (averaging 20%) and a permeability of about 10 md. The oil API gravity varies from 16 to 28° (averaging 22°). The Sulphur content of the oils is 2.94.64% (averaging 3.5%).

18.7.6.2.9 Hartha-Tayarat

The Lower Campanian-Maastrichtian Hartha Formation (including the "Pilsner Formation") is' present in a depocentre extending along the western side of the Mesopotamian Zone and along the eastern side of the Salman Zone (Chapter 12). The formation was deposited as shoals and banks with rudist debris *(Hippurites)* and as oolitic carbonates and sabkha carbonates and evaporites (especially on the Salman Zone and the Rutba subzone). The formation is up to 450 m thick near Najaf. The Hartha Formation reservoir is found in 30 structures in S, Central and N Iraq. The net reservoir thickness generally does not exceed 45 m. The overlying Tayarat Formation has similar characteristics and is mostly developed along the Salman Zone.

The porosity of the formation where best developed is 2124%. The API gravity of its oil ranges from 15 to 30° (averaging about 25°) with a sulphur content varying from 1.45-5.9% (averaging about 4%). The lowest sulphur values are found in Injana and Sasan structures indicating derivation from fully mature source rocks

18.7.6.2.10 Shiranish

The Shiranish Formation consists of mudstone, marl and occasional limestone beds. It often forms the seal above the Hartha and Tayarat reservoirs in S Iraq, but in central and N Iraq it can act as a reservoir where it is tectonically fractured in the cores of anticlines.

Matrix porosity is typically very low (3% in Butmah Field). Reservoir permeability is thus controlled by fractures. An average permeability of 13 md is recorded from the Sufaiyah field in NW Iraq, but is locally much higher. The API gravity of oil varies from 14° to 63° (average -25). The API gravity is highest in the Chemchemal field of NE Iraq. The sulphur content varies from 0.14 and 4.3%.

18.7.7 Tertiary system

18.7.7.1 Source rocks

Tertiary source rocks may occur in the Aaliji Formation of Palaeocene-Early Eocene age. However, it is unlikely that the source is mature except, perhaps, in the Badra area along the eastern parts of the Mesopotamian Zone. The equivalent Pabdeh Formation of SW Iran is a well documented source in the Dezful Embayment (Bordenave, 2002). Palaeogene source rocks are also reported in the Euphrates Graben in Syria.

18.7.7.2 Reservoirs and seals

The Tertiary oil is "seepage" oil that migrated from deeper reservoirs. The folds of the Foothill Zone grew mainly during the Pliocene. Two type of oil are contained within the Tertiary reservoirs, these are high API gravity oils in NE Iraq and low API gravity oils in the Mosul High of N Iraq. Since the Tertiary and Late Cretaceous sources in NE Iraq are immature to early mature, the light oil (37 API) in Kirkuk field must have migrated from deeper source rocks through fractures. The Lower Cretaceous and Jurassic source rocks are the most likely sources for these hydrocarbons in NE Iraq (Dunnington, 1958). The low API gravity high sulphur oil of the Qalyarah, Qasab and Najmah structures is most likely sourced from less mature source rocks (around the Mosul High). In S Iraq, oil in the Tertiary reservoirs is restricted to both sides of the Mesopotamian Zone where the oil has also migrated from deeper levels. Tertiary reservoirs are important gas reservoirs in the Foothill zone of the Kirkuk Embayment.

The oil and gas within the Tertiary reservoirs is trapped below two widely distributed anhydrite seals: the Lower Miocene Dhiban and the Middle Miocene Fatha (L Fars) formations. The Fatha Formation has a much wider areal distribution and is the most effective seal in the Tertiary section. There are three important Tertiary reservoirs in Iraq: the Kirkuk Group, and the Euphrates and Jeribe formations; and the lower carbonate section of the Fatha (L Fars) Formation sometimes acts as a reservoir. Other less significant reservoirs include the Avanah, Pila Spi, Gercus, Aaliji, Umm Er Radhuma, Jaddala and Ghar.

The main Tertiary reservoir units of N Iraq include the Jeribe, Euphrates and the Kirkuk Group; the units are sometimes grouped under the name "Main Limestone". However, the Main Limestone may sometimes include only the Kirkuk Group (Fig. 18-14).

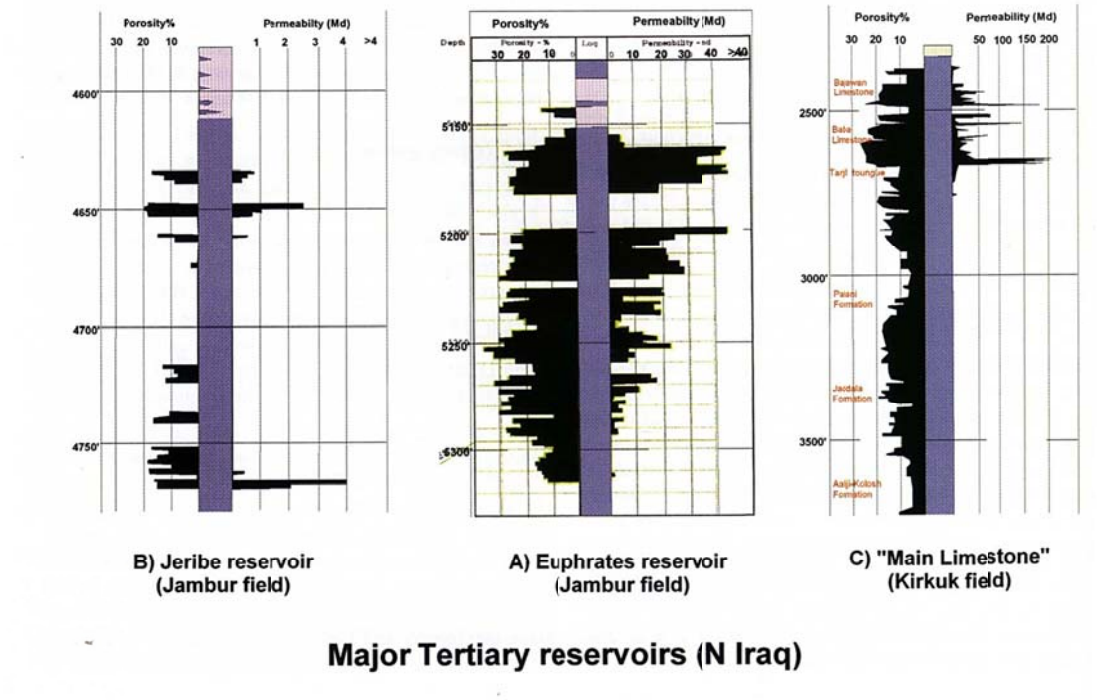
18.7.7.2.1 Kirkuk Group

The Kirkuk Group is represented by a complex of backreef/reef/forereef and basinal units. In many fields the whole of the Oligocene Kirkuk Group and the overlying Euphrates and Jeribe formations form one reservoir unit sealed by the Fatha (L Fars) evaporite section. The reservoir units of the Kirkuk Group are related to reef/forereef facies fringing the shoreline of the Oligocene basin. The NE reservoir belt extends from the Mosul area in the NW to the Iranian border at Naft Khaneh. The SW reservoir belt extends from the western desert in the NW towards Hit, crossing the Mesopotamian Zone towards the Amara area in SE Iraq.

The Kirkuk Group is a reservoir unit in the Khurmala, Avanah and Baba domes of the Kirkuk structure, and in the Judaida, Khabaz, Bai Hassan, Ajeel and Hemrin fields in N Iraq. In S Iraq it is a reservoir in the Jabal Fauqi, Haifaya and Buzurgan fields. The whole complex of the Kirkuk Group, Euphrates and Jeribe is referred to as the Main Limestone and is equivalent to the prolific Asmari carbonates in the oil fields of the Dezful Embayment of SW Iran.

The porosity and permeability of the carbonates of the Kirkuk Group are usually good; some wells within the Baba dome produced 100,000 bbl/day. The porosity ranges from 15 to 25% (averaging about 22%) and the average permeability is about 100md. The API gravity of oil ranges from 18° to 36° (average 30°); the sulphur content is 1.5- 4%. The lightest oil with the lowest sulphur content is recorded in the Kirkuk structure. Oils in Oligocene reservoirs in the S Iraq oil fields are relatively heavy (20° API) and may have been derived from a mid mature Cretaceous source rock.

Fig. 18-14: The Tertiary reservoirs of some of the main oil fields of N Iraq (depth in feet)



18.7.7.2.2 Euphrates and Jeribe

The Euphrates and Jeribe Miocene Formations are important reservoirs in N Iraq and locally in S Iraq. They contain oil and gas in over 30 structures (see Appendix 2). Both formations are inner shelf carbonates with both primary porosity and secondary porosity due to dolomitization. In many structures of the Mosul High the formations are bituminous indicating that that they once contained oil prior to breaching of the seal or flushing by meteoric water at shallow depth. Many sulphur deposits around Mosul are related to oil and gas escaping from the Jeribe Formation into the evaporitic Fatha Formation (Jassim et al., 1999).

The Euphrates Formation ranges in porosity from 15% to 30% (averaging about 20%) Its permeability ranges from 8 to 500 md (averaging 10 md). Its API oil gravity varies from 18 to 36.7° (averaging 30°) and its sulphur content varies from 1.5 to 3.97% (averaging 2%). The Jeribe reservoir porosity ranges from 14 to 21% (averaging about 17%). Its permeability varies from 1 to 1146 md (averaging about 200md). Its API oil gravity varies from 15 to 51 ° (averaging 35°) and the sulphur content varies from 0.4 to 7.1 %. The heaviest oils with the highest sulphur contents are found in fields in the Mosul area where seepages occur. In S Iraq, where the formations contain oil in the Jabal Fauqi, Abu Ghirab, Buzurgan and Halfaya fields, the oil is also heavy (18 API) with high sulphur content (3%).

18.7.7.2.3 Fatha (L Fars)

Fatha (L Fars) Formation has a limestone-dominated unit at its base, often referred to as the "Transition Beds", overlain by an anhydrite-dominated unit. The carbonates of the lower unit in the Mosul area often contain heavy oil and bitumen. The formation has been identified as a reservoir in 11 structures, mostly in NE Iraq and in S Iraq along both flanks of Mesopotamia. The Fatha Formation contalns gas in Chia Surkh and oil and gas in the Gilabat, Khashm Ahmar and Mansuriya structures in N Iraq, Ajeel in central Iraq and Subba, Zubair, Rumaila, Suhain, Majnoon, Nahr Umr and Kifl in S Iraq. The porosity ranges from 15 to 20% (averaging 15%);

permeability is about 100 md. The API gravity of the oil ranges from 12.9 to 41 ° (averaging 19°). The highest API values are restricted to the central and NE Iraq while oils of the S Iraq oil fields are generally heavy «22° API).

18.7.8 Hydrocarbon budget and exploration potential

Knowledge of source rock properties in Iraq is still very limited (Section 18.7). Knowledge of the properties of the Silurian source rocks are based on data from two wells in W .Iraq and some data from the surrounding countries. Little data has been published on the properties of the Cretaceous source rocks; published analyses of' Jurassic source rocks are limited to scattered outcrops in NE Iraq and a few wells. No published analyses of Triassic source rocks are available. Consequently there is significant uncertainty in the volume of oil and gas generated in the source kitchens in Iraq.The volume of oil generated from the Mesozoic source rocks in Iraq can be conservatively estimated at 2 trillion barrels (2000 billion barrels) assuming a total mature kitchen area of 300,000 sq km, an average net source rock thickness of 20 metres, an oil yield of 25 kg/tonne of source rock, an average maturity of 75%, a source rock density of 2.4 tonnes/cubic metre and an average oil density of 830 kg/cubic metre. If 25% of this oil was expelled and reached traps following secondary migration the volume of Oil in Place in Iraq's oil fields would be about 500 billion barrels. However this volume could be much higher if the average thickness and oil yield of the source rocks has been underestimated or significantly lower if large volumes of oil have been lost by seepage in central W Iraq and in the fold belt of NE Iraq.

The Undiscovered Hydrocarbon resources of Iraq have been assessed by the United States Geological Survey (USGS) (Verma et al 2004). The USGS estimated the range of undiscovered resources using 95%, mean and 5% probability levels for each petroleum system in Iraq. The Palaeozoic Petroleum system was estimated to contain undiscovered oil resources of 0.5-3.1 billion barrels of oil (mean 1.6 billion barrels), and undiscovered gas resources of 12.6-68.8 trillion cubic feet of gas (mean 38.7 trillion cubic feet). The Jurassic Petroleum System was estimated to contain undiscovered oil resources of 1.7-9.2 billion barrels of oil (mean 5.3 billion barrels), and undiscovered gas resources of 5.0-32.8 trillion cubic feet (mean 17.6 cubic feet). The combined Cretaceous and Tertiary Petroleum Systems were estimated to contain undiscovered oil resources of 12.0-71.7 billion barrels of oil (mean 38.2 billion barrels) and undiscovered gas resources of 19.2125.4 trillion cubic feet (mean 63.7 trillion cubic feet).

Al-Khirsan and Al-Siddiki (1989) noted that only 114 out of a population of about 400 closed structures in Iraq had been drilled. They estimated that the remaining exploration potential in Mesozoic and Tertiary reservoirs in structural traps in Iraq was probably 40 billion barrels and possibly as high as 80 billion barrels. Al-Gailani (1996) noted that only 59 deep exploration wells had been drilled in Iraq of which 39 reached the Jurassic, 12 reached the Triassic, and 8 had been drilled to the Palaeozoic. 131 exploration prospects had been drilled in Iraq by 2003 (Al-Gailani 2003). This corresponds to a very low density of exploration drilling for a large onshore petroleum province. The distribution of undrilled and dry structures (Al-Gailani 2003) is shown in Fig 18-1. Undrilled structures comprise anticlines defined by surface geological mapping in the High Folded Zone, and structures defined by seismic or potential field surveys in the rest of Iraq. Details of drilled structures are provided in Appendix 2. A major oil and gas exploration programme is required to fully evaluate the remaining exploration potential of structural and stratigraphic traps in the petroleum systems of Iraq.

Chapter 19

Hydrogeology

by

Jiri Krasny, Saad Alsam and Saad Z. Jassim

19.1 Introduction

Although Iraq benefits from two big rivers, the Tigris and the Euphrates, their water and that of their tributaries is only utilised in a narrow belt along river valleys in N Iraq and in the Mesopotamian plain of central and S Iraq. Canals taking water from rivers were used in ancient times for water supply. The well-known 70 km long aqueduct supplying the Assyrian capital Niniva with water from the dam at the Gomel River was completed by King Sennacherib in 690 BC. In historical times extended irrigation systems were also established; one was fed by the 300 km long Nahrawan canal built in Neo-Babylonian times (6^{th} Century BC) and later reclaimed by the Abbasids in 800 AD. However the present total area irrigated by surface waters covers only about 25% of Iraq. Groundwater will thus play an important role in the development of the remaining 75% of the country.

Drilling of groundwater wells in Iraq did not start until the 1920's. However hand-dug wells date from the Babylonian civilisation. Hand-dug wells within the flood plain of Iraq were discovered in the old ruins of Babylon. The Abbasids dug wells along the pilgrimage route between Najaf and Mecca (Darb Zubaida) at intervals of forty kilometres (corresponding to a days travel by caravans). Some of these wells in limestones were 100 m deep and 8 m wide. Thousands of wells have since been dug in Iraq to supply drinking water, and later to provide water for irrigation.

Due to the importance of groundwater for Iraq's economy, especially for the supply of drinking water and for irrigation, hydrogeological investigations were conducted in the last century. A groundwater governmental authority was created as a small section within the irrigation office after the independence of Iraq in 1921. Significant groundwater research commenced when the General Directorate of Groundwater was formed within the Ministry of Irrigation. Regional groundwater studies were carried out by GEOSURV and later by the Desert Development Project within the Ministry of Irrigation.

The hydrogeological synthesis for Iraq presented in this chapter is based on data available to the authors from the 1920's to the late 1990's.

19.2 Available data and methodology of treatment of hydrogeological data

Hydrogeological data are available mostly in unpublished reports. The basic work is still the comprehensive study by the Parsons Company of the Groundwater Resources of Iraq, published in 13 volumes in 1955 and 1957. Elerdashvili (1973) presented a hydrogeological synthesis of Iraq. Marinov et al. (1974) described the hydrogeology of Iraq within the hydrogeological context of Asia. Macdonald (1960) studied irrigation in Iraq. Riykov et al. (1975) presented important results on water resources and land development in Iraq. The groundwater of the Mesopotamian Plain was studied by a Russian team (1980) contracted with the Ministry of Irrigation in the late 1970's. They established observation boreholes in the Mesopotamian Plain near Shanafiya, Nasiriya, Baiadruz, Diwaniya, Shatra, Dujalla, Amara, Hawija and Dibuni.

Regional hydrogeological studies in the 1970's and 1980's were carried out for the 7 blocks of the desert and compiled by: Al Rawi et al. (1983) for blocks 1-3, Southern Desert Salman area;

Idrotecnico (1977) for block 4, Southern Desert-Nukhaib area; Consortium Yugoslavia (1978 and 1981), for block 7, Western Desert-Ramdi-Anah-KI60 settlement and block 5, Rutba area). These studies included groundwater regime observations and drilling of relatively deep wells; the deepest well reached 1600 m near Ga'ara in W Iraq.

GEOSURV conducted regional hydrogeological studies during geological mapping projects. GEOSURV sampled springs and hand-dug wells, and drilled and observed new wells. Important studies were conducted in the Tikrit Baquba area (Krasny 1982e), in the Samarra plain and in Block 8, Jezira area of NW Iraq (Alsam and Hanna, 1989), in the Foothill Zone (Krasny 1983a), west of Tharthar (Alsam and Hanna, 1989) and in south and north Sinjar (Alsam and Hanna, 1989). Groundwater observations were also carried out in the Erbil, Altun Kupri and Khazir-Gomel areas (Alsam and Hanna, 1983). GEOSURV prepared a series of reports on the hydrogeology of the Mesopotamian Plain (Krasny 1980, 1981a, b, c, 1982a, b, c, d, 1983b). In 2000-2002 an important regional hydrogeological project was conducted in Northern Iraq by the FAO (Stevanovic and Markovic 2004).

The hydrogeological data used in this book were obtained from over 1000 boreholes, 500 of which contain full hydrogeological data derived from the regional hydrogeological studies listed above by government bodies and their contracting organizations as summarized by Alsam et al. (1990).

The methodology of hydrogeological investigations differed in particular areas depending on the quantity and reliability of hydrogeological data. In areas where data are scarce (mountainous and Jezira areas) hydrogeological conclusions are approximate and often based on geological analogues. In the Western and Southern deserts, intensive hydrogeological studies were carried out allowing regional syntheses .to be made. In some areas there is sufficient hydrogeological and hydrochemical data from drilled and hand dug wells for statistical analysis, for example in the Foothill Zone (the most important hydrogeological unit of the whole Iraq), and in the northern part of the Mesopotamian depression (Tikrit Baquba region).

Where possible, transmissivity magnitude and variability is assessed and compared using the objective classification system" (Krasny 1993). In most hydrogeological basins groundwater flow is represented by equipotential (and flow) lines of the piezometric surface of the upper regionally extensive groundwater body. Prevailing salinity and chemical types of groundwater have been assessed in most regions. Variation in groundwater chemical properties can be used as a basis for vertical and horizontal hydrochemical zonality and to recognise local anomalies and temporal changes in groundwater quality. For water use, saline waters and waters with high sodium content are a hazard.

19.3 Natural conditions influencing hydrogeological conditions

Hydrogeological conditions are determined by geological, *climatic morphological* .and *hydrographic* factors. Their degree of influence differs from place to place, resulting in very complex and variable hydrogeological conditions in distinct hydrogeological units (see section 19.5). These factors are discussed below.

19.3.1 Geological conditions

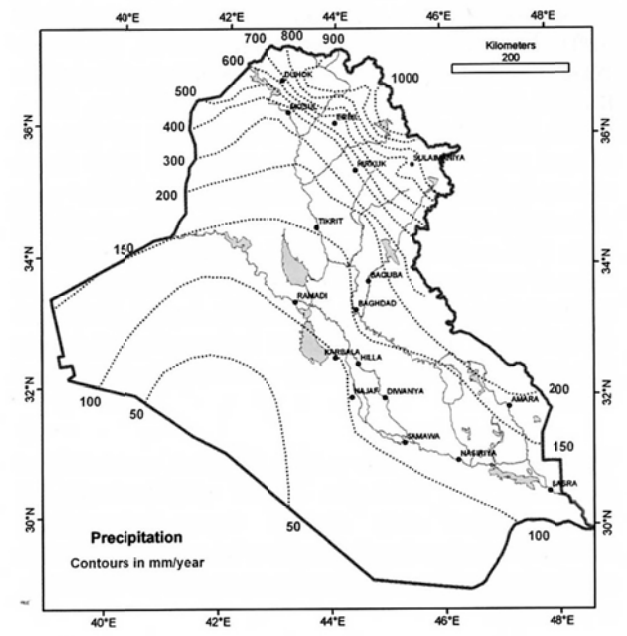
Geological factors determine the geometry (extent and thickness), porosity and permeability of aquifers and aquitards. Lithological variations and structural conditions control the hydrogeological environment affecting groundwater flow and accumulation. Hard (crystalline) rocks only contaln fracture porosity. Intergranular porosity is characteristic of young unconsolidated deposits (aquifers). Diagenesis and compaction reduce intergranular porosity and permeability. Fracture porosity is controlled by tectonic factors .. Limestones and other soluble deposits such as gypsum may be karstified resulting in an increase in permeability. Dissolution of these rocks may strongly influence the salinity (or Total Dissolved Solids, TDS) and the chemical composition of groundwater, mainly in the upper hydrodynamic zone.

19.3.2 Climatic conditions

Climatic conditions determine, within the geological framework, the rate of groundwater recharge in aquifers, the intensity of groundwater flow and water losses due to capillary effects, evaporation and transpiration. Long-term average values, and the short-term distribution of precipitation and seasonal temperature changes are important factors affecting groundwater resources.

To understand the importance of groundwater for Iraq, (75% of its total area is dependent on groundwater for water supply), it is important to firstly understand the distribution of rainfall. Rainfall in Iraq varies from 50 mm per year in me *SW* to 1200 *mm per year in the NE (fig.* 19-1). *The* western desert of Iraq mostly receives < 100 mm per year. The Mesopotamian flood plain and the Jezira area receive 100-300 mm of precipitation per year. Rainfall in the foothills is 300-700 mm per year; the mountainous region of N and NE Iraq receives> 700 mm of rain. Over half of Iraq lies within the arid and semi-arid zones (with <150 mm/year rainfall).
Direct water recharge in extensive areas occurs through vertical downward percolation of precipitation from the surface. Indirect vertical seepage from permanent water courses or wadis with ephemeral water flow also recharges groundwater bodies, and is very important in Iraq. Direct recharge occurs in the effluent sectors of rivers mostly in the Foothill zone and in the Mesopotamian Plain where surface water often flows above the level of surrounding groundwater bodies. Percolation of surface water from wadis is characteristic of most of the south and west of Iraq (deserts and Jezira).

Fig. 19-1: Precipitation map (after Alsam et al., 1990)



Most precipitation occurs between October and May, usually in bursts. In the western desert the rainfall is 50-100 mm/year and is usually sporadic but also extremely variable in time and space. On rainy days precipitation may exceed 40 mm in 24 hrs; the maximum dally recorded rainfall at some stations exceeds the total recorded during a whole dry year. This rainfall pattern allows wadies to quickly drain into the Euphrates thus restricting recharge of groundwater aquifers. However short precipitation bursts decrease the amount of water lost to evaporation. Annual evaporation is estimated as 2500-3000 mm of which 400-500 mm occurs in both July and August alone.

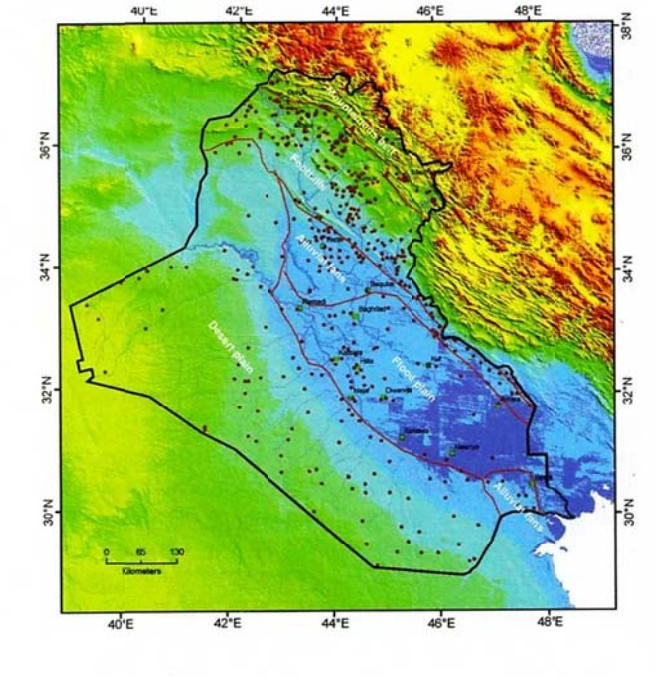
19.3.3 Morphological and hypsometric conditions

The morphology of Iraq is relatively simple (see Chapter 1) characterised by a central depression flanked by elevated areas to the SW, NW, N and NE (Fig. 19-2). The central flood plain (the Mesopotamian Plain) is covered by flat lying alluvium, deposited by the interacting Tigris (and its tributaries Adhaim and Diyala) and Euphrates rivers. The plain is flanked by alluvial fans derived from the Hemrin Pesh-e-Kuh range in the NE, the desert plateau in the SW and by Jezira in the NW.

The Southern and Western Deserts and the Jezira area lie to the S, Wand NW of Mesopotamia while the Foothill Zone lies to the N. The Foothill Zone contalns long anticlines separated by broad synclinal depressions filled in by Pliocene and Quaternary sand and gravel. The mountain belt dominates N and NE Iraq. It consists of folds built by carbonates, largely of Mesozoic age, separated by narrow synclines containing Palaeogene and Neogene clastics. *Along* the Iraq-Iran border in NE Iraq a more complex mountain system of igneous and metamorphic rocks dominates the landscape. Its elevation is >1500 m ASL, reaching 3609 m ASL at the highest point (Hasr-i-Rust). Five principal morphological zones, broadly corresponding to the tectonic subdivisions of Buday and Jassim (1984 and 1987) are described in detail in Chapters 4 to 6 (Fig. 19-2).

Morphological and hypsometric conditions determine, within the geological framework, the position of groundwater recharge and discharge zones and the depth of the water table. Variation in the permeability of aquifers and in hydraulic gradient control the intensity and depth of groundwater flow. Morphological and hypsometric conditions also co-determine the influent or effluent character of water courses and lakes and thus the relationship between surface water and groundwater. Closed basins and sabkhas form due to a combination of all morphological and structural-geological factors.

Fig. 19-2: Topography of Iraq with superimposed morphological units and location of water wells used for the hydrogeological evaluation



19.3.4 Hydrography

The two great rivers, the Tigris and the Euphrates, traverse Iraq from N (NW) to S (SE). Both rivers rise in Turkey near Lake Van. From Turkey the Euphrates flows through Syria's semi-desert plateau entering Iraq at Rumanah (AL Qaim); then it passes through the desert entering the Mesopotamian Plain at Falluja. At Qurna, 60 km NNW of Basra, the Euphrates merges with the Tigris forming the Shatt AL-Arab. Within Iraq the Euphrates has no permanent tributaries. The Tigris crosses N Iraq where it acquires various important left-bank permanent water courses flowing down from the Zagros Mountains such as the Greater and Lesser Zab, Adhaim and Diyala Rivers. Near Baghad, the Tigris converges to within 70 km of the Euphrates after which both rivers diverge again into the Mesopotamian Plain, often meandering and losing substantial volumes of their water in marshes and by irrigation.

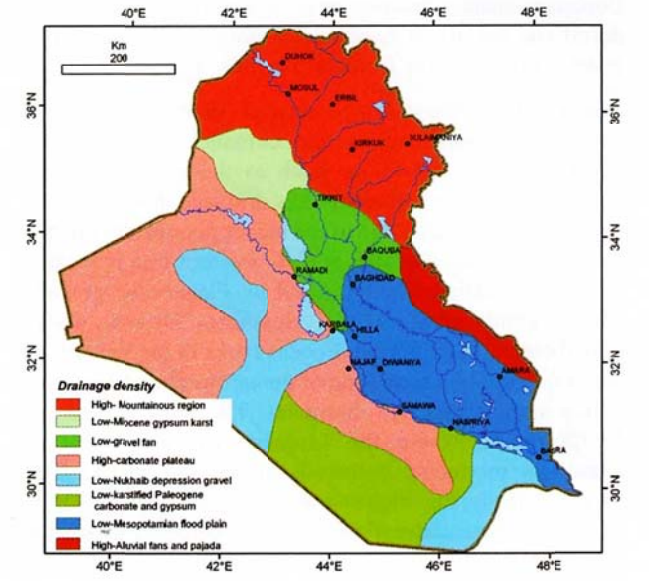
The Euphrates is 2700 km long (1213 km in Iraq) with a catchment area of 765000 km-. The Tigris is *1718* km *long* (1418 km in Iraq) with a catchment area of 375000 km-. The average flow rate of the Euphrates is only *1100* m^3/s compared with that of the Tigris of 4000 m^3/s despite its greater length. In spate in spring, the flow of the Euphrates can reach 50000 m^3/s, usually at the beginning of May, whereas that of the Tigris reaches 80000 m^3/s in March and April. The Tigris

has a much greater capacity than the Euphrates mainly because it does not flow through arid desert and because it is also fed within Iraq by numerous water courses flowing from the Zagros.
The density of the drainage network shown in Fig. 19-3 reflects geomorphological and climatic conditions and hydrogeological conditions such as the permeability of rocks. Five areas of relatively low drainage density can be recognised and are all due to the higher permeability of the underlying rocks. The first zone in western Iraq is located along the Nukhaib Graben filled by Pleistocene gravels. The second area is the Southern Desert where karstification of gypsum in Eocene rocks in the subsurface has resulted in the formation of numerous closed basins in which surface drainage dissipates. The third area is the Jezira region where the Miocene gypsum beds are karstified, producing numerous closed salt playas. The fourth zone is the Pleistocene gravel fan of the Tigris which originates from Fatha and is dominated by coarse gravel with high permeability. The fifth area is located along the borders with Saudi Arabia and Kuwalt and is associated with the gravel of the Dibdibba Formation.

The Jezira region and some other desert regions contaln numerous closed depressions which, under natural conditions are fed only by torrential wadi inflows, with no outflow. All water is lost, mostly by evaporation, leaving salty or gypsiferous crusts. The most extensive are the Tharthar and Abu-Dibbis depressions which follow an important structural element (the Abu Jir Fault) and some closed depressions in the Jezira area.

The natural flow regimes of the rivers have been considerably influenced by human activities. The Dokan and Derbendikhan dams were built in the upper reaches of the Lesser Zab and the Diyala rivers respectively. Along the Tigris and the Euphrates Rivers the Mosul and the Qadisiya (Haditha) dams, respectively, were completed during the 1980's. Numerous dams on the Tigris and Euphrates rivers have been proposed by the Ministry of Irrigation. In central Iraq diversion canals supply the Tharthar depression with water from the Tigris, and the Habbaniya and Razzaza (Abu-Dibbis) depressions with water from the Euphrates. This human influence has created extensive artificial lakes. Branching rivers and a network of artificial canals take water off the Euphrates and Tigris (for example the Hilla and Gharraf rivers) and supply many extensive irrigation systems in the Mesopotamian Plain.

Fig. 19-3: Drainage density map with density represented by drainage length in kilometres per 100 square kilometres of area (after Alasam et al., 1990)



19.4 General features of hydrogeological conditions in Iraq

19.4,1 Main aquifers

Lithological and structural geological conditions determine the spatial distribution and extent of hydrogeological bodies (aquifers, aquitards) and their hydrogeological environment.

In Iraq fourteen main aquifers/aquifer groups, identified by their relationship to geological formations, can be defined. The surface and near surface distribution of these aquifers within Iraq is shown in Fig. 19-4. The same classification is used in the assessment of groundwater resources in section 19.6. The fourteen aquifers are:

1. Fractured Cretaceous-Tertiary limestones of the Digma, Tayarat Akashat and Ratga formations west of Rutba

2.Sandstones of the Permian Ga'ara and Bir El Rah formations within the Rutba Subzone

3. Fractured limestone and sandstone of Triassic Cretaceous age including the Mulussa, Zor Hauran, Ubaid, Hussainiyat, Amij, Muhaiwir, Saggar, Nahr Umr, Rutba-Msad, Hartha and Tayarat formations in the Western Desert belonging to the Rutba Subzone

4.Limestone of the Palaeogene-Neogene Euphrates Formation, Kirkuk Group and Ghar formations of the Western and Southern deserts of the Rutba Subzone and the Salman Zone

5.Karstified and fractured limestones of the Palaeogene Um-Er Radhuma, Jill and Dammam formations of the Southern Desert of the Salman Zone

6, Sandstone and conglomerate of the Miocene to Pleistocene Ghar and Zahra formations and the Nukhaib Graben fill of the Western and Southern deserts of the Rutba Subzone and the Salman Zone

7.Sandstone of the Mio-Pliocene Dibdibba Formation of the Southern Desert in the Salman Zone

8.Alluvial fan sand and gravel of Wadi AL-Batin of the Southern Desert in the Mesopotamian Zone

9.Karstified gypsum and limestone of the Middle Miocene Fatha Formation of the Jezira area of NW Iraq, in the Jezira Subzone

10. Sands of the Quaternary Mesopotamian Flood Plain of Central and S Iraq, in the Mesopotamian Zone
11. Gravel and sand of the Quaternary alluvial Fans of the Makhul, Hemrin and Pesh-e-Kuh range, of central and S Iraq, along the boundary of the Mesopotamian and Foothill zones
12. Sandstones of the Mio-Pliocene Injana (U Fars) and Mukdadiya (L Bakhtiari) formations in N and NE Iraq in the Foothill Zone
13. Quaternary conglomerates and conglomerates of the Pliocene Bai Hassan (U Bakhtiari) Formation in synclines of NE Iraq, belonging to the Foothill Zone and parts of the High Folded Zone.
14. Mesozoic-Tertiary limestone, igneous and metamorphic rocks of the mountainous and high folded sub province.

The distribution of the specific capacity of aquifers, based on point data from water wells is shown in Fig. 19-5. The variation in the specific capacity and in the transmissivity index Y and transmissivity is discussed in detail below for each aquifer system hydrogeological region listed in section 19.5. The specific capacity of most aquifers is generally <1 litre/sec/metre. Values of 1-3 are more common in the Southern Desert and in the northern part of the Mesopotamian

Fig. 19-4: Main aquifers/aquifer groups of Iraq (after Alsam et al., 1990). Aquifer number is quoted in section 19.5.1 and Table 19-2 and 19-3

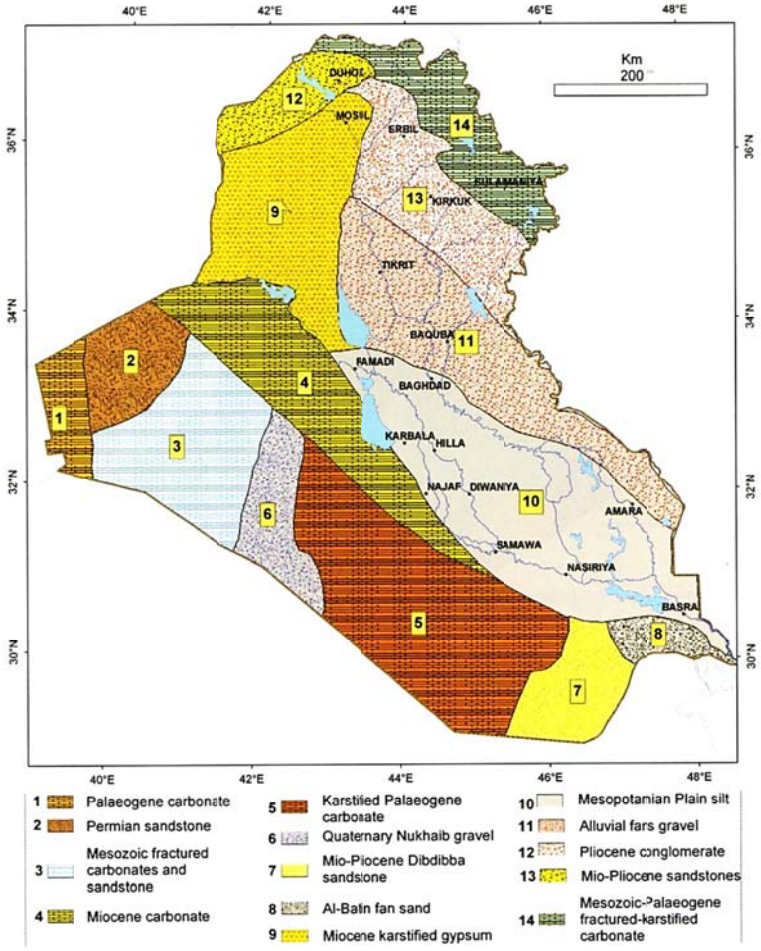
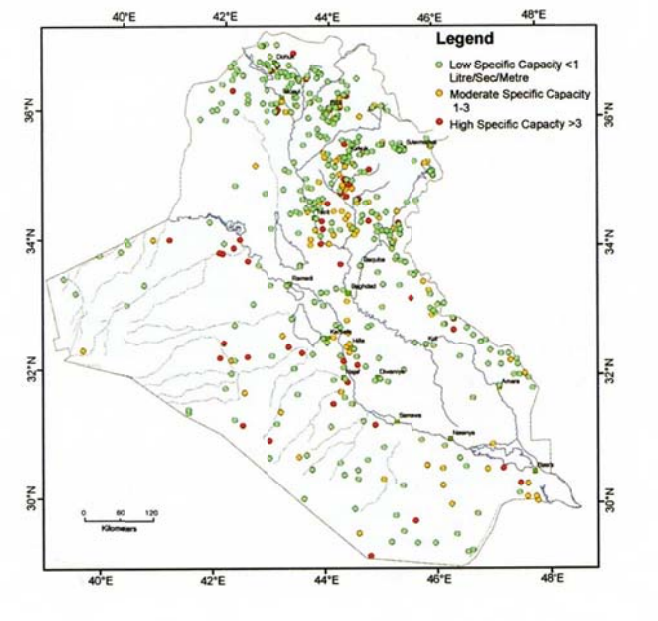


Fig. 19-5: Specific capacity in litre per second per metre drawdown



19.4.2 Regional groundwater flow and level

In the Arabian Shelf, which covers most of the country, and the Taurus-Zagros belt of the N and NE Iraq, different hydrogeological environments occur. In the Shelf area vast hydrogeological basins occur, usually represented by extensive hydrogeological bodies enabling regional groundwater flow to form vast aquifer systems and subsystems. In the Taurus and Zagros Mountains, the occurrence of crystalline or "hard" rocks and frequent lithological changes result in areally limited aquifer systems.

Despite great variation in hydrogeological conditions in Iraq the general features of groundwater flow can be represented by so-called hydrodynamic zones. Vertically, they comprise zones of local (intensive, shallow), intermediate (retarded) and regional (slow or negligible, deep, sometimes even stagnant) groundwater flow. Horizontal extensions of these zones differ; the local zones have limited areal extent. The intermediate and especially regional zones are very extensive. Recent results of deep drilling in different parts of the world suggest a very deep zone of groundwater flow is present in sedimentary basins (Krasny 2003).

Over one thousand wells were used to construct the equipotential synoptic map of Fig. 19-6 that indicates the main directions of regional groundwater flow in the upper aquifers. The piezometric surface faithfully reflects morphology. Groundwater generally moves towards the central depression of the Mesopotamian Plain.

In the desert area two groundwater level highs (piezometric elevations) are present, separated by the Nukhaib depression to which groundwater flows from both highs. The remaining groundwater, which does not flow towards the Nukhaib depression, flows towards the Euphrates (obstructed by the Euphrates Boundary Fault) (Fig. 19-6); it ultimately reaches the Mesopotamian depression. Along the Euphrates Boundary Fault numerous springs have discharges of 201000 LIs (totaling 3000 LIs), they form a conspicuous "line of springs" more than 400 km long.

In the Jezira area groundwater flows from the Tayarat structural high westwards towards the AL Tawila depression along the Iraq-Syria border in the west, the Sunailsla depression in the north, the Euphrates valley in the south, and the Tharthar valley and ultimately the Tharthar depression in the E and SE. In the foothills, groundwater generally flows towards the tributaries of the Tigris and ultimately into the Tigris and the Mesopotamian Plain. Long anticlines of the Foothills often form groundwater divides causing groundwater to move laterally towards the Tigris tributaries such as the Greater Zab, Lesser Zab, and Adhaim and Diyala rivers.

The depth of the water table from the surface is shown in Fig. 19-7. In the Western Desert, the depth to the water table increases westwards from 10 m along the Euphrates River to >250 m near the Iraq-Jordan Saudi border. Near the Euphrates River, a sharp gradient exists along the Euphrates Boundary Fault where the water table depth quickly decreases towards Mesopotamia. In the Jezira area the water table is generally at 10-20 m whereas in the foothill area it is at 20-30 m. The Mesopotamian Plain has a shallow ground water depth, generally <1 m in the area south of Kut and 1-5 m between Kut and Baghdad. This very shallow ground water of high salinity adversely affects the soil of Mesopotamia.

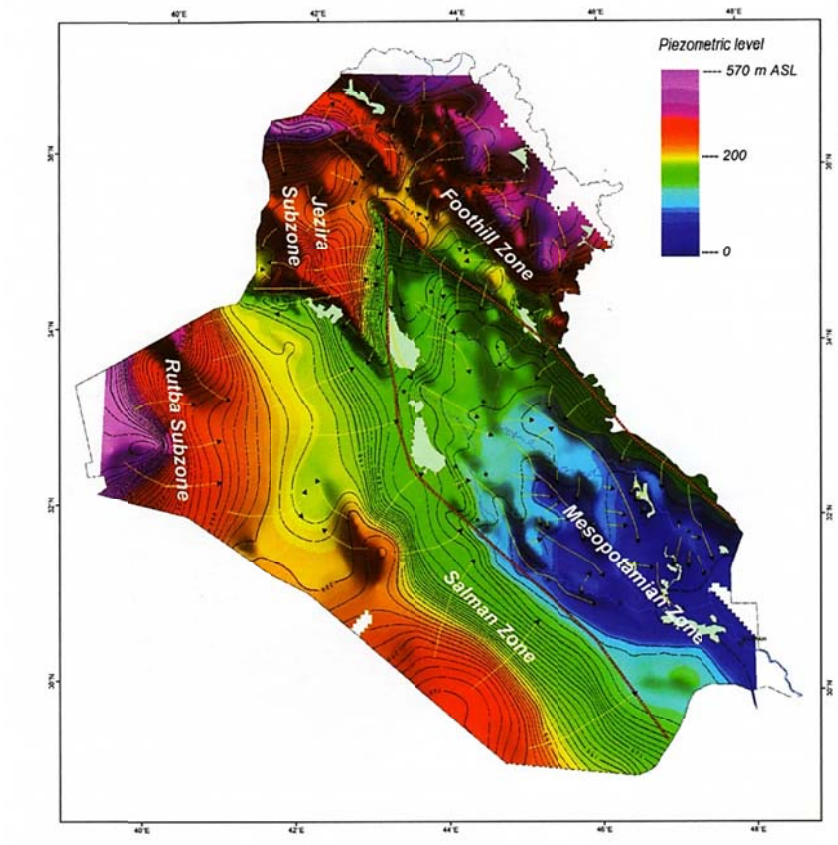


Fig. 19-6: Equipotential map (m ASL) with flow direction of upper aquifer groundwater and some of the main tectonic lines influencing water movement (after Araim 1990, hydrogeological map of GEOSURV)

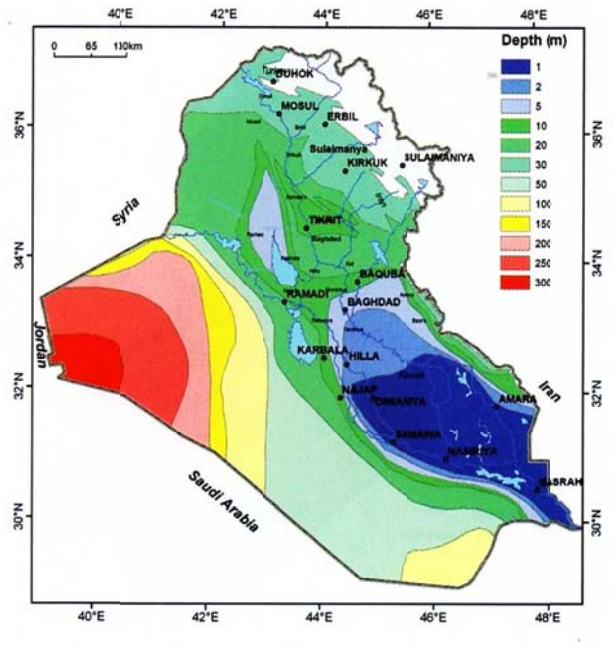


Fig. 19-7: Groundwater depth from ground surface in metres

19.4.3 Chemical composition and salinity

Groundwater salinity (Fig. 19-8) is presented as a shallow groundwater quality map with six water quality levels, these are: Potable water (<1 g/L), irrigation water (1-3 g/L), limited irrigation water (3-5 g/L), water seldom used for irrigation (5-10 g/L), unusable water (10-20 g/L and 20-50 g/L) and brine (>50 g/L).

Salinity increases in the central, topographically lower, Mesopotamian Plain and Jezira area. Water with a salinity of 3-10 mg/L dominates with pockets of unusable water near salt playa basins. The groundwater of the Mesopotamian Plain is generally extremely saline in the SE. Areas flanking this topographically low area contaln less saline ground water. The Western Desert contalns waters with salinity of 1-3 g/L with two pockets of fresh water near Rutba and the Nukhaib depression with salinity of <I g/L. The southern desert contaln relatively more saline irrigation water with a salinity of 3-5 g/L in the west and 5-10 g/L in the east near the Mesopotamian depression.

The mountainous region in N and NE Iraq is dominated by fresh water of <1 g/L salinity in the high mountains and the eastern part of the Foothill Zone and irrigation water of <3 g/L salinity in the rest of the Foothill Zone.

Groundwater type classifications are numerous and generally follow the Fresenius principle. Particular cations and anions are successively combined to form progressively less soluble salts. First potassium is combined with nitrates. Excess of potassium is combined with chlorides etc. If there are more nitrates their excess is combined with sodium etc. So the sequence of cations (potassium, sodium, magnesium, and calcium) is successively combined with anions following the order: nitrates, chlorides, sulphates, bicarbonates. On precipitation the reverse anion order takes over. Thus, hypothetical salts are created, some of them forming salt of strong acids and others salt of weak acids. In the classification of Gazda (I 971) the designation of the chemical type corresponds to the prevailing, (so called first) hypothetical salt component. If this first component reaches a concentration of >50% the type is designated as "basic" and when the concentration exceeds 67% it is designated as "expressive basic". If the concentration of no component exceeds

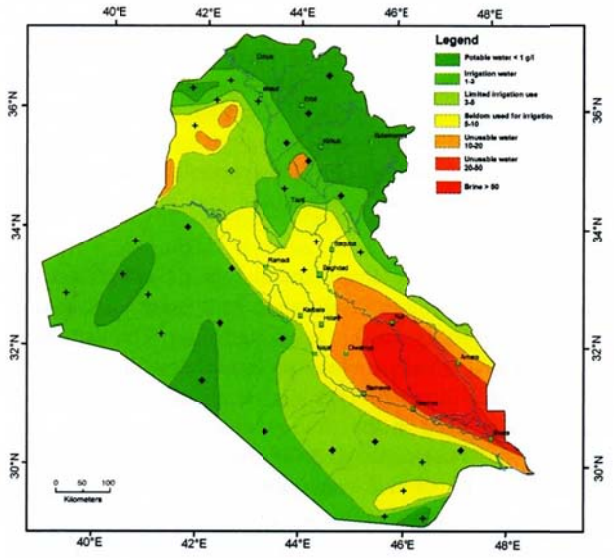
50% the chemical type is designated as "transient" (when two components each have a concentration of 3350%), or "mixed" (when not more than one component has a concentration of 33-50%).
In this book the classification of ground water type used by Aralm (1990) on the GEOSURV hydrogeological map of Iraq (which identifies six basic classes of water types) is adopted. These are the bicarbonate, bicarbonate-sulphate, bicarbonate chloride, sulphate, chloride-sulphate, and chloride types (Fig. 19-9).
Within recharge areas all ground water starts as the low salinity bicarbonate water type which soon changes composition as it infiltrates and flows through rocks. The ultimate water type after long passage into more stagnant basins is the chloride water type. After a passage through limestone rocks, groundwater mostly changes composition to a calcium-bicarbonate type. When groundwater water is enriched in sulphates salts, it may precipitate gypsum or even sodium sulphate.

The bicarbonate water type (Fig. 19-9) is restricted mostly to the mountainous region or the pediment of some high mountains in Jabal Sinjar. Mixed bicarbonate-sulphate water dominates the Foothill Zone, especially the Makhul-Hemrin Subzone. The Western Desert area has isolated regions of low salinity bicarbonate water; elsewhere it is dominated by the carbonate-chloride water type probably sourced from deeper aquifers. The Southern Desert contalns predominantly bicarbonate-sulphate water and sulphate water especially in its eastern parts due to flow of water through the anhydrite-bearing Rus Formation. The

Mesopotamian Zone is dominated by the chloride water type with a surrounding zone of sulphate water or transitional chloride-sulphate type. The high salinity sodium chloride brine within the SE part of the Mesopotamian Plain is probably a result of the natural progression of long-distance groundwater movement into a semi-closed stagnant basin.
High linear correlation coefficients occur between salinity and sodium, magnesium, sulphate and chloride concentrations (Krasny 1980). The distribution of the sulphate waters usually coincides with formations containing gypsum. In areas of saline water, higher chloride contents may indicate the influence of fault zones which act as conduits for mineralised water from the Euphrates Formation to flow into the Fatha Formation, for example in the area south of Mosul and in some places along the Euphrates Boundary Fault. However in areas of high salinity, increased amounts of bicarbonate together with salinities of <1000 ppm indicate hydraulic connection with relatively unmineralised surface (pluvial) water; the best opportunity for such connection apparently exists in ephemeral valley fill.
In the shallow zone of the mountain regions, as in temperate climatic zones, calcium/magnesium and carbonates/ sulphates typically prevail in groundwater. The salinity is here very low, usually up to a few hundreds of mg/L. In arid and semi-arid areas of Iraq the chemical composition of groundwater even in the shallow subsurface zone is very variable mostly depending on the quality of recharged water and the depth of the water able. Sodium and chloride contents generally increase with depth and in deep-seated zones sodium/calcium and chloride brines prevail. These vertical chemical changes of groundwater composition are accompanied by a general depth-related increase in salinity.

Past and present hydrogeological conditions of Iraq, natural accumulation and leaching stages, and the impact of the anthropogenic stage are important in controlling groundwater quality (Krasny 2001). Compared with other regions, the anthropogenic stage has lasted in Iraq for a relatively long time due to early human activities. Anthropogenic impacts were intensified in the last century due to extensive irrigation without drainage and by the diversion of huge volumes of surface water by many canals and extended irrigation systems.

Fig. 19-8: Salinity (TDS) of shallow groundwater in grams per litre



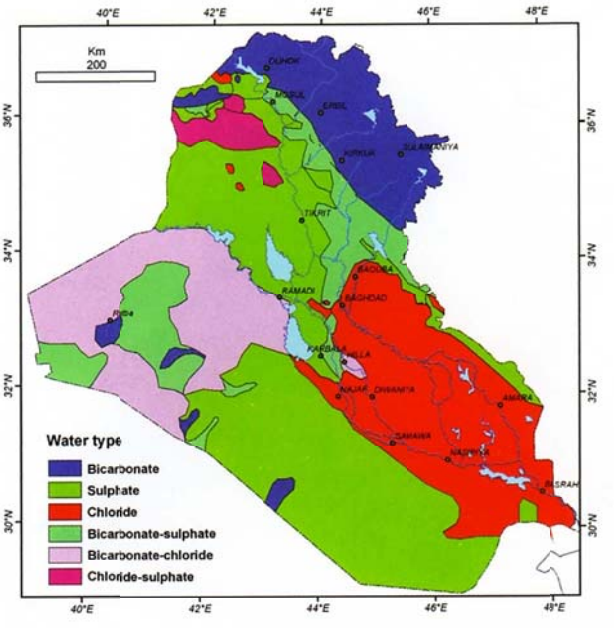


Fig. 19-9: Chemical types of shallow groundwater in Iraq (modified from Araim, 1990; hydrogeological map of GEOSURV)

19.5 Hydrogeological provinces of Iraq

Hydrogeological units of different orders can be identified in Iraq. Definition of first order hydrogeological units (hydrogeological or groundwater provinces) reflects the principal structural geological divisions of Iraq. These units can be subdivided based on specific hydrogeological properties and elements. The extent and depth of groundwater flow can be used to define different scales of aquifer systems (mega systems, systems, subsystems, and partial systems). Units consisting of various juxtaposed aquifers (and aquitards), with variable hydraulic communication are often of basin-wide extent. Within an aquifer system, groundwater flow can be considered to occur in closed systems between recharge areas of groundwater accumulation and discharge areas thus enabling the groundwater balance to be estimated. This is the first step in assessing groundwater resources.

Iraq belongs to two major hydrogeological provinces: the Nubio-Arabian and Taurus Zagros Provinces (Fig. 19-10).

The Nubio-Arabian Groundwater Province comprises the Nubio-Arabian platform comprising crystalline ("hard") rocks and its unfolded/gently-folded sedimentary cover. Within Iraq regional groundwater flow occurs in the extensive Mesopotamian aquifer megasystem with well defined hydrodynamic and hydrochemical zones. Intensive groundwater flow occurs in the upper part of the megasystem, especially in its SW and NE flanks where several basin-wide aquifer systems or sub-systems with relatively independent groundwater flow occur. Recharge occurs in various areas; discharge mostly occurs in lowlying regions through springs or slow seepage into rivers and closed basins, for example in the Shari Lake depression and originally, (prior to human influence) in the Tharthar and the Abu-Dibis depressions. At depth groundwater flows very slowly or is even stagnant. The discharge zone of the whole megasystem is in the Mesopotamian Zone.

The Mesopotamian Aquifer Megasystem of the Nubio Arabian Groundwater Province consists of five hydrogeologic units (Fig. 19-10):

1. The Aquifer System of the Western and the Southern Desert (Section 19.5.1).
2. The Jezira Hydrogeologic Region, including the Sinjar region (Section 19.5.2).
3. The Aquifer System of the Mesopotamian Plain, including the Baquba- Tikrit region (Section 19.5.3)
4. The Aquifer systems of alluvial fans, Mandali-Badra- Tib region (Section 19.5.4).

5.The Aquifer system of the Foothills (Section 19.5.5). The Taurus-Zagros Groundwater Province is located in intensively folded and thrusted rocks (Section 19.5.6). It contalns small aquifer systems in hard rocks, clastics and karstified carbonates mostly with local, confined, relatively shallow groundwater flow. However some of these aquifers act as an external recharge zone to the Mesopotamian Aquifer Megasystem, especially through deep-seated, regional groundwater flow.

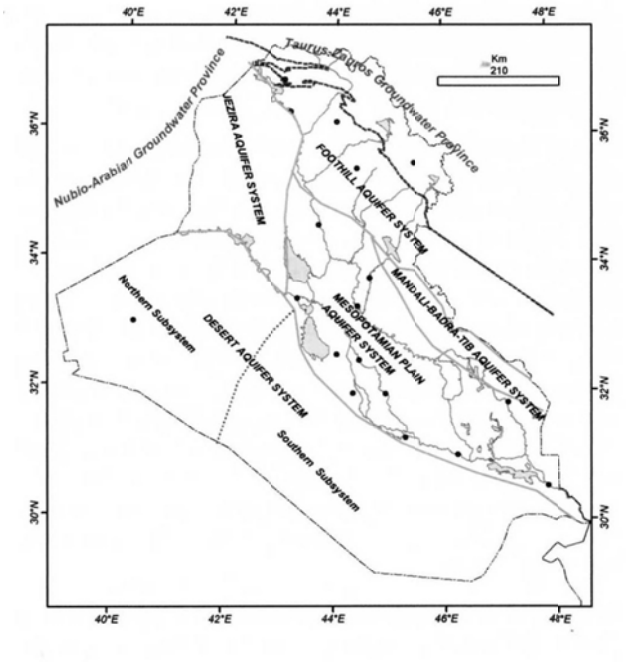


Fig. 19-10: Major hydrogeological divisions of Iraq

19.5.1 Aquifer System of the Western and Southern Deserts

19.5.1.1 Fractured Cretaceous-Tertiary limestone of the Rutbah, Digma, Tayarat Akashat and Ratga formations (Aquifer Group **1)**

Aquifer Group I comprises the following formations and aquifers: the Ratga Formation (0-120 m depth) which consists mainly of limestone and chalky limestone, the Akashat aquifer (120-200 m depth) comprising dolomites, limestone with beds of argillaceous chalky limestone and phosphorite, and the Hartha ffayarat aquifer (200-330 m depth) which consists of dolomitised limestone with shale beds. These aquifers are fractured and karstified with heterogeneous secondary porosity and a wide range of storage properties. They have very variable productivity which is difficult to predict without detailed surveys. Wells are thus often deepened to penetrate the underlying Mulussa (Group 3) or Ga'ara (Group 2) aquifers to ensure that they will produce groundwater. From 350 m to 400 m depth the Rutba Formation (Cenomanian) aquifer is usually encountered. It comprises fine-coarse grained sand and sandstone. It outcrops near Rutba town.
In this aquifer zone the groundwater elevation is 450-500 m ASL. Groundwater flows N towards Syria (towards the Euphrates River valley) and S towards Saudi Arabia (towards the Nafud basin). The depth of the water table from the ground surface varies from 150 m in the NE to about 400 m in the SW. The depths of exploitation boreholes are 400500 m below ground level.

The salinity of the groundwater of this aquifer zone (No.1) is 1-3 g/L. The water is suitable for domestic use, irrigation and watering livestock (Fig. 19-8).

19.5.1.2 Sandstones of the Permocarboniferous Ga'ara and Bir El-Rah formations (Ga'ara Aquifer, Group 2)

The Ga'ara Aquifer is the most important aquifer in the area, not only where it outcrops or is near the surface but also where it lays below aquifer groups 1 and 3. It consists of beds of sandstone and shale. Within the Ga'ara depression the aquifer comprises two water bearing units. The Upper Ga'ara is not uniform in distribution. It lies at a depth of 200-400 m. In the depression area several wells to this horizon went dry; here the Upper Carboniferous section consists of the shale-dominated Bir EI Rah Formation. In the Akashat area the Ga'ara aquifer consists of homogeneous sandstone at depths of 400-700 m.

To the NE of the depression, Lower Permian sands of the Ga'ara Formation produced water from wells at depths of about 90 m. A deeper aquifer in the Ga'ara depression was encountered in well 1<5/1 at 970 m. About 90 m of cavernous limestone of the Lower Carboniferous Harur Limestone Formation contained confined water of low salinity «3 g/L) with a static water level of about 400 m ASL (100m BGL). The transmissivity of the Ga'ara aquifer varies from <100 m^2/day in its upper part, to about 250 m^2/day in its lower part; the aquifer is confined and the storage coefficient is of the order of 10-4. The depth to groundwater varies from 150 m in the N and NE part to about 300 m in the SW part of the aquifer.

The yields of boreholes tapping the upper and lower aquifers are about 4 L/sec and 20 L/sec respectively. Groundwater salinity in the SE is <1 g/L, and 1-3 g/L elsewhere. Note that the salinity of the upper aquifer is lower than the salinity of the lower aquifer by about 0.5-1 g/L. The groundwater of both aquifers is suitable for domestic use, irrigation, and for watering livestock.

19.5.1.3 Fractured limestones and sandstones of Triassic-Cretaceous age (Aquifer Group 3)

In the Rutba area, groundwater occurs in the Upper Triassic Mulussa Formation which comprises limestone and dolomites, interbedded with marl. Wells targeting the Mulussa aquifer around Rutba town should be 120-180 m deep. The aquifer is fractured carbonate with very variable permeability.

East of Rutba the formations penetrated during drilling are the Muhaiwir (70 m thick), Arnij (40m thick), Hussainiyat (120 m thick), Ubaid (90 m thick), Zor Hauran (50 m thick), and Mulussa (180 m thick). The Ga'ara Formation is reached at a depth of 550 m. The Mulussa and Muhaiwir formations are good aquifers. The Ubaid is a poor aquifer because of its low specific capacity of about 0.1 L/sec/m (Fig. 19-5). The Muhaiwir aquifer consists of well-bedded limestones and argillaceous limestone. The transmissivity and specific capacity of the Mulussa and Muhaiwir aquifers depend entirely on fractures, bedding planes and karst features. The hydraulic parameters thus vary widely. The specific capacity of wells penetrating the Muhaiwir aquifer is 1-10 L/sec/m, and the transmissivity varies from <200 m^2/day to > 600 m^2/day.

In this aquifer zone, the static groundwater level varies from 200 m ASL in the discharge area to 500 m ASL in the recharge area. The groundwater flows partly towards the regional discharge area (Abu Jir Fault) but mostly towards the Nukhaib Graben (Aquifer Group 6). The water table is at a depth of 150-300 m, except in the uplifted Rutba area where it is at about 100 m. The depths of exploitation boreholes are 200-400 m below ground level.

The groundwater salinity is 1-3 g/L, except in the recharge area near Rutba where it is <I g/L. The groundwater is suitable for domestic use, irrigation and watering livestock.

19.5.1.4 Limestone of the Euphrates Formation (Aquifer Group 4)

Gently dipping limestone beds of the Euphrates Formation outcrop along the W side of the Euphrates River. The limestones contaln impermeable clay and marls. Near the surface the limestones are weathered, fractured and karstified, and have enhanced permeability. Karstification is usually restricted to the 10m thick basal conglomerate unit of the formation. The unit consists entirely of carbonate pebbles and cobbles, which are prone to solution due to their high original primary porosity. It forms a very effective aquifer.

Surface water infiltrates into cavities and fractures and flows towards the Euphrates or issues at the Euphrates Boundary Fault and the Abu Jir Fault as a long line of springs of variable discharge. Some of the largest springs are Haqlan, Hit, Shithatha and Imam Abdullah. The Hit spring and some others are highly saline, sulphurated, and rich in bitumen due to the mixing of heavy oil and brines from deep confined aquifers with the ground water in the desert aquifers. The Haqlan spring originates in fractured limestones of the Euphrates Formation in a 150 m wide front at the mouth of the Wadi Haqlan (elevation about 100 m ASL). Tile discharge of individual springs is 20-100 L/s.
The total discharge is 600 L/sec. The water has an H_2S odour, a salinity of about 3 g/L, and a temperature of 18°C. Other springs of lower discharge issue upstream of Haqlan in Haditha and Anah.

In Shithatha town springs issue at a level of about 90 m ASL. Spring water is collected in a big basin built in the centre of town and diverted by canals for irrigation. The biggest spring of Shithatha is Ain Kabeer ("large spring") with a discharge of about 150 L/sec. The total discharge of the Shithatha springs is about 1000 L/sec. Other large springs are Imam Abdullah (570 L/sec) with a salinity of about 2.5 g/L, and Ain Assaf (about 500 L/sec). Groundwater also discharges through the alluvial plains, creating swamp-like areas on the right bank of the Euphrates River.

The total length of the spring line along the Euphrates Boundary and Abu Jir faults is about 450 km; the total discharge of springs is >3000 L/sec. The discharge of springs is controlled by the degree of karstification and varies seasonally.

The groundwater level in the Euphrates Aquifer Zone varies from 200 m ASL in the NW to 100 m ASL in the SE. The groundwater flows towards the Abu Jir Fault and the Euphrates Boundary Fault. The depth to groundwater varies from 20 m to 200 m. The depth of exploitation boreholes drilled in the aquifer is 50-100 m. Water wells along this fault zone overflow with big discharges. This is thought to be the result of sealing of permeable layers in the Euphrates by impermeable mudstone of the Fatha and Injana formations due to displacement along those faults, creating confining conditions.
The salinity of groundwater in the aquifer is usually 1-3 g/L but near Karbala and Najaf it is 3-5 g/L (Fig. 19-8). Highly saline, sulphurated and bitumen-rich springs issue from this aquifer along fault zones near the Euphrates. However the Euphrates Formation is a promising aquifer since this high salinity zone is restricted to a narrow belt.

19.5.1.5 Karstified and fractured limestones of Palaeocene-Eocene of the Southern Desert (Aquifer Group 5)

The Urn Er Radhuma and Jill (Rus) formations comprise dolomite and dolomitic limestone with beds of gypsum and anhydrite. The upper part of the Urn Er Radhuma Formation is the main aquifer. It is about 125 m thick and consists of dolomites and limestones. The lower part of the formation (200-400 m thick) consists of beds of argillaceous and chalky carbonate. It forms an aquiclude between the overlying Urn Er Radhuma aquifer and the underlying Maastrichtian Tayarat limestone aquifer.

Strong karstification occurs where the upper part of the Umm Er Radhuma and Jill formations outcrop. Karstification causes dissolution of the underlying gypsum, producing sinkholes and depressions in the overlying carbonates. Where the lower part of Urn Er-Radhuma Formation outcrops, recharge is restricted and the rainwater accumulates on the surface as runoff water. Locally near the contact with the permeable carbonate rocks the runoff water infiltrates into the aquifer, and fresh water accumulates over the main recharge zone. The permeability of the aquifer in the main recharge area is very variable and is controlled by the intensity of karstification.

The Dammam carbonate is one of the most important aquifers in SW Iraq. Its karst porosity, associated with fissures, controls the aquifer storage properties. Karstification and high permeability near the water table is controlled by groundwater level fluctuations. Permeability decreases with depth. Highest permeabilities occur in depressions where strong water circulation occurs.

The potential rate of evaporation in the desert is several times greater than the average rainfall. Sporadic flush precipitation helps recharge by minimising evaporation losses. Infiltration through the karst system occurs quickly also facilitating ground water recharge as indicated in Fig. 19-3 which shows that this aquifer zone (unlike other parts of the desert) has a low drainage density. Significant recharge occurs through sinkholes, depressions and highly permeable wadi beds. Although these features occupy a relatively small area, they have great hydrogeological importance. Some buried river beds (see Chapter 5) may also be important recharge zones.

In the discharge area, some groundwater issues from large springs; locally it is discharged forming lakes (Sawa Lake and Samawa salt lake). The remaining groundwater is confined below the relatively impermeable layers of the Mesopotamian Plain.

The static water level varies from 300 m ASL near the Saudi Arabian border to 50 m ASL near the Abu Jir Fault. The groundwater flows E towards the Abu Jir Fault and the Euphrates Boundary Fault and WNW towards the Nukhaib Graben. The depth to groundwater is typically 100-200 m rising to 5-20 m in the discharge area. The depth of exploitation boreholes is 50-150 m. Groundwater salinity is typically 3-5 g/L and only suitable for irrigation and watering livestock (Fig. 19-8). However groundwater salinity in wells near recharge karst depressions is <1 gm. /L. The mapping of the karst system is important to identify water suitable for domestic use.

19.5.1.6 Miocene sandstones and Pleistocene conglomerate of the Nukhaib Graben (Aquifer Group 6)

Miocene sandstones, up to 20 m thick, occur in a graben near Nukhaib, Quaternary conglomerates (18 m thick) fill the Nukhaib Graben itself. Most exploitation boreholes in the Nukhaib depression penetrate the underlying Dammam aquifer. The Miocene and Quaternary clastics feed rainfall into the Dammam. Their high permeability and the runoff water flowing into the Nukhaib Graben from many wadis result in excellent groundwater quality (salinity usually <1 g/L). Aquifers No.3 and No.5 partly discharge groundwater into this aquifer.

. The static water level in this aquifer is about 200 m ASL.

The groundwater mostly flows towards the central part of the graben and then flows N and NE towards the Euphrates. The depth to groundwater is 100-200 m, and the depth of exploitation boreholes is 150-200 m.

The groundwater in the centre of the Nukhaib Graben has a salinity of <1 g/L and is suitable for drinking but in the peripheral areas of the graben, where the salinity is up to 3 g/L the water is only suitable for livestock and irrigation. This is probably due the presence of a dome containing saline water in the Umm Er Radhuma Formation. Because of the scarcity of drinking water in this region groundwater from this aquifer should only be used for drinking. Water for irrigation should be obtained from marginal areas of the graben or from other aquifers.

19.5.1.7 Sandstones of Miocene-Pliocene Dibdibba Formation (Aquifer Group 7)

The Dibdibba Formation contalns permeable sandstones (partly pebbly) with beds of mudstone, siltstone, and marl associated with secondary gypsum. It is 30-260 m thick. The sandstones are probably hydraulically connected due to lateral pinch out of the impermeable layers. Available hydrogeological data indicate that the Dibdibba aquifer is complex; stratification affects groundwater movement and chemical composition.

The sandstones outcrop extensively facilitating infiltration of rainwater and runoff water of Wadi Al-Batin through surface depressions. In the higher parts of the aquifer, relatively permeable sandy soil retains most of the precipitation which then evaporates. The other source of groundwater to the Dibdibba aquifer is leakage from the underlying Urn Er-Radhuma and Dammam carbonate aquifers (No.5), and the S part of Wadi Al-Batin basin which extends into Saudi Arabia.

The permeability of the aquifer above 250 m depth is low. Specific capacity is 0.1-0.5 L/sec/m (Fig. 19-5), and borehole discharge is 0.5-0.7 L/sec. The static water level varies from 200 m ASL in the recharge area near the Saudi Arabian border to 25 m ASL in the discharge area near the Euphrates Boundary Fault. The groundwater flows towards aquifer No.8. The depth to groundwater varies from 100 m in the recharge area to 5 m in the discharge area. The depth of exploitation boreholes drilled in the area varies from 200 m in the recharge area to 50 m in the discharge area. The salinity of groundwater of the Dibdibba aquifer varies from <l g/L near the Saudi Arabian border (the recharge area) locally increasing here to 5-10 g/L. Elsewhere the salinity is 3-5 g/L except near the Euphrates Boundary Fault where it increases to 10-20 g/L (Fig. 19-6). The anomalously salinity of groundwater pockets near the recharge area suggest that local leakage occurs from lower aquifers. The groundwater can be used for domestic use, irrigation and watering livestock except in areas of extremely high salinity in the E.

19.5.1.8 Alluvial fan of Wadi Al-Batin (Aquifer Group 8)

Well data in the alluvial fan of Wadi Al-Batin indicate it comprises permeable gravels and coarse sand, alternating with marl. The discharge rate of drilled wells is 5->20 L/see. The specific capacity of the wells is typically 0.5-3 L/sec/m. Seasonal groundwater level fluctuations have very small amplitude. In wet years (with a rainfall of about 150 mm/year) the groundwater level varies by 0.2-0.8 m, and in dry years «75 mm/year) by 0.04-0.06 m.

Transmissivity is very high (500 to 6000 m^2/day) and averages 2500 m^2/day. The mean storage coefficient is 0.085-0.10. Static water level varies from 25 m in the recharge zone to <5 m ASL in the discharge zone. Groundwater flows towards the Shatt Al-Arab. Depth to groundwater varies from about 50 m in the recharge area to < I m in the discharge area.

Groundwater salinity is 3-5 g/L in the recharge area and >20 g/L in the discharge area. Groundwater of salinity 3-10 g/L can be used for irrigation (because the soil in the area i very permeable) and for watering livestock. Note that overproduction from tills aquifer may cause inland movement of sea water through sediments of the Arabian Gulf.

19.5.2 Jezira Hydrogeological Region (Aquifer Group 9)

The system extends from the Tigris and Tharthar Valley in the NE and SE, the Sinjar Mountain in the N, the Der Al Zor depression in the W to the Euphrates in the S. The Fatha (Lower Fars) Formation outcrops in the Tigris valley in N Iraq and in the Jezira area between the Euphrates and Tharthar. It comprises beds of gypsum, marl and thin limestones. The gypsum beds only act as aquifers where they have been extensively karstified. However the interbedded organo detrital limestones can act as aquifers.

Aquifer recharge is controlled by rainfall infiltration, which is influenced by the drainage pattern and karst phenomena. Where the formation outcrops there are usually many springs on both sides of the Tigris River and the Tel Afar anticline. The spring water is bitter and saline with an H_2S odour. Sulphured water issues along fractures from the sulphur-bearing confined aquifer at the base of the formation. In the Jezira area, there are about 25 springs, whose discharge varies from <1 L/sec to 10 L/sec averaging 3 L/sec. In the south Sinjar area, during drilling and testing of boreholes, the pumped water contained bitumen which originates from the limestones of Fatha Formation of this region.

Wells overflow at different depths. Piezometric levels indicate the water bearing horizons are hydraulically connected with each other and sometimes with the underlying Jeribe Formation. The discharge of wells in this zone is very low, many wells have been abandoned. However, near the Tigris and the Tharthar valley there is a possibility of better well yields (up to 30 L/sec). The permeability of the aquifer is related to the primary porosity in limestone and a network of joints and fractures. The primary transmissivity of the Fatha aquifer for the major parts of the zone is about 1 m^2/day. Much higher values are recorded locally due to karstification (reaching >400 m^2/day).

The groundwater quality depends mainly on the type of permeability. The permeability may change laterally in a very short distance and in the vertical direction. Secondary permeability is restricted to the upper 15 to 25 m of the aquifer. At depths greater than 25 m the salinity increases

sharply from 3 g/L (sulphate type) to over 30 g/L chloride type). Wells should not be drilled into this saline zone.

Groundwater level elevations vary from 300 m ASL in the Abu Rassain High (recharge area) to 100 m ASL towards Wadi Tharthar and Tharthar Lake (the main discharge area). Towards the Wand SW, the groundwater flows from the recharge area towards the Euphrates to the S and the Tawila playa to the W (Fig. 19-11). To the north, discharge occurs in the Sunailsla depression. Several local playas with closed water systems also occur along the Hadr-Bekhme Fault. The depth to groundwater is 10-20 m in the central part of the Abu Rassain High, 5 m in the main discharge area of the Tharthar and <1 m near salt playas.

Salinity is usually 3-5 g/L, but in the discharge area near the salt lakes, the salinity increases to 20 g/L. The groundwater of most of the area has been used for irrigation and watering livestock although this breaks international guidelines. It seems that local sheep breeds can tolerate water with a salinity of up to 12 g/L.

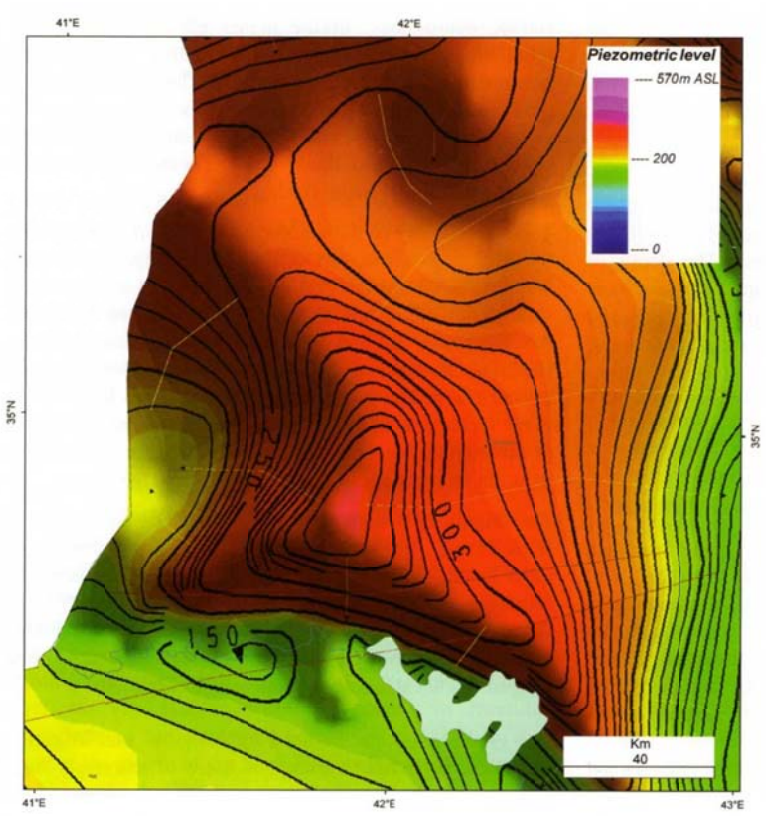


Fig. 19-11: Piezometric level of groundwater of the Jezira region

19.5.3 Aquifer System of the Mesopotamian Plain (Mesopotamian Aquifer System-Aquifer Group 10)

19.5.3.1 Extension and general features

The Mesopotamian Plain of SE and central Iraq is a flat, or very gently dipping, surface bounded by the Foothill Zone (Makhul, Hemrin and Pesht-i-Kuh ranges) in the E and the Salman Zone in the W. Elevation varies from 2 m above sea level near Basra, to 35 m near Baghdad and 180 m near Baiji. The Mesopotamian Aquifer System covers an area of approximately 110,000 km.

The Tigris enters the aquifer system at Fatha gorge (at the col between Jabal Hemrin and Jabal Makhul). The main left bank tributaries of the Tigris, the Adhaim and the Diyala rivers, enter the region through deeply incised valleys located at other structural cols in the Hemrin anticlinal range. The Euphrates generally follows the SW boundary of the Plain. The Tigris and the Euphrates are the only water courses flowing through the Plain south of Baghdad.
The Flood Plain of Mesopotamia contalns Quaternary fluvial sediments of the interacting Tigris and Euphrates rivers, merging into a marsh land north of Basra and the Shatt al Arab delta plain between Basra and the Arabian Gulf. The drainage density of the Mesopotamian Plain is naturally low but is artificially high due to channels of extensive irrigation systems several thousands years old.
The Mesopotamian Plain forms the central part of the Mesopotamian Aquifer Megasystem consisting of several partly independent aquifer systems or sub-systems (see Section 19.5). The plain is the main regional groundwater discharge zone of the whole Megasystem.

Very large depressions lie between the dejection cone of the Euphrates and the Salman Zone. The Tharthar, Habbaniya, Razzaza and Bahr-Al-Najaf depressions were formerly important groundwater discharge zones for the area surrounding Mesopotamia. However, their ground water regime has been altered due to their use as flood protection reservoirs. Smaller depressions also exist along the eastern side of the Plain the most important of which is the Shari Lake east of Samarra.
Human habitation has flourished in Mesopotamia for over 6000 years. During this time people have depended mainly on surface water except for springs which issue in restricted peripheral areas of the Plain, and shallow hand dug wells. Ground water was not used since irrigation canals supplied enough water for all uses, and is almost everywhere of better quality than groundwater. However, in the last century the importance of groundwater in the Mesopotamian Plain has been highlighted due to its major role in soil salinisation. Many land reclamation projects focused on groundwater in the shallow subsurface zone, a few metres deep. In addition to Baghdad and Basra, the important population centres of Tikrit, Samarra, Baquba, Hilla, Diwaniya, Samawa, Nasiriya, Kut and Amara and numerous major towns are located on banks of the Tigris, Euphrates and Diyala. Other populated areas are supplied by extended irrigation systems e.g. the Khalis and the Dujail systems. Over 60% of the population of Iraq relies on the Mesopotamian Plain.

19.5.3.2 Geological setting, spatial distribution of hydrogeological bodies

Despite the importance of the Mesopotamian Plain for the Iraqi economy, it had been poorly studied until the geological surveys of GEOSURV were completed in the 1980's. These surveys provided important geological and hydrogeological results.

The Mesopotamian Plain contalns relatively thick Quaternary sediments of fluvial origin (-280 m), alluvial fans on the flanks (-50 m) and aeolian sediments. Near Baghdad, the Quaternary deposits are up to 80 m thick. Their thickness increases to >250 m in the SE part of the Aquifer System near Basra. The sediments of the plain consist of levee silts and clays, flood plain clays and stacked river channel sand bodies (See Chapter 15), with occasional marsh deposits. The Quaternary sediments overlie Mio-Pliocene molasse or Lower Miocene carbonates.
Regularly spaced geological boreholes of GEOSURV were utilised in the hydrogeological evaluation of the plain. Most of these boreholes were drilled to a depth of 20 m, some to 40 m. A few deep boreholes, drilled to depths >200 m, penetrated the whole Quaternary sequence and were

located along three transverse profiles. From N to S these are the: Iskandariya-Salman Pak-Mandali profile (Fig. 19-12), the Diwaniya-Kut-Karmashiya profile and the Nasiriya-Amara profile. A longitudinal profile connects the Amara and Basra areas. Fig. 19-12 shows that the Tigris basin dominates the northern part of Mesopotamia while the Euphrates basin is restricted to the area between the Salman Zone and the Pleistocene ridge extending from Falluja to Iskandariya.

Direct correlation of aquifers and aquitards was impossible due to their spatial variability. The proportions of aquitards were counted in particular depth intervals from all the available "shallow" geological boreholes. The depth of the boreholes usually exceeds 20 meters; values for five intervals were available to assess vertical changes in lithology and consequently aquifer or aquitard occurrences in each borehole. The sand isolith maps are presented as Figs. 15-2a to 15-2e of chapter 15 (for sand aquicludes). The ratio of the total thickness of aquifers to aquitards (aquiferaquitard ratio) was determined and expressed in a logarithmic form. All the data were computerised and plotted in the form of contour maps (Kunstman, 1981). The results obtained within the whole Mesopotamian Plain were reported by Krasny (1983b) and are outlined below:
Within the studied depth intervals down to 20 m, higher sand and gravel contents occur in the deeper parts indicating a fining upwards sequence, especially in the northern half of the Mesopotamian Plain. Stacked channel bodies are locally dominant and concentrated in conspicuous linear zones (Chapter 15, Fig. 15-3). They trend roughly N-S in the N part of the Plain (possibly indicating the earlier Diyala river course) and NW-SE south of Baghdad (indicating earlier Euphrates or Tigris courses). Other "sandy" accumulations trending E- W which occur to the SW, (for example between Shanafiya and Samawa) were evidently derived from the desert region through wadis. The present day Shaibs AthThimad and Abu Julud wadis still discharge into the Mesopotamian Plain. A few other inlets of sandy material from the Southern Desert occur near Samawa and AL-Khidhr and between Karbala and Najaf. Southwest of Basra, coarse grained alluvial fan sediments relate to Wadi Al-Batin.

The NE flank of the Mesopotamian Plain contalns mostly fine grained sediments (sheet-run-off deposits), which form a belt between the Tigris and Hemrin, and sandy and gravelly alluvial fan deposits (Section 19.5.4).

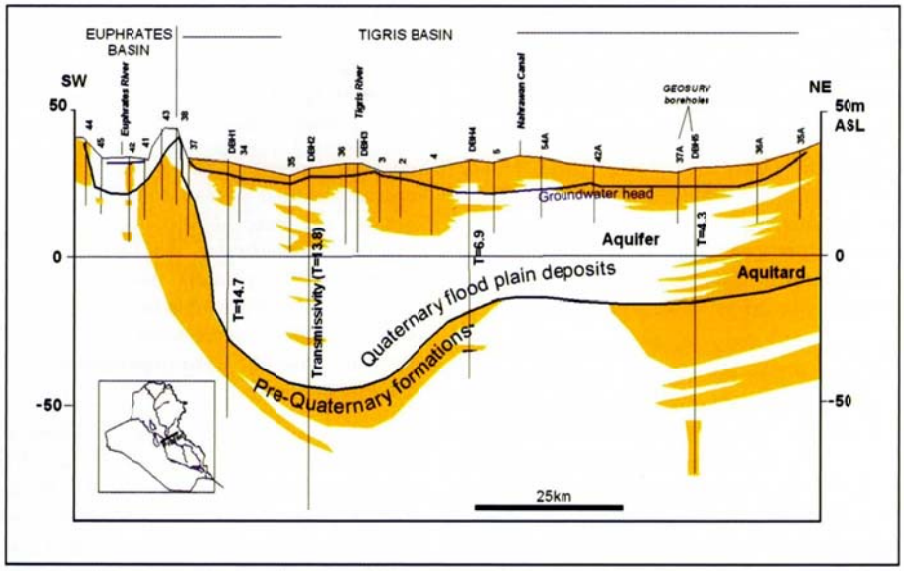


Fig. 19-12: Synoptic hydrogeological profile across the Mesopotamian Plain along the line Iskandariya-Salman Pak-Mandali (modified from Krásný 1981a)

19.5.3.3 Transmissivity and permeability of the deposits

Low permeability deposits form a regionally extensive aquitard in the upper part of the layered Quaternary sequence of Mesopotamia.

The upper aquitard is usually about to m thick, locally up to 20 m thick (Fig. 19-12). This aquitard is a very important factor for groundwater protection. It is underlain by an aquifer tens of metres thick. The aquifer thickness near the Iskandariya-Salman Pak-Mandali profile reaches approximately 60 m. The aquifer thins towards the E (40 m) and is finally replaced by an aquitard (Fig. 19-12). Towards the SE the interconnected aquifer of the Tigris basin is thickest (at least 200 m) near Kut based on deep borehole data. It comprises mainly fine- to medium-grained sand sometimes cemented by gypsum. Interbedded clays and silts form less permeable bodies (aquitards); the extent of these aquitards can not be delineated with certainty as they could not be correlated between boreholes. The thickness of individual sand layers is typically a few tens of metres. The thickest sandy layer (120 m) was found in well DBH 8 from 17 to 137 m depth; it contalns only a few thin clay and silt beds. Aquitards were also found in three other deep boreholes.

Values of the coefficient of hydraulic conductivity were quoted in Riykov et al. (1975), mostly based on the results of Mac Donald et al (1960) and Binnie et al. (1956) who investigated the irrigation projects of Mesopotamia. Permeability was determined to depth of 5-7 m. Most of the tested deposits were anisotropic, with a $k_x fk_z$ ratio of 5-9. Relatively low hydraulic conductivities were found in the Hilla-Diwaniya area (the average value of horizontal component of hydraulic conductivity k_x is 1.63 *mid* and the vertical component k_z is 0.33 *mid).* In the Shinafiya Nasiriya area, the average k, is 1.95 *mid* and k, is 0.22 *mid.* In the Amara area k, is 2.25 *mid,* k_z is 0.29 *mid,* and the ratio $k_x fk_z$ is 7.8. In the East Gharraf area k, is 2.38 *mid* and k, is 0.32 *mid*.

These values are probably representative of silts and clays of the upper aquitard. They are consistent with data listed by Elerdashvili (1973). Values representative of silty and clayey-silty materials (6.9 x 10-^{6} *mls)* accord with those recommended by Riykov et al. (Op. Cit.) for irrigation

calculations, determined as the geometrical mean of the average horizontal and vertical components of hydraulic conductivity, mostly between 7.5 and 8.8 x 10^{-6} mls (0.8-0.9 *m/d).*

Aquifer tests were carried out in some water wells. The highest transmissivity was found in the SW part of the Tigris basin. Geological data and aquifer tests performed in deep boreholes indicate that the transmissivity of Quaternary sediments decreases from the central part of the Tigris basin *(69-138 m^2/d)* to the east (43 m^2/d). A similar decrease in transmissivity probably occurs towards the W related to the thinning of the Quaternary aquifer over the Iskandariya and Falluja Pleistocene ridges.

In the Baghdad metropolitan area, high permeability and transmissivity is indicated by high discharges of drilled wells (Parsons, 1957b). A total discharge of 226 LIs (min. 1.2 LIs, max. 15.8 LIs per well) is pumped from 27 wells at depths of 30-100 m. Along the Hilla River, the transmissivity of the upper part of the Quaternary deposits of the Mesopotamian Plain to a depth of a few tens of metres is 100-200 m^2/d. Alsam et al. (1979) assessed the transmissivity in the Babylon area to be as high as 300-400 m^2/d with storage varying from 0.0004 to 0.13. South and W of Suwaira (60 km S of Baghdad), however, the transmissivity is <80 m^2/d. In the central Mesopotamian Plain the transmissivity is about 100 m^2/d based on a pumping test performed in the ISO m deep water well near Afaq.

In the area bordering the Mesopotamian Plain to the SW (between Karbala and Najaf), two additional aquifers can be distinguished. The lower limestone aquifer occurs between. 70 m to 300 m depth. It outcrops to the W, e.g. in the Shithatha (Ain Tamr) area where its transmissivity is often many hundreds of m^2/d (see section 19.5.1, Desert Aquifer System). In the subsurface between Karbala and Najaf, the transmissivity of the limestone aquifer decreases and only exceptionally exceeds 100 m^2/d. The upper aquifer consists of sand and gravel with beds of clay. It outcrops and forms a separate basin between Karbala and Najaf. In the central part it is up to 70 m thick. The transmissivity of this aquifer varies greatly and reaches 1000 m^2/d. The reliability of available data in this region, however, is questionable. In the central parts of the Mesopotamian Plain these aquifers are separated by an aquitard of clay, calcareous clay and marl up to 200 m thick. Some hydraulic connection between these aquifers and the shallower aquifers of the Mesopotamian Plain is likely.

In the S part of the Mesopotamian plain, sediment permeabilities are low in the shallow zone down to depths of 19-25 m except west of Basra where clastic deposits of the Dibdibba Formation and of the alluvial fan of Wadi Al-Batin occur (Section 19.5.1). These deposits have high permeabilitiy and transmissivity. Local deposits of coarse permeable sand also occur along the SW side of the Plain over a range of depths indicating possible connection between the sandy aquifers of the Southern Desert and those of the Mesopotamian Plain.

The northernmost part of the Mesopotamian Aquifer System in the Tikrit-Baquba region comprises coarse grained sediments of coalescing alluvial fans originating from the Hemrin range. The fans consist of lenticular bodies of poorly sorted fine- to coarse-grained sand and gravel with varying clay content deposited by braided rivers. The fans unconformably overlie conglomerates of the Bai Hassan (Upper Bakhtiari) Formation. The largest and oldest of these fans originated at Al Fatha, north of Baiji (200 km north of Baghdad) and was described by Jassim (1981). This fan is the product of the Tigris and extends to Baghdad where it is present about 18 m below the flood plain level of Mesopotamia. The Baiji Fan also extends W towards the Euphrates River at Falluja. The thickness of the fan sediments exceeds 50 m in some channels. Sand and gravel tongues

border the Plain from the SW which include the extensive sandy-gravel bodies of the Dibdibba and Wadi Al Batin accumulations west of Basra.

The hydrogeological characteristics of these fans differ. The Baiji Fan and other coherent fans in the Tikrit-Baquba region can be considered part of the Mesopotamian Aquifer System as they pass laterally into the plain deposits forming a hydraulically connected hydrogeological body with continuous regional groundwater flow (Section 19.5.3.4).

The hydrogeological connection of fans bordering the Mesopotamian Plain to the SW with the plain water bodies varies depending on whether the fans are in a "blocked" or "unblocked" position. The most extensive fans of the Dibdibba Formation and the Wadi Al-Batin fan may belong to the Desert Aquifer System (section 19.5.1). The fans NE of the plain between Mandali and Tib are hydraulically separated from the aquifers of the Mesopotamian Plain by very low permeability sheet-ron-off deposits. They can be considered as independent Aquifer Systems of the Mandali Badra-Tib region (see Section 19.5.4).

Widespread terrace deposits are important aquifers. Thick sand, gravel and conglomerate terrace deposits occur on both banks of the Tigris. Three to five terrace levels can be differentiated. The thickness of these deposits does not exceed 19-25 m (see Chapter 15).

Sabkha deposits occur within ephemeral lakes scattered in the area. The Shari Lake is the largest and the best known of the ephemeral lakes. It receives surface water from Wadi Asam in the N and Wadi Al Khar in the E. It is filled during the winter and spring and dries out during summer. During dry seasons, it is covered by a whitish salt crust with sodium-sulphate salts. The Tikrit-Baquba part of the Mesopotamian Aquifer System forms a triangular-shaped hydrogeological basin filled by clastic sediments of very variable grain size. Terrace gravels and dune sands form the only extensive aquifers. Drilling on the west bank of the Shari Lake proved an aquitard comprising a 33-47 m thick sequence of clays and silty clays overlying a confined aquifer composed of gravels and sands up to 50 m thick. However neither aquifers nor aquitards are regionally extensive in this basin. The basin is a lithologically complex aquifer sub-system with variable hydraulic connectivity.

Statistical treatment of transmissivity data from water wells was possible in the Tikrit-Baquba region. Values of ransmissivity are highest in the central part of the region on the left bank of the Tigris River (east of Tikrit) and to the S in the area east of Samarra where values of the Y index were usually determined to be >6.0, i.e. approximately equivalent to a transmissivity >120 m^2/d. High transmissivity is predicted to the SSW of the Adhaim River-Tigris River confluence. In the S part of the Tikrit-Baquba area, there is insufficient data to assess the transmissivity. The transmissivity generally decreases from W to E with a Y index of <6.0 near Jabal Hemrin and <5.0 (transmissivity about 15 m^2/d) E of Wadi Tharthar (Krasny 1982e). Two wells located on the W shore of the Shari Lake have transmissivity values of 285 and 375 m^2/d (Aralm et al. 1978) corresponding approximately to Y indices of 6.3 and 6.5 respectively. Comparable transmissivity values were determined by statistical analysis in the whole Tikrit Baquba region (Krasny 1982e). Maximum values of hydraulic conductivity of 10-20 *mid* were found E of Samarra in relatively shallow drilled wells. In about 90% of the area the hydraulic conductivity is 3-7.5 m/day, decreasing to <3 *mid* on the W bank of the Tigris W of Tikrit.

Depth-related changes in transmissivity based on well data indicate higher permeability in the upper 50 m of the layered sediments. Below this depth the mean permeability appears to be lower but is almost unchanged at least down to 175 m depth.

19.5.3.4 Groundwater flow

The piezometric surface shown in Fig. 19-13 is based on "untreated" data uncorrected for salinity dependent variations in specific gravity. Salt water with a salinity of 100 g/L has a specific gravity of 1.078, compared to 1 for fresh water. A column of salt water is therefore heavier than a column of fresh water of the same height. For the water columns to be in hydraulic equilibrium the fresh water column must be thicker. A 54 m fresh water column is required to balance a 50 m column of salt water with the above salinity. Recalculation of the groundwater head to the comparable data (effective piezometric surface), i.e. to the water of the same salinity will significantly smooth the map of the piezometric surface. Consequently, the rate of groundwater flow is even lower. The groundwater may even be stagnant. Hydrochemical data indicate complex groundwater flow in these areas, complicated by irrigation activities.

Groundwater flows towards the Mesopotamian basin from all the neighbouring regions and deep-seated brines tend to ascend towards the land surface (Fig. 19-4). The Mesopotamian Plain is thus a regional discharge zone for the whole Mesopotamian Aquifer Megasystem (section 19.5). Within this Aquifer System the piezometric surface of groundwater is in general inclined to the SE determining the main horizontal direction of shallow groundwater flow.

Groundwater piezometric elevations and directions of groundwater flow (Fig. 19-13) are based on available data on groundwater levels from drilled wells and geological boreholes spaced throughout the Mesopotamian Aquifer System. The interpreted flow directions assume that a generally continuous and interconnected groundwater body exists throughout the Delta Plain, as stated by Parsons (1957b). This interpretation is supported by local investigations at the Khalis irrigation canal by Al-Rawi et al. (1971) where a continuous groundwater level was observed both in clay deposits and in interbedded sandy layers.

Alluvial fans occur in the Desert Aquifer System SW of Mesopotamia. Alluvial fans also occur in the NE between Mandali and Tib along the Iraq-Iran border which can be considered part of the Mesopotamian Megasystem. Both elevated flanks form potential recharge zones from which groundwater tends to flow to the central discharge zone (Mesopotamian Plain). In both the desert region and alluvial fans, however, most of groundwater is discharged before reaching the Plain. Therefore, they can be considered hydrogeologic ally independent aquifer systems (sections 19.5.1 and 19.5.4).

Water-level measurements in geological boreholes and other investigations indicate that, even in the upper part of the sediments of the plain, vertical groundwater flow occurs. The phenomenon is partly caused by the upper aquitard in most of the area which creates semi-confined or confined conditions within the underlying aquifer. Downward flow only occurs in limited areas.

Smirnov et al. (1981) reported on the potential upward direction of groundwater flow in an experimental plot located 25-30 km NW of Basra. In September 1979, the head of a confined lower groundwater body was 0.74 m above the static level of an upper water-table body. Based on the hydraulic conductivity (permeability) of the intervening 13 m thick aquitard (approximately 0.01 *mid)* the authors estimated that the natural discharge of confined water into the water-table aquifer through the aquitards is about 570 $m^3/d/km^2$, i.e. 6.6 L/s/km". In the spring season the difference in groundwater heads decreases as the range of water level rise of the upper groundwater body considerably exceeds the fluctuation of the piezometric surface of the confined body. This assessment can be used to indicate the loss of groundwater due to vertical seepage in the Mesopotamian Plain.

Groundwater level fluctuations are related to the quantity and distribution of rainfall. In addition, within narrow belts along streams and canals, it is controlled by surface water level fluctuations. The annual water level fluctuations within the Mesopotamian Plain typically start in winter and spring with an abrupt rise of water levels due to recharge caused by precipitation, high water tables in streams, and irrigation activities. During summer and autumn water levels fall because of lack of recharge; an increase in evapotranspiration relative to groundwater runoff occurs under favourable geological and hydrogeological conditions. The largest annual amplitude of the water table may reach 10 m but it is usually lower and is locally <l m.

The piezometric head (static water level) of groundwater is >200 m ASL near Jabal Makhul), decreasing slightly along the Jabal Hemrin piedmont area to the SE. The course of the equipotential lines (Fig. 19-4) indicates an increase in hydraulic gradient in the mountain area (Jabal Hemrin and Jabal Makhul) reflecting the special natural conditions there, the generally lower permeability of the sediments, and interbedding of layers of different permeability. An abrupt decrease in piezometric head can be followed to the S, SW and SE. The head reaches approximately 50 m ASL south of Samara (along the Tigris) and at Ramadi in the Euphrates valley (Fig. 19-4). From there, the groundwater head declines to 25-30 m ASL near Baghdad. To the SE near Basra the groundwater head is around 5m ASL. The rate of decline in the head is very low indicating the presence of almost stagnant groundwater bodies.
Confined aquifers occur where layers of low and high permeability alternate in the vertical direction. Aquitards covering aquifers can (depending on hydrogeological position) cause groundwater to flow from wells up to the surface. The lithology of both the Quaternary and Pre-Quaternary deposits (mainly of the Bai Hassan and Mukdadiya formations) indicates that the Pre-Quaternary sediments are in places in hydraulic communication with the Quaternary sediments. Surface water and groundwater can be in a mutual hydraulic interconnection to different degrees. Consequently, rivers and irrigation or diversion canals of influent or effluent character form important external and internal hydraulic boundaries of the aquifer system.

In the northern part of the Mesopotamian Plain (Tikrit Baquba region) recharge from direct precipitation is restricted almost entirely to winter and spring seasons when rain is the important water source feeding groundwater bodies especially through intermittent wadis in elevated areas. Recharge from rivers and canals occur in some restricted areas: most recharge occurs along the left bank of the Tigris R, downstream of Tikrit. Additional influent seepage may also occur along the right bank of the Tigris south of Samarra and within areas fed by large irrigation systems such as the Is'haqi and the irrigation canals diverted at the Diyala weir (particularly the Khalis canal).

Groundwater discharge is commonly confined to narrow zones following river courses and to land-locked depressions. The main zones of groundwater discharge are:

1. The Wadi Tharthar in the west. In addition to the discharging effect of the wadi bed, springs issue at higher elevations where conditions are suitable. Natural conditions have been changed in the S part of Wadi Tharthar since the Tharthar depression was filled by water diverted from the Tigris River (a canal takes off water at Samarra). Surface water levels in the Tharthar Lake have risen by 50-60 metres. At the present water level, flow has reversed from the original natural flow towards the Tharthar; the lake is presently recharging the Mesopotamian aquifer to the south.

2. The Tigris River between Al-Fatha and Tikrit which drains groundwater from both banks. Downstream, however, between Tikrit and Samarra, the effluent effect of the river seems to be retained on its west bank only. The E bank has become influent. The regional discharge zone is shifted eastward and follows the depression of the Shari Lake including its S extension as far as Balad. Near this lake groundwater is discharged from the whole catchment SW of Jabal Hemrin as far as the groundwater divides between the Tigris River and Wadi Tharthar. Some groundwater is discharged by numerous springs on the slopes of Jabal Hemrin. Their yield is low, usually < 1 L/s. South of Balad natural conditions are strongly influenced by the extensive irrigation system. Near Balad-Dujalla, because of the smaller hydraulic gradient of groundwater, the discharge zone is less apparent.

3. The Adhaim River. The discharge of the river is not very strong as it drains groundwater in the parallel direction to the regionally prevailing groundwater flow.

4. The Diyala River area. This is strongly influenced by irrigation. In the north of the plain, the depth to groundwater level in drilled wells ranges from a few metres to a few tens of metres. Shallow perched water table aquifers can be tapped in hand-dug wells where horizontal impermeable layers occur above the regional piezometric surface (Fig. 19-4). Groundwater at depths < 5 m occurs only exceptionally. Deeper drilled wells, located in groundwater discharge zones, can overflow. The amount of overflow increases with the depth of the well. Flowing wells occur in the Wadi Tharthar valley and near the Shari Lake.

   In a broad area around Baghdad the main regional features of groundwater flow can be characterised as follows: 1) Influent seepage occurs from the Euphrates River to its left-shore area. 2) The character of the Tigris changes considerably. Its left bank upstream of the confluence with the Diyala River, and its right bank to the S of Baghdad have effluent character; so has the Diyala River on both banks. This phenomenon is strengthened by irrigation activities. When these rivers are in spate their effluent character can change to an influent one. This is probably so for the Tigris to the S of Baghdad. Within the remaining right bank area, and the left bank area downstream of the confluence with the Diyala River, seepage from the Tigris has a predominantly influent character. 3) Three main depressions in the piezometric surface occur: a) Between the Euphrates and the Tigris, where the depth to groundwater is shallow and the drainage is probably caused by evaporation (evapotranspiration). b) On the right bank of the Tigris to the NW of Baghdad related to the discharge and the drainage effect of the Is'haqi drain system. c) A depression SE of Baghdad. The latter two depressions have a relatively deep groundwater level, > 10m.

   Between the Euphrates and the Tigris common discharge areas should be assumed when rivers are in spate or during the high level stage. Regional groundwater flow from the Euphrates towards the Tigris occurs in the upper zone during low level stages; some of the water evaporates in these depressions. This general pattern of groundwater flow may be modified where Quaternary deposits thin out (e.g. in the area of Iskandariya mesa where Pleistocene sediments outcrop).

   In the S part of the Mesopotamian Plain the piezometric surface slopes generally to the SE, locally to the S. However conspicuous piezometric highs follow the main surface water streams (especially the Tigris, Hilla and Gharraf Rivers). These "highs" are most prominent in humid seasons, but even during dry seasons the rivers do not lose their influent character. The piezometric highs follow the main rivers. Their shape and extent is influenced by the topography of adjacent areas. Other piezometric ridges follow different irrigation canals or whole irrigated areas (e.g. the Musalyib irrigation system). Groundwater levels are modified near the Kut barrage.

Upstream from the barrage, where differences between maximum and minimum Tigris levels are relatively small, the influent character of the Tigris is continuously strengthened.

Between the piezometric highs, several extensive piezometric lows often occur beneath vast surface depressions containing marshes and lakes which represent important zones of groundwater discharge. Large piezometric depressions also occur to the north of the Tigris in S Iraq (Haur Ash-Shuwalja and Haur Al-Jassan) and to the S of the Tigris both E and W of the Shatt Al-Gharraf, Wadis originating from the foothills often end in the depressions to the E or N of the Tigris, passing into marshes, inland depressions and sabkhas due to the high elevation of the Tigris levees. Two large piezometric depressions also flank the Hilla River. The depression to the N extends to the E where it joins the vast depression between Afaq and Numaniya, and to the S of the Tigris. The largest, but rather shallow, piezometric depression lies between the Gharraf River in the W, the Tigris in the E and the Euphrates in the S.

The water table depth is > 10 m to the N and W of Baghdad, but to the S the Mesopotamian Plain contalns shallow groundwater, generally shallower than 5 m (between Kut and Baghdad) and at a depth of <l m south of Kut-Najaf. This is mainly the case in irrigated areas following the main river streams and irrigation channels (which form piezometric highs). This very shallow groundwater, combined with frequent secondary soil salinisation, has adversely affected the soil of Mesopotamia. It is therefore very important to implement water exploitation policies to relieve the Mesopotamian Plain from this water congestion.

Hydraulic conditions along the SW and NE boundaries of the Mesopotamian Plain considerably influence the hydrogeological conditions in those regions. In areas where the Dibdibba gravels and sands occur, a common aquifer is formed in Dibdibba and Quaternary (Plain) deposits. However the Eocene and Miocene limestone aquifer appears to be separated from the Quaternary aquifer by less permeable deposits, especially those of the Fatha Formation. Water recharged into limestone within the Western and Southern Deserts, generally flows towards the NE (towards the Plain) and is discharged in springs along the Euphrates Boundary Fault. Groundwater is also discharged by slow vertical seepage; consequent evaporation has created mudflats and sabkhas bordering the Mesopotamian Plain in the SW. Piezometric conditions are very favourable for this phenomenon throughout the "zone of springs" as groundwater head, in almost all wells drilled there, is above the ground surface. Part of the groundwater has retalned its original direction of flow even in the NE area of the "zone of springs" (between Karbala and Najaf, and near Samawa).

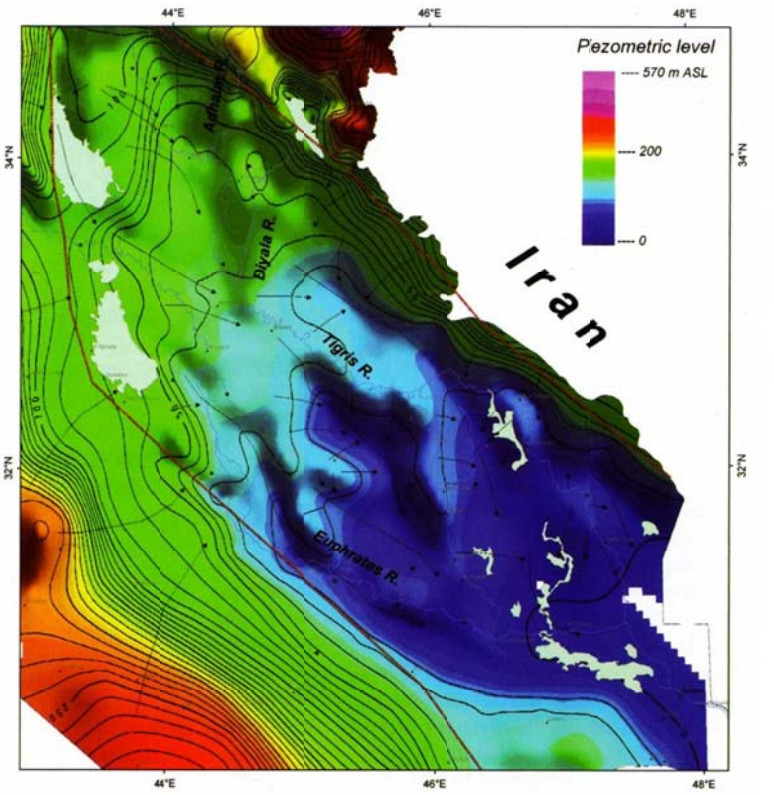


Fig. 19-13: Piezometric level of groundwater of the Mesopotamian Aquifer System

19.5.3.5 Groundwater quality

The Mesopotamian Plain is the regional groundwater discharge zone of the whole extended Mesopotamian Aquifer Megasystem. Consequently, dissolved solids have been transported by both ground and surface water from different directions and from below. After humid seasons, when groundwater level is high (especially in irrigated areas without adequate drainage) surface water is often present in depressions. Evaporation subsequently increases the salinity in the remaining water and in soils. As this process was repeated, large quantities of salts accumulated in the Mesopotamian ground waters and soils. Present-day hydrogeological issues of vital practical importance are those connected with land reclamation and possible present and future groundwater development.

The chemical composition of ground water within the Mesopotamian Plain varies especially in the shallow zone.

Generally, from the N (NW) to the S (SE) and from the borders of the Plain towards its central parts (especially in piezometric lows), the salinity increases and the chemical water type changes from calcium-sulphate to sodium chloride. Sodium-chloride type brines predominate in deeper zones.

In the northern part of the Plain ("the Tikrit-Baquba region") the salinity is 1 g/L->l0 g/L. Salinities of 2-3g IL were found in parts of Jabal Hemrin foothill zone and along the Tigris near Tikrit. Elsewhere the salinity is usually higher and generally increases towards the Mesopotamian Plain. Water from flowing wells on the western bank of the Shari Lake has a salinity slightly >5 g/L. Salinity also increases west of the Tigris (toward the Jezira region) where it is > 12 g/L.

The prevailing chemical type in the N part of the Plain is calcium (magnesium)-sulphate. The locally relatively high content of sodium sulphate in groundwater in the Shari Lake watershed may

influence the chemical composition of surface water in the lake. Between the Adhaim and the Diyala rivers transient and little expressive sodium chloride water types prevail. This may be due to the low topography of the area, and its proximity to the Mesopotamian Plain where the same type of groundwater is quite common. Sodium chloride water type of groundwater is more frequent in the western portion of the Tikrit-Baquba region (east of Wadi Tharthar). Due to the different extent and geological conditions of catchments, surface water from the Diyala River and its canals has a lower salinity and relatively high content of bicarbonates compared to the Adhaim River. Several small springs issuing from fractured gypsum of the Fatha Formation along the SW flank of Jabal Hemrin and Jabal Makhul are highly mineralised. Calcium-sulphate type waters predominate in hand dug wells.

A close relation between the salinity and chemical composition of groundwater was found. Waters with salinity <0.5 g/L are usually of calcium-bicarbonate type. Little expressive calcium-bicarbonate type prevails within a salinity range of 0.5 to 2.0 g/L with stronger calcium bicarbonate constituent at the lower limit of the interval. At higher salinities, pure, very expressive and expressive calcium-sulphate water types prevail. At salinities >4.0 g/L, sodium-chloride often occurs as the second constituent and the water type is of little expressive calcium-sulphate type. At salinities of 5.0-5.5 g/L, both calcium-sulphate and sodium-chloride transient types occur. The latter type (often little expressive) prevails at salinities> 12.0 g/L. High linear correlation coefficients were determined between salinity and sodium, magnesium, sulphate and chloride concentrations near the Adhaim River (Krasny 1980).

High chloride content may indicate the influence of a deeper hydrochemical zone. An increase in bicarbonates and a low salinity of <1 g/L indicates hydraulic connection with surface (pluvial) water. This often occurs in ephemeral valley fills.

In the central area (around Baghdad) and in the southern parts of the Mesopotamian Plain two sets of data were used.

These comprise data from previous reports and from water wells drilled by the State Organization for Ground Water (SOGW) water wells, and chemical analyses of samples taken from geological boreholes drilled during the investigation of the Quaternary of Mesopotamian Plain. Geological boreholes were sampled a few days after completion without performing pumping tests or cleaning. Aquifer tests were made only exceptionally in some deep geological boreholes.

Large differences in salinity and chemical composition were found between analyses from geological boreholes and those from other sources. The samples from the former are usually higher in salinity than other groundwater samples taken in the same area. The composition of water samples from the geological boreholes may have been contaminated by leaching of the sediments penetrated and also by the drilling process. Geological boreholes are spread quite regularly over most of the Plain giving a random data population. Other groundwater points are unlikely to represent average groundwater compositions: sampling was largely confined to hand-dug and/or drilled wells, or springs. Sampling points were thus preferentially located in areas where freshwater occurs. Hand dug and drilled wells with unsatisfactory quality of water, which had been abandoned in the past, could not usually be sampled. Therefore, water quality and changes in chemical composition are best assessed using mainly analyses of water samples from geological boreholes. Data from dug and drilled wells show areas of better groundwater quality sometimes caused by pumping when water of better quality can flow towards wells, for example

near irrigation canals and rivers. Pumping can also locally cause deterioration in water quality due to water encroachment especially from deeper zones.

Around Baghdad the groundwater salinity within the upper part of the Quaternary deposits generally increases eastwards, reaching tens of g/L at the eastern boundary of the Plain. Maximum salinity was found in a deep geological borehole at Khan Bani Saad, 40 km NE of Baghdad (D53, total depth 165.5 m, salinity 48.4 g/L) and in another deep borehole DPH 4 (depth 75.15 m, salinity 55.4 g/L). Lower salinities usually occur between the Tigris and the Euphrates W of Baghdad. The minimum value was found in the borehole BH55 (0.7 g/L) located about 1.5 km from the Tigris River. Low salinities are due to the influent seepage from the river. Similarly low salinity groundwater occurs along the shores of rivers and irrigation canals where natural or artificial conditions enable seepage from surface water courses. This process supplies groundwater bodies with fresh water and reduces their salinity. Fresh water bodies were found in shallow hand dug wells and drilled wells, a few tens of metres deep, sometimes yielding groundwater of relatively good quality, for example near Baghdad.

Salinity also generally increases with depth. High salinities between Falluja and Latifiya may be due to the occurrence of gypsiferous veins or to movement of deep-seated saline waters up a fault zone along the SW side of the Tigris basin.
Vertical changes in groundwater chemical composition were also reported by Barica (1968) from the Abu Ghraib area west of Baghdad. All the tests were performed on closely spaced wells to restrict horizontal changes in groundwater composition and opened in the very bottom part of the well to allow groundwater inflow in a narrow well-defined vertical zone. Highest salinities (- 44 g/L) occur in the uppermost part of the vertical section (0.5-1.8 m); this is due to evaporation of groundwater and irrigation water and consequent salt concentration in soils. The salinity then decreases to a depth of 30 m where it reaches 11.8 g/L. It then increases slowly to 30 g/L at 90 m depth. Scarce deep well data (D25, D53 and DBH 4) and oil exploration wells (Ditmar and Iraqi-Soviet team, 1971 and 1972) indicate salinity continues to increase with depth.

In the Mesopotamian Plain E and SE of Baghdad, groundwater salinity is generally high. Highest salinities were found in areas of surface (and piezometric) depressions which act as discharge zones, usually between river courses, for example in Haur Ash-Shubaicha and Haur Al Suwaiqiya north of the Tigris. In these depressions shallow geological boreholes have salinities> 100 g/L (the highest value in BH17 is 149 g/L). High salinities were also found E of the Tigris between Ali Al-Gharbi and Kumait and in elevated areas between the lower reaches of the Tib and Dewairij Rivers. South of the Tigris, the salinity is generally lower due to irrigation along the Shatt Al-Gharraf and other main streams and channels. Salinity is especially low in shallow hand dug wells where the water is of calcium magnesium -bicarbonate type of similar composition to surface waters (for example in Shatt Al-Gharraf). Only occasionally the salinity may reach 50-80 g/L in some localised areas. Elswhere in the Plain, except for areas influenced by seepage from main rivers and irrigation systems, groundwater of basic or expressive basic sodium chloride types occur.

In the southernmost part of the Mesopotamian Plain groundwater composition is also influenced by seepage from surface water courses and reservoirs and is relatively fresh. Beneath this shallow fresh water lies highly mineralised salt water with salinities of many tens of g/L. In the W part of this area salinity does not vary much under natural conditions. In the "zone of springs" along the Euphrates Boundary Fault it is 4-5 g/L in both springs and wells. To the S of the "zone of springs",

in limestones, differences in salinity are larger. Locally higher values may appear due to the "overdraft-time factor" which may control groundwater quality as in the Busaiya area where the salinity has increased from 0.9 to 4.9 g/L as shown by four wells drilled in 1955-1962. Better quality water occurs in perched groundwater bodies (well D500) where the groundwater head is approximately 50 m higher than in other wells in the same regional aquifer.

Salinity increases to the east probably due to outcrops of the less permeable Fatha Formation containing evaporites where the salinity is 8-22 g/L. Groundwater is of better quality near Snafi Jabde, 60 km SE of Suq Ash-Shuyukh and S of Haur Al-Hammar where, in seven wells, the salinity is 0.5-2.8 g/L. The difference in salinity compared with the Luhais area (salinity about 9 g/L) about 15 km to the S of Snafi Jabde is due to the combined influence of both natural and artificial conditions. Wells at Luhais are deeper (90-110 m) than those at Snafi Jabde (approx. 60 m) which are located in an almost closed depression in which several desert wadis empty, delivering fresh water to the groundwater body. Evaporation in this depression is slight as the groundwater level is as deep as 40 m. In the easternmost portion (around Basra, Zubair, Safwan.) the salinity is usually 3-8 g/L. Barica (1968) and Haddad and Hawa (1979) noted that a thin layer of fresh water flows above the lower salt water body, fed directly by precipitation or indirectly by seepage from intermittent flows in wadis. The presence and thickness of the flowing fresh water body depends on soil permeability. When groundwater is pumped salt water encroachment from below increases groundwater salinity. Many hand dug and drilled wells in the area were abandoned because of increasing salinity.

In the western part (the Southern Desert with limestone outcrops) the prevailing water type is calcium-sulphate. In the remaining part sodium-chloride water type prevails. In the Basra-Zubair-Safwan area, the chemical composition of groundwater depends to a large degree on human activities. Normally, the groundwater of many shallow hand-dug wells and of some drilled wells is of calcium-sulphate type but after pumping and irrigation, the salinity can increase and the chemical composition can change to sodium-chloride type.

19.5.3.6 Present-day groundwater use and possibilities of future groundwater supply

Land reclamation (desalinisation) and groundwater development are important hydrogeological issues in the Mesopotamian Plain. Groundwater contamination issues will also become important. Land reclamation schemes through both irrigation and drainage depend directly or indirectly on hydrogeological conditions. In the Plain most surface water is used for irrigation. Seepage of water from canals or during irrigation raises groundwater levels which can cause soil salinisation when the so-called "critical depth" to groundwater level is reached. During hot seasons water rises by capillary action. Evaporation then leads to salt accumulation in the soil. During the rainy season the salt is leached and transported downward by percolating water towards deeper groundwater bodies where the salinity continuously increases. This process occurs in many irrigated areas where the water table is usually highest in April and May when it is often dangerously high. To prevent soil salinisation, groundwater levels must be lowered below the "critical depth" by drainage. Three types of hydrogeological conditions ("conceptual models") were distinguished throughout the Mesopotamian Plain by Riykov et al. (1975), these are:

1. Homogeneous-anisotropic stratum, 15-100 m thick (hydraulic conductivity 8.1 x 10^{-6} *m/s)*
2. Homogeneous-anisotropic stratum (hydraulic conductivity 8.1 x 10^{-6} *m/s)* underlain at a depth of 5-7 m by a relatively impermeable layer.

3. Two-layer stratum consisting of an anisotropic, low permeability upper layer 15m thick (coefficient of hydraulic conductivity 2.9 x 10-^{6} *m/s)* and a lower homogeneous layer with a transmissivity coefficient of 3.5 x 10-^{3} m^2/s (ca 300 m^2/day).

   For each of these hydrogeological conditions special drainage schemes can be recommended. In the first two models, horizontal drainage with a drain spacing of 50-250 m is required. Under two-layer conditions a combined drainage scheme is necessary, comprising horizontal drains in the upper low permeability layer and drainage wells drilled to a depth of 30-40 m in the lower high permeability layer to intensify the drainage process. Well boosters allow drain spacing to be increased by 2-6 times. Geological boreholes indicate that natural conditions adequate for the establishment of the combined drainage occur in various areas of the Mesopotamian Plain.

   Vertical drainage (i.e. drainage by wells only) was studied comprehensively by Haddad et al. (1976) in the experimental field at Fudhaliya to the NE of Baghdad. Based on interpretation of aquifer tests, they concluded that wells could be used to drain groundwater on a large-scale if hydrogeological conditions permit. Vertical drains are cheaper to construct but more expensive to operate and maintain than horizontal drains.

   The upper parts of the Mesopotamian Plain are favourable for groundwater exploitation. In many areas discharge of wells or transmissivity coefficients are reported to be high. The upper aquitard occurring beneath most of the plain protects the lower groundwater body. However groundwater quality is a serious problem. Most of the groundwater is too saline for use as potable or even irrigation water. However, locally better quality groundwater was found. In some "close-to-river-zones" influent seepage from rivers or irrigation canals occurs during pumping. Storage of groundwater, compared to surface water storage in artificial reservoirs, allows better water quality protection and prevents evaporation losses. The issue of groundwater storage is very complex; hydrogeological and hydrochemical data, necessary for its adequate solution, are very scarce. There are important differences between the two stages of groundwater development in "close-to-riverzones" (Fig. 19-12): Before pumping, deterioration of groundwater quality occurs; weak influent seepage of freshwater only occurs near influent streams or canals. After groundwater levels are lowered in "close-to-river-zones" important influent seepage from rivers occurs under favourable hydrogeological conditions, substantially improving groundwater quality. Lowering of groundwater levels by pumping could be followed by important changes in hydrogeological and hydrochemical conditions. Evaporation and/or transpiration of groundwater will cause salt accumulation in soil. However once most of the accumulated salts are leached by irrigation activities and precipitation (and removed in pumped groundwater), downward percolation of better quality water to groundwater bodies should occur. However salt-water encroachment from adjacent and deep-seated aquifers into the pumped groundwater body may take place.

   Artificial recharge can also improve groundwater quality. An increase in the number of ameliorating processes and weakening of some deteriorating ones can be expected during pumping in "close-to-river zones". Under suitable natural conditions, following sufficient pumping, fresh water may extend beyond the "close-to-river zone". Technical plans for groundwater development require specifications for well spacing, depth of wells, screened intervals, and estimates of discharges, draw downs, changes in water quality and extension of fresh-water zones. These plans must be based on continuing regional hydrogeological investigations and case studies. Parsons (1955a, b) and Krasny (1982e) assessed potential groundwater development along an influent river (the Tigris in the Tikrit-Baquba region). Parsons estimated a recharge of 190 L/s from the river per kilometre, and a total safe yield of 38 m^3/*s*

pumped within a belt 100 km long and 7.5 km wide on both river banks. These values may be overestimated because of the high transmissivity value *(1200 m^2/d)* used for the calculations. A more likely transmissivity along the Tigris is 50-70 m^2/d. Krasny (1982c) presented more conservative estimates of total possible pumping of up to 2 m^3/s (fed by direct recharge) and about 16 m^3/s of induced resources along both banks of the Tigris within a belt 100 km long.

The composition of surface waters and of waters from handdug wells (and exceptionally water from other water wells) often indicates a low sodium hazard.

19.5.4 Aquifer systems of alluvial fans (Mandali-Badra-Tib region)

19.5.4.1 Extension of the system and its general features

Alluvial fans border the Mesopotamian Plain in different areas. Most of them are hydraulically connected to the Mesopotamian Plain system except the series of fans of Mandai-Badra-Tib which are hydraulically separated from the aquifers of the Mesopotamian Plain by very low permeability sheet-run-off deposits. They are thus defined as independent aquifer systems. The lower distal parts of these aquifer systems lies within Iraq while the proximal higher parts mostly lie within Iran.

Due to their importance for groundwater supply, these alluvial fans were studied by Parsons (1955a, 1957d} and Hassan (1977). Mac Donald et al. (1969) presented numerous reports dealing with land reclamation issues of this system. Hydraulic evaluation of the Bakhtiari Formation was carried out by Alsam (1976) in the Tib area.

19.5.4.2 Geological setting, spatial distribution of hydrogeological bodies, transmissivity and permeability of rocks

The Mandali-Badra- Tib alluvial fans occur along the foot of mountains along the Iraqi-Iran frontier in S Iraq. These coalescing alluvial fans comprise gravelly and sandy sediments deposited by braided rivers. They overlie the Injana, Mukdadiya and Bai Hassan formations which outcrop in the mountainous area along the state frontier (Fig. 19-14).

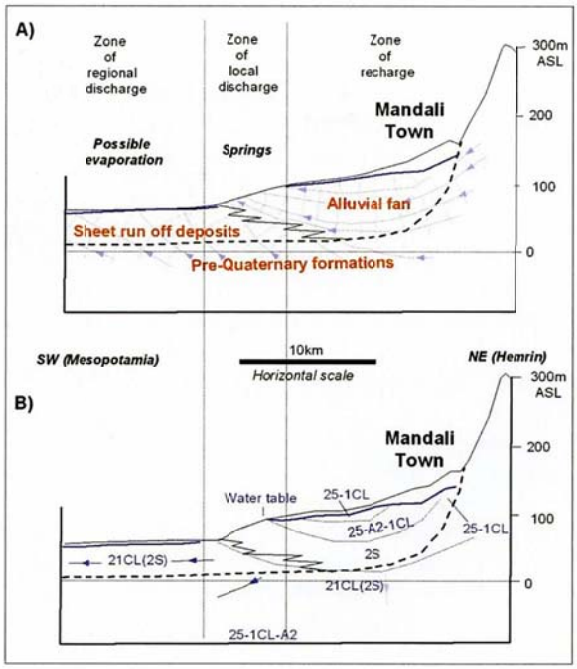
Based on drilling results the maximum thickness of the sand-gravel fan deposits reaches 100m near Mandali and 65 m near Badra. In other areas data on the fan thicknesses are unavailable. Fan deposits consist of lenticular bodies of poorly sorted fine- to coarse-grained sand and gravel (mostly composed of limestone pebbles) with varying amounts of clay. Correlation of layers is difficult because of rapid lateral variations in lithology. However two regionally extensive clay layers were identified near Badra (Hassan et al., 1977). One separates the Quaternary deposits from the Bai Hassan Formation; the other acts as an aquitard separating the upper and lower parts of the fan, giving rise to two aquifers: an unconfined upper aquifer and a confined lower aquifer.

Hydrogeologically, the fans are complicated aquifers due to their stratification, variable lithology and uneven recharge. Aquifers occur close to the mountain range where the fan deposits are coarsest. The highest transmissivity of 10002000 m^2/day occurs where the aquifer thickness is high. Y indices of >6.5 were found in some wells near Bagsaya. The transmissivity coefficient is about 400-500 m^2/d in the Mandali area and in the Badra-Zurbatiya area it is typically *300-500* m^2/d, and averages 336 m^2/d (Hassan et al., 1977). Elswhere the Y index is 5.5-6.5, corresponding to a transmissivity of 50-300 m^2/d. Lower transmissivites with Y indices <5.5 probably prevail locally for example between Jassan and Karmashiya and in the E of the region where the

transmissivity is <40 m^2/d.

The hydraulic conductivity is 5-25 m1day. Salinity is about 1 g/L where groundwater flow is rapid and increases to >5 g/L where flow is slow. The specific capacity of wells in the fan deposits are 1-5 *L/sec/m* and the well discharge is 5-> 20 L/s. Specific yield was estimated at 0.16-0.21.

Fig. 19-14: Schematic hydrogeological and hydrochemical sections through the Mandali alluvial fan (after Krásný 1981b)



19.5.4.3 Groundwater flow (extension, depth, recharge, through flow, discharge)

Groundwater replenishment originates from river-influent seepage where river courses run across elevated outcrops of alluvial fan deposits. In other areas groundwater bodies are fed mostly by precipitation. During wet seasons intensive influent seepage from the Galal Gangir was proved in the Mandali area by Parsons (1957d). Consequently, the Galal Gangir flows only in the marginal portion of the fan. A similar situation occurs in part of the Galal Badra watershed area (Hassan et al. (1977). The same phenomenon may occur in other coalescing alluvial fans (e.g. Galal Tursaq, Galal-i- shur-o- shirin). Ground water flow regional from elevated areas of coalescing alluvial fan to the or to the S. The piezometric surface varies from about 100 m ASL in recharge zones to 25 m ASL in discharge zones. Groundwater discharge occurs in the distal portions of the alluvial fans by springs, by the drainage effect of rivers, where the groundwater level approaches the ground surface, by evaporation and transpiration, or anywhere by groundwater withdrawals (Fig. 19-12).
In the Mandali alluvial fan groundwater is discharged by springs or by groundwater seepage towards the surface and afterwards by evapotranspiration as there is no river incised into the fan deposits. The depth to groundwater level in upper parts of the fan is locally >35 m. The groundwater level in the fan was measured continuously during a 18 month period by Parsons (1957b) who noted that the largest fluctuations (» 10 m) were controlled mainly by recharge from Galal Gangir in the upper portion of the fan (recharge zone) and become progressively less toward the zone of springs.

Water levels in drilled wells are usually lowest in January and February. Later the Galal flow increases; groundwater levels rise rapidly and fairly uniformly until April and May when the rate of rise decreases. Highest water levels are reached in June or July. Water levels in shallow hand dug wells are lowest in November and December and then increase until April or May when generally the highest levels are reached. Few data are available to assess longterm groundwater level fluctuation except near Mandali for the period 1951-1957 when water levels declined, forcing lowering of pumps and abandonment of some drilled wells. Older hand-dug wells were either deepened or abandoned.

19.5.4.4 Groundwater quality

The groundwater of the coalescing alluvial fans has relatively low salinity, especially compared with the highly mineralised groundwater of the neighbouring Mesopotamian Plain. The salinity is usually 1-7 g/L, increasing from NW to SE, (from the Mandali to the Tib areas). This increase in salinity is accompanied by changes in chemical composition of the groundwater. For waters with lower salinity basic and expressive basic calcium sulphate types are typical while in highly mineralised waters the sodium-chloride type prevails. These differences in chemical composition and salinity are mostly caused by different natural conditions (geology, hypsornetry and climate) and by a gradual deterioration of groundwater quality due to locally excessive water abstraction.

In the Mandali and Badra-Zurbatiya areas the salinity and chemical composition of the groundwater is influenced by the quality of the recharging water (mostly of river origin). In the Mandali area good recharge occurs from the Galal Gangir (Fig. 19-13). Better quality groundwater results from fast groundwater flow enabling leaching of aquifers and removal of salts. These conditions occur within the Mandali and the Badra-Zurbatiya alluvial fans where groundwater is discharged by spring and by the river, in most spring and band dug well have salinities of 1-2 g/l salinities in drilled well are lower 1-1.5 g/l (parsons 1957b and d).

In the Badra-Zurbatiya area the salinity is generally higher than in the Mandali alluvial fan, usually up to 2-3 or even 4 g/L. This may be due to higher annual precipitation in the Mandali area (almost 300 mm) than in the Badra area (about 100 mm). In the elevated areas between Zurbatiya and Tursaq (Kulak-i-Buzurg Mountain) outcrops of the Fatha (Lower Fars) Formation contaln evaporites. Dissolution of these evaporites may cause high salinities in groundwater, for example in the salt spring that issues about 10 km NE of Zurbatiya with a salinity of 263 g/L.

To the SE, in the Karmashiya-Bagsaya area the salinity is usually 2-3.5 *g/L* and in the Tib area it is 4-7 g/L (locally reaching 11 *g/L).* However in some parts of this area groundwater salinity is significantly lower, for example west of Bagsaya, NE of Ali Al-Gharbi, and SE of Tib. In some of these areas a confined aquifer where groundwater was tapped at a depth of 30-60 m, and a deeper unconfined aquifer below 50-65 m occur. The groundwater in these aquifers is of good quality, sometimes better than surface water in the main rivers (Tib etc.).

19.5.4.5 Groundwater use

Safe yield assessments for the whole Mandali-Badra area are 5.5-8.5 m^3/s (Parsons, 1955a, b; Smirnov et al., 1981). Subsequent more detailed investigations showed that safe yields assessments of 370 L/s in the Mandali alluvial fan (Parsons 1957) and 256 L/s in the Badra-Zurbatiya fans (Hassan et al. 1977) are more reliable. In the foothill area to the SE, which has lower precipitation, safe yields estimates may be much lower.

Amelioration of the groundwater balance in the Mandali area by artificial recharge through surface water spreading and by supply wells was investigated by Parsons (1955c), but found to be very difficult and prohibitively expensive.

19.5.5 Aquifer system of the Foothill zone (Foothill Aquifer System)

19.5.5.1 Extension and general features

The Aquifer System of the Foothill Zone covers a vast NWSE trending area of approximately 37000 km-. Jabal Hemrin and Jabal Makhul form the SW boundary of the System. To the E and in Central Iraq the area extends up to the border with Iran. In N and NE Iraq the N and NE limits follow an important structural boundary dividing the Foothill and High Folded zones.

The System is the most promising region for large-scale development in Iraq. It has been studied by hydrogeologists and people responsible for water management. Regional hydrogeological studies were performed by Parsons (1955c, d and e and partly a and b), Araim and Hameed (1980) and Alsam and Hanna (1983). Hydrogeological synthesis of the whole Aquifer System was carried out by Krasny (1983a). Extensive areas adjacent to the High Folded Zone were studied by Stevanovic and Markovic (2004). The State Organisation for Ground Water collected large amount of data from hand-dug and drilled wells.

The major part of the Aquifer System is characterised by a plain controlled by broad synclinal structures and linear hilly belts following anticlines and dissected by river valleys. Elevation increases from <100 m ASL near Diyala River in the SW to > 300 m in the NE. Mountainous topography occurs locally, for example at Jabal Sinjar and Jabal Qara Chauq where the elevation may reach 1000 m ASL. The System is characterised by a high drainage density due to high rainfall and trellis drainage development.

Main rivers form axes of surface water drainage (especially along their lower reaches) and of groundwater discharge zones. The main ground water divides usually conform to surface water divides especially in the elevated parts of the Foothill Zone where groundwater discharge occurs along surface streams and where rivers usually have an effluent character. Important rivers traverse the area (from SE to NW): the Diyala River with its main tributary the Narin Chay; the Adhaim River with its main tributaries the Tuz Chay (Aq Su), Tawuq Chay, Qadah Chay (Khassa Su) and Zughaytun Chay; the Lesser Zab River; and the Greater Zab River with its main tributaries the Khazir and Gomel Rivers. These rivers flow into the Tigris except for the Diyala and Adhaim that empty their water beyond the SW boundary of the System in the Mesopotamian Zone. The Tigris traverses the area from N to S, entering it NW of Mosul and abandoning it at AL-Fatha pass between Jabal Hemrin and Jabal Makhul.

The climate of the area is semi-arid with hot summers and mild to cold winters. Rainfall occurs

during autumn, winter and early spring months, with no precipitation during summer and early autumn. In elevated areas the mean precipitation is 600-800 mm/year. In the SW part of the zone the minimum precipitation is about 200 mm/year.

The main populations centres are Mosul, Erbil and Kirkuk cities but numerous towns are located above this aquifer system.

19.5.5.2 Geological setting, spatial distribution of hydrogeological bodies, transmissivity and permeability of rocks

The Foothill Aquifer System covers most of the area designated as the Foothill or Low Folded Zone which comprises long narrow anticlines (trending NW-SE in NE Iraq and E- W in N Iraq) of different amplitude with outcrops of the gypsum-bearing Fatha (Lower Fars) Formation. Older carbonate formations outcrop in cores of some anticlines near Mosul, and in Qara Chauq and Sinjar. These anticlines are often separated by broad synclines containing thick molasse of the Mukdadiya (Lower Bakhtiari) and Bai Hassan (Upper Bakhtiari) formations and Quaternary sediments. This geological setting strongly influences the hydrogeology of the area.

The hydraulic parameters differ due to variations in lithology and aquifer thickness. Clay beds hinder direct rainfall recharge into underlying permeable layers. Differences in lithology often cause semi-confined to confined conditions.

The regional distribution of transmissivity within the Foothill Aquifer System was studied by Krasny (1983a), based on statistically processed available data on transmissivity in 39 areas covering the whole aquifer system. The principle of the data processing used assumes that the transmissivity populations (samples) have a lognormal probability distribution (compare Krasny 1993). The logarithmic expression of transmissivity (the index of transmissivity "Y") was used to convert from a log-normal distribution to a normal one, to facilitate processing.

To process transmissivity data in the Foothill Aquifer System only results from drilled wells were used, as hand dug wells were not hydraulically tested. A fairly dense network of drilled wells with depths of about 80-100 m (sometimes >200 m) exists. Pumping test data obtained from balling were not included because of their low reliability. Drawdowns equal to or <0.2 m were also neglected since they often resulted in unrealistically high transmissivity values (index Y usually >7.0, sometimes >8.0).

Despite the low reliability of pumping tests, data processing enabled important geological and hydrogeological conclusions to be drawn as summarized below:

1. The prevailing transrrussrvity in most statistically treated areas ranges from tens to hundreds of m^2/d (medium to high transmissivity).
2. Aquifer transmissivity often increases in the central parts of the synclines filled by the Bal Hassan Formation, for example in the syncline between Jabal Gilabat and Jabal Qumar and in the Makhmur Plain. Similar increases in transmissivity occur in the central part of the syncline between the Kirkuk and Qara Chauq structures and close to the Lesser Zab River. The decrease in transmissivity along the flanks of anticlines is due to exposure of the less transmissive Fatha and Injana formations. The transmissivity of the Mukdadiya Formation (exposed in synclines) reaches 100-230 m^2/day; the transmissivity of the Injana Formation is only 1-10 m^2/day.

3. Aquifer transmissivity often increases along river courses due to the accumulation of coarse Quaternary deposits which form promising aquifers, for example along the Zughaytun Chay, Khirr Dabli and Qadah Chay rivers.
4. Aquifer transmissivity may also increase along buried river channels like the Aq Su (Tuz Chay) River; these buried channels sometimes cross anticlinal structures.
5. Relatively high transmissivities can occur around confluences of rivers, for example around the confluence area of Nahr Chinchal and Narin Chay, and of the Tuz Chay and Adhaim. The transmissivities of the upper water table aquifer around the confluence of the Khazir and Gomel rivers reaches 7000 m^2/d decreasing to 2000 m^2/d away from it (AL sam and Hanna, 1983).
6. Transmissivity may be high in buried alluvial fans.
   Possible examples occur near Kirkuk, where the Qadah Chay passes through the Kirkuk Structure and in the syncline to the Sw. Another example is the Erbil Plain where a conspicuous N-S belt of high transmissivity exists, occurring in the central part of the plain, possibly indicating a complex system of buried alluvial fans.
7. In the treated sampled populations, the depth of drilled wells does not seem to significantly influence the transmissivity. Many shallow wells have higher transmissivity/specific capacity than deeper nearby wells due to a reduction in permeability with depth. The depth of most water wells is 75-150 m. Their discharge can vary under favourable conditions from 10 to 50 L/sec. In groundwater discharge zones overflowing wells occur in Khazir-Gomel, Erbil, Qara Tapa areas and near Mosul.

19.5.5.3 Groundwater flow (recharge, through flow, extension, depth, discharge) of the sub-systems of the Foothill Zone

Regional groundwater flow prevails in the Foothill Aquifer System, mostly with well-defined regional discharge zones along the main left-bank tributaries of the Tigris River such as the Khabour, Greater and Lesser Zab, Adhaim and Diyala, and their own tributaries. Discharge by springs is rare within the Foothill Zone except near Mosul where confined sulphurated waters seep to the surface on both flanks of the Tigris River.

Depth to groundwater often varies significantly over short distances due to the variable topography of the area and may exceed many tens of metres (Fig. 19-15). Rivers form important influent or effluent hydraulic boundaries of some aquifer sub-systems, depending on the piezometric surfaces of neighbouring aquifers.
The Foothill Aquifer System was originally divided by Krasny (l983a) into aquifer sub-systems with particular groundwater flow conditions controlled by hydraulic conditions at their boundaries. This division was modified based on studies by Stevanovic and Markovic (2004) who defined ten sub systems (Fig. 19-16).

In addition to the hydraulic boundaries along river courses, structural geological elements (anticlines, faults) often form regionally important hydrogeological boundaries. Some discontinuities are of first order importance. Long anticlines may act as barriers forcing groundwater to move almost perpendicular to the regional direction of groundwater flow (towards S or SW). Some hydraulic boundaries are represented by groundwater divides which follow piezometric highs. In elevated areas of the aquifer system groundwater divides are usually

pronounced. In the synclinal plains, groundwater divides are much less pronounced and can be easily influenced and shifted by human activities (for example irrigation and heavy groundwater pumping). Understanding smaller scale hydrogeological discontinuities (for example alternations of permeable and impermeable layers, and the occurrence of (fissured zones) may be of great importance in solving local hydrogeological problems.
The aquifer sub-systems represented in Fig. 19-16 are:

A _ Zakho Sub-system is an almost closed E- W trending intermountain basin filled by over 2000 m of clastic sediments of the Injana, Mukdadiya and Bai-Hassan formations and Quaternary terrace deposits. It is limited in the Sand N by ridges of the Fatha, Pila Spi and older formations. Groundwater flows towards the main river Khabour and its tributaries. The eastern extension of the Zakho Sub-system passes into the narrow Amadiya basin which is in the catchment area of the upper reaches of the Greater Zab River. The sub-system is actually located within the High Folded Zone but its hydrogeological character is similar to the aquifers of the Foothill Zone.

B _ Khazir-Gomel Sub-system is bounded in the N and S by High Mountain ridges (Jabal Aqra, Jabal Maqlub and Jabal Bardarash). Its western boundary follows the groundwater divide close to Ain Sifni. In the E, the Subsystem comprises parts of the Aqra- Bardarash and Harir basins, as defined by Stevanovic and Markovic (2004) and is mostly bounded by older rocks belonging to the neighbouring Taurus-Zagros Groundwater Province. The Sub-system is traversed by the Khazir River, its tributary the Gomel River and by the middle reaches of the Greater Zab River. The main zone of groundwater discharge occurs in the confluence area of the Khazir and Gomel rivers and along the Greater Zab River. Overflow was encountered in many deep drilled wells. In some areas near permeable limestone outcrops of the adjacent Taurus-Zagros Province, clastic aquifers are fed by ascending water from underlying karstic aquifers.

C _ *Alqosh Sub-system* comprises the western part of the Foothill System, to the west of the Khazir-GomelGreater Zab and Erbil Sub-systems. In the E, outcrops of the Fatha and Pila Spi formations and occasional anticlinal ridges divide the sub-system into separate portions. Its hydrogeological character is thus similar to the adjacent Jezira Region. In the westernmost part of the sub-system (within the Small basin as defined by Stevanovic and Markovic, 2004) containing clastic sediments of the Injana Formation and terrace sediments, regional groundwater flow is mostly towards the S. The water table depth is often 10-20 m and in places exceeding 40 m.

D _ *Erbil Sub-system* comprises the catchments of the lower reaches of the Khazir and Greater Zab Rivers, forming mostly extensive plains to the south of Jabal Bardarash and Jabal Pirmam, for example the Erbil Plain. Its SW boundary is the NW extension of the Kirkuk anticline; the Wand E boundaries are represented by groundwater divides. Groundwater typically flows towards the Greater Zab River, where most of it is discharged, and partly towards the Khazir River. The high discharge of the Greater Zab River was proved by base-flow records from 1970 to 1973 between the two gauging stations, Irfaz and Eski Kelek, situated some 20 km apart (Haddad et al. 1973). The observed increase in the river flow of >50 m^3/s must be due to groundwater discharge. Differences in the regional hydraulic gradient in areas Wand E of the town of Erbil probably reflect transmissivity differences and structural conditions (Demir Dagh region). The depth of

intensive groundwater exchange, guaranteeing good quality of water, is not known. However estimates of thickness of clastic sediments in the centre of the Sub-system of >850 m are promising. The water table is at 25-30 m or deeper.

E _ Altun Kupri -Koysanjaq Sub-system belongs to the catchment of the upper reaches of the Lesser Zab River. It is bounded on the SW by the Kirkuk anticline and on the NE by the Taurus-Zagros Groundwater Province. The NW and SE boundaries follow poorly pronounced groundwater divides limiting the catchment. The main recharge occurs in the elevated NE part of the subsystem. Groundwater flows from there (and partly from the Kirkuk Structure) towards the discharge area along the Lesser Zab River and its confluences. The regional discharge zone of the whole sub-system occurs along the Lesser Zab River at Altun Kopri. The water table is often many tens of metres deep, and in places exceeds 50 m.

F _ Dibika Sub-system is represented by a NW-SE trending syncline of the Mukdadiya and Bai Hassan Formation clastics and is bounded by the two ridges along Jabal Qara Chauq and Jabal Batiwa in the SW and along the Kirkuk and Quwair anticlines in the NE. A groundwater divide between the catchments of the Lesser Zab and the Adhaim Rivers confluences forms the SW boundary of the sub-system. Groundwater flows first from the flanks of the syncline to its axis and then along prevailing structural features to the main discharge zones to the NW into the Greater Zab River and from both sides to the Lesser Zab River in the SE. The water table depth is >50 m close to the groundwater divide in the centre of the Sub-system, decreasing towards the regional discharge zones.

G - *Makhmur Sub-system* forms a triangular-shaped area bounded by Jabal Qara Chauq in the NE, the Tigris River in the W and by the groundwater divide between the Lesser Zab and the Adhaim Rivers catchments in the SE. In the southernmost part, the boundary of the Subsystem is the ridge of Jabal Hemrin. Due to exposure of the low permeability Injana Formation clastics along the Tigris River the western boundary appears to be less prone to influent seepage during possible groundwater pumping in "close-to-river" areas than the lower reaches of the Lesser Zab River. Groundwater generally flows from NE to SW; the direction of flow gradually changes near both main rivers. South of the Lesser Zab River the discharging effect of the river causes groundwater flow to the Wand SW. The water table is often at 19-30 m in the Qara Chauq foothills but becomes shallower towards the Tigris River.

H - Tawuq Sub-system comprises the lower reaches of the Adhaim River catchment to the NE of the Jabal Hemrin. Low amplitude groundwater divides of neighbouring catchments form the NW and SE boundaries of the subsystem, towards the Lesser Zab and the Diyala Rivers respectively. Its NE boundary is complex and controlled by a series of en echelon low anticlinal NW-SE trending ridges. From N to the S these are Kirkuk, Tawuq and Pulkhana (Kifri) anticlines. The extensive plain to the SE and S of the town of Kirkuk has a prevailing southwesterly regional groundwater flow.

In addition to direct precipitation, groundwater bodies are fed by influent seepage from the streams originating beyond the NE boundary of the sub-system. The most intensive recharge of this type takes place on the SW slopes of the mountain ridges bounding the sub-system in the NE. Piezometric highs follow some of the surface streams (e.g. the Qadah Chay). The water table depth in the zones of influent seepage may exceed 30 m even near the main streams, because

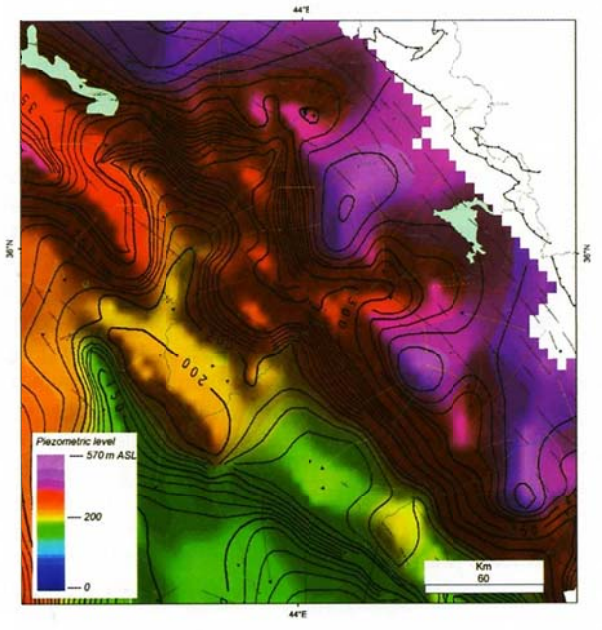
recharge from streams is insufficient due to the low permeability of the upper part of the aquifer and the high hydraulic diffusivity of the saturated part of the aquifer. After percolated water has reached the water table it may be dispersed quickly.

Locally in the sub-system, heavy groundwater pumping may cause groundwater levels to decline. The main natural regional groundwater discharge zone follows the Zughaytun Chay Valley which runs parallel to Jabal Hemrin as far as the Adhaim "narrows" in Jabal Hemrin. The water table approaches the ground surface there; some drilled wells even overflow. Some of the groundwater can thus be lost by evapotranspiration.

I- *Chemchamal-Klar Sub-system* is an extensive area represented by the upper reaches of the Adhaim River catchment and the Sirwan (Diyala) River between the Taurus-Zagros Groundwater Province in the NE and the Kirkuk and Kifri structures in the SW. The groundwater divide between the Lesser Zab River and the Adhaim River catchments forms the NW boundary, while in the SE the system extends to the Iraq-Iran border. Large parts of the Chemchamal, Sangaw-Bazian and Kalar basins, as defined by Stevanovic and Markovic (2004), also belong to the Sub-system. Groundwater flows regionally towards the SW; the flow direction is often altered near effluent perennial rivers. Important groundwater discharge zones occur along the anticlines bordering the sub-system in the SW, where rivers leave the area.

J - ***Qara*** *Tepe-Khanaqin Sub-system* belongs to the Diyala River catchment between the Kifri anticline in the NE and Jabal Hemrin South in the Sw. Jabal Gilabat and its SE extension, the Naodoman anticline, divide the subsystem into two areas of independent groundwater flow. Within these areas groundwater flows from elevated flanks to the centres of synclines, and ultimately into the Diyala River to the SE. In the SE part of the subsystem the Naft-Khana anticline separates the two areas near Khanaqin and Jalawla forming a groundwater divide. In both areas groundwater flows to the Wand is discharged into the Diyala River.

Fig. 19-15: Piezometric level of groundwater of the Foothill Zone



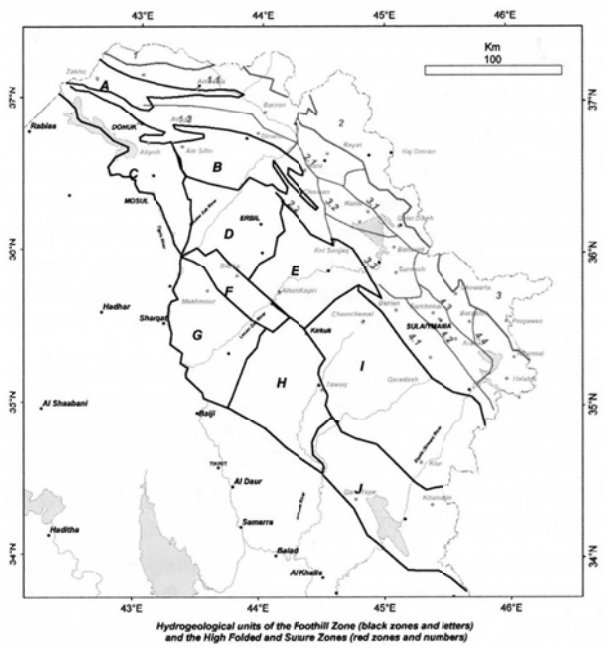


Fig. 19-16: Aquifer sub-systems of the Foothill and High zones (modified from Krásný 1983a)

19.5.5.4 Groundwater quality

Within the Foothill Aquifer System, from north to south, the salinity increases from <0.5 g/L to 6 g/L and locally> 10 *g/L,* and the chemical composition changes from a prevailing calcium (-magnesium)-bicarbonate type to calcium (-magnesium)-sulphate type. Other water types occur in the Jezira region and along the SW boundary of the Foothill Aquifer System.

The boundary between the two main hydrochemical types follows the Kirkuk Structure and other anticlines to the south, for example the Tawuq and Pulkhana (Kifri) anticlines. Changes in groundwater chemical composition may be either abrupt or gradual depending on structural geological factors and other natural conditions controlling groundwater recharge and discharge. Thus within the Foothill System two different hydrogeological regimes can be distinguished here designated as "unblocked" and "blocked".

"Unblocked" areas of the Aquifer System are not separated from the highly elevated Taurus-Zagros Groundwater Province by any prominent structural element. However blocked areas suffer from inadequate recharge as they are structurally separated from the best groundwater sources. Recharge from influent streams may change prevailing chemical composition and lower salinity even in blocked areas. Local anomalies of groundwater chemical composition both within unblocked and blocked areas can typically be caused by differences in chemical composition of their respective water-bearing rocks.

In general, groundwater with low salinity and of the Ca (-Mg)-$HC0_3$ type occurs where areas are unblocked by prominent structural elements, where there is sufficient fresh water recharge, and where there is adequate discharge enabling leaching of aquifers allowing continuous disposal of salts and preventing retarded flow or stagnation.

Groundwater within the Foothill Aquifer System is generally of good quality. However water from shallow wells, located near human settlements or in large cities, is very often contaminated either chemically or bacterially. This is mostly a consequence of untreated sewage water seeping into the ground.

The compilation of the hydrochemical conditions was mostly based on chemical analyses of groundwater from wells drilled by the State Organization for Ground Water. Although data are very scarce in some areas, the groundwater quality can be characterised in the upper zone of the System to a depth of about 100-150 m as many wells were drilled to a depth of 150 m or deeper. Other available data (chemical analyses mainly from hand-dug wells and springs) were also used. Simple probability treatment of available data was carried out to define the expected salinity and the probable prevailing chemical composition of groundwater.

A short description of hydrochemical conditions of the Foothill Aquifer System follows its particular Sub-systems as defined in section 19.5.4.3. The groundwater in the Zakho Sub-system (A) is typically of low salinity with prevailing Ca (-Mg)-$HC0_3$ type. Within the Khazir-Gomel Sub-system (B) the salinity is usually 0.2-0.4 g/L. Along the Sand W boundaries of the sub-system it increases slightly but is only rarely >0.65 g/L. The prevailing chemical type is calcium (-magnesium)-hydrocarbonate, usually expressive to pure. Groundwater of the Alqosh Sub-system (C) is often influenced by the presence of Fatha (Lower Fars) Formation sediments occurring in extensive areas where the salinity and sulphate content are high. **In** the W part (Sumall basin), groundwater quality is better and often suitable for human consumption.

The vast Erbil Sub-system (D) is characterised by low salinities (usually <0.3-0.4 g/L) and Ca (-Mg)-$HC0_3$ water type, little expressive to pure. In some parts of the subsystem a regional increase in salinity and a change in the prevailing chemical composition of groundwater was observed, for example NE of the Kirkuk anticline (NE of Dibika) where the salinity often reaches 0.6-0.8 g/L and sometimes exceeds I g/L. Transient and mixed Ca (-Mg) HC03 type occurs there, locally changing into transient or little expressive Ca (-Mg)-S04 type. This regional anomaly may be explained by supplementary groundwater recharge from the Kirkuk Structure and retardation of groundwater flow. A similar regional increase in salinity is evident SW of Demir Dagh. The chemical composition of groundwater, however, varies from transient or mixed Ca (-Mg)-S04' Na-S04, Ca (-Mg)-$HC0_3$ and even Na-Cl types, probably due to the presence of an important regional discharge zone. Thus in addition to discharge of groundwater usually occurring in the upper hydrochemical zone of the Subsystem, deeper hydrochemical zones are also partly discharged there. West of the Khazir River, the salinity is typically higher, usually 1-3 g/L.

In the Altun Kupri-Koysanjaq Sub-system (E) groundwater with salinity of 0.2-0.4 g/L is common almost everywhere. The salinity is rarely > I g/L. Shallow groundwater is usually of the Ca (-Mg)-$HC0_3$ type, usually little to very expressive and only replaced by the transient Ca (-Mg)-S04 type locally. Deep wells can tap water with high salinity with increased contents of sulphates, chlorides and sodium.

In the Dibika Sub-system (F) the salinity is usually 3-4 g/L but where no surface water recharge occurs it reaches 5-6 g/L. Such areas lie between Jabal Qara Chauq and Quwair anticlines where the groundwater discharges into the Greater Zab River and also S of Dibis (where discharge into Lesser Zab occurs.). The prevailing chemical type is Ca (Mg)-S04' usually transient to little expressive. Salinities <I g/L characterise the area SE of Dibika where groundwater recharge and

large hydraulic gradients occur. The prevailing chemical type is transient to little expressive Ca (-Mg)-S04' **In** some areas Na-S04 (usually transient) type is common. Exceptionally Ca (-Mg)-$HC0_3$ type (in recharge zones) and Na-Cl types of waters (in discharge zones) occur.

The Makhmur-Hawija Sub-system (G) is characterised by salinities of 2-4 g/L. **In** some places groundwater with salinity >5 g/L occurs. Salinities <I g/L occur exceptionally in areas where fresh water is recharged close to the Lesser Zab River. Transient to very expressive Ca (-Mg)-S04 type prevails only in areas of fresh water recharge and may be exceptionally substituted by the Ca (-Mg)-$HC0_3$ type.

The Tawuq Sub-system (H) is characterized by high salinity, very often 3-6 g/L (and in some places> 10 g/L) except for areas fed by surface water from influent rivers and wadis where the salinity may be <I g/L. Thus, several extensive groundwater bodies of adequate quality occur along the Qadah Chay and its left-bank tributary in the Lailan- Badawa syncline as far as Taza Khurmatu, in the area fed by the Tawuq Chay and Quri Chay south of Tawuq, and along the Tuz Chay (S and SW of Tuz Khurmatu). Groundwater with salinity of 1-2 g/L occurs very locally. Within areas with intensive surface water recharge the Ca (-Mg)-$HC0_3$ transient-little expressive water type occurs. Throughout the remaining Sub-system transient to little expressive Ca (Mg)-S04 type prevalls. **In** the zone of regional groundwater discharge along Zughaytun Chay transient Na-Cl type occurs. **In** some areas concentrations of Na-S04 type (usually transient one) were observed.

In the Chemchamal-Klar Sub-system (I) particular blocked areas are divided by several anticlines and have groundwater with relatively high salinity. Better quality water is present in the SE part along the Sirwan (Diyala) River. Deep wells contaln saline water with high calcium, sodium and chloride concentrations derived from the evaporites of the Fatha Formation. Water can also be contaminated by oil and dissolved H2S gas (Stevanovic and Markovic 2004). Sometimes even shallow wells have water with dissolved H2S gas (7-9 ppm) as in the Kifri-Sarqala area.

Within the Qara Tepe-Khanaqin Sub-system (1) high salinity occurs in parts that are blocked by structural elements so that no fresh water from mountain areas can recharge respective aquifers. Such conditions occur in the N part of the sub-system W of the Diyala River where the salinity is often 5-7 g/L, locally reaching 11-13.5 g/L. Fresh groundwater bodies occur in the NW part where water from the Tuz Cha and Narin Chay, and locally from the Kursah Chay recharge the aquifer. The water derived from the Narin Chay fresh water body extends as far as the SE limit of the area to the Diyala River. The prevailing water type is transient Ca (-Mg)-S04 and only exceptionally substituted by transient Ca (-Mg)-$HC0_3$ type or by Na-CI type. To the east of the Diyala River low salinities (typically <I g/L) occur close to the river especially in the central parts of the two synclines separated by the Naft-Khana anticline where an area of high transmissivity occurs. Transient or little expressive Ca (-Mg)-S04 and Ca (-Mg)-$HC0_3$ types prevail there. The salinity generally increases towards the margins of both synclines. However, it does not usually exceed 3.0 g/L. Pure Ca (-Mg)-S04 type prevail.

19.5.5.5 Present-day groundwater use, possibilities of future groundwater supply

The Foothill Aquifer System is the most promising hydrogeological unit for regional scale groundwater development in Iraq. In areas where the prevailing transmissivity is high to very high large quantities of groundwater can be abstracted. In the N and NE portions of the system, groundwater recharge is 2-5 L/s km^2 and is locally higher due to natural influent seepage from rivers. Pumping in "close-to-river zones", where induced groundwater resources are formed, can increase the recharge. Groundwater quality in many areas is adequate for water supply as potable and irrigation water.

However despite of all these favourable conditions and due to high transmissivity, excessive groundwater withdraw could easily deplete groundwater resources leading to a regional decline in the piezometric surface. Therefore, knowledge of the rate of groundwater recharge is of vital importance for future groundwater development assessment. Mean annual recharge from direct precipitation in the Foothill Aquifer System was first estimated by Parsons (l955e) based on data available on precipitation and adjusted temperature and evaporation. The difference between precipitation and basin loss results in a total runoff of about 90% of the mean annual groundwater recharge. The mean annual recharge was estimated as 1-1.8 mm in the plains S of the Kirkuk Structure
(about 0.03-0.06 L/s km-) and 20 mm in Erbil Plain (about 0.6 L/s km-'). Over the hills and mountains the annual recharge was estimated to increase to the N and NW (with increasing elevation) in a wide range of 3-43 mm (about 0.09-1.37 L/s km-). The highest values were expected by Parsons to occur in mountains N of Chemchemal and E of Erbil as 81-83 mm (about 2.6 L/s km-').
Long-term recharge ("dynamic resources") in the Khazir Gomel basin were later assessed by Alsam and Hanna (1983) to be about 3.8 L/s km^2 for the first (upper) aquifer and about 1.85 L/s km^2 for the second (artesian) aquifer. These estimates are considerably higher than those previously made by Parsons.

Groundwater resources from direct precipitation are important and can cover water consumption in areas where no surface water is available. In areas traversed by rivers, recharge from rivers may be the major groundwater source, both under natural conditions and under artificial ones when pumping may cause influent seepage into areas near a river. As transmissivity in many parts of the Foothill Aquifer System is high, the possibilities of groundwater development in areas along rivers may be good. Influent seepage possibilities from rivers is strongly influenced by the permeability of deposits in the upper part of the layered sequence and by the permeability of the river bed itself which could be clogged by clay and silt, especially in areas where a river has had a long-term influent character. This would lower recharge possibilities from rivers to a considerable extent.
Groundwater quality is a limiting factor for water supply especially in the Sand W parts of the Aquifer System where salinity and unfavourable chemical composition can render groundwater development impossible. Even in areas where groundwater quality is acceptable excessive pumping can cause intrusion of highly mineralised water from neighbouring areas and especially from below during a decline of water head. Knowledge of vertical changes in groundwater quality is thus important where heavy pumping is planned.

19.5.6 Taurus-Zagros Groundwater Province

19.5.6.1 Extent and general features

The Taurus-Zagros Groundwater Province comprises the High Folded and the Suture Zones. It follows the Iraq frontier with Turkey (in the N) and with Iran (in the NE). The boundary with the Foothill Zone in the Sand SW is often marked by the last of the continuous outcrops of the Eocene carbonates exposed in cores of anticlines. The province covers an area of approximately 30,000 km-'.

The Taurus-Zagros Groundwater Province differs from the Nubio-Arabian Groundwater Province whose aquifer systems are mostly characterised by extensive regional groundwater flow. In the Taurus-Zagros Groundwater Province, the complex structural geology and variations in rock type have created localised small scale aquifer systems:

1. The elevated areas of the High Folded Zone are typically built by Tertiary, Mesozoic or older carbonates, which are often karstified. Many springs of good quality and high discharge issue from the karsts. Some springs have yields of thousands of L/s. The most famous are Serchanar near Sulalmaniya, Ser Chawa, Bekhal near Rowanduz and Khurmal in the Avroman range. The karstified aquifer systems are very promising for concentrated large-scale groundwater development.
2. Old rocks are often separated by synclines of Tertiary and Quaternary clastics which form isolated to semi-isolated aquifer systems.
3. The highest parts of the province belonging to the Suture Zone (along the Iraq frontier) comprise mostly intensely folded metamorphic and igneous rocks and compacted Palaeozoic sediments. Groundwater is usually present only in fissures from which only small spring’s issue.

Topographic elevation in the province varies from 1000 m ASL in river valleys to >3000 m ASL on some mountain ridges. The highest ridge in Iraq is the Hasari-i-Rust which reaches an elevation of 3609 m ASL. The climate of the mountainous belt is semi-arid, hot and dry in summer (almost no rain between June and September) and cold and wet in winter with annual rainfall of 750 to 1000 rom/year. All the precipitation falls during the rainy season that lasts from autumn through winter to early spring. In some years, however, total precipitation varies considerably. Droughts can last for several-years. Water balance in N and NE Iraq is also influenced by snow that generally falls above 800 m ASL. The mean snow line occurs at 1160 m ASL in March and at 1380 m ASL in April. The maximum snow depth exceeds 2 m at an elevation of 2500 m ASL. The maximum water equivalent of the snow cover was assessed to be about 2000 mm at elevations of 2500 m and more in April (Stevanovic and Markovic 2004).

This province has the most favourable water balance in Iraq with the highest total precipitation (both rain and snow). Consequently, many important rivers with tributaries originate there or in the neighbouring countries. From NW to SE, the most important rivers are the Khabour, Greater Zab, Lesser Zab and Sirwan (downstream name is Diyala). The province is therefore characterised by high drainage density (Fig. 19-3). Two important dams were constructed in the 1950's: the Dokan dam on the Lesser Zab River and the Derbendikhan dam on the Sirwan River. New dams are planned.

The courses of many river valleys are controlled by structure; most valleys are parallel to the main tectonic features. The rivers, mostly effluent in character, form axes of surface water drainage and groundwater discharge zones. In areas built by carbonate rocks, some water courses can be

influent; water is lost into intensively fractured or karstified systems. Close to the boundaries with the Low Folded Zone the main rivers cut down through the elevated zones transverse to structural elements. When passing through the neighbouring Foothill Aquifer System they may lose part of their water in influent reaches (see Section 19.5.5) before emptying into the Tigris River as left-bank tributaries.

Hydrogeological conditions of the Taurus-Zagros Groundwater Province were not studied systematically until the investigation of Stevanovic and Markovic (2004) whose monograph provided most of the information and data used in this section.

19.5.6.2 Geological setting, spatial distribution of hydrogeological bodies, transmissivity and permeability of rocks

The structural setting and lithology of rocks control hydrogeological conditions within the province. The deformed rock layers often dip very steeply or vertically especially on the Sand SW flanks of anticlines. Thus hydrogeological bodies have very variable geometry, extent and thickness. Regional faults and local fracture systems, longitudinal or transversal to the main structural features, control the direction of valleys and the predominant pathways of groundwater flow.

The main hydrogeological units within the Groundwater Province are as follows:
The Palaeozoic-Triassic deposits occur mostly in the N part of the High Folded Zone and consist of quartzites, siltstones, conglomerates and shales, volcanic rocks, limestones, dolomites and some evaporites. Jurassic and Cretaceous carbonates outcrop over much of the province. Tertiary sequences often outcrop in synclinal areas in the NE and in the cores of anticlines in the SW. They comprise clastics of the Kolosh and Gercus formations and carbonates of the Sinjar, Avanah and Pila Spi formations. Hydrogeologically, the most important units are the Cretaceous carbonates which form the majority of the terrain of the High Folded Zone; their total thickness exceeds 2000 m.
Two main groups of carbonate aquifers (aquifer complexes) were defined by Stevanovic and Markovic (2004), based on geological and hydrogeological similarities:

1. The Bekme Karst Aquifer (which includes the carbonates of Qamchuqa, Dokan and Kometan formations). It covers large areas mostly in the N and central N part of the Taurus-Zagros Province, where it is very thick. The Bekhme is a typical heterogeneous anisotropic aquifer, intensively fractured and often karstified with many specific karst features such as channels and caves. Stevanovic and Markovic (2004) studied the karst caves and identified two fossil karst systems (with only percolated water) and three active karst systems connected with existing springs. Cavities sometimes> 10m high were identified during drilling of water wells. Karst depressions and sinkholes are rarely seen in outcrops but air photos reveal that cores of some of the major anticlines are strongly pitted due to karstification. The base of fractured and karstified section is generally deeper than 100 m, enabling large quantities of groundwater to accumulate in the deeper parts of the aquifer. The transmissivity is 9-8000 m^2/day (Stevanovic and Markovic, 2004). Wells of depths of 100-150 m have yields of up to 50 L/s with very small drawdown, for example, at Shaqlawa and Harir.

2. The Pila Spi Fractured Karst Aquifer (also including the carbonate of Sinjar, Khurmala and Avanah formations). It outcrops extensively mainly in the central and S part of the Province. This aquifer is heterogeneous and anisotropic, up to 200 m thick, fractured and well karstified. The degree of karstification is similar to the Bekhme aquifers. Some cave systems in the Pila Spi or Sinjar limestones are even better developed than in the Bekhme Aquifer group. However the limestones of the Pila Spi Aquifer are often argillaceous and fracture systems are thus less well developed than in the Bekhme aquifer. The base of karstification is at a depth >80 m. The Pila Spi Aquifer typically outcrops in hilly areas up to 10 km wide at Bedool near Atrush. Transmissivity is 3.5-42000 m^2/day (Stevanovic and Markovic, 2004). The depth of water wells often reaches 119-150 m, with yields up to 40 L/s, for example in the Hamammok -Kousenjaq exploitation field. The Sinjar Limestone Formation is usually separated from the Pila Spi aquifer by the Gercus clastics except in the S part of the Qara Dagh basin S of Sulalmaniya where the Gercus layers are missing. Here the Palaeocene Kolosh-Aaliji marls are present.

   In addition to these very important carbonate aquifer complexes, some clastic units, for example the Kolosh and Tanjero formations are sufficiently permeable to form local fractured aquifers. In some areas, the equivalent Suwais Red Beds can form complex aquifer systems together with carbonate rocks and different types of hard rocks (igneous, metamorphic and highly cemented sedimentary rocks) in the Suture Zone. No hydrogeological data from hard rock areas are available. However, their specific hydrogeological environment can be described as follows:
   The shallow zone of relatively high permeability of hard rocks ("close-to-surface" aquifer) reaches depths of several tens of meters and generally conforms to the land surface. It consists of an upper weathered zone of basement rocks with juxtaposed non-indurated Quaternary deposits and a lower fractured zone. The transmissivity of the close-to-surface aquifer is usually 1-10 m^2/day but in intensively fractured zones it may exceed many tens of m^2/day. The "close-tosurface aquifer" is underlain by a so-called massive zone where only few permeable fractures occur. Local deep seated fracture zones occur in fault zones in igneous rocks creating hot springs.

   Tertiary and Quaternary deposits are often hydraulically connected to the carbonate rocks thus forming a joint aquifer system. The Fatha and Injana formations (Lower and
   Upper Fars), and the Mukdadiya and Bai Hassan formations (Lower and Upper Bakhtiari) are best developed in the neighbouring Foothill Aquifer System. These formations are less estensive in the Taurus-Zagros Province. Quaternary deposits represented by slope, pediment, flood plain and terrace sediments cover extensive areas of the Province especially near the Dokan and Derbendikhan artificial lakes and also in valleys along the upper reaches of rivers such as the Lesser Zab, Sirwan (Tanjero) valleys, where they often cover older Tertiary deposits.

19.5.6.3 Groundwater flow (extension, depth, recharge, through flow, discharge)

Geological structures control the geomorphology of the province. The most conspicuous geomorphological features are linear mountain ridges and intervening valleys. In the Taurus Mountains in N Iraq and along the boundary with Turkey these features trend E- W, while in the area SE of the Greater Zab River they trend NW-SE. Within the province several hydrogeological units were defined by Stevanovic Markovic (2004) as represented in Fig. 19-16 and Table 19-1.
Water-table bodies occur in the upper part of the carbonate aquifers. The respective groundwater bodies can thus be fed almost everywhere by direct precipitation during the rainy season in winter and spring and partly also by influent seepage from water courses under adequate hydrogeological

conditions. From recharge zones, the prevailing directions of groundwater flow follow the differences in hypsometry of the land surface. The piezometric surface (groundwater level varies from 1000 m to 2000 m ASL in the mountain slopes to approximately 500 m ASL in deeply incised river valleys. In less permeable hard rocks, the piezometric surface usually conforms to the ground surface but in highly permeable karst areas the water table often varies widely, over short distances due to the topographic complexity of the area. Locally it is at a depth of tens or even hundreds of metres.

In hard rock areas natural groundwater flow is localised and aquifer systems usually coincide with surface water catchments. Despite relatively low prevailing transmissivity, long-term mean groundwater runoff from this environment is high, typically several L/s km-, due to the large hydraulic gradient of groundwater bodies in "near surface" aquifers. The formation of natural groundwater resources, however, strongly depends on climatic conditions. In wet years runoff of around 10 L/s km^2 or more can be expected in high hypsometric positions whereas during dry seasons these values drop considerably.

The karst aquifer complexes of Bekhme and Pila Spi outcrop in large areas and can therefore store large quantities of groundwater. The average effective recharge is estimated by Stevanovic and Markovic (2004) to be >50% of the total rainfall for the Bekhme complex and >30-40% for the Pila Spi complex (up to 10-15 L/s km2). These relatively high estimates of groundwater resources are supported by the occurrence of highly fractured and karstified rocks, high precipitation during the wet season, reduced evaporation and absence of vegetation (almost no transpiration), and poorly developed hydrography. Perennial or temporary streams do not occur. However due to the high permeability of intensively fractured and karstified environments and prevailing large hydraulic gradients, mostly very rapid, turbulent water flow occurs. Consequently, groundwater can be rapidly evacuated from the karstic systems.

Part of the karst groundwater is discharged by subsurface drainage, i.e. by diffuse seepage or concentrated discharges into river courses. Stevanovic and Markovic (2004) described an example from the Qalat Dizeh-Rania basin where the stream flow almost doubles between two profiles indicating concentrated drainage from a karst aquifer at a rate of 5-11 m^3/s. They also determined a noticeable increase in stream flow in narrow gorges in Sulalmaniya Governorate. Discharges in three observations areas were 340, 650 and 760 L/s.

Groundwater of karst aquifers is discharged mainly by numerous springs, often occurring at the contacts of carbonate aquifers with the underlying non-carbonate rocks which often border the karst massifs. Faults, fracture zones, extensions of hydrogeological catchments and favourable geomorphological conditions also control the position of major karst springs.

The minimum yield of the five largest springs in the Bekhme and the Pila Spi aquifer complexes, based on monitoring in 2001 is 555-1750 L/s (Stevanovic and Markovic 2004); more than ten other springs have minimum yield of >200 L/s. In the Sulalmaniya Governorate the total mean yield of 214 springs is 41.8 m^3/s; 80% of these springs issue from the Bekhme aquifer and 15% from the Pila Spi aquifer. The largest known spring at Sarchawa has an estimated average yield of 6.7 m^3/s. It issues from the Bekhme limestones.

The yield of karst springs can vary considerably. Monitoring of 40 springs in the monitoring network showed the total minimum discharge at the end of the 2001 recession period was 11 m^3/s. The total maximum discharge recorded in the rainy season of 200112002 was 160 m^3/s (Stevanovic and Markovic, 2004). The ratio of the minimum and maximum yields of all the

monitored karst springs during 2001-2002 in the Taurus-Zagros Province is 1: 10 for the Bekhme aquifer (total minimum yield of 67 monitored springs is 10.6 m^3/s) and 1:7 for the Pila Spi aquifer (total minimum yield of 31 monitored springs is 3.1 m^3/s). The dependence of karst groundwater resources on climatic conditions was demonstrated in a three year period of drought preceeding the climatically normal season of 200112002, when many springs and shallow wells previously used for water supply dried-up.

Within the carbonates, Stevanovic and Markovic (2004) defined and delimited several karst drainage (aquifer) systems each extending from recharge areas through groundwater transfer zones to discharge zones, and represented -by a spring or group of springs. They defined the following aquifer systems: 1) Karstic Bekhme aquifer springs that include Saruchawa-Mackok, Zulam, Sarchinar Chaq Chaq, Saraw-Gallal, Bestansoor-Geldara, Bekhal (Plate 19-1) and Krbish Ulja. 2) Fractured-karstic Pila Spi aquifer springs which includes the springs of Deraboon, Bani Khelan, Awa Spi and Mamlaha. Most of these springs belong to the High Folded Zone except for Zulam that dralns the Avroman Limestone of the Qulqula-Khwuakurk Zone and the Awa Spi and Mamlaha springs that belong to the Foothill Zone aquifer system.

Carbonate layers can also form important parts of the combined aquifer systems when they are overlain by the clastic Fatha, Injana, Mukdadiya and Bai-Hassan formations. Carbonate rocks form external zones of discharge either to intermountain basins (aquifer systems) within the Taurus Zagros Province or to the aquifer sub-systems belonging to the neighbouring Foothill Aquifer System. Differences in lithology, and the low permeability of overlying clastic deposits can cause semi-confined to confined conditions to develop in deeper karst aquifers. Stevanovic and Markovic (2004) noted that high artesian pressure and discharge were observed when wells penetrated the Pila Spi limestones at depths >50 m in Swarawa near Qara Dagh, and in the well field for water supply of Malta near Dohuk. In discharge zones the less permeable confining beds of clastic deposits reduce the rate of groundwater flow in underlying carbonate aquifers facilitating storage of large quantities of groundwater.
The Taurus-Zagros Province can be considered as the best aquifer system in the whole of Iraq. It is of great importance also for the neighbouring Foothill Aquifer System which benefits from the rivers which flow through it.

The hydrogeological zonation of N Iraq is based on the recommendations of Stevanovic and Markovic (2004). They divided the Zagros-Taurus Province into two major hydrogeological zones, the Suture and the High Folds zones.
The Suture Hydrogeological Zone includes the oldest Palaeozoic "hard rocks", clastic and carbonate rock units and igneous and metamorphic rocks. Little hydrological data is available from this zone. The largest known Zulam spring has a minimum yield of 0.38 m^3/s and a "normal" yield of over 2.0 m^3/s. The practical water-management importance of this zone is low for several reasons, including its small extent and distance from main population centres. Three hydrogeological regions ("basins") were defined including: 1) Kani Mase hydrogeological region in the north, along the Iraqi-Turkey border. 2) Sidakan hydrogeological region in the center, along the N part of the Iraq-Iran border. 3) Penjween hydrogeological region in the SE, along the southern part of the Iraq-Iran border.

The High Folds Hydrogeological Zone, where the most important aquifers occur in fractured and karstified carbonates, is divided into four major hydrogeological "basins" and subdivided into eleven "sub-basins" (Table 19-1).

19.5.6.4 Groundwater quality

The Zagros-Taurus Province is characterised by low salinity water, typically with a salinity <0.5 g/L and only exceptionally reaching 1.0 g/L. The prevailing type of karst water is Ca (Mg)-$HC0_3$, with increasing magnesium content in dolomites. Water is neutral with pH of 6.5-8.0. Under natural conditions, groundwater from karst and fissured-karst aquifers is of a very good quality.
Large aquifers in recent deposits in the Shaharzoor and Dokan areas contaln fresh groundwater of karst origin derived from the Cretaceous Kometan, Balambo or the Palaeogene Sinjar formations and partially from the Palaeogene clastics of the Kolosh Formation.
The salinity and chemical composition of groundwater is changed in the presence of gypsum, anhydrite and halite in the Fatha Formation which is sometimes present in the S and SW parts of the province. The salinity and content of sodium, sulphates, and chlorides can increase considerably, and water often contalns dissolved H_2S; maximum reported H_2S concentration is 77 ppm. The H_2S originates from deep bitumen-bearing layers as noted by Stevanovic and Markovic (2004).They also noted that even the composition of groundwater of karst origin from the Pila Spi limestones that flows through and discharges from the Fatha deposits is changed considerably in the Qayatol, Mamlaha and Awa Spi springs in the Sangaw area of the Sulalmaniya Governorate. In Khweilin village local people produce salt by evaporation of saline spring water of this type.

Several hot springs such as Garaw and Garawi Mil' Sald are probably connected with deep aquifers by regional faults.
Water quality for drinking, domestic and agricultural purposes was evaluated during the last FAO project and compared with existing Iraqi and WHO (1996) standards. In the Sulalmaniya region, water samples had a high content of $N0_3$ unsuitable for potable water. Chemical and/or bacteriological contamination of groundwater, including karst springs near human settlements, is frequent due to seepage of sewage from houses and septic tanks. The sanitary situation is serious as stated in the project proposal for the Three- Year-Plan N Iraq (2003), submitted to UNICEF. Stevanovic and Markovic (2004) stated: "Lack of adequate and safe water supply and poor environmental sanitation, both in the urban and rural areas, had been among the causes for high incidence of diarrhoea, intestinal and skin infections, acute respiratory infections (among children), cholera, and heavy workload for women and children (girls) in transporting water from far distances". There are no limitations for the use of karst waters in agriculture, land and orchard irrigation since the Sodium Absorption Ratio (SAR) is <3 and the salinity hazard is low.

19.5.6.5 Present-day water use, possibilities of future groundwater supply

In the neighbouring Foothill Aquifer System favourable transmissivity is present almost everywhere enabling abstraction of large quantities of groundwater. However in the Taurus-Zagros Province concentrated groundwater withdrawals are limited to small appropriate sites at high yield karst springs or other geologically well defined zones (Table 19-1). This is mainly due to the extremely high heterogeneity and anisotropy of karst aquifers that result in uneven regional distribution of karst springs and large differences in productivity of water wells. Consequently, the potential for of groundwater extraction is erratic. Many areas of the province have insufficient groundwater resources.

Some of the large cities within the Taurus-Zagros Province and at the boundary with the adjacent Foothill Aquifer System such as Dohuk, Salahaddin, Koisinjaq, and Darband Bazian are supplied from wells drilled into the Pila Spi aquifer. Groundwater is also widely used for irrigation. Some of the most productive wells in the Pila Spi aquifer- are located at anticlinal plunges with permanent yields reaching 10-30 L/s; wells often overflow after the rainy season. Sometimes groundwater can be tapped in the Pila Spi limestone after passing through the Fatha mudstones and marls, for example at the N edge of the Qara Dagh basin, S of Sulalmaniya. There are also important alluvial aquifers along large rivers. The conglomerates and sands of the Red Beds Series accumulated in a depression alongside the Zagros Suture.

Many towns and settlements are supplied directly with good quality water from karst springs. A good example is the Sarchinar spring that supplies municipal water for Sulalmaniya which during the drought period of 1999-2000 yielded 600 L/s. The well known Bekhal spring which has a discharge ranging from 750 L/s to an estimated 17 m^3/s is very important for future water management of the central and N parts of the Erbil Governorate. It was listed in the potential UNDP project for small hydropower plant. Presently this spring is partly used to supply the town of Diana. Traditionally many kahrezes supply water, for example between Sulalmaniya and Arbat in the Tanjero valley to the SE where these water intake objects were constructed in the deluvial deposits and tap the water that drains the Azmur Mountain range.

Recently an ambitious FAO project was carried out in N Iraq in the Taurus-Zagros Province and extensive parts of the Foothill Aquifer System (Stevanovic and Markovic, 2004). In addition to important water inventory and technical studies an extensive drilling programme was conducted. By March 2003 about 500 water wells were drilled capable of pumping about 3000 L/s for irrigation and livestock breeding purposes. 59 of these wells were drilled in the Bekhme Complex and 82 in the Pila Spi Complex having a total potential capacity of more than 1 m^3/s. Wells in the Pila Spi aquifers were more productive (average yield 8.3 L/s per well) than in Bekhme aquifers which had an average yield of 5.9 L/s. Failed wells are more frequent in the Bekhme aquifers because of the high altitudes of the selected well sites (sometimes much higher than the local base of erosion) and because the targeted carbonate aquifers were often covered by steeply dipping confining layers.

19.6 Estimation of groundwater resources

Integrated groundwater management has to be based on groundwater resource assessment. An inventory of groundwater for domestic water supply, irrigation and industrial uses should be prepared. This involves the determination of exploitable groundwater resources ("safe yield"), i.e. groundwater resources that can be technically developed under economically feasible conditions which do not damage the environment and do not result in long-term groundwater depletion ("groundwater mining"). Groundwater resources are defined as the amount of water that enters aquifers under natural conditions, such as recharge from rainfall or from rivers, leakage from the overlying and underlying aquifers, and from the neighbouring catchment areas. Groundwater resources are sometimes assessed as gravitational resources represented by the total volume of rock occupied by groundwater that can be drained by gravity ("specific yield"). During exploitation groundwater can be released from storage due to the elastic properties of rocks and groundwater; this is important mainly in extended confined aquifers. Groundwater recharge can be increased by construction of dams and irrigation canals, by pumping in close-to-river zones and by intentional artificial recharge (induced and/or artificial resources). Water losses can also be limited

during groundwater development due to the lowering of the water table and consequent decrease in evapotranspiration. The results-of calculations of the modulus of groundwater flow are given in Fig. 19-10 and in Tables 19-2 and 19-3. There are some differences in groundwater flow modulus estimated for the western desert sub-province. In the hydrogeological reports of Blocks 4, 5 and 7 (Water Development Project, 1978 and 1981), the estimated modulus of groundwater flow was equal to 0.025 L/s km-, calculated on the basis of elastic ground water resources. In this book, the modulus (Table 19-2) is calculated based on gravitational groundwater resources.

19.6.1 Exploitable Resources and Groundwater Use

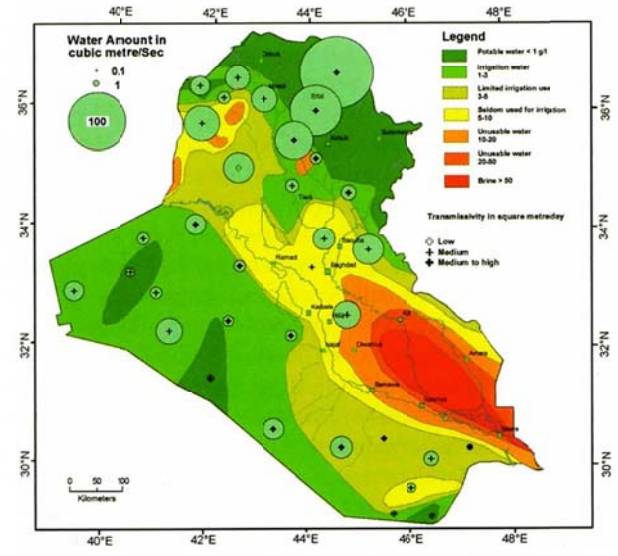
Alsam et al. (1990) calculated exploitable groundwater resources. The total dynamic reserves of water in three categories (domestic, irrigation and livestock and unusable) are summarized in Table 19-3.

Groundwater exploitation in Iraq is still very limited, because the only water intake systems that produce groundwater continuously are in Erbil and Kirkuk cities where the actual working time of boreholes is about 18 hours per day. The maximum working time for exploitation boreholes used for irrigation is about 1600 hours per year. In Iraq, there are about 8500 drilled boreholes, and about 40,000 hand-dug wells. The mean groundwater discharge of these wells is about 10 L/sec and the total groundwater discharge (the product of the total number of boreholes and the actual boreholes discharge) is 87300 L/s (about 2.7 billion cubic metres per year).

The total amount of available dynamic groundwater resources suitable for domestic and irrigation purposes is estimated to be 12.6 billion cubic metres per year. Thus only about 20% of the available resources have so far been exploited.

The technology of well drilling and pump installation has not changed in Iraq in the last 30 years. All drilled boreholes have small diameters and nearly all pumps have small discharge, which are not optimal for irrigation purposes (one of the important uses of groundwater). One way to make up the deficiency in fresh water supply is to make use of the dynamic groundwater resources of higher salinity (110 *g/L)* which can be used without desalinization for industrial, irrigation and some domestic purposes. However water laws in most countries forbid the use of fresh groundwater below 1 g/L except for domestic purposes; use of saline groundwater for industrial and irrigation purposes is allowed to supplement the fresh water resources. Tables 2 and 3 indicate that the total amount of groundwater suitable for domestic use with salinity <1 g/L is about 6.3 billion cubic metres per year. The total amount of groundwater suitable for irrigation and watering livestock, with salinity of 1 -3g IL, is 3.8 billion cubic metres per year. The amount of groundwater restricted for watering livestock and accepted for irrigation with a salinity of 3-5 g/L is 2.5 billion cubic metres per year. The amount of groundwater of very limited use for watering livestock and irrigation with a salinity of 5- 1 0 g/L is 2.25 billion cubic metres per year. The amount of groundwater with a salinity of> 10 g/L is equal to 1.54 billion cubic metres per year; this groundwater can only be used for industrial purposes. The map of figure 19-17 summarizes the water resource by showing the salinity, amount of water and transmissivity and indicates that fresh water, of salinity < 1 g/L dominates the mountainous region and small parts of the Western Desert near Rutba and the Nukhaib Graben.

Fig. 19-17: Water use map showing water salinity zones and water amount in cubic metres per second as scaled points



19.7 Environmental issues

The most serious environmental issue facing Iraq in the future is the salinisation of the Mesopotamian water and soil. Both natural conditions and human activities are responsible for this deterioration. The Plain is the discharge zone of groundwater for the whole Mesopotamian Aquifer Megasystem. Dissolved solids have been transported by groundwater within this vast hydrogeological catchment from different directions to the Plain and also by groundwater from below. Despite the relatively slow groundwater flow (of the order of metres per year as a maximum), especially in the deep aquifers, the quantities of transported salts during long time spans are enormous. When groundwater level is high in the Plain after humid seasons, surface water is often present in closed depressions. Evaporation increases the salinity of the water resulting in accumulation of salts in soils close to the land surface. The process, which has occurred during the last few thousand years, has been speeded up by irrigation without adequate drainage and by filling up of the natural depressions.

The practically flat topography of the Plain also enhances the process of salinisation. Under the arid and semi-arid climatic conditions large amounts of salts have accumulated in shallow groundwater. The groundwater salinity is > 100 *g/L* and locally >200 *g/L*. However better quality groundwater is present in the N part of the Mesopotamian Plain, along its flanks and along rivers and irrigation canals. Surface water quality is often affected by highly saline groundwater discharged into rivers during dry seasons which increases surface water salinity especially in the central and S parts of the Plain.

Depending on hydrogeological conditions, pumping of groundwater can cause two distinct environmental effects:
In zones with potentially sufficient groundwater resources, along influent river courses with good quality water, heavy pumping may gradually improve the quality of groundwater. However in areas with limited groundwater resources under desert conditions, where fresh groundwater often "flows" over underlying saline water, intensive withdrawals above the limits of natural

groundwater replenishment ("groundwater mining") may cause a decrease in yield of water wells. Groundwater quality deteriorates due to invasion of deeper brines. Increase in salinity due to over pumping has been reported especially in the S part of the Plain near Basra. It is therefore very important to implement water exploitation policies to relieve the Mesopotamian plain from this water congestion. The second environmental issue is waste disposal. The Mesopotamian Plain is the most densely populated region of Iraq. Over 60% of the population of Iraq (currently 25 million people) lives in 10 large cities and numerous towns. Consequently, waste products of urbanisation and industrialisation have contaminated groundwater to a degree that has not yet been fully appreciated. Of particular concern is the contamination connected with the oil industry related to leakage of petroleum into the subsoil. Heavy use of fertilisers has increased nitrate levels in shallow aquifers. The nitrates are ultimately transported into the rivers.

In the Foothill Zone, regional hydraulic connections in the very transmissive aquifers of the system can result, under heavy groundwater abstraction, in regional lowering of groundwater levels (piezometric surface) and a decrease in surface runoff. This can limit seepage from influent river courses. Heavy groundwater pumping can also lead to salinity increase and to intrusion of neighbouring or underlying water of inferior quality. This may endanger groundwater quality especially along the SW boundary of the aquifer system where ground waters have relatively high salinity. In these areas soil and water salinisation can occur if irrigated plots are not adequately drained (compare with Section 19.5.3.5).

A decrease in surface runoff and deterioration of surface water quality can be caused by intensive river water diversions and by disposal of poor quality irrigation water into rivers.

Due to higher living standards, especially in the cities (Mosul, Kirkuk and Erbil) and towns in the NE part of the aquifer system, good groundwater management is necessary. However, waste products of urbanisation and industrialisation have had serious environmental impacts with severe contamination of groundwater. Of special concern is the contamination resulting from oil extraction and transport with oil leakage into soil and groundwater, and from untreated sewer water often drained in septic tanks in many population centres. Due to the great importance of water management in the Foothill Aquifer System, groundwater and surface waters should be carefully monitored both quantitatively and qualitatively.

Gradual settlement of the Southern and Western Deserts will require careful town planning and strict groundwater utilisation policies. At the same time the problems of salinity of Mesopotamia must be carefully addressed and well planned drainage systems should be implemented. These policies are long term and expensive. They are, however, necessary due to the diminishing capacity of the Tigris and Euphrates Rivers because of over-damming in Turkey and Syria and partly in N Iraq and possibly due to future fast advancing climatic changes.

Table 19-1: Hydrogeological units of the High Folded Zone (after Stevanovic-Markovic 2004) as shown in Fig.19-16

Hydrogeological basin	Hydrogeological sub-basin	Main hydrogeological characteristics	Recommended solutions for groundwater use
1. NW Barzany	1.1 Amadia-Barzan 1.2 Atrush -Dinarta	- Prevalence of karstic and karstic-fissured aquifers. - Small basins mostly filled with impervious rocks.	1. Tapping karstic spring water. 2. Developing shallow alluvial aquifer. 3. Deep-well drilling only in karstic foothill areas.
2. Central Harir	2.1 Diana-Mergasoor 2.2 Harir-Shaqlawa	- Karstic and karstic fissured aquifers; prevalence at the edges. - Basins often filled with impervious rocks.	1. Tapping karstic spring water. 2. Deep-well drilling in karstic foothill areas (Hawdiyan, Harir, Shakrok, 3. Shaqlawa).
3. Central Dokan	3.1 Sarsang 3.2 Rania–Choarta 3.3 Bangard-Surdash	- Karstic and karstic fissured aquifers predominate at the edges of basins. - Basins often filled with highly productive recent deposits.	1. Tapping water of karstic springs at the edges (gravity systems). 2. Developing shallow alluvial and terrace aquifers. 3. Deep-well drilling in foothill karstic areas or in recent deposits.
4. SE Sharazoor	4.1 Bazian-Qaradagh 4.2 Sarchinar-Arbat 4.3 Choarta-Baraznja 4.4 Khurmal-Halabja	- Occurrence of karstic and karstic fissured aquifers on the edges of basins. - Basins often filled with highly productive recent deposits. - Variable permeability and lateral / horizontal changes in lithology of basin layers.	1. Tapping karstic spring water at the edges (gravity systems), developing large scheme projects from highly productive springs. 2. Developing shallow alluvial and terrace aquifers including artificial recharge. 3. Deep-well drilling in foothill karstic areas or in recent deposits.

Table 19-2: Water resources of main aquifer zones of Iraq for the 14 aquifers mentioned in text of section 19-4

Aquifer No	Tot Area km²	Modulus L/s km²	Resource L/sec	Less than 1 g/L		From 3-5 g/L		From 5-10 g/L		More than 10 g/L	
				Area km²	Resource L/sec	Area km²	Resource L/sec	Area km²	Resource L/sec	Area km²	Resource L/sec
1	12300	0.75	9225	0	0	0	0	0	0	0	0
2	10000	0.5	5000	3300	1650	0	0	0	0	0	0
3	43300	0.5	21650	6400	3200	0	0	0	0	0	0
4	31800	0.5	15900	0	0	6300	3150	5600	2800	0	0
5	61200	0.35	21420	0	0	31700	11095	900	315	0	0
6	18400	0.25	4600	7700	1925	0	0	0	0	0	0
7	21900	0.4	8760	1300	520	13100	5240	5600	2240	1000	400
8	6400	0.5	3200	0	0	2700	1350	1500	750	2200	1100
9	40100	1	40100	0	0	21700	21700	11300	11300	2900	2900
10	79300	0.75	59475	0	0	200	150	23400	17550	55500	41625
11	37600	2	75200	0	0	10800	21600	14600	29200	1700	3400
12	10600	3	31800	3100	9300	1200	3600	1600	4800	0	0
13	40700	2.5	101750	24300	60750	2000	5000	1200	3000	0	0
14	24500	5	122500	24500	122500	0	0	0	0	0	0

Table 19-3: Total amount of ground water and water use

Total amount of ground water (billions of cubic metres) and water use				
Subprovince	**Aquifer No**	**Domestic 1 g/L**	**Irrigation & livestock 1-3 g/L**	**Unusable 3-5 g/L**
Western desert	1,2,3,4,5,7,8	0.23	1.66	0.63
Jezera	9	0	0.13	0.68
Baiji-Tib	11	0	0.55	0.92
Baghdad Basra	10	0	0	0.004
Foothill zone	12,13	2.21	1.48	0.27
High folded zone	14	3.86	0	0
Total		6.3	3.82	2.504



Plate 19-1: Bekhal spring located along the contact of Qamchuqa and Bekhme formations, W of Rowanduz



Plate 19-2: Sayid Sadiq spring, SSE of Sulaimaniya, issuing from the Balambo Formation

Chapter 20

Metallic and industrial rocks and minerals

by

Khaldoun* S. *Al-Bassam and Jaroslav Hak

20.1 Introduction

Systematic exploration for mineral raw materials in Iraq started in the early 1950's. The Site Investigation Co. (UK) implementing an exploration program of local geological mapping and geophysical exploration on various scales in N and NE Iraq. The program also included evaluation of small areas for the cement industry, and some exploratory visits to W Iraq. The main aim of the early exploration was to locate and preliminary evaluate the mineral wealth of Iraq. The information obtained during this survey helped locate some metallic mineral deposits in N and NE Iraq. The exploration work was resumed by Russian teams from 1960-1964, who evaluated mineral deposits suitable for industrial use including phosphorite, native sulphur, quartz sand, dolomite, limestone and ironstone.

GEOSURV commenced comprehensive regional geological mapping and mineral investigation projects that provided new valuable information on the distribution of new resources of mineral raw materials throughout Iraq. These surveys were followed by detailed exploration and prospecting projects that resulted in delineation of several important deposits including phosphorite, sulphur, kaolinitic clays, sedimentary ironstones and building raw materials (limestone, gypsum, gravel, sand, and clay). Meanwhile new mineral raw materials were discovered and appraised in detail, including karst bauxite, flint-clay, celestine, feldspathic sand, heavy mineral bearing sand and montmorillonite-palygorskite clays.

20.2 Minerogenic zonation

The data presented in this book are based mainly on published papers, postgraduate theses and some unpublished internal reports of GEOSURY. The mineral and industrial rock potential was summarised in a map published by GEOSURV at 1:1,000,000 scale (Al-Bassam et al., 1987). Iraq was divided into minerogenic provinces, zones and districts according to the type and origin of the dominant mineral commodity available at the surface or near-surface (Al-Bassam, 1986). The surface and near surface geology and tectonic subdivisions were used to define genetic subdivisions (Fig. 20-1). They comprise:

1) Non-metallic deposits, 2) Marine sedimentary deposits, 3) Marine evaporites, 4) Continental evaporites, 5) Fluvial deposits, 6) Aeolian deposits, 7) Laterites, 8) Bioepigenetic deposits, 9) Metallic mineralization, 10) Low- temperature hydrothermal vein and strata-bound deposits, 11) Placer and secondary deposits, 12) Magmatic deposits, 13) Hydrothermal vein and strata-bound (regionally metamorphosed) deposits, and 14) Volcanosedimentary deposits.

Metallic mineralization is restricted to the Neo- Tethyan Suture Zones and is related to various phases of the plate tectonic history of the region. Low-temperature hydrothermal deposits occur in the Northern Thrust (Ora) Zone, including Pb-Zn, Ba, pyrite mineralization (e.g. the Serguza deposit). Placer and secondary deposits occur in the Balambo- Tanjero Zone and include some chromite placers and secondary Cu minerals in sedimentary clastics derived from the Qulqula-Khwakurk Zone. Magmatic Cr Ni, Cu and Fe mineralization is associated with basic and ultrabasic igneous intrusives (e.g. Mawat Cr-Ni, Cu and Penjween Fe). Hydrothermal and strata-

bound mineralization of Pb-Zn and Fe (e.g. Marapasta) and volcano-sedimentary deposits of Mn-Fe are associated with the Qulqula Group.

The Arabian Shelf units contaln non-metallic minerals and industrial rocks. Marine sedimentary deposits (chemical and biogenic) include phosphorite, limestones and dolomites. Marine evaporites are found in the Jezira Subzone and the Foothill Zone and include gypsum and rock-salt deposits. Continental evaporite deposits include halite salterns in the Jezira Subzone and the Mesopotamian Zone. Fluvial deposits of sand and gravel occur in the Mesopotamia Zone and Foothill Zone. Unique fluvial deposits of feldspar-rich sands with epigenetic celestite mineralization are found (separately) in fan deposits of the Dibdibba Formation, deposited on the W margin of the Mesopotamian Zone (Najaf-Karbala District). Aeolian sand deposits are found in the Mesopotamia Zone as dunes and sand sheets.

Bio-epigenetic strata-bound native Sulphur deposits occur in the area between Fatha in Central Iraq and Mosul in the N where mineralization is restricted to the Middle Miocene Fatha Formation.

Laterite deposits occur in the Western Desert Zone in W Iraq and comprise karst bauxite and ironstone, associated with kaolinitic clays, quartz-sand and heavy-mineral bearing sandstones. A few grains of gold were reported from ferruginous rocks of the Ga'ara depression (MacFadyen, 1935; Antonets et al., 1962 and Vasiliev et al., 1964). Laterite horizons were identified in boreholes in the stable platform indicating possible bauxites.

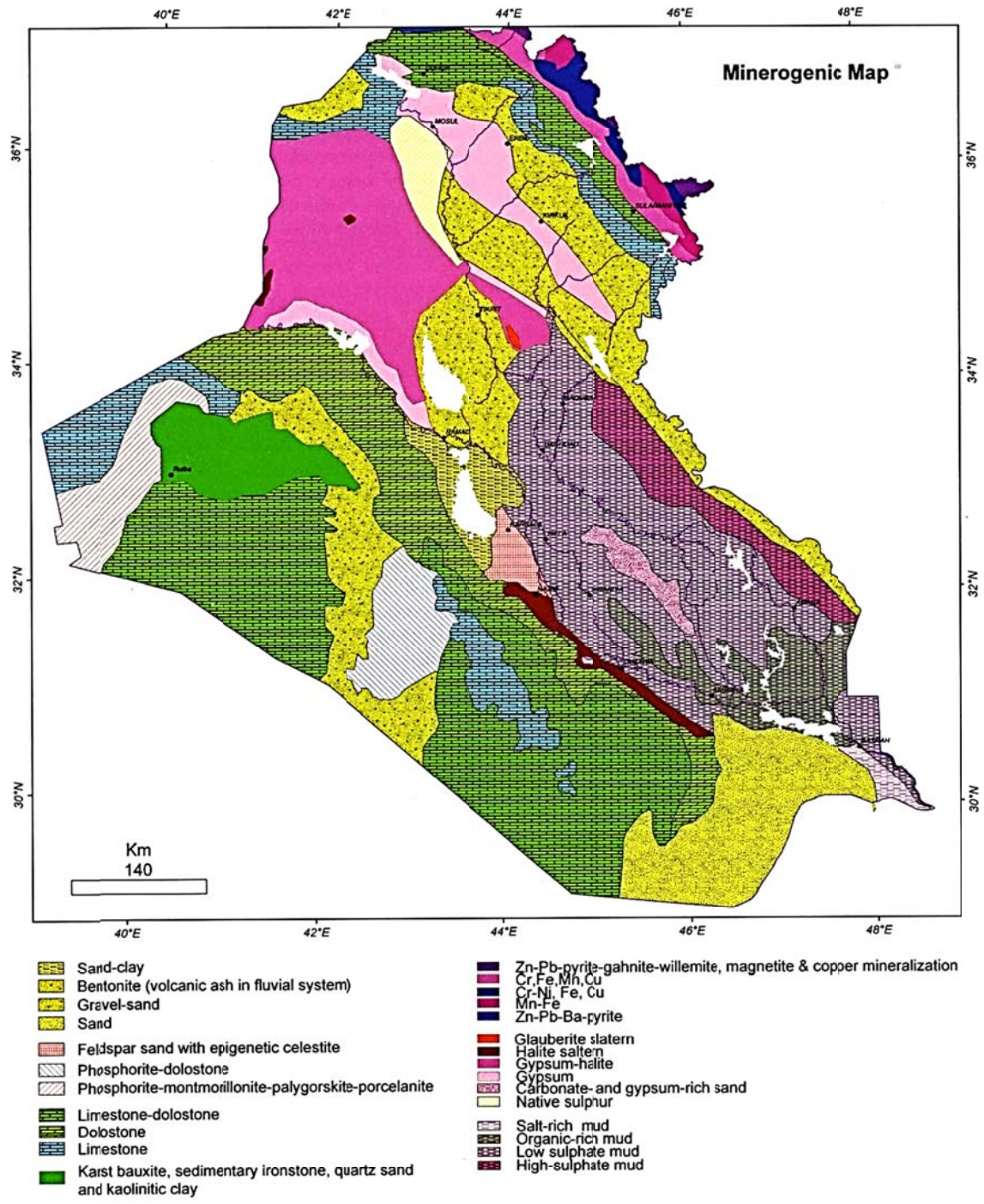


Fig. 20-1: Minerogenic map of Iraq

20.3 Metallic Mineral deposits

Metallic mineral deposits are found in the Zagros Suture Zone in N and NE Iraq. Igneous activity along the NE margin of the Arabian Plate may have been associated with deep-seated fault zones which acted as conduits for upward movement of hydrothermal mineralising fluids. Contact metamorphism occurred around gabbros that were intruded in Cretaceous and Early Tertiary time; hydrothermal mineral deposits may have formed in adjacent rocks layers.

Metallic mineral deposits have been studied since the 1950's. A survey of heavy minerals in stream sediments was scheduled for the 1980's and early 1990's to help detect metallic mineral deposits but was not fully implemented due to the Iraq-Iran and Gulf wars.

The overall economic potential for metallic minerals is generally poor, because of the inaccessibility of the rugged mountain areas which lack infrastructure, the low grade of the deposits and lack of processing facilities. Low-grade sedimentary Iron ores on the Stable Platform are unsuitable for use in the metal industry but might be useful for production of resistant cement.

20.3.1 The principal minerogenic features of the Zagros-Taurus sutures

The geology of the Zagros-Taurus suture is favourable for the occurrence of metallic mineral deposits of hydrothermal origin connected directly or indirectly with igneous activity. The deposits were formed within the Northern Thrust Zone and the Zagros Suture units (see Chapters 4 and 6). The Northern Thrust Zone represents a ridge that developed at the plate margin whereas the Zagros Suture formed within the Neo- Tethyan oceanic domain. The Northern Thrust Zone contalns base metal deposits with barite, pyrite mineralization, rare copper and some siderite veins. The Zagros Suture is characterised by copper and iron ores; lead and zinc mineralization is rare, although one base metal deposit (Marapasta) is the most promising in Iraq. Some indications of nickel, chromite, manganese ores and asbestos were also identified in the area.

20.3.2 Mineralization of the Northern Thrust Zone

The Northern (Ora) Thrust Zone is located near the border with Turkey. It is about 140 km long and 20 km wide and built mainly by Mesozoic carbonates. Palaeozoic rocks (Ordovician to Permian) outcrop in the cores of two major anticlines (Ora and Kaista). Buday (1970) and Buday and Vanecek (1972) considered that the Northern Thrust Zone has been thrust obliquely to the south over the platform units. The major structural features are ramp anticlines offset by reverse faults.

Base metal occurrences in the Northern Thrust Zone occur in two districts (Vanecek 1972), the western district NE of Zakho and the eastern district to the N of Amadiya (Fig. 20-2). They represent hydrothermal vein mineralization. The western district includes seven occurrences of lead and zinc mineralization accompanied by barite. The most important of these is the Berzanik deposit which is restricted to a fault zone of NE-SW strike in the Upper Permian Chia Zairi Formation limestones and dolomites. The total length of the mineralised zone is about 1200 m associated with three outcrops of gossans with barite. The mineralization consists of barite, limonite, galena, sphalerite, smithsonite, calcite, siderite and ankerite. Similar outcrops of barite veins and grossans with Pb-Zn mineralization were also found near Alanish, Patruma-Massis, Banik, Shiranish Islam, Lefan and Bosol.

In the eastern district of the Northern Thrust Zone McCarthy (1955) described a Cu-Pb occurrence about 6 km W of Ora village which may have been the site of an ancient mine. It comprises a vein striking NW-SE, about 1 m thick from which malachite, azurite, chalcocite and possibly even galena were obtained. Other occurrences include Gire Zivi (Silver Hill) and the Skefta Totaye. These deposits are located near the contact of the Chia Zairi limestones and the Mirga Mir shales at an altitude of about 2100 m ASL. They consist of a tectonic breccia of limestone fragments cemented by barite and quartz. Barite veins and pockets, stained with malachite and azurite, are up

to 0.5 m thick. A chunk of altered limestone with veinlets of barite and fluorite was found close to these outcrops. Fluorite veinlets, up to 1.5 cm thick, are comprised of massive, mediumgralned, light violet to light green fluorite. This is the only occurrence of fluorite in Iraq. Pebbles and fragments of galena (2 cm) in scree were found near Benavi in 1961 (Mironov and Sitchenkov, 1962). A calcite vein let with galena in dark grey dolomitic limestone in the lowest part of the southern slope of the Kurra Darmani Mountaln, about 0.5km NW Benavi village was found by Vanecek (1972).

The largest known deposit of base metals in the Northern Thrust Zone is in Serguza (Duri Serguza) about 17 km NW of Amadia (Fig. 20-1). It was studied by AL-Bassam et al. (1982). Wetzel (1950) described abundant hematite breccias consisting of angular fragments of hematite enclosed in ferruginous limestone of the Upper Cretaceous Hadiena Formation. This breccia was described as a coarse ferruginous sandstone (5-6 m thick) (McCarthy (1955), and as a hematite sandstone by Boukhtoyarov and Yewlentyev (in Vanecek, 1972). The breccia extends for at least 1 km in a 20-30 m thick interval as noted by Ibrahim Al-Rawi in 1970 (Vanecek, 1972). Microscopic studies show this horizon is a fine-grained breccia consisting of calcite grains in a ferruginous carbonate matrix. Abundant siderites veins of hydrothermal origin up to several metres thick occur in fault zones near the Serguza deposit.

Some gossans of unknown origin were reported from localities at Moi, Kani Mase, Benavi, Seraru and Noola. These gossans have relatively simple mineralogy, and dolomitic host rocks of Perrnian- Triassic age. They are associated regional thrust faults; the mineralization usually occurs in the hanging walls.

Two occurrences of gossans with galena, pyrite, chalcopyrite, sphalerite in quartz gangue occur near Herki and Stuni. Buday and Jassim (1987) assumed that this region belongs to the Shalair Zone. The Herki area is now considered part of the Northern Thrust Zone. The mineralization is located NW of Mega Sur village (Vanecek, 1972). Some iron ores were also reported from this region.

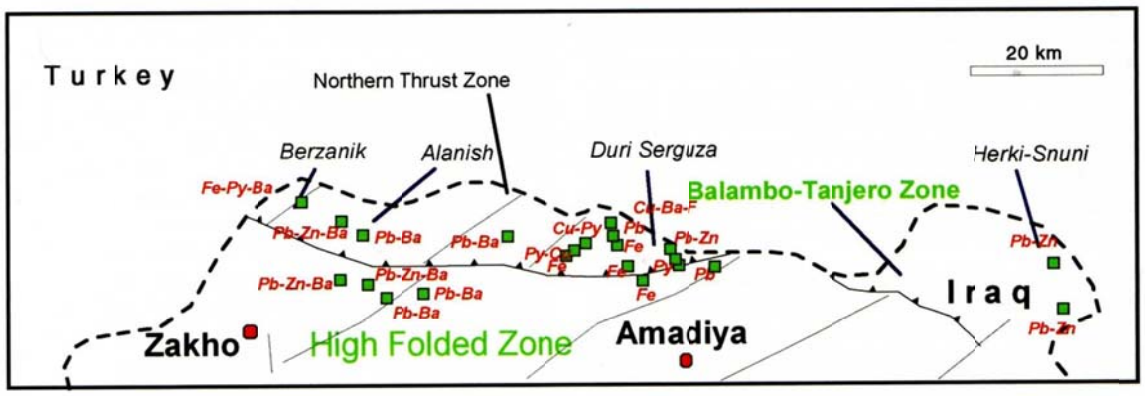


Fig. 20-2: Mineral occurrences of the Northern Thrust Zone

20.3.2.1 Serguza lead-zinc deposit and its origin

The Serguza area was mapped geologically at 1:20,000 and 1:2,000 scales (Mironov and Sitchenkov 1962), the larger scale was later updated by Aqif et al. (1971). Geophysical SP measurements (Abbas 1971) and a soil geochemical survey were conducted by Mironov and Sitchenkov (1962) and later by Al-Bassam (1980). Ore mineralogy was studied by Al-Bassam (1972) and Al-Bassam et al. (1982). AlQaraghuli and Lange (1978) investigated the minor and trace element content of the primary and oxidized ore minerals.

The deposit is situated about 17 km NW of Amadiya Town in an area dominated by Middle and Upper Triassic limestones and dolomites, and mudstones and siltstones of Miocene and Eocene age. The highly faulted and brecciated Triassic rocks form the high mountains and cliffs whereas Tertiary rocks, being usually softer, represent the lower parts and valleys. Three major tectonic structures were recognized in Serguza. These are: 1) An E- W striking thrust fault accompanied by a thick zone of brecciated massive Middle Triassic dolomites. 2) A NE-SW highly crushed SE-dipping fault zone. 3) A crush zone with a WNW-ESE trend.

The main part of the sulphide ore body is located at the tectonic contact between the Triassic and Tertiary rock units. It is a massive pyrite body which contalns nests and small veins of sphalerite and galena. The oxidized part of the ore body extends several hundred meters east and west of the sulphide body as 5-10 m thick gossans, conformable with the Middle Triassic dolomite beds.

Microscopic studies of ore minerals reveal two generations of sulphide minerals. The first generation of sulphides shows sedimentary structures: banding, lamination and micro-folding. The second generation appears in small veins and as impregnations in breccia zones, frequently associated with secondary dolomite and quartz. The ore minerals are highly deformed, brecciated and recrystallized. The sulphides form intergrowths with the dolomite; calcite occurs more frequently in the oxidized zone.

Pyrite represents the major sulphide mineral occurring as fine to medium crystalline aggregates, highly fractured and deformed massive concentrations, and also as euhedral crystals in country rocks. Colloform textures are rare. In the brecciated zones the fragmented pyrite is often cemented by galena or sphalerite and is relatively enriched with arsenic. Its Ni content is much higher than that of Co (Co/Ni ratio of 0.1) indicating a sedimentary origin (Cambel and Jarkovsky 1967).

The first generation of galena occurs as aggregates, filling fractures and cracks between the pyrite crystals. A second generation of galena occurs in country rock dolomites as scattered aggregates together with sphalerite. Galena may have suffered flow-like deformation. It is poor in silver and contalns high amounts of antimony characteristic of a sedimentary origin (Vaugham, 1976; Mercer, 1976).

Sphalerite occurs mainly as massive dark grey concentrations in the main pyrite ore body. Second generation sphalerite is usually lighter in colour forming veinlets and filling cracks in the dolomite host rock. The sphalerite has suffered deformation and fracturing. It contalns tiny inclusions of second-generation pyrite. It has very low iron and manganese contents. The remobilized sphalerite is almost depleted in iron. Cd and Ge contents are relatively high. These geochemical features are typical of low temperature strata bound sphalerite (Vaughan 1976, Hall and Heyl, 1968).

Gangue minerals comprise dolomite and quartz. Dolomite displays different textures, and is usually associated with second-generation sulphides in small veins. Quartz is associated mostly with galena and sphalerite, appearing in small veins within country rocks and as scattered crystals in the main ore body. Secondary minerals are represented by major limonite and goethite

accompanied by minor cerussite usually replacing the galena partly or completely, and very minor smithsonite.

The average ore grade of the Seguza Pb-Zn deposit is: 9.7% Zn, 5.7% Pb and 10.9% Fe (mostly as pyrite). The silver content (62 ppm) is related to the Pb content of the galena. Copper content in the ore is very low (384 ppm); arsenic (As) concentrations are relatively high with an average of 4467 ppm. Cadmium (443 ppm) correlates well with zinc, and antimony is shared between galena and sphalerite, averaging 153 ppm in the ore body.
The chemistry of the ore minerals is shown in Table 20-1. Geochemical differences between the two generations of sulphides indicate different conditions of formation. The second generation of these sulphides may have formed at higher temperatures than the primary sulphides, following intense Late Tertiary tectonic deformation.
The Middle Triassic carbonates comprise light grey dolomite and dark grey calcareous limestone. The ore occurs in highly brecciated and recrystallized dolomites. The Tertiary dolomites contaln higher amounts of clastic components (quartz, clay minerals and iron oxides). The Middle Triassic dolomites contaln the highest amounts of Pb, Zn, Ag, Cu and F which are not related to the clastic fraction.

20.3.2.1.1 Sulphur isotopes

Hand picked samples of galena; sphalerite and pyrite were analyzed for their sulphur isotopic composition. The results are summarized in Table 20-2 (the page 292).

Differences in isotopic composition of the samples suggest the original material was inhomogeneous. However, the trend $\delta^{34}S_{py} > \delta^{34}S_{sph} > \delta^{34}S_{ga}$ indicates that these minerals are close to isotopic balance. The narrow spread of the 834S values around zero suggests that only minor biologic activity occurred during formation of the sulphides (Jensen 1967). Marine sulphate bearing waters could have been the parental fluid from which sulphides precipitated. However, a volcanic-exhalative origin is also possible.

20.3.2.1.2 Genesis of the deposit

The model age t 6-7 and t 8-7 was calculated, using a method employed by the Czech Geological Survey. The results suggest that galena from the Serguza deposit is 140-160 Ma old ~ate Jurassic-Early Cretaceous). The results have a relatively large error range of ±40Ma.
The Serguza lead-zinc-pyrite deposit has indications of both a syn-genetic (including early diagenetic) sedimentary origin, and an epigenetic hydrothermal origin. The occurrence of primary ore minerals is stratigraphically controlled by the Middle Triassic dolomites but the ore did not necessarily form during the Triassic. The ore initially formed after deposition of the host carbonates (probably with anhydrite) and before folding. Iron, base metals, and most sulphur were probably derived from very low temperature metal-bearing chemically active solutions. Remobilization of these ores, during Late Tertiary deformation, led to the formation of second-generation galena, sphalerite and pyrite. These minerals were epigenetically re-precipitated in crush zones, fault planes and small cracks and fractures in the Triassic and Tertiary rocks. The mineral deposits may occur preferentially in recrystallization solution breccias in the Triassic carbonates which formed by dissolution of anhydrite.

The Serguza deposit with its simple mineralogy, Triassic dolomitic host rock, strata-bound features and geochemical characteristics is similar to other Alpine strata-bound Pb-Zn deposits of the Mediterranean belt described by Antonijevic (personal communication, 1980). This mineralization may be the result of volcanicity associated with the early rifting of the Southern Neo-Tethys (Chapter 3).

Table 20-1: Minor and trace elements of the Serguza deposit ore minerals. Contents are in ppm except for Fe, Pb, and Zn and As in pyrite which are all in %. Data on the ore body average composition are calculated from data published by Al-Qaraguli and Lange (1978). The analyzed dolomites are ore-bearing

Galena	**Ag**	**Sb**	**Bi**	**Cu**						
First generation	448	3000	85	310						
Second generation	620	1500	357	530						
Sphalerite	**Fe**	**Sb**	**Mn**	**Cu**	**Cd**	**Ge**	**Ga**			
First generation	1.0	1600	20	850	2250	135	6			
Second generation	0.1	950	280	430	2870	270	140			
Pyrite	**Co**	**Ni**	**Mn**	**Cu**	**As**					
First generation	6	78	16	110	1.32					
Second generation	5	51	19	260	0.16					
Dolomite	**Fe**	**Pb**	**Zn**	**Ni**	**Cu**	**Cd**	**Ag**	**As**	**Ga**	**Mn**
M Triassic	2.23	0.09	0.92	48	17	20	1	160	1	290
Younger veins	0.60	0.06	2.01	510	40	70	3	100	12	770
Ore body	**Fe**	**Pb**	**Zn**	**As**	**Cu**	**Sb**	**Cd**	**Ag**		
Sulphide	10.87	5.68	9.69	4467	384	153	443	62		
Oxidised	45.63	0.29	0.61	588	152	14	44	137		

Table 20-2: Sulphur isotopic composition of major sulphide minerals

Mineral	$\bar{a}^{34}S$ (per mill)
Galena	- 1.8
Galena	- 2.6
Sphalerite	- 0.4
Sphalerite	0.0
Pyrite	+ 0.2
Pyrite	+ 3.6

20.3.3 Mineralisation in the Zagros Suture

Buday (1970) distinguished three tectonic units in NE Iraq thrust belt: the intermontane Tertiary foredeep or Intermediate Zone, the Cretaceous Qulqula Nappes, and the Tertiary Nappes. In this book the Qulqula Zone is referred to as the Qulqula-Khwakurk Zone; the Tertiary nappes are divided into the Penjween- Walash and the Shalair Zones. The Shalair Zone is an integral part of the Sanandaj-Sirjan Zone of Iran (see Chapter 6). The distribution of mineral deposits of the Zagros Suture is shown in Figs. 20-2, 20-3 and 20-4.

Three types of Iron mineralization are found in the Zagros Suture: 1) contact metasomatic or skarn deposits, 2) magmatic segregation deposits, and 3) hydrothermal veins and lenses of siderite. The major iron occurrences of contact metasomatic character are concentrated near Penjween (Fig. 20-4). The largest one is the Asnawa deposit, located about 3.5 km SSW of Penjween Town. Two

NE-SW trending zones containing magnetite were recognized. Magnetite occurs in small lenses in siliceous limestones and schists in the lower unit of the Penjween Group accompanied by minor pyrrhotite, pyrite, chalcopyrite and arsenopyrite. Teretenko and Khadikov (1961) classed the mineralization as contact metasomatic and considered that it originated along the contact of diorite intrusion in the carbonates of the Penjween Group.

The iron mineralization at Mishav, in the easternmost part of the Shalair Valley, consists of nine small magnetite-hematite bodies in limestones, andesite tuffs and porphyries of the Shalair and Katar Rash Group. The iron minerals occur in skarns containing garnet and actinolite. The mineralization appears to be related to small granodiorite intrusions that penetrate volcanosedimentary units. Similar mineralization in the Katar Rash Group was reported elsewhere in the Shalair Valley.

Skarn-type magnetite mineralization was also described by Bolton (1956) from the Marapasta area in the Qandil range of the Zagros Suture Zone, NE of Ranya. Buday and Vanecek (1971) described some siderite veins at this locality.

Iron mineral deposits of magmatic origin occur as magmatic segregations associated with chromite, or are related to serpentinization of ultramafic bodies. Magnetite-chromite bodies are restricted to two main districts: Penjween and Rowanduz. Numerous small vein-like and irregular magnetite bodies accompanied by chromite occur in ultramafic rocks (mostly serpentinized peridotite) in the Penjween intrusive massif. The most extensive mineralisation in the Penjween Massif occurs at three localities: Karigapla, Buban and Kani Manga. Similar iron mineral deposits are associated with chromites in the Mawat massif. The chromite-magnetite mineralization in the Rowanduz area is confined to small serpentinite bodies in two localities near Darband Rayat (Rowanduz Valley); they occur in three zones with 8 small bodies. Vasilijev and Pentelkov (in Vanecek 1972) related this mineralization to hydrothermal alteration of primary ferruginous conglomerates. Loletti (in Vanecek 1972) considered this deposit to be of contact metasomatic origin. The iron mineralization is accompanied by about 4% Cr203, and Ni, Cu and Co concentrations of 0.5-2%. Iron mineralization in serpentinite containing 2-3% Cr203 and about 0.5% Ni was reported adjacent to these ore deposits near the Babakrawa village. High Cr and Ni contents may indicate magmatic segregation of the Derband Rayat magnetite. Mafic and ultramafic rocks have been altered to serpentinite at Shetna Sheikhan NE of Rowanduz. The serpentinite intrudes limestones; six small chromite lenses accompanied by magnetite were reported by Polnikov and Nikolayev (1962). At Darband Rayat the ultramafic rocks are overthrust by Tertiary volcanosedimentary rocks of the Naopurdan Group.

Chromite occurrences were described by Vanecek (1972) in the Mawat Massif. They occur in serpentinized peridotite near Kurra Dawi village. Placer chromite was reported from Kani Sard NE of Sulalmaniya which were probably derived from the Mawat Massif.

Manganese ores are mostly restricted to the Qulqula Group and are exposed between Sulalmaniya and Penjween. Some manganese occurrences were also reported NE of Ranya (Vanecek 1972). The association of these manganese deposits with the radiolarian chert suggest a deep oceanic origin, possibly related to manganese nodule formation. Manganese minerals such as psilomelane, pyrolusite and manganite occur as coatings, crusts and nests. The only manganese deposit in Iraq, which is clearly related to volcanicity, is at Gola, NW of Penjween where psilomelan and pyrolusite occur in five zones at the contact of a basaltic intrusion with cherty slates of the Qulqula Group. These deposits are probably of exhalation origin (SmirnovNelidov 1962).

Small veins of Nickel mineralization were described by Vasiliev and Pentelkov (1962) at nine sites near the Bard-iZard village in the Darband Rayat area. They contaln niccolite, rarnmelsbergite, arsenopyrite, pyrite, carbonates and secondary annabergite and morenosite. Some nickel and cobalt contents were also reported in serpentinized peridotite in the Penjween Massif and are accompanied by arsenic in the Hero Valley in the Bulfat region.

Copper ores in the Zagros Suture occur in two forms: disseminated mineralization in ultramafic and mafic magmatic rocks and as hydrothermal mineralization in quartz veins. Copper occurrences are widespread but most are not of economic interest; they are related to serpentinised ultramafic rocks and gabbros of the Penjween, Mawat and Bulfat massifs and to metavolcanites. Copper mineralization is represented by coatings of malachite and azurite, or disseminated grains of chalcopyrite accompanied by pyrite. The copper ores at Bir Achminda-Benosa in the Bulfat Massif are associated with phyllites of the Walash Group intercalated with crystalline limestone and greenstone (meta-andesite). The mineralization consists of malachite, chalcocite, chrysocolla, limonite (replacing pyrite) and quartz. More than ten copper occurrences containing malachite and Cu-bearing pyrite were reported near lira village east of Qalat Dizeh town where they are related to phyllites and epidote-bearing schists of the Bulfat Group cut by granite dikes (Vanecek 1972). Copper ores of probable hydrothermal origin were investigated by Roulkovsky (1962) near Spidareh village in the Pushtahashan Valley of the Qandil Range. They comprise local veins and impregnations in tuffaceous phyllites, norites and quartz-albitophyres. They contaln quartz, chalcopyrite, pyrite, sphalerite and malachite. Some copper and nickel mineralization was reported in serpentinite bodies outcropping for a distance of about 8 km near Galala (Darband Rayat), E of Rowanduz.

Copper deposits in the Waraz area of the Mawat Massif were studied by GEOSURV in the early 1970's. Electromagnetic surveys were conducted. In 1990, detailed mapping in the area was carried out. A 300 m deep exploration borehole was drilled. Copper is associated with metabasalts (> 600 m thick) of the Mawat Group, as lenses of malachite between volcanic flows or as disseminated chalcopyrite within the volcanics. The borehole data showed that chalcopyrite is disseminated throughout the metabasalts but is sometimes concentrated in basalt flows (Saad Z. Jassim, personal communication).

Vanecek (1972) reported several lead and zinc occurrences in the Zagros Suture; the most important is the Marapasta deposit. Weak base metal mineralization, in a steeply dipping NE-SW striking quartz-marcasite zone extending for about 5 km near Sirnah, was described by Bolton (1956).

A few grains of placer gold were described by Smirnov and Nelidov (1962) in the Shalair Valley (N of Deza village) which were thought to be derived from small intrusive bodies of granite, granodiorite and quartz porphyry exposed at several sites in the valley. However, the location of the placers suggests they were derived from the volcanics of the Katar Rash Group exposed on the northern flank of the Shalair anticline. Gold is known to be associated with arc volcanics (dacites) in the Andes (Vanecek, 1994, p. 279).

Fig. 20-3: Distribution of metallic mineral deposits and occurrences in the N part of the Zagros Suture (after Vanecek, 1972)

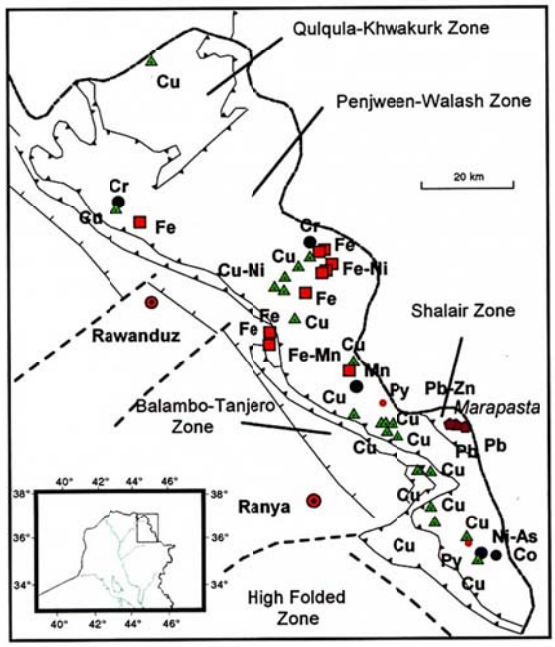
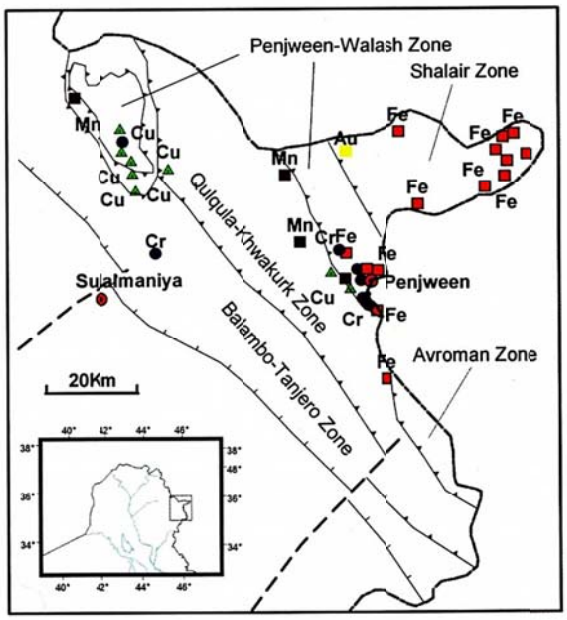


Fig. 20-4: Distribution of metallic mineral deposits and occurrences in the S part of the Zagros Suture (after Vanecek, 1972)



20.3.3.1 The Marapasta base metal deposit and its origin

The Marapasta locality is one of the most important base metal deposits in Iraq. The Marapasta area was studied by Bolton (1956), Polnikov and Nikolayev (1961), Akif and Vanecek (1972),Vanecek (1972), Akif et al.(1973), Sattran et al.(1973) and Hak et al. (1983). Exploration geochemistry and geophysics studies were conducted by (Al-Bassam 1977) and (Nahab and Rahman 1974) respectively. Al Bassam and Akif (1977) studied the ore petrology of the deposit. Hak et al. (1983) provides information on ore petrology, the chemistry of major and minor minerals, and isotope studies and discusses the origin of the deposit.

The Marapasta area is situated about 1.5 km from the Iranian border, about 6 km behind the thrust front at an altitude of 2000-2400 m ASL. The rocks were subdivided by Buday and Vanecek (1971) into two series: the Qandil Series and the Marapasta Series (correlated with the Shalair Group); the Marapasta Series has been thrust over the Qandi1 Series. The layering in the Marapasta Series rocks dips at about 30°-40° to the NNE. The host rocks are phyllites, locally tuffaceous, and massive deformed lenticular recrystallized limestones that are fractured and brecciated. These rocks are part of a thrust sheet which has been transported for a considerable distance. The underlying Qandil Series comprises alternating beds of grey and white sheared limestones.

There are two main systems of faults recognized in Marapasta. Reverse faults strike NE-SW and normal faults strike NW-SE. Some thrust faults have been reactivated during movement on younger NW-SE trending thrust faults, creating a complex fault pattern. Ore occurs in three localities: Seh Kutchika which is the highest peak in the area (2410 m ASL.), Darman about 800 m NW of Seh Kutchika

. (2200 m ASL) at the edge of a steep gully, and Narta about 1 km E of Seh Kutchika (2100 m ASL). The ore bodies are folded, fractured, faulted and locally recrystallized, and covered by gossans particularly at Seh Kutchika. The country rocks are similarly deformed. Trenches dug to

evaluate the deposits failed to establish any structural relationship between them. Bolton (1956) suggested that the main ore body was situated at Seh Kutchika and that the lower occurrences are due to landslides.

Mafic and ultramafic intrusive rocks outcrop near Qandil, a few kilometres NW, Wand SW of Marapasta. According to Akif et al. (1973), sills occur locally in the "Marapasta Series"; blocks of sills have been found in the scree. The sills are 2-30 m thick and at least 100-200 m wide. They comprise diabase, olivine basalt and diorite porphyry.

The mineralisation consists of two different assemblages. One assemblage consists of galena, sphalerite, pyrrhotite, pyrite, marcasite and rare arsenopyrite. Another "skarntype" assemblage consists of magnetite, willemite, gahnite, and rare garnet and nickeline. Secondary minerals smithsonite, limonite and cerussite frequently occur.' The mineral assemblages have different textures. The first assemblage is characterised by orientated linear textures in massive and banded sulphides and occurs at Darman and at Narta. The skarn assemblage occurs at Seh Kutchika. The skarn assemblage appears to be either younger than the strata-bound deposit or contemporaneous, but of different chemical composition. The strata-bound assemblage is characterized by sphalerite with a consistent iron content of about 9% Fe. Sphalerite of the skarn assemblage has low iron content «0.5%) (Table 20-2), and is sometimes compositionally zoned with cores richer in Fe than the rims. Both sphalerite occurrences have Mn, Cd and Cu contents.

Magnetite is characterized by a relatively high content of Ti and N; the concentrations of Cr, Co, Mn and Zn are below the detection limits of the electron probe. The intimate intergrowths of most minerals made the examination of minor and trace elements in individual minerals difficult using emission spectrometry. Ag, As, Ba, Ca, Co, Cr, Cd, Cu, Ga, Ge, **In,** K, Mn, Na, Ni, Sn, Ti, V, Y, Yb and Zr consistently occur in the major minerals: magnetite, pyrrhotite, pyrite, galena and sphalerite in minor or trace amounts. Contents of AL, Mg and Si are high in mixtures of rock and gangue minerals. B, Be, Mo, Sb, Sc, Sr and Te are present in very low concentrations. Bi was found in one galena sample.

The lead model age of the deposit was determined to be 180-200 Ma ± 30 Ma (Table 20-4).

Table 20-3: Electron probe analyses of sphalerite in weight%. 1) Sphalerite with poikiloblastic magnetite and minor nickeline enclosed by galena. 2) Sphalerite adjacent to partially oxidized galena. 3) Sphalerite partially altered to willemite. 4) Unaltered sphalerite enclosed by galena. 5) Sphalerite adjacent to galena in pyrrhotite (partially altered to pyrite and marcasite). 6) Sphalerite pod with inclusions of carbonate with pyrite, marcasite and arsenopyrite. 7) Sphalerite enclosed by pyrite. 8) Sphalerite with rare pyrrhotite blebs in contact with pyrrhotite and pyrite. 9) Sphalerite near arsenopyrite in pyrrhotite. 10) Sphalerite with galena, marcasite, arsenopyrite. 11) Clear sphalerite adjacent to galena pyrite and sphalerite with abundant pyrrhotite inclusions. 12) Sphalerite with pyrrhotite, galena, pyrite and arsenopyrite

	1	2	3	4	5	6	7	8	9	10	11	12
Locality	Seh Kutchika	Seh Kutchika	Seh Kutchika	Seh Kutchika	Darman	Darman	Darman	Darman	Darman	Darman	Darman	Darman
No of analyses	5	2	2	1	5	3	1	3	3	3	2	2
Zn	66.14	67.93	66.40	64.82	57.69	58.28	57.37	57.29	56.95	57.78	57.20	56.57
Fe	0.45	0.08	0.10	0.40	8.16	8.42	9.66	9.60	9.89	9.69	9.36	9.68
S	33.03	33.61	33.20	32.37	33.72	33.25	33.83	33.76	33.39	33.79	33.96	33.79
Total	99.62	101.62	99.70	97.60	99.58	99.94	100.87	100.94	100.23	101.26	100.52	100.04

Table 20-4: Lead model age of galena from Marapasta. The model age t_{6-7} and t_{8-7} has been calculated using a method employed at the Czech Geological Survey, Prague and carried out by Dr J. Legierski

Locality	Pb^{204}	Pb^{206} Pb^{206}/Pb^{204}	Pb^{207} Pb^{207}/Pb^{204}	Pb^{208} Pb^{208}/Pb^{204}	t_{6-7} Ma t_{8-7} Ma
Seh Kutchika	1.351	25.02 18.52	20.35 15.80	52.28 38.70	180 180
Seh Kutchika	1.341	25.01 15.89	20.01 15.89	52.28 38.90	180 190
Darman	1.346	24.98 18.56	20.38 15.88	52.29 38.85	190 200
Ore body Z	1.348	25.01 18.55	20.36 15.84	52.28 38.78	180 190

20.3.3.2 Comments on the ore genesis

Early studies suggested the mineralization had a hydrothermal metasomatic origin in which a "skarn-type" mineral assemblage rich in zinc and iron preceded the lead sulphide formation (Akif et al., 1973). Later observations based mostly on microscopy and chemistry suggest a different origin for the Marapasta deposit. The finer-grained massive or banded sulphide material has a metamorphic texture. The ore bodies at the Darman locality occur in phyllitic slates and marbles; associated mafic volcanic rocks suggest that the ores initially formed in a volcanogenic sedimentary environment. The ores and country rocks were probably later affected by low-grade metamorphism. The consistent sphalerite composition and textures (e.g., porphyroblastic pyrite and evident foliation) support this model.

The older strata-bound Pb-Zn deposit may have been fractured allowing flow of solutions rich in silica and oxygen, which resulted in formation of silicates and oxides of zinc and iron, where faults intersected ore-bearing strata. During this water-rock interaction zinc and iron would have been mobilised from the original strata-bound deposit to form secondary minerals, later metamorphosed to willemite, zincite, magnetite, gahnite, garnet and chlorite. Removal of sulphur led to the formation of pyrite-marcasite that frequently replaced pyrrhotite in banded ores (bird's eye texture). Younger pyrite veinlets cutting the banded ores and even pyrite porphyroblasts in adjacent rocks may have formed during this process. However pyrite may have been an original

constituent of the sedimentary rocks and recrystallized during metamorphism. Original sphalerite and galena may have been remobilized by hydrothermal solutions prior to the formation of the magnetite ore. Wall rock alteration (indicated by oxide mineral assemblages) suggests this process may have occurred.

Further work on the origin of the deposit is required. The existence of strata-bound metamorphosed ores however has been confirmed. Laterally extensive banded Pb-Zn ores may thus occur in the area. In Turkey several deposits in the ophiolitic zone of the Tauride are believed to be of volcanogenic-sedimentary origin (Akif et al.l973 and Bernard 1971). Large lead-zinc deposits in Iran (the largest is at Anguran) are thought to have been formed by metasomatism in carbonate rocks and may also be of volcanogenic-sedimentary origin.

20.4 Non-metallic mineral and industrial rocks

20.4.1 Non-metallic minerogenic stratigraphy

Outcropping non-metallic mineral and industrial rocks range in age from Permian to Recent. The stratigraphic distribution of non-metallic mineral deposits is shown in Table 20-5. On the Stable Shelf the Palaeozoic strata contaln quartz-sand and kaolinitic clay of the Ga'ara Formation (Permocarboniferous). The Mesozoic rocks of the Stable Shelf (surrounding Rutba Uplift) comprise dolomites (Upper Triassic), lateritic ironstone (Lower Jurassic), heavy mineral bearing sandstones (Middle Jurassic), karst bauxite and quartz-sand (Lower Cretaceous) and phosphorites with montmorillonite- palygorskite- porcelanite associations (Upper Cretaceous and Palaeogene). Mesozoic carbonates also occur in the Unstable Shelf area in cores of anticlines in the High Folded and Foothills zones.

Barite occurrences are recorded in the Triassic and Jurassic units of the Northern Thrust Zone. Marbles formed during regional metamorphism of carbonate units of the Qandil Series. Hydrothermal activity in the Northern Thrust Zone was associated with barite mineralization in the Cretaceous carbonates of Shiranish and Aqra and Bekhme formations.

The Tertiary sediments on the Stable Shelf and parts of the Unstable Shelf contaln phosphorite, claystone (montmorillonite-palygorskite) and porcelanite. Palaeogene limestones and dolomites occur on the Unstable Shelf. Igneous activity along the active margin of the Arabian Plate locally led to the formation of marble in the Walash Group.

The Neogene sequences contaln extensive Lower Miocene carbonates in the Unstable Shelf (Euphrates Formation). The Middle Miocene units contaln evaporite deposits; gypsum and rock salt deposits are common in the Jezira and Foothills zones. Bio-epigenetic stratiform native sulphur deposits formed during the Pleistocene. Pliocene fresh water limestones contaln smectite-palygorskite claystones (Zahra Formation). The Quaternary sediments are dominated by fluvio-lacustrine and aeolian clastic deposits, inland sabkha and salt deposits.

Table 20-5: Minerogenic stratigraphy of the non-metallic minerals and industrial rocks in Iraq (Al-Bassam, 1986)

Age	Western and Southern Deserts	Mesopotamian Zone	Jezira and Folded Zone	N and NE Thrust Zones
Permian	kaolinite, quartz-sand, dolomite sedimentary Fe heavy minerals			
Triassic	Dolomite			barite, limestone
Jurassic	lateritic Fe, sand, kaolinite dolomite, heavy minerals			barite
Cretaceous	karst bauxite, quartz-sand, phosphorite, montmorillonite palygorskite, porcelanite		limestone	marble, barite igneous rocks
Palaeocene	phosphorites, porcelanite montmorillonite			marble, igneous rocks
Eocene	limestone, phosphorite, dolomite		dolomite, limestone	marble, igneous rocks
Oligocene			limestone, dolomite	
Miocene	clay, sand, limestone, dolomite		native Sulphur, gypsum dolomite, rock-salt, limestone	
Pliocene	Sand	Sand and gravel	Bentonite, palygorskite veins, gravel and sand	
Pleistocene	sand and gravel	Sand and Clay	gravel and sand, clay glauberite, halite	

20.4.2 Deposits

20.4.2.1 Kaolinitic claystone

Kaolinitic claystone deposits occur in Pre-Cretaceous units in the Western Desert. The upper part of the Ga'ara Formation (Permocarboniferous) in the Ga'ara area contalns white and multi-coloured kaolinitic claystones. They also occur in the lower part of the Hussainiyat Formation (Lower Jurassic) along Wadi Hussainiyat and in the Amij Formation (Middle Jurassic) at Wadi Amij (Mahdi and Al-Delaimi, 1999). The Jurassic kaolinitic deposits are highly ferruginous and of low grade (Table 20-6). Flint-clays occur as karst-fill deposits of Early Cretaceous age associated with bauxite and bauxitic clay in very restricted localities in the Western Desert (Al-Rubali, 1997). All kaolinitic clay's of Iraq were transported as kaoline from source areas in the S, SW and Wand were deposited in a fluvial system.

Table 20-6: Chemical composition of montmorillonite and palygorskite claystones (Al-Bassam et al., 1989; Al-Bassam and Al-Sa'adi; 1985; Zainal, 1977; Aswad et al., 2000; Al-Sayegh et al., 1976)

Wt. %	Ga'ara Fn.		Hussainiyat Fn.		Amij Fn.	Karst-fill
	white	coloured	NE	SW		Flint clay
SiO_2	48.1	51.1	50.7	45.0	48.0	38–45
TiO_2	1.1	1.5	1.4	1.9	1.5	1.4–3.0
Al_2O_3	35.7	28.7	28.7	31.0	29.0	35.0–41.5
Fe_2O_3	0.9	7.0	5.5	5.5	6.1	0.5–2.0
LOI	12.7	10.3	9.6	12.3	11.0	13–15

20.4.2.2 Montmorillonite and Palygorskite

Extensive montmorillonite-rich marine sedimentary claystones occur in the Upper Cretaceous Digma Formation and to a lesser extent in the Palaeocene Akashat Formation in association with phosphorite (Al-Bassam and Al-Sa'adi, 1985). These claystones were originally black shales, rich in carbonaceous matter (Al-Bassam and Al-Haba, 1990). Palygorskite is associated with montmorillonite in these deposits and is the dominant clay mineral in shallow, near- shore areas of the basin (AL-Bassam, 2000). The montmorillonite-palygorskite claystones in these units are 1-10 m thick. They are calcareous and slightly phosphatic (Table 20-7).

Palygorskite veins were discovered in the Mukdadiya (Lower Bakhtiari) Formation in N Iraq at Jabal Maqlub and Ba'ashiqa. They are vertically or steeply dipping and 1 to 50 cm thick. The veins probably formed by direct precipitation from solution, either by pedogenic or hydrothermal processes (AL-Sayegh et al., 1976). Montmorillonite and palygorskite are the dominant clay minerals in Iraq from the Upper Cretaceous and Tertiary formations. Kaolinite is more dominants in older rocks; this may be due to climatic factors (AL-Bassam, 1996).

Table 20-7: Chemical composition of montmorillonite and palygorskite claystones (Al-Bassam et al., 1989; Al-Bassam and Al-Sa'adi; 1985; Zainal, 1977; Aswad et al., 2000; Al-Sayegh et al., 1976)

	Montmorillonite		**Bentonite**	**Palygorskite**	
Wt%	**Digma**	**Akashat**	**Mukdadiya**	**Digma**	**Mukdadiya**
SiO_2	62.7	56.8	51.0	57.9	60.2
Al_2O_3	13.3	15.7	20.2	12.6	11.2
Fe_2O_3	5.4	5.1	2.4	6.2	0.8
CaO	3.4	4.5	7.7	1.8	0.3
MgO	4.5	3.4	5.0	8.6	10.2
Na_2O	0.5	1.1	0.7	1.4	0.2
K_2O	0.5	0.6	0.4	0.6	0.2
LOI	8.3	9.5	11.3	10.5	16.1

20.4.2.3 Bentonite

Small deposits and occurrences of bentonite "sensostricto" occur in the Mukdadiya Formation (Pliocene) in Jabal Hemrin South, 120 km NE of Baghdad and along the Baghdad-Kirkuk highway. These deposits formed by alteration of a volcanic ash horizon deposited in a fluvial basin. They are associated with tuffs and fluvial clastics. Glass shards indicate these deposits are of volcanic origin (Zainal, 1977).

Montmorillonite clays also occur in playas and topographic depressions in Mesopotamia, in desert depressions, and in synclinal areas in the Foothills and High-Folded zones. They are associated with fluvial deposits, with other clay minerals: chlorite, palygorskite, illite and kaolinite, and with carbonates and quartz (Alsinawi et al., 1977, Al-Hilali 1980 and Shanshal, 2004». These deposits are an important raw material for the cement and brick industry. Typical chemical analyses are shown in Table 20-8.

Table 20-8: Chemical composition of Quaternary clays (Shanshal, 2004)

Wt. %	Range	Mean
SiO_2	30.8-53.4	38.7
Fe_2O_3	2.3-4.3	3.4
Al_2O_3	6.6-8.7	7.6
CaO	15.3-20.3	18.3
MgO	2.4-5.9	4.2
SO_3	0.3-7.2	2.1
LOI	14.9-25.3	20.6

20.4.2.4 Phosphorite

The phosphorite deposits of Iraq are part of the Tethyan phosphogenic province extending from Senegal and Mauritania in the W to Iraq, Iran and Turkey in the E. They are marine sedimentary deposits, which range in age from Late Cretaceous to Eocene. They are granular in texture, associated with limestones, black shales (mostly smectite), porcelanite and chert.

Thin beds of phosphorite occur in the Digma Formation (Maastrichtian). Thick beds occur in the Akashat Formation (Palaeocene) and in the Ratga Formation (Eocene). The phosphorite beds are 0.5-12 m thick. The Digma and Akashat Formation phosphorites have an intraclasticbioclastic and a pelloidal-ooidal texture respectively.

Coprolites and phosphorites with intraclastic textures occur in the Eocene deposits. The cementing material is usually calcite; some siliceous cemented phosphorites occur. Francolite is the only phosphate mineral in the Iraqi deposits (AL-Bassam, 1976 and 1992). The chemical composition of some of the known phosphorite deposits is shown in Table 20-9.

The Iraqi phosphorites, (like all Tethyan phosphorites) were deposited under special palaeogeographic conditions by upwelling of deep oceanic phosphate rich waters onto shallow shelves (Sheldon, 1981). Francolite was deposited at and below the sediment-water interface via a biogenic phase (AL-Bassam, 1976). A recent study has shown clear evidence of microbial activity in the formation of the Iraqi phosphorites (AL-Bassam et al., 2000a).

Table 20-9: Chemical analysis of some Iraqi phosphorites (Al-Bassam, Al-Dahan and Jamil, 1983; Al-Bassam, 1976; Al-Bassam and Hagopian, 1983)

Wt.%	Digma Fn. Maastrichtia	Akashat Fn. Palaeocene	Ratga Fn. Eocene
P_2O_5	25.6	22.1	20.8
SiO_2	10.1	1.8	0.4
Al_2O_3	0.8	0.3	0.1
CaO	40.9	53.0	54.4
MgO	0.2	0.5	0.4
SO_3	1.7	1.4	1.1
Na_2O	0.7	0.8	0.5
F	3.3	2.9	2.4
LOI	11.4	16.7	20.5

20.4.2.5 Porcelanites

These are siliceous rocks, composed of opal-CT (cristobalite-tridymite crystal stratification) derived from biogenic amorphous opal silica (mainly from diatoms). They are part of the phosphorite-bearing sequences of the Maastrichtian and Palaeocene in the Western Desert (Digma and Akashat formations respectively). Several porcelanite horizons were identified as 0.5-1.0 m thick layers associated with shale, phosphorite and chert (AL-Bassam and Al Sa'adi, 1985; AL-Bassam et al., 2000b). Their chemical composition is shown in Table 20-10.

Table 20-10: Chemical composition of some Iraqi porcelanite (Al-Bassam and Al-Sa'adi, 1985; Al-Bassam et al., 2000b)

Wt%	Maastrichtian (3 horizons)	Palaeocene
SiO_2	58.0-82.2	77.8
Al_2O_3	1.1-3.8	3.0
Fe_2O_3	0.5-1.5	0.6
CaO	0.8-9.9	5.3
MgO	2.7-8.3	1.1
Na_2O	0.4-1.2	2.3
P_2O_5	0.7-2.3	–
LOI	5.4-17.4	8.5

20.4.2.6 Native Sulphur

Native Sulphur deposits and occurrences in Iraq are stratigraphically controlled in the Middle Miocene rocks of the Fatha Formation. The Fatha Formation consists of two members; the lowermost member contalns Sulphur deposits in the crests of some anticlines. The Sulphur-bearing horizons comprise secondary calcite, sulphur and some aragonite. Their original lithology comprised gypsum and anhydrite (Al-Sawaf, 1977). Sulphur originated via bioepigenetic alteration of primary gypsum induced by reduction and oxidation processes under favourable structural and hydrogeological conditions in close association with hydrocarbons (Jassim et al., 1997). Gypsum beds were reduced by e bacteria *(Desulfovibrio desulphuricans)* in hydrocarbon-rich brines flowing from the underlying confined Euphrates Formation to form H_2S during periods of low infiltration of meteoric water. The H_2S gas was then oxidised by reaction with water which flowed into the formation during periods of higher meteoric water infiltration leading to the deposition of economic Sulphur deposits (Jassim et al., 1997).

The Sulphur-bearing horizons are up to 108 m thick, with a sulphur content of 10-30% (average 23%); the Sulphur is present as coarsely-crystalline native Sulphur, filling pores, nests and caverns or as bands alternating with layers of secondary calcite and hydrocarbons.

Most of the native Sulphur deposits and occurrences of Iraq occur in a zone extending from Mosul to Fatha (Fig. 20-1). The Sulphur formation in these deposits may have occurred during the Pleistocene (Jassim et al., 1997). The Iraqi deposits are the largest known occurrence of stratiform bioepigenetic native Sulphur in the world (Barker et al., 1979).

20.4.2.7 Gypsum

Almost all the economic gypsum deposits of Iraq occur in the Middle Miocene Fatha Formation (Lower Fars). They are thick bedded and formed by evaporation in closed or semi-closed marine basins in association with carbonates and claystones. The main deposits are found in the Foothill Zone where more than ten gypsum horizons are recorded in the Fatha Formation. A typical chemical analysis (Mansour and Toma, 1977) is: S03 43--46%, CaO 32-33%, Fe203+ Al_20_3 <0.1%, H_20 19-21 % and Insoluble Residues 1-2 %

20.4.2.8 Halite

Thick rock-salt deposits are recorded in subsurface sections within the Middle Miocene Fatha Formation and the Lower Miocene Dhiban Formation. They were deposited in the central parts of large evaporitic basins in association with gypsum. Thick rock-salt deposits are encountered in three main areas in Iraq: South of Sinjar, S of Kirkuk and between Amara and Kut. The total thickness of the salt beds in these basins ranges from 80 to 165 m; they mostly occur in the lower and middle parts of the Fatha Formation (Dimitrov et al., 1983 and Mustafa et al., 1984). The Lower Miocene Dhiban Formation also contalns thick salt layers near Sinjar.
Several salterns of Quaternary age contaln >95% halite which is being seasonally deposited from groundwater brines. The source of the brines is believed to be deep-seated aquifers in contact with rock salt deposits. Many of these salterns with halite occur in the Jezira area but the largest salt playa is located near Samawa in S Iraq (AL-Baldari, 1988 and Al-Badri et al., 1990).

20.4.2.9 Thenardite and Glauberite

These salt deposits are found in the Shari Lake saltern located 30 km E of Samarra Town. Thenardite (Na2S04) constitutes up to 13% of the 10 cm thick halite salt crusts. Glauberite [Na2Ca (S04hJ occurs in concentrations of up to 50% in the underlying 6.5 m thick clayey sediment (Jassim, 1979). The lateral sequence of salts from the edge to the centre of the saltern is: gypsum-gypsum and glauberiteglauberite-glauberite and thenardite-halite.

Glauberite may have formed due to an increase in the Na" concentration of the brine after precipitation of gypsum, by alteration of gypsum in contact with the brine into glauberite. Alternatively glauberite may have precipitated directly from a brine rich in Nat, Ca^{+2} and $S04^{-2}$ (Jassim et al., 1999). Some species of salt-tolerant bacteria may have caused the oxidation of H2S produced from the disintegration of plant remains to form $S04^{-2}$ thus enhancing the formation of sulphate minerals (Jassim et al., 1998).

20.4.2.10 Barite

Almost all barite occurrences in Iraq are located in the Northern Thrust Zone within the Upper Permian Chia Zairi and the Upper Cretaceous Shiranish formations. They are usually associated with Zn-Pb-pyrite occurrences as veins up to I m thick. Most of these occurrences are believed to be of low-temperature hydrothermal origin and stratigraphically controlled. Samples from Berzanik and Lefan occurrences were reported to contaln 77% and 83% BaS04 respectively (Mironov and Sitchenkov, 1962 and Stevens, 1953).

20.4.2.11 Celestite

Small occurrences of celestite were recorded in the fluvial Injana and Dibdibba formations in the Najaf-Karbala area (AL-Bassam, 1995 and AL-Baldari, 1997). The celestite deposits are lenticular cemented horizons (0.5-1.0 m thick) in mudstones and sandstones. The celestite is present as euhedral crystals with inclusions of calcite and aragonite. Up to 43% celestite was recorded in some samples, associated mainly with quartz, calcite, aragonite and palygorskite (ALBassam, 1995). The celestine is believed to be epigenetic, precipitated from Sr-rich ground waters seeping through springs along the Euphrates Boundary Fault Zone. It formed by direct crystallization and also by replacement of aragonite and calcite (Dawood, 2000).

20.4.2.12 Ironstone

The Hussainiyat sedimentary ironstone deposit of the Liassic Hussainiyat Formation is the main iron deposit in Iraq. It is located in the Western Desert, in the SE parts of Wadi Hussainiyat. The ironstone is about 3 m thick, pisolitic, oolitic, intraclastic and concretionary in texture, and is associated with kaolinitic mudstones and orthoquartzite. The deposit consists of goethite, hematite, kaolinite and quartz. The average chemical and mineral composition of the Hussainiyat ironstone deposit is shown in Table 20-11.

The ironstone and the associated clastics unconformably overlie a weathered and karstified surface at the top of the Liassic Ubaid Formation. Iron and the associated clastics were transported by rivers from deeply weathered source rocks in the Rutba Uplift in the SW. Iron were mostly attached to the clay fraction and organic matter. After deposition, iron concretions were mostly

formed by bacterial build-up in swamps and marshes. They were subsequently embedded in organic-rich kaolinitic mud. Pisolites and oolites grew in situ in the kaolinitic soil at the upper limit of a fluctuating water table, forming a groundwater laterite blanket (ferricrete) under oxidizing pedogenic conditions and seasonally wet climate. The iron intraclasts were formed by the reworking of the ferric rete by ephemeral streams and rivers and were redeposited as channel lag deposits with sand and other clastics (Jassim, 1982; AL-Bassam and Tamar-Agha, 1998).

The upper parts of the sandstone unit of the Ga'ara Formation in the NW rim of the Ga'ara depression is highly ferruginous and can be classified as ironstone. It consists of almost equal proportions of hematite-goethite and quartz. The iron minerals are epigenetic and form the cementing material in the sandstone. The ore bodies are discontinuous, and occur as lenses 200-300 m long and 1-2 m thick (Petranek and Jassim, 1980 and Tobia, 1983).

Table 20-11: Chemical and mineralogical composition of the Iraqi ironstones (Al-Bassam and Tamar-Agha, 1998; Tobia, 1983)

Oxides/minerals %	**Hussainiyat Fn.**	**Ga'ara Fn.**
SiO_2	32.0	50.5
Fe_2O_3	38.4	39.0
Al_2O_3	16.3	1.9
H_2O	9.4	5.1
Geothite-hematite	42	42
kaolinite	41	5
quartz	13	50
others	2	3

20.4.2.13 Karst Bauxite

Bauxite and· bauxitic kaolinite were discovered infilling deep karsts up to 70 m deep in the carbonates of the Liassic Ubaid Formation in the Western Desert. The karst-fill deposits consist of several fining upward cycles of quartz sandstone and kaolinitic claystone with (or without) bauxite and bauxitic flint-clay lenses in the middle (AL-Rubali, 1997).

The mineralogy of the bauxite deposits consists of boehmite and to a lesser extent gibbsite. Non-bauxitic minerals include kaolinite, quartz and hematite (AL-Bassam, 1998). The bauxite minerals are colloformic in texture including pisoids, ooids and pelloids. All grades of bauxitization are found in these deposits.

However, high quality bauxites are absent. The chemical composition is reported in Table 20-12. The age of the karst fill deposits is controversial. The authors believe they formed in the Aptian and that bauxitization occurred at the Aptian-Albian boundary at the same time as the bauxite profile at Zabira in Saudi Arabia (Al-Bassam, 1998).

Table 20-12: Chemical composition of the karst bauxite (Al-Rubaii, 1997)

Oxides	Range	Mean
SiO_2	17.7-22.3	20.6
Al_2O_3	47.7-60.9	55.6
Fe_2O_3	0.4-1.6	0.7
TiO_2	1.2-4.3	2.6

20.4.2.14 Quartz sand

Massive deposits of quartz-sands are encountered in the Nahr Umr (Albian) and Rutba (Cenomanian) formations in the Western Desert. These deposits are >20 m thick and extend in an E- W direction for more than 100 km along the Baghdad-Amman highway. In addition, some Lower Permian sand layers below the Ga'ara depression floor consist almost entirely of quartz. These deposits were derived from granitic source rocks in the Arabian Shield or have been recycled from Palaeozoic sedimentary rocks in the Wand Sw.
The sand consists of 95-99% quartz and generally <1 % Fe203' Occasional thin clay lenses and sandstone lenses cemented with secondary calcite occur. The quartz grains are generally 0.1-0.5 mm in size and sub-rounded to subangular. The Ga'ara Formation quartz-sands are generally fine grained; some coarse grained sands occur in the upper parts of the formation (Shaposhikov and Babushkin, 1961, Shaker, 1983 and Tamar-Agha et al., 1992).

20.4.2.15 Heavy mineral bearing sandstone

Heavy minerals occur in considerable concentrations in the sandstones of the Lower Permian Ga'ara Formation (Table 20-13) and the Liassic Amij Formation (Table 20-14) in the Western Desert. Zircon and rutile are the main heavy minerals in the Ga'ara Formation. Zircon, rutile and monazite are the main minerals in the Amij Formation.
opaques (mean 65.8%), 9-41% zircon (mean 20.8%) and 1-11% rutile (mean 5.1%). The Ga'ara zircons are Hf-rich with high concentrations of Y and rare earths, whereas the rutile is Nb-rich with high concentrations of Cr and V (Table 20-12). The Ga'ara sandstone deposits were probably deposited in meandering river channels (TamarAgha et al., 1984).

Table 20-13: Chemical analysis of zircon and rutile in the Ga'ara sandstones (Ismail, 1989)

Oxides%	Zircon	Oxides%	Rutile
SiO_2	32.23	SiO_2	0.21
ZrO_2	40.84	TiO_2	97.84
HfO_2	20.85	Cr_2O_3	0.28
Y_2O_3	2.21	V_2O_3	0.35
ThO_2	0.85	Fe_2O_3	0.13
UO_2	0.21	Al_2O_3	0.15
Al_2O_3	0.15	Nb_2O_5	0.34

Table 20-14: Chemical analysis of Zircon, Rutile and Monazite from Amij Formation, W Iraq (after Ismail, 1996)

Wt%	Zircon	Wt%	Rutile	Wt%	Monazite
SiO_2	30.61	TiO_2	98.04	SiO_2	0.28
ZrO_2	57.65	FeO	0.47	ThO_2	4.41
HfO_2	7.03	SiO_2	0.18	UO_2	0.51
$Y2O_3$	2.03	Al_2O_3	0.23	La_2O_3	13.03
ThO_2	0.56	CaO	0.38	Ce_2O_3	28.28
UO_2	0.18	MgO	0.02	Nd_2O_3	13.64
Al_2O_3	0.18	Cr_2O_3	0.33	Sm_2O_3	1.25
				Gd_2O_3	1.66
				P_2O_5	29.63

20.4.2.16 Feldspathic sands

The sands and sandstones of the Dibdibba Formation (Pliocene) in the Najaf area contaln appreciable concentrations of feldspar (mainly potash feldspar). The sand gralns comprise 15% feldspar, 70% quartz and 15% rock fragments of igneous and sedimentary origin (Sadik, 1977). The feldspar is concentrated in the coarse fraction as angular to rounded grans, generally more than 0.5 mm (and up to 10 mm) in size. The sands were derived from the mechanical

disintegration of granites in the Arabian Shield and were transported by rivers into Iraq where they formed fan deposits (Ghalib, 1988). Their chemical composition is shown in Table 20-15.

Table 20-15: Chemical analysis of the feldspar-bearing sands in the Najaf area (Al-Bassam et al., 1999)

Oxide%	Raw sand	Sieved (+710 µm)
SiO_2	88.7	86.2
Al_2O_3	3.7	1.1
MgO	0.5	0.2
CaO	0.9	0.4
Na_2O	0.7	1.3
K_2O	1.5	2.8
LOI	2.1	0.4

20.4.2.17 Limestone

Huge deposits of high quality limestone deposits are found in Iraq. The main limestone-bearing units are the Triassic and Cretaceous units in the Thrust Zone, the Miocene units (Serikagni, Euphrates and Fatha formations) in the Foothills and Folded Zone and the Eocene, Miocene (Dammam, Ratga and Fatha formations) in the western and southern deserts. Most of the economic limestone deposits are in the Dammam, Ratga, Euphrates and Fatha formations (Table 20-16) (Mansour and Petranek, 1980).

Table 20-16: Chemical composition of some limestone deposits (Mansour and Petranek, 1980; Sa'eed, 1988)

Oxide %	Dammam Fn.	Ratga Fn.	Euphrates Fn.	Fatha Fn.
CaO	54.20	54.20	53.50	47.60
MgO	0.19	0.24	0.65	1.6
SiO_2	1.65	1.79	1.20	9.80
Al_2O_3	0.12	0.27	0.60	1.37
Fe_2O_3	0.08	0.13	0.15	1.65
SO_3	0.38	0.38	0.18	0.63

20.4.2.18 Dolomite

The main dolomite deposits in Iraq are found in the Folded Zone, and in the Western and Southern deserts. In the Folded Zone the Upper Eocene Pila Spi Formation is the main dolomite-bearing unit. In the Western Desert, the following formations contaln thick beds of dolomite: Upper Triassic Mulussa and Zor Hauran, the Liassic Ubaid and Hussainiyat, the Upper Cretaceous M'sad and Hartha, the Palaeogene Umm Er Radhuma and Dammam, and the Lower Miocene Euphrates. High quality dolomites, suitable for industrial purposes, are available in many of these formations (Table 20-17).

Table 20-17: Chemical composition of some dolomite deposits (Al-Bassam, 1984)

Oxide %	Zor Hauran Fn.	Hussainiyat Fn	Euphrates Fn.	Dammam Fn.
CaO	30.13	30.76	29.40	29.55
MgO	20.62	19.50	18.35	20.48
SiO_2	2.33	2.08	5.24	2.08
Al_2O_3	0.53	0.14	1.69	0.31
Fe_2O_3	0.51	0.51	0.97	0.15
SO_3	0.26	0.07	0.74	0.36

20.4.2.19 Marble

Marble is found in the Penjween-Walash Zone (Qandil Series) at Gimo, Kani Kuwish and Rawkan, and in the Walash Group (Palaeogene) at Galala, Kewarta, Darband and Rayat. The marbles formed by regional and local metamorphic processes. Some unmetamorphosed carbonate rock units are suitable for use as decorative stones (orthomarble) especially the Pila Spi Formation (Eocene) at Salahuldin, Derband Bazyan and Derbendikhan areas (Mansour et al., 1979).

20.4.2.20 Industrial igneous rocks

Granites in the Katar Rash Volcanic Series and gabbro in the Mawat and Bulfat igneous complexes may have some economic value as decorative stone. Basalt flows within the Shalair and Katar Rash Series, may be useful for rock-wool production. Nepheline syenite dykes in the intrusive complex of Bulfat may be useful in the ceramic industry.

References

Abdulla, F. H. A. and Kinghorn, R. R. F., 1996. *A preliminary evaluation of Lower and Middle Cretaceous source rocks in Kuwait.* Journal of Petroleum Geology, 19, p. 461-480.

Abd Al-Rahman, B. K., 1979. *Sedimentological investigation of Rutba sands and sandstones.* MSc Thesis, Baghdad University, Iraq.

Agar, R. A., Stacey, J. S. and Whitehouse, M. J., 1992. *Evolution of the southern Afif Terran; a geochronologic study. Ministry of Petroleum and Mineral Resources,* Directorate General of Mineral Resources, Jeddah, Saudi Arabia, DGMR-OF-10-15, 41p.

Al-Azzawi, M., 1986. *La sedimentation actuelle sur la plaine de la basse Mesopotamie, Irak.* PhD Thesis, University of Paris, Orsay, France.

Al-Badri, A. S., Al-Baidari, A. P. and Kittana, Y. A., 1990. *Geochemistry and origin of Al-Tawila-Albu Gharis salterns in the NW Badiya, Iraq.* Iraqi Geol. J., 23, p. 26-41.

Al-Baidari, A. P., 1988. *Genesis and geochemistry of some salt deposits in Iraq.* MSc Thesis, Baghdad University, Iraq.

Al-Baidari, A. P., 1997. *Mineralogy, geochemistry and assessment of claystones from Injana Formation in Najaf-Kerbala area.* PhD Thesis, Baghdad University, Iraq.

Al-Bassam, K. S., 1972. *Reconnaissance mineralogical study of some lead-zinc deposits in northern and northeastern Iraq.* MSc Thesis, University of Wales, UK.

Al-Bassam, K. S., 1976. *The mineralogy, geochemistry and genesis of the Akashat phosohorite deposit, western Iraq.* J. Geol. Soc. Iraq., 9, p. 1-33.

Al-Bassam, K. S., 1977. *Geochemical prospecting in the Marabasta area, NE Iraq.* Manuscript report, GEOSURV, Baghdad.

Al-Bassam, K. S. and Aqif, A., 1977. *The ore mineralogy of the Marabasta lead-zinc deposit, northeastern Iraq.* J. Geol. Soc. Iraq, 10, p. 12-32.

Al-Bassam, K. S., 1980. *Geochemical study and genesis of the Duri-Serguza lead-zinc-pyrite deposit, N Iraq.* Manuscript report, GEOSURV, Baghdad, 35p.

Al-Bassam, K. A., Hak, J. and Watkinson, D. H., 1982. *Contribution to the origin of the Serguza lead-zinc-pyrite deposits. Northern Iraq.* Mineral deposits, 17, p. 133-149.

Al-Bassam, K. S. and Hagopian, D., 1983. *Lower Eocene phosphorites of the Western Desert, Iraq.* Sed. Geol., 33, p. 295-316.

Al-Bassam, K. S., Al-Dahan, A. and Jamil, A., 1983. *Campanian-Maastrichtian phosphorites of Iraq: Petrology, geochemistry and genesis.* Mineral Deposits, 18, p. 215-233.

Al-Bassam, K. S., 1984. *Final report on the regional geological survey of Iraq, volume 5, Economic Geology.* Manuscript report, GEOSURV, Baghdad.

Al-Bassam, K. S. and Al-Sa'adi, N., 1985. *A new discovery of montmorillonitic clay deposit in Iraq.* J. Geol. Soc. Iraq, 18, p. 218-228.

Al-Bassam, K. S. and Al-Saadi, N., 1986. *The economic importance of the newly discovered montmorillonite clay deposits, south of H3, West Iraq.* Manuscript report, Geological Survey of Iraq.

Al-Bassam, K., 1986. *Metallogenic aspects of Iraq.* J. Geol. Soc. Iraq, 19, p. 183-199.

Al-Bassam, K. S., Mohammad, G. and Saeed, L., 1989. *Detailed mineral investigation of high-grade montmorillonitic claystone deposit, Horan-Traifawi area, Western Desert.* Manuscript report, GEOSURV, Baghdad.

Al-Bassam, K. S. and Al-Haba, Y., 1990. *The geology and organic geochemistry of the Upper Cretaceous and Lower Tertiary black shales and associated phosphorites and limestones from the Western Desert, Iraq.* Iraqi Geol. J., 23, p. 1-15.

Al-Bassam, K. S, Bidawi, J. and Al Kadhimi, J., 1992. *Extension of the Hail Arch in Iraq: New findings.* Geosiences and Arab Development, numbers 1 & 2, p. 12-23.

Al-Bassam, K. S., 1992. *Genesis of the Late Cretaceous-Early Tertiary phosphorites in Iraq.* Iraqi Geol. J., 25, p. 80-103.

Al-Bassam, K. S., 1995. *The Najaf celestite showing: Mineralogy, geochemistry and genesis.* Iraqi J. Sci., 28, p. 80-89.

Al-Bassam, K. S., 1996. *Contribution to the age of the bauxite-bearing karst deposits, Western Desert, Iraq.* Iraqi Geol. J., 29, p. 93-97.

Al-Bassam, K. S. and Tamar-Agha, M. Y., 1998. *Genesis of the Hussainiyat ironstone deposit, Western Desert, Iraq.* Mineral Deposits, 33, p. 266-282.

Al-Bassam, K. S., 1998. *Mineralogy and geochemistry of Cretaceous bauxite deposits in western Iraqi desert and NE of Saudi Arabia.* 13th Iraqi Geological Congress, 18-20 May, 1998, Baghdad.

Al-Bassam, K. S, Al-Ka'aby, A., Al-Timimi, M. and Rasheed, S.,1999. *The use of feldspar-bearing sands from the*

Dibdibba Formation and other Iraqi raw materials in the preparation of porcelain bodies and glazing material. Manuscript report, GEOSURV, Baghdad.

Al-Bassam, K. S., 2000. *Distribution of Iraqi palygorskites in space and time.* In: K.S. Al-Bassam (ed.), The Iraqi Palygorskites: Geology, mineralogy, geochemistry, genesis and industrial uses. GEOSURV, Baghdad (237p). p. 1-9.

Al-Bassam, K. S., Al-Haza'a, S. and Aba Hussain, A., 2000a. *Microbial role in phosphogenesis: Evidence from Late Cretaceous-Early Tertiary phosphorites of Iraq.* 14th Iraqi Geol. Congress., Baghdad, 15-17 Oct., 2000.

Al-Bassam, K. S., Tamar-Agha, M. Y. and Jabboury, W. M., 2000b. *The Upper Cretaceous porcelanites from the Western Desert of Iraq, geology, mineralogy, chemistry and uses.* Iraqi J. Sci., 41c, p. 115-129.

Al-Bassam, K. S., Al-Azzawi, A., Dawood, R. and Al-Bedaiwi, J., 1999-2000. *Subsurface study of the pre-Cretaceous regional unconformity in the western desert of Iraq.* Iraqi Geological journal, 32-33, p. 1-25

Al-Chalabi, I., 2001. *Future Prospects of Iraq's Oil Industry.* MEES 44,8, 19th February 2001, pp. D1-D7.

Al-Din, T. S., Alsinawi, S. A. and Matolin, M., 1970. *Al Um Chaimin depression, Western Iraq.* J. Geol. Soc. Iraq, 1, p. 73-88.

Al-Gailani, M., 1996. *Iraq's significant hydrocarbon potential remains undeveloped.* Oil and Gas Journal, 94, issue 31, p. 108-112.

Al-Gailani, M., 2003. Assesing *Iraq's oil potential.* Geotimes website, October 2003.

Al-Hajri, S. A., Filatoff, J., Wender, L. E. and Norton, A. K., 1999. *Stratigraphy and operational palynology of the Devonian System in Saudi Arabia,* GeoArabia, 4, p. 53-68.

Al-Hilali, M., 1980. *A study of some geochemical and physical aspects of Baladrooz area clays, Diyala Governerate.* MSc Thesis, Baghdad University, Iraq.

Al Hassan, M. E., 1975. *Comparative petrologic study between Mawat and Penjween igneous complexes, northeastern Iraq.* MSc Thesis, Baghdad University, Iraq, 114p.

Al Hassan, M. E. and Hubbard, F. H., 1985. *Magma segregations in a tectonic remnant of basal ophiolite, Penjwin, NE Iraq.* In: Ophiolites through time; proceedings, Desmons, J. (ed.). Ofioliti. 10; 2-3, p. 139-146.

Al Hassan, M. E., 1987. *Rare-earth element pattern of layered gabbro, Penjwin Complex, NE Iraq.* In: Geochemistry of ophiolites. Delaloye, M. and Bechon, F. (eds.). Ofioliti. 12; 1, 238p.

Al Hashimi, H. A., 1973. *The Sedimentary Facies and Depositional Environment of the Eocene Dammam & Rus Formations.* J. Geol. Soc. Iraq, 6, p. 1-18.

Al-Heety, E., 1990. *Crustal Structure Study in Iraq from Seismological Data.* Unpublished PhD Thesis, Baghdad University, Iraq.

Al Jallal, A. I., 1994. *The Khuff Formation: Its reservoir potential in Saudi Arabia and other Gulf countries; depositional and stratigraphic approach.* Geo94, p. 103-119.

Aljawadi, Y., 1990. *Extensional block-faulted structures of Central Iraq and oil findings.* AAPG Bull., 74, 597p. (Abstract).

Al-Khafaji, S.J., 1989. *Rare-earth elements geochemistry of industrial clay deposits in Iraq.* MSc. Thesis, Baghdad University, Iraq.

Al-Khattab, A. A., 1972. *Basrah City: a study of urban geography.* PhD Thesis, University of London, 382p.

Al-Kindy, G., Mahmoud, S. and Uthman, B., 1984. *Reserves estimation of the kaolinitic clay deposit of the Hussainiyat area.* Manuscript report, GEOSURV, Baghdad, Iraq.

Al-Khirsan, H. and Al-Siddiki, A. 1989. *Hydrocarbon Exploration in Iraq.* 28th International Geological Congress. Washington, D.C. USA July 9-19, 1989. Abstracts Volume 1, p. 28.

Al Laboun, A. A., 1986. *Stratigraphy and hydrocarbon potential of the Palaeozoic succession in both Tabuk and Widyan Basin, Arabia.* In M. I. Halbouty (ed.), Future petroleum of the world. AAPG Memoir 40, p. 373-397.

Al Laboun, A. A., 1987. *Unayzah Formation: A new Permian-Carboniferous unit in Saudi Arabia.* AAPG Bull., 71, p. 29-38.

Al-Mehaidi, H. M., 1974. *Geological investigation of Mawat-Chuwarta area, northeastern Iraq.* Manuscript report No. 609, GEOSURV, Baghdad.

Al Mogren, S., 2004. *Geophysical investigations on the Najd Fault System.* PhD Thesis, Newcastle University, 209p.

Al-Mubarek, M. A., 1983. *Regional Geological mapping of the Southern and Western Deserts of Iraq.* Manuscript report, GEOSURV, Baghdad.

Al-Naqshabandi, S. A. O., 1988. *Palynological study for the determination of biostratigraphy and paleogeogeaphy of Suffi Formation, Western Desert, Iraq.* MSc Thesis, Salahaddin Univesity, Erbil, Iraq.

Al Rawi, Y. T. and Al-Ansari, N. A., 1971. *Effects of irrigation canals on the water table, a case study.* J. Geol. Soc .Iraq, 4, p. 73-80.

Al Rawi, N. N., Alsam, S. I. and Shkavarka, L., 1983. *Hydrogeology, hydrochemistry and water resources in the Southern Desert (Blocks 1, 2, and 3).* Manuscript report, GEOSURV, Baghdad.

Al-Rubaii, D. A., 1997. *Geochemistry and mineralogy of the karst bauxitic rocks in the Western Desert of Iraq.* MSc Thesis, Baghdad University, Iraq.

Al-Sakini, J., 1986. *Neotectonic activity in Basrah vicinity and the dryness of western canals of Shatt Al-Arab.* Proceedings of the first symposium on Khor Al-Zubair, Marine Science Centre, Basra University, 415-416 (In Arabic).

Alsam, S. I., Hanna, F. and Yacoub, S., 1979. *Preliminary study about the possibility of lowering the underground water level in Babylon.* Manuscript report, GEOSURV, Baghdad.

Alsam, S. I. and Hanna, F., 1983. *Evaluation of groundwater resources in Khazir-Gomel basin.* Manuscript report, GEOSURV, Baghdad.

Alsam, S. I. and Hanna, F., 1989a. *Hydrogeological investigations in Block 8, west of Tharthar area.* Manuscript report, Al-Furat Centre, Baghdad.

Alsam, S. I. and Hanna, F., 1989b. *Hydrogeological investigations in Block 8, South of Sinjar area.* Manuscript report, Al-Furat Centre, Baghdad.

Alsam, S. I., Jassim, S. Z. and Hanna, F., 1990. *Water balance of Iraq: stage 2, geological and hydrogeological conditions.* Manuscript report, Ministry of Irrigation, Iraq.

Al-Sawaf, F. D. S., 1977. *Sulfate-reduction and sulfur deposition in the Lower Fars Formation, northern Iraq.* Econ. Geol., 72, p. 608-618.

Al-Sayegh, A., Ojha, D. and Aswad, K., 1976. *New occurrence of palygorskite in the Neneva District, Iraq.* Rafidain J. Sci., 1, p. 19-43.

Al-Sharhan, A. S. and Kendall, C. G., 1986. *Precambrian to Jurassic rocks of the Arabian Gulf and adjacent areas: their facies, depositional setting and hydrocarbon potential.* AAPG Bull., 70, p. 977-1002.

Al-Siddiki, A. A., 1978. *Subsurface geology of southeastern Iraq.* 10th Arab Petroleum Congress, Tripoli, Libya, 47p.

Alsinawi, S., Sa'adallah, A., Al-Rawi, S. and Al-Jassim, J., 1973. *A general survey of clay minerals occurrences in Iraq and their geological consideration.* Bricks Seminar, Baghdad, 27-31 Jan., 1973. Building Research Center, Iraq.

Alsinawi, S. A and Ghalib, H. A., 1975a. *Seismicity and seismotectonics of Iraq.* Bull. Coll. Sc., 16, p. 369-41.

Alsinawi, S. A and Ghalib, H. A., 1975b. *Historical seismicity of Iraq.* Bull. Seism. Soc. of Amer., 65, p. 541-547.

Alsinawi, S. A. and Banno, I. S., 1976. *The first microearthquake recording in Iraq.* Tectonophysics, 36, T1-T6.

Alsinawi, S. A. and Al-Eqabi, G. I., 1980. *Induced microearthquake activity in the Mishraq sulphur mine.* J. Geol. Soc. Iraq, 13, p. 1-8.

Alsinawi, S. A. and Al-Shukri, H. J., 1982. *Amplitude spectra of some earthquakes recorded in Iraq.* Iraqi Jour. Sc., 22, p. 589-612.

Alsinawi, S. A. and Issa, A. A., 1986. *Seismicity and seismotectonics of Iraq.* J. Geol. Soc. Iraq, 19, p. 39-59.

Alsinawi, S. A. and Al-Heety, E. A. M., 1987. *Microseismicity of Ga'ara, an example of intraplate seismicity. Proceedings of Regional Crustal Stability and Geological Hazards.* IGCP Project 250, Bejing, p. 7-11.

Alsinawi, S. A. and Al-Ridha, N., 1988. *Microseismicity of Iraq 1974-1982.* Iraqi Jour. Science, 29, 91p.

Alsinawi, S. A., 1988. *Historical seismicity of the Arab Countries.* Proceedings of the Third Arab Seismological Seminar, King Saud University, Riyadh, Saudi Arabia, p. 11-33.

Alsinawi, S. A. and Ameer, S. A., 1989. *Microseismicity of Al-Baghdadi area, West-Central Iraq.* Proceedings of the Regional Crustal Stability and Geological Hazards-IGCP project 250 Institute of Geomechanics-CAGS Beijing, 2, p. 4-8.

Alsinawi, S. A. and Al-Banna, A. S., 1990. *An E-W Transect section through central Iraq.* Proceedings of the 9th International Conference on Basement Tectonics, Canaberra, Australia., p. 195-200.

Alsinawi, S. A. and Hamad, J. M., 1991. *Seismicity of Al-Mashriq area.* The Conference on the Geodynamics Development of the Arabian Lithosphere, Al Yarmuk University, Erbid-Jordan.

Alsinawi, S. A. and Ziyai, M. M. A., 1995. *Prediction of Strong Motion from microearthquakes data from Northeast Iraq.* Jour. Annals Geophysicae, Hamburg, 13 (abstract).

Alsinawi, S. A., 1997. *Fundamentals of seismology.* Abadi Center for Publications and Studies, Sana'a,Yemen, 338p (in Arabic).

Alsinawi, S. A. and Al-Heety, E. A., 1997. *Composite focal mechanism of microearthquakes parameters in North-Central Iraq.* Journal of Al Anbar University (Pure and Applied Sciences), Iraq, 1, p. 102-112.

Alsinawi, S. A. and Al-Tikriti, S. K., 2000. *Attenuation of earthquake generated P-waves in Iraq.* Dirasat, Pure Sciences, University of Jordan, Jordan, 27, p. 258-276.

Alsinawi, S. A. and Al Qasrani, Z. O., 2003. *Earthquake hazards consideration for Iraq.* Proceedings, Fourth International Conference of Earthquake Engineering and Seismology, Tehran, Iran.

Al-Shanti, A. M. S. and Mitchell, A. H. G., 1976. *Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia.* Tectonophysics, 30, T41-T47.

Al Shanti, M. and Roobol, M. J., 1979. *A Late Proterozoic ophiolite complex at Jabal Ess in northern Saudi Arabia.* Nature, 279, p. 488-491.

Al-Shanti, A. M. and Gass, I. G., 1983. *The Upper Proterozoic ophiolite melange zones of the easternmost Arabian Shield.* Journal of the Geological Society of London, 140, p. 867-876.

Altiner, D., 1984. *Upper Permian foraminiferal biostratigraphy in some localities of the Taurus Belt.* In O. Tekeli and M. C. Gonuoglu (eds.), Geology of the Taurus Belt, Edited by, MTA Ankara, Turkey, p. 255-268.

Altiner, D., 2000. *Late Permian foraminiferal biofacies belts in Turkey: palaeogeographic and tectonic implications.* In E. Bozkurt, J. A. Winchester and J. D. A. Piper (eds.) Tectonics and Magmatism in Turkey and the Surrounding Area. Geological Society, London, Special Publication 173, p. 83-96.

Altinli, I. E., 1966. *Geology of eastern and southeastern Anatolia.* Turkey Min. Rep. Explor. Inst. Bull., Foreign Edition, Ankara, 60, p.35-76.

Al-Qaraghuli, N. and Lange, H., 1978. *Geochemical and mineralogical investigation of pyrite-sphalerite-galena deposit in the Duri-Serguza area, northern Iraq.* J. Geol. Soc. Iraq, 11, p. 46-66.

Al-Zamel, A. Z., 1983. *Geology and oceanography of*

Recent sediments of Jezirat Bubiyan and Ras As-Sabiyah, Kuwait, Arabian Gulf. PhD Thesis, University of Shefield, UK.

Ambraseys, N. N., 1978. *Middle East appraisal of seismicity.* Quart. Jour. Eng. Geol., 11, p. 19-32.

Ameer, S. A., Sharma, M. L., Wason, H. R. and Alsinawi, S. A., 2005. *Probabilistic seismic hazard assessment for Iraq using complete earthquakes catalogue files".* PAGEOPH, 662, p. 951-966.

Andrews, L. J., Abu Lihie, O., Makhlouf, I., Abu Saad, L., Taani, Y., Al-Bashaish, M. and Al-Hiayri, A., 1991. *Palaeozoic Stratigraphy in the subsurface of Jordan.* Publication of the Natural Resources Authority, Jordan, 65p.

Antonets, V. B. and Aksenov, S. Y., 1962. *Report on prospecting exploration of the Rutba phosphate deposit carried out in 1960-61 and reserves estimation as of Jan.* 1st 1962. Technoexport Report, Manuscript report No. 294 GEOSURV, Baghdad.

Aoudeh, S. M. and S. A. Al Hajri, 1994. *Regional distribution and chronostratigraphy of the Qusaiba Member of the Qalibah Formation in the Nafud Basin, Northwestern Saudi Arabia.* Geo94, 1, p. 143-154.

Aqif, A., Al-Kabi, A., Al-Rufaie, A., Mohamed, M. and Al-Qazas, D., 1971. *Report on geological surveying and prospecting of the Duri-Serguza, Benavi and Ora areas, northern Iraq.* Manuscript report, GEOSURV, Baghdad, 35p.

Aqif, A. and Vaneček M., 1972. *The role of geological environments in location of ore occurrences in northern Iraq (Kurdistan).* 24th Int. Geol. Congress, Proceedings, Section 4-mineral deposits, p. 131-136, Montreal, Canada.

Aqif, A., Sattran V. and Al-Rufaie A., 1973. *Report on exploration of lead-zinc mineralisation of Marabasta, North Iraq.* Manuscript report, GEOSURV, Baghdad.

Aqrawi, A. A. M. and Damoian, S. A., 1988. *Statistical facies analysis of Recent surfacial carbonate sediments of Khor Al-Umaya, Northwest Arabian Gulf.* Marina Mesopotamica, 3: p. 209-225.

Aqrawi, A. A. M., 1993a. *Recent sediments of the Tigris-Euphrates Delta: the southern marshlands (Ahwar).* Unpublished PhD Thesis, University of London, Imperial College of Science, Technology and Medicine. UK.

Aqrawi, A. A. M., 1993c. *Palygorskite in the Recent fluvio-lacustrine and deltaic sediments of southern Mesopotamia.* Clay Minerals, 28: p. 153-158.

Aqrawi, A. A. M. and Evans, G., 1994. *Sedimentation in lakes and marshes (Ahwar) of the Tigris-Euphrates Delta, southern Mesopotamia.*

Aqrawi, A. A. M., 1995a. *Brackish-water and evaporitic Ca-Mg carbonates in the Holocene lacustrine/deltaic deposits of southern Mesopotamia.* Journal of the Geological Society London, 152: p. 259-268.

Aqrawi, A. A. M., 1995b. *Correction of Holocene sedimentation rates for near-surface compaction; the Tigris-Euphrates Delta.* Marine and Petroleum Geology, 12: p. 409-416.

Aqrawi, A. A. M., 1997. *The nature and preservation of organic matters in the lacustrine/deltaic sediments of southern Mesopotamia.* Journal of Petroleum Geology, 20: p. 69-90.

Aqrawi, A. A. M., 2001. *Stratigraphic signatures of climatic change during the Holocene evolution of the Tigris-Euphrates delta, lower Mesopotamia.* In Fard, A. M. (Editor of Special Issue), Recognition of abrupt climate changes in clastic sedimentary environments, In Cloetingh et al. (Editors), Global and Planetary Change, 28: p. 267-283.

Araim, H. I. and Said, H., 1980. *Groundwater regional study in the Adhaim River basin with emphasis on the plain area.* Manuscript report, GEOSURV Baghdad.

Araim, H. I., 1991. *Geological Map of Iraq 1:1,000,000 Scale Series, Sheet 5, Hydrogeological map of Iraq.* Publication of GEOSURV, Baghdad.

Aswad, K. J. and Elias, E. M. 1988. *Petrogenesis, geochemistry and metamorphism of spilitized subvolcanic rocks of the Mawat ophiolite complex, NE Iraq.* Ofioliti, 13, 2/3, p 95-109.

Aswad, K. J., Hermiz, S. and Al-Bassam, K. S., 2000. *Palygorskite deposits of the Safra Beds (Maastrichtian) in the Ga'ara-Akashat area, Western Desert, Iraq.* In: K. Al-Bassam (ed.), The Iraqi Palygorskites: geology, mineralogy, geochemistry, genesis and industrial uses. GEOSURV, Iraq, p. 35-50.

Baltzer, F. and Purser, B. H., 1990. *Modern alluvial fan and deltaic sedimentation in a foreland tectonic setting: the Lower Mesopotamian Plains and the Arabian Gulf.* Sedimentary Geology, 67: p. 175-197.

Basi, M. A. and Jassim, S. Z., 1974. *Baked and fused Miocene sediments from the Injana area, Hemrin South, Iraq.* J. Geol. Soc. Iraq, 7, p. 1-11.

Bechennec, F., Le Metour, J., Rabu, D., Villey, M. and Beurrier, M., 1988. *The Hawasina Basin: a fragment of a starved passive continental margin, thrust over the Arabian platform during obduction of the Semail Nappe.* Tectonophysics, 151 p. 323-343.

Best, J. A., Barazangi, M., Al Saud, D., Sawat, J. and Gebran Ali, 1993. *Continental Margin Evolution of the Northern Arabian Platform in Syria.* AAPG Bull, 77, p. 173-193.

Barker, J. M., Cochran, D. E. and Semard, R., 1979. *Economic geology of Mishraq native sulphur deposit, Northern Iraq.* Economic Geology, 74, p. 484-495.

Beccaluva, L., Maciotta, G., Piccardo, G. B., and Zeda, O., 1984. *Petrology of lherzolitic rocks from the Northern Apennine ophiolites.* Lithos, 17, 299-316.

Blendinger, W, Van Vliet, A, and Hughes Clarke, M. W., 1990. *Updoming, rifting and continental margin development during the Late Palaeozoic in northern Oman.* In Roberston, A. H. F, Searle, M. P & Ries, A. C (eds) 1990. the Geology and Tectonics of the Oman Region. Geological Society Special Publication No. 49, p. 27-37.

Beer, H., 1966. *Geologie der Phosphatfuhrenden Schichtfolge des Raumes Mardin, Derik,* Mazigadi. MTA.

Bellen, R. C. Van, 1956. *The stratigraphy of the Main Limestone of the Kirkuk, Bai Hassan, and Qara Chauq Dagh structures in Northern Iraq.* Inst. Petroleum Journ., 42, London.

Bellen, R. C. Van, Dunnington, H. V., Wetzel, R. and Morton, D., 1959. *Lexique Stratigraphique Internal Asie. Iraq.* Intern. Geol. Conger. Comm. Stratigr, 3, Fasc. 10a, 333p.

Berggren, W. A., 1969a. *Biostratigraphy and planktonic foraminiferal zonation of the Tertiary System of the Sirte basin of Libya, North Africa:* In Bronnimann, P. and Renz, H. H. (eds.). Proc. 1st Int. Conf. Plank. Microfoss., Geneva, 1967, 1, 104-120.

Berggren, W. A., 1969b. *Palaeogene biostratigraphy and planktonic foraminifera of northern Europ:* In Bronnimann, P. and Renz, H. H. (eds.), Proc. 1st Int. Conf. Plank. Microfoss., Geneve, 1967, 1, 121-159.

Berggren, W. A., 1972a *A Cenozoic time scale-some implications for regional geology and paleobiogeography.* Lethia, 5, 195-215.

Berggren, W. A., 1972b. *Cenozoic biostratigraphy and palaeobiogeography of the North Atlantic:* In: Laughton et al. Initial report of the Deep Sea Drilling Project, leg 12, Washington, 12, 905-1001.

Bernard, J. H., 1971. *Isogenetic Pb+Zn associations of Turkey.* Metu Jour. of Pure and Aplied Sciences, 4, 3, pp. 249-282. Ankara.

Beydoun, Z. R., 1991. *Arabian Plate hydrocarbon geology and potential-A Plate Tectonic Approach.* Studies in Geology, American Association of Petroleum Geologists, Tulsa, Oklahoma, USA, publication 33, 77p.

Binnie, Deacon and Gourley, 1956. *Z.A.D. Irrigation Projects.* Vol. I, II, Development Board, Government of Iraq. Baghdad.

Bolton, C. M. G., 1955. *Report on the geology and economic prospects of the Rowanduz area.* Manuscript report No. 265, GEOSURV, Baghdad.

Bolton, C. M. G., 1956. *The geology and economic prospects of the Rania area.* Manuscript report No. 269, GEOSURV, Baghdad

Bolton, C. M. G., 1958a. *Geological map-Kurdistan series, scale 1:100,000. sheet K4, Ranya.* Manuscript report No. 276, GEOSURV, Baghdad.

Bolton, C. M. G., 1958b. *Geological Map-Kurdistan Series, scale 1:100,000 Sheet K5 Chuwarta.* Manuscript report No. 277, GEOSURV, Baghdad

Bolton, C. M. G., 1958c. *Geological Map-Kurdistan Series, scale 1:100,000 Sheet K6 Halabja.* Manuscript report No. 278, GEOSURV, Baghdad

Bolton, C. M. G., 1958d. *The geology of the Ranya area.* Manuscript report No. 271, GEOSURV, Baghdad.

Bolton, C. M. G. and others, 1960. *Geological Map of Iraq, 1:1,000,000.* Government of Iraq, Baghdad.

Bonatti, E., Hamlyn, P. R. and Ottonello, G., 1981. *The upper mantle beneath a young oceanic rift: Peridotites from the island of Zabargad (Red Sea).* Geology, 9, p. 474-491.

Bordenave, M. L. and Burwood, R., 1990. *Source Rock Distribution & Maturation in the Zagros Orogenic belt: Provenance of the Asmari & Bungestan Reservoir Oil Accumulations.* Organic Geochemistry, 16, p. 369-387.

Bordenave, M. L., 1993. *The Cretaceous source rocks in the Zagros Foothills of Iran: an example of large size intracratonic basin.* AAPG Bull., 77, p. 386 Abstract.

Bordenave, M. L., 2002. *The Mid Cretaceous to Early Miocene petroleum systems in the Zagros domain of Iran, and its prospects evaluation.* AAPG Bull, 86, Abstract.

Boudier, F., and Nicolas, A., 1985. *Harzburgite and lherzolite subtypes in ophiolitic and oceanic environments.* Earth Planet. Sci. Lett. 76, p. 84-92.

Bray, J. T., 1960. *Final report on well Injana 5.* Manuscript Report No. FWR 25, INOC Library, Baghdad.

Braud, J., 1973. *La nappe du Kuh-e-Garun (region de Kermanshah, Iran), chevauchement de l'Iran central sur le Zagros.* Bulletin de la Societe Geologique de France. 13, p. 416-419.

Braud, J., 1989. *La Suture du Zagros au niveau de Kermanshah (Kurdistan iranien): reconstitution palaeogeographique, evolution geodynamique, magmatique et structurale.* mem. GEODIFFUSION, 5, 489p.

Brew, G., Litak, R., Barazangi, M. and Sawaf, T., 1999. *Tectonic evolution of northeast Syria: Regional implications and hydrocarbon prospects.* GeoArabia, 4, p. 289-318.

Brown, G. F. and Jackson, R. O., 1960. *The Arabian Shield.* Intern. Geol. Congr. XXI Session. Rep. IX, Copenhagen

Brown, G. F., Schmidt, D. L. and Huffman, A. C., 1989. *Geology of the Arabian Peninsula: Shield area of western Saudi Arabia.* U. S. Geological Survey Professional Paper 560-A, Scale 1:1,000,000, 188p

Buda, G. and Al-Hashimi, W. S., 1977. *Petrology of Mawat ophiolitic complex, Northern Iraq.* Jour. Geol. Soc. of Iraq, 10, p. 69-98.

Buda, O., Sahagian O. and Salem, W., 1978. *Igneous and Metamorphic Petrology of the Qalat Dizeh area.* Manuscript report No. 917, GEOSURV, Baghdad.

Buday, T., 1970. *Explanatory notes to the structural sketch map of Iraq.* Manuscript report No. 61, GEOSURV, Baghdad.

Buday, T., Vaněček, M., 1971. *Outline of mineral occurrences of Iraq and general investigation programme for 1971-1990.* Manuscript report, GEOSURV, Baghdad.

Buday, T., 1975. *The two main structural units of the Tertiary eugeosyndine of Northeastern Iraq.* Jour. Geol. Soc. of Iraq, Special Issue, Baghdad

Buday, T., 1980. *The Regional Geology of Iraq. Vol.1: Stratigraphy and Palaeogeography.* Publications of GEOSURV, Baghdad, 445p.

Buday, T. and Hak, J., 1980. *Report on the geological survey of the western part of the western desert, Iraq.* Polytechna, Prague, Manuscript report No. 1000, 265p., GEOSURV, Baghdad.

Buday, T. and Jassim, S. Z., 1984. *Geological Map of Iraq,*

1:1,000,000 Scale Series. sheet No. 1, Tectonic Map, Publication of GEOSURV, Baghdad.

Buday, T. and Jassim, S. Z., 1984. *Geological map of Iraq 1:1,000,000 Scale Series, sheet No. 2, Tectonic Map of Iraq.* Publication of GEOSURV, Baghdad.

Buday, T. and Jassim, S. Z., 1987. *The Regional Geology of Iraq, Vol.2: Tectonism, Magmatism and Metamorphism.* Publication of GEOSURV, Baghdad, 352p.

Caglayan, M. A., Inal, R. N. and Sengun, M., 1984. *Structural setting of the Bitlis Massif:* In: Tekeli, O. and Gonuoglu, M. C. (eds.), Geology of the Taurus Belt. MTA Ankara, Turkey, p. 245-254.

Camp, V. E., 1984. *Island arcs and their role in the evolution of the western Arabian Shield:* Geological Society of America Bulletin, 95, 913-921.

Cambel, B. and Jarkovský, J., 1967. *Geochemie der Pyrite einiger Lagerstatten der Tschechoslowakei.* VSAV Bratislava, 493p.

Carter, J. M. L. and Tunbridge, I. P., 1992. *Palaeozoic Tectonic History of Southeast Turkey.* Journal of Petroleum Geology, 15.

Chatton, M. and Hart, E., 1960. *Revision of Tithonian-Albian stratigraphy of Iraq.* Manuscript report, GEOSURV, Baghdad.

Chatton, M. and Hart, E., 1961. *Review of the Cenomanian to Maastrichtian stratigraphy in Iraq.* Manuscript report No. 2/141, INOC Library, Baghdad.

Cloud, P., Awramik, S. M., Morrisom, K. and Hadley, D. G., 1979. *Earliest Phanerozoic or latest Proterozoic fossils from the Arabian Sheild, Kingdom of Saudi Arabia.* Precambrian Research, 10, p. 73-93.

Cobbett, G. P. R., 1956. *Preliminary report on the geology of Rutba phosphate area.* Manuscript report, GEOSURV, Baghdad.

Cobbett, G. P. R., 1957. *Geology of the Kani Rash area.* Manuscript report No. 270, GEOSURV, Baghdad.

Cole, G. A., Abu-Ali, M. A., Halpern, H. H., Carrigan, W. J., Savage, G. R., Scolaro, R. J. and Al-Sharidi, S. H., 1994. *The Source Rock Geochemistry of the Midyah & Laizan Basins of the Red Sea, Saudi Arabia.* Geo94, 1, p. 307-319.

Consortium Yougoslavia, 1978. *Annual report, geology of Block 7.* Desert Development Project Directorate, Baghdad.

Crawford, A. J., Falloon, T. J. and Green, D. H., 1989. *Classification, petrogenesis and tectonic setting of boninites.* In: Boninites and related rocks, A.J. Crawford (ed.), Unwin Hyman, London, UK, p. 1-49.

Crank, K. A. M. and Ritchie, G., 1955. *Final report on well Atshan No. 1.* MPC Report, INOC Library, No. FWR 8, Baghdad.

Ctyroky, P. and Karim, S. A., 1971a. *Stratigraphy and paleontology of the Oligocene and Miocene strata near Anah, Euphrates valley.* Manuscript report, GEOSURV, Baghdad

Ctyroky, P. and Karim, S. A., 1971b. *Stratigraphy and paleontology of the Umm Er Radhuma Formation in the Akashat phosphate deposit, Ga'ara area, Western Iraq.* Jour. Geol. Soc. of Iraq, 4.

Ctyroky, P., 1973. *Permian flora from the Ga'ara region (Western Iraq).* Neues Jahrb. Geol. Paleont. Monatshefte. 1973/7, Stuttgart

Daniel, E. J., 1968. *Lexique Stratigraphique International. Asie.* Fasc. 10 C1B Syrie interieure, Paris.

Darmoian, S. A., 1975. *Stratigraphy and micropaleontotigy of the Upper Cretaceous Aruma Supergroup, South Iraq.* Jour. Geol. Soc. of Iraq, Special Issue.

Davoudzadeh, M., Lensch, G. and Weber-Diefenbach, K., 1986. *Contribution to the paleogeography, stratigraphy and tectonics of the Infracambrian and Lower Palaeozoic of Iran.* N.Jb. Geol. Palaont., 169, p. 284-306.

Davoudzadeh, M. and Weber-Diefenbach, K., 1987. *Contribution to the paleogeography, stratigraphy and tectonics of the Upper Palaeozoic of Iran.* N.Jb. Geol. Palaont., 175, p. 121-146.

Dawood, R. M., 2000. *Mineralogy, origin of celestite and the factors controlling its distribution in Tar Al-Najaf, Najaf Plateau.* MSc Thesis, Baghdad University, Iraq.

Dimitrov, D., Mustafa, M. and Toma, N., 1983. *Main industrial mineral deposits of the Lower Fars Formation (Tortonian) in Iraq.* 2nd Geol. Congr. On Middle East (GEOCOME II), Baghdad, Oct., 1983.

Delfour, J., 1970. *Le Group de J'balah une Nouvelle de Bouclier Arabe.* BRGM Bulletin, 2, p. 10-32.

Delfour, J., 1977. *Geological Map of the Nuqrah quadrangle, sheet 25E, Kingdom of Saudi Arabia.* Saudi Arabian Deputy Ministry For Mineral Resources, Jeddah, Saudi Arabia, Geoscience, Map GM 28, Scale 1:250,000, 32 p.

Dilek, Y., and Thy, P., 1998. *Structure, petrology and seafloor spreading tectonics of the Kizildag ophiolite, Turkey.* In: Mills, R.A. and Harrison, K. (eds.): Modern Ocean Floor Processes and the Geological Record, Geological Society, London, Special Publications, 148, p. 43-69.

Dilek, Y., Thy, P., Hacker, B. and Grundvig, S., 1999: *Structure and petrology of Tauride ophiolites and mafic dike intrusions (Turkey):* Implications for the Neo-Tethyan ocean. - Geological Society of America Bulletin, v. 111, 1192-1216.

Dilek, Y. and Ahmed, Z., 2003. *Proterozoic ophiolites of the Arabian Shield and their significance in Precamrian tectonics.* In: Y. Dilek ans P.T. Robertson, Ophiolites in Earth History. Geological Society of London, special publication No. 218., pp. 284-700.

Dilek, Y. A. & Robinson, P. T. (eds) 2003. *Ophiolites in Earth History.* Geological Society, London, Special Publications, 218.

De Villiers, P. R., 1957. *The geology of Shalair Valley.* Manuscript report, GEOSURV, Baghdad.

Ditmar, V. and Iraqi-Soviet Team, 1971. *Geological conditions and hydrocarbon prospects of the Republic of Iraq (Northern and Central parts).* Manuscript report, INOC Library, Baghdad.

Ditmar, V. and Iraqi-Soviet Team, 1972. *Geological conditions and hydrocarbon prospects of the Republic of Iraq, Vol. II, South Iraq.* Manuscript report, INOC

Library, Baghdad.

Douban, A. F. and Medhadi, F., 1999. *Sequence chronostratigraphy and petroleum systems of the Cretaceous Megasequences, Kuwait.* AAPG Inernational Conference and Exhibition, p. 152-155.

Dubertret, B., 1966. *Liban, Syrie et bordure des pays voisins.* Notes and Memoires Meyen Orient, Vol. VIII, Paris.

Dunnington, H. V., 1953a. *Subsurface rock unit nomenclature for Northern Iraq.* Manuscript report No. IDLR, INOC Library, Baghdad.

Dunnington, H. V., 1953b. *Thickness and facies variation in Upper Cretaceous (Upper Campanian-Maastrichtian) of Northern Iraq.* Manuscript report, INOC Library, Baghdad.

Dunnington, H. V., 1958. *Generation, accumulation, and dissipation of oil in Northern Iraq.* In Weeks, L. G. (ed.) Habitat of Oil, AAPG, Tulsa, Oklahoma, USA, p. 1194-1251.

Edgell, S., 1977. *The Permian System as an oil and gas reservoir in Iran and Arabia.* Proc. Second Iranian Geological Symposium, Tehran, p. 161-201.

El-Naggar, Z. R., 1966. *Stratigraphy and planktonic foraminifera of the Upper Cretaceous-Lower Tertiary succession in the Esna-Idfu region, Nile valley, Egypt.* Brit. Mus. Sup., 2, 1-291.

Elerdashvili, S. I., 1971. *Hydrogeology and engineering geology of Iraq (in Russian).* Nedra, Moskva. 350 p.

Elliot, E. K., Cox, J. M. and James, A. V., 1954. *Report on Twai al Hashash and Khobrar Rachi axes. Winter and Spring season 1953-54.* Manuscript report No. BGR 23, INOC Library, Baghdad.

Evans, G. 1989. *The control of source and climate on coastal facies and their associated economic deposits: is there a rational?.* Geol. Soc. France Bull., 8, p 1055-1064.

Fahmi, K. J. and Al Abbasi, J. N., 1989. *Some statistical aspects of earthquake occurrence in Iraq.* Earth Spectra, 4, p. 735-765.

Fairbridge, R. W., 1958. *Dating of the latest movements of the Quaternary sea level.* Trans. N.Y. Acad. Sci. Ser., 2, 20: 471-482.

Fediukova, E., 2004. *Sekaninaite, a new rock-forming mineral for Iraq.* Czech. Bull. Mineral.Petrolog. Odd. Nár. Muz. (Praha), 12.

Fontaine, J. M., Monod, O., Braud, J. and Perincek, D. , 1989. *The Hezan units, a fragment of South Neo-Tethyan passive continental margin in Southeast Turkey.* Journal of Petroleum Geology, 12, p. 29-50.

Frisch, W. and Al-Shanti, A., 1977. *Ophiolite belts and the collision of island arcs in the Arabian Shield.* Tectonophysics, 43, p. 293-306.

Furst, M., 1970. *Stratigraphie und Werdegang der Oestlichen Zagrosketten Iran, Erlanger.* Geol. Abhandlungen, 80, Erlangen.

Gaddo, J., Algawi, M. O. and Osborne, J., 1958. *Final report on well Falluja 1.* Manuscript report No. FWR 14, INOC Library, Baghdad.

Gaddo, J. and Parker, D. M. F., 1959. *Final report on well Khleisia No. 1.* Manuscript report No FWR 28, INOC Library, Baghdad.

Garfunkel, Z., 2004. *Origin of the Eastern Mediterranean basin: a re-evaluation.* Tectonophysics, 391 p. 11-34.

Ghalib, H. A. and Alsinawi, Sahil A., 1974. *On The Seismotectonics Of The Arabian Peninsula; A Global Tectonic Approach.* Bull. Coll. Sci., 15, p. 151-169.

Ghalib, A. A., 1988. *Study of the geomorphology of Najaf Plateau.* MSc Thesis, Baghdad University, Iraq.

Gazda, S., 1971. *Modification of the Palmer' s classification systems (in Slovak).* Hydrogeol. Ročenka 1969-1970, 122-126. Praha.

Ghazi, A. M., Pessagno, E. A., Hassanipak, A. A., Kariminia, S. M, Duncan, R. A. and Babaie, H. A., 2003. *Biostratigraphic zonation and 40Ar-39Ar ages for the Neo-Tethyan Khoy ophiolite of NW Iran.* Paleogeography, Paleoclimatology, Paleoecology, 193, p. 311-323.

GETECH and Jassim, S. Z., 1998. *North Arabia basement morphology study: Integrated geological, geophysical and hydrocarbon potential study.* GETECH, School of Earth Sciences, University of Leeds, England, Report no. G904, 219p.

GETECH and Jassim, S. Z., 2000. *Libya: A tectonic and depth-to-basement study using well, gravity and magnetic data.* GETECH, School of Earth Sciences, University of Leeds, England, Report no. G0030, 323p.

GETECH and Jassim, S. Z., 2002. *The Basin Development of Arabia.* GETECH, School of Earth Sciences, University of Leeds, England, Report no. G0227, 414p.

Glennie, K. W., 2005. *The Geology of the Oman Mountains; an outline of their origin.* Second edition. Scientific Press Ltd.

Goncuoglu, M. C. and Turhan, N., 1983. *New results on the age of Bitlis Metamorphics.* Mineral Res. Exploration Bull., 95/96, p. 1-5.

Goncuoglu, C., and Turhan, N., 1984. *Geology of the Bitlis Metamorphic Belt.* In: Tekeli, O. and Gonuoglu, M. C. (eds.), Geology of the Taurus Belt. MTA Ankara, Turkey, p. 237-244.

Goncuoglu, M. C., Turhan, N., Senturk, K., Oxcan, A., Uysal, S. and Yalinz, M. K., 2000. *A geotraverse across northwestern Turkey: tectonic units of the Central Sakarya region and their tectonic evolution.* In Bozkurt, E., Winchester, J. A. and Piper, J. D. A. editors. Tectonics and Magmatism in Turkey and the Surrounding Area. Geological Society Special Publication No. 173, p. 139-161.

Godwin, H., Surggate, R. P. and Wills, E. H., 1958. *Radiocarbon dating of the eustatic rise of ocean-level.* Nature, 181, p. 1518-1519.

Gradstein, F. M. and Ogg, J., 1996. *A Phanerozoic Time Scale.* Episodes, 19, p. 3-5.

Gray, D. R. and Gregory, R. T., 2003. *Ophiolite obduction and the Semail Ophiolite: the behaviour of the underlying margin.* In Dilek, Y. and Robinson, P. T. (eds.), Ophiolites in Earth History. Geological Society

Special Publication No. 218, p. 449-465.

Guiraud, R. and Bellion, Y., 1995. *Late Carboniferous to Recent Geodynamic evolution on the west Gondwanan, cratonic, Tathyan margin.* In. Aaln E. M. Nairn, Luc-Emmanuel Ricou, Bruno Vrielynck and Jean Decourt, The ocean basins and margins, The Tethys Ocean. Plenum Press, New York, 8, p. 101-124.

Gunatilaka, A., 1986. *Kuwait and the northern Arabian Gulf, a study in Quaternary sedimentation.* Episodes, 9: 223-231.

Habba, Y. and Abdulla, M. B., 1989. *Geochemical Study of the Hydrocarbon Source Rocks in Northeast Iraq.* Oil & Arab Co-operation, 15, p. 12-51.

Habba, Y. A., Samarrai, A., Al-Jubouri, F, Georgis, N. N. and Ahmad, I. M., 1994. *Exploration for the Palaeozoic prospects in Western Iraq, Part 1: Exploration of the Palaeozoic System in Western Iraq.* Proceedings of the Second Seminar on hydrocarbon potential of deep formations in the Arab countries (OAPEC), Cairo 10-13 October (in Arabic).

Haddoum, H., Guiraud, R. and Moussine-Pouchkine, 2001. *Hercynian compressional deformations of the Ahnet-Mouydir basin, Algerian Saharan Platform: far-field stress effects of the Late Palaeozoic orogeny.* Terra Nova, 13, p. 220-226.

Hadley, D. G., 1974. *The Taphrogeosynclinal Jubaylah Group in the Mashhad area, North-eastern Hijaz.* Saudi Arabian Directorate General of Mineral Resources Bulletin, 10, 18p.

Hak, J., Watkinson, D. H. and Al-Bassam, K. S., 1983. *The origin of the Marabasta base metal deposit, NE Iraq.* Věstník Ústřed. ústavu geologického, 58, 3, pp. 141-148. Prague.

Hall, P. K., 1956a. *Geology of the Baibu area, east of Amadiya.* Manuscript report, GEOSURV, Baghdad.

Hall, P. K., 1957. *The geology of Rikan and Zibar.* Manuscript report, GEOSURV, Baghdad.

Hall, P. K., 1958. *Geological map Kurdistan Reconnaissance Series, Scale 1:100,000, Sheet K2, Amadiya.* Manuscript report, GEOSURV, Baghdad.

Hall, W. E. and Heyl, A. V., 1968. *Distribution of minor elements in ore and host rocks, Illinois-Kentucky fluorite district and upper Mississipi Valley lead-zinc district.* Econ. Geol. 63, pp. 655-670.

Hall, R., 1984. *Ophiolites: fragments of ophiolitic lithosphere.* In: Gass I. G., Lippard S. J., Shelton A. W. (eds.) Ophiolites and oceanic lithosphere. Geol. Soc. London, Spec. Publ., 13, p. 393-404.

Halliwell, A. S., 1960. *Final well report on Shawiya No. 1.* Manuscript report No. FWR 51INOC Library, Baghdad.

Hamilton, W. B. 1995. *Subduction systems and magmatism.* In: J. L. Smellie (ed.): Volcanism associated with extension at consuming plate margins. Geol. Soc. Special Publ. 81, London, p. 3-28.

Hamza, N. M. and Isaac, E. A., 1971. *Geological survey of the area between Benavi village and Greater Zab River.* Manuscript report, GEOSURV, Baghdad.

Haq, B. U., Vail, P. R., Hardenbol, J. and Van Wagoner, J. C., 1988. *Sea Level History.* Science, 241, p. 596-602.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G., 1990. *A geologic time scale 1989.* Cambridge University Press, 263 p.

Harris, S. A., 1964. *Ecology of the freshwater mollusca of Iraq.* Canadian Journal of Zoology, 43: 509-526.

Hart, S. R., Glassley, W. E. and Karig, D. A., 1972. *Basalts and seafloor spreading behind the Mariana island arc.* Earth Planet. Sci. Lett. 15, p. 12.

Hassan, A. H. and others, 1977. *Galal Badra Project area. Part I-IV.* Inst. for Applied Research on Nat. Resources Techn. Bull. 106.

Hay, J. T. C. and Hart, R. E., 1959. *Final report on welt Anah 2.* Manuscript report No. FWR 7, INOC Library, Baghdad.

Hay, J. T. C. and Algawi, M. O., 1958. *Final report on well Mileh Tharthar No. 1.* Manuscript report No. FWR 35, INOC Library, Baghdad.

Henson, F. R. S.1951. *Oil occurrences in relation to regional geology of the Middle East.* Geol. Soc. Tulsa, Digest., 19, p. 72-81.

Heine, C. J., 2000. The Permoicarbonoferous Unayzah depositional system of Saudi Arabia. AAPG Bull, 84, p. 1395-1518.

Homci, H. AL, 1975. *Isopach maps of Tithonian to base of Tertiary.* Manuscript report, GEOSURV, Baghdad.

Huber, H., 1940. *Final well report on Awasil No. 5.* Manuscript report No. FWR 9-RG 58, INOC Library, Baghdad.

Hudson, J. M., 1958. *Permian corals from northern Iraq.* Palaeontology, 1.

Hudson, R. G. S., Eames, F. E. and Wilkins, G. L., 1957. *The fauna of some Recent marine deposits near Basrah, Iraq.* Geol. Mag., 94: p. 393-401.

Hughes, G. W. & Beydoun, Z. R., 1992. *The Red Sea-Gulf of Aden: biostratigraphy, lithostratigraphy and palaeoenvironments.* Journal of Petroleum Geology, 15, p. 135-156.

Humphreys, A. and others, 1959. *Final well report on Pulkhanah 5.* MFC Report No. FWR 41, INOC Library, Baghdad.

Husseini, M. I., 1991. *Tectonic and Depositional Model of the Arabian and Adjoining Plates during the Silurian-Devonian.* AAPG V.75, 1, p. 108-120.

Husseini, M. I., 1992. *Upper Palaeozoic tectono-sedimentary evolution of the Arabian and adjoining plates.* Journal of the Geological Society, London, 149, p. 419-429.

Husseini, M. I., 2000. *Origin of the Arabian Plate structures: Amar collision and Najd rift.* GeoArabia, 5, p. 527-542.

Ildefonse, B., Billiau, S. and Nicolas, A., 1995. *A detailed study of mantle flow away from diapirs in the Oman ophiolite.* In R. L. M. Vissers and A. Nicolas (eds.): Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites, Petrology and Structural Geology, 6., p. 163-177.

Idrotecneco Consult Project, 1977. *Western desert development, Block 4, (Iraq).* Final report, Western

Desert Development Project, Block 4, Ministry of Agriculture ana Agrarian Reforms, Iraq.

Iraqi-Soviet Team, 1979. *Geological conditions and hydrocarbon prospects of the Republic of Iraq.* Manuscript report, INOC Library, Baghdad.

Irvine, T. N. and Baragar, W. R. A., 1971. *A guide to the chemical classification of common volcanic rocks.* Canad. Earth Sci. Journ., 8, p. 523-548.

Irvine, T. N., 1982. *Terminology for layered intrusions.* Journal of Petrology, 23, p. 127-162.

Irvine, T. N., 1987. *Layering and related structures in the Duke Island and Skaergaard intrusions. Similarities, differences, and origins.* In Parsons, I. (ed.), Origins of igneous layering. Dordrecht, p. 185-245.

Ismail, S. A., 1989. *Mineralogical-geochemical study of zircon and rutile in the sandstones of Ga'ara Formation, W. Iraq.* MSc Thesis, Baghdad University, Iraq.

Jackson, N. J., Walsh, J. N. and Pegram, E., 1984. *Geology, Geochemistry And Petrogenesis of Late Precambrian Granitoids* In The Central Hijaz Region of The Arabian Shield: Contributions to Mineralogy and Petrology, 87, p. 205-219.

Jacobson, T., Adams, R. M., 1958. *Salt and silt in ancient Mesopotamian agriculture.* Science,128: 1251p.

James, G. A. and Wynd, J. G., 1965. *Stratigraphic nomenclature of Iranian Oil Consortium Agreement area.* AAPG Bull., 49/12, Tulsa, Oklahoma.

Jameson, T. H. B., 1961. *Amended final well report Chemchemal 2.* Original report by Melville and Fothergil 1956, Manuscript report, GEOSURV, Baghdad.

Jargees, S. and Santrucek, P., 1975. *Report on geological investigation of clay deposit of Duekhla area , southern rim of Al-Ga'ara depression.* Manuscript report, GEOSURV, Baghdad.

Jassim, S. Z., 1972. *Geology of the central sector of the Mawat Igneous Complex.* Manuscript report, GEOSURV, Baghdad.

Jassim, S. Z., 1973. *Geology of the central sector of the Mawat Igneous Complex, Northeastern Iraq.* J. Geol. Soc. Iraq,. 6, p. 83-92.

Jassim, S. Z., Al Shaibani, S.K. and Ajina, T. M., 1975. *Possible Middle Eocene block movements in the Derbendikhan area, Northeastern Iraq* J. Geol. Soc. Iraq, Special Issue, Baghdad.

Jassim, S. Z. and Al Hassan, M. I., 1977. *Pertrography and origin of the Mawat and Penjween Igneous Complexes: A comparison.* J. Geol. Soc. Iraq, Special Issue, p. 169-210.

Jassim, S. Z., 1981a. *Early Pleistocene gravel fan of the Tigris River from Al Fatha to Baghdad, Central Iraq.* J. Geol. Soc. Iraq, 14, p. 25-34.

Jassim, S. Z., 1981b. *Excursion guide to the western desert of Iraq.* Sixth Iraqi Geol Congr. 28-31 Dec.1981, Baghdad.

Jassim, S. Z., Buda, G., Neuzilova, M. and Suk, M., 1982a. *Metamorphic development of the Iraqi Zagros Ophiolitic Zone.* Krystalinikum. 16, p. 21-40.

Jassim, S. Z., Waldhausrova, J. and Suk, M., 1982b. *Evolution of magmatic activity in Iraqi Zagros complexes.* Krystalinikum, 16, p. 87-108.

Jassim, S. Z., Karim, S. A., Basi, M., Al-Mubarak, M. A. and Munir, J., 1984. *Final report on the regional geological survey of Iraq, Vol.3, Stratigraphy.* Manuscript report, Geological Survey of Iraq.

Jassim, S. Z. and Karim, S. A., 1984. *Final report on the regional geological survey of Iraq, Vol.4, Paleogeography.* Manuscript report, Geological Survey of Iraq.

Jassim, S. Z., Hagopian, D. and Al Hashimi, 1987. *Geological Map of Iraq 1:1,000,000 Scale Series, Sheet No. 2, Geological Map.* Publication of GEOSURV, Baghdad.

Jassim, S. Z. and Al-Naqib, S., 1989. *Ninivite, a new form of porcellanite and the associated alunite and jarosite minerals: A suite associated with sulphuric acid seepages.* J. Geol. Soc. Iraq, 22, p. 112-122.

Jassim, S. Z. and Al-Murib, S., 1989. *Geology and reserve estimation of the M3 sector of the Mishraq sulphur deposit.* Manuscript report, GEOSURV, Baghdad.

Jassim, S. Z. and Ghulam, B., 1991. *Geology and reserve estimatiom of sulphur in the Zanguba area, Lazzaga mineralisation centre, Northern Iraq.* Manuscript report, GEOSURV, Baghdad.

Jassim, S. Z., Jibril, A. S. and Numan, N. M. S., 1997. *Gypsum karstification in the middle Miocene Fatha Formation, Mosul area, northern Iraq.* Geomorphology. 18, p. 137-149.

Jassim, S. Z., Raiswell, R. and Bottrell, S. H., 1999. *Genesis of the Middle Miocene stratabound sulphur deposits of northern Iraq.* Journal of the Geological Society of London. 156, p. 25-39.

Jassim, S. Z. and Green, C. M., 1999. *The basin configuration, tectonic history and hydrocarbon potential of northern Arabia.* AAPG International Conference and Exhibition (abstract).

Jassim, S. Z., 2000. *Regional Geology and Structural Timing of Tethys-Palaeogeography and Hydrocarbon Systems.* AAPG Cairo 2000 Conference on Ancient Oil - New Energy (abstract).

Jassim, R. Z., 1979. *Mineralogy, geochemistry and origin of Shari saltern deposit NE Samarra, Iraq.* PhD Thesis, Baghdad University, Iraq.

Jassim, R. Z., Al-Rawi, Y. and Falih, M. T., 1998. *The role of bacteria in Shari playa and their pathogenic effect.* J. Babylon Univ., 3, p. 259-262.

Jassim, R. Z., Al-Rawi, Y. and Habib, R., 1999. *Mineralogy of evaporite minerals in the Shari playa saltern deposit.* Iraqi J. Sci., 40C, p. 7-20.

Jensen, M. L., 1967. *Sulfur isotopes and mineral genesis.* In: Geochemistry of hydrothermal ore deposits. Barnes H. L. (ed.), Holt, Rinehart and Winston Inc., New York, pp. 143-165.

Johnson, P. R. and Stewart, I. C. F., 1995. *Magnetically inferred basement structures in central Saudi Arabia.*

Tectonophysics, 245, p. 37-52.

Johnson, P. R., 2000. *Proterozoic geology of Saudi Arabia: Current concepts and issues. A contribution to a workshop on geology of the Arabian Peninsula.* 6th meeting of the Saudi Society for earth Sciences, King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia.

Johnson, R. E., 1961. *Final well report on Samarra-1.* Manuscript report FWR 50, INOC Library, Baghdad

Kadhim, S. A. R. and Nasser, F., 1971. *Upper Jurassic prospects in Iraq.* 10th Iraqi Engineering Congress, Research No. 4, Baghdad.

Kassim, I., 1985. *Petrology and geochemistry of Upper Cretaceous-Palaeocene phosphatic rocks in the Rutba-H3 area, western desert.* MSc thesis, Baghdad University, Iraq.

Kasim, F. A. Al., 1960a. *Final well report on Kifl No. 1.* Manuscript report No. FEW 30, INOC Library, Baghdad.

Kasim, F. A. Al., 1960b. *Final well report on Tuba No. 1.* Manuscript report No. FWR 55, INOC Library, Baghdad.

Kasim, F. A. Al., 1962a. *Final well report on Mussaiyiab No. 1.* Manuscript report No. FWR 37, INOC Library, Baghdad.

Kasim, F. A. Al., 1962b. *Final report on Nahr Umr No. 2.* Manuscript report No. FWR 40, INOC Library, Baghdad.

Kassab, I. I. M., 1972. *Micropaleontology of the Upper Cretaceous-Lower Tertiary of North Iraq.* PhD Thesis, University of London, London.

Kassab, I. I. M., 1973. *Planktonic Foraminiferida of the Shiranish Formation type locality (Northern Iraq).* J. Geol. Soc. Iraq, 6, p. 100-109.

Kassab, I. I. M., 1975a. *Planktonic foraminiferidal ranges in the type Tanjero Formation (Upper Campanian-Maastrichtian) of Northern Iraq.* J. Geol. Soc. Iraq, 8, p. 73-86.

Kassab, I. I. M., 1975b. *Biostratigraphic study on the subsurface Upper Cretaceous-Lower Tertiary of the well Injana No. 5. Northeastern Iraq.* J. Geol. Soc. Iraq, Special Issue. Baghdad.

Kassler, P., 1973. *The structural and geomorphic evolution of the Persian Gulf.* In: B. H. Purser (Editor) The Persian Gulf, Springer-Verlag, Berlin, 11-32.

Kent, P. E., Slinger, F., C. and Thomas, A. N., 1951. *Stratigraphical exploration surveys in SW Persia.* 3rd World Petroleum Congress, Sect. 1.1, The Hague.

Khalaf, F., Al-Kadi, A. and Al-Saleh, S., 1985. *Mineralogical composition and potential sources of dust fallout deposits in Kuwait, Northern Arabian Gulf.* Sed. Geol., 42, p. 255-278.

Klein, 2004. *Geochemistry of the igneous oceanic crust.* In: H. D. Holland and K. K. Turekian (eds.), Treatise on geochemistry. Elsevier-Pergamon. Oxford.

Krásný, J., 1980. *Hydrogeology of the Mesopotamian Plain and its environs. Adhaim area.* Manuscript report , GEOSURV, Baghdad, Iraq.

Krásný, J., 1981a. *Hydrogeology of the Mesopotamian Plain and its environs: Baghdad area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1981b. *Hydrogeology of the Mesopotamian Plain and its environs: Mandali-Zurbatiya area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1981c. *Hydrogeology of the Mesopotamian Plain and its environs: Hilla-Shithatha area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1982b. *Hydrogeology of the Mesopotamian Plain and its environs: Diwaniya-Samawa area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1982c. *Hydrogeology of the Mesopotamian Plain and its environs: Nasiriya-Amara area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1982d. *Hydrogeology of the Mesopotamian Plain and its environs: Al Qusair-Suq Ash Shuyukh-Basra area.* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1982e. *Hydrogeology and hydrochemistry of the Tikrit-Baquba area (with hydrogeological and hydrochemical maps in 1:250,000).* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1983a. *Hydrogeology and hydrochemistry of the Foothill Zone (with hydrogeological and hydrochemical maps in 1:250,000).* Manuscript report, GEOSURV, Baghdad.

Krásný, J., 1983b. *Extension and distribution of main types of deposits within the upper part of the Mesopotamian Plain; Regional approach in computer data processing.* Manuscript report, GEOSURV, Baghdad.

Kukal, Z. and Saadallah, A., 1973. *Aeolian admixtures in the sediments of the northern Persian Gulf.* In: B. H. Purser (ed.), The Persian Gulf, Springer-Verlag, Berlin, p. 115-121.

Kunstman, A., 1981. *Hydroinf-system. Computer system of archivisation and processing of hydrogeological data from Iraq territory.* Groundwater Development Administration. Baghdad.

Kureshy, A. A., 1979. *The Cretaceous-Tertiary boundary in Pakistan.* In: Birkelund, T. and Chrisensen, W. K. (eds.), Cret-Tert. Boundary Events Symp., p. 214-221.

Larsen, C. E., Evans, G., 1978. *The Holocene geological history of the Tigris-Euphrates-Karun Delta.* In: Price, W. C. (ed.), The Environmental History of the Near and Middle East. Academic Press, London, p. 227-244.

Larter, R. D. and Leat, P. T. (eds) 2003. *Inta-Oceanic Subduction Systems: Tectonic and Magmatic Processes.* Geological Society, London, Special Publications, 219.

Laws, E. D and Wilson, M, 1997. *Tectonics and magmatism associated with Mesozoic passive margin development in the Middle East.* Journal of the Geological Society, London, 154, p. 459-464.

Lees, G. M. and Falcon, N. L., 1952. *The geographical history of the Mesopotamian Plain.* Geogr. Journ., 118p.

Lloyd, S. 1949. *Foundation in the dust, a story of the Mesopotamian exploration.* 2nd Edition. Oxford Univ. Press., London, 237p.

Loeblich, A. R. and Tappan, H., 1957. *Planktonic*

foraminifera of Plaeocene and Early Eocene from the Gulf and Atlantic coastal plains. Bull. US Nat. Mus., 215, p. 173-198.

Loletti, M. A. (year unknown). *Iron and steel industry in Iraq: Outline of the eventual operation schedule.* Manuscript report No. 247, GEOSURV, Baghdad.

McCarthy, M. J., 1955. *Final report on geology between the Zab and Khabour Rivers.* Manuscript report, GEOSURV, Baghdad.

Macdonald, M., 1960. *Diyala and Middle Tigris Projects.* 10 reports, Ministry of Agriculture, D.G. of Irrigation, Baghdad.

Macfadyen, W. A. and Vita-Finzi, C., 1978. *Meospotamia: The Tigris-Euphrates Delta and its Holocene Hammar fauna.* Geol. Mag., 115, p. 287-300.

MacFayden, W. A., 1935. *Mineral deposits of Iraq.* Manuscript report, GEOSURV, Baghdad.

Mahdi, M. A. and Al-Delaimi, M. R., 1999. *Kaolinitic claystones in Iraq.* Manuscript report, GEOSURV, Baghdad.

Maheo, G., Bertrand, H., Guillot, S., Mascle, G., Pecher, A., Picart, C. and de Sigoyer, J., 2000. *Evidence of an immatureTethyan arc in ophiolites from southern Ladakh, India, northwestern Himalayas.* Comptes Rendus de l'Academie de Sciences, Serie 2, 330, p. 289-295.

Majid, A. H. and Veizer, J., 1986. *Deposition and chemical digenesis of Tertiary carbonates, Kirkuk oil field, Iraq.* AAPG Bull., 70, p. 898-913.

Makris, J. and Henke, C. H., 1992. *Pull-apart evolution of the Red Sea.* Journal of Petroleum Geology, 15, p. 127-134.

Macleod, J. H., 1961. *Final well report on Afaq No. 1.* Manuscript report, INOC Library, Baghdad.

Mansour, J., Zaidan, S. and Ibrahim, S., 1979. *Iraqi marble.* Manuscript report, GEOSURV, Baghdad.

Mansour, J. and Petranek, J., 1980. *Major occurrences and deposits of limestone in Iraq.* Manuscript report, GEOSURV, Baghdad.

Mansour, J. and Toma, N., 1983. *Gypsum rocks and gypcrete in Iraq.* Manuscript report, GEOSURV, Baghdad.

Marzouki, F. M. H., Jackson, N. J., Ramsay, C. R. and Darbyshire, D. P. F., 1982. *Composition, age and origin of two Proterozoic diorite-tonalite complexes in the Arabian Shield:* Precambrian Research, 19, 31-50.

Mašek, J. and Etabi, W., 1973. *Petrology of the Mawat igneous-metamorphic complex, northeastern Iraq.* Manuscript report, GEOSURV, Baghdad.

May, P. R., 1991. *The Eastern Mediterranean Mesozoic Basin: evolution and Oil Habitat.* AAPG, 75, p. 1215-1252.

Melville, E. M., 1949a. *Final report on well Mushorah 1.* Manuscript report No. FWR 38, INOC Library, Baghdad.

Melville, E. M. and Fothergill, T., 1956. *Final well repon on Chemchemal 2.* Manuscript report No. FWR 10, INOC Library, Baghdad.

Menzies, M. A. and Dupuy, C., 1991. *Orogenic massifs: Protolith, process and provenance.* Journal Petrology, Orogenic lherzolites and mantle processes (spec. vol.), p. 1-16.

Mercer, W., 1976. *Minor elements in metal deposits in sedimentary rocks: A review of the recent literature. Handbook of strata-bound deposits.* In: Wolf K. H. (ed.), Vol. 2, Elsevier, Amsterdam-Oxford-New York, p. 1-27.

Mercolli, I., 2000. *The mantle-crust transition in the Semail ophiolite, Sultanate of Oman. Crust-mantle interactions.* Proceedings of the International School Earth and Planetary Sciences, Siena 2000, p. 125-138.

McGillivray, J. G. and Husseini, M. I., 1992. *The Palaeozoic petroleum geology of Central Arabia.* AAPG Bull., 76, p. 1473-1490.

Milner, P. A., 1998. *Source rock distribution and thermal maturity in the Southern Arabian peninsula.* GeoArabia, 3, p. 339-356.

Minarikova, D., 1979. *The results of the Quaternary sediments investigations in the borthern part of the Mesopotamian Plain.* Manuscript Report, GEOSURV, Baghdad.

Mironov, G. A. and Sitchenkov, N. M., 1962. *Report on prospecting exploration of the Duri-Serguza lead-zinc deposit and Berzanik ore occurrence in 1960-1961.* Manuscript report, GEOSURV, Baghdad.

Mitchell, A. H. G., 1976. *Tectonic settings for emplacement of subduction-related magmas and associated mineral deposits.* Special Paper, Geological Association of Canada. 14, Metallogeny and plate tectonics, p 3-21.

Mitchell, R. C., 1957. *Notes on the geology of Western Iraq and Northern Saudi Arabia.* Geol. Rundechau., 46, Pt. 2, Stuttgart

Mitchell, R. C., 1958. *The Al Um Chaimin, a crater of possible meteoric origin in Western Iraq.* Geogr. Jour., 123, p. 578-580.

Miyashiro, A., 1973. *Metamorphism and metamorphic belts.* 1-492, George Allen-Unwin Ltd. London.

Mooney, W. D., Laske, G. and Masters, T. G., 1998. *CRUST 5.1, a global crustal model at 5×5.* Journal of Geophysical research, 103, p. 727-747.

Moores, E., Kellogg, L. H. and Dilek, Y., 2000: *Tethyan ophiolites, mantle convection, and tectonic "historical contingency": a resolution of the "ophiolite conundrum".* In: Y. Dilek, E. M. Moores, D. Elthon and A. Nicolas (eds.), Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program, Special Paper, Geological Society of America, Boulder, CO. USA, vol. 349, 3-12.

Mullen, E. D., 1983. *MnO/ TiO_2/P_2O_5; a minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis.* Earth and Planetary Science Letters. 62; 1, p. 53-62.

Murris, R. J. 1980. *The Middle East: Stratigraphic evaluation and oil habitat.* AAPG Bull., 64, p. 597-618.

Mustafa, M., Al-Badri, A. and Dimitrov, D., 1984. *Salt deposits and occurrences of Iraq.* Manuscript report,

GEOSURV, Baghdad.

Nahab, M. and Rahman, A. Y., 1974. *Magnetic and electromagnetic measurements in Marabasta-1973.* Manuscript report, GEOSURV, Baghdad.

Naqib, K. M. Al, 1967. *Geology of the Arabian Peninsula, Southeastern Iraq.* USGS Professional, paper No. 560-G., 54p

Nehlig, P., Asfirane, F., Genna, A., Guerrot, C., Nicol, N., Salpeteur, I., Shanti, M. and Thieblemont, D., 2002. *Aeromagnetic map constrains cratonization of the Arabian Shield.* Terra Nova, 13, p. 347-353.

Nicolas, A. and Boudier, F., 2003. *Where ophiolites come from and what do they tell us.* Geological Society of America. Spec. Paper, Boulder, CO, USA, 373.

Nuttli, Otto W., 1980. *The Excitation and Attenuation of Seismic Crustal Phases in Iran.* Bull. Seis. Soc. Amer., 70, p. 469-485.

Odishu, K. Y. and Othman, R. S., 1992. *Preliminary Geochemical Evaluation of Hydrocarbon Source Rock in Northern Parts of Iraq.* Iraqi Geological Journal, 25(2), p. 136-153.

Ojha, D. N., 1978. *Occurrence of prehnite in the altered gabbro of the Penjwin igneous Complex, Northeastern Iraq.* Geol. Soc. of Iraq. II, 160-169. Baghdad.

Owen, R. M. S. and Nasr, S. N., 1958. *The stratigraphy of the Kuwait-Basrah area,* in: Weeks G. L. (editor) Habitat of Oil a Symposium. Am. Assoc. Petr. Geol., Tulsa.

Pallister, J. S., Stacey, J. S., Fischer, L. B., and Premo, W. R., 1988. *Precambrian ophiolites of Arabia: geologic settings, U-Pb geochronology, Pb-isotope characteristics, and implications for continental accretion:* Precambrian Research, 38, 1-54.

Parsons, R. M., 1955a. *Ground-water resources of Iraq.* Khanaqin-Jassan Area, Vol. 1. Development Board, Min. of Development, Government of Iraq. Baghdad

Parsons, R. M., 1955c. *Ground-water resources of Iraq. Baiji-Samarra Area, Vol. 3.* Development Board, Min. of Development, Government of Iraq. Baghdad

Parsons, R. M., 1955d. *Ground-water resources of Iraq, Kirkuk Liwa, Vol. 4.* Development Board, Min. of Development, Government of Iraq. Baghdad

Parsons, R. M., 1955e. *Ground-water resources of Iraq, Jezira Desert, Vol. 5.* Development Board, Min. of Development, Government of Iraq. Baghdad

Parsons, R. M., 1955f. *Ground-water resources of Iraq, Erbil Liwa, Vol. 6.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1955g. *Ground-water resources of Iraq, Southern Desert, Vol. 7.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1955h. *Ground-water resources of Iraq, Northern Desert, Vol. 8.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1955i. *Ground-water resources of Iraq. Hydrologic aspects of selected areas (Introductory to the hydrology of Iraq with detailed hydrogeological data on certain areas), Vol. 9.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1957a. *Ground-water resources of Iraq, Dulaim Liwa, Vol. 10.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1957b. *Ground-water resources of Iraq, Mesopotamian Plain, Vol. 11.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1957c. *Ground-water resources of Iraq, Sulaimaniyah Liwa, Vol. 12.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Parsons, R. M., 1957d. *Ground-water resources of Iraq, Mandali Area, Vol. 13.* Development Board, Min. of Development, Government of Iraq. Baghdad.

Pascoe, E. H., 1922. *Geological notes on Mesopotamia with special reference to occurrences of petroleum.* Memoirs Geol. Surv. India V.48, p 1-90.

Pearce, J. A., Alabaster, T., Shelton, A. W. and Searle, M. P., 1981. *The Oman ophiolite as a Cretaceous arc-basin complex; evidence and implications.* Phil. Trans. R.Soc. Lond, 300, 299-317.

Perincek, D., 1979. *Geological investigation of the Celikhan-Sincik-Kocali area (Adiyaman Province).* Istanbul Universitesi Fen Fakultesi Mecm., Seri B, 44, p. 127-147.

Perincek, D., 1980. *Volcanics of Triassic age in Bitlis Metamorphic rocks.* Bulletin of the Geological Society of Turkey, 23, p. 201-211.

Perincek, D., 1990. *Hakkari ili ve dolayinin stratigrafisi, Guneydogu Anadolu, Turkiye.* Turkiye Petrol jeologari dernegi Bulteini, 2, p. 21-68.

Peters, T. and Mercolli, I., 1997. *Formation and evolution of the Masirah Ophiolite (Sultanate of Oman).* Ofioliti, 22, p. 15-34.

Philip, G., 1966. *Mineralogy of recent sediments and some detrital deposits.* Bull. Col. Sci., Baghdad University, 9, Baghdad.

Philip, G., 1967. *Note on the petrography of the Khabour Quartzite.* Bull. Coll. Sci., Baghdad University, 10, Baghdad

Philip, G., Saadallah, A. and Ajina, T., 1968. *Mechanical analysis and mineral composition of the Ga'ara sandstone. Part I. Mechanical analysis.* J. Geol. Soc. Iraq, 1, Baghdad.

Pillevuit, A., Marcoux, J., Stampfli, G. and Baud, A., 1997. *The Oman Exotics: a key to the understanding of the Neo-Tethyan geodynamic evolution.* Geodinamica Acta (Paris), 10, p. 209-238.

Pitman, J. K., Steinshouer, D. and Lewan, M. D., 2004. *Petroleum generation and migration in the Mesopotamian basin and Zagros fold belt of Iraq: results from basin-modeling study.* GeoArabia, 9, 4, p. 41-71.

Poirier, J. P. and Taher, M. A., 1980. *Historical seismicity in the Near and Middle East, North Africa and Spain from Arabic documents* (VIIth-XVIIIth Century, Bull. Seism. Soc. Am., 70, p. 2158-2201.

Polnikov, G. A. and Nikolayev, V. F., 1962. *Report on 1:200 000 prospecting correlation of the Rania-Qala Dizeh area carried out in 1961.* Technoexport report. Manuscript report, GEOSURV, Baghdad.

Ponikarov, V. P., Kazmm, V. G., Mikhailov, I. A., Razvaliayev, A. V., Krasheninnikov, V. A., Kozlov, V. V., Soulid-Kondratiyev, E. D., Mikhailov, K. Ya., Kulakov, V. V., FaradzHev, V. A. and Mirzayev, K. M., 1967. *The geology of Syria pan 1. Stratigraphy, igneous rocks and tectonics*. Dept. Geology and Min. Research, Ministry of Industry, Syria, 230p.

Powell, J. H., 1989. *Stratigraphy and sedimentation of the Phanerozoic rocks. Part A: Ram and Khreim Group.* Bulletin 11, Natural Resources A.uthority, Jordan, 72p.

Powers, R. W. Ramirez, L. F., Redmond, C. D. and Elberg, E. L., 1966. *Sedimentary geology of Saudi Arabia.* In: The geology of the Arabian Peninsula. USGS Prof. Paper No. 560-D., 177p, Washington.

Pratt, B. R. and Smewing, J. D., 1990. *Jurassic and Early Cretaceous platform margin configuration and evolution, central Oman Mountains.* In Robertson, A. H. F., Searle, M. P and Ries, A. C (eds.) The Geology and Tectonics of the Oman Region. Geological Society, London, Special Publication, 49, p. 69-88.

Prazak, J., 1974. *Stratigraphy and paleontology of the Miocene of the Western Desert, W. Iraq.* Manuscript report, GEOSURV, Baghdad.

Purser, B. H., 1973. *The Persian Gulf: Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea.* Springer-Verlag, Berlin, 471p.

Puttonen, J. and Varpasuo, P., 1982. *Seismic Risk Analysis for Northern Iraq.* Earthquake Engineering and Structural Dynamics, 10, 606-614.

Rabinowicz, M., Ceuleneer, G. and Nicolas, A., 1987. *Melt segregation and flow in mantle diapirs below spreading centers: evidence from the Oman ophiolite.* Journal of Geophysical Research, 92, p. 3475-3486.

Rabu, D., Le Metour, J., Bechennec, F., Beurrier, M., Villey, M., DE Grissac, C. H., 1990. *Sedimentary aspects of the Eo-Alpine cycle on the northeast edge of the Arabian Platform.* In: A. H. F. Robertson, M. P. Searle and A. C. Ries (eds.) *The Geology and Tectonics of the Oman Region.* Geological Society, London, Special Publication, 49, p. 49-68.

Raji, W. and Salman, B., 1983. *Palaeontological and environmental study of the Mesopotamian plain in Samawa-Nasirriya area.* Geol. Survey of Iraq, Baghdad, Unpublished Report.

Ricou, L. E., 1994. *Tethys reconstructed: plates, continental fragments and their Boundaries since 260 Ma from Central America to South-eastern Asia:* Geodinamica Acta (Paris) 7, No 4, p 169-218.

Riykov, A. and others, 1975. *General scheme of water resources and land development in Iraq.* Report of stage 1, Vols. 1, 2. Selkhozpromexport, Min. of Irrigation. Baghdad-Moscow.

Robertson, A. H. F., 1986. *The Hatay ophiolite (southern Turkey) in its Eastern Mediterranean tectonic context: a report on some aspects of the field excursion.* Ofioliti, 11, 2, p. 105-119.

Robertson, A. H. F., Blome, C. D, Cooper, D. J. W, Kemp, A. E. S and Searle, M. P, 1990a. *Evolution of the Arabian continental margin in the Dibba Zone, Northern Oman Mountains.* In A. H. F. Robertson, M. P. Searle, and A. C. Ries (eds.). The Geology and Tectonics of the Oman Region. Geological Society Special Publication No. 49, p. 251-284.

Robertson, A. H. F., Kemp, A. E. S, Rex, D. C. and Blome, C. D, 1990b. *Sedimentary and structural evolution of a transform lineament margin: the Hatta Zone, Northern Oman Mountains.* In Robertson, A. H. F., Searle, M. P. and Ries, A. C. (eds.). The Geology and Tectonics of the Oman Region. Geological Society Special Publication No. 49, p. 285-305.

Robertson, A. H. F. and Searle, M. P, 1990c. *The northern Oman Tethyan continental margin; stratigraphy, structure and controversies.* In A. H. F. Robertson, M. P. Searle, and A. C. Ries (eds.). The Geology and Tectonics of the Oman Region. Geological Society Special Publication No. 49, p. 3-25.

Robertson, A. H. F., 1998. *Mesozoic-Tertiary tectonic evolution of the Easternmost Mediterranean area: integration of marine and land evidences.* Proc. Ocean Drill. Progr. Sci. Results 160, p. 723-782.

Robertson, A. F. H and Pickett, E. A. 2000. *Paleozoic-Early Tethyan evolution of melanges, rift and passive margin units in the Karaburun Peninsula (western Turkey) and Chios Island (Greece).* In E. Bozkurt, J. A. Winchester, and J. D. A. Piper (eds.) Tectonics and Magmatism in Turkey and the Surrounding Area. Geological Society, London, Special Publications, 173, p. 43-82.

Robertson, A. H. F., 2002. *Overview of the genesis and emplacement of Mesozoic ophiolites in the Eastern Mediterranean Tethyan region.* Lithos, 65, p. 1-67.

Rolleigh, L. F., 1960. *Final well report on Gha/aisan No. 1.* Manuscript report No. FWR 16, INOC Library, Baghdad.

Rolleigh, L. F., 1961. *Final well report on Safawi No. 1.* Manuscript report No. FWR 48, INOC Library, Baghdad.

Roulkovsky, M. F., 1961. *Report on prospecting exploration of the Spiradeh copper occurrence.* Manuscript report, GEOSURV, Baghdad.

Searle, M. P. and Cox, J., 2002. *Subduction zone metamorphism during formation and emplacement of the Semail ophiolite in the Oman mountains.* Geol. Mag. 139, 3, p. 241-255.

Sadik, J. M., 1977. *Sedimentological investigation of the Dibdibba Formation, southern and central Iraq.* MSc Thesis, Baghdad University, Iraq.

Sadooni, F. N., 1993. *Stratigraphic Sequence, Microfacies & Petroleum Prospects of the Yamama Formation, Lower Cretaceous, Southern Iraq.* AAPG Bull, 77, p. 1971-1988.

Sa'eed, L., 1988. *Mineral investigation of Swab limestone deposit.* Manuscript report, GEOSURV, Baghdad.

Safar, V. M., 1961. *Final well report on Dujaila No. 1.* Manuscript report No. FWR 13, INOC Library, Baghdad.

Sampo, M., 1969. *Microfacies and microfossils of the*

Zagros area, southwestern Iran (from pre-Permian to Miocene). In: J. Cuvillier, J. H. M. Schuermann and E. J. Brill (eds.), International sedimentary petrographical series, Leiden, Netherlands. P.102. 1969.

Samthein, M., 1971. *Sediments and the history of the postglacial transgression in the Persian Gulf and Gulf of Oman.* Mar. Geol., 12: p. 245-266.

Sattran, V., Al-Rafaie, A., Mustafa, M., Al-Bayati, K. and Al-Mubarek, K., 1973, *Geophysical mapping of the Marabasta area at scale 1:5000.* Manuscript report, GEOSURV, Baghdad.

Sattran, V., Aqif, A. and Kaabl, A., 1973. *Preliminary report on the mineralisation of the SerShiv ultrabasic body.* Manuscript report, GEOSURV, Baghdad.

Schettino, A. and Scotese, C., 2002. *Global kinematic constraints to the tectonic history of the Mediterranean region and surrounding areas during the Jurassic and Cretaceous.* In: G. Rosenbaum and G. S. Lister, Reconstuction of the evolution of the Alpine-Himalayan Orogen. Journal of the Virtual Explorer, 8, p. 149-168.

Schmidt, C. C., 1964. *A review of Permian and Mesozoic formations exposed near the Turkey-Iraq border at Harbol.* MTA Bulletin, Foreign Edition, 62, Ankara.

Schmidt, D. L., Hadley, D. G., Greenwood, W. R., Gonzalez, L., Coleman, R. G., and Brown, G. F., 1973. *Stratigraphy and tectonism of the southern part of the Precambrian Shield of Saudi Arabia.* Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Jeddah, Saudi Arabia, Bulletin 8, 13p.

Scotese, C. R., 1997. *Phanerozoic Plate Tectonic Reconstructions.* Animated map collection, Dept of Geology, University of Texas, Arlington.

Seber, D. and Mitchell, B. J., 1992. *Attenuation of surface waves across the Arabian peninsula.* Tectonophysics, 204, p. 137-150.

Searle, M. and Cox, J., 1999. *Tectonic setting, origin, and obduction of the Oman Ophiolite.* GSA Bulletin, 111, p. 104-122.

Searle, M. P., Warren, C. J., Waters., D. J. and Parrish, R. R., 2003. *Subduction zone polarity in the Oman Mountains: implications for ophiolite emplacement.* In Y. Dilek and P. T. Robinson (eds.) Ophiolites in Earth History. Geological Society, London, Special Publication, 218, p. 467-480.

Searle, M. P., Warren, C. J., Waters, D. J. and Parrish, R. R., 2004. *Structural evolution, metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman Mountains.* Journal of Structural Geology, 26, p. 451-473.

Seilacher, A., 1963. *Kaledonischer Unterbau der Irakiden.* Neues Jahrb. Geol. Paleont. Abt. A. Monatshefte No. 10.

Sengor, A. M. C., 1990. *A new model for the late Palaeozoic-Mesozoic tectonic evolution of Iran and implications for Oman.* In A. H. F. Robertson, M. P. Searle, M. P. and A. C. Ries (eds.), The Geology and Tectonics of the Oman Region. Geological Society, London, Special Publication, 49, p. 797-831.

Serryea, O. A., 1990. *Geochemistry of organic matter and oil.* Oil and Arab Cooperation, 16, p. 32-75 (in Arabic).

Setudehnia, A., 1978. *The Mesozoic sequence in South-West Iran and adjacent areas.* Journal of Petroleum Geology, 1, p. 3-42.

Shahidi, A. and Jalali, A., 2004. *Geological map of Iran, scale 1:100,000, sheet Satdasht.* Geological Survey of Iran, Tehran, Iran.

Shaker, M. M., 1983. *Report on the geological exploration and prospecting of quartz-sand for thermostone industry and glass industry in Wadi Amij, Km. 160, Anbar Gov.* Manuscript report, GEOSURV, Baghdad.

Shanshal, S. M., 2004. *Environmental impact of leatherr-tanning plants on soil and water in the Nahrawan area, Baghdad.* MSc Thesis, Baghdad University, Iraq.

Shaposhikov, E. T. and Babushkin, G. I., 1961. *Report on geological prospecting and investigation carried out at Rutba glass-sand deposit.* Manuscript report, GEOSURV, Baghdad.

Sharland, P. R., Archer, R., Casey, D. M., Hall, S. H., Heward, A. P., Horbury, A. D. and Simmons, M. D., 2001. *Arabian Plate Sequence Stratigraphy.* GeoArabia Special Publication 2, Gulf Petrolink, Bahrain, 371p.

Sheldon, R. P., 1981. *Ancient marine phosphorites.* Ann. Rev. Earth Planet. Sci., 9, p. 251-284.

Shinaq, R., 1996. *Subsurface Triassic Sediments in Jordan: Stratigraphic & Depositional Characterristics, & Hydrocarbon Potential.* Journal of Petroleum Geology, 19, p. 57-76.

Sibrava, V., 1964. *Double fluvial accumulations in the area of Bohemian Massif and the Carpathian Foredeep.* Sbor. geol. věd, Antropozoikum. Praha.

Smirnov, V. A. and Nelidov, V. P., 1962. *Report on 1: 200 000 prospecting correlation of the Sulaimaniya, Choarta, Penjwin area carried out in 1961.* Manuscript report, GEOSURV, Baghdad.

Snow, J. E. and Dick, H. J. B., 1995. *Pervasive magnesium loss by marine weathering of peridotite.* Geochim. Cosmochim. Acta, 59, p. 4219-4235.

Spath, L. F., 1950. *A new Tithonian Ammonoid fauna from Kurdistan, North Iraq.* British Museum (Nat. Hist.), Geology Bull., 1, London.

Stacey, J. S. and Stoeser, D. B., 1983. *Distribution of oceanic and continental leads in the Arabian-Nubian-Shield.* Contributions to Mineralogy and Petrology, 84, p. 91-105.

Stacey, J. S., Stoeser, D., Greenwood, W. R. and Fischer, L. B., 1984. *U-Pb zircon geochronology and geological evolution of the Halaban-Al Amar region of the eastern Arabian Shield, Kingdom of Saudi Arabia.* Journal of the Geological Society of London. 141; 6, p. 1043-1055.

Stacey, J. B. and Agar, R. A., 1985. *U-Pb isotopic evidence for the accretion of a continental microplate in the Zalm region of the Saudi Arabian Shield.* Journal of the Geological Society of London, 142, p. 1189-1203.

Stampfli, G. M., 2000. *Tethyan Oceans.* In E. Bozkurt., J. A. Winchester and J. D. A. Piper (eds.), Tectonics and

Magmatism in Turkey and the Surrounding Area. Geological Society, London, Special Publication 173, p 1-23.

Stevanovic, Z. and Markovic, M., 2004a. *Hydrogeology of Northern Iraq. Volume 1, Climate, Hydrology, Geomorphology and Geology.* Food and Agriculture Organization of the United Nations, Rome

Stevanovic, Z. and Markovic, M., 2004b. *Hydrogeology of Northern Iraq. Volume 2, General hydrogeology and aquifer systems.* Food and Agriculture Organization of the United Nations, Rome

Stevens, J. R., 1952. *Notes on field survey of metallic mineral prospects located by Mr. R. Williams in 1949-1951.* Manuscript report, GEOSURV, Baghdad.

Stocklin, J., 1968. *Structural History & Tectonics of Iran: A Review.* AAPG Bulletin, 52, p. 1229-1258.

Stocklin, J. and Nabavi, M., 1973. *Tectonic map of Iran.* Geological Survey of Iran Publication

Stoeser, D. B. and Camp, V. E., 1985. *Pan-African microplate accretion of the Arabian Shield.* Geological Society of America Bulletin, 96, p. 817-826.

Stoeser, D. B. and Stacey, J. S., 1988. *Evolution, U-Pb geochronology, and isotope geology of the Pan-African Nabitah organic belt of the Saudi Arabian Shield.* In: S. El-Gaby and R. O. Grriling (eds.), The Pan-African Belt of Northeast Africa and Adjacent Areas. Viewing and Sohan, Braunschweig/Wiesbaden.

Stoffers, P. and Ross, D. A., 1979. *Late Pleistocene and Holocene sedimentation in the Persian Gulf and Gulf of Oman.* Sed. Geol., 23, p. 181-208.

Stoneley, R., 1981. *The geology of the Kuh-e dalneshin area of southern Iran, and its bearing on the evolution of southern Tethys.* Journal of the Geological Society, London, 138, p. 509-526.

Tamar-Agha, M. Y., Abdul Amir, W. and Aboud, A., 1984. *Prospecting for silica-sand in the Ga'ara depression.* Manuscript report, GEOSURV, Baghdad.

Tao, W. C., and O'Connell, R. J., 1993. *Deformation of a weak subducted slab and variation of seismicity with depth.* Nature, 361, p. 626-628.

Templeton, R. S. M., Crank, K. A. M. and Bousinger, A. D., 1956. *Final report on well Makhul No. 2.* Manuscript report No. FWR 34, INOC Library, Baghdad.

Teretenko, N. A. and Khadikov, B. B., 1961. *Report on prospecting exploration of the Asnawa iron ore deposit and Mishau iron ore occurrence.* Manuscript report No. 298, GEOSURV, Baghdad.

Terkin, J. M. J. and Frewin, N. L., 1998. *The Q Petroleum system of Oman.* AAPG International Conference and Exhibition, p. 489.

Thomas, H., Behnam, H. A. M. and Ligabue, G., 1981. *New Discoveries of Vertibrate Fossils in the Bakhtiari Formation, Injana Area, Hemrin South, Iraq.* J. Geol. Soc. Iraq, 14. p. 43-53.

Thsieger, W., 1967. *The marsh Arabs.* Penguin, London, 233p.

Tobia, F. H., 1983. *Geochemistry and mineralogy of the iron deposits of the Ga'ara Formation in Iraqi Western Desert.* MSc Thesis, Baghdad University, Iraq.

Tyracek, J. and Youbert, Y., 1975. *Report on the regional geological survey of Western Desert between T1 Oil pumping station and Wadi Hauran (Western Iraq).* Manuscript report, GEOSURV Baghdad.

Tyracek, J., 1980. *The Quaternay. In T. Buday: The Regional Geology of Iraq, Stratigraphy and Palaeogeography.* Dar A-Kutub Publishing House, University of Mosul, Iraq.

Tyracek, J., 1987. *Terraces of the Euphrates River.* Sbor. geol. věd, Antropozoikum, 18. Praha.

Upadhyay, H. D. and Neale, E. R. W., 1979. *On the tectonic regimes of ophiolite genesis.* Earth and Planet. Sci. Lett., 43, p. 93-102.

Vail, J. R., 1991. *The Precambrian Tectonic structures of North Africa.* In: Salem et al. (ed.), Geology of Libya. 6, p. 2259-2268.

Van Der Kaaden, G., 1971. *Basement rocks of Turkey.* In: A. Campbell (ed.), Geology and History of Turkey. The Petroleum Society of Libya, Tripoli, Libya.

Vaněček, M., 1972. *The principal metallogenic features of Iraq.* Acta Universitatis Carolinae-Geologica No. 3, p. 237-252. Prague

Vasiliev, M. M., Polnikov, G. A. and Vexler, V. I., 1964. *Report on geological investigations into iron ores of the Al Ga'ara Depression carried out during 1963-1964 with estimation of reserves as of June 1, 1964.* Manuscript report No. 314, GEOSURV, Baghdad.

Vaugham, D. J., 1976. *Sedimentary geochemistry and mineralogy of the sulfides of lead, zinc, copper and their occurrence in sedimentary ore deposits.* In: K. H. Wolf (ed.), Handbook of strata-bound and stratiform ore deposits. 2, Elsevier, Amsterdam-Oxford-New York, p. 317-363

Vejlupek, M. J., 1980. *Distribution of some minor and trace elements in Iraq.* J Geol. Soc. Iraq, 13, p. 217-224.

Versfelt, Jr. P. L., 2001. *Major hydrocarbon potential in Iran.* In: M. W. Downey, J. C. Threet, and W. A. Morgan (eds.), Petroleum provinces of the twenty-first century: AAPG Memoir 74 p. 417-427.

Verma, M. K., Ahlbrandt, T. S. and Al-Gailani, M., 2004. *Petroleum reserves and undiscovered resources in the total petroleum systems of Iraq: reserve growth and production implications.* GeoArabia, 9, p. 51-74.

Waples, D. W., 1980. *Time and temperature in petroleum formation: Application of Lopatin's method to petroleum exploration.* AAPG Bull., 64, p. 916-926.

Warburton, J., Burnhill, T. J., Graham, R. H. and Isaac, K. P., 1990. *The evolution of the Oman Mountains Foreland Basin.* In A. H. F. Robertson, M. P. Searle, M. P. and A. C. Ries (eds.), The Geology and Tectonics of the Oman Region, Geological Society, London, Special Publication, 49, p. 419-427.

Warren, C. J., Parrish, R. R., Searle, M. P. and Waters, D. J., 2003. *Dating the subduction of the Arabian continental margin beneath the Semail ophiolite, Oman.* Geology, 31, 889-892.

Weber, H., 1963. *Ergebnisse erdolgeoloischer*

AufscMussarbeiten der DEA in nordost Syrien. Erdol-Kohle, Erdgas, Petroleum, 14, Hannover-Wien.

Wetzel, R., 1950. *Stratigraphy of the Amadia region. MPC report No.IR/RW 12.* Manuscript report, GEOSURV, Baghdad.

Xypolias, P., Dorr, W. and Zulauf, G., 2006. *Late Carboniferous plutonism within the pre-Alpine basement of the External Hellenides (Kithira, Greece): evidence from U-Pb zircon dating.* Journal of the Geological Society, London, 163, pp. 539-547.

Ya'acoub, S. Y., Purser, B. H., Al-Hassani, N. H., Al-Azzawi, M., Orzag-Sperber, F., Hassan, K. M., Plaziat, J. C. and Younis, W. R., 1981. *Preliminary study of the Quaternary sediments of SE Iraq.* Joint project between the Geological Survey of Iraq and Univ. of Paris XI, Orsay. (Unpublished Report).

Yilmaz, Y., 1985. *Geology of the Cilo Ophiolite: An ancient ensimatic island arc fragment on the Arabian Platform, SE Turkey.* Ofioliti, 10, p. 457-484.

Yilmaz, Y., 1991. *Allochthonous terranes in the Tethyan Middle East: Anatolia and the surrounding regions.* In: J. F. Dewey, I. G. Gass, G. B. Curry and A. M. C. Sengor. (eds.), Allochthonous Terranes. Cambr. Univ. Press, p. 155-168.

Yilmaz, Y., 1993a. *New evidence and model on the evolution of the southeast Anatolian orogen.* Geological Society of America Bulletin, 105, p. 251-271.

Yilmaz, Y., 1993b. *Ophiolites and metamorphic assemblages of southeast Anatolia and their significance in the geological evolution of the orogenic belt.* Tectonics, 12, p. 1280-1297.

Zainal, Y. M., 1972. *Geological report on Qara Tappah bentonite.* Manuscript report, GEOSURV, Baghdad.

Zainal, Y. M., 1977. *Mineralogy, geochemistry and origin of some Tertiary bentonites in Iraq.* PhD Thesis, Sheffield University, UK.

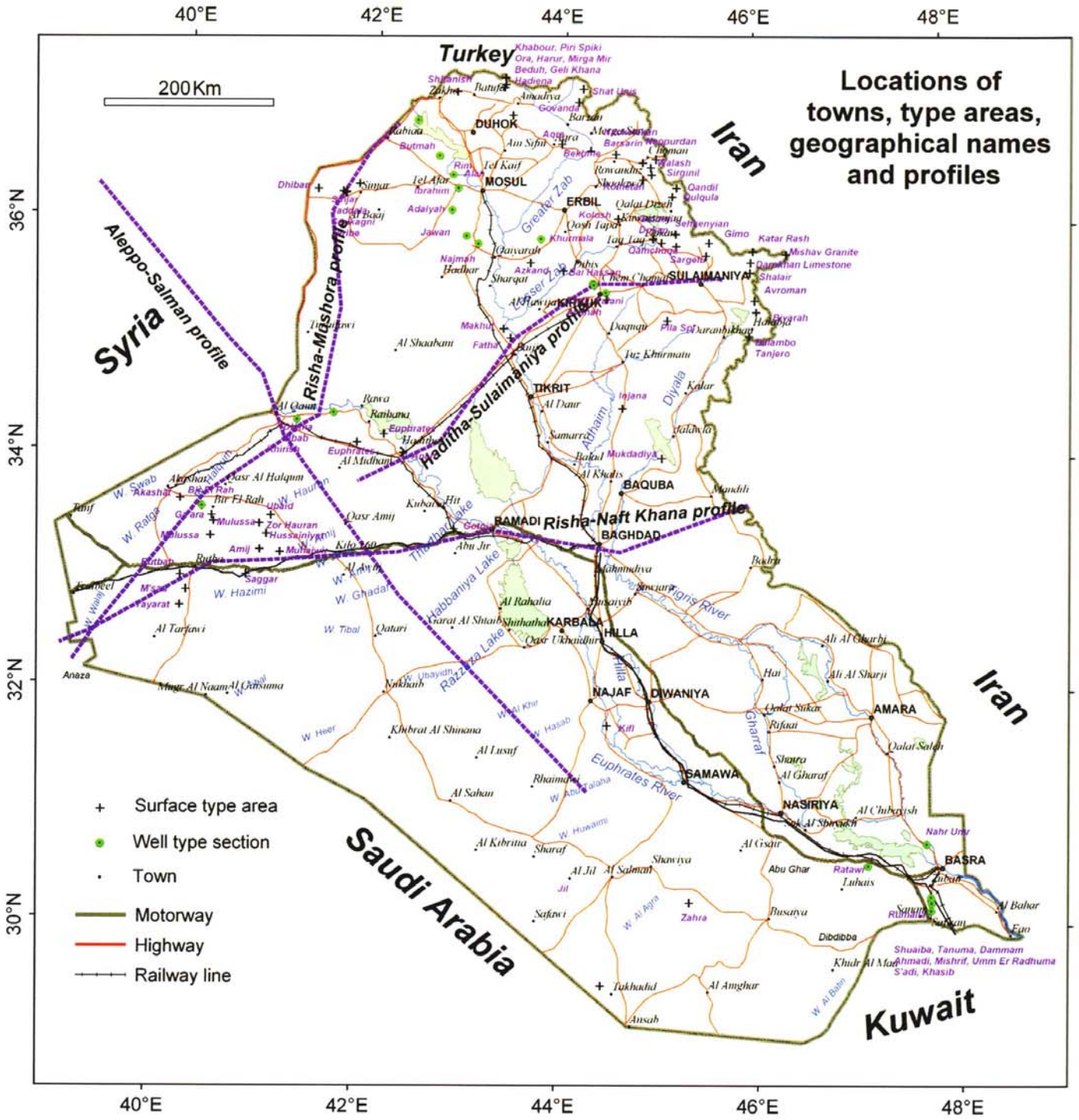
Ziegler, P. A., Cloetingh, S. and Van Vees, J. D., 1995. *Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples.* Tectonophysics, 252, 7-59.

Ziegler, M. 2001. *Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences.* GeoArabia, 3, p. 445-504.

Zwain, J. A., 1976. *Analysis from air photographs of fracture traces in northern Iraq: a structural-geological study with reference to oil exploitation.* PhD Thesis, Imperial College, London, UK.

Zwain, J. A., 1983. *The structural analysis of geological fracture traces in Mushorah-Ain Zalah area.* Northern Iraq. J. Geol. Soc. Iraq, 16, p. 22-51.

APPENDIX 1


Locations of towns, type areas, geographical names and profiles
200 Km
Turkey
Iran
Syria
Saudi Arabia
Kuwait
Aleppo-Salman profile
Risha-Mashora profile
Hadiitha-Sulaimaniya profile
Risha-Naft Khana profile
DUHOK
MOSUL
ERBIL
SULAIMANIYA
KIRKUK
TIKRIT
BAQUBA
RAMADI
BAGHDAD
KARBALA
HILLA
NAJAF
DIWANIYA
SAMAWA
NASIRIYA
AMARA
BASRA
Surface type area
Well type section
Town
Motorway
Highway
Railway line
40°E
42°E
44°E
46°E
48°E
36°N
34°N
32°N
30°N

APPENDIX 2

Table of basic reservoir data from the on stream Iraqi oil fields, evaluated fields and drilled structure. The Appendix comprises: tectonic zone (FZ Foothill Zone, MZ Mesopotamian Zone, SZ Salman Zone, RSZ Rutba Subzone). Name of field/structure, Length, Width, reservoir formation, age, main lithology, depth to reservoir, pay thickness, porosity (Por%), permeability (perm), API°, Sulphur content % (S), hydrocarbon shows and date of completion or on stream.

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
FZ	Abtakh		2	Fatha	Miocene	Carb.	956	--	--	--	--	--	Oil&Gas	1978
				Jeribe	Miocene	Carb.	1407	--	--	--	--	--		
				Shir./Hartha	Camp-Maast	Carb.	2401	--	--	--	--	--		
				Mushorah	Turonian	Carb.	2656	--	--	--	--	--		
				Mus	Liassic	Carb.	3298	--	--	--	--	--		
				Butmah	Liassic	Carb.	3509	--	--	--	--	--		
				Kurra Chine	U Triassic	Carb.	3574	--	--	--	--	--		
				Geli Khana	M Triassic	Carb.	4104	--	--	--	--	--		
	Abu Ghirab N	8	2	Kirkuk Group	Oligocene	Carb.	3014	--	18	400	24	3.93		
				Mishrif	Cen-Tur	Carb.	3797	--	12	93	24.9	3.6		
				Maudduad	Albian	Carb.	4258	--	13	5.6	26	3.07		
	Abu Ghirab S	19	4	Jer./ Euph.	Miocene	Carb.	2887	--	20	500	21	3.23		1971 On stream
	Adaiyah			Shiranish	Camp-Maast	Marl	326	--	--	--	15	--	Heavy	1938
				Butmah	Liassic	Carb.	1226	--	--	--	31	--		
				Kurra Chine	U Triassic	Carb.		--	--	--	--	--		
	Ain Ghazal	14	4	Jeribe	Miocene	Carb.	1084	--	--	--	--	--	Oil&Gas	1983
				Euphrates	Miocene	Carb.	1386	--	--	--	--	--		
	Ain Zalah	15	4	Shiranish	Camp-Maast	Carb.	1607	90	3	Fr. Res	31.5	2.6		1951 On stream
				Mushorah	Senonian	Carb.	2231	--	18	--	31.4	2.7		
				Maudduad	Albian	Carb.	3438	223	18	--	31.4	2.7		
	Ajeel	20	6	Fatha	Miocene	Carb.	644	--	--	--	41	--	Oil&Gas	1998 On stream
		7	3	Jer/Dhiban	Miocene	Carb.	944	--	--	--	34	--		
				Euphrates	Miocene	Carb.	989	--	--	--	30	--		
				Chia Gara	Tithonian	Carb.	2924	--	--	--	27	--		
				Gotnia	U Jurassic	Carb.	3175	--	--	--	38	--		
				Sargelu	M Jurassic	Carb.	3243	--	--	--	42	--		
	Alan	28	4	Sargelu	M Jurassic	Carb.	1247	17.4	--	--	13.3	2.5	Heavy	1937&1955
				Kurra Chine	U Triassic	Carb.	2320	50.3	--	--	34.1	1		
				Kurra Chine	U Triassic	Carb.	--	--	--	--	29.1	1.57		
	Atshan	30	3	Sargelu	M Jurassic	Carb.	951	--	--	--	34.2	1.8	Heavy	1954
				Mus/ Adaiyah	Liassic	Carb.	1273	--	--	--	34	1.9		

			Butmah	Liassic	Carb.	1381	--	--	--	34	1.5	
			Kurra Chine	U Triassic	Carb.	1991	--	--	--	--	--	
			Geli Khana	M Triassic	Carb.	2539	--	--	--	--	--	
Avanah-Kirkuk	27	4	Kirkuk Group	Oligocene	Carb.	666	472	25	200	36.1	1.95	1933 On stream
			Shiranish	Camp-Maast	Marl	1448	--	--	--	33	--	
			Kometan	Turonian	Marl	1670	--	--	--	33	--	
Baba-Kirkuk	50	4	Kirkuk Group	Oligocene	Carb.	363	747	25	250+	36.7	2.05	1934-On_St
			Shiranish	Camp-Maast	Carb.	925	--	--	--	33	--	
			Kometan	Turonian	Marl	1150	--	--	--	33	--	
			Mauddud	Albian	Carb.	1275	--	--	--	38	--	
			Shuaiba	Aptian	Carb.	1571	--	--	--	29	--	
Bai Hassan	22	4	Jeribe	Miocene	Carb.	788	--	--	--	--	--	1930 On stream
			Kirkuk Group	Oligocene	Carb.	801	378	20	30 - 200	34	2.6	
			Jaddala	Eocene	Chalk	1036	--	--	--	28	--	
			Aaliji	Pal-Eoc	Marl	1152	--	--	--	28	--	
			Shiranish	Camp-Maast	Marl	1188	--	--	--	31.5	--	
			L Kometan	Turonian	Marl	1480	--	--	--	11	--	
			Mauddud	Albian	Carb.	1549	--	--	--	22	--	
			Shuaiba	Aptian	Carb.	1822	--	30	125	26.5	3.7	
Bohaira	--	--	Kurra Chine	U Triassic	Carb.	--	--	--	--	--	--	1998
Butmah East	8	3	Shiranish	Camp-Maast	Carb.	1277	152	3	Fr. Res	29.3	2.6	1954
			Kurra Chine	U Triassic	Carb.	2981	--	--	--	36.2	1.08	1954
Butmah West	8	3	Kurra Chine	U Triassic	Carb.	2790	--	--	--	35	1.2	1986 On stream
	--	--	Geli Khana	M Triassic	Carb.	3775	--	--	--	34	0.04	
Chemchemal	74	5	Pila Spi	Eocene	Carb.	508.4 (fr	--	--	--	43	0.14	1930&1960
			Shiranish	Camp-Maast	Marl	1825	--	--	--	63.1	0.14	
			Sadi	Senonian	Carb.	--	--	--	--	Gas	--	
			Kometan	Turonian	Marl	--	--	--	--	Gas	--	
Chia Surkh	6.5	1.6	Fatha	Miocene	Carb.	1010	--	20	--	41	0.58	1954
			Jeribe	Miocene	Carb.	1720	--	18	--	43	0.67	
Demir Dagh	10	3	Gercus	M Eocene	Carb.	1017	--	--	--	14.9	4.9	1980
			Shiranish	Camp-Maast	Carb.	1567	--	--	--	22	3.9	
			Pilsener/Har.	Senonian	Carb.	?	--	--	--	14.9	--	
			Bekhme	Camp-Maast	Carb.	1626	--	--	--	22	--	

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
				Maudud	Albian	Carb.	1763	--	--	--	18	--		
				Najmah	U Jurassic	Carb.	2209	--	--	--	8	5.9		
	Fauqi South	12	2	Jeribe	Miocene	Carb.	2974	--	15	5-1000	18	3.4		1974
				Euphrates	Miocene	Carb.	2980	--	19	5-1000	18	3.5		
				Kirkuk Group	Oligocene	Carb.	3004	--	20	5-1000	18	3.97		
				Mishrif	Cenomanian	Carb.	3862	--	17	5-150	26	2.96		
	Gilabat			Injana	Miocene	Clast.	1493	--	17.9	275	41.3	0.7	Oil & Gas	1978
				Fatha	Miocene	Carb.	1900	--	20	--	39.6	0.86		
				Jeribe	Miocene	Carb.	2086	--	16	--	51.1	1.07		
				Euphrates	Miocene	Carb.	2302	--	19	--	42.6	1.38		
	Gullar	12	4	Fatha/ Jeribe	Miocene	Carb.	695	--	--	--	--	--		1957
				Aaliji	Pal-Eoc	Carb.	1484	--	--	--	--	--		
				Shiranish	Camp-Maast	Carb.	1884	--	--	--	--	--		
				Mushorah	Senonian	Carb.	2646	--	--	--	35.7	--		
	Gusair	13	5	Shiranish	Camp-Maast	Marl	957	--	--	--	14	--	Heavy	1954
				Maudud	Albian	Carb.	2100	--	--	--	12.7	--		
	Hemrin-Fudhul	25	4	--	--	--	--	--	--	--	--	--		1976
	Hemrin-Nukhaila	13	2	Jeribe	Miocene	Carb.	491	--	15	44	30	3.2		1976
				Dhiban	Miocene	Carb.	540	--	18	1.8	30	1.5		
				Euphrates	Miocene	Carb.	616	--	17	0.06	26	1.67		
				Kirkuk Group	Oligocene	Carb.	675	--	24.6	27.3	32	3.51		
				Mishrif	Cenomanian	Carb.	1185	--	11	8.07	21	2.5		
	Hemrin-Allas	30	4	Jeribe	Miocene	Carb.	423	--	15	43.8	30	3.6	Oil & Gas	1976
	Hibbarah	35	5	Jeribe	Miocene	Carb.	299	--	--	--	16	--	Heavy	1938
				--	--	--	--	--	--	--	--	--		
	Ibrahim	9	2	Shiranish	Camp-Maast	Marl	463	--	--	--	--	--	Oil&Gas	1957
				Hartha	Camp-Maast	Carb.	1274	--	--	--	--	--		
				Kurra Chine	U Triassic	Carb.	2591	--	--	--	28	--		
	Injana	15	4	Jeribe	Miocene	Carb.	1238	--	--	--	40	--	Oil & Gas	1958
				Shiranish	Camp-Maast	Marl	1961	--	--	--	33	1.8		
				Kometan	Turonian	Marl	3112	--	--	--	33	1.75		

Ismail	--	--	Kirkuk Group	Oligocene	Carb.	--	--	--	--	--	--	Oil&Gas	1997
Jambur	26	5	Jeribe	Miocene	Carb.	1554	102	20	4	40.5	1.2		1955 On stream
			Euph/Serik	Miocene	Carb.	1586	64	30	40	40.6	1.3		
			Shiranish	Camp-Maast	Marl	2082	--	--	--	--	--		1978
Jaria Pika	15	5	Jeribe	Miocene	Carb.	1457	--	--	--	48	2.2	Gas	1976
			Dhiban	Miocene	Carb.	1509	--	--	--	52	0.1		
			Euphrates	Miocene	Carb.	1626	--	--	--	52	0.1		
			Serikagni	Miocene	Marl	1651	--	--	--	52	0.1		
Jawan	16	5	Jeribe	Miocene	Carb.	175	150	--	--	15	7		1936
			Euphrates	Miocene	Carb.	254	50	--	--	19	6.8		
			Hartha	Camp-Maast	Carb.	693	200	--	--	20	5.8		
Judaida	5	1	Jeribe	Miocene	Carb.	2236	--	17.4	0.29	26	2.9	Oil & Gas	
			Dhiban	Miocene	Carb.	2286	--	16.9	21.1	25	--		
			Euphrates	Miocene	Carb.	2385	--	18.5	7.8	24.9	--		
			Kirkuk Group	Oligocene	Carb.	2445	--	17.8	36.5	25	4.18		
			Kometan	Turonian	Marl	3247	--	8.9	0.04	18	--		
Kand	33	5	nd	--	Carb.	--	--	--	--	--	--		1983
Khabaz	15	4	Jeribe	Miocene	Carb.	2063	--	20	1146	37	2.08		1994 On stream
			Kirkuk Group	Oligocene	Carb.	2111	--	15	740	37	1.5		
			Mauddud	Albian	Carb.	2753	--	12	25	29	2.05		
			Shuaiba	Aptian	Carb.	3045	--	8	83	39	2		
Khanuqah	33	3	Jeribe	Miocene	Carb.	265	--	--	--	--	--	Gas	
			--	--	--	--	--	--	--	--	--		1929
Khashim Ahmar	11	3	Fatha	Miocene	Carb.	955	--	15	--	--	--	Gas	1928&1980
			Jeribe	Miocene	Carb.	1338	--	21	--	--	--		
			Dhiban	Miocene	Carb.	1393	--	15	--	--	1.17		
			Euphrates	Miocene	Carb.	1543	--	19	--	38	1.05		
Khurmala	24	5	Kirkuk Group	Oligocene	Carb.	815	300	--	150	34	1.95		
			Mauddud	Albian	Carb.	1771	--	--	--	38	--		
			Shuaiba	Aptian	Carb.	2031	--	--	--	29	--		
Kor Mor			Jeribe	Miocene	Carb.	1931	85	20	Fr. Res	57	--		1990 On stream
			Euphrates	Miocene	Carb.	1595	--	--	--	--	--		
			Kirkuk Group	Oligocene	Carb.	1711	--	--	--	--	--		
Makhmur	5	1	Jeribe	Miocene	Carb.	460	--	--	--	--	--	Oil & Gas	1980

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
				Hartha	Camp-Maast	Carb.	919	--	--	--	--	--		
	Makhul	55	4	Euphrates	Miocene	Carb.	230	--	--	--	--	--		1939
				Shiran./ Har.	Camp-Maast	Carb.	381	--	--	--	--	--		
				Jawan	Albian	Carb.	1005	--	--	--	--	--		
				Shuaiba	Aptian	Carb.	1285	--	--	--	--	--		
				Garagu	L Cretaceous	Carb.	1475	--	--	--	--	--		
				Gotnia	U Jurassic	Carb.	1769	--	--	--	--	--		
				Alan/ Mus	L Jurassic	Carb.	2434	--	--	--	--	--		
				Adaiyah	L Jurassic	Carb.	2959	--	--	--	--	--		
				Butmah	L Jurassic	Carb.	3217	--	--	--	--	--		
	Mansuria	40	5	Fatha	Miocene	Carb.	1110	--	--	--	--	--	Gas	1980
				Jeribe	Miocene	Carb.	1348	--	--	--	--	--	Gas	
				Dhiban	Miocene	Carb.	1415	--	--	--	--	--	Gas	
	Mushorah	21	4	Shiranish	Camp-Maast	Carb.	1616	--	--	--	14	--		1949
				Mushorah	L Senonian	Carb.	2012	--	--	--	14	--		
				Mauddud	Albian	Carb.	2172	--	--	--	14	--		
	Naft Khana	15	3	Jeribe	Miocene	Carb.	579	71	20	500	43	2.5		1927 On stream
	Najmah	14	3	Euphrates	Miocene	Carb.	283	--	--	--	15.3	7.4		1936 On stream
				Hartha	Camp-Maast	Carb.	686	219.5	--	--	17.3	5.9		
	Nau Doman	12	7	Jeribe	Miocene	Carb.	2505	--	14	500	47	0.4		1977
				--	--	--	2294	--	--	--	--	--		
	Pulkhana	39	4	Jeribe	Miocene	Carb.	1063	--	13	5.4	35.8	2.1	Oil & Gas	1927&1959
				Euphrates	Miocene	Carb.	1087	--	17	9.8	33	2.1		
				Shiranish	Camp-Maast	Marl	1637	--	--	--	27	2.71		
	Qaiyarah	12	3	Jeribe	Miocene	Carb.	184	177	--	--	15.3	7.4	Oil&Gas	1936 On stream
				Euphrates	Miocene	Carb.	300	50	--	--	15.2	5.8		
				Hartha	Camp-Maast	Carb.	688	200	--	--	17.3	5.9		
	Qalian	16	3	Hartha	Camp-Maast	Carb.	511	--	--	--	--	--	Heavy	
				Najmah	U Jurassic	Carb.	878	--	--	--	--	--		
				Kurra Chine	U Triassic	Carb.	2135	--	--	--	--	--		
	Qara Chauq N	23	2	Maud./ Jawan	Albian	Carb.	865	--	--	--	12.6	--	Oil & Gas	1961

			Shuaiba	Aptian	Carb.	1039	--	--	--	12.6	--		
			L Sarmord	L Cretaceous	Marl	1210	--	--	--	34.4	--		
			Gotnia	U Jurassic	Carb.	1300	--	--	--	36.6	--		
			Butmah	L Jurassic	Carb.	2009	--	--	--	39	--		
Qasab	24	5	Jeribe	Miocene	Carb.	195	150	--	--	22	7.4		1936 On stream
			Euphrates	Miocene	Carb.	275	45	--	--	18	5.6		
			Hartha	Camp-Maast	Carb.	710	190	--	--	17	5.7		
Qumar	33	5	Jeribe	Miocene	Carb.	2268	--	--	--	37	2.2	Oil & Gas	1979
Quwair	25	4	--	--	--	--	--	--	--	--	--		1939
			--	--	--	--	--	--	--	--	--		
Raffan	18	4	Shiranish	Camp-Maast	Carb.	1550	--	--	--	18.2	--		1976
			Sargelu	M Jurassic	Carb.	2373	--	--	--	23.7	--		
			Adaiyah	L Jurassic	Carb.	2850	--	--	--	28.4	--		
Sadid	8	1	Jeribe	Miocene	Carb.	250	--	--	--	--	--		
			Hartha	Camp-Maast	Carb.	590	--	--	--	--	--		
			Mishrif	Cenomanian	Carb.	669	--	--	--	--	--		
Sasan	--	--	Sargelu	M Jurassic	Carb.	2332	--	--	--	25	--		
	--	--	Mus	Liassic	Carb.	2535	--	--	--	--	--		
	12	4	Shiranish	Camp-Maast	Marl	325	--	--	--	41	1.43	Oil&Gas	1956&1975
	--	--	Hartha	Camp-Maast	Carb.	1687	--	--	--	29.7	1.45		
	--	--	Mishrif	Cenomania	Carb.	2130	--	--	--	36.7	--		
	--	--	Jawan	Albian	Carb.	2153	--	--	--	42	--		
Sufaiyah	11	2	Shiranish	Camp-Maast	Carb.	1409	47	11	13	25	4.3		1984 On stream
			Mushorah	Senonian	Carb.	1704		13	14	25	--		
			Gir Bir	Cen-Tur	Carb.	1732		12	7	27	--		
Suhain	--	--	Fatha	Miocene	Carb.	1385	--	--	--	--	--		1958
Taq Taq	18	8	Pila Spi	Eocene	Carb.	552	--	--	--	24	--		1961-&1978
			Shiranish	Camp-Maast	Marl	1624	--	--	--	47	--		
			Kometan	Turonian	Carb.	1859	--	--	--	47	--		
			Qamchuqa	Haut-Alb	Carb.	1957	--	--	--	46	--		
Tel Ghazal	20	5	Jeribe	Miocene	Carb.	2547	--	20	4	41	0.71		1980
			Dhiban	Miocene	Carb.	2605	--	--	--	33	--		
			Euphrates	Miocene	Carb.	2760	--	15	--	30	3.3		
Tel Hajar	16	7	Euph./ Serik.	Miocene	Carb.	1312	--	--	--	41	2.68	Oil&Gas	1976

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
				--	--	--	--	--	--	--	--	--		
JSZ	East Anah	215	8	Hartha	Camp-Maast	Carb.	2338	--	--	--	--	--	Heavy	1939
				Mushorah	Turonian	Carb.	2412	--	--	--	--	--		1959
				Alan	Liassic	Carb.	2698	--	--	--	--	--		
				Adaiyah/ Mus	Liassic	Carb.	2732	--	--	--	--	--		
				Butmah	Liassic	Carb.	2885	--	--	--	--	--		
	Khleisia	20	20	Khabour	Ordovician	Clast.	2544	--	--	--	--	--	Oil&Gas	1959
	West Anah	215	8	--	--	--	--	--	--	--	--	--		
MZ	Afaq	4	2	Aaljl	Pal-Eoc	Mari	1195	--	--	--	--	--	Oil & gas	1961
		2	5	Hartha	Camp-Maast	Carb.	1690	--	--	--	--	--		
				Ahmadi	Cenomanian	Carb.	2457	--	--	--	--	--		
				Mauddud	Albian	Carb.	2519	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	2873	--	--	--	--	--		
	Ahdab North	10	2	Tanuma	Senonian	Carb.	2542	--	23	--	25	--	Oil & gas	1982
				Khasib	Turonian	Carb.	2595	--	22.5	80	25	--		
				Mishrif	Cenomanian	Carb.	2700	--	14.8	63	25	--		
				Rumaila	Cenomanian	Carb.	2806	--	19.2	63	24	--		
				Mauddud	Albian	Carb.	3080	--	16.7	0.7	22	--		
				Nahr Umr	Albian	Carb.	3385	--	--	--	22	--		
				Shuaiba	Aptian	Carb.	3482	--	--	--	22	--		
	Ahdab South	7	3	Hartha	Camp-Maast	Carb.	2263	--	22.5	--	25	--	Oil & gas	1982
	Amara			Khasib	Turonian	Carb.	2801	--	--	--	21	--	Oil & gas	1985
				Mishrif	Cenomanian	Carb.	2880	--	--	--	23	--		
				Mauddud	Albian	Carb.	3308	--	--	--	12	--		
				Nahr Umr	Albian	Clast.	3673	--	--	--	30	--		
	Badra	20	10	Mauddud	Albian	Carb.	4525	--	9	--	36	1.2	Oil & gas	
	Balad	35	3	Hartha	Camp-Maast	Carb.	1682	--	21	--	16.2	4.18	Oil & gas	1984
				Sadi	Senonian	Carb.	2023	--	22	--	16.2	--		
				Khasib	Turonian	Carb.	2401	--	19	--	23.1	--		
				Nahr Umr	Albian	Clast.	3100	--	16	--	32	--		
				Chia Gara	Tithonian	Carb.	3975	--	4	--	37	1.6		

Buzurgan South	27	5	Kirkuk Group	Oligocene	Carb.	2864	--	24	20	25	--	Oil & gas		
			Mishrif	Cenomanian	Carb.	3733	--	16	47	23	3.9		1980	
Dhufriya South	10	3	Zubair	L Cretaceous	Clast.	4107	--	15	--	23.6	--	Oil & gas	1984	
Dibdiba	8	3	Mauddud	Albian	Carb.	2810	--	--	--	--	--	Oil & gas	1984	
			Nahr Umr	Albian	Clast.	2917	--	--	--	--	--			
			Yamama	L Cretaceous	Carb.	4051	--	--	--	--	--			
			Sulaiy	Ilth-Berr	Carb.	4282	--	--	--	--	--			
Dujaila	9	3	Mishrif	Cenomanian	Carb.	2839	--	--	--	14	--	Oil & gas	1961&1982	
			--	--	Carb.	--	--	--	--	--	--			
East Baghdad (EB)	100	6	Hartha	Camp-Maast	Carb.	1874	--	24	--	19	5.18	Oil & gas	1989 On stream	
EB Diyala	30	7	Khasib	Turonian	Carb.	2432	--	30	--	21	3.81	Oil & gas		
			Mishrif	Cenomanian	Carb.	2590	--	15	--	19	3.76			
			Nahr Umr	Albian	Clast.	3213	--	20	--	32	1.3			
			Zubair	L Cretaceous	Clast.	3408	--	20	--	27	1.5			
EB NE	40	7	Sadi	Senonian	Carb.	2192	--	15	--	20	3.95	Oil & gas		
EB Rashdiya	30	5	Tanuma	Senonian	Carb.	2316	--	20	--	22	3.6	Oil & gas		
Ekhaidher	12	7	Hartha	Camp-Maast	Carb.	563	--	--	--	--	--	Oil & gas		
			Nahr Umr	Albian	Clast.	1387	--	--	--	--	--			
			Zubair	L Cretaceous	Clast.	1533	--	--	--	--	--			
Ekhaidher 1	8	3	Hartha	Camp-Maast	Carb.	468	--	--	--	--	--	Oil & gas		
			Nahr Umr	Albian	Clast.	1264	--	--	--	--	--			
			Zubair	L Cretaceous	Clast.	1417	--	--	--	--	--			
Fallujah	2	4	Hartha	Camp-Maast	Carb.	788	--	--	--	15.1	5.9	Heavy	1958	
	3	4	Maotsi	Cenomanian	Carb.	1195	--	--	--	16.4	5.9	Oil & gas		
	2	4	Fahad	Cenomanian	Carb.	1272	--	--	--	--	--			
			Chia Gara	Tithonian	Carb.	2777	--	--	--	11.5	--			
			Gotnia	U Jurassic	Carb.	2812	--	--	--	11.5	--			
			Najmah	U Jurassic	Carb.	2877	--	--	--	Gas	--	Heavy		
			Sargelu	M Jurassic	Carb.	2884	--	--	--	Gas	--	Oil & gas		
Ghuraf	21	7	Mishrif	Cenomanian	Carb.	2200	--	20	491	24	--	Oil	1984	
			Zubair	L Cretaceous	Clast.	2996	--	17	1838	16	--			
			Ratawi	L Cretaceous	Carb.	3441	--	18	--	28	--			
			Yamama	L Cretaceous	Carb.	3601	--	10	--	37	--			

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
	Halfaya	25	7	Jeribe	Miocene	Carb.	1902	--	18	--	22	--	Oil & gas	1978
		10	2	Euphrates	Miocene	Carb.	--	--	20	--	22	--		
				Kirkuk Group	Oligocene	Carb.	1913	--	24	--	22	--		
				Sadi	Senonian	Carb.	2608	--	18	--	26	--		
				Tanuma	Senonian	Carb.	2733	--	16	--	26	--		
				Khasib	Turonian	Carb.	2748	--	16	--	21	--		
				Mishrif	Cenomanian	Carb.	2833	--	17	--	20	4.7		
				Nahr Umr	Albian	Clast.	3505	--	18	--	31	2.12		
				Yamama	L Cretaceous	Carb.	4369*	--	9	--	27	--		
	Huwaiza	15	5	Hartha	Camp-Maast	Carb.	2912	--	--	--	26	--	Oil & gas	
				Sadi	Senonian	Carb.	2966	--	--	--	26	--		
				Khasib	Turonian	Carb.	3078	--	--	--	20	--		
				Mishrif	Cenomanian	Carb.	3145	--	--	--	20	--		
				Nahr Umr	Albian	Clast.	3721	--	--	--	20	--		
				Zubair	L Cretaceous	Clast.	4095	--	--	--	--	--		
				Yamama	L Cretaceous	Carb.		--	--	--	--	--		
				--	--	--	--	--	--	--	--	--		
	Jabel Sanam	5	5	Mishrif	Cenomanian	Carb.	2552	--	--	--	--	--	Oil & gas	
				Ahmadi	Cenomanian	Carb.	2771	--	--	--	--	--		1978
				Nahr Umr	Albian	Clast.	3041	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	3412	--	--	--	--	--		
	Jraishan	8	5	Khasib	Turonian	Carb.	--	--	--	--	--	--	Oil & gas	1976
				Mishrif	Cenomanian	Carb.	--	--	--	--	--	--		
				Mauddud	Albian	Carb.	--	--	--	--	--	--		
				Shuaiba	Aptian	Carb.	--	--	--	--	--	--		
				Nahr Umr	Albian	Clast.	2750	--	18	532	30	--		
				Ratawi/ Yam.	L Cretaceous	Carb.	--	--	--	--	--	--		
				Sulaiy	Tith-Berr	Carb.	--	--	--	--	32.7	1.73		
	Khashab	12	3	Fatha	Miocene	Carb.	1200	--	20	--	--	--	Gas	1980
				--	--	--	--	--	--	--	--	--		

Khidr Al Mas	10	2.5	Nahr Umr	Albian	Clast.	2582	--	--	--	--	--	Heavy	1983
			Zubair	L Cretaceous	Clast.	2948	--	--	--	--	--		
			Ratawi	L Cretaceous	Carb.	3526	--	--	--	--	--		
			Yamama	L Cretaceous	Carb.	3703	--	--	--	--	--		
			Najmah	U Jurassic	Carb.	4783	--	30	--	--	--		
Kifl	13	7	Didibba	Miocene	Clast.	65	--	--	--	--	--	Oil & gas	1960
			Fatha	Miocene	Carb.	84	--	--	--	--	--		
			Aaliji	Pal-Eoc	Marl	507	--	--	--	--	--		
			Hartha	Camp-Maast	Carb.	845	--	--	--	--	--		
			Nahr Umr	Albian	Clast.	1787	--	20	--	26	--		
			Zubair	L Cretaceous	Clast.	2001	--	23	--	20	--		
			Yamama	L Cretaceous	Carb.	2488	--	--	--	14	--		
			Gotnia	U Jurassic	Carb.	2951	--	--	--	--	--		
			Najmah	U Jurassic	Carb.	3026	--	--	--	--	--		
			Sargelu	M Jurassic	Carb.	3177	--	--	--	--	--		
Kumait	15	3	Mishrif	Cenomanian	Carb.	3049	--	11.3	--	23	3.92	Oil & gas	1983
			Nahr Umr	Albian	Clast.	3645	--	18.5	--	30	2.9		
Luhais	24	10	Nahr Umr	Albian	Carb.	2482	--	20	--	32	--	Oil & gas	1978 On stream
			Zubair	L Cretaceous	Clast.	2776	--	20	--	33	--		
			--	--	Carb.	--	--	--	--	--	--		
Majnoon	48	10	Fatha	Miocene	Carb.	962	--	20	--	Gas	--	Oil & gas	1977
			Ghar	Miocene	Carb.	1255	35	20	200	24	3.45		
			Shiranish	Camp-Maast	Carb.	1992	40	15	143.5	20.4	--		
			Hartha	Camp-Maast	Carb.	2109	--	21	76	30	3.08		
			Sadi	Senonian	Carb.	2210	--	18	10	19.5	4.64		
			Khasib	Turonian	Carb.	2343	--	15	4	25	--		
			Mishrif	Cenomanian	Carb.	2385	140	13	330	21	3.9		
			Ahmadi	Cenomanian	Carb.	2622	70	25	368	21	4.12		
			Nahr Umr	Albian	Clast.	2955	25	16	515	30	2.29		
			Shuaiba	Aptian	Carb.	3129	50	15	150	30	--		
			Zubair	L Cretaceous	Clast.	3279	25	20	254	27.5	2.18		
			Yamama	L Cretaceous	Carb.	3818	150	10	180	35	0.98		
Merjan	10	5	Hartha	Camp-Maast	Carb.	549	--	--	--	26	--	Oil & gas	1983
Mileh Tharthar	16	6	Jeribe	Miocene	Carb.	185	--	--	--	--	--	Oil & gas	1957

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
				Kift/ Mishrif	Cenomanian	Carb.	806	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	1227	--	--	--	--	--		
				Gotnia	U Jurassic	Carb.	1569	--	--	--	--	--	Heavy	
				Sargelu	M Jurassic	Carb.	1875	--	--	--	--	--		
				Alan	Liassic	Carb.	2052	--	--	--	--	--		
				Butmah	Liassic	Carb.	2283	--	--	--	--	--		
				Kurra Chine	U Triassic	Carb.	2777	--	--	--	--	--		
	Mussaiyib	4	2	Hartha	Camp-Maast	Carb.	1260	--	--	--	--	--	Staining	1980
				Ratawi	L Cretaceous	Carb.	3050	--	--	--	--	--		
				Sarmord	L Cretaceous	Carb.	3220	--	--	--	--	--		
				Chia Gara	Tithonian	Carb.	3622	--	--	--	--	--		
				--	--	--	--	--	--	--	--	--		
	N Rumaila	32	8	Fatha	Miocene	Carb.	294	--	--	--	12.9	--	Oil & gas	1977 On stream
				Mishrif	Cenomanian	Carb.	2240	--	--	--	25	--		
				Nahr Umr	Albian	Clast.	2609	--	20	--	24	--		
				Shuaiba	Aptian	Carb.	2987	--	--	--	34	--		
				Zubair	L Cretaceous	Clast.	3072	--	15	--	34	--		
				Ratawi	L Cretaceous	Carb.	3389*	--	8.6	20	34	--		
				Yamama	L Cretaceous	Carb.	3499*	--	12.5	13	43	--		
				Najmah	U Jurassic	Carb.	4388*	--	--	--	48	--		
				Mus	Liassic	Carb.	4944*	--	--	--	--	--		
	Nafatah	3	2	--	--	--	--	--	--	--	--	--		1938
	Nahr Umr	27	12	Fatha	Miocene	Carb.	332	--	--	--	21.6	--	Oil & gas	1949
				Ghar	Miocene	Carb.	638	--	--	--	24	--		
				Sadi	Senonian	Carb.	1780	--	--	--	19	--		
				Khasib	Turonian	Carb.	1882	--	--	--	25	--		
				Mishrif	Cenomanian	Carb.	1939	--	16	--	21.5	--		
				Nahr Umr	Albian	Clast.	2423	--	22	--	41	0.88		
				Zubair	L Cretaceous	Clast.	2933.5*	--	25	303	30	--		
				Yamama	L Cretaceous	Carb.	3308*	--	12	74	38	--		
	Nahrawan	8	2	Hartha	Camp-Maast	Carb.	2382	--	12	--	29	5.1	Oil & gas	1981

			Khasib	Turonian	Carb.	2900	--	18	--	16	3.7		
Nasiriya	26	10	Mishrif	Cenomanian	Carb.	1943	--	22	500	24	3.62	Oil & gas	1979
			Nahr Umr	Albian	Clast.	2321	--	22	--	35	--		
			Ratawi	L Cretaceous	Carb.	3101	--	10	--	37	--		
			Yamama	L Cretaceous	Carb.	3178	--	9.2	--	37	2.2		
Noor	20	8	Mishrif	Cenomanian	Carb.	3308	--	14	--	23	--	Oil & gas	1978
	--	--	Nahr Umr	Albian	Clast.	3947	--	22	120	25	--		
Rachi	16	5	Nahr Umr	Albian	Clast.	2614	--	--	--	28	--	Oil & gas	1957
			Zubair	L Cretaceous	Clast.	2938	--	--	--	32	--		
			Yamama	L Cretaceous	Carb.	3855	--	14	1	39	--		
Rafidian	--	--	Mauddud	Albian	Carb.	2799	--	21	--	25	--	Oil & gas	
	28	4	Mishrif	Cenomanian	Carb.	2432	--	15	--	26	--		1981
			Nahr Umr	Albian	Clast.	3045	--	23	--	25	--		
			Zubair	L Cretaceous	Clast.	3294	--	24	--	39	--		
			Ratawi	L Cretaceous	Carb.	3703	--	20	--	27	--		
			Yamama	L Cretaceous	Carb.	3836	--	10	--	34	--		
Rafidian E	--	12	Mishrif	Cenomanian	Carb.	2677	--	--	--	24	--	Oil	1979
			Ratawi	L Cretaceous	Carb.	3923	--	--	--	30	--		
			Yamama	L Cretaceous	Carb.	4073	--	--	--	30	--		
Ratawi	25	13	Mishrif	Cenomanian	Carb.	2094	--	18	44	26	--	Oil & gas	1950
			Ahmadi	Cenomanian	Carb.	2324	--	23	9.2	15	--		
			Mauddud	Albian	Carb.	2458	--	18	10.2	15	--		
			Nahr Umr	Albian	Clast.	2574	--	20	152	25	--		
			Yamama	L Cretaceous	Carb.	2533	--	13	17.2	42	1.24		
Rifaee	20	5	Yamama	L Cretaceous	Carb.	4180	--	14	--	34	--	Oil & gas	
Rumaila South	34	7	Fatha	Miocene	Carb.	152	--	--	--	--	--	Oil & gas	1954-on-St
			Mishrif	Cenomanian	Carb.	2228	--	--	--	25	--		
			Nahr Umr	Albian	Clast.	2685	--	--	--	30	--		
			Zubair	L Cretaceous	Clast.	3025	229	20	2500	35.4	2		
Samarra	6	1	Jeribe	Miocene	Carb.	921	--	--	--	--	--	Heavy	1960
			Euphrates	Miocene	Carb.	966	--	--	--	--	--		
			Shiranish	Camp-Maast	Marl	1215	--	--	--	--	--		
			Hartha	Camp-Maast	Carb.	1274	--	--	--	--	--		

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
				Maotsi	Cenomanian	Carb.	1797	--	--	--	--	--		
				Mauddud	Albian	Carb.	2124	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	2560	--	--	--	--	--		
				Garagu	L Cretaceous	Carb.	2679	--	--	--	--	--		
				Chia Gara	Tithonian	Carb.	3276	--	--	--	--	--		
	Samawa	5	3	Hartha	Camp-Maast	Carb.	907	--	--	--	--	--	Oil & gas	1959
				Mishrif	Cenomanian	Carb.	1490	--	--	--	--	--		
				Nahr Umr	Albian	Clast.	1713	--	--	--	--	--		
				Shuaiba	Aptian	Carb.	1895	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	1928	--	--	--	--	--		
				Yamama	L Cretaceous	Carb.	2496	--	--	--	--	--		
				Gotnia	U Jurassic	Carb.	2609	--	--	--	--	--		
				Najmah	U Jurassic	Carb.	2660	--	--	--	26.5	1.94		
				Sargelu	M Jurassic	Carb.	6063	--	--	--	--	--		
				Alan	Liassic	Carb.	3510	--	--	--	--	--		
				Mus	Liassic	Carb.	3577	--	--	--	--	--		
				Adaiyah	Liassic	Carb.	3670	--	--	--	--	--		
				Butmah	Liassic	Carb.	3731	--	--	--	--	--		
	Siba	6	5	Zubair	L Cretaceous	Clast.	3426	--	16	135	33	1.36	Oil & gas	
		10	8	Yamama	L Cretaceous	Carb.	3911	--	10	16	45	--		
	Sindibad	12	7	--	--	Carb.	--	--	--	--	--	--	Oil	1975
	Subbah	12	5	Nahr Umr	Albian	Clast.	2493	--	21	3099	28	2.53	Oil & gas	
		13	7	Zubair	L Cretaceous	Clast.	2792	--	19	1091	30	2.06		1990
				Yamama	L Cretaceous	Carb.	3416*	--	11	--	36	--		
	Tikrit	8	1	Mishrif	Cenomanian	Carb.	2410	--	30	23	--	4.1	Oil&Gas	1960
				Mauddud	Albian	Carb.	2522	--	260	23	--	3.65		
				Nahr Umr	Albian	Clast.	2800	--	17	23	--	--		
				Zubair	L Cretaceous	Clast.	3125	--	17	23	--	--		
	Tuba	22	7	Fatha	Miocene	Carb.	204	--	--	--	--	--	Oil & gas	1960
				Mishrif	Cenomanian	Carb.	2334	--	20	390	28.6	--		
				Nahr Umr	Albian	Clast.	2837	--	18	152	25.8	3.16		

			Zubair	L Cretaceous	Clast.	3202	--	19	--	26.7	--			
			Yamama	L Cretaceous	Carb.	3899	--	7.3	4	35.5	--			
Umm Qasir	9	3.5	Mishrif	Cenomanian	Carb.	2189	--	--	--	--	--	Oil & gas	1979	
			Nahr Umr	Albian	Clast.	2697	--	--	--	--	--			
			Zubair	L Cretaceous	Clast.	3084	--	--	--	--	--			
Ur	--	--	--	--	Carb.	--	--	--	--	--	--	Oil & gas	1990	
West Kifl	12	5	Hartha	Camp-Maast	Carb.	600	--	25	--	26	--	Oil & gas	1975	
West Luhais	8	4	Nahr Umr	Albian	Clast.	2494	--	23.3	427	31.9	2.34	Oil	1973	
			Zubair	L Cretaceous	Clast.	2745	--	21.6	564	32.4	--			
	1.5	4	Nahr Umr	Albian	Carb.	2509	--	20	--	32.5	--			
			Zubair	L Cretaceous	Clast.	2829	--	20	--	32.4	--			
West Qurna	35	8	Sadi	Senonian	Carb.	2017	--	20	--	28	2.89	Oil & gas	1976 On stream	
			Mishrif	Cenomanian	Carb.	2238	--	20	775	27	3.7			
			Zubair	L Cretaceous	Clast.	3075	--	16	--	30	1.83			
			Ratawi	L Cretaceous	Carb.	3426	--	12	--	36	1.6			
			Yamama	L Cretaceous	Carb.	3509	--	18	--	41	--			
			Najmah	U Jurassic	Carb.	4400	--	20	--	46	--			
Zubair (Rafid.)	17	4	Nahr Umr	Albian	Clast.	2679	--	18	150	30	--	Oil & gas	1952	
	--	--	Zubair	L Cretaceous	Clast.	3012	--	20	400	34	2			
Zubair (Safwan)	11	6	Nahr Umr	Albian	Clast.	2726	--	--	--	--	--	Oil & gas	1977	
	--	--	Zubair	L Cretaceous	Clast.	3094	--	--	--	35	--			
Zubair (Shuaiba)	34	8	Fatha	Miocene	Carb.	268	--	--	--	--	--	Oil & gas	1950 On stream	
			Nahr Umr	Albian	Clast.	2737	--	18.8	--	30	--			
			Mishrif	Cenomanian	Carb.	2204	--	15	--	25	--			
			Zubair	L Cretaceous	Clast.	3107	244	18	1000	36.4	2			
			Yamama	L Cretaceous	Carb.	3852	--	--	--	41	0.92			
RSZ Akkas	27	12	Khabour	Silurian	Clast.	2328	25	--	--	48	0.01	Oil & gas	1993	
SZ Abu Jir	1	1	--	--	--	--	--	--	--	--	--		1939	
Abu Khema	9	5	Ratawi	L Cretaceous	Carb.	2628	--	--	--	--	--	Oil & gas	1976	
			Yamama	L Cretaceous	Carb.	2947	--	--	14	34.5	1.53			
			Gotnia	U Jurassic	Carb.	3170	--	--	--	--	--			
			Najmah	U Jurassic	Carb.	3264	--	--	--	--	--			
Awasil	3	2	--	--	--	--	--	--	--	--	--		1940	
			--	--	--	--	--	--	--	--	--			

Zone	Structure	Length (km)	Width (km)	Reservoir	Age	Reservoir Lithology	Depth (m)	Net pay (m)	Por%	Perm (md)	API°	S%	Shows	Date Completed or On stream
	Diwan	15	13	Hartha	Camp-Maast	Carb.	935	--	--	--	--	--	Oil & gas	
				Sadi	Senonian	Carb.	1276	--	--	--	--	--		
				Nahr Umr	Albian	Clast.	1760	--	--	--	22	--		
				Ratawi	L Cretaceous	Carb.	2534	--	--	--	22.8	--		
				Najmah	U Jurassic	Carb.	2815	--	--	--	19.5	--		
				Sargelu	M Jurassic	Carb.	3236	--	--	--	19	--		
				Alan	Liassic	Carb.	3603	--	--	--	--	--		
				Butmah	Liassic	Carb.	3875	--	--	--	--	--		
	Ghaluisan	3	5	Dammam	Eocene	Carb.	100	--	--	--	--	--	Oil	1960
				Tayarat	Camp-Maast	Carb.	411	--	--	--	--	--		
				Hartha	Camp-Maast	Carb.	642	--	--	--	--	--		
				Kifl	L Turonian	Carb.	1159	--	--	--	--	--		
				Rumaila	Cenomanian	Carb.	1169	--	--	--	--	--		
				Nahr Umr	Albian	Clast.	1356	--	--	--	--	--	Bitumen	
				Zubair	L Cretaceous	Clast.	1488	--	--	--	--	--	Oil	
				Yamama	L Cretaceous	Carb.	1794	--	--	--	--	--		
				Sulaiy	Tith-Berr	Carb.	1815	--	--	--	--	--		
				Gotnia	U Jurassic	Carb.	1828	--	--	--	--	--		
				Najmah	U Jurassic	Carb.	1883	--	--	--	--	--		
	Hit	3	1	--	--	--	--	--	--	--	--	--		1939
		3	2	--	--	--	--	--	--	--	--	--		
	Sufawi	3	4	Nahr Umr	Albian	Clast.	1122	--	--	--	Heavy	--	Oil & gas	1961
				Zubair	L Cretaceous	Clast.	1200	--	--	--	Heavy	--		
				Yamama	L Cretaceous	Carb.	1401	--	--	--	Heavy	--		
	Shawiyah	6	3	Tayarat	Camp-Maast	Carb.	534	--	--	--	--	--	Oil & gas	1960
				Khasib	Turonian	Carb.	1342	--	--	--	--	--		
				Kifl	Cen-Tur	Carb.	1390	--	--	--	--	--		
				Nahr Umr	Albian	Clast.	1580	--	--	--	--	--		
				Zubair	L Cretaceous	Clast.	1763	--	--	--	--	--		
	Ubaid	7	4	--	--	Carb.	--	--	--	--	--	--	Oil & gas	1960



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