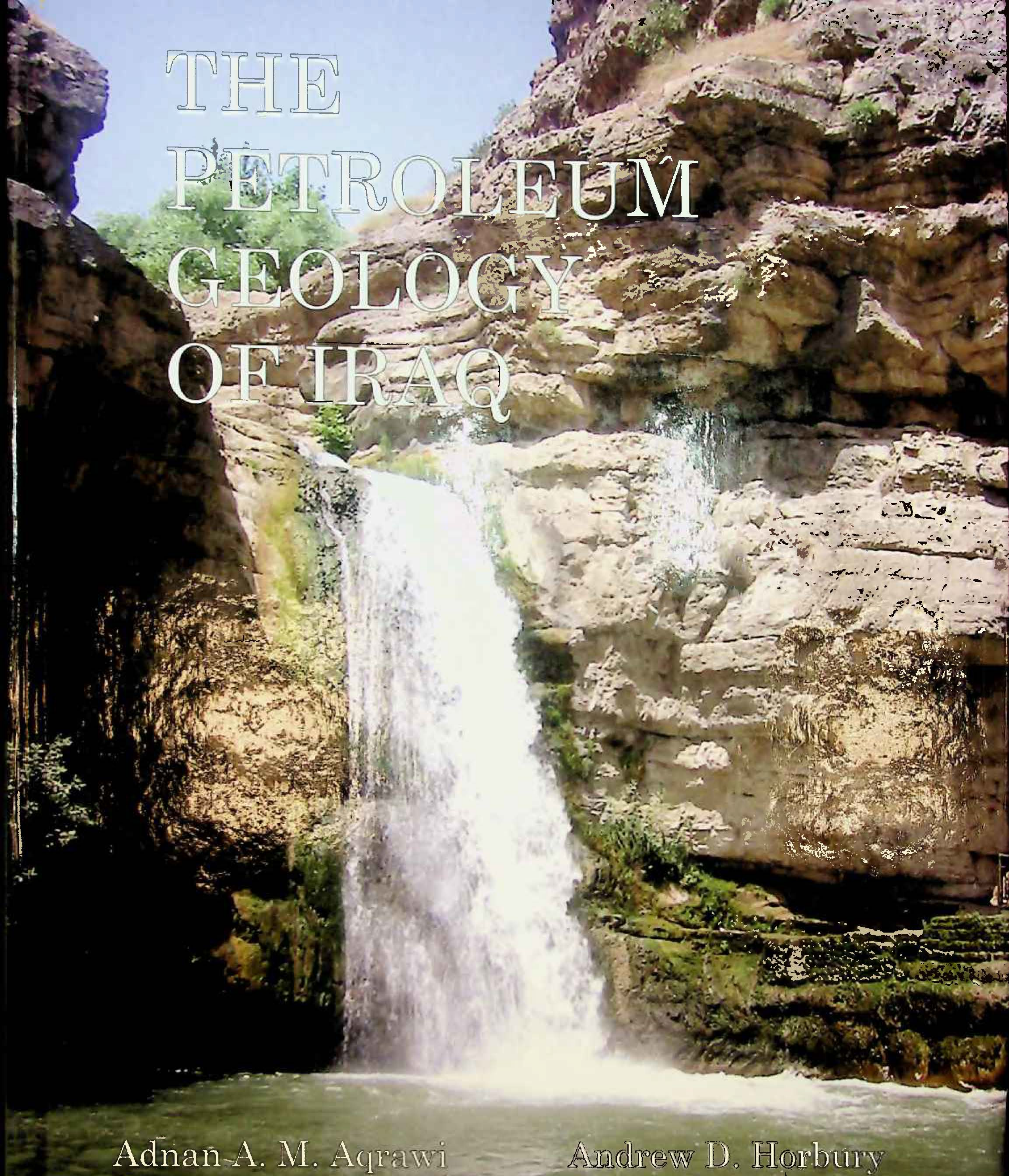
THE PETROLEUM GEOLOGY OF IRAQ



Adnan A. M. Aqrawi
Jeremy C. Goff
Andrew D. Horbury
Fadhil N. Sadooni

Statoil
Scientific Press
bp

The outcrop photograph on the front cover, taken by Adnan Aqrawi during a trip to Iraqi Kurdistan in Summer 2005, shows the dolomitic limestones of the Lower Cretaceous Qamchuqa Formation at the Geli Ali Beg waterfall in the High Folded Zone about 85 km north of the city of Erbil.

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Foreword

The *Baba Gurgur-1* discovery well at the super-giant *Kirkuk* oilfield in northern Iraq blew out with a column of oil some 40 m high in October, 1927. This was a defining moment for the oil industry in Iraq. For the next four decades, the industry was run by a consortium of European and American companies. Gravity and early seismic surveys in SE Iraq led to the discovery of the *Zubair* and *Rumaila* oilfields in 1949 and 1953, respectively. The focus on oilfield development from 1954 to 1961 and disputed exploration rights (1961-1967), however, resulted in limited exploration activity. Nationalization of the oil industry took place in the early 1970s. There followed a decade of progress in exploration and development as major oilfields were discovered. Oil reserves were raised to 100 billion brls and production increased to more than 3.5 million b/d. However, the following twenty years were marked by wars, sanctions and economic downturn, culminating in the events of 2003.

The Iraqi oil industry faces a new beginning. Recently, foreign oil companies have bid for contracts to develop some of the country's super-giant oilfields. Major international oil companies have negotiated with, and signed agreements with, the Iraqi Government. This foreign investment is intended to increase Iraq's oil production significantly in the near future. Iraq has around 115 billion brls of proven oil reserves. Much work needs to be done to bring these reserves on-stream.

Iraq has been relatively lightly explored. Fewer than 200 exploration wells have been drilled in an area of some 500,000 sq. km. Significant exploration potential remains in the established Mesozoic and Tertiary plays. Encouraging exploration results are currently being reported in these plays in Iraqi Kurdistan. The Palaeozoic section, with a single hydrocarbon discovery to-date (*Akkas*), is a true exploration frontier.

Aqrawi, Goff, Horbury and Sadooni (two of whom are Iraqi and two British) are well qualified as authors of the present volume. They are well known as a result of their work and previous publications. Aqrawi and Sadooni have many years' experience of research with oil companies and universities both within and outside Iraq. Horbury and Goff have visited Iraq and neighbouring countries frequently in the course of their professional careers. The authors have worked together previously during company projects, co-presenting joint research at international conferences and in journals. It would be hard to find a better-qualified team.

This book is in part an update of the classic *Iraq Lexicon* compiled by R. C. van Bellen, R. V. Dunnington, R. Wetzel and D. M. Morton in 1959. Following the practices of the day, van Bellen *et al.* summarised the geology of Iraq from a lithostratigraphic point of view using data collected during the previous forty years of field surveys and investigations. By contrast, Aqrawi *et al.* have adopted a regional sequence-stratigraphic approach. The Palaeozoic, Middle Permian – Middle Jurassic, Mid-Upper Jurassic, Cretaceous and Cenozoic successions are each described in separate chapters, at the end of which are brief discussions of source, reservoir and cap rocks. These stratigraphic chapters are necessarily detailed and, together with the structural Chapter 3, form the backbone of the book, providing the context within which the Petroleum Systems (Chapter 9) can be understood.

Future studies in Iraq will include surface geological investigations and sedimentological, structural and geophysical studies, combined with sequence stratigraphy and petroleum systems modelling. To assist with this future work, Aqrawi *et al.* have provided a comprehensive and well-illustrated account of the petroleum geology of Iraq based on available scientific literature, enhanced by their own insights and experience. They will be the first to agree, however, that the book may soon require revision to take into account the expected flood of new data and interpretations emerging from the "new Iraq".

Hashim Alkhersan

President, Pioneer Natural Resources Tunisia Ltd (2000-present)
Technical and Commercial Advisor, Mobil Oil (1993-2000)
Director General, Iraqi Oil Exploration Co. (1982-1991)
President, Northern Oil Organization (1979 -1982)
Director General, Exploration, INOC (1976-1979)

Preface

After the publication by Sadooni and Aqrawi (2000) of the "Cretaceous stratigraphic review and hydrocarbon potential of the Mesopotamian Basin", these authors realised that there was a need for an informative and relatively brief review of the petroleum geology of the whole of Iraq. This need was emphasised in the light of the events of 2003. Sadooni and Aqrawi saw the importance that such a review would have at the start of a new era for the upstream oil industry in Iraq. They met co-authors Goff and Horbury during *Geo2004* in Bahrain and the idea was discussed. Each of the four co-authors had previously worked (and published) with some of the others; Sadooni, Goff and Horbury had worked together, for example, on a basin evaluation study of northern Iraq in the late-1980s.

The four co-authors met at the BP offices in Sunbury-on-Thames in late-October, 2004 and planned how the book was to be written: each chapter was to have primary and secondary authors, and the other two co-authors would contribute to the final edit. It was also agreed that the authors would be listed alphabetically on the title page. The book was to be sponsored by Statoil and BP. Agreement was also reached with Scientific Press Ltd, publishers of the *Journal of Petroleum Geology*, regarding editing and publishing.

A second authors' meeting took place at the Statoil offices in Stavanger in April, 2005. This was followed by a series of meetings in London, initially at the Geological Society – in the Buckland Room, surrounded by the tomes of the "greats" of geology for inspiration – and subsequently at the Statoil offices. The authors also met on other occasions including the Sixth International Conference on Middle East Geology in Al-Ain and at *Geo2006* in Bahrain. The book was officially announced in late-November, 2005 in Doha, Qatar, during the IPTC Conference. A series of meetings then took place in London in 2008/9, with a final discussion in November 2009 at the offices of Cambridge Carbonates.

The objective of the book is to provide the reader with an up-to-date review of the reservoir rocks, source rocks, seals and traps that control Iraq's petroleum systems and resources. The authors have attempted to bring together into a single volume published information on the petroleum geology of Iraq from diverse and sometimes obscure sources. Although the book is based only on information in the public domain, they hope it will provide a valuable source of information for petroleum geologists, researchers and graduate students. In particular, the book is intended to complement future detailed studies based on proprietary data – for example, where a researcher requires rapid access to a regional overview of play elements in a particular area, an overview which would not otherwise be available without reading a multitude of references in Arabic, English and other languages.

A.A.M.A., J.C.G., A.D.H. & F.N.S.
London, Autumn 2009

Acknowledgements

The preparation and production of this book was supported and approved by BP and Statoil. The authors gratefully acknowledge these companies' generous sponsorship without which the book could not have been published.

A.A. thanks colleagues at Statoil for their support and valuable reviews. He thanks in particular Peter Mellbye (*Executive VP for International E&P*); Bill Maloney, Tim Dodson, Gregory T. Himes and Eigil Rasmussen (*of International Global Exploration*); and Torgeir Kydland, Kjetil Tonstad and Svein Roar Engelsen (*of International Business Development*) for their kind support. He also acknowledges Pål Haremo and Knut Georg Røssland for their overall review and approval of the whole book; and Geir Jøssang, Morten Rye-Larsen, Kjetil Tungland, Tore Sund, Svein H. Breivik, Jan Rangvald Torsvik, Jesper Børs-Lind and Terje Bartnes for their valuable comments.

He thanks Maher Hijazin (*General Manager*) and Hisham Al-Rabi and Ahmed Almasri (*NRA Jordan*) for logistic assistance with field trips to Triassic and Palaeozoic outcrops in Jordan. Finally, he thanks Kent Norton and colleagues in the Palaeozoic Exploration Team *(Saudi Aramco)* for inviting him to join a field trip to the Tabouk Basin in April, 2006.

J.G. thanks Andrew Brayshaw (*BP*) for his initial encouragement to contribute to the book, and David Dalton (*BP*) for his support during the final stages of the book's preparation. He also thanks colleagues at BP (past and present) for valuable discussions on the geology of Northern Iraq: Bob James, Mike Bilbo, Tim Dodd, Robin Cleverly, Barry Hickmott, Bob Jones, David Parker, Frank Peel and Andrew Wright. He acknowledges with particular gratitude his former colleague Edward Hart for introducing him to the geology of Iraq and for his advice over many years. Frank Gosling and Peter Wamsley provided further insights into the geology of Iraq which are gratefully acknowledged, as are stimulating geological discussions with Saad Jassim.

A.H. thanks Martin Insley for use of the satellite images (Plates 3.4-3.7), and Infoterra for permission to use Fig. 7.19. He thanks Sterling Energy (in particular Matt Brown) for permission to use the images of field samples in Chapter 8. Advice from Gitte Laursen *(Statoil)* and Steve Packer *(Milennia)* on Cenozoic micropalaeontology, and from James Keegan on Palaeozoic palynology, is acknowledged with thanks, as is biostratigraphic data provided by Steve Starkie (Ph.D thesis). Discussions with Norman Kent *(ex-US Economic Affairs Office, Baghdad)* helped his understanding of the tectonic structure of Iraq. The library staff at the Geological Society, London, in particular Wendy Cawthorne, are thanked for their tireless pursuit of references which were out-of-print or otherwise almost impossible to find.

J.G. and A.H. thank their Iraqi colleagues who helped facilitate their work on Northern Iraq in 1988-1990, in particular Shaban K. Shaban, Gailan A. Dhehni, Adnan Samarrai and Ahmed Al-Siddiki *(OEC)*. They also thank Ron Miller (*retired archivist of IPC*) for valuable assistance with Chapter 2. Finally, they thank Guy Stubbs for giving them both the opportunity of working on the fascinating geology of Iraq.

J.G., A.H. and F. S. would like to thank former colleagues from Idemitsu, in particular Teruyuki Takahashi and Hirsohi Arikawa.

All four authors thank Moujahid Al-Husseini (*Gulf PetroLink*; Editor-in-Chief of *GeoArabia)* for kindly agreeing to the republication of a number of figures from *GeoArabia.* They also acknowledge Saad Jassim who kindly helped at many stages of the writing process and made available a draft of his book "Geology of Iraq" (co-edited by J.G.). Colleagues in Iraq are thanked for help with access to their recent publications (and for discussions with A.A. and A.H.): they include Govand H. Sherwani; Thamer Al-Ameri; Mazin Tamar-Agha; Fazel Lawa; Thamer A. Mahdi and Ali Gayara.

Graham Banks and Fugro Robertson are thanked for providing the Landsat DEM images in

Plates 3.1-3.3. Eric Blanc *(Statoil)* and CASP kindly agreed to the reproduction of photographs taken during fieldwork in Iraqi Kurdistan. Other outcrop photos were provided by Maurice Tucker *(Durham University)* and Basim Al-Qayim *(Sulaimaniya University)*, and are acknowledged with thanks.

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Christopher Tiratsoo (*Journal of Petroleum Geology*) managed the editing and publication process on behalf of Scientific Press Ltd. He acknowledges the assistance at various times of Adam Tiratsoo, Emily Burt, Joanna Hughes and Madeleine Tiratsoo. Francis Witkowski (*Cambridge Carbonates*) assisted with photomicrographs and image enhancement. Simon Kettle *(Cambridge Carbonates)* helped with compilation of the References.

Hamdi Kandil (*UAE University*) initiated the artwork. Drafting and the final presentation of all the figures was the work of Rowland Benbrook (*RB Graphics: www.rbgraphics.eu*).

Finally, the authors thank their work colleagues and in particular their wives and families for their patience and tolerance while the "Iraq Book Club" met and consumed valuable time.

Contents

Adnan, Jeremy, Andrew and Fadhil dedicate this book to their wives (Ibtisam, Fenella, Herma Juliana and Ghada) and families

1. INTRODUCTION

Iraq is located in the NE corner of the Arabian Plate and has a surface area of some 440,000 sq. km (Fig. 1.1). In the north and NE are the Zagros Mountains whose highest peaks (Cheekha Dar and Halgurd) are both a little over 3600 m in elevation. The country is otherwise dominated by the Mesopotamian Plain across which flow the Tigris and Euphrates Rivers; these reach a confluence at Qurnah, just north of Basra, where they link to form the Shatt-Al-Arab River. To the west, NW and SW are elevated stony desert plains (the Western, Northwestern and Southwestern Deserts). Topography rises westwards to a maximum of 930 m at Jebel Unayzah at the boundary with Jordan and Saudi Arabia. The surface geology of Iraq is illustrated in Fig. 1.2.

Major Iraqi cities are Baghdad on the Mesopatamian Plain, Basra on the Shatt-al-Arab River, Mosul in the foothills of the Zagros Mountains in the north, and Erbil, the capital of Iraqi Kurdistan. The human population is concentrated along the watercourses while the desert plains and mountainous areas are less inhabited.

Data Sources and Quality

The data presented in this book are derived from published sources although some of the interpretations are the authors' own. The book is intended to complement the one recently published by Jassim and Goff (2006a) which covered all aspects of the geology of Iraq. Here, the focus is on the geology of Iraq's hydrocarbon resources; oil- and gasfields and key wells are shown in Fig. 1.3.

The quality of published geological data from Iraq is variable. Limited macro- and micro-palaeontological data has made the stratigraphic definition of some successions difficult, particularly in the pre-Jurassic. Within both the Triassic - Lower Jurassic and the lower Miocene successions, problems have arisen where the stratigraphy is dominated by alternating dolomites and anhydrites. The incorrect location of interbedded carbonates within these successions (e.g. due to poor lithostratigraphic definitions in published work) has led to stratigraphic mis-correlations and mis-datings, both within Iraq and between Iraq and adjacent countries such as Syria (Sadooni and Alsharhan, 2004; Al-Husseini and Mattner, 2007). For example, carbonate beds within the Miocene Lower Fars have been confused with those in the Jeribe Limestone Formation; there is widespread confusion between the Anah, Euphrates and Jeribe Formations; while in the Liassic, the basal Butmah Formation has been confused with the Mus Formation. One purpose of this book is to highlight such areas of confusion, and to attempt to define a more rigorous litho- and chronostratigraphy.

Another problem is that the importance of unconformities within the Iraqi stratigraphy has frequently been overlooked in the past. Although the lithostratigraphy is often relatively straightforward, the compounded nature of many unconformities can produce a complex final stratigraphic architecture.

Compared to many parts of the Arabian Plate, very few 2D seismic sections or detailed well logs have been published from Iraq or are available in the public domain. Only very limited 3D data has been obtained and none of this has been released. Exploration wells are mainly located upon surface anticlines which can be seismically "opaque" and consequently reveal little about off-structure geology. This lack of data together with a bias in data location has hindered the discussion of Iraq's stratigraphy at a country-wide scale; instead, more local datasets, where available, have been integrated and compiled.

There are frequent conflicts and ambiguities in the published data relating to the geology of Iraq. The authors have tried to resolve as many of these conflicts as possible and to present a balanced and accurate review of Iraq's petroleum geology. However, some fundamental problems have not been resolved due to the lack of data. Consequently, neither the accuracy of the data nor the validity of the interpretations presented can be guaranteed.

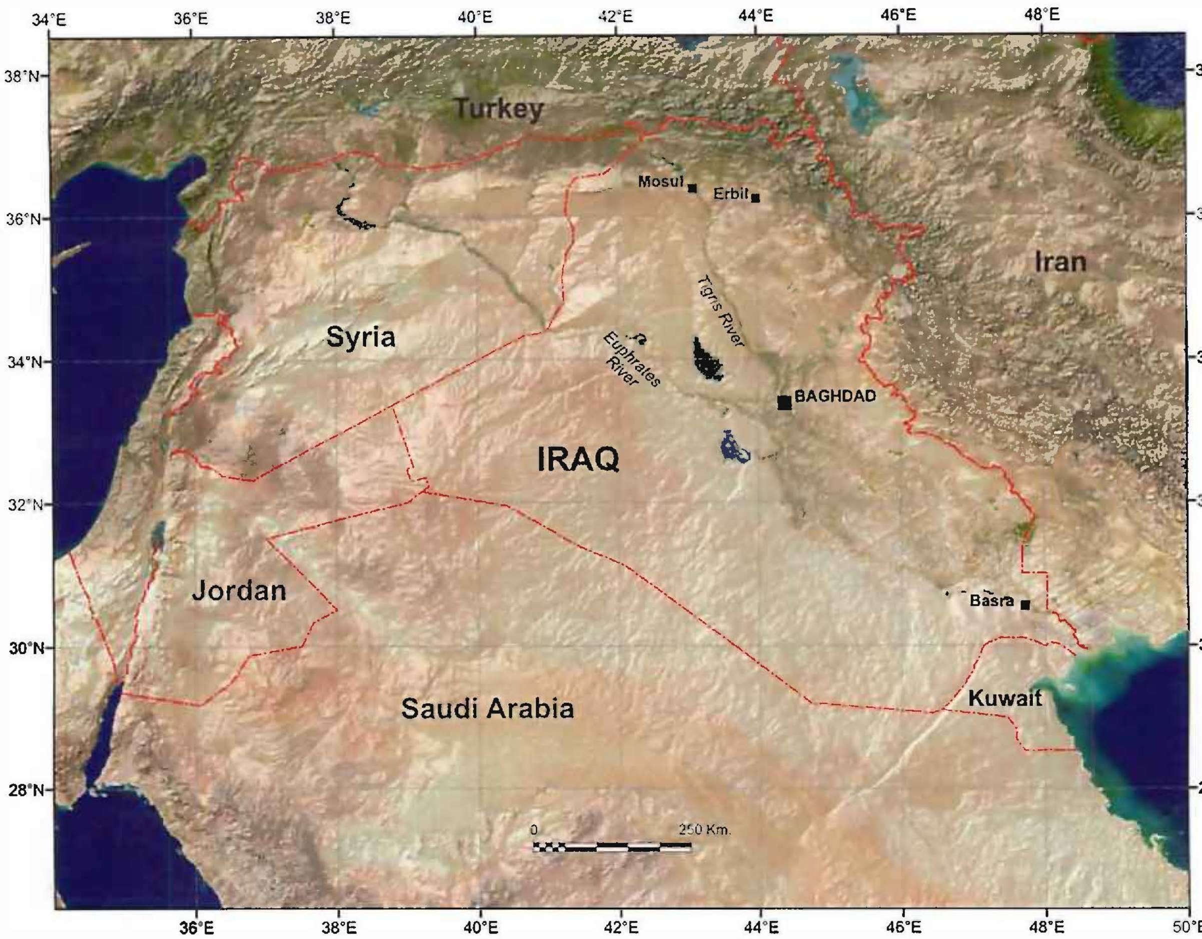


Fig. 1.1. Topographic map of Iraq and surrounding countries. Background map courtesy of NASA Visible Earth (colour mosaic of MODIS satellite images); shading extracted from NASA GTOPO30 dataset.

Organization of the book

The book is organized into four main sections:

- an **Introduction** (including the historical background to the oil industry, and the tectonic setting of Iraq) on pages 1 - 64;
- a five-chapter section on **stratigraphic elements** (pages 65 - 284);
- a review of the **petroleum systems** in Iraq (pages 285 - 382), including an outline of the characteristsics of two well-documented oilfields;
- and finally, a brief discussion of some of the **Future Challenges** which face the Iraqi oil industry (pages 383 - 388).

The historical background relies on both published and unpublished accounts. The tectonic section draws on the publications of Buday and Jassim (1987) and Jassim and Goff (2006a). Sources of information in the "stratigraphic" chapters (4 to 8) are diverse. Of particular note, however, are recent publications by Jassim and Goff (2006a), who summarised the results of the Geological Survey of Iraq published in 1983-1984; and the Palaeozoic review by Al-Hadidy (2007). The organization of these chapters follows the megasequence scheme defined by Sharland *et al.* (2001) (Fig. 1.4). Within each chapter, megasequences are divided to a supersequence or sequence level. The sequences are Vailian and are defined on the basis of sequence boundaries (following the recommendations by Sharland *et al.*, 2004) rather than on maximum flooding surfaces. Most Vailian sequence boundaries can be correlated chronologically with cycle and subcycle boundaries defined by both van Bellen *et al.* (1959) and Buday (1980). This allows the original formation names in Iraq, as used in these publications, to be re-used within a modern stratigraphic context.

Spelling and transliteration

Iraqi formation, well and place names have frequently been spelled in different ways within the English-language literature, often as a result of different transliterations from Arabic or Kurdish. Spellings used here follow those used in the Iraq *Lexicon* (*see below*: van Bellen *et al.*, 1959) because this publication represents the first formal documentation of the stratigraphy of Iraq.

Where there is confusion, names are used as they first appeared in the literature; these names tend to be spelled as originally defined (either

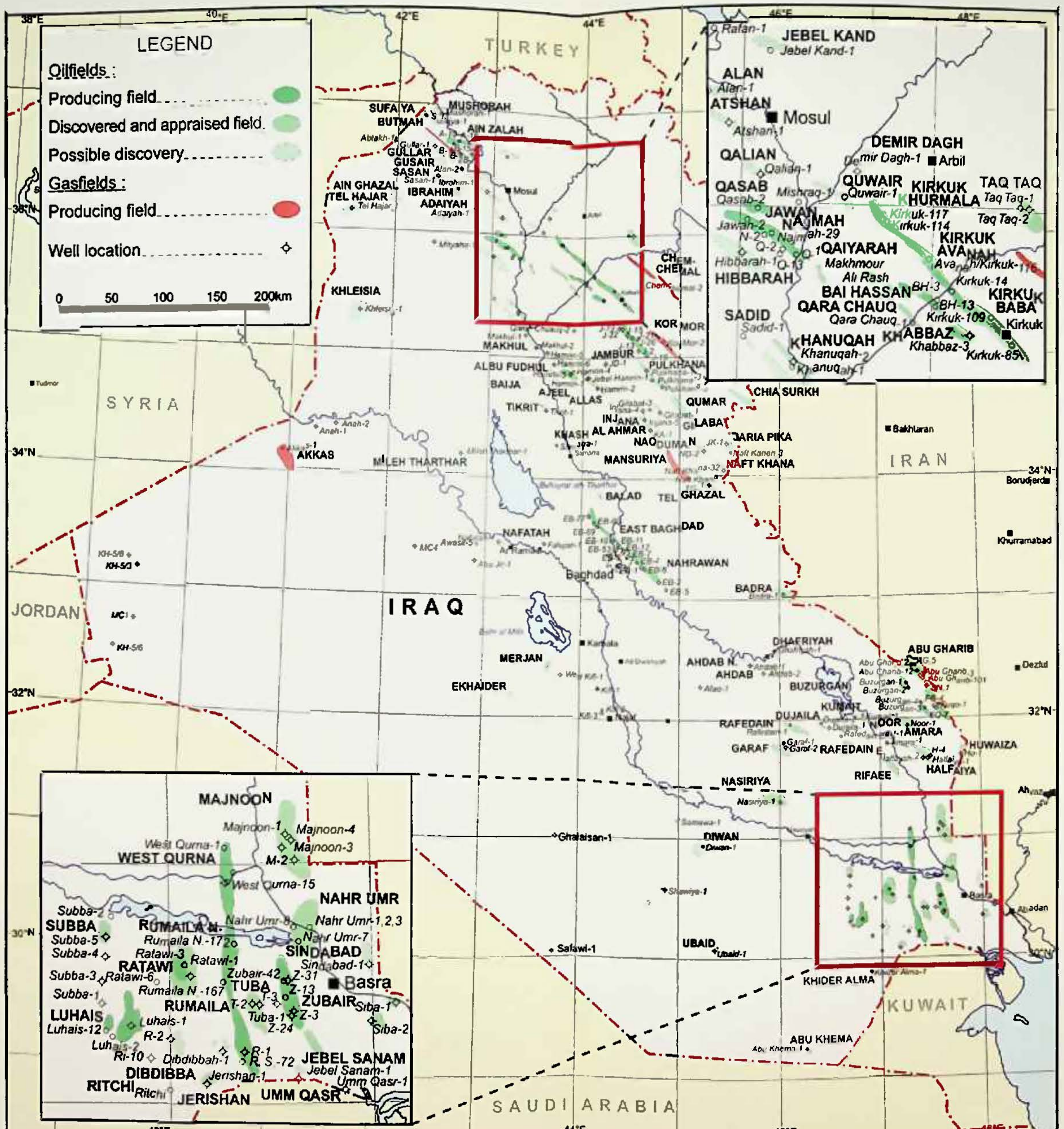


Fig. 1.3. Location map of Iraq's oil- and gasfields (redrawn from a variety of published sources, compiled by Cambridge Carbonates Ltd, 2009). Field outlines are shown schematically. (This and other maps in this book do not represent a reference for international borders between Iraq and its neighbours, and are mainly based on public domain information).

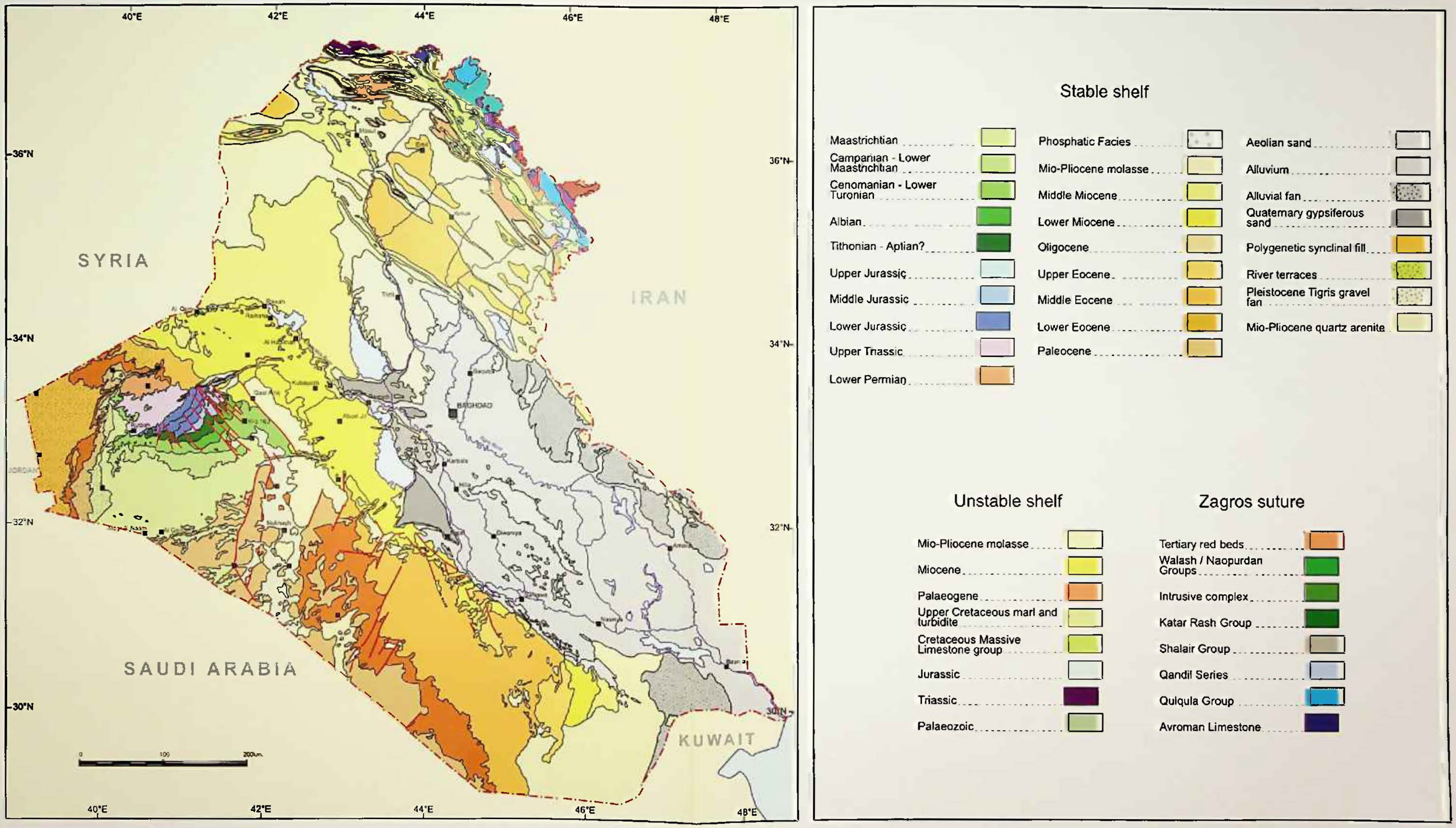


Fig. 1.2. Geological map of Iraq (after "Geological Map of Iraq", Jassim *et al.*, 1986). In northern Iraq, the Stable Shelf, Unstable Shelf and Zagros Suture correspond to the Unfolded Zone, Folded Zone and Nappe Zone of Fig. 3.6.

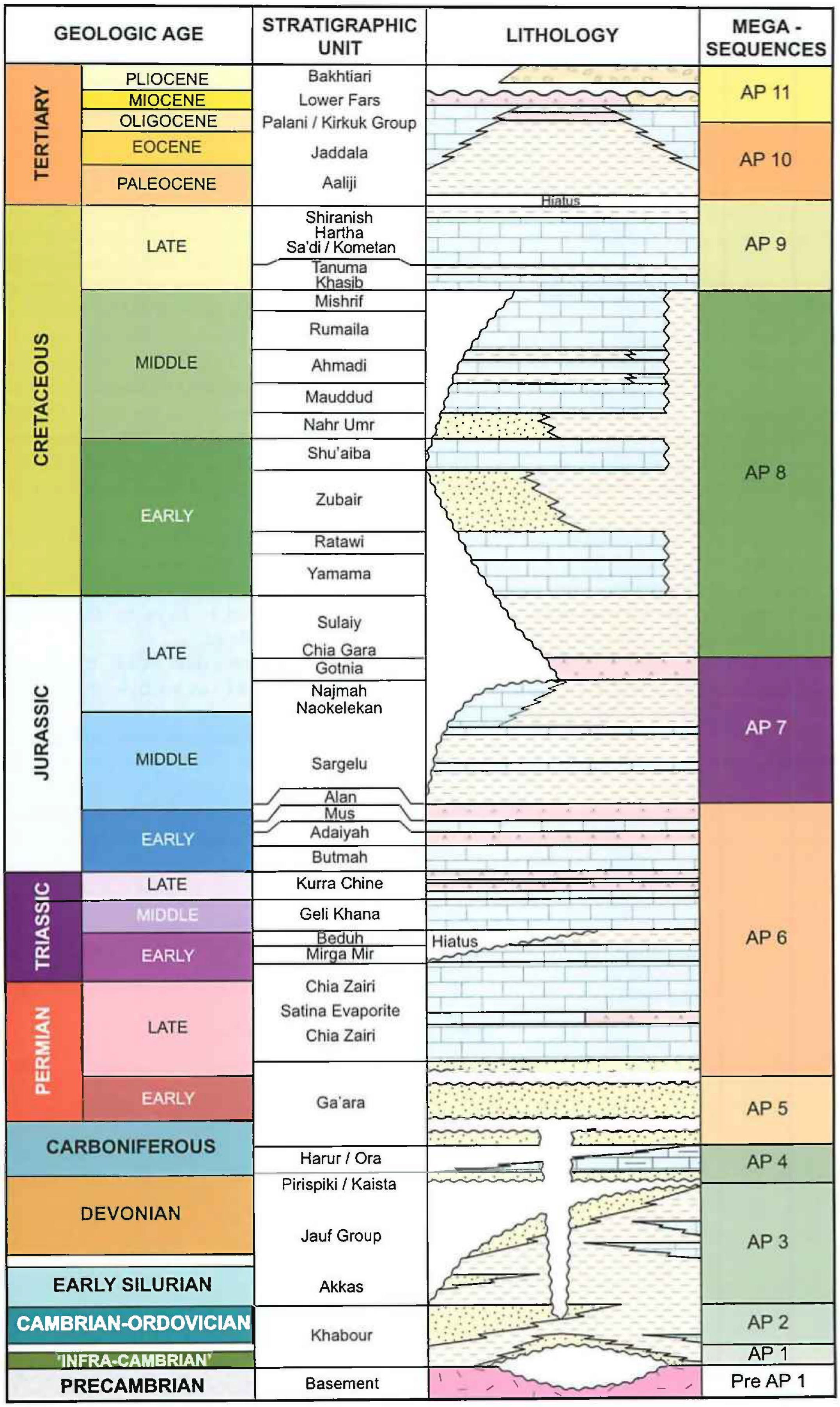


Fig. 1.4. Generalised stratigraphic column for Iraq showing the principal formations in each megasequence together with age and lithology. Modified after Verma *et al.* (2004), with permission of *GeoArabia*; megasequences after Sharland *et al.*, (2001).

formally or informally) on well headers or in company reports. For example, *Khleisia-1* was first mentioned by Tikrity and Al-Ani (1972), and therefore this spelling has been used for both the well and the palaeohigh upon which the well is situated; however, alternative spellings such as *Khlessia-1, Khleissia-1* and *Khlesia-1* have also been used. Similarly, the Kifl Formation was first formally defined by Al-Naqib (1967) although the unit is often referred to as the Kifel Formation.

Nomenclature and terminology

Although the stratigraphic architecture of Iraq is frequently complex, a simplified nomenclature has in places been adopted for the sake of clarity and simplicity. Thus in Chapter 7 for example, the late Tithonian (uppermost Jurassic) is included in the discusion of Cretaceous stratigraphy. Also, the overviews of the petroleum systems in Chapter 9 are necessarily simplified.

Stratigraphic Stage names have been followed as they appear in the original publications, and have not been replaced by the names proposed in IGS 2004. Use of the revised names would require chronostratigaphic redefinition which in many cases is not supported by the data available.

Figs 1.5a and b summarise lithological and other symbols used in the figures throughout the book.

References

A key publication on the geology of Iraq is the *Lexique Stratigraphique International vol. III, ASIE, Fasc 10a, Iraq,* published by the Centre National de la Recherche Scientifique (Paris) — often referred to simply as the "*Iraq Lexicon*". This invaluable book is often cited in geological publications as "*van Bellen et al., 1959*", after one of the main contributors. However, only the Cenozoic section of the *Lexicon* was written by R.C. van Bellen himself. The present authors felt that it was important that the authors of the Palaeozoic and Mesozoic sections of the *Iraq Lexicon* — H.V. Dunnington, R. Wetzel and D. M. Morton — were also properly acknowledged. Therefore, when the *Lexicon* as a whole is referred to, the phrase "van Bellen *et al.* (1959)" is used; for the Cenozoic section of the *Lexicon*, "van Bellen (1959)" is specified; while the Mesozoic and Palaeozoic sections of the *Lexicon* are referred to in the style "Dunnington *et al.* (1959)". Although some formations described in the *Lexicon* were formally named by other authors, these authors are not cited here for the sake of simplicity.

The book "Geology of Iraq", edited by S. Z. Jassim and J. C. Goff (2006), is a multi-author volume of more recent importance. Individual chapters in this book are referred to here by the names of the contributing authors.

Finally, the two-part study by Al-Haba *et al.* (1994) is referred to as a single volume.

A full list of References cited in this book is given on pp. 389-413. The brief list of Additional References (pp. 414-418) includes publications on the geology of Iraq which have not been cited but which may be of use to reseachers.

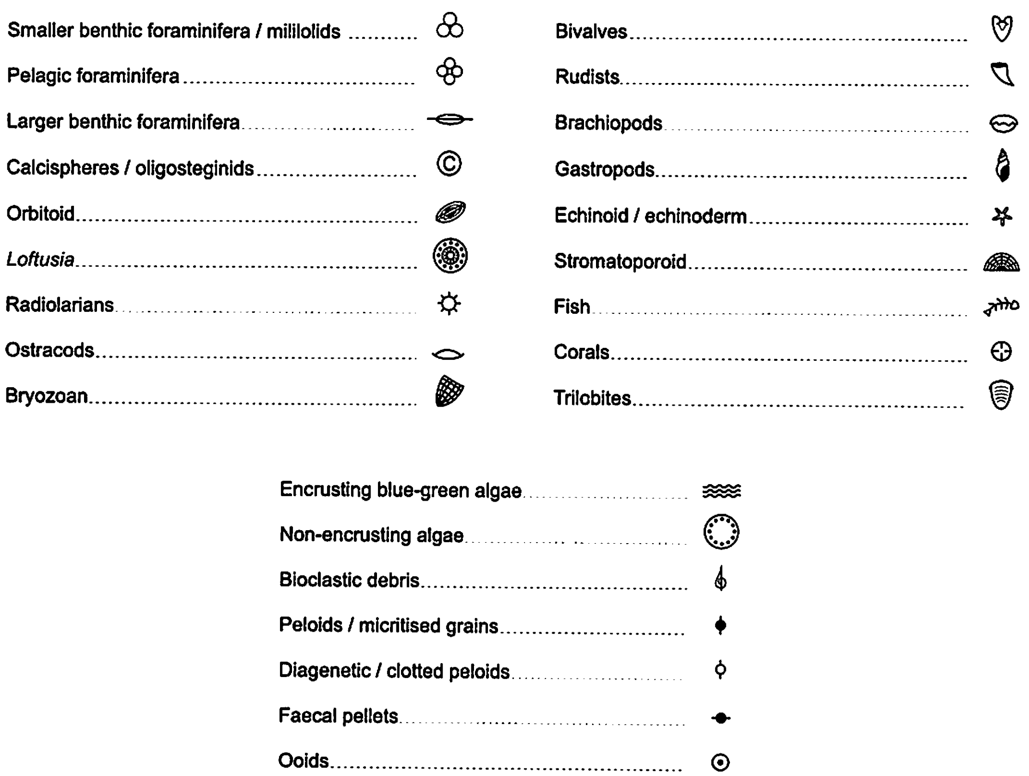


Fig. 1.5a. Lithological and other symbols used in this book.

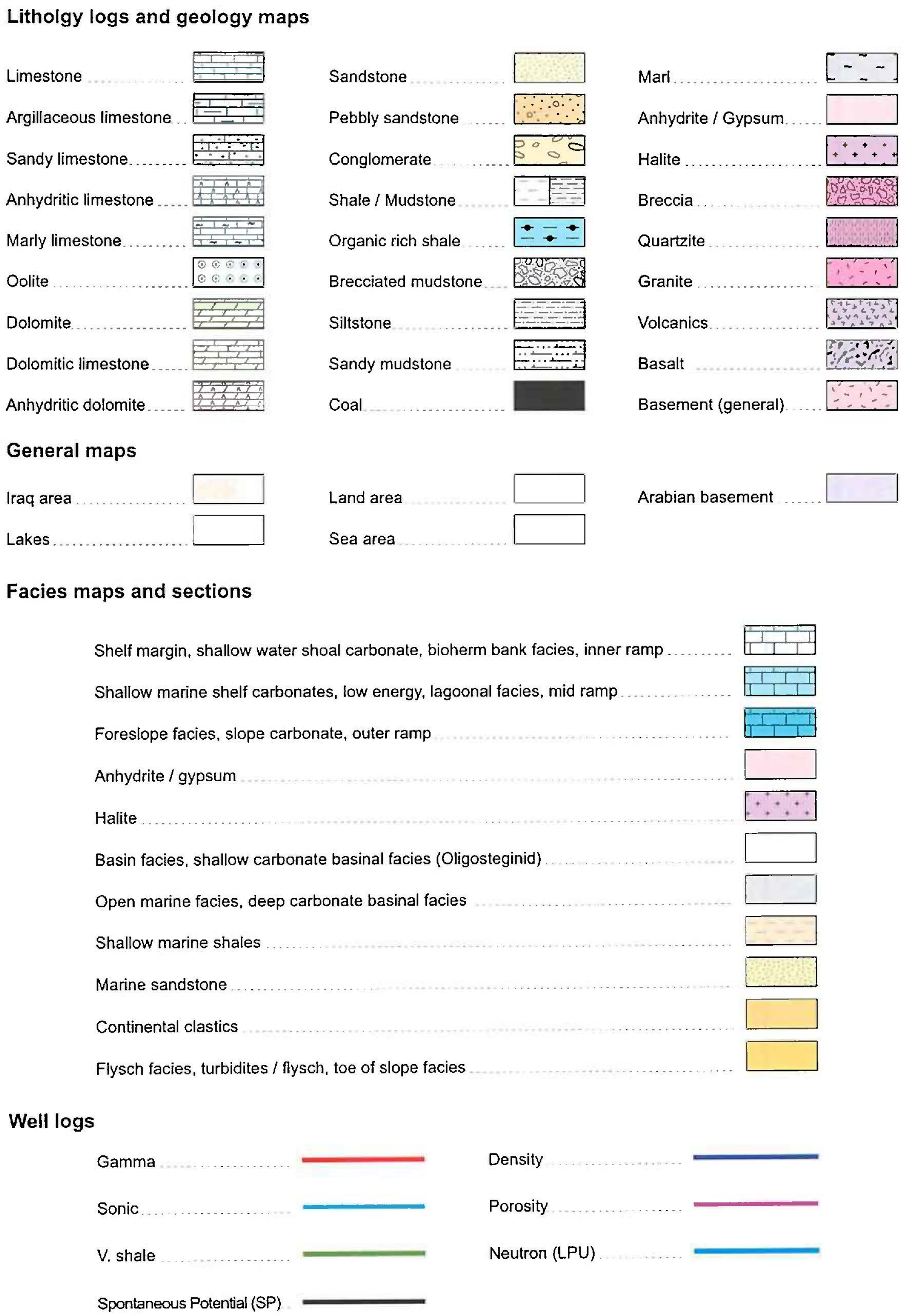


Fig. 1.5b. Lithological and other symbols used in this book (*cont.*).

2. HISTORY OF OIL EXPLORATION IN IRAQ

The history of oil exploration in Iraq began in the late-1880s. Geological research since that time has been interrupted by major wars, disputes over oil exploration and production rights, and periods of challenging social and economic conditions. Under these circumstances, the oil industry has not developed as fast in Iraq as it has in the Gulf countries to the south or elsewhere in the world. At least 80% of Iraqi oil production has been obtained from two exceptional reservoirs, the Main Limestone (at *Kirkuk*) and the Zubair Sandstone (at *Rumaila* and *Zubair*). Much of the oil in the stacked petroleum systems in Iraq remains undeveloped or only partially developed. This chapter summarises the history of oil exploration in Iraq which has relied on the application of new play concepts and technologies.

The history of the discovery of oil in Iraq was first related to a wide audience in the *AAPG Memoir* **6** "Trek of the Oil Finders" (Owen, 1975). Longrigg (1969) summarised the "Origins and Early History of the Iraq Petroleum Company" (known from 1912 to 1929 as the Turkish Petroleum Company), covering the period from 1900 to 1939. Chapter 9 ("Day of Destiny") in the book "Adventure in Oil" by Henry Longhurst describes the events from the 1890s to the discovery of oil at *Kirkuk* in 1927. This chapter draws on these and other publications, and also on the unpublished memoirs of Harold Dunnington.

Ancient uses of bitumen in Iraq

The early use of bitumen in Iraq and the earliest records of seeps were reviewed by Forbes (1936) and Barber (1948). The following account is based on these publications. Surface seepages of oil and bitumen have been exploited in Mesopotamia (present-day Iraq) for several thousand years. The seepages are mostly in the mid-Euphrates area and around Babylon in central Iraq, and in the upper Tigris river valley in the north. Bitumen use dates back to the Ubaidian Culture of 5000 – 4000 BC. The Ubaidians built the first temples in Mesopotamia and used underground bitumen-coated silos to store grain. In the later cities of Erech, Ur and Kish which were built before 3000 BC, bitumen was used as a building material and for plumbing and water proofing. Clay figures of goddesses with decorative bitumen hair date to 4000 BC. Bitumen was also used for decorative purposes to mount carved figures and friezes made of lapis lazuli, mother of pearl and limestone dating from 3000–2600 BC. The Akkadians recorded "oil springs" in northern Iraq around 2300 BC.

King Tukulti II (890–884 BC) of Assyria referred to the "Usmeta Stones by the bitumen springs in front of Hit", which were identified much later as mixtures of gypsum, sulphur and bitumen. Associated rumbling noises related to the escape of natural gas were regarded as the "mutterings of gods". Bitumen was used in the Assyrian capital Nineveh, near present-day Mosul, for cementing bricks, tiles and mosaic pavements in the 9th and 8th centuries BC. King Nabopolassar (625-604 BC) built the "Procession Road" in Babylon "glistening with asphalt and burnt bricks". King Nebuchadnezzar (604-516 BC) probably used bitumen from Hit (in the mid-Euphrates valley) in the rebuilding of Babylon and for paving in the Hanging Gardens. The 5th century BC Greek historian Herodotus records that bitumen was brought to Babylon (probably from seeps at Hit) in 450 BC. He described the "Eternal Fires" or burning gas seep on the crest of the Kirkuk anticline at Baba Gurgur (Kurdish for "Father of Flames"). This seep is thought to have been alight for at least 4000 years; it may be the "burning fiery furnace" into which, according to the Old Testament, King Nebuchadnezzar threw Shadrach, Meshach and Abednego (Daniel, 3:19-30). According to Plutarch, oil from seeps was used for illumination when Alexander the Great passed through the Mosul region in c.331 BC. Oil was later distilled using a primitive apparatus to make lamp oil. By the 8th century AD, a number of large "oil pits" are known to have been worked; the largest of these at Qaiyarah, south of Mosul, yielded both oil and bitumen which was used for surfacing roads.

The late 19th and early 20th Centuries

For several hundred years until the First World War, Mesopotamia was part of the Ottoman Empire. An Expert Commission from Turkey visited Iraq in 1871 and noted the presence of large-scale "probable" resources of oil in the Tigris/ Euphrates areas. Negotiations took place in Istanbul in 1890–1910 concerning the rights to exploit and develop these resources. The Armenian entrepreneur C. S. Gulbenkian compiled a special report in 1892 on the oil prospects of Mesopotamia. In 1899, the German Deutsche Bank was granted a concession by the Ottoman authorities to build a railway from SW Turkey to Baghdad. They also acquired poorly-defined rights to operate mines within a 20 km strip on either side of the railway line. The bank sent a geological expedition to Mesopotamia in 1905, which included Dr A. Kissling (the bank's Chief Geologist) and C. Porro (a consultant petroleum geologist from Como). They prepared a report with a detailed description of petroleum seepages in northern Iraq near Mosul in the Tigris valley and Hit on the Euphrates (Porro *et al.*, 1905). In 1907, P. Grosskoff also reported on the "petroleum deposits" of Mesopotomia for the Ottoman authorities (Grosskoff, 1907). Work on the railway took place between 1903 and 1914 (it was eventually completed in the 1940s), but no exploration for petroleum by the Deutsche Bank took place.

In 1912, the Turkish Petroleum Company (TPC), a Company incorporated under English law, was formed to acquire concessions for the development of oilfields in the Ottoman Empire. Shares in TPC were held by the Deutsche Bank, the Anglo Saxon Petroleum Company (a subsidiary of Royal Dutch Shell) and the National Bank of Turkey (a British Bank established in 1910). Calouste Gulbenkian also had a 5% holding. Two years later, the National Bank's shares were transferred to the D'Arcy Group, associated with the Anglo Persian Oil Co. The shareholding in TPC before the First World War was therefore Anglo Persian Oil Co., 47.5%; Royal Dutch Shell, 22.5%; Deutsche Bank, 22.5%; and C.S. Gulbenkian, 5%. By June 1914, TPC were in discussions with the Ottoman authorities to access the *"petroleum deposits already discovered or to be discovered in the vilayets [administrative regions or provinces] of Mosul and Baghdad"*.

At the outbreak of the First World War in the following August, the terms of an exploration licence had still not been concluded. Turkey entered the war on the German side in November 1914, and negotiations ended. Military activity on what was referred to as the "Mesopotamian Front" began in November, 1914 in Basra and reached Mosul four years later.

Before the outbreak of the First World War, significant oil seepages had been noted in Iraq at Zakho, Kirkuk, Tuz Khormatu, Naft Khanah, between Fathah and Mosul in the Tigris Valley (particularly around Qaiyarah), and along the Euphrates Valley near Hit and south of Nasiriya at Tel al Mughaiyir. In 1910, small-scale refineries were operating at Kirkuk, Tuz Khormatu, Mandali and Hit, and up to 200 gallons of "refined" oil are believed to have been produced at each location. The bitumen deposits at Hit were reported to have a capacity to yield "over 2000 donkey loads a day". During the War, German engineers hand-drilled seven wells to depths of 170 ft at the Qaiyarah seepages from which they bailed up to 10 tons of oil per day (Noble and Evans, 1919). One well had a 12 inch casing and was evidently intended as a deep test. The oil was distilled and a yield of about 10% petrol and 20–30% kerosene was reportedly obtained.

Discovery of *Masjid-i-Suleiman*

As a digression, it is instructive to review the geological thinking which underpinned the discovery (May, 1908) of oil at *Masjid-i-Suleiman* in Iran, the first major Middle East discovery which preceded the discovery of oil at Kirkuk by twenty years. This provided an important analogue for early exploration in NE Iraq. The following discussion and quotations are based on material from the Anglo Persian Oil Co. archives in London.

In 1901, oil was observed in Miocene sandstones in small pits dug at the oil springs at Naft Safid (in Iran). Oil springs were also known at Chia Surkh in NE Iraq near the Iran border where the sandstones were deformed into a small anticlinal fold. Drilling of the first well in the Middle East began at Chia Surkh in November, 1902. In 1903, a second well was begun and encountered oil a depth of 756 ft flowing an estimated 600 b/d of oil and salt water. These wells were abandoned at depths of 2315 and 1348 ft respectively in June, 1904 when operations at Chia Surkh were suspended. The first well had encountered oil shows at a depth of about 2000 ft; the second well, drilled up-dip near the axis of the fold structure, had encountered oil at 756 ft but was considered non-commercial.

It had been noted during fieldwork that the *"oil occurrences were also associated with an extensive outcrop belt of gypsum"*, and the prediction was made that *"other oil bearing localities would be found along this belt"*. Following a geological reconnaissance in 1902-1903, it was concluded that there was likely to be a *"continuous recurrence of accumulations of oil, the commercial value of which can only be determined by test drilling at judiciously selected points"*. A ranking of other oil prospects in the

Anglo Persian Oil Co. concession area was prepared. *Masjid-i-Suleiman* was ranked second behind *Shardin*. Drilling began at the latter location on 22nd August, 1906, and at *Masjid-i-Suleiman* on 23rd January, 1908 in gypsum beds at the site of oil seepages; the overlying sandstone beds had been eroded.

The geologists at *Masjid-i-Suleiman* had attempted to identify the source of oil at the seepage locations. It was thought that the gypsum beds were slightly porous but that the underlying crystalline Miocene limestones were not. However, small amounts of thick, black oil had been observed seeping from a crack in the crystalline limestones from beneath gypsum beds on the adjacent Asmari anticline. It was therefore thought that the oil was probably stored in a reservoir beneath the limestones, probably in the Cretaceous succession. The location for the first well at *Masjid-i-Suleiman* was carefully selected *"at the intersection of two small surface folds in the gypsum beds where it was felt the underlying limestone beds were cracked considerably thus accounting for the active oil seepages"*. It was noted that: *"where a change in strike occurs, the crystalline limestone bent already in the form of the arch of an anticline is insufficiently elastic to admit to the bending in another direction, and the oil stored below is found to issue at this spot."* It was some years before the significance of the structural detachment between the complexly folded Miocene evaporites and the underlying simple and much larger anticline in the Asmari Limestone was identified, and the porous nature of the Asmari limestone was established.

The anticlinal theory of oil entrapment then became widely accepted with the discovery in 1912 of the *Cushing* field in Oklahoma. The scene was now set for the geological expeditions that took place in Mesopotamia during, and in the years immediately following, the First World War.

Pioneering Geological Expeditions

While hostilities were still taking place in 1917, G. W. Halse, who had been undertaking geological field work in the Bakhtiari area of the Zagros in Iran, was summoned to Baghdad to examine the oil occurrences in Mesopotamia (Halse, 1918). In the winter of 1917-1918, Halse *"travelled in a Ford motor car over a route of about 1000 miles from Baghdad accomplishing his work with maximum speed and efficiency"*. He travelled to locations up to 30 miles beyond the front line trenches with escorts of armoured cars or cavalry (Halse, 1918).

Halse described the petroleum seepages at Nafatah, Abu Jir and Hit in central Iraq. At Nafatah ("oil fountain" or "oil seep" in Arabic), there was a hand-dug well some 10 ft deep in which 2 to 4 gallons of oil collected daily. He attributed the source of the seepage to the Asmari Limestone which was buried under alluvium. At Abu Jir, he observed an impressive pitch lake approximately one mile long and 400 yards wide. Liquid bitumen associated with cold, sulphurous water and combustible gas bubbled up at five main springs in the lake. Halse suggested that these springs were related to a postulated NNW-SSE trending fold in the underlying Asmari Limestone, continuing as far as the bitumen occurrences at Jebhah (which covered an oval area about half a mile long) and Ain Al Awasil, seven and 16 miles NNW of Abu Jir, respectively.

At Hit, Halse observed five active asphalt springs, located adjacent to outcrops of a horizontally-bedded limestone equivalent to the Asmari Formation of Iran. Other surface occurrences of bitumen were noted within a five-mile radius. The springs were locally vigorous. At Ain Larj, there was a pool of liquid pitch, 25 ft in diameter, which was continuously disturbed into large bubbles; when these burst, the escaping gas made a noise like steam blowing off from a boiler. At Ain Marj, a pitch lake some 90 m in diameter occurred in an area of flat alluvium. The semi-solid pitch formed a crust nine inches thick, resting on sulphurous water. Under a man's weight the pitch slowly subsided as water and gas bubbled and hissed through fissures in the crust. Halse interpreted the Hit area as a "partial dome structure" of very slight inclination, at which the bitumen seepages indicated that a substantial accumulation had formed. He noted that at the outcrops near Hit, the 16 m of exposed Asmari-equivalent limestone was unusually porous and cavernous, with the possibility that dolomitisation of beds of limestone occurring beneath the outcrops had created "an excellent reservoir rock" (Halse, 1918).

In the winter of 1918-1919, E. H. Pascoe of the Geological Survey of India made a geological reconnaissance north of Baghdad from the railhead at Tikrit up the east bank of the River Tigris to Mosul and into the hinterland to the east (Pascoe, 1922). He studied the area north of that visited by Halse. His journey was difficult with *"incessant violent storms, the unsettled state of the country, unspeakably bad roads, lack of local supplies and fuel, and the death of two camels"*. Pascoe grouped the localities he visited into five risk categories. The first three categories comprised: (i) areas of First Class Importance (Qaiyarah and Quwair), (ii) areas less certain but of decided promise (Hamrin and Makhul), and (iii) areas of uncertain prospects but sufficiently promising to warrant a test boring (Mishraq and Kirkuk). The fourth and fifth categories comprised speculative areas.

At Kirkuk, Pascoe described at outcrop a small overturned fold of uncertain lateral extent. The presence and significance of a major structural detachment in a halite unit near the base of the Lower Fars Formation was not known at that time (the same structural problem had been encountered at *Masjid-i-Suleiman*). Pascoe thus had reservations about the size of the Kirkuk structure and the location of oil-bearing reservoirs within it. In one of the first descriptions of exploration risk, he noted that *"any company drilling in the area must be prepared to face indifferent success or failure"*.

The geologists Noble and Evans of the Anglo-Saxon Petroleum Co. visited Kirkuk in 1920, and noted that a *"fault cut off the SW flank of the anticline"*. They agreed with Pascoe that *"the anticline is overfolded and probably isoclinal in places with a reversed fault on the SW limb, and that the prospect of obtaining oil in large quantities is speculative"*. However, during a later mapping expedition in 1925-26, it became apparent to Noble that the Kirkuk anticline was a huge structure; as the field work progressed, *"it became evident that it was continuous for about seventy miles, and that if it were oil bearing it would be one of the greatest oil fields in the world"* (Noble, 1954).

Noble and Evans also visited the Qaiyarah bitumen seepages in 1919. As Noble recalled: *"We started to map the large anticline, a text book structure several miles long and our survey showed that Qaiyarah fulfilled all the conditions of a potential oilfield. And so it proved to be when it was tested some ten years later. Unfortunately the oil was heavy and sulphurous – and, of course, the geologists were blamed for this!"* (Noble,1954).

Meanwhile in the Mishraq area (south of Mosul), E. H. Pascoe described an occurrence of sulphur and small bitumen seepages in the Lower Fars Formation. A lake in the blocked branch of the Tigris River contained a vast pool of yellow water containing sulphur. This was referred to locally as "the fountain of hell", and it was known that hydrogen sulphide gas would overcome anyone who approached too closely. The Mishraq sulphur deposit was in later years identified as the world's largest stratiform ore body containing 100–250 million tons of sulphur (Barker *et al.*, 1979); sulphur production began in 1972 and peaked at 1.25 million tons per year in 1988. Three other sulphur mineralisation centres were subsequently discovered along the Tigris Valley (Jassim *et al.*, 1999).

Exploration in Northern and Central Iraq

Following the First World War, the newly formed Compagnie Francaise des Petroles acquired the German share in TPC, and negotiations were reopened with King Faisal of Iraq at the end of 1921 to finalise the latter's contract for oil exploration. The State of Iraq came into being the following year. In 1923, *Naft Khanah* (to the east of Baghdad, near the border with Iran) was confirmed as Iraq's first commercial oilfield. Shortly afterwards, a syndicate of seven US oil companies acquired a stake in TPC, whose structure by 1924 comprised equal holdings (of 23.75%) by the Anglo Persian Oil Co., Royal Dutch Shell, Compagnie Francaise des Petroles and the US syndicate; the remaining 5% was retained by Calouste Gulbenkian.

TPC's contract with the Iraqi authorities was finalized in March, 1925 and covered a concession area of about 76,000 sq. miles to the west of the River Tigris. TPC had the right, within 32 months, to select 24 exploration blocks each covering eight sq. miles. The target formation was the equivalent of the Asmari Limestone, the formation which was productive at *Masjid-i-Suleiman* and *Naft Khanah*. A geological team led by the Hungarian Professor Hugo de Boeckh (Geological Advisor to the Anglo Persian Oil Company) proceeded to map and rank individual structures in the concession area. Drilling rigs were ordered and shipped, railheads established, roads to locations constructed, and American drillers contracted.

A meeting was held in Mosul in September, 1926 and a ranking of prospects was drawn up by de Boeckh as follows: 1. Injana, 2. Khashm al Ahmar, 3. Pulkana, 4. Jambur, 5. Khanuqah, 6. Kormor, 7. Tarjil, 8. Qaiyarah. Other TPC geologists, including Noble and Shaw, disagreed with this ranking and succeeded in inserting Qaiyarah and Baba Gurgur (Kirkuk) as the fifth- and sixth-ranked prospects, respectively. Noble considered that *"the prospects of the Kirkuk structure are good; there is excellent closure to the south and north, the seepages of oil and gas are strong, at the Baba Gurgur crest it should be possible to make a location with considerable certainty of striking the reservoir at drillable depth"*. De Boeckh, however, did not recommend a borehole at Baba Gurgur. He considered that the Main Limestone was only likely to be oil bearing where it was in "lagoonal facies" (based on his work in Iran). He noted that lagoonal facies were absent at the outcrops at Qarah Chauq Dagh.

The geological map of Kirkuk was prepared by H. K. Long and E. W. Andrau in 1925/26. The eventual selection of two drilling locations on Kirkuk (Baba Gurgur and Tarjil) reflected uncertainty in the subsurface structure. It was noted that the crest of the structure at the Main Limestone level did not necessarily underlie folds in the Lower Fars (Fowle, 1978).

In April and May, 1927, wells were spudded in the Jebel Hamrin area at *Khashm Al-Ahmar* and *Injana*, and at *Pulkhana*, but were abandoned without reaching the Main Limestone, the principal reservoir target. Later the same year, wells were spudded on the Kirkuk Anticline at *Baba Gurgur* (30th June), at *Tarjil* (August) and at *Jambur* (15th September). To the west of the Tigris, a well was spudded at *Qaiyarah* in July, 1927. Drilling at *Khanuqah* was delayed because of access problems, although subsequently a gas well and a dry hole were drilled on the structure. A total of 16,750 ft was drilled by TPC in 1927 without great success, and by October of that year, only one month remained until the deadline for selecting blocks was due to expire.

Based on his diaries of the time, Fowle (1978) recalled the penetration of the oil reservoir in *Baba Gurgur-1*: the daily drilling report of 23rd September indicated the drilling speed was high. The resident geologist at Kirkuk (T. F. Williamson) reported that hardly any cuttings were being recovered. Fowle requested that a core was cut, and that drilling be suspended until it had been examined. He examined the 3 ft core (1518 – 1521 ft) which consisted of broken pieces of oil-saturated limestone and was amazed to see Nummulites, indicating that the well had already penetrated into the Oligocene level of the Main Limestone at a far shallower depth than had been expected. The situation demanded urgent action. There was over 1000 ft of 15 inch open hole including an unknown thickness of Main Limestone. The 10¾ in casing was run and set. The poor quality cutting samples from the 15 inch open hole were examined. The "highest limestone" (a porcellaneous milliolid bearing limestone) was noted at 1172 ft indicating the well had been drilled 350 ft into the oil reservoir.

The drillers changed from a rotary to a cable drilling system to avoid mudding-off the pores in the limestone. At 3 am on 14th October, the *Baba Gurgur* well "came in" unexpectedly at 1521 ft and blew-out at a rate of 90,000 b/d of 35° API oil which flooded nearby wadis. The blow-out claimed the lives of two Americans and three Iraqis. The well was brought under control at a pressure of 275 psi on 22nd October. The blow-out occurred because the drillers had bailed out most of the mud in the casing, and had only kept a 500 ft column of water which provided insufficient back pressure.

The discovery of oil at *Baba Gurgur* overshadowed the result of *Qaiyarah-1* which had flowed 1000 b/d of viscous sulphur-rich oil on 13th October, 1927. It marked a decisive change in TPC's fortunes, and heralded the beginning of the Iraqi oil industry.

The second well, *Tarjil-1* was located 13 miles to SE of *Baba Gurgur-1*. It drilled through about 2500 ft of deformed Lower Fars Formation before reaching the Main Limestone. Fowle (1978) recalled how important appraisal data was collected from this well: a test indicated the limestone was "tight"; some oil and water was swabbed in, but no flow resulted. A reservoir engineer (Y. P. Wilson) thought that *Tarjil-1* had penetrated an "oil/edge water contact". Meanwhile the drillers had filled the well with mud, and had started to dismantle the rig. Wilson persuaded them to clear out the mud and allow the well to stand. The objective was to allow the oil from the tight formation to rise to the surface and to obtain a static pressure measurement. After several weeks oil reached the surface. Wilson was able to verify that the static pressure (allowing for surface elevation difference) was almost the same as in *Baba Gurgur-1*. He concluded that the oil accumulation was probably continuous over the 13 miles from *Baba Gurgur* (and an unknown distance to the NW), and that an oil column of about 2200 ft was present.

The application of geophysical methods in Iraq was first discussed at a meeting of geological advisors to TPC in June, 1928 (Miller, 2007). A refraction survey was carried out in NE Iraq from September 1928 to June 1929 over the Kirkuk, Pulkhana, Kashm Al-Ahmar and Hamrin structures, the objective being to determine the structure of the "Main Limestone". The survey was carried out by a team of eleven specialists from the Seismos Gmbh Co. (Hannover, Germany), some of whom had previously worked on salt dome detection in Texas. Results were reported at the end of October, 1929. The survey accurately located a shallow anhydrite unit in the Miocene Lower Fars Formation, but results were poor at deep levels in the formation due to the presence of halite layers of variable thickness.

Selection of exploration blocks by TPC did not occur in the allotted time-period. TPC was renamed the Iraq Petroleum Company (IPC) in 1929. A new agreement was eventually signed in March, 1931 which gave IPC a blanket concession east of the River Tigris containing many structures including the whole of the Kirkuk anticline. A geological conference held by IPC in Kirkuk in 1931 concluded that the *Kirkuk* oilfield extended with "hydrostatic continuity" for some 40 miles (65 km), with an oil column of >2000 ft and 500 ft of porous limestone, with sufficient reserves to *"fill a pipeline to the Mediterranean for 25 years"*. From 1932-1939, IPC geologists at Kirkuk selected well locations, undertook rig-site geological work, and studied the structure of the Avanah and Khurmala Domes. Meanwhile, unsuccessful drilling was conducted by IPC at Mishraq, Qasab, Jawan, Najmah, Sadid and Hibbarah between 1933 and 1935.

In April 1932, British Oil Development Ltd (BOD) signed an agreement to explore for oil within area of about 46,000 sq. miles to the west of the River Tigris and north of latitude 33°. The terms of the licence were that exploration drilling was to begin within eight months, that three drilling rigs were to be operating within 18 months, and that nine rigs had to be operating continuously within one year of striking oil until oil export had begun. Wells were drilled at *Qaiyarah* and *Mishraq* using cable tool rigs, and a nine-rig programme using rotary rigs then focused on drilling-up the Qaiyarah anticline and adjacent anticlines (Najmah, Jawan and Qasab). Heavy oil was discovered in the Euphrates Limestone and lighter oil in the underlying Cretaceous Pilsener Limestone – so named because of the resemblance of its oil to a beverage familiar to the well-site personnel. Exploration wells drilled on the Alan, Hibbarah and Safid anticlines were unsuccessful. By 1935, however, BOD was in financial difficulties and IPC was approached for financial assistance.

Mosul Petroleum Co. (MPC) inherited BOD's onerous drilling obligation. In 1937 wildcat exploration began on outlying surface folds (characterized by outcrops of Lower Fars Formation), which lacked surface seepages. At first this programme was unsuccessful, with dry holes drilled at *Adaiyah-1, Ain Zalah-1* and *Butmah-1*. In 1939, small quantities of light oil were tested from Triassic carbonates in *Qalian-1* (the first indication of an active Triassic petroleum system in Iraq). In July of that year, *Ain Zalah-2* tested 5500 b/d from a 1000 ft thick, fractured Upper Cretaceous argillaceous limestone (the Shiranish Formation). An earlier well, *Ain Zalah-1*, had been spudded in 1936 but was suspended with oil shows in Eocene limestones due to the limitations of the drilling rig. Drilling continued at *Ain Zalah* until 1941.

No exploration wells were drilled during the Second World War, but exploration resumed in NW Iraq following the cessation of hostilities. An exploration well (*Ain Zalah-16*) was begun at *Ain Zalah* in 1948 in search of a deeper reservoir below the Shiranish Formation. Three years later, the well flowed 4000 b/d of 31° API oil from carbonates assigned to the Middle Cretaceous Qamchuqa Formation. The field was put on production in 1952 at 27,000 b/d. A second well on the Butmah structure was spudded in 1951, and discovered oil in the Shiranish but not in the Qamchuqa. The well was deepened in 1954 and flowed 2000 b/d of light oil from Triassic dolomites. Later exploration drilling in NW Iraq on surface anticlines included unsuccessful wells at Gusair, Alan, Atshan, Makhul, Sasan, Gullar and Ibrahim in 1955-1957.

Exploration in Southern Iraq

In July 1938, a few months after the discovery of oil in the Lower Cretaceous Burgan Sandstone in Kuwait, the Basra Petroleum Company (BPC) – a subsidiary of IPC – was awarded a licence covering the whole of Iraq south of latitude 33°. The terms of the concession were that drilling with two rigs (capable of drilling to 10,000 ft) should start within three years; at least 12,000 ft should be drilled per year prior to discovery of oil; and 20,000 ft/yr should be drilled following the discovery of oil and prior to export. In addition, exploration was to start in three areas within at least eight months.

During the first geological reconnaissance of the Basra area in the winter of 1938, a small seepage of flammable gas was noted at *Nahr Umr* (north of Basra) on the east bank of the Tigris. In March 1939, five geophysicists from the Torsion Balance Exploration Co. (Houston, Texas) began a survey of the area using three "Bamberger type" torsion balances, and worked continuously to the end of the year. A contract was then signed with the "Geophysical Company" (formerly the Mott-Smith Corporation) in May, 1940 for a major gravity survey between July, 1940 and June, 1941 covering several areas including the North Basra region. The gravity survey located an anomaly at Nahr Umr which was interpreted as a piercement salt dome like Jebel Sanam, a hill located 50 miles to the south.

After the end of hostilities in 1945, extensive geophysical surveys were carried out by IPC (Yacu, 1959). As related by Owen (1975), gravity residual maps were prepared and used to guide the location of follow-up seismic surveys using single deep holes and single geophones. The Zubair structure was first identified by a Rayco gravimeter survey as a "positive nosing". Follow-up seismic surveys in 1947 identified anticlines at Nahr Umr and Zubair. *Zubair-1* and *Nahr Umr-1* were spudded in February and March 1948, respectively. *Zubair-1* tested 3000 b/d of 26° API oil from Middle Cretaceous (Mishrif Formation) limestones in August, 1948, and 3000-4000 b/d of 35° API oil from the Zubair Formation during the following month. *Nahr Umr-1* tested 2000 b/d of 43° API oil from the Nahr Umr Formation in 1949. An anticline was also identified from seismic data at *Rumaila*.

From 1950 to 1952, BPC focused their attention on development drilling in the *Zubair* field. Well *Rumaila-1* was spudded on 21st February, 1953, and oil was discovered at the end of October in the same Zubair Formation as at *Zubair* field. By 1954, it was apparent from well data that the large north-south trending subsurface anticlines in SE Iraq had undergone structural growth in mid-late Cretaceous time, with down-flank thickening of strata of this age. Seismic surveys were subsequently performed in northern and western Iraq but with mixed results often due to difficult surface and shallow subsurface geological conditions. Techniques using multiple patterns of geophones and shallow shot-holes were developed to acquire better quality data.

An important observation from these early regional seismic surveys was that, as Yacu (1959) noted: "*Large anticlines were not as common and easy to discover as expected. Thousands of feet of north east dip were mapped on the homoclinal flank of a geosyncline, broken only by structural terraces, plunging to the south east. We have followed these terraces for great distances, hoping to find closure, only to see them gradually merge into the regional slope and disappear*". Yacu (1959) provided a compilation of graphs of seismic travel time as a function of depth at 18 locations in Iraq derived from velocity and well surveys.

Scott Reid (1954) described the early seismic surveys in SE Iraq: "*Seismic parties arrive on location after geological and gravitational surveys have suggested that a further and more detailed investigation of the area is desirable.*" Seismic surveys were extended into the marshes of southern Iraq. Seven ton "marsh buggies" with wheels three metres in diameter were used to bulldoze through marshland and reed swamps. Air boats with 190 hp aircraft engines navigated the network of waterways at speeds of up to 40 mph. Water caravans formed the headquarters of the mobile seismic parties.

IPC Studies and the Iraq Stratigraphic *Lexicon*

Over a 33 year period from 1925 to 1958, extensive stratigraphic studies were performed by the geologists of the Iraq Petroleum Company, culminating in the preparation of the *Lexique Stratigraphique International: Iraq* (van Bellen *et al.*, 1959). It is instructive to look at the database on which this work was based.

After the Second World War, detailed surface stratigraphic surveys in Iraq began in 1946 and control sections were measured at more than 110 locations with a combined thickness of 60,000 m. About 19,000 field samples were collected; 140,000 thin sections of field samples were prepared from Northern Iraq alone. In addition, 10,500 macrofossils were sent to the IPC's Regional Geological Laboratory in London. Apart from papers by Spath (1950, 1952), and on stromatoporoids by Hudson (1958), work on the macrofossils remained unpublished.

Surface geological data was integrated with data from exploration and production wells. By 1958, 78 wells had been drilled into the Mesozoic, although only one well had penetrated the entire Mesozoic and entered the Permian (*Atshan-1*). One hundred and ninety wells had drilled into the Tertiary without reaching the Mesozoic. Samples from all wells were retained over a total drilled thickness of 750,000 ft from thirty individually-drilled structures. Some 360,000 thin sections were prepared from these well samples.

By the late-1950s, Palaeozoic rocks were known only from outcrops in NE Iraqi Kurdistan and comprised Ordovician quartzites, sandstones and shales assigned to the Khabour Formation. An exploration well was spudded in August, 1958 at Khleisia in NW Iraq, located on a large seismically-defined structure; the well was intended to target an interval within the Mesozoic succession. The IPC exploration management then read with disbelief a telex from the rig geologist describing the occurrence of trilobites in a limestone core apparently recovered from the target unit (Edward Hart, *pers. com.* to J. C. G.). In fact, the well had uncovered the presence of a major and hitherto unknown unconformity between the Triassic and Carboniferous sequences.

In 1958, H. V. Dunnington (then Divisional Palaeontologist with IPC in Iraq) presented a paper at the AAPG in New York titled "*Generation, Migration, Accumulation, and Dissipation of Oil in Northern Iraq*". One of the authors of this book (J. C. G.) recalls reading this seminal paper on joining the oil industry in 1976. A second author (F.N. S.) acknowledges the advice which Professor Dunnington gave him while he was studying the Qamchuqa Formation for his Ph.D thesis at Bristol University in the 1970s. Although written before the thermal mechanism of oil generation was widely accepted (a point which a contemporary reader needs to be aware of), Dunnington's 1958 paper remains one of the most influential papers written on Middle East petroleum geology and is still used as a general reference. In this paper, Dunnington introduced the concept of vertical oil migration from the Jurassic and Cetaceous section into Tertiary reservoirs

Exploration from 1961 to the present day

i. Pre-nationalization (1961-1972)

Following the discovery of oil in Cretaceous reservoirs in Southern Iraq, several factors delayed intensive exploration. These include an emphasis on field development (1955–1961), a dispute over exploration rights (1961–1967), and later (i.e. after nationalization) the Iraq-Iran war in the 1980s and subsequent economic sanctions.

By 1960, less than 200 exploration wells had been drilled in Iraq. Under pressure from the Iraq Government to conduct further exploration, IPC drilled four shallow "stratigraphic and structural test wells" in SW Iraq (*Ghalaisan, Safawi, Shawiya* and *Ubaid*). On April 6th 1961, the oil companies were prohibited from further exploration drilling in their concession areas. Drilling was thus suspended at three locations across the country *(Hamrin, Luhais* and *Taq Taq)*.

However, IPC were permitted to explore in their retained development areas, totalling just under 2000 sq km. In 1962, IPC drilled two deep exploration wells in the *Jambur* field and discovered oil in the Lower Cretaceous Qamchuqa Formation. No exploration drilling took place for six years between late-1962 and October, 1968. During this time, IPC focused their efforts on development drilling in the *Kirkuk, Jambur* and *Bai Hassan* fields, with emphasis on the Cretaceous carbonate reservoirs at *Bai Hassan.*

In 1964, the Iraqi National Oil Company (INOC) was formed. Its initial objective was to explore the areas expropriated from IPC. In November 1967, INOC contracted the French Company ERAP (Elf Iraq) to explore for oil in SE Iraq near Amara (i.e. Maysan Province). The terms of the ERAP licence were that 50% of the agreement area was to be relinquished within three years, 75% within five years, and the remainder of the area (excluding proved fields) within six years. *Siba-1* was spudded in October, 1968 and tested oil the following year from the Zubair and Yamama Formations. A later appraisal well, *Siba-2,* found water in the Yamama. *Burzurgan-1* discovered oil in the Mishrif Formation in 1970 and three appraisal wells were drilled in 1970–1971. Further oil discoveries were made at *Abu Ghirab* and *Jebel Fauqi* in 1971 and 1974, respectively. A six-fold seismic survey was acquired by CGG to map the Buzurgan structure from August, 1968 to March, 1969. The location of the survey was chosen using an archive geological map and earlier single-fold seismic surveys; after the discovery of the field, a twelve-fold seismic survey was acquired (December, 1969 – March, 1970) to better define the structure (Al-Ani, 1975).

The Bulgarian Government signed a contractual agreement for drilling and seismic surveys in North Iraq in 1970, covering the Mityaha, Sufaiyah, Jebel Kand, Sassan and Raffan structures. The Romanian Government signed a similar agreement in 1971 covering the East Baghdad, Jebel Hamrin and Diyala areas.

Following increasing political pressure by the Iraqi Government, IPC was nationalized in June, 1972 and compensation was agreed the following year. The American (Exxon and Mobil) shares in BPC were also nationalized at the outbreak of the October 1973 Arab-Israel War, while the British (BP), French (CFP) and Dutch (Shell) shares in BPC were eventually nationalised two years later.

ii. Post-Nationalization

In August 1972, the Brazilian company Braspetro was awarded a contract for three blocks in southern Iraq in a concession area of 7900 sq. km including the *Nahr Umr* field. (Three wells at *Nahr Umr* had originally been drilled by BPC prior to the transfer of operations to INOC in 1971). Braspetro started development drilling here the same year, and conducted seismic surveys throughout the three blocks. Their first exploration well was spudded in mid-1975 *(Sindabad-1),* located north of the city of Basra, and was suspended as a dry hole. The second well in the block *(Majnoon-1)* was spudded in mid-1976. Oil was discovered in five reservoirs. Appraisal wells *Majnoon-2* and *-3* were drilled in 1977 and 1978, respectively. Braspetro relinquished its interest in *Majnoon* and *Nahr Umr* fields in early 1980 in exchange for access to a supply of oil at favourable prices and reimbursement of its past exploration and appraisal costs. INOC then took over operations at the fields. Appraisal work stopped in September, 1980 due to the outbreak of the Iran – Iraq War.

In September 1970, INOC established the "General Enterprise for Oil and Gas Exploration" which was later renamed the Oil Exploration Company (OEC). In the early 1970s, INOC developed the *North Rumaila* field. *North Rumaila* corresponds to the area which BPC (Basra Petroleum Company) had been appraising with additional seismic surveys prior to 1961, when IPC's rights over non-producing discoveries (and those of Associated Companies) were revoked (Beydoun, 1988).

In 1976, ONGC completed the most southerly exploration well in Iraq (*Abu Khaimah-1*). The well was abandoned at 3000 m with stuck pipe in the Gotnia Formation salt. ONGC relinquished their concession in early 1977.

In September 1970, the first Iraqi seismic crew was commissioned (Mohammed, 2006) using multifold seismic, and INOC introduced digital recording in 1973. By the end of 1974, three Iraqi seismic crews were operating with dynamite as a seismic source in the marshlands (Ahwar) of southern Iraq and in the Western Desert. Ten seismic crews were operating in Iraq by 1980, some of whom were specially trained to work in marsh or desert terrain, and Vibroseis was introduced shortly afterwards. A centre for seismic processing was established in 1981 and upgraded in 1985-1988. Modern laboratories for regional exploration were established in the mid-1980s. By 1990, 230,000 km of seismic data had been acquired, covering 90% of the area designated for exploration in Iraq; 60,000 km of Vibroseis data had been acquired in the Western Desert alone with an average seismic grid of 5 x 5 km (Al-Dabagh, 1999).

Exploration by INOC led to the discovery of oil in several Cretaceous carbonate reservoirs in SE and Central Iraq (Al-Sakini, 1992). Major achievements of INOC in the 1970s were the discovery of additional giant oilfields producing from the Mishrif Formation, and the discovery of the underlying Yamama Formation carbonate reservoirs in SE Iraq. Significant discoveries included *West Qurna* (1973), *Halfaiya* (1976) and *Majnoon* (1976). Sadooni (1993) described the results of exploration drilling in the Yamama Formation which led to oil discoveries at *Nasiriya, Halfaiya, West Qurna, North Rumaila, Zubair, Nahr Umr* and *Ratawi* fields.

Seismic surveys in Central Iraq indicated the presence of large-scale block-faulted structures at East Baghdad, Balad, Samarra and Tikrit (Aljawadi, 1990). These structures form gentle monoclines dipping to the NE and plunging to the SE (Sadooni, 1993). The structures are compartmentalized by sealing faults and have internal horsts and grabens. Growth faulting occurred in the Late Cretaceous with up to 200 m of structural growth (Aljawadi, 1990). The East Baghdad structure, a block-faulted anticline, is over 120 km long and 20-30 km in width (Sadooni, 1996). The structure is compartmentalized due to wrench faulting which began in Cenomanian time; flower structures are observed on seismic sections.

The *East Baghdad* oilfield was discovered by INOC in March, 1979 on the outskirts of Baghdad City. The main reservoir is the Khasib Formation in which the oil is heavy, typically 15–16° API, but locally lighter (25–27° API) at the crest. There is a widespread layer of heavy oil and asphalt at the base of the reservoir (Pittion, 1983). Light oil was discovered in the Zubair Formation sandstones. By the end of 1979, about 80 wells had been drilled and development drilling began the following year with technical assistance from Total, with directional drilling from multi-well sites. The *East Baghdad* field is reported to have commenced production at 50,000 b/d of 23° API in April, 1989 following the end of the Iraq-Iran War. INOC's studies led to the discovery of the satellite *Nahrawan* field near *East Baghdad*, and also of the *Balad* and *Tikrit* fields in the "East Tigris" area.

Sadooni (1996) noted that Dunnington (1959, p. 226) had predicted the existence of a "true rudist reef" in the area adjacent to the *Makhul-1* exploration well which had encountered both lagoonal (anhydritic) and oolitic limestones (with rudist debris). This prediction was confirmed by the discovery of oil in the Hartha Formation (of Late Cretaceous age) in *East Baghdad* field, which extends almost as far north as *Makhul*. Sadooni (1996) recorded that well *Merjan–1*, which had targeted an alleged Jurassic reefal build-up, tested 700 b/d of oil from the Hartha Formation, and that good oil shows were present in wells drilled in both the northern part of *East Baghdad* and in the *Ahdab* field. The Hartha Formation is equivalent to the former Pilsener Formation of northern Iraq (to the west of the Tigris River), which contains heavy oil in the *Qaiyarah* and adjacent fields.

Post-nationalization, key achievements by INOC included the development of the *North Rumaila* field in SE Iraq, the discovery of large volumes of medium-gravity oil in the Mishrif Formation in a series of new fields identified from seismic surveys, and the discovery of light oil in the Lower Cretaceous Yamama Formation from beneath already-producing reservoirs.

A programme of water wells and shallow stratigraphic tests was initiated with Yugoslavian assistance in the Western and SW Deserts in the 1980s. Wells included *Key Hole (KH) 5/1* (TD: 1620 m) which was spudded in 1980, and *KH 5/6* (TD: 1240 m), spudded in 1981. Three deep test wells were drilled during this period, comprising *West Kifl-1* in the centre of the country (1980; TD at 5872 m), *Jebel Kand-1* in the NW (spudded 30th January, 1983, TD at 5848 m); and *Diwan-1* in the SE (TD at 5482 m). In 1989, INOC discovered light (49.5° API), low sulphur oil in the Upper Jurassic at a depth of 4700 m in *Rumaila*, following the discovery of light oil in Jurassic rocks by deep drilling in West Kuwait and *Burgan* by KOC.

The Iran–Iraq War (1980–1988) led to considerable disruption of the oil industry in Iraq. However in the late 1980s, the discovery of gas in Ordovician sandstones at *Risha* in Jordan, near the border with Iraq, together with the discovery of a Silurian source rock (from analysis of cuttings and logs of well *Khleisia-1*, which had been drilled some 30 years earlier in 1959), had drawn attention to the possibility of a working Palaeozoic petroleum system in western Iraq. An exploration well, *Akkas-1*, was drilled on a structural trap adjacent to the Anah Graben in 1993 near the Syrian border. It tested oil from Silurian sandstones and gas from Ordovician sandstones, opening up a new frontier for Iraqi exploration (Al-Haba *et al.*, 1994; Aqrawi, 1998).

Minimal exploration took place in Iraq in the 1990s. However, a series of oil discoveries have been made in recent years in Iraqi Kurdistan. Well *Tawke-1*, located near Zakho (the site of a historical oil seepage) was spudded in late-2005 and tested 5000 b/d. Three successful appraisal wells have been drilled and a 3D seismic survey was acquired over the field. The 25-27° API oil reportedly comes from Tertiary and Cretaceous fractured carbonates. A joint venture has been appraising naturally-fractured carbonate reservoirs in the Taq Taq structure since 2006. Oil has been tested from the Pila Spi, Shiranish, Kometan and Qamchuqa Formations. Well *Taq Taq-1* was drilled by IPC in 1961 but was suspended in the Shiranish Formation; then an oil discovery was made in well *Taq Taq-2* in 1978.

Recent discoveries in Triassic and Jurassic reservoirs have also been reported.

Discovered Oil and Gas Reserves

Official data for the oil–in-place and recoverable oil reserves of individual oilfields in Iraq have not been released. However total proven oil reserves and historical oil production in Iraq are reported on an annual basis by OPEC, and assessments of oil reserves and undiscovered resource potential have been given by Al-Khirsan and Al-Siddiki (1989), Al-Sakini (1992) and Verma *et al.* (2004). The oil resource estimates summarised below are taken from published information and do not necessarily represent the views of the authors.

Al-Khirsan and Al-Siddiki (1989) reviewed the history of oil exploration in Iraq. They noted that from 1927 (the year of the Baba Gurgur discovery) to the early-1960s, 62 structures were drilled and that hydrocarbons were discovered in 35 of them – a success rate of better than 1:2. From the late-1960s to 1989, 52 structures were drilled with the discovery of 38 new oilfields, a success rate of 1:1.5. New reservoirs were also found in 30 oilfields. Based on these new discoveries, the proven reserves of Iraq were increased from 34 billion brls (pre-nationalization) to 100 billion brls (Al-Khirsan and Al-Siddiki, 1989). Al-Khirsan and Al-Siddiki *(ibid.)* also noted that geophysical surveys had identified 400 closed structures of which only 114 had been drilled.

Al-Sakini (1992) reported the stratigraphic distribution of Iraq's oil reserves as follows: 16% in Tertiary reservoirs, 14% in Upper Cretaceous reservoirs, 40% in Middle Cretaceous reservoirs, and 30% in Lower Cretaceous reservoirs, with < 1% in Jurassic and older reservoirs. Al-Khirsan and Al-Siddiki (1989) proposed that the proven oil reserves in Iraq were distributed as follows: 24 billion barrels in Tertiary reservoirs, 76 billion barrels in Cretaceous reservoirs, and about 100 million barrels in Jurassic and Triassic reservoirs. At that time no hydrocarbons had been discovered in Palaeozoic rocks.

Verma *et al.* (2004) listed seventeen giant and super-giant oil fields in Iraq, each containing more than 1 billion brls of initial oil reserves, with a combined initial oil reserve of 123 billion brls (based on data from 1999). At the end of 1998, Iraq was reported to have proven oil reserves of 112 billion brls (OPEC statistics) giving initial oil reserves of 137 billion brls allowing for a cumulative oil production of 25 billion brls. The giant and super-giant oilfields account for about 90 % of the total initial oil reserves in Iraq. At the end of 2007, Iraq's proven oil reserves were reported by OPEC to be 115 billion brls, with cumulative oil production of 32 billion brls, giving an initial oil reserve of 147 billion brls. This represents an increase of 10 billion brls since the end of 1998, which may be attributed to revisions of the initial oil reserves in individual fields in the absence of new significant oil discoveries in this time period.

In the absence of official data on individual oilfields, and with historical oil production being dominated by *Kirkuk* and *Rumaila*, it is difficult to comment on reserves growth in individual fields though time in Iraq. The unofficial oil reserves data for individual fields noted by Verma *et al.* (2004) probably anticipate the future benefits of standard secondary recovery techniques which have not yet applied to most of the reservoirs in Iraq. However future technological advances and enhanced oil recovery techniques should provide scope for further reserves growth. OPEC data indicate major revisions in Iraq's official remaining oil reserves were made in 1987 (an increase of 28 billion barrels) and in 1997 (an increase of 12 billion barrels) following assessment of the new oil discoveries of the 1970s, and reassessment of the oil-in-place or recovery factors in existing fields.

At the end of 1998, three fields (*Kirkuk, Rumaila* and *Zubair*) had a cumulative oil production of 23.5 billion brls accounting for more than 90 % of Iraq's cumulative oil production of 25 billion barrels (based on data in Verma *et al.*, 2004). *Kirkuk* accounted for about 55% of this production, with 45% from *Rumaila* and *Zubair*. Most of this production had come from two prolific reservoir intervals (the Oligocene carbonates of *Kirkuk*, and the Lower Cretaceous Zubair Formation sandstones at *Rumaila)*. Production from twenty other fields amounted to about 1.5 billion brls at the end of 1998.

Ahlbrandt *et al.* estimated in 2002 that the undiscovered oil reserves of Iraq were in the range 14– 84 billion brls (within a probability range of 95–5%) with a mean estimate of 45 billion brls (Verma *et al.*, 2004). Independently Al-Khirsan and Al-Siddiki (1989) estimated probable undiscovered oil reserves in the Cretaceous and Tertiary reservoirs in Iraq at 40 billion brls with an additional 40 billion brls of possible undiscovered oil reserves.

Biographies of authors of the Iraq Stratigraphic Lexicon

This chapter is concluded with short biographies of the four authors of the *Iraq Lexicon*: H. V. Dunnington, R. Wetzel, D. M. Morton and R. C. van Bellen.

Harold Vincent Dunnington (1919-1981) was posted as Divsional Palaeontologist to Kirkuk in 1946 and stayed there until 1958. During this time he wrote a remarkable paper (1955) on high-resolution biostratigraphy, using abundances and ratios of planktonic foraminifera to determination the progradation of flysch, and the uplift and erosion of Late Cretaceous structures. This paper was some four decades ahead of its time. His understanding of basin evolution and petroleum systems was excellent, culminating in the 1958 paper *"Generation, Migration, Accumulation and Dissipation of Oil in Northern Iraq"*. Dunnington's role in the formalization of Iraqi stratigraphic nomenclature was pivotal, but regrettably his contribution is often overlooked; he wrote over half of the *Iraq Lexicon* (van Bellen *et al.*, 1959). As a mark of the continuing relevance of his work, his 1958 paper was recently republished in *GeoArabia* (vol. **10**, no. 2, 2005) (*the Iraq Lexicon has also been reprinted by GulfPetrolink*). Dunnington rose to the position of Chief Geologist and finally Manager of the Exploration Division of IPC prior to his retirement in 1974. He published papers on subjects as diverse as salt tectonics (1968) and petroleum geology (1967a, 1975). Together with E. N. Tiratsoo, he was founding editor of the *Journal of Petroleum Geology* in 1978.

René Wetzel (1909-1981) was known as a meticulous field geologist (Beydoun, 1982). He was employed by IPC for 19 years starting in 1937. Together with D. M. Morton, Wetzel led arduous geological expeditions in SE and SW Arabia in 1947-50. Later he worked in the Khabour area of Iraqi Kurdistan from 1952 before becoming Chief Geologist of the Compagnie Francaise des Petroles in 1956. Wetzel and Morton's work on the Palaeozoic stratigraphy of Iraqi Kurdistan provided a foundation for more recent studies, including that by Al-Hadidy (2007) in which some of Wetzel's original logs were republished.

Douglas Michael Morton (1924-2003) joined IPC in the 1945 and was initially based in Haifa and worked in Jordan with René Wetzel before undertaking further projects in southern Arabia. He arrived in Iraq in the early 1950s, in time to participate in the studies of the Palaeozoic and older Mesozoic succession in the High Zagros area of Iraqi Kurdistan. His adventures in Kurdistan are recounted in Chapter 11 "Strangers Within the Gates" (pp. 128-132) of the book "In the Heart of the Desert" (Morton, 2006).

Robert Carel van Bellen joined IPC in 1946 and worked on the stratigraphy and biostratigraphy of Oligo-Miocene limestones. His 1956 paper on the Tertiary micropalaeontology of the Kirkuk area shows a level of detail and insight which was largely absent from other publications of the time. van Bellen was a key contributor to the *Iraq Lexicon*, the benchmark 1959 publication with which his name is most frequently linked. As an example of the continuing importance of this publication, both Horbury *et al.* (2003) and Sharland *et al.* (2004) applied van Bellen's biostratigraphic scheme to the Tertiary succession in Iran.

3. TECTONICS AND TECTONIC EVOLUTION

The northern and NE margins of the Arabian Plate are limited by the collisional Taurus-Zagros suture (Fig. 3.1) (Beydoun, 1991). The western plate boundary is marked in the NW by the left-lateral transtensional Dead Sea fault zone, and in the SW by the Red Sea spreading axis. To the south, the Gulf of Aden continues this extensional margin which connects to the Zagros suture via the Owen Fracture Zone, the Makran subduction zone and the Minab fault zone.

The Arabian Plate can be divided into the Arabian Shield and the Arabian Shelf. The **Arabian Shield** (Fig. 3.2) is an area of present-day Precambrian outcrops which was uplifted and exposed for much of Phanerozoic time (Baker and Henson, 1952). The **Arabian Shelf** forms an eastward-deepening Phanerozoic basin which contains up to 14 km of sediment (Powers *et al.*, 1966; Konert *et al.*, 2001) (Fig. 3.2).

The regional geological structure of Iraq in the NE of the Arabian Plate (Figs 3.1, 3.2) is known as a result of surface geological mapping, seismic surveys, exploration drilling and from the interpretation of regional gravity and magnetic data. In Northern Iraq, three major structural zones were defined by early geological mapping: the Nappe, Folded and Unfolded Zones. Hydrocarbon exploration initially targeted prominent surface anticlines in the Folded Zone. Early seismic surveys in SE Iraq imaged subsurface anticlines which had been located by gravity surveys. Later seismic surveys in Central Iraq identified long, narrow horsts and grabens in the subsurface. In the 1970s and early 1980s, major seismic surveys were conducted. These surveys imaged further buried anticlines in SE Iraq, and more complex structures in the centre and NW of the country. At the same time, the Geological Survey of Iraq conducted regional structural studies based on new surface mapping in the Nappe and Folded Zones and the interpretation of potential field data. The results of this work were reported by Buday (1980), Buday and Jassim (1987) and Jassim and Buday (2006a).

The tectonic history of Iraq is discussed on pp. 43-57. This history, and in particular the Precambrian to Early Cambrian period of plate accretion, has influenced stratigraphic and facies changes through time and has controlled the development of unconformities and onlap geometries. Present-day tectonic subdivisions and palaeostructural elements are thus relevant to petroleum geology because they have affected source, reservoir and seal distribution as well as structural style and trap development.

Knowledge of the deep structure of Iraq is based mainly on gravity-magnetic data, as first interpreted by Tikrity and Al-Ani (1972). The only recently published regional seismic line available is a SW-NE oriented profile through Baghdad and the Sirwan area of SE Iraqi Kurdistan which was presented by Mohammed (2006) (Fig. 3.3). This profile shows faults bounding the Ma'ania Depression, the Abu Jir Fault Zone, and the trend of the *East Baghdad* field.

There are very few published regional cross-sections through Iraq. A series of cross-sections drawn to the top of the Precambrian basement have been prepared for this book and are presented at the end of the chapter (pp. 58-64).

Precambrian Basement

Jassim (2006b) reviewed the formation of the Arabian Plate by terrane accretion in Precambrian time, and extrapolated the known Precambrian terranes of the Arabian Shield into Iraq using magnetic and gravity data. Basement terranes interpreted by Jassim (2006b) are shown in Fig. 3.4 and are discussed briefly below and on pp. 65-66.

The **Afif Terrane** in westernmost Iraq has a north-south trending structural grain. It is bounded to the west by the Nabitah suture zone (Jassim, 2006b). In central Iraq, the approximately north-south trending **Ar Rayn Terrane** forms the basement of the Salman Zone (Jassim 2006b). This was formerly referred to as the Salman-Sharaf Zone

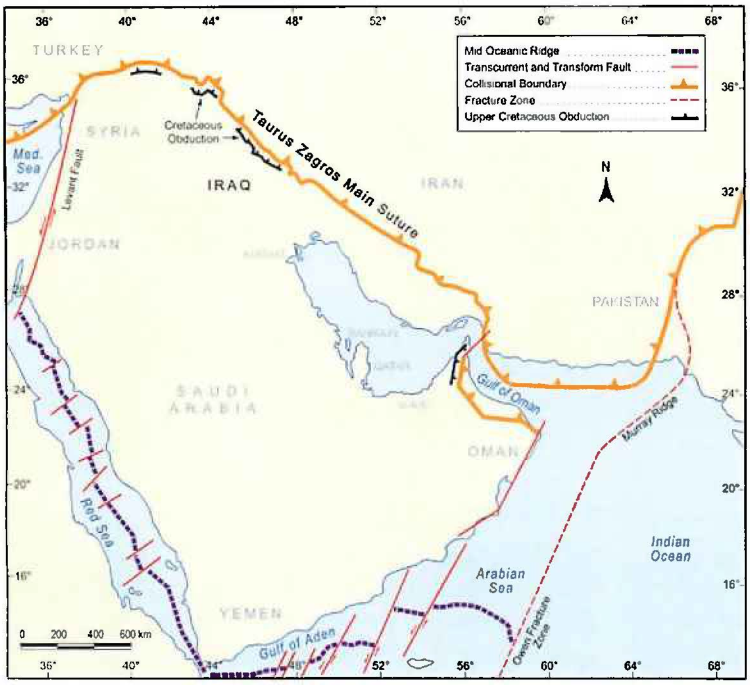


Fig. 3.1. Boundaries of the Arabian Plate (after Jassim and Goff, 2006b). The Red Sea and Gulf of Aden margins are currently extensional; the western (Levant) margin is the site of left-lateral transpression/ transtension; while the northern and NE margins are compressional.

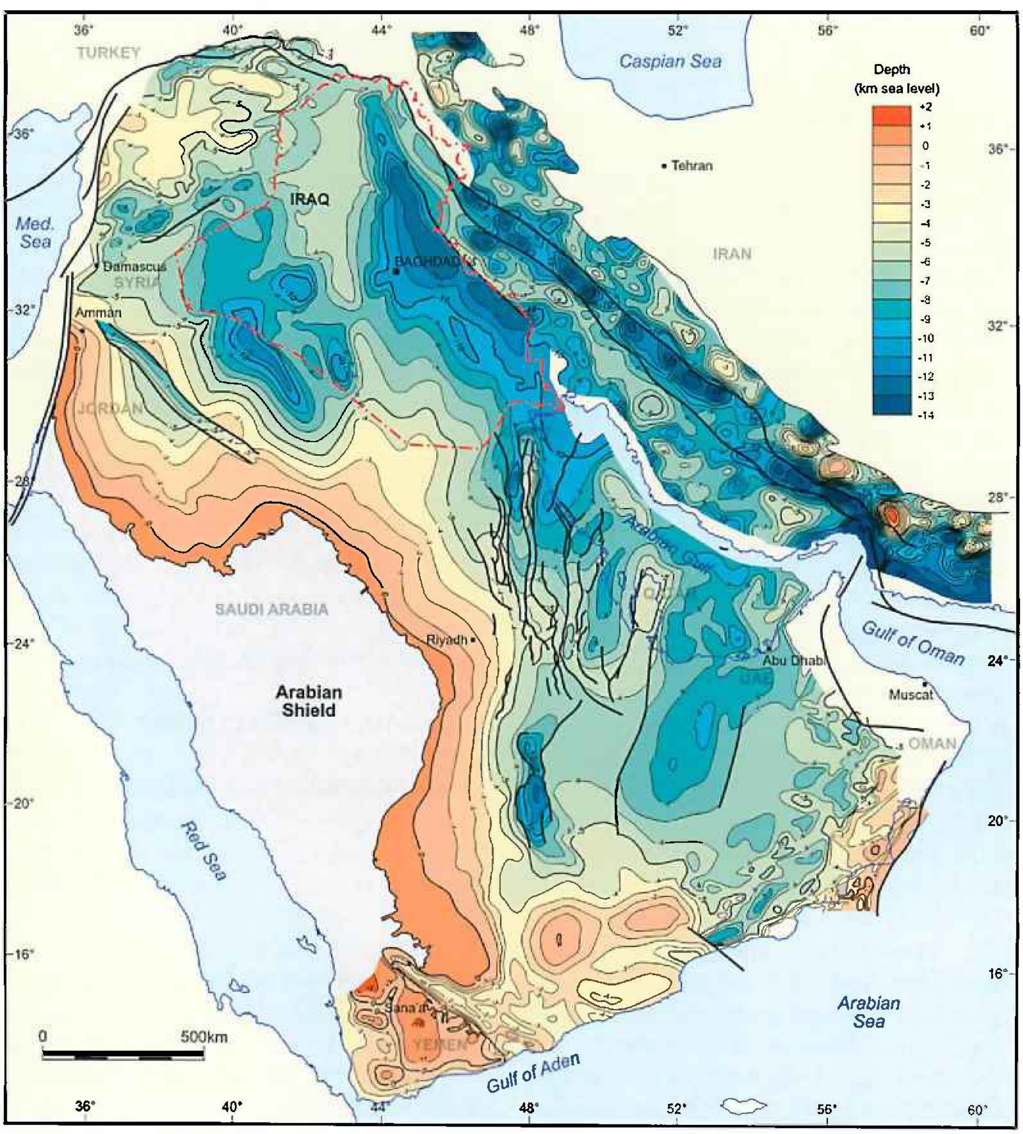
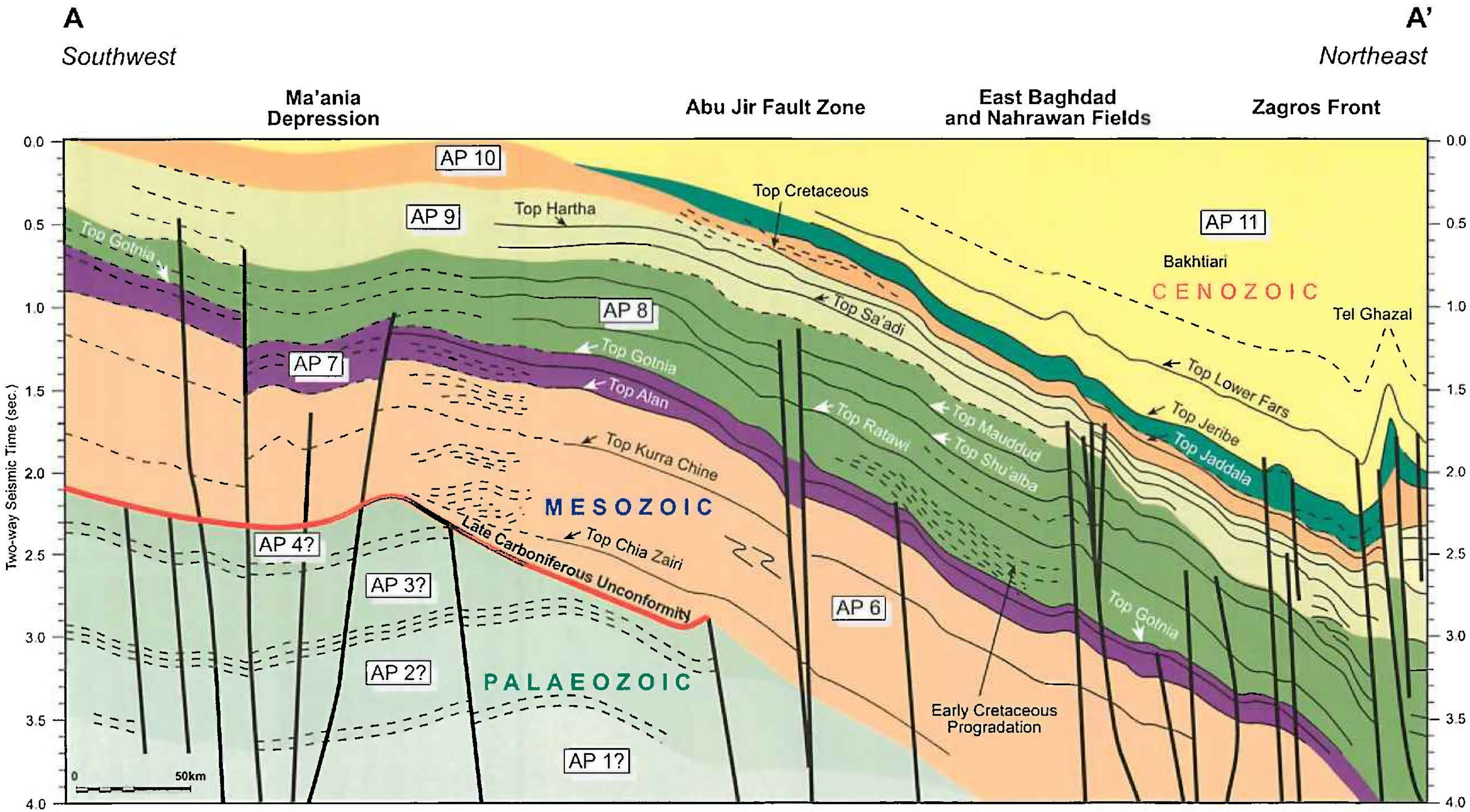


Fig. 3.2. Depth to basement of the Arabian Plate. Modified after Konert *et al.* (2001) and Jassim and Buday (2006a).



AP 1 = Infracambrian - Early Cambrian
AP 2 = Mid Cambrian - Ordovician
AP 3 = Silurian - Mid Devonian
AP 4 = Late Devonian - Early Carboniferous
AP 5 = Late Carboniferous - Mid Permian (absent)
AP 6 = Mid Permian - Early Jurassic
AP 7 = Mid - Late Jurassic
AP 8 = Early Cretaceous
AP 9 = Late Cretaceous
AP 10 = Paleogene
AP 11 = Neogene

Fig. 3.3. Interpretation of the regional-scale seismic profile published by Mohammed (2006). The stratigraphy is coloured to follow the tectonic megasequences defined by Sharland *et al.*, 2001. The major unconformity separating Megasequences AP4 and AP6 is the Late Carboniferous (formerly "Hercynian") unconformity. Profile location is marked on Fig. 3.7. Note that the structure at Palaeozoic level in the western part of the profile is very poorly constrained from the seismic data. The change in fault throws with depth cannot be resolved. Approximate vertical exaggeration: x 30.

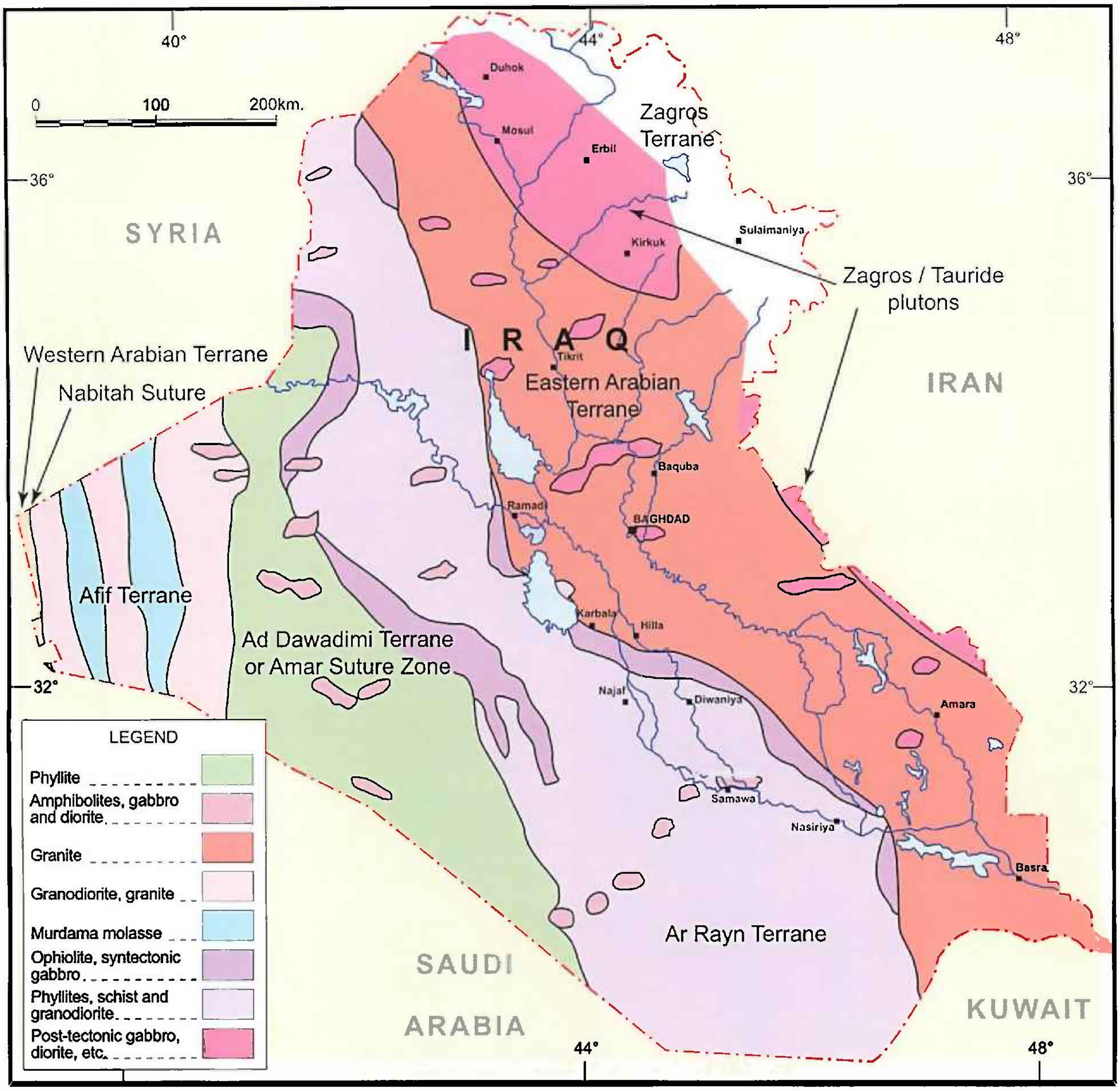


Fig. 3.4. Precambrian terranes in Iraq. See brief descriptions below and on pp. 65-66. (After Jassim, 2006b).

or the Salman-Sharaf-Sinjar Divide (Buday and Jassim, 1987). It is the northern extension of the Summan Platform of Saudi Arabia (Al-Husseini, 2000). The eastern boundary of the Ar Rayn Terrane changes strike from north-south to NW-SE in central South Iraq (Fig. 3.4). SW-NE oriented structures are also prominent. An example is the Al Batin Fault (Al-Husseini, 2000), a SW-NE trending lineament between Iraq and Kuwait.

The Ar Rayn Terrane is separated from the **Ad Dawadimi Terrane** to the west by ophiolites of the Amar Suture Zone of Stoeser and Camp (1985). To the east, it is separated from the Eastern Arabian Terrane by another suture zone containing ophiolites which may represent the northern extension of the Summan Suture of Saudi Arabia. The **Eastern Arabian Terrane** forms the basement beneath the Mesopotamian Basin. To the NE lies the **Zagros Terrane**.

The Infracambrian Amar Orogeny formed gneiss domes and major north-south to NNW-SSE trending anticlines referred to as Rayn Anticlines (Al-Husseini, 2000). The majority of the "giant" oilfields in Arabia *(Ghawar, Burgan, North Dome)* are situated above Rayn Anticlines in the East Arabian Terrane which were periodically re-activated in the Phanerozoic, producing both structural and stratigraphic traps and influencing facies patterns.

Basement Depth

Precambrian basement has been penetrated in the Burgan High in SE Kuwait (Strohmenger *et al.*, 2003) in three deep wells at depths of about 5245, 5365 and 6750 m (Strohmenger *et al.*, 2003) (cross-section 11, page 63).

Al-Saigh *et al.* (1993) identified a deep seismic reflector (interpreted as top- Basement) at a depth

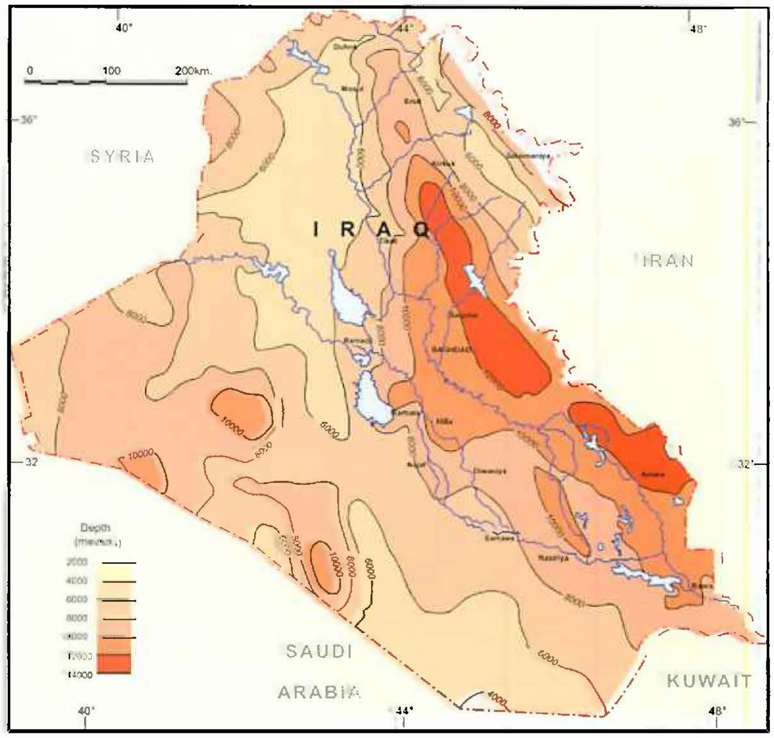


Fig. 3.5. Depth to basement map of Iraq compiled from gravity data. Simplified from Jassim and Buday, 2006a.

of 6 – 13 km along a geotransect from Baghdad to Dohuk near the Turkish border which was prepared as an Iraqi contribution to the Global Geoscience Transects (GGT) project (cross-section 10). In the Akkas area of western Iraq, Al-Hadidy (2007) interpreted top-basement to be at about 6.5 km subsea (cross-section 12).

Brew *et al.* (1997) modelled the depth to basement along a 300 km long north-south trending seismic refraction profile in NE Syria which starts in the south about 10 km from the Iraq border (cross-section 14). The profile crosses the Euphrates Graben and Abd El Aziz Uplift. Brew *et al. (ibid.)* estimated the top of the basement to lie at a depth of 8.5–9 km beneath the Euphrates Graben, at a minimum depth of 8–8.5 km to the south of the graben, and at 5.5–6.5 km to the north of the graben. A minimum depth to basement of 5.5 km was estimated beneath the Abd El Aziz Uplift.

Brew *et al.* (1997) also modelled the crustal structure along a NE–SW trending gravity profile in NE Syria, extending from the Iraq border at about lat. 33.5°N, long. 39° E to the Iraq border at about 35.4°N, 41.3°E. The approximate (maximum) depth to basement ranges from 10 km in the south to 6.5 km in the north beneath a large Bouguer anomaly. A separate smaller anomaly (which extends eastward into Iraq) was modelled using a steeply dipping, high density mafic igneous body in the crust (? ophiolitic suture zone) without invoking a shallower depth to basement.

Jassim and Buday (2006a) modelled the depth to basement beneath Iraq by iteration of gravity interpretation and estimates of megasequence thicknesses. The resultant map shows a large, shallow central basement high in which the top of the basement is modelled to lie at a depth of 5 to 6 km (Fig. 3.5). This high extends from Dohuk and Mosul in the north through Central Iraq to the border with Saudi Arabia in the south.

The SW-NE regional seismic profile in Fig. 3.3 crosses this gravity high in southern Iraq. The seismic data is of poor quality below the Permian Chia Zairi Formation. However a TWT thickness of at least 700 msec of Lower Palaeozoic rocks is tentatively interpreted beneath the gravity high, corresponding to a thickness of at least 1700 – 1900 m of preserved section. Estimated depth to basement was interpreted to be at about 6.5 km beneath the high from gravity and magnetic data. The depth to basement map of Jassim and Buday (2006a) gave a value of about 5 km at the same location, where the base of the Upper Palaeozoic is at about 4500 m depth. This implies a preserved thickness of Lower Palaeozoic section of < 500 m. This gravity high may be caused partly by the presence of rock bodies of unusually high density in the crust, and the depth to basement may thus locally be significantly deeper than modelled by Jassim and Buday (2006a). The thickness of Lower Palaeozoic stratigraphy preserved here may thus (at least locally) be greater than that predicted by Jassim and Buday (2006a). High resolution seismic and well data is required to resolve the thickness of the Lower Palaeozoic in this area.

Thickness of the Continental Crust

The thickness of the continental crust (depth to the Moho) in Iraq has been estimated from gravity data to be 32 – 38 km (Alsinawi and Al-Bana, 1992; Jassim and Buday, 2006a), SW of the Zagros thrust belt in NE Iraq. Al-Saigh *et al.* (1993) calculated

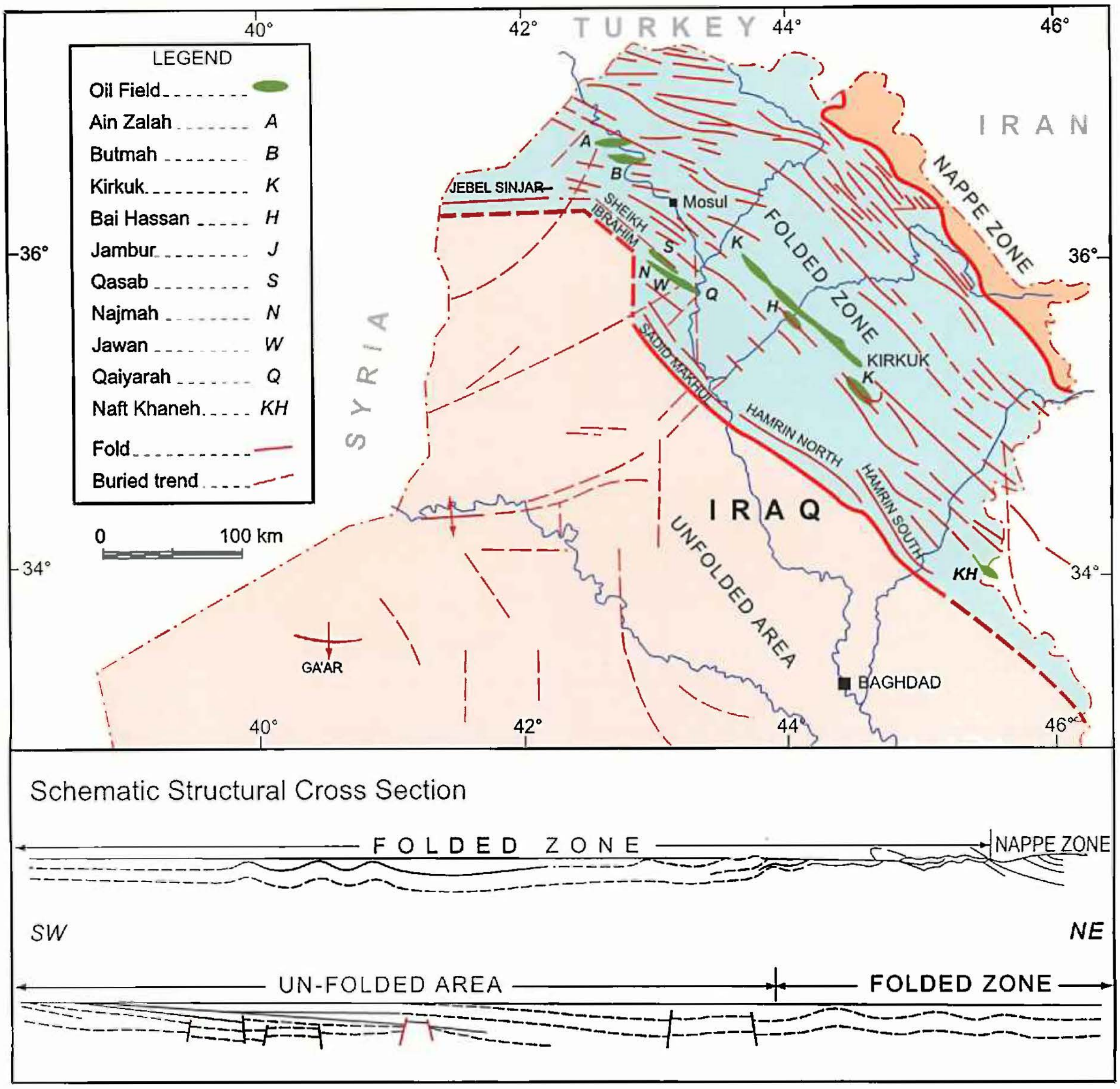


Fig. 3.6. Map of northern Iraq where Nappe, Folded and Unfolded Zones are recognised. The southern margin of the Folded Zone is marked by a series of folds including the Sinjar, Sheikh Ibrahim, Makhul and Hamrin anticlines. After Dunnington (1958).

the depth to the Moho to be 35.5 km along the Baghdad-Dohuk crustal transect beneath Central Iraq and 30.5 km near the Turkish border. These depths were derived from gravity modelling integrated with deep seismic reflection data. Alsinawi (2006) calculated the Moho to be at about 37 km depth in the Jezira area along the same transect. Al-Heety (2002) calculated a depth of 36.5 km between Baghdad and Rutbah from analysis of earthquake P-wave data. Alsinawi (2006) also analysed earthquake data recorded by the Iraq Sesismological Network at receiving stations at Mosul, Rutbah, Baghdad and Sulaimaniya. Moho depths at these locations were calculated to be 31-34, 33-35, 38 and 41-43 km, respectively.

Apart from the Zagros Thrust Belt, where the continental crust was tectonically thickened in the late Miocene, the depth to the Moho thus ranges from 31 to 38 km.

Tectono-physiographic subdivisions of Iraq

The Arabian Shelf in northern Iraq can be divided into an unfolded area or **Stable Shelf** and a folded zone or **Unstable Shelf** (Henson, 1951; Dunnington, 1958; Buday, 1980; Buday and Jassim, 1987; and Jassim and Buday, 2006b, c) (Fig. 3.6).

IPC (1956) divided Iraq into four units based on topography: (i) a strongly folded mountain belt in the east (the Zagros Mountains), which passes westwards into (ii) a foothill region containing discrete folds (which form anticlinal traps for oil- and gasfields in North Iraq). This is bounded to the west by (iii) a region of plains broken by long, linear folds separated by wide and apparently flat-bottomed synclines. (iv) In SE Iraq is flat country with buried anticlines which provide structural traps for oilfields in the Basra area.

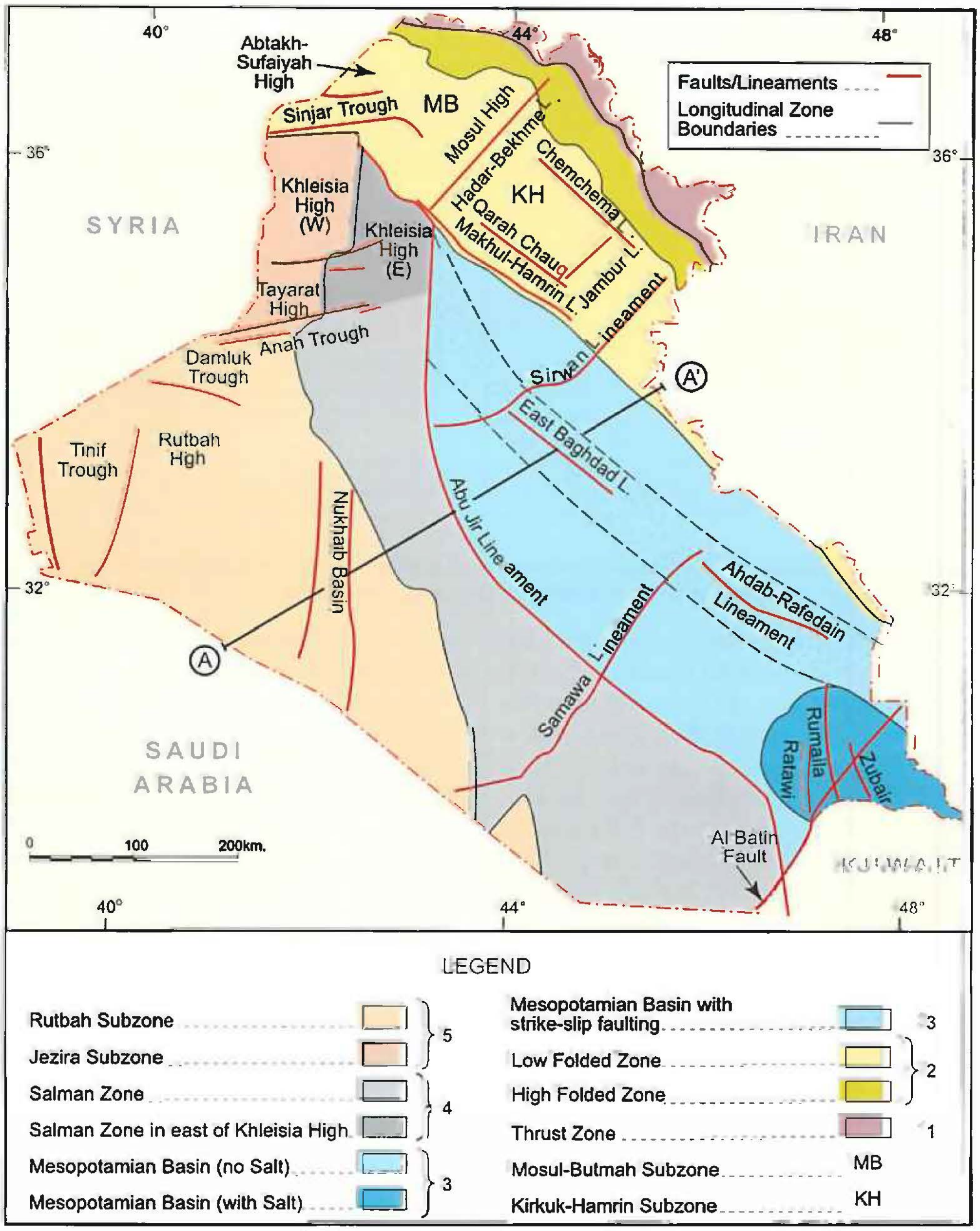


Fig. 3.7. Structural elements of Iraq. Compiled after various sources and original interpretation by the authors. MB: Mosul-Butmah subzone; KH: Kirkuk-Hamrin subzone. Profile A-A' marks the line of section in Fig. 3.3. Numbers 1-5 in the legend refer to tectono-physiographic subdivisions discussed in the text.

Buday and Jassim (1987) and Jassim and Buday (2006b,c) expanded the IPC scheme. They recognised five tectono-physiographic zones: three in the Unstable Shelf, and two in the Stable Shelf (Fig. 3.7). The zones are characterised by varying degrees of Neogene structural deformation, often with present-day topographic expression, and are generally bounded by major faults which represent deep-seated structural elements. These zones are from NE to SW (Fig. 3.7):

1. The **Thrust Zone**, forming a narrow belt along the northern and NE borders of Iraq with Turkey and Iran, respectively;

2. The **Folded Zone**, comprising mountainous areas in the north and NE of Iraq;

3. The **Mesopotamian Basin**, consistng of the flat, broad plains of the Tigris and Euphrates Rivers;

4. The **Salman Zone**, a palaeohigh with shallow basement in the east of the Stable Shelf;

5. The **Rutbah-Jezira Zone**, a Palaeozoic Basin in western Iraq.

The zones are discussed briefly below in turn.

1. The Thrust Zone

The Thrust Zone contains exposed metamorphic and igneous rocks including ophiolites and highly folded and faulted Palaeozoic and Lower Mesozoic sedimentary rocks. From SW to NE, External, Central and Internal Sub-Zones are recognized, each of which may be further subdivided (Mitchell,

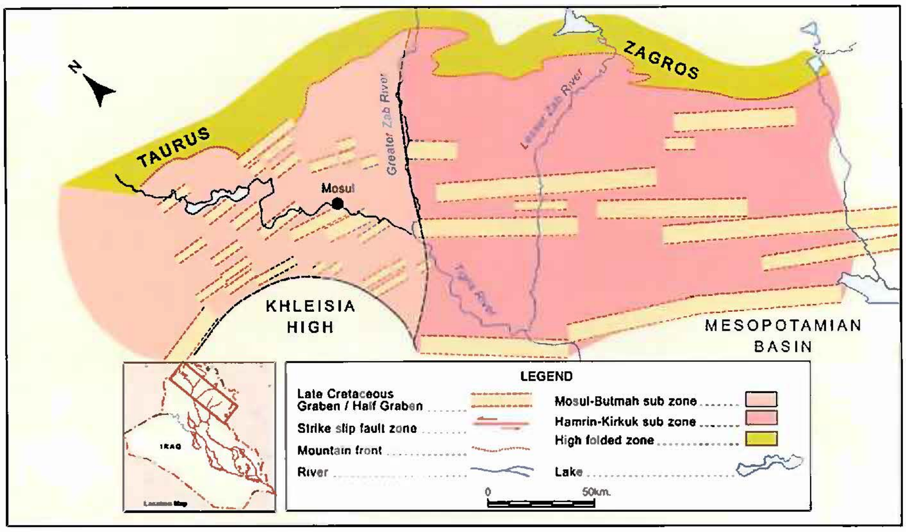


Fig. 3.8. Suggested positions of Mesozoic grabens and half-grabens in northern Iraq. These structures are located schematically. Modified after Ameen (1992).

1960a,b). The External Sub-Zone represents a Late Cretaceous – Tertiary foreland trough in the NE and a thrust-dominated unit in the north, near the Turkish border. The Central Sub-Zone has a radiolarian-volcanogenic basinal succession of Late Cretaceous – Paleogene age (Jassim and Buday, 2006c). The Internal Sub-Zone in the NE includes both metamorphic and volcaniclastic sequences (Jassim *et al.*, 2006b). Thrusting is thick-skinned.

2. The Folded Zone

The Folded Zone is typically 200 km wide. It has been divided (Fig. 3.7) into the **High Folded Zone** with outcropping Mesozoic rocks; and the **Low Folded / Foothill Zone** in which mainly Cenozoic rocks are exposed. Shortening varies from 10-33% in the High Folded Zone to 3-17% in the Low Folded Zone (Ameen, 1991a,b, 1992). Vertical structural closures often exceed 500 m.

The **High Folded Zone** (Fig. 3.7) is an arcuate belt 25-50 km wide containing imbricates and faulted folds (Ameen, 1991a,b, 1992). These folds are deeply eroded, often down to Jurassic or older levels (Jassim *et al.*, 1986; Jassim and Buday, 2006c). Long, asymmetric tight anticlines, probably controlled by thrust faults, are separated by narrow synclines (Ameen, 1991a,b, 1992). Folds verge to the SW or south and may be connected at depth to the tiplines of thrusts. The High Folded Zone was formed by Zagros deformation during the late Cenozoic. Prior to that, it formed a marginal molasse basin in the Paleogene and a flysch trough during the Late Cretaceous.

The boundary between the Low and High Folded Zones (Plate 3.4, page 31) is sharp and is probably controlled by a basement lineament, reactivated as a major thrust in the Late Miocene.

The **Low Folded Zone** contains outcropping Neogene sedimentary rocks; the cores of anticlines may expose Eocene limestones or Upper Cretaceous sedimentary rocks (Jassim *et al.*, 1986; Jassim and Buday, 2006c). The Low Folded Zone comprises the Kirkuk-Hamrin and Mosul-Butmah subzones, separated by the SW-NE Hadar-Bekhme lineament (Fig. 3.7) coinciding approximately with the course of the Greater Zab River (Fig. 3.8). The Kirkuk-Hamrin subzone is further divided into Hamrin-Makhul and Kirkuk-Chemchemal zones (Buday and Jassim, 1987).

The **Mosul-Butmah subzone**, to the NW of the Greater Zab River (Fig. 3.8), contains short, oval or dome-shaped anticlines, often arranged *en échelon* (Ameen, 1992). Examples include the Sasan and Gusair anticlines which are shown in Plate 3.2. Henson (1951) noted that folds in this subzone are often associated with gravity anomalies, and that *"many, if not all, of the prominent anticlines in Syria and Western Iraq are fault-bounded beneath later cover"*. These surface anticlines may thus be underlain by complex palaeostructures (the "Block Tectonics" of Henson, 1951), which control changes of facies belt orientations in the subsurface (Dunnington, 1958; Sayyab and Valek, 1968; Ameen, 1992). Bounding faults may control the orientations of the folds. Fold terminations may be controlled by basement lineaments or lateral ramps (Ameen, 1992).

The **Kirkuk-Hamrin subzone** to the SE of the Greater Zab River contains long, unbroken anticlines (Ameen, 1992) (Fig. 3.8; Plates 3.1, 3.6 and 3.7). The *Kirkuk* anticline for example (K: Fig. 3.6) contains three separate culminations or domes (Fig. 3.9a). Structures are open and simple with few thrusts (Ameen, 1992). Folds generally flatten towards the Mesopotamian Basin where relatively narrow anticlines are separated by wide synclines.

Recent studies based on regional seismic data suggest that the Hamrin and Kirkuk structures (Fig. 3.6) are inversion "pop-ups" on opposite sides

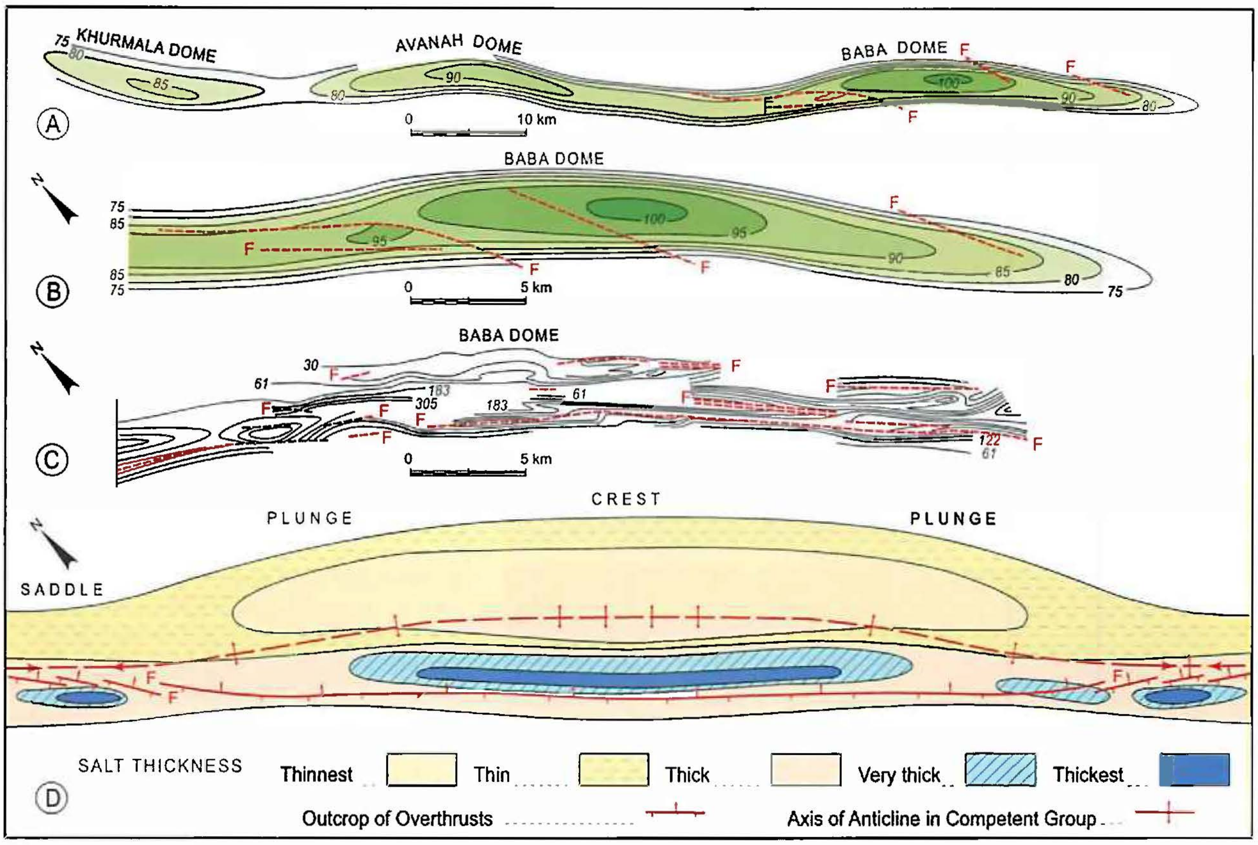


Fig. 3.9. Folding and thrusting within the Lower Fars Formation on the *Kirkuk* structure and final position of thickest salt. After Dunnington (1968).
(a) Structure contours (hundreds of feet) on top of basal Fars conglomerate in the Kirkuk anticline. Note: structural datum used by Dunnington was at an unspecified depth below sea level.
(b) Detail of (a) for the Baba Dome.
(c) Isopach map of middle Miocene salt for the Baba Dome (in metres).
(d) Generalised isopach map of middle Miocene salt for the Baba Dome showing the relationship of present-day salt thickness to the underlying anticlinal axis and the outcrops of overthrusts. The Competent Group is the undeformed unit at the base of the Lower Fars Formation (see Fig. 8.29).

of a single Late Cretaceous basin (N. Kent, *pers. comm.* to A.H., 2008).

Outlying anticlines

Large-scale, tightly-folded asymmetric anticlines occur along the SW margin of the Folded Zone (Plate 3.5) and include Jebel Sinjar (Henson, 1951) (cross-section 15) and Jebel Hamrin to the SE (Fig. 3.6). They formed by inversion of Late Cretaceous half-grabens. The folds in the NW developed around the flanks of a "buttress" marking the northern limit of the Unfolded Area or Stable Shelf which is known as the Khleisia High (Fig. 3.10) (Hart and Hay, 1974; Lovelock, 1984; Ameen, 1992). Reactivated graben-bounding faults may show reverse offset at shallow levels but preserve an extensional geometry at depth (e.g. Hart and Hay, 1974). An analogous structure with a similar geometry at Jebel Abd El Aziz in Syria (Figs 3.11, 3.12) has been interpreted as an inverted graben (Kent and Hickman, 1997). An extensive Late Cretaceous graben system developed in eastern Syria (Fig. 3.13; cross-section 13). Seismic data (Caron *et al.*, 2000) indicate that the Euphrates Graben comprises a series of narrow, complexly faulted half grabens, tilted faulted blocks and horsts, which provide an analogue for the original synrift geometry of the Sinjar Trough. The Euphrates Graben has suffered only slight inversion.

The Euphrates Graben has a length and width of 160 and 90 km respectively, an estimated 6 km of extension, and a β factor of only 1.06 (Litak *et al.*, 1998). This is significantly lower than β factors in other continental rifts such as the Rhine graben ($\beta = 1.1$ to 1.3), the North Sea ($\beta = 1.55$ to 1.9), and the Gulf of Suez (β = 1.1 to 1.9). Major listric bounding faults are absent and many high-angle planar normal faults occur over a wide zone (Caron *et al.*, 2000).

Levels of detachment

The large-scale Zagros anticlines in Iraq probably formed by a combination of thick-skinned deformation involving the basement, and thin-skinned deformation above a basal detachment near the base of the Lower Palaeozoic (McQuarrie, 2004) (cross-sections 5-8, pp. 60-61). In the present-day Folded Zone, it is likely that many pre-existing

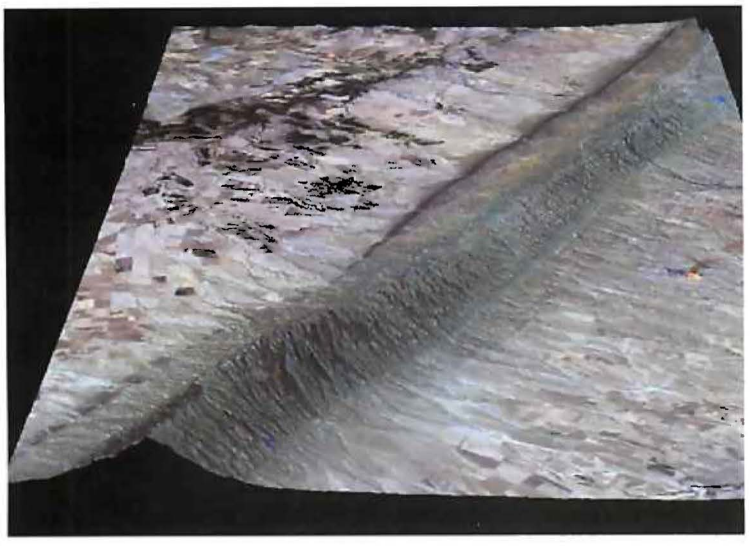
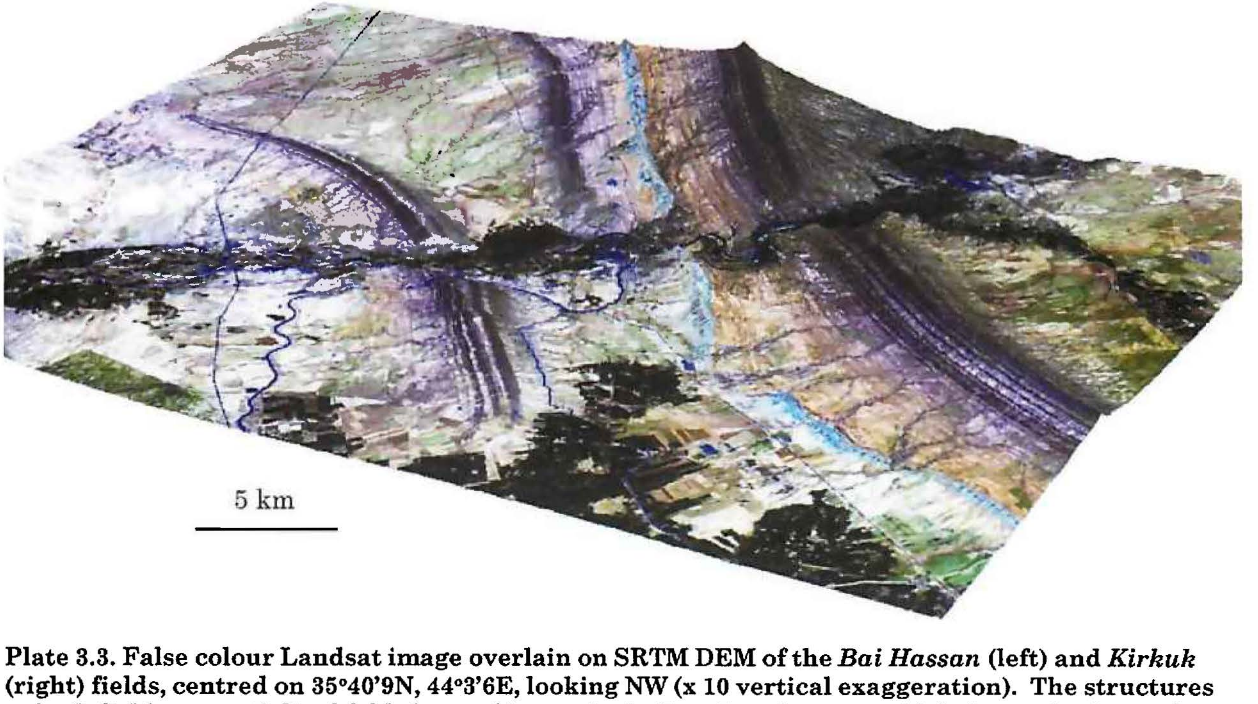


Plate 3.1. False colour Landsat image overlain on SRTM DEM of the fault-related Hamrin anticline, centred on 34°56'47N, 43°54'36E, looking east. This anticline is part of a long, high aspect ratio system of folds. Its geometry suggests that it is a forced fold above the suspected Zagros Foredeep Fault zone, which is thought to have been reactivated in the Pliocene to Recent. Image courtesy of G. Banks (*Fugro Robertson*).

5 km

Plate 3.2. False colour Landsat image overlain on SRTM DEM of the Sasan (left) and Gusair (right) anticlines, centred on 36°32'6N, 42°21'57E, looking NE (x 10 vertical exaggeration). These are short, low aspect ratio buckle folds, part of an *en échelon* system which may be controlled by the underlying Sinjar Herki fault zone. Image courtesy of G. Banks (*Fugro Robertson*).

5 km



5 km

Plate 3.3. False colour Landsat image overlain on SRTM DEM of the *Bai Hassan* (left) and *Kirkuk* (right) fields, centred on 35°40'9N, 44°3'6E, looking NW (x 10 vertical exaggeration). The structures at both fields are anticlinal folds located beneath shallow detachments which decouple the surface structure from the underlying reservoir. Image courtesy of G. Banks (*Fugro Robertson*).

Plate 3.4. Frontal folds (limited by faults) bounding the High Folded Zone which marks the SW limit of the Zagros Mountains. In the foreground is the relatively flat Low Folded Zone. To the NE is the Zagros Suture Zone. Landsat image, courtesy of M. Insley.

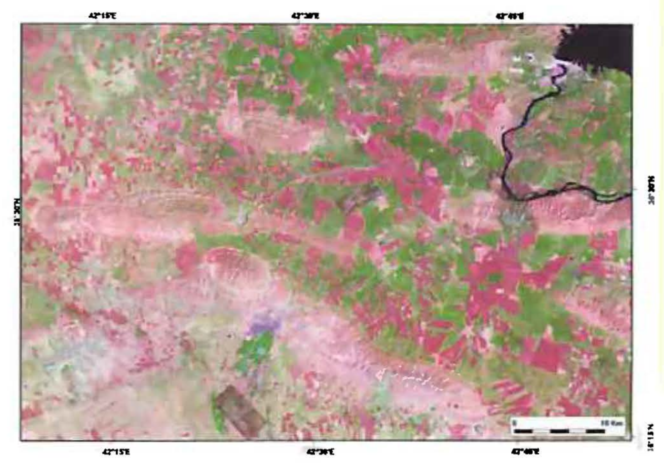


Plate 3.5. Anticlines around the NE margin of the Khleisia High (Mosul-Butmah subzone), formed by inversion of half graben. Note that the anticlines appear to wrap around the high to the SW. Landsat image, courtesy of M. Insley.

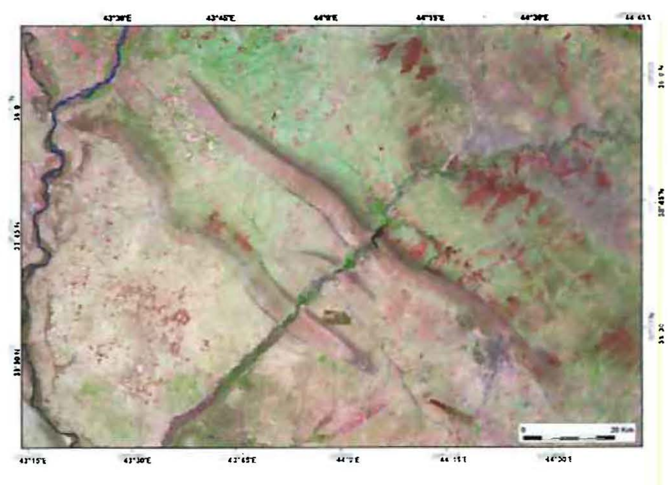


Plate 3.6. Elongate anticlines at Kirkuk (to the NE) and Qarah Chauq Dagh (SW) in the Kirkuk-Hamrin subzone, separated by wide synclines. Landsat image, courtesy of M. Insley.

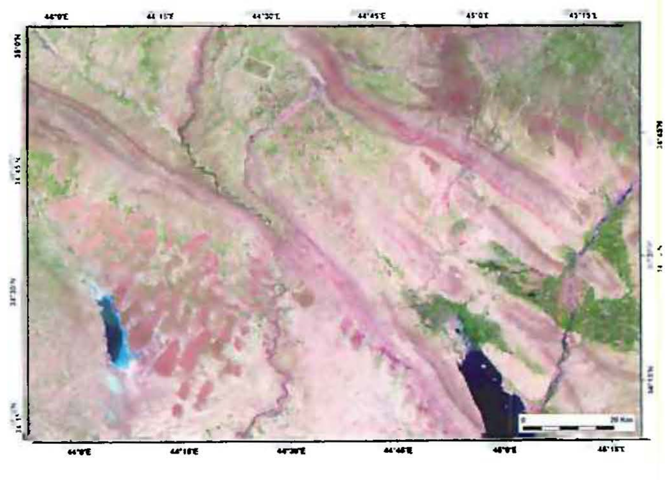


Plate 3.7. NW-SE trending Hamrin and Injana anticlines (crossing the centre of the image) mark the boundary between Mesopotamian zone and the Low Folded Zone of Jassim and Buday (2006b,c). Landsat image, courtesy of M. Insley.

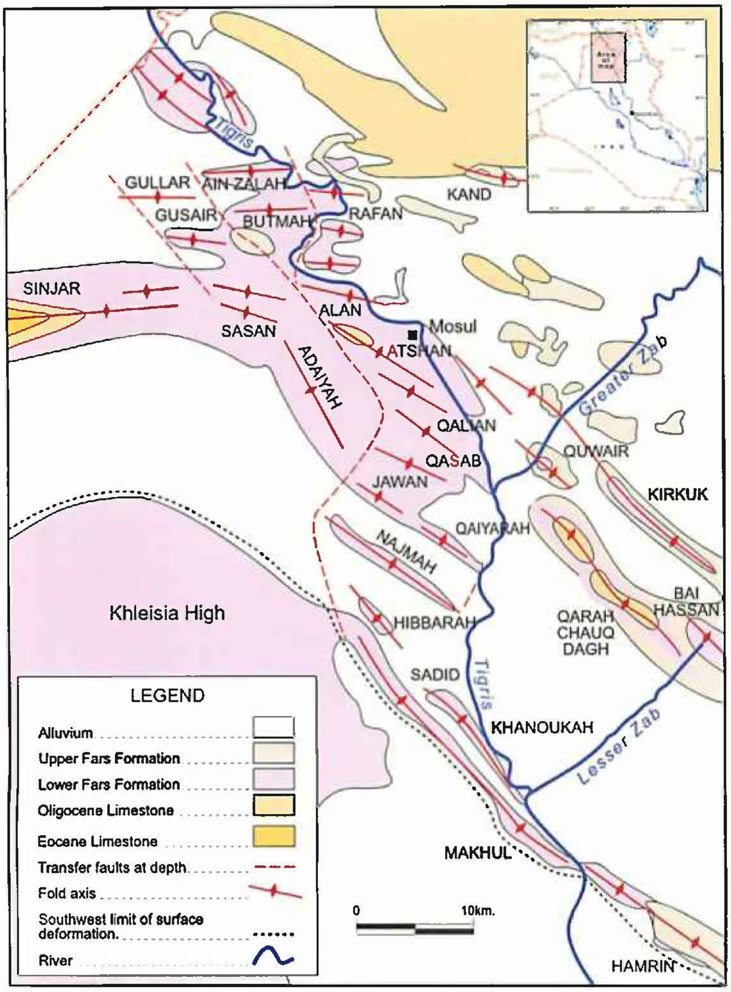


Fig. 3.10. Map of NW Iraq showing the location of the "outlying" anticlinal folds (inverted graben) around the margins of the Khleisia High at the northern limit of the Stable Shelf. (After IPC, 1956).

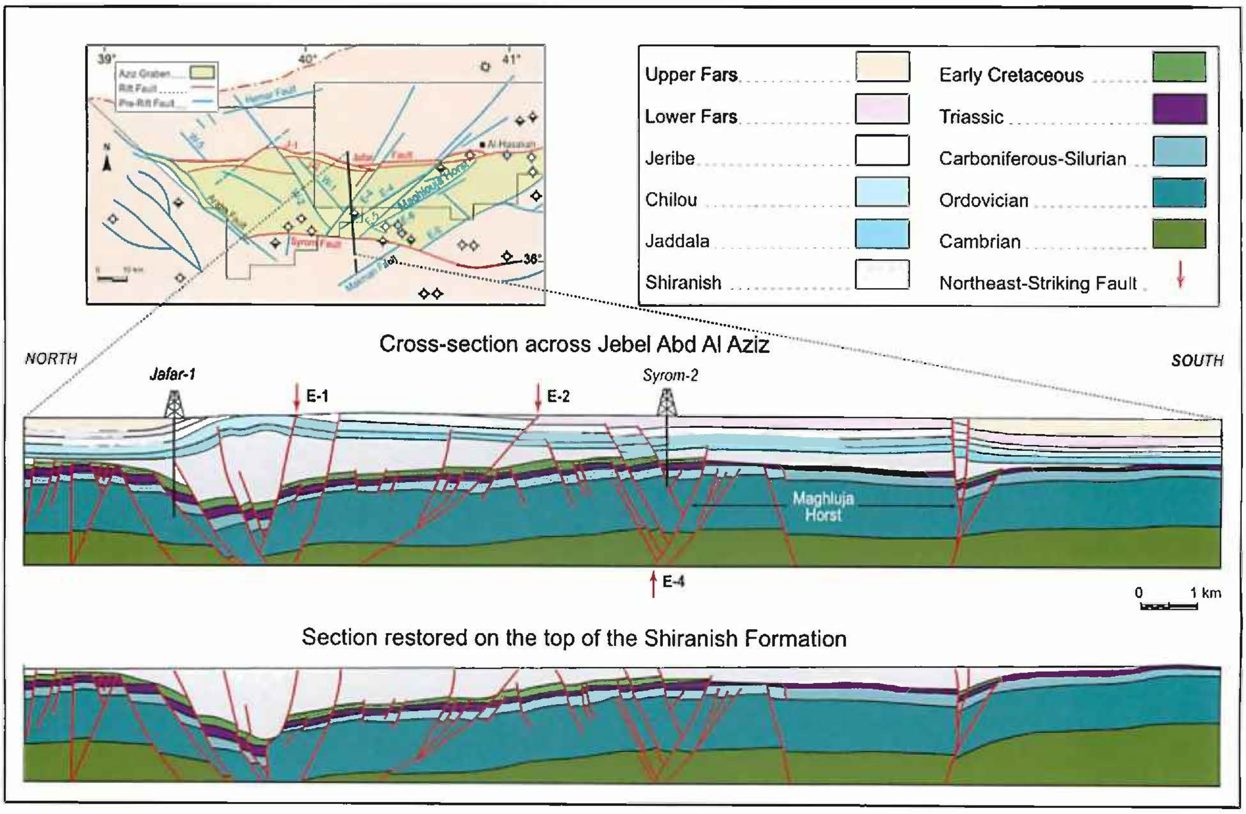


Fig. 3.11. Structural cross-section across Jebel Abd El Aziz, an inverted half-graben in NE Syria (location in Fig. 3.12). After Kent and Hickman, 1997. Analogous inverted structures may be present in NW Iraq.

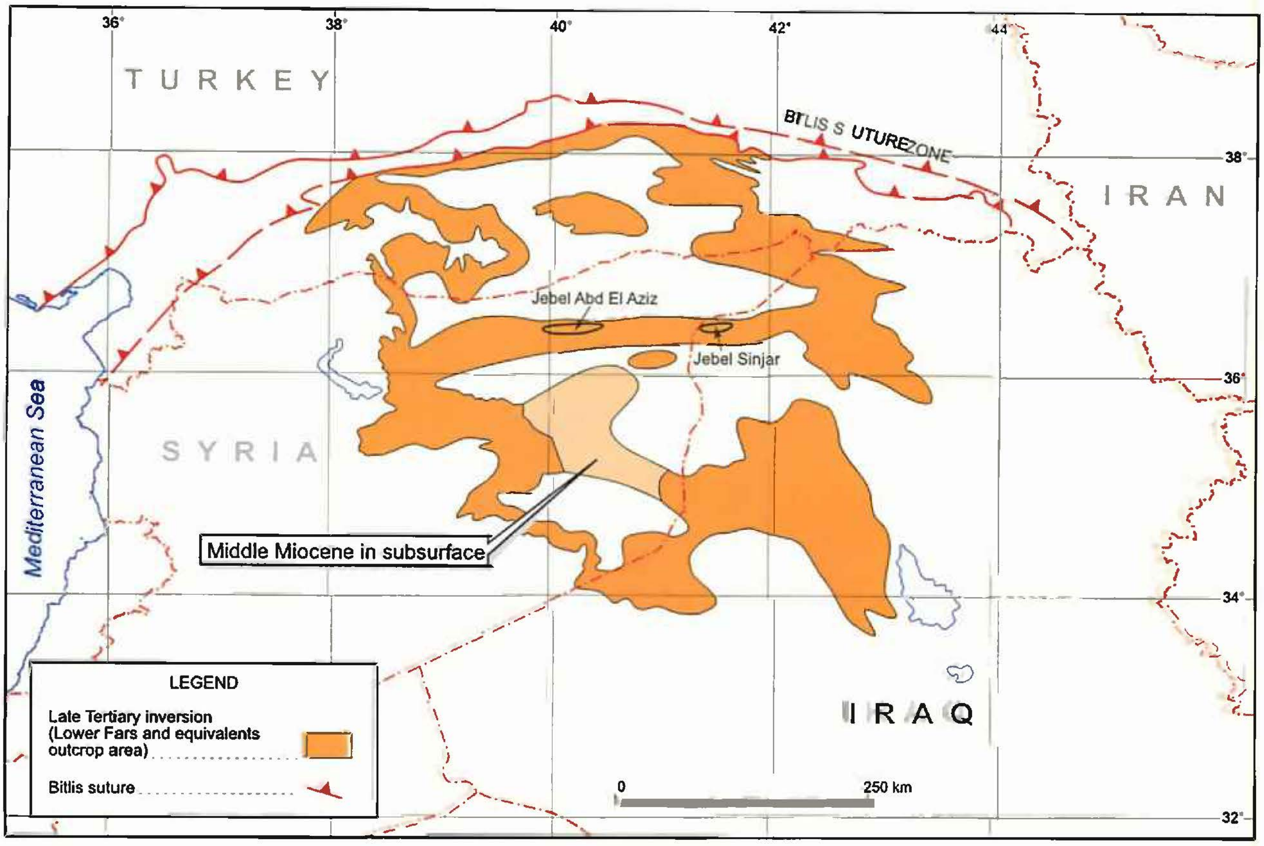


Fig. 3.12. Map of Syria, SE Turkey and NW Iraq showing areas where the Middle Miocene Fars Formation outcrops due to Late Tertiary inversion associated with regional compression. Interpreted inversion structures include Jebel Abd El Aziz in Syria and Jebel Sinjar in Iraq. After Kent and Hickman (1997).

extensional or strike-slip faults affecting the basement (which were active in Late Cretaceous time) were reactivated by compression in the late Miocene – Pliocene. There is evidence from some Late Tertiary anticlines (from well and seismic data) of thickness changes in the Upper Cretaceous section indicating an earlier phase of extensional or strike-slip faulting. Important facies changes in Mesozoic and Paleogene sediments are associated with several anticlinal structures (e.g. *Kirkuk*). It is thus plausible that many major anticlines in NE Iraq have a basement control.

An important detachment level is provided by halite layers in the mid-Miocene Lower Fars Formation (cross-section 9). Other possible detachment layers occur in the underlying stratigraphy, particularly in the thick mudstones of Ordovician and Silurian ages. These mudstones are probably strongly overpressured where they have been deeply buried below the Neogene foreland basin sediments. It is likely that both reactivation of basement faults and creation of new faults in the Phanerozoic cover influenced the structural growth of Late Tertiary anticlines in Iraq.

At a regional scale, the NW Lurestan area of the Iranian Zagros is topographically higher and more deformed than adjacent Iraqi territory. This area contains a much thinner Neogene section compared to the Kirkuk and Dezful Embayments (Fig. 3.14). There may be an underlying basement control on the morphology of the Folded Zone in this area.

Deep detachment of thrusts on Infracambrian Hormuz Salt in the Iranian Zagros is well documented (Harrison, 1930; King, 1937; Stöcklin, 1968, 1972; Kent, 1970). However there is no evidence for the presence of Hormuz Salt beneath the Iraqi Zagros. Higher-level detachments may occur within Lower Palaeozoic shales, as suggested by the deformation style in the Ordovician section in SE Turkey.

Detachments also occur within Triassic and Jurassic evaporites, as indicated by the intense deformation in these rocks observed in well *Makhul-2* at the southern boundary of the Folded Zone (Dunnington *et al.*, 1959). Triassic evaporites may form the main *décollement* in the Palmyra area (Searle, 1994).

Small-scale structures

Thin-skinned thrust and flow structures in the Folded Zone occur within the Miocene Lower Fars Formation, which is composed of marls, anhydrites and intervals of halite (Baker, 1938; Dunnington, 1968; Al-Fadhili *et al.*, 1979). The NE limbs of anticlines may be thrust over the SW limbs, with a detachment at the base of the Lower Fars evaporites (Dunnington, 1968) (Fig. 3.15; cross-

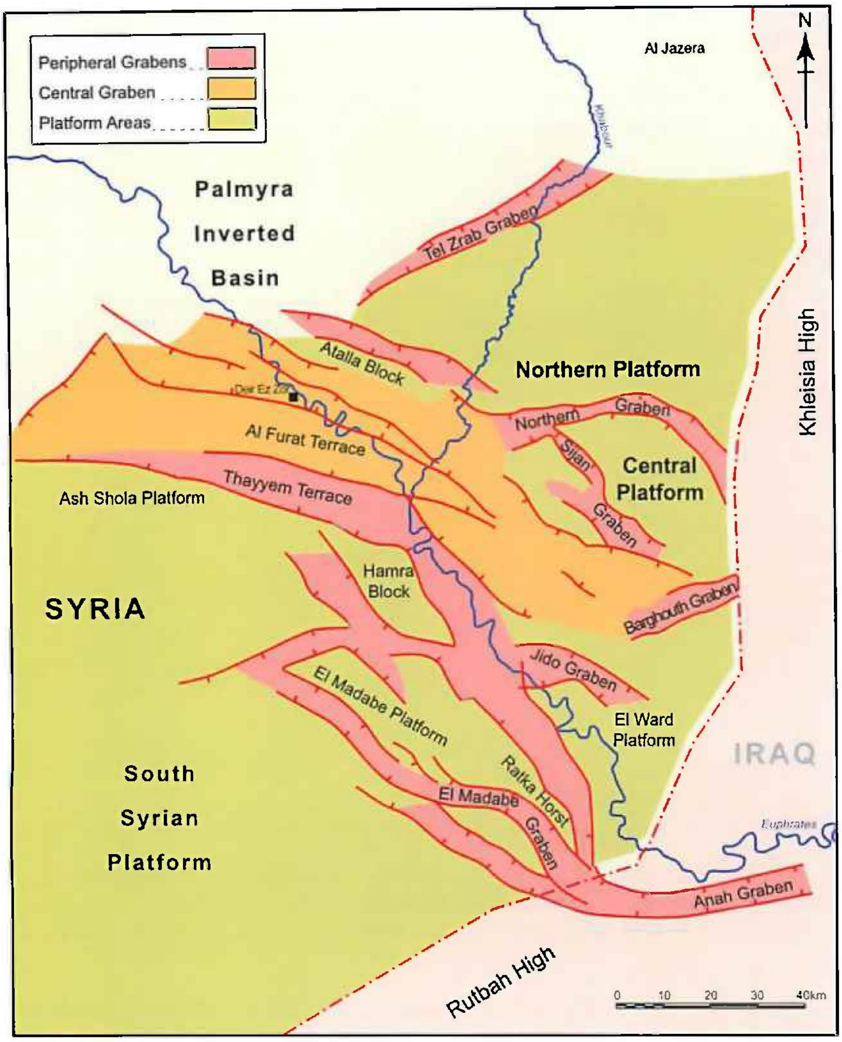


Fig. 3.13. The Late Cretaceous rift system in Eastern Syria. After de Ruiter *et al.*, 1995.

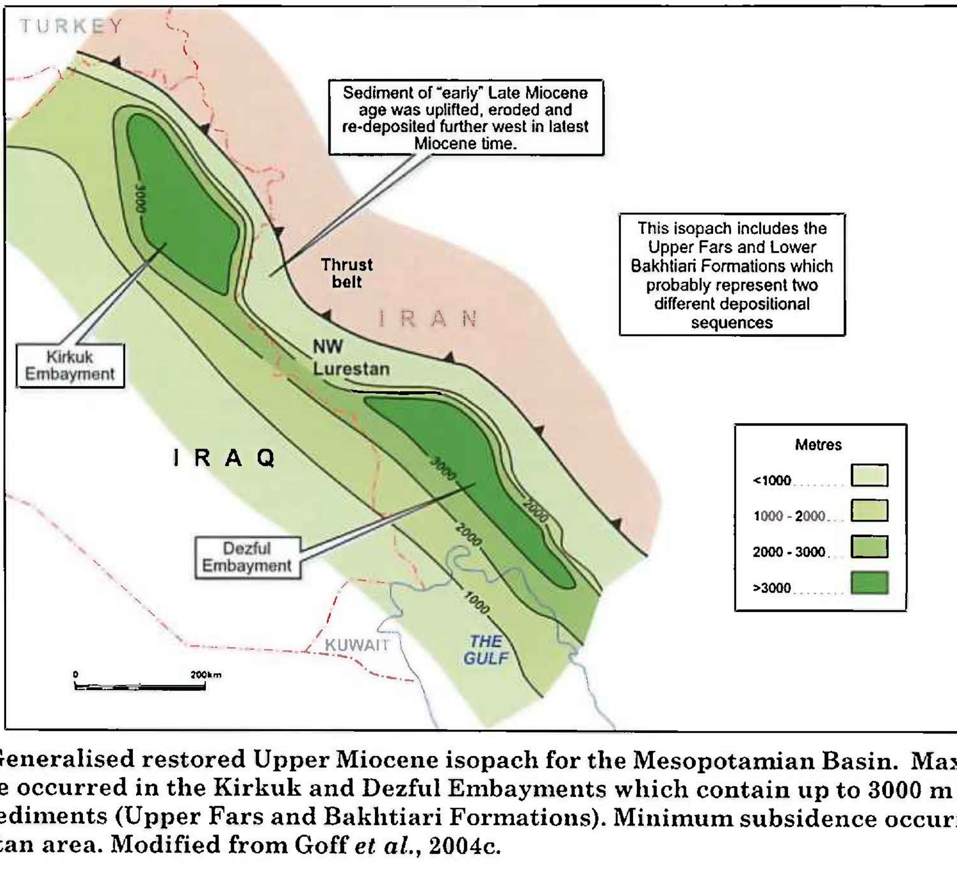


Fig. 3.14. Generalised restored Upper Miocene isopach for the Mesopotamian Basin. Maximum subsidence occurred in the Kirkuk and Dezful Embayments which contain up to 3000 m of Upper Miocene sediments (Upper Fars and Bakhtiari Formations). Minimum subsidence occurred in the NW Lurestan area. Modified from Goff *et al.*, 2004c.

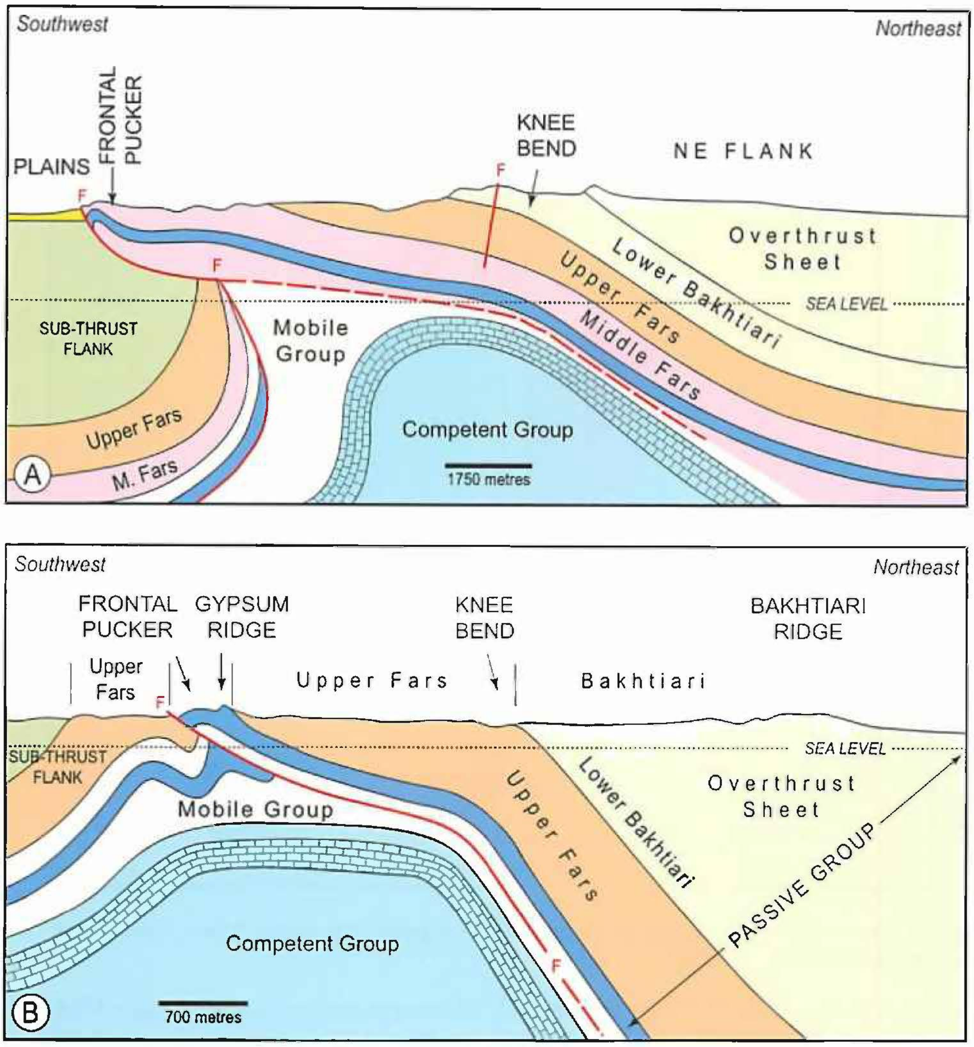


Fig. 3.15. Folding and thrusting within the Miocene Lower Fars Formation on the *Kirkuk* structure. After Dunnington (1968). The Mobile Group is the halite-bearing unit in the Lower Fars Formation (see Fig. 8.29).

section 9). As in Iran, however, the sub-Lower Fars structure is rarely affected by this deformation, and although some seepage of hydrocarbons may occur along these thrusts, there is little overall effect on seal integrity (Dunnington, 1968).

As a result of this small-scale structural deformation within the Lower Fars Formation (controlled by the shallow detachment levels), it is often difficult to locate the top of the underlying anticlines (Baker, 1938). Anticlines frequently become tighter with depth (see figures in Dunnington, 1968). A well located on the basis of surface structures will not necessarily find the crest of a deeper trap. Careful geophysical interpretation and structural mapping is required in order to locate subsurface closures on many structures. This is demonstrated in Iran, where at both *Agha Jari* and *Gachsaran*, the surface crest of the anticline does not coincide with the crest of the Asmari Formation reservoir. At *Gachsaran*, the surface anticline coincides with a subsurface syncline (Ion *et al.*, 1951; Slinger and Crichton, 1959).

3. The Mesopotamian Basin (Zone)

The Mesopotamian Basin contains the largest and richest petroleum province in Iraq and is dominated by Cretaceous plays. At the present day, the basin forms a flat-lying area located between northern Central Iraq and Kuwait (Fig. 3.7). The basin is covered by loess and Quaternary fluvial-plain deposits of the Tigris and Euphrates Rivers. Anticlines and horsts lie beneath undeformed or gently deformed Neogene cover, and are frequently related to long-lived palaeostructures. In the Basra area, they may be also related to movement of Infracambrian Hormuz Salt (Jassim, 2006c). IPC (1956) first suggested that the *Nahr Umr* structure was a salt-associated dome.

The Mesopotamian Basin was subdivided from south to north into the Zubair, Euphrates and Tigris subzones on the Tectonic Map of Iraq (Buday and Jassim, 1984). The basin is an asymmetric foredeep with a regional dip to the NE and east (cross-sections 1-5). The base-Upper Jurassic surface lies at 2000–3500 m subsea in the west, deepening to > 6000 m subsea in the east (Fig. 3.16). The western margin

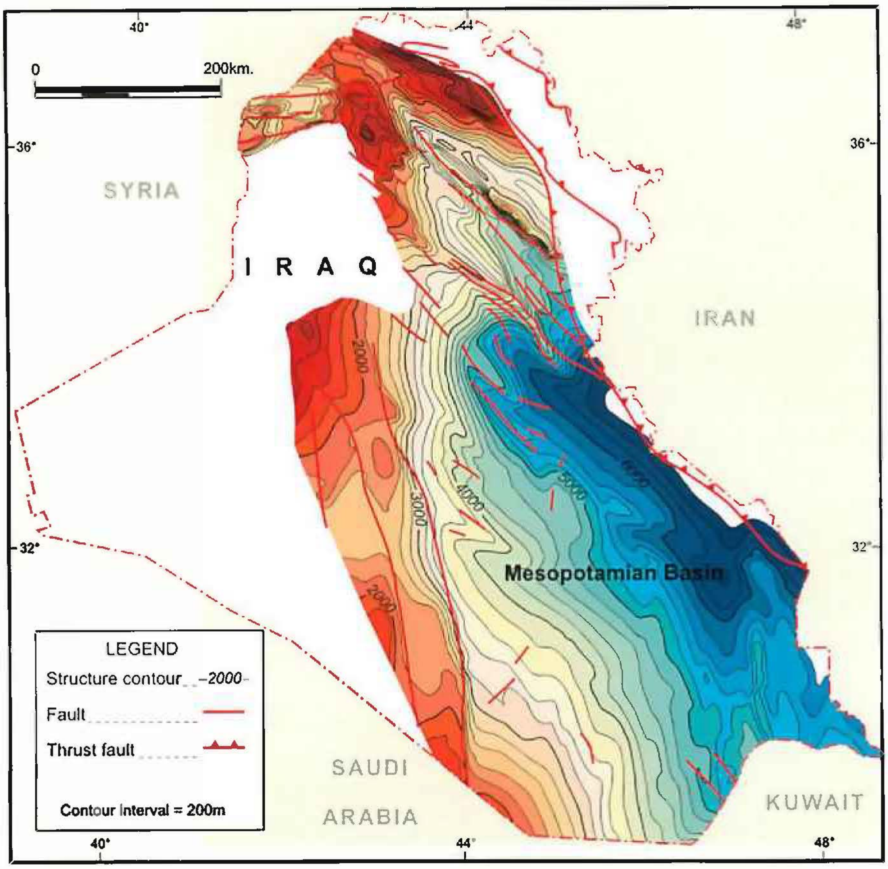


Fig. 3.16. Present-day burial depth for the base of the Upper Jurassic. After Pitman *et al.*, 2004, with permission from *GeoArabia*.

of the Mesopotamian Basin is interpreted to be bounded by significant NNW-SSE trending fault zones. The amount of displacement along these fault zones is poorly constrained and may be very limited (Fig. 3.3). The most prominent fault zone is the 300 km long Abu Jir Lineament (Fig. 3.7). North of Hit, the western margin of the basin strikes north-south for some 200 km. The NE margin of the basin is marked by a series of folds along the SW margin of the Folded Zone including the Makhul and Hamrin anticlines (Fig. 3.6). The basin margin then passes into Iran, reappearing in SE Iraq before passing back into Iran along the SW margin of the Abu Ghirab and Jebel Fauqi anticlines (Fig. 3.7).

Further details of the internal structure of the Mesopotamian Zone were given by Jassim and Buday (2006b).

4. The Salman Zone

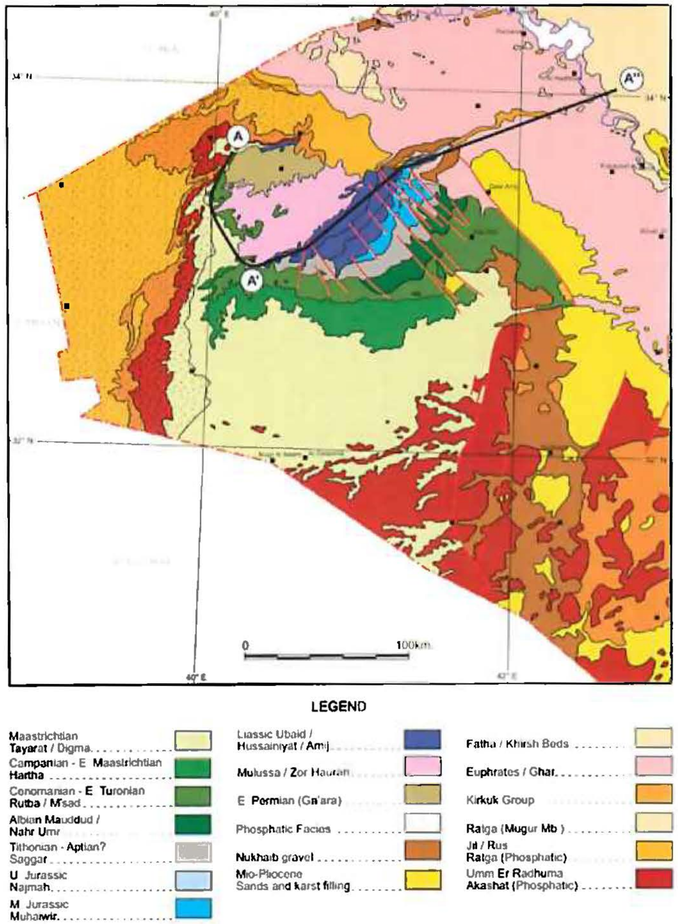
The north-south oriented Salman Zone lies along the western margin of the Mesopotamian Basin (Fig. 3.7). It may be a late Precambrian palaeohigh that was re-activated in Late Carboniferous time. A depth-to-basement map (Fig. 3.5) shows a prominent basement ridge extending along the length of the Salman Zone, with top- basement at depths of 5000–6000 m below sea level. The basement surface dips to the east to about 8000 m below sea level along the boundary with the Mesopotamian Basin. A thin Cambro-Ordovician section (1000 m thick) is modelled (from gravity interpretation) to occur between basement and the Late Carboniferous unconformity (Jassim and Buday, 2006b). However, the interpreted seismic line in Fig. 3.3 shows a much thicker Lower Palaeozoic section beneath the Salman Zone, implying a considerably deeper basement (Mohammed, 2006).

The Salman Zone contains a thinner, less complete Mesozoic and Tertiary stratigraphic succession than the Mesopotamian Basin to the east. The base-Cretaceous surface in the Salman Zone dips gently to the east, from about 1000 to 3500 m sub-sea (Fig. 3.3). Overlying Miocene and Paleogene sedimentary rocks have a gentle dip.

The Salman Zone is bounded by Early Palaeozoic basins to the west and Mesozoic-Cenozoic basins to the east. It is limited to the east by the Abu Jir Lineament (Mohammed, 2006) (Fig. 3.3, 3.7).

5. The Rutbah – Jezira Zone

This zone (Fig. 3.7) covers the present-day Western Desert of Iraq (including the Rutbah area near the Jordanian border) where rocks as old as Westphalian (Late Carboniferous) crop out. It extends as far north as the southern margin of the Folded Zone which is marked by anticlines including Jebels Sinjar, Ibrahim, Sadid and Makhul



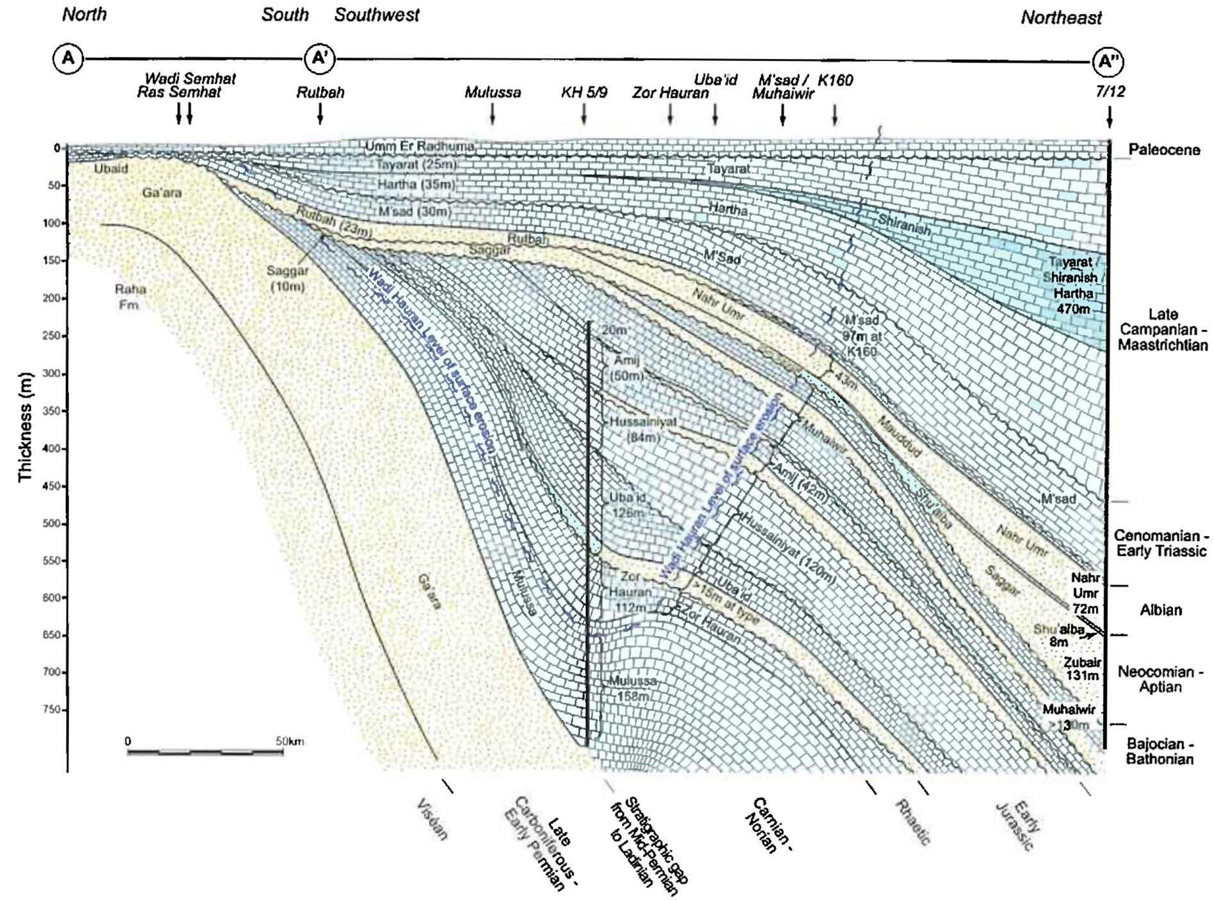


Fig. 3.17. (a, left) Regional geological map of the Western Desert of Iraq (after Jassim *et al.*, 1986). Note present-day erosion level shown on the cross-section in (b).
(b, right). Restored cross-section through the Western Desert with a base-Paleocene datum. The line of section is marked in the map in (a); note the change in profile orientation at Rutbah. Compiled from various sources including Dunnington *et al.*, 1959; Buday, 1980; Kaddouri, 1986; Hassan, 1986; Jassim and Buday, 1987; and Jassim and Goff, 2006a. Permian and Triassic rocks crop out in the core of the Hauran anticline to the SE of location A.

(Fig. 3.6). The zone is a continuation of the Hail/ Jauf Highs of western Saudi Arabia and Jordan (Lovelock, 1984; Al-Laboun, 1986) and has a regional dip of less than 1° to the NE. It is cut by the narrow east-west trending Anah Trough or graben (Fig. 3.13) which contains up to 2000 m of Late Cretaceous marls.

The **Rutbah subzone** to the south of the Anah Trough (Fig. 3.7) is an inverted Palaeozoic basin with a Cambrian – Silurian succession inferred to be 6000 m thick (Jassim and Buday, 2006b). It is covered by a thin, incomplete Devonian – Paleogene succession (< 1500 m thick in the western and central parts of the subzone), containing significant unconformities. The Rutbah subzone is dominated by the Hauran Anticlinorium, a fold in which the base-Cretaceous surface plunges from 650 m above sea level at the Iraq–Jordan border to sea level some 300 km to the NE (see Fig. 5-7 of Jassim and Buday, 2006b). At a regional scale, the Rutbah subzone forms a very prominent uplift visible on the surface (Jassim *et al.*, 1986). Paleogene limestones crop out along the western margin of the Hauran Anticline and over the eastern part of the subzone; Lower Miocene strata crop out in the north (Fig. 3.17). The core of the Hauran Anticline (covering an area of about 1000 sq. km) exposes Permian – Lower Cretaceous strata unconformably overlain by Upper Cretaceous carbonates.

The **Jezira subzone** to the north of the Anah Graben (Fig. 3.7) extends from the eastern limit of the Euphrates graben system in Syria (Fig. 3.13) to the SW limit of the Folded Zone in Iraq. The Iraqi portion of the subzone can be divided into the Khleisia and Tayarat Highs (Fig. 3.7). These highs are cut by the east-west trending Khleisia and Tayarat Grabens. The Tertiary and Cretaceous cover is thin over the crest of the Khleisia High. Depth to the base-Cretaceous surface is probably < 750 m sub sea, while at the Hauran Anticline (in the Rutbah subzone) it is < 500 m subsea.

Prominent "horst-block" structures in the Rutbah-Jezira Zone (Buday and Jassim, 1984) (Fig. 3.17) comprise six features within the Hauran Anticlinorium, two large-scale north-south trending highs in the eastern Rutbah subzone, and a high corresponding to the Tayarat Anticline in the Jezira subzone.

Palaeostructural Elements in Iraq

Many lineaments, structures and faults have been identified in Iraq (Buday and Jassim, 1984). They have been described in detail by Jassim and Buday (2006a). Here, we consider those features which influenced the Phanerozoic development of facies patterns and depocentres (Fig. 3.7, 3.18). Other structures may also prove to be significant in future.

Subsurface geological data indicate considerable structural complexity in Iraq which is not apparent from the geometries of the surface tectono-physiographic zones. Dominant palaeostructural trends in Iraq are oriented NW-SE, NE-SW, west-east and north-south, and comprise faults or fault complexes (sometimes referred to as "lineaments", for example by Buday and Jassim, 1987). These structural orientations were first noted by E. J. Daniel (cited by Henson, 1950; and Henson, 1951).

Major Faults

Jassim and Buday (2006a) interpreted three major Precambrian fault systems in Iraq and reviewed their influence on the thickness of major stratigraphic intervals. They relied mainly on gravity data to identify faults, integrated with magnetic data and satellite imagery. The fault systems comprise the NW-SE trending "**Najd Fault System**, the NE-SW trending "**Tranversal Fault System**", and the north-south trending "**Nabitah Fault System**" (Fig. 3.18). These fault systems were reactivated at different times during the Phanerozoic, controlling the distribution of subtle structural highs and lows which influenced subsidence and facies patterns.

NW-SE trending faults and lineaments

Major NW-SE trending faults in Iraq locally form prominent structural features. However, it is important to note that the correlation of these fault systems across Iraq, and their geological significance, is yet to be confirmed by high resolution seismic data. They may be controlled by the Infracambrian "Najd" trend, and are rooted in zones of weakness within the Precambrian basement.

Jassim and Buday (2006a) recognised six NW-SE trending fault systems (Fig. 3.18). The *Tar Al Jil Fault*, along the border between Iraq and Saudi Arabia (Fig. 3.18), significantly affects surface topography (Jassim and Buday, 2006a). The SE portion of the *Euphrates Boundary Fault* controls the margin of the Quaternary Mesopotamian Basin. This fault probably acted as a hinge zone along its entire length during Miocene subsidence; only limited subsidence occurred to the SW. The Abu Jir Fault between Kifl and Samawa (Fig. 3.7) marks the eastern limit of the thick Najmah Formation in southern Iraq, as defined by Sadooni (1997).

The *Ramadi-Musaiyib Fault* (Fig. 3.18) (or Fallujah-Amara Fault) controls the location of the subsurface West Baghdad structure.

The *Tikrit-Amara Fault* (also referred to as the Balad-Baghdad Fault) controls the location of subsurface strike-slip related structures, which formed in the Late Cretaceous and were identified by seismic surveys leading to the discovery of the *East Baghdad* and *Balad* oilfields. This fault zone was interpreted by Mohammed (2006) (Fig. 3.3). It may control the SW margin of a shallow-water carbonate system of Cenomanian – early Campanian age in the East Baghdad area. The *East*

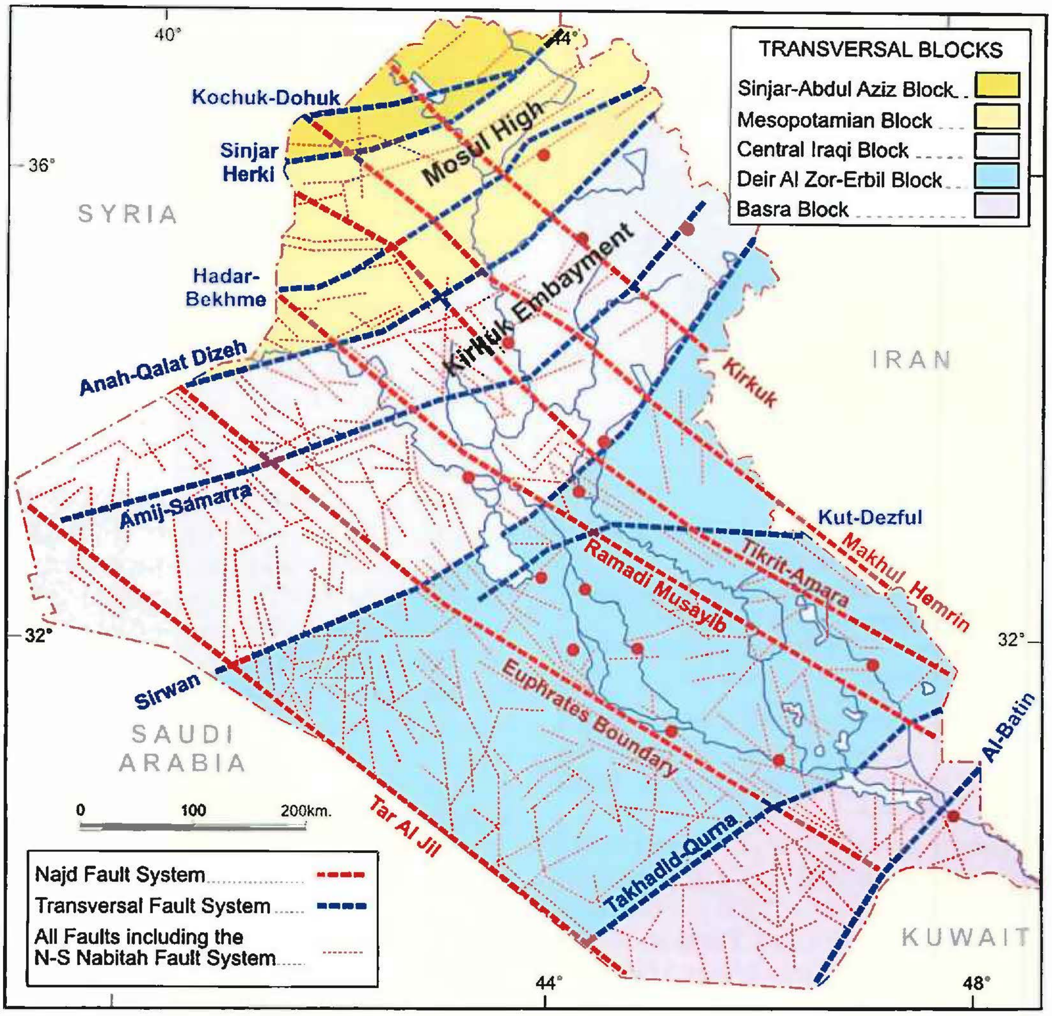


Fig. 3.18. Map of Iraq showing tectonic zones according to Jassim and Buday (2006a). Also shown are the three principal Precambrian fault systems: Najd (NW-SE); transversal (NE-SW); and Nabitah (north-south). Note that the correlation of these fault systems across Iraq is yet to be confirmed by high resolution seismic data.

Baghdad structure is compartmentalised into at least ten fault blocks and has been interpreted as a positive flower structure (Aljawadi, 1993; Sadooni, 1996, 2004). A zone of similar flower structures may extend towards the Iranian frontier (Fig. 3.7). The trend is along strike from an unnamed feature indicated by gravity data in SE Iraq (Jassim and Buday, 2006a; their Fig. 4-1) along the Ahab-Rafedain structure.

The *Makhul-Hamrin Lineament* (Fig. 3.7, 3.18) comprises a line of anomalously high surface anticlines (Makhul and Hamrin) defining the SW limit of the Folded Zone (Fig. 3.6), which formed during late Miocene – Pliocene compression. This trend has a pronounced gravity anomaly (Sayyab and Valek, 1968) (Fig. 3.19; see also Fig. 4-1 of Jassim and Buday, 2006a). It may be related to the southernmost of three Late Cretaceous half grabens with a major fault to the SW downthrowing to the NE (Haddad and Ameen, 2007). Lovelock (1984) suggested that the fault is part of an oblique-slip transcurrent system linked to the opening of the Sinjar Trough, although detailed studies of fold geometries along this trend do not support transtension (N. Kent, *pers. com.* to A. H., 2008). The continuation of this fault system into Iran may define the northern margin of the Bala Rud trend, and thus control the SE extension of the Cretaceous (Qamchuqa Formation) shelf margin.

Finally, the NW-SE oriented *Kirkuk Fault* (Fig. 3.18) controls the location of the Kirkuk anticline.

Three other NW-SE lineaments are: the *Qamchuqa Lineament* which controlled the location of the long-lived (30 Ma), NW-SE trending Qamchuqa Formation carbonate shelf margin in Iraqi Kurdistan; the *Chemchemal Lineament* (Fig. 3.7), controlled partly by a Late Cretaceous fault which throws down to the NE (Haddad and Ameen, 2007); and the *Qarah Chauq Lineament* (Haddad and Ameen, 2007) (Fig. 3.7). Neogene uplift of Qarah Chauq relative to neighbouring structures (Paleogene rocks are exposed in its core) suggest that it is an inverted graben.

These NW-SE trending structures are contiguous with the Euphrates and Azraq Grabens of Syria (Fig. 3.13) and Jordan, respectively

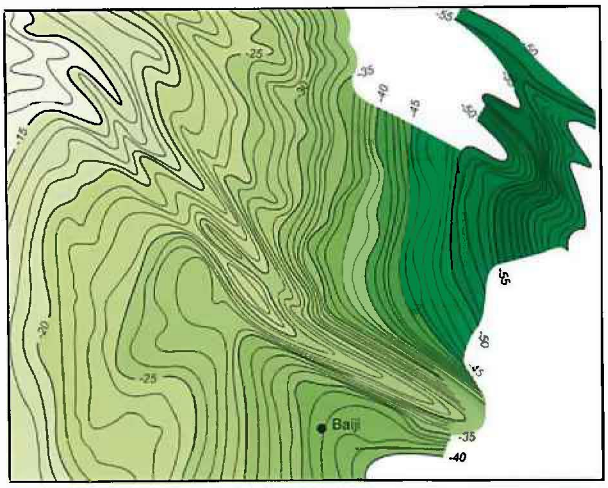


Fig. 3.19. The gravity anomaly at Jebel Makhul (Sayyab, 1968) (location: Fig. 3.10). This approximately 2 km wide anomaly disrupts the north-south oriented regional gravity field, unlike other anticlinal structures in Iraq,and suggests the involvement of basement.

(Lovelock, 1984). Grabens and half-grabens with a similar orientation containing Cretaceous sediments also occur in the Jauf area of Saudi Arabia (Helal, 1968).

Synsedimentary normal faults of Neocomian age occur in the Western Desert, and define narrow graben (Jassim *et al.*, 1986) (Fig. 3.17) within which sandstones of the Saggar/S'Ker Formation are preserved (Jassim *et al.*, 1987; Kaddouri, 1989) (see page 187).

NE-SW trending palaeostructural elements: The "Transversal System" (Fig. 3.18)

Buday and Jassim (2006a) interpreted nine major NE-SW trending faults which affect thickness variations in the Jurassic, Cretaceous and Tertiary sediments in Iraq. Several of these faults correspond to major structural features. The western portions of the *Sinjar-Herki* and *Kochuk-Dohuk faults* probably correspond respectively to the southern and northern bounding faults of the Sinjar Trough. The western part of the *Anah-Qalat Dizeh Fault Zone* controls the location of the narrow, deep Anah Graben (Fig. 3.13). Some of these faults are active at the present day as indicated by earthquake data.

The Rutbah-Khleisia-Mosul Highs (Fig. 3.7) form a regional anticlinorium which plunges gently to the NE. This structure was initiated during the Late Carboniferous and represents an inverted Early Palaeozoic basin. It has a relatively thin Permian-Cretaceous section. Subtle movement of the high influenced sedimentation during the Neogene, when it separated the NE Syrian and Mesopotamian Lower Fars salt basins.

The Mosul High is bounded to the SE by the NE-SW oriented *Bekhme-Hadar Lineament* of Jassim (2006a) (Fig. 3.7; Fig. 3.18). Caron and Mouty (2007) suggested that the margin of the Hamad Uplift in SE Syria (part of the same system of palaeohighs) is controlled by a major NE-SW oriented normal fault which runs along the Iraqi side of the Iraq-Syria border.

The NE-SW oriented *Al-Batin Lineament* (Figs. 3.7, 3.18) is a prominent surface feature along the Iraq-Kuwait border. The influence of this feature is uncertain within Iraq. To the SW it bounds the NW side of elevated basement blocks in Kuwait and eastern Saudi Arabia, separating them from the Widyan Basin to the NW (Al-Laboun, 1986; Al-Husseini, 2000).

In northern Iraq, a range of NE-SW oriented features may have controlled facies patterns and have influenced the response to Tertiary structural deformation (Jassim and Buday, 2006a). For example, the Albian-Barremian Qamchuqa Formation shelf margin, which trends NW-SE through Iraqi Kurdistan, abruptly changes strike to NE-SW in the vicinity of the *Kirkuk* and *Jambur* structures. This change in strike may be controlled by a segment of the *Amij-Samarra-Halabja Fault* (Fig. 3.18) (proposed by Jassim and Buday, 2006a) which limits the Kirkuk Embayment. The shelf margin then strikes NW-SE again along the Makhul-Hamrin Lineament.

The topography and geology of the Zagros fold-and-thrust belt (Fig. 1.1) show that the anticlines in Lurestan lie in a salient of the foldbelt along the margin of the Mesopotamian Basin. The boundary between Lurestan and SE Iraqi Kurdistan is thus defined by the *Sirwan Lineament* (Figs 3.7, 3.14, 3.18), corresponding to a series of SW-NE trending magmatic anomalies (interpreted as intrusions).

Another gravity/magnetic anomaly forming a NE-SW lineament runs from the border between Iraq and Saudi Arabia, via well *Samawa-1*, into the Mesopotamian Basin at least as far as well *Ahdab-1* (Fig. 3.7). This lineament also corresponds to intrusions interpreted in the Precambrian basement (Jassim, 2006b).

East-west trending palaeostructural elements

East-west trending elements are less common than NE-SW or NW-SE elements in Iraq. Examples include (Fig. 3.7):

1. The Sinjar Trough including the Sinjar Anticline (Dunnington, 1958; Lovelock, 1984);
2. The Tayarat Graben and Tayarat High on the southern margin of the Khleisia High (Jassim and Buday, 2006b);
3. The Anah Trough or Graben which separates the Khleisia and Rutbah Highs, as first defined by Dunnington (1958) (Fig. 3.13).

Outside Iraq, Jebel Abd El Aziz in northern Syria also has an east-west orientation (Kent and Hickman, 1997) (Fig. 3.11), as does the northern part of the Euphrates Graben system where it links with the Palmyra Basin (de Ruiter *et al.*, 1995; Caron *et al.*, 2000) (Fig. 3.13).

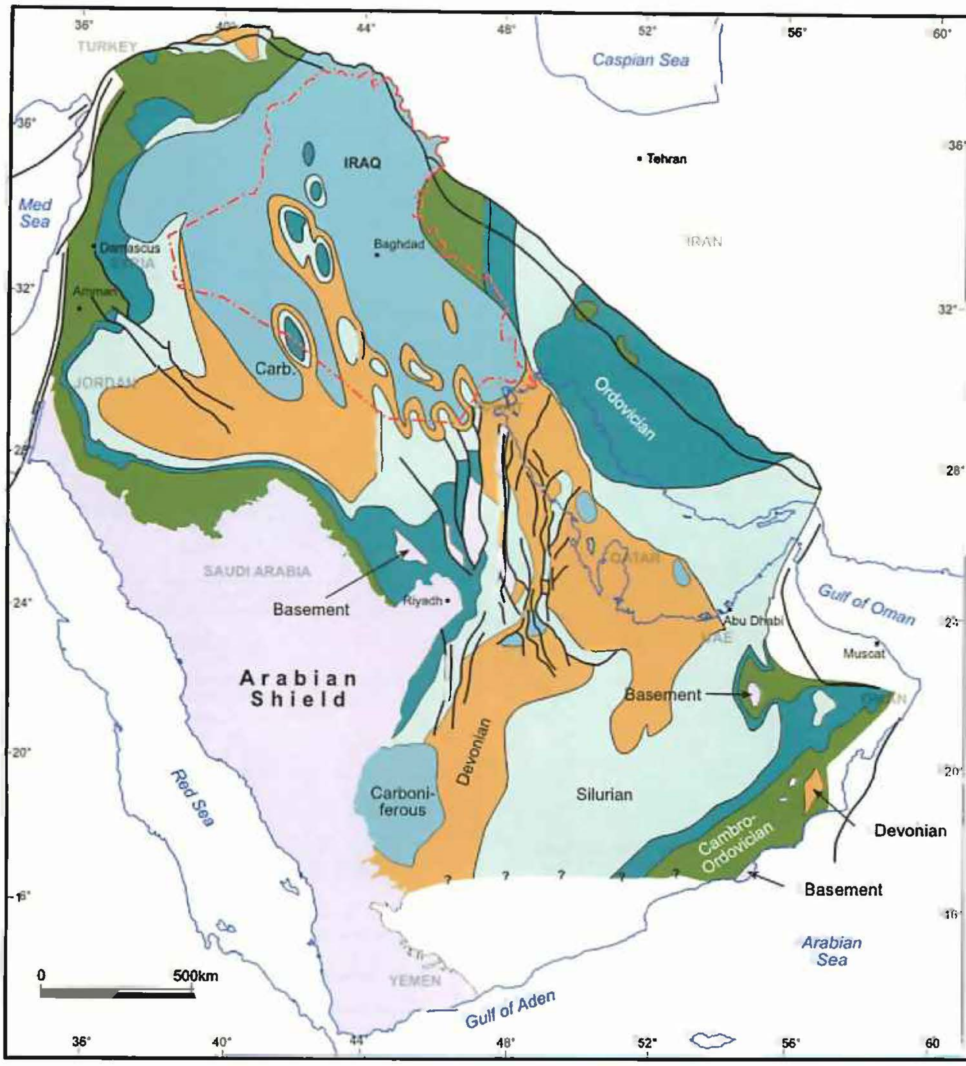


Fig. 3.20. Late Carboniferous (AP5) subcrop in the Arabian Plate. Adapted from various sources including Andrews *et al.*, 1991; Best *et al.*, 1992; Konert *et al.*, 2001; and Jassim, 2006c.

East-west structural elements may function as transfer zones between NW-SE and NE-SW lineaments. If the NW-SE fault systems were transtensional in the Late Cretaceous (c.f. Lovelock, 1984; Caron *et al.*, 2000), the east-west fault systems may represent pull-apart basins.

East-west oriented elements cut across regional palaeohighs. Within the Stable Shelf, the Rutbah and Jezirah subzones are separated by the Anah Graben. A small high in the Abtakh area (a continuation of the Karachok-Souedie high in NE Syria: Nikolaevskiy, 1972) is separated from the Khleisia High by the Sinjar Graben.

North-south trending palaeostructural elements

The north-south Ar Rayn Terrane is a prominent tectonic zone in Saudi Arabia (Wender *et al.*, 1998; Al-Husseini, 2000). The Salman Zone is a similar major north-south trending tectonic element in southern and central Iraq. It is bounded by the Abu Jir Lineament to the east (Mohammed, 2006) (Fig. 3.7), which separates the Unstable and Stable Shelves. The Abu Jir Lineament has little vertical displacement as apparent on the regional seismic line (Fig. 3.3). Lovelock (1984) suggested that offset was mainly due to strike-slip movement.

Other north-south structures include the "Nabitah" trend of Jassim and Buday (2006a). The Nabitah suture forms the boundary between the Precambrian Afif and Western Arabian Terranes (Fig. 3.4), and was modified into an easterly-dipping monocline during Late Carboniferous deformation. North-south structures in the Afif Terrane control the margins of the Cretaceous Tinif Trough (Al-Bassam and Al-Haba, 1990; Al-Bassam and Karim, 1992) (Fig. 3.7).

The *Rumaila, Zubair* and *Ratawi* structures in SE Iraq (Fig. 3.7) are north-south oriented highs which formed by reactivation of basement faults and movement of Infracambrian Salt in the Late Cretaceous (Sadooni and Aqrawi, 2000). They are part of a group of north-south structures, including *Abqaiq* in Saudi Arabia and the Dammam and Awali Domes with limited erosion at the Late Carboniferous unconformity (Wender *et al.*, 1998).

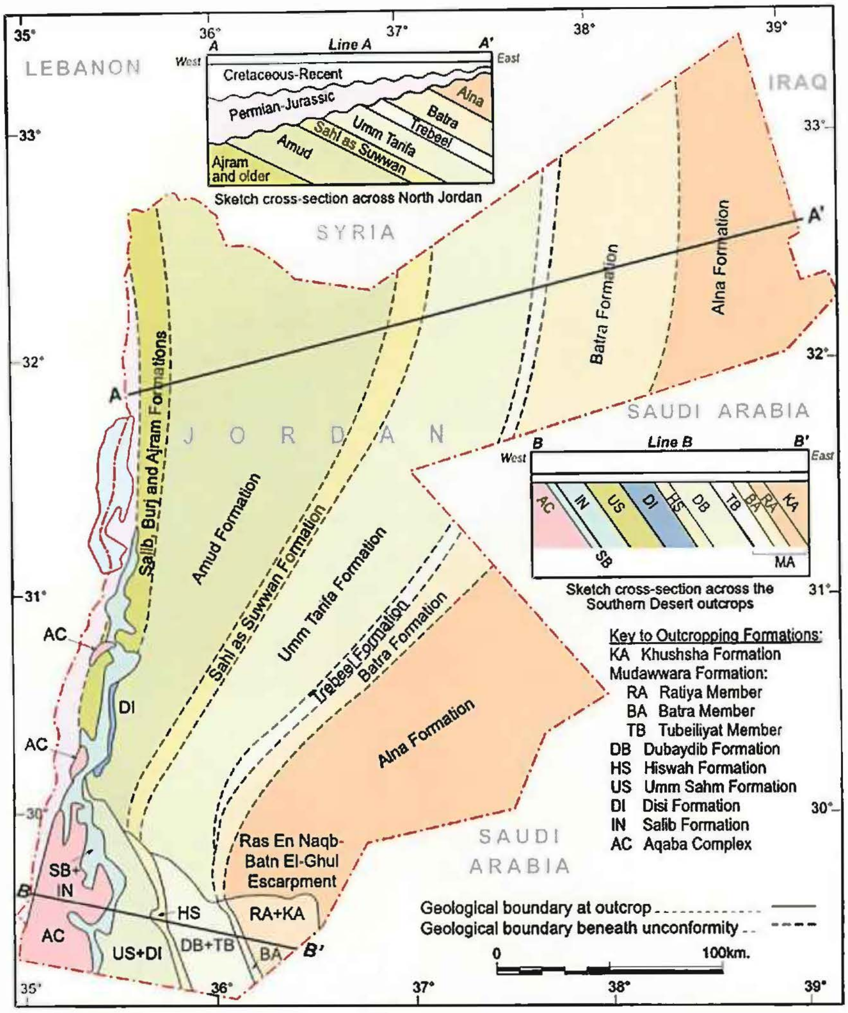


Fig. 3.21. Subcrop map of Silurian and older rocks beneath the Late Carboniferous unconformity surface in Jordan. From Andrews *et al.*, 1991.

These contrast with intervening anticlines in which Hormuz Salt is absent and which have a deeply eroded Palaeozoic section due to Late Carboniferous uplift (Al-Husseini, 2000). An example is the Burgan High in Kuwait (Kahn, 1989).

The Late Devonian and Late Carboniferous regional unconformities

Important regional unconformities have been identified in the Late Palaeozoic section in Iraq.

Jassim (2006c) interpreted an angular unconformity to be present at the base of the Upper Devonian in Iraq with progressive subcrop of older Lower Palaeozoic units to the north (pp. 88-89). Silurian rocks are interpreted to be absent because of erosion at the unconformity in northern Iraq approximately to the north of lat. 36°N. The occurrence of basalts above the unconformity in northern Iraq (Dunnington *et al.*, 1959) suggest that it may have formed during a phase of thermal uplift. However the extent and magnitude of the Late Devonian unconformity in Iraq cannot be mapped at present

A "Late Carboniferous Tectonic Event", defined by Ruban *et al.* (2007), marks the end of Megasequence AP4 of Sharland *et al.* (2001). The associated "Hercynian" unconformity was termed the "Pre-Unayzah Unconformity" by Al-Laboun (1986, 1987) and Al-Husseini (2000) and is referred to here as the Late Carboniferous unconformity.

A plate-wide subcrop map at this unconformity is shown in Fig 3.20. Ordovician – Silurian sediments subcrop the unconformity on the SE and NW margins of the present-day Arabian Plate. In the Levant, Cambrian and Precambrian rocks subcrop Triassic rocks at an angular unconformity at the crest of the "Hercynian Geanticline of Helez" (Gvirtzman and Weissbrod, 1984). The subcrop pattern at this unconformity on the eastern flank of this huge uplift in Jordan is shown on the map and cross-sections in Fig 3.21. The subcrop to the Late Carboniferous unconformity and the onlap of post- Carbonifeorous sequences onto it is shown in a profile (constrained by seismic and well data) through Jordan and Syria in Fig 3.22.

In Iraq, a prominent north-south trending Late Carbonifeous uplift and unconformity has been interpreted in the Salman Zone (Fig 3.20). The geometry of this unconformity in Iraq is further discussed on page 99.

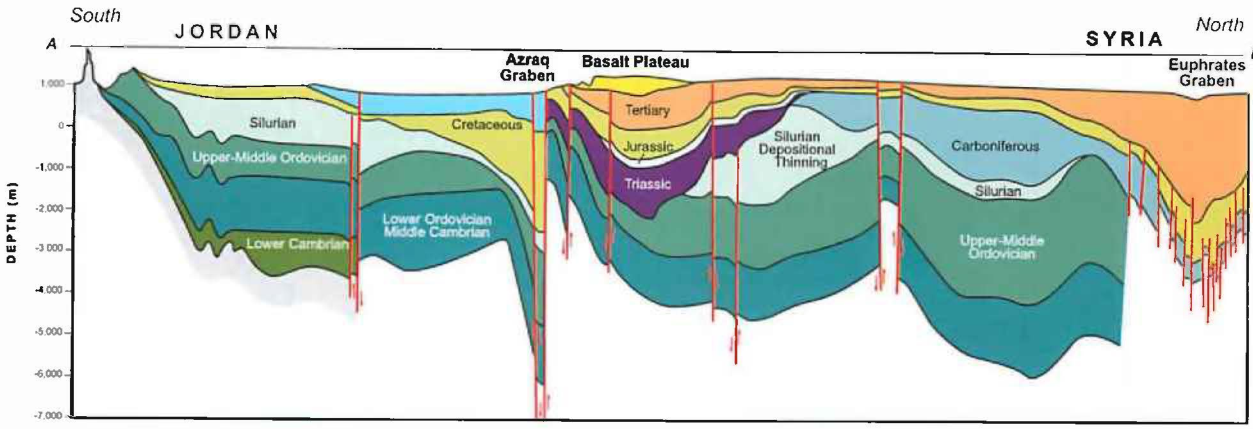


Fig. 3.22. South-north cross-section from Jordan through the Risha/Rutbah area into the Euphrates valley. After Konert *et al.*, 2001.

Tectonic Evolution

The Late Precambrian to Recent evolution of the northern margin of Gondwana and the Arabian Plate is discussed in the following pages. The drift of the Arabian Plate during the Phanerozoic is shown in Fig 3.23.

To understand the tectonic evolution of Iraq, it is necessary to consider data from a wide area including NE Iraq, eastern Turkey and west Iran which formed part of the northern margin of Gondwana bordering the Tethyan Realm. The geological history of Iraq has been strongly influenced by events along this margin. Much of the data for the interpretation of these events comes from allochthonous tectonic units whose geology is complex and poorly understood.

Late Precambrian – Early Cambrian (AP I)

The Arabian Plate formed by terrane accretion in Late Precambrian time (Jassim, 2006b). The terranes which form the basement of Iraq are shown in Fig. 3.4 and are described on pages 65-66. The Western Terranes formed by island arc accretion from 900 – 680 Ma (Nehlig *et al.*, 2001). The Afif Terrane collided with the Western Terranes during the Nabitah Orogeny (680 – 640 Ma) forming the Nabitah Suture Belt (Al-Husseini, 2000). This collision formed north-south trending structures (e.g gneiss domes), and may have initiated movement on the NW-SE trending Najd Fault System (Nehlig *et al.*, 2001, 2002). Synorogenic molasse was deposited in intermontane basins in the Afif Terrane. Subduction along the western side of the Ar Rayn Terrane created the Amar Volcanic Arc; associated plutons in the Ar Rayn Terrane are dated at 650 Ma (Al-Husseini, 2000).

The Ar Rayn Terrane probably accreted from 640 – 620 Ma during the Amar Orogeny (Stoeser and Camp, 1985; Al-Husseini, 2000). Metamorphic ages of low-grade metasediments in the Eastern Arabian Terrane range from about 670 – 605 Ma. By ca. 605 Ma, the accretion of the Eastern Arabian Terrane to the Ar Rayn Terrane had been completed. Ophiolites occur in narrow elongate suture zones between the terranes (Dilek and Amed, 2003). They represent remnants of the oceanic crust by which the terranes were formerly separated. The ophiolitic bodies along the terrane boundaries probably contain major serpentinite units and are thus zones of structural weakness. Many important structures in Iraq may be have been formed by reactivation of these ophiolitic sutures during Phanerozoic tectonism.

From about 620 to 520 Ma, widespread granite intrusion occurred within the northern margin of Gondwana including Iraq. The portion of the Ar Rayn Terrane in Saudi Arabia contains post-orogenic granites dated at 620-565 Ma (Al-Husseini, 2000; Baubron *et al.*, 1976; Fleck and Hadley, 1982). The Shamar rhyolite has an alkaline and per-alkaline composition (Al-Husseini, 2000) and is similarly dated at about 580-560 Ma (Fleck *et al.*, 1986; Brown *et al.*, 1989). Hassanzadeh *et al.* (2008) dated twenty granite samples from Iran (from the Sanandaj-Sirjan Zone, Central Iran Block and Alborz Block) at 601-522 Ma with a mean age of 561 Ma. The Doran granite was dated at 567 +/- 19 Ma. Volcanic rocks (quartz porphyry and rhyolite) in the Gharadash Formation of NW Iran were interpreted as the extrusive equivalents of this granite by Stocklin (1972). Granites in Iran intrude sedimentary rocks and low grade metasediments. The Doran granite intrudes the Kahar Formation (Stocklin, 1972) which comprises > 1600 m of slaty shales, sandstones and dolomites. Small granite plutons and dykes in the Bitlis Block (Turkey) have been dated at 552 – 528 Ma (Ustaomer *et al.*, 2009).

The above observations indicate that widespread subduction-related calc-alkaline magmatism occurred along the northern margin of Gondwana in Infracambrian time, and thus that the Infracambrian basins in the Arabian Plate formed

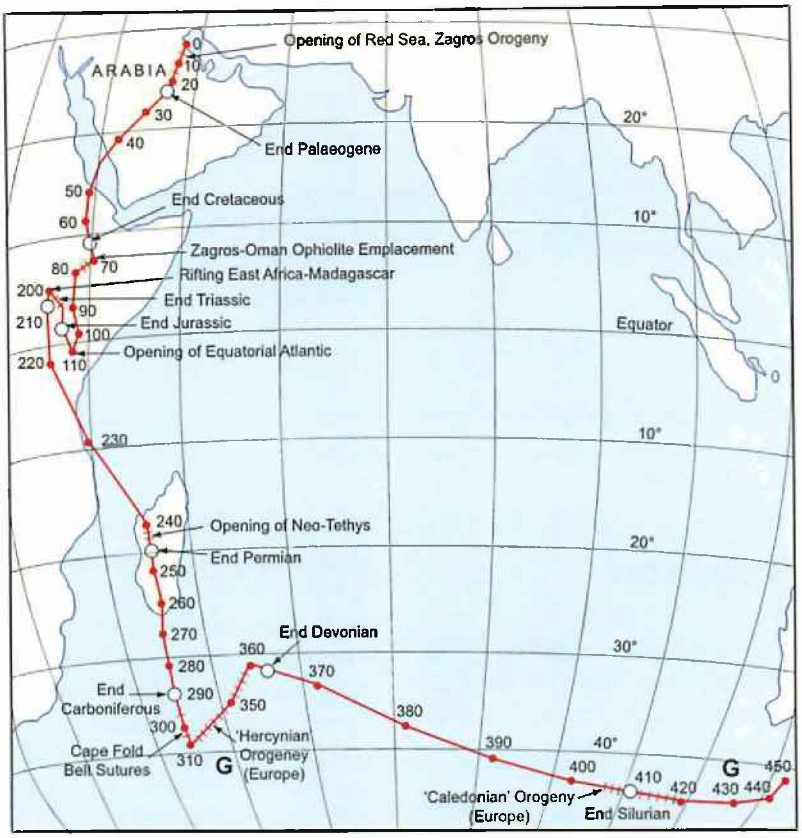


Fig. 3.23. Drift of the Arabian Plate during the Phanerozoic. After Al-Fares *et al.* (1989) and Konert *et al.* (2001), as presented in Sharland *et al.* (2001).

in a back-arc setting. Granite intrusion had ceased on the northern margin of Gondwana by the end of the Early Cambrian (520 Ma).

Granite intrusion was accompanied by tectonic extension. In Saudi Arabia, the Infracambrian Jubaylah Group occurs in narrow NW-SE trending extensional basins controlled by large-scale left-lateral faults of the Najd System (Fig 3.24). The Group overlies granite dated at 620 Ma (Hadley, 1974). It comprises a basal unit of boulder conglomerates and continental sandstones, a middle unit of andesitic basalts (dated at 540 +/- 18 Ma), and an upper unit of cherty and dolomitic limestones locally overlain by andesitic basalt (Hadley, 1974). The Jubaylah Group is unconformably overlain by the Siq Sandstone which has been dated at 520 Ma by Sharland *et al.* (2001).

Dyer and Husseini (1991) interpreted a major Infracambrian graben system in the western Rub' Al Khali of Saudi Arabia (Fig 3.25). They correlated the fill of this graben system (up to 3000 m thick) with the Jubaylah Group and the Huqf Group of Oman.

The distribution of Infracambrian basins in Iraq was modelled by Jassim (2006c) from gravity and magnetic interpretation. Seismic data from Jordan (Fig 4.6) supports an extensional origin for the Infracambrian basins interpreted by Jassim 2006c) (Fig 4.4) which are predicted to contain at least 1000 m of sediment. These basins were a northern continuation of the Infracambrian basin system of Saudi Arabia and the Gulf (Fig 3.24). Halite is predicted to be present in the Basra area of SE Iraq and in the Nukhaib Basin (Fig 4.4).

Major north-south basement highs (e.g the Qatar Arch) lie between the Infracambrian depocentres in the Arabian Plate. Several of these highs were reactivated during Phanerozoic compressional tectonic events in Late Carboniferous, Late Cretaceous and Late Miocene time to form structures hosting major oil- and gasfields. Some north-south trending anticlines in SE Iraq may have formed by inversion of Infracambrian half grabens or by movement of Infracambrian salt.

Mid-Cambrian – Ordovician (AP2)

Stampfli (2000) considered that in Late Cambrian – Early Ordovician time, the northern boundary of Gondwana was a passive margin flanking an oceanic area termed the "Proto-Tethys" (Fig 3.26a). Present-day Iraq was located about 1000 km south of this margin at this time.

Following the end of subduction-related magmatism in the Early Cambrian and consequent cooling of the lithosphere beneath northern Gondwana, a major marine transgression occurred

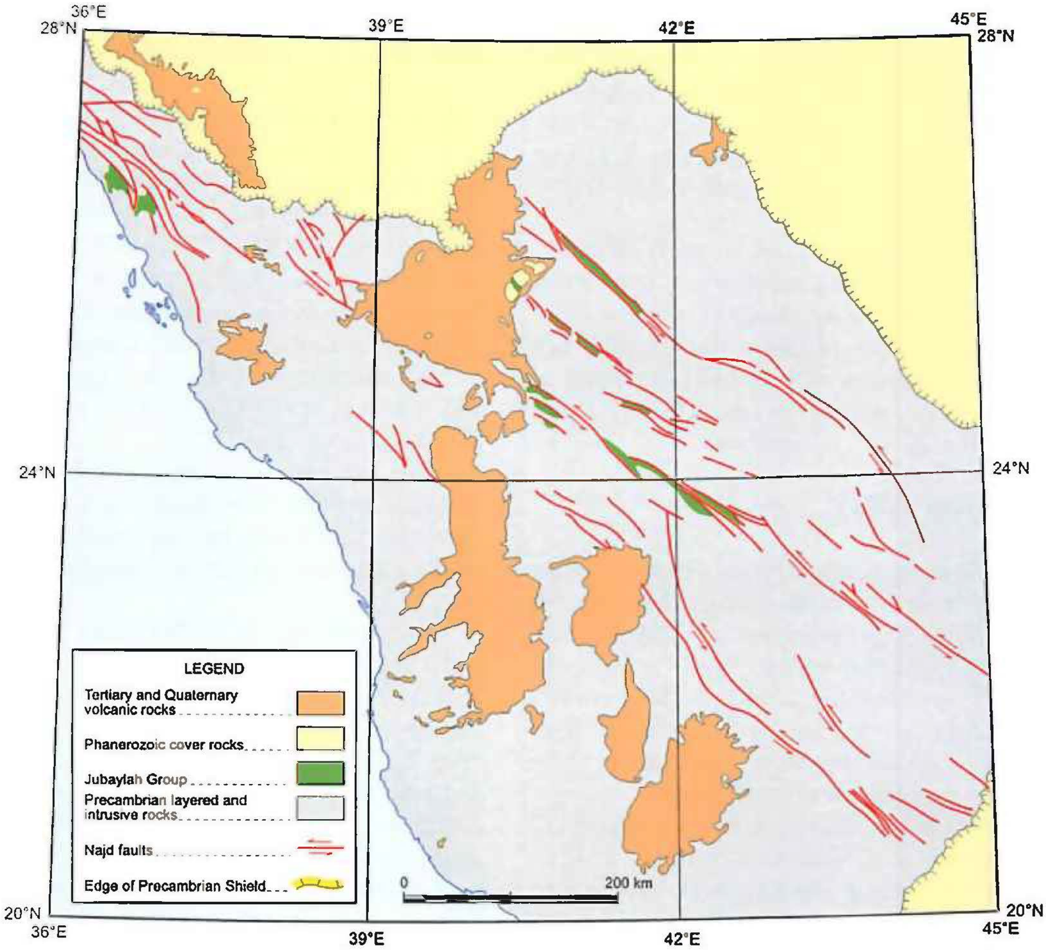


Fig. 3.24. Najd Fault System and related narrow Infracambrian basins containing the synrift Jubaylah Group in the Arabian Shield. After Hadley, 1974.

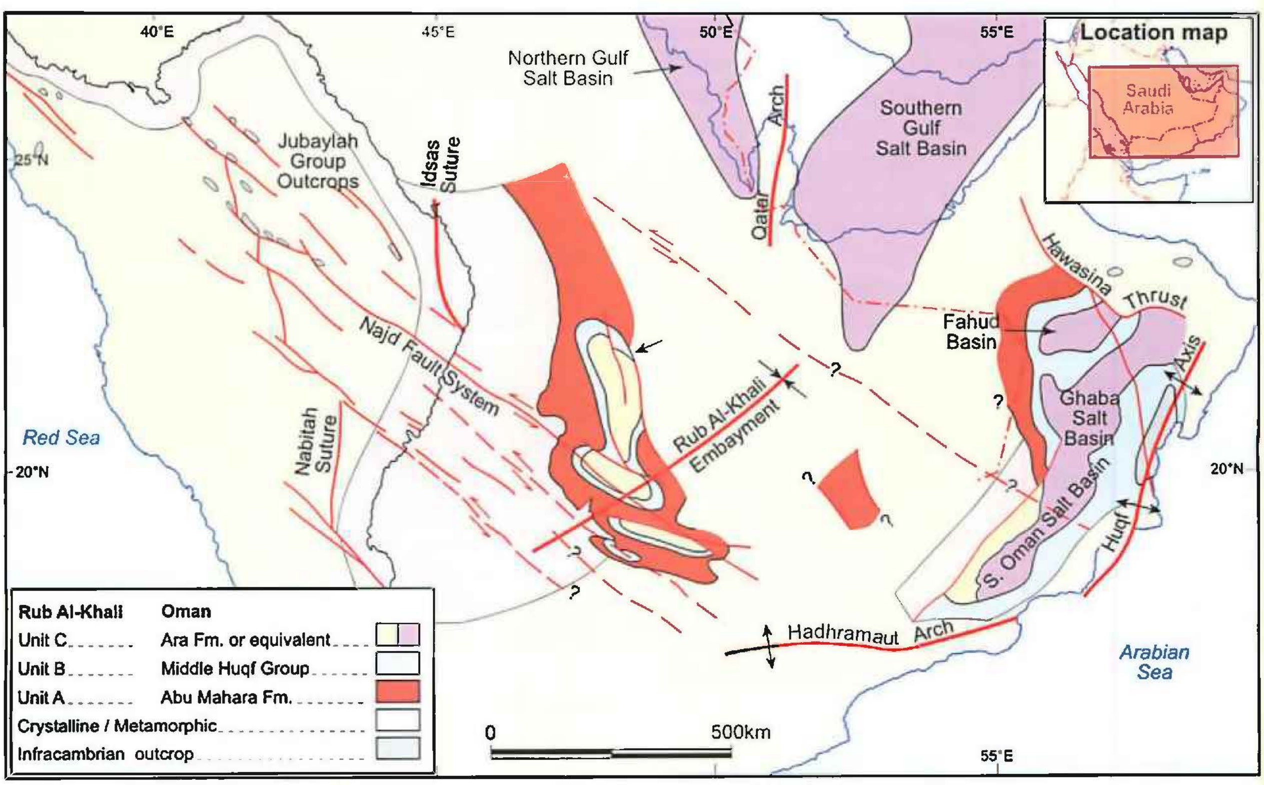


Fig. 3.25. Infracambrian basins and tectonic elements on the southern Arabian Plate, showing the distribution of Infracambrian stratigraphic units. After Dyer and Husseini, 1991.

in the Mid Cambrian. The transgression covered the Arabian Plate including Iraq and is associated with deposition of the Burj Limestone (page 74). Regional thermal subsidence occurred in Late Cambrian – Early Ordovician time. A major glaciation occurred in Gondwana in the latest Ordovician (Fig 3.26b).

In Iraq, seismic data tied to well *Akkas-1* indicates that the Middle Cambrian – Ordovician megasequence (AP2) is up to 4500 m thick. The megasequence probably underlies the whole of Iraq (Jassim, 2006c) though it is locally reduced in thickness due to erosion at the Late Devonian and Late Carboniferous unconformities.

Silurian (lower AP3)

Stampfli (2000) proposed that Palaeo-Tethys opened diachronously from east to west along the northern margin of Gondwana in Ordovician – Early Silurian time, with the spreading-away from Gondwana of a narrow micro-continent (the "Hun Superterrane") (Fig 3.27). The major marine transgressions over the Arabian Plate in the Early Silurian may be related to the opening of Palaeo-Tethys.

In the Early Silurian, the northern margin of Gondwana north of Arabia was composed of the Tauride Block of Turkey, the Sanandaj-Sirjan zone and the Alborz and Central Iran Blocks. Observations from Turkey and Iran provide evidence for deep-water sedimentation and volcanism along the Gondwanan margin at this time.

In the Central Taurides, the Lower Silurian comprises 225 m of coarse-grained pebbly sandstones, turbiditic sandstones and black shales capped by a marker bed with *Orthoceras* (Demirtasli, 1984). The overlying Upper Silurian consists of about 300 m of black shales, calciturbidites and nodular limestones with *Orthoceras*. These facies indicate relatively deep-water slope deposition. Further north in the Taurides, Goncuoglu and Kozlu (2000) reported that the Late Silurian section comprises turbidites, olistostromes and radiolarites associated with MORB and OIB oceanic basalts. In the Alborz Block of NE Iran, Shahri (2008) reported that the Upper Ordovician contains turbidites and tholeiitic basalts, and that the Silurian section contains basalts erupted in a submarine environment.

In Iraq, the Silurian is predicted to comprise up to 2000 m of marine mudstones and sandstones in the SW and Western Deserts (page 84, Fig 4.16). These Silurian sediments were deposited during a phase of passive thermal subsidence on the proximal part of the passive margin facing Palaeo-Tethys. Deeper-water Silurian facies including turbidites may have been deposited in northern Iraq, but may have been removed due to uplift and erosion in Late Devonian time.

Devonian to Early Carboniferous (upper AP3 - lower AP4)

Ruban *et al.* (2007) suggested that regional uplift occurred in northern Gondwana in mid-Palaeozoic time. The erosional phase associated with this uplift has been termed the "Middle Palaeozoic Event" (Ruban *et al.*, 2007) or "Middle Palaeozoic Hiatus" (Al-Hadidy, 2007) and is recorded throughout the Arabian Plate including Iraq (pp. 88, 89). The origin of this tectonic event is not understood.

The uplift resulted in a major unconformity which occurs at the base of the Upper Devonian in northern Iraq (Fig. 4.20). The unconformity is overlain by red beds and basalts. Differential tectonic movements associated with this Late Devonian uplift may have created structural traps involving Lower Devonian and older reservoirs in Iraq.

Observations from Turkey, Iran and Iraq indicate that shallow-marine sedimentation occurred along the northern passive margin of Gondwana in the Devonian – Early Carboniferous (Fig. 3.26c, d). In the southern part of the Central Taurides (Demirtasli, 1984), the Lower Devonian comprises about 300 m of marine sandstones, shales and coral-bearing limestones. An angular unconformity occurs here at the base of the Middle Devonian, above which are 330 m of conglomerates, "megabreccias", cross-bedded sandstones and limestones with corals and *Amphipora*. The Middle Devonian and Upper Devonian (550 m thick) consists of platform limestones and dolomites with corals, crinoids and gastropods, capped by shales with phosphate nodules.

In the northern part of the Central Taurides (Demirtasli, 1984), the uppermost Devonian comprises about 80 m of sandstones with thin shelly limestones, overlain by sandstones with plant debris, sandy limestones and shales with phosphate nodules.These are overlain by about 290 m of Carboniferous (Tournaisian – Gzelian) platform carbonates (oolitic grainstones and packstones) and sandstones.

In the Maku area in the extreme NW of Iran, 2550 m of Lower Devonian – Lower Carboniferous platform carbonates and subordinate sandstones unconformably overlie metamorphic basement (Alavi and Bolourchi, 1973).

In Iraq, up to 700 m of Lower to Middle Devonian marginal to shallow-marine clastics and carbonates were probably deposited at a proximal location on the passive margin (Jassim, 2006c) (page 86).

Late Carboniferous to Early Permian (upper AP4 to AP5)

The southern part of Gondwana (South America / South Africa) approached polar latitudes around 310 Ma, resulting in extensive glaciation (Konert *et al.*,

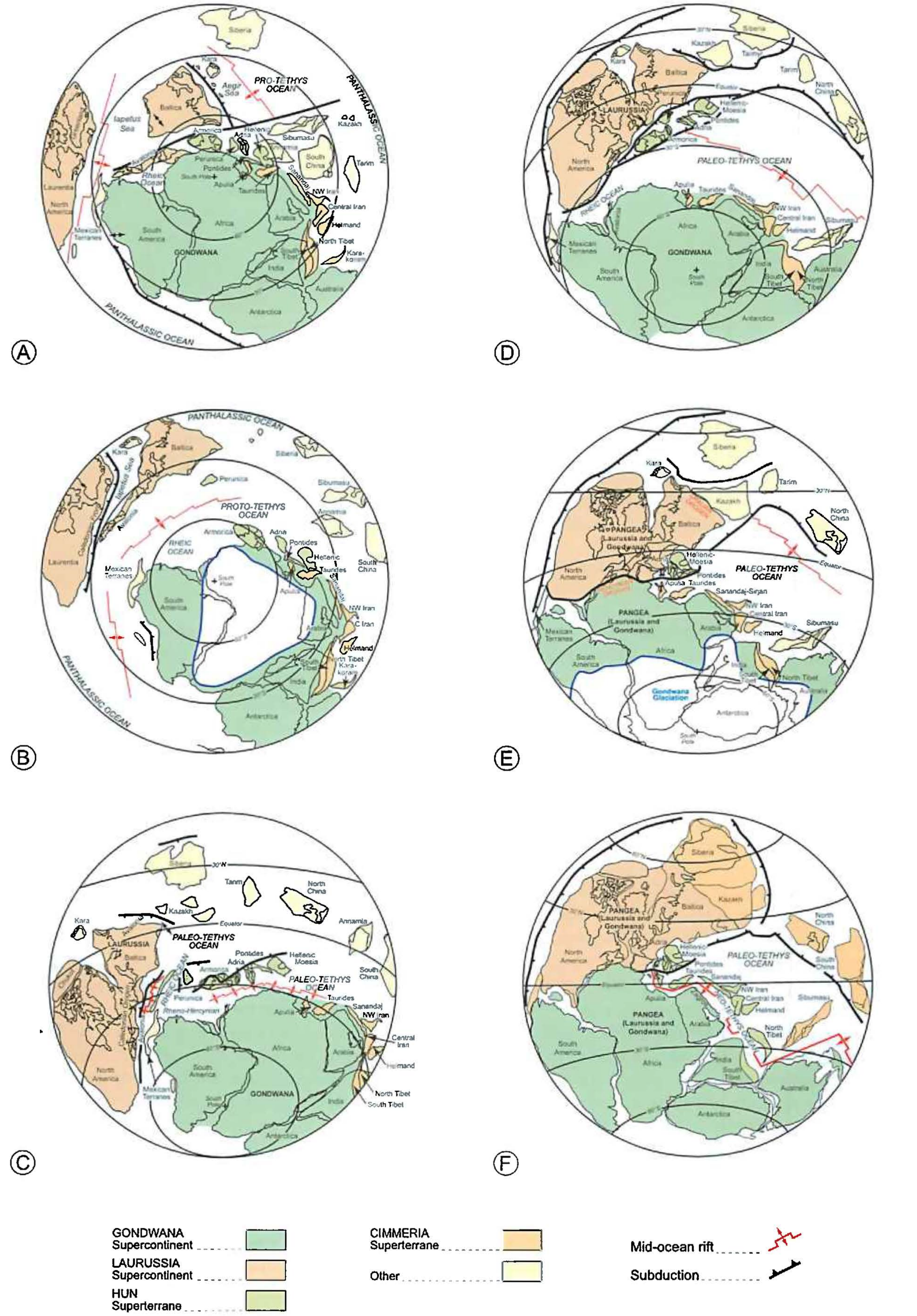


Fig. 3.26. Global plate configurations after Ruban *et al.* (2007), reproduced courtesy of *GeoArabia*. (a) Late Cambrian; (b) Late Ordovician; (c) Early Devonian; (d) Early Carboniferous; (e) Late Carboniferous: the main Hercynian orogenic belt is located to the west of Arabia; (f) Late Permian.

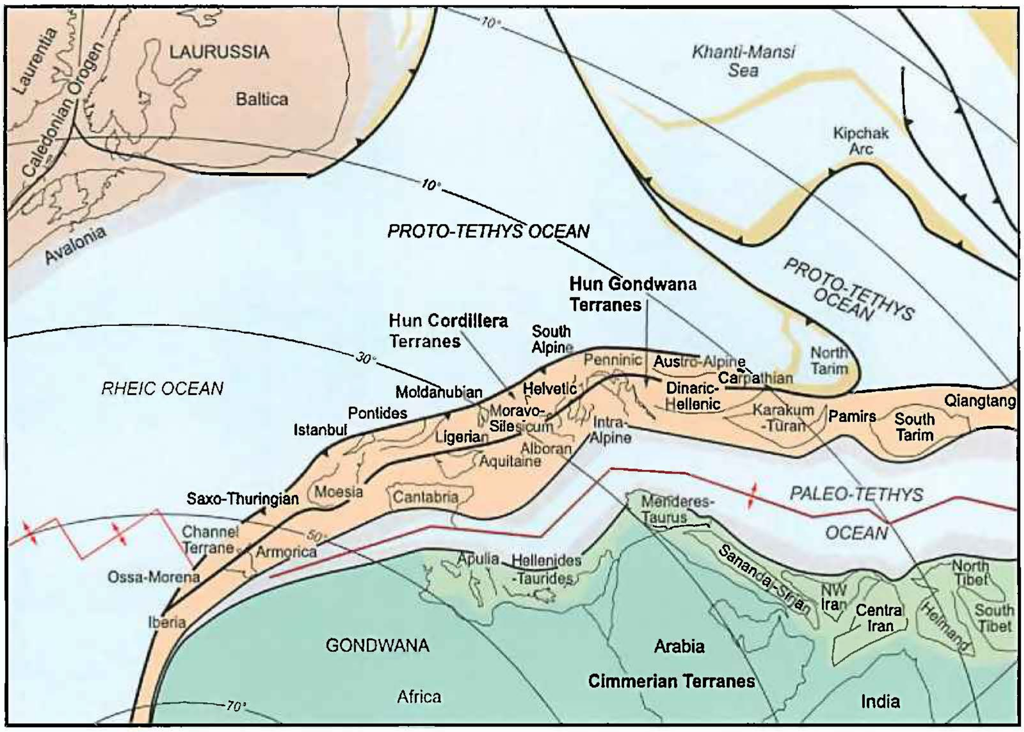


Fig. 3.27. Late Silurian plate configuration. After Ruban *et al.* (2007), reproduced courtesy of *GeoArabia*.

2001; Levell *et al.*, 1988) (Fig. 3.26e).The southwards motion of the Arabian Plate ceased abruptly at this time, and rapid northward movement then occurred from 310 to 290 Ma (Al-Fares *et al.*, 1998) (Fig. 3.23). However the Arabian Plate remained south of lat. 30°S during the remainder of the Late Carboniferous.

The change in plate motion was synchronous with a phase of regional Late Carboniferous deformation. The precise cause of this deformation is still a matter of dispute. The accompanying unconformity (previously referred to as "Hercynian" but here referred to as "Late Carboniferous") is recognised throughout the Arabian Plate and Iraq (page 99).

In Iraq, gravity and magnetic interpretation indicate that the Late Carbonifeorus unconformity is very prominent (Jassim, 2006c), although the subcrop pattern at the unconformity is currently poorly understood. The geometry of the Late Carboniferous unconformity in Iraq and adjacent countries is illustrated in Figs 3.20-3.22 and Fig. 4.29. The Salman Zone (Fig. 3.7) is interpreted to have been uplifted and deeply eroded in Late Carboniferous time (Fig 3.20) (Jassim, 2006c).

A global plate reconstruction for Late Carboniferous time (Fig 3.26e) shows that Palaeo-Tethys had closed along the "Hercynian" Suture in the west but that it remained open in the east (Ruban *et al.*, 2007). Stampfli (2000) considered that northern Gondwana was a passive margin during this time interval, and that Palaeo-Tethys was consumed by northward subduction. However other authors (Sengor, 1990; Husseini, 1991, 1992) have proposed that southward subduction of Palaeo-Tethys beneath Gondwana occurred in the Late Palaeozoic. Late Palaeozoic regional metamorphism and granite intrusion in the Cimmerian blocks in Turkey (Goncuoglu *et al.*, 2000) support the model of an active plate margin in the Carboniferous (Jassim and Goff, 2006b). Also, southward subduction may provide a better explanation for the Late Carboniferous compressional deformation which is recorded in the Arabian Plate, than long-distance propagation of compressional stresses from the Hercynian orogenic belt to the west.

A remarkable tectonic mélange occurs in the islands of Chios and the Karaburun Peninsula at the western end of the Taurides (Robertson and Pickett, 2000). The mélange is 2000 – 4000 m thick and contains blocks up to hundreds of metres across comprising platform and pelagic limestones of Silurian, Devonian and Carboniferous ages. Blocks of turbiditic sandstones, Silurian – Lower Carboniferous radiolarites and pillow lavas (associated with Silurian limestones) also occur. The mélange is unconformably overlain by Lower Triassic rocks. It may record the southward subduction of Palaeo-Tethyan oceanic crust (Robertson and Pickett, 2000) beneath the northern margin of Gondwana in Late Carboniferous time. Blocks of platform limestone may have been derived from the forearc region. The mélange has probably been preserved locally along a north-south trending transfer zone orientated oblique to the main direction of subduction.

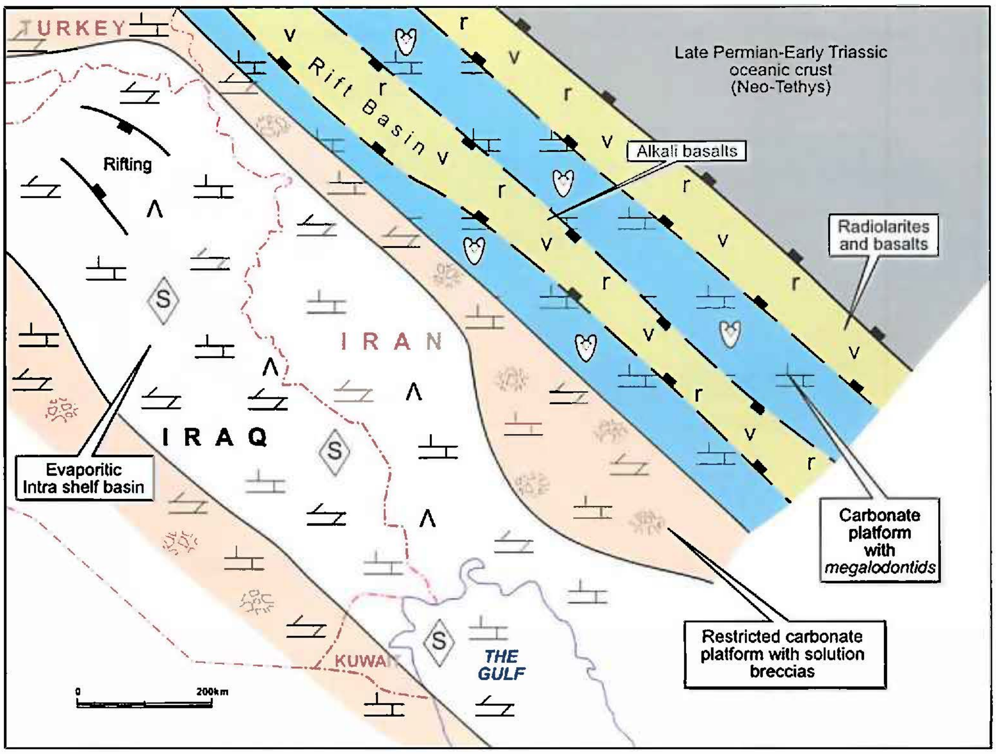


Fig. 3.28. Middle-Late Triassic (Ladinian - Carnian) palaeotectonic setting of Iraq and the SW margin of Neo-Tethys. Modified from Goff *et al.*, 2004c.

Early Permian – Early Triassic (AP5 to lower AP6)

During the Late Permian – Early Triassic, the Arabian Plate continued to drift northwards (Konert *et al.*, 2001) (Fig. 3.23). A passive continental margin developed in the NE of the Arabian Plate, and seafloor spreading resulted in opening of the oceanic Neo-Tethys in the mid-Permian (Fig. 3.26f). Spreading continued in the Early Triassic. Thermal subsidence led to a marine transgression over the Arabian Plate and formation of a north-facing carbonate platform (Altiner, 1984).

The opening of Neo-Tethys must have been preceded by major rifting. Jassim and Goff (2006b) proposed that this rifting occurred to the north and east of Iraq, and that most of Iraq formed an emergent, low-relief area unaffected by subsidence from 290 to 255 Ma. There is little direct evidence for Permian rifting in the present-day Arabian Plate. Early to mid-Permian sedimentary rocks are absent over large areas, and where present often comprise thin, poorly-dated continental clastics.

Sengor (1990) proposed that Neo-Tethyan rifting on the northern margin of Arabia took place in a back-arc setting. Thermal uplift of Oman and northern India during the initial stages of opening of Neo-Tethys was centred on the Indian Plate – Tibet Block (Levell *et al.*, 1988).

Iraq was located several hundred km south and west of the Neo-Tethyan margin in Late Permian to Early Triassic time (Jassim and Goff, 2006b). Imbricate slices of deep-water nautiloid- and ammonite-bearing red limestones emplaced onto the Arabian Plate in the Late Cretaceous probably represent a fragment of this passive margin (Jassim *et al.*, 2006b).

The rifted margin of northern Gondwana subsequently underwent Triassic – Jurassic extension, with the possible separation of a narrow micro-continent during the Early Cretaceous which was then subducted in the Late Cretaceous. The leading edge of the Arabian Plate was itself subducted in Late Cretaceous time and overthrust in the Late Tertiary. *Evidence for Permian rifting to the north of Iraq has thus been destroyed.*

Opening of the Neo-Tethys led to the separation of continental blocks from the northern margin of the Arabian Plate comprising Precambrian basement with Palaeozoic cover. They include the Sanandaj-Sirjan Zone of Iran; the Central Iran block; and a narrow sliver of continental crust represented by the Pontides of northern Turkey (Ruban *et al.*, 2007) (Fig. 3.26f).

Stampfi (2000) suggested that the Tauride block also split from Arabia during the Permian and that sea-floor spreading may have begun in the Mediterranean at this time. However the Late Permian platform carbonates in the Taurides and Arabia are very similar (Altiner,1984; Altiner, 2000), suggesting that they formed part of the same continental margin.

In Iraq, shallow-marine sediments of Mid Permian – Early Triassic age (lower part of Megasequence AP6) onlap the Late Carboniferous unconformity (page 104). They form a wedge which

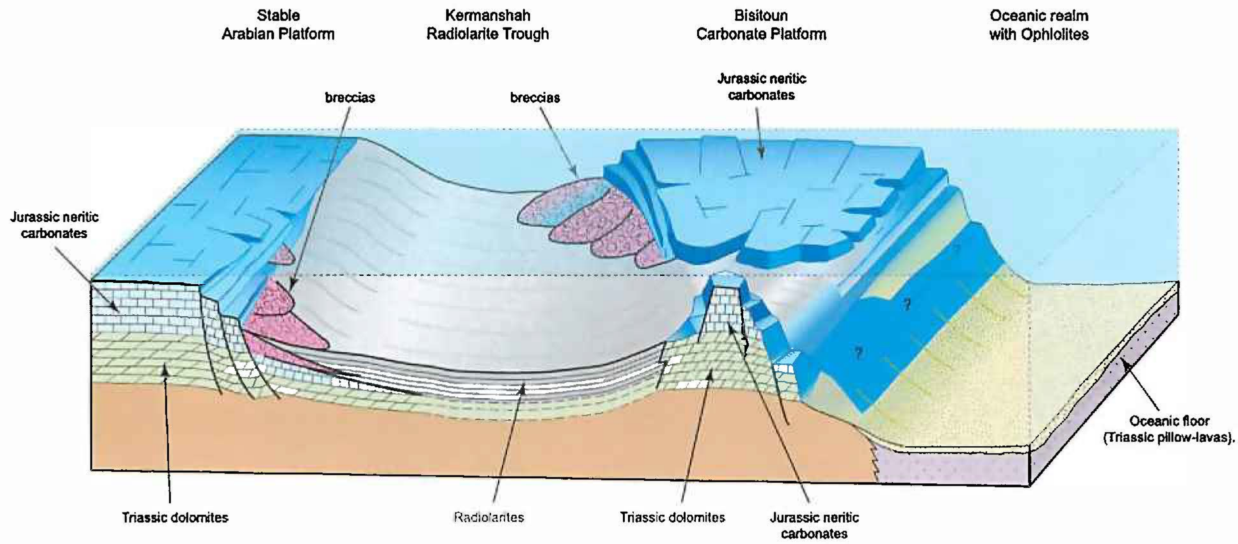


Fig. 3.29. Geometry of Mesozoic plate margin basin and high in the Bisitoun area, SW Iran. After Fontaine *et al.*, 1989.

thickens eastwards to a maximum of about 1200 m (Jassim *et al.*, 2006a). This wedge formed the proximal section of the passive margin flanking Neo-Tethys. Subsidence rates slowed markedly in latest Permian – Early Triassic time.

Mid –Triassic – early Toarcian (Upper AP6)

In Mid-Triassic – Early Jurassic time, further tectonic extension occurred within the north-facing continental margin of northern Gondwana. The leading edge of the Arabian Plate north and east of Iraq comprised a 500 km wide belt of tilted fault blocks created during mid-Triassic rifting (covered with platform carbonates) and fault-bounded troughs (Fig 3.28, 3.29). The troughs were sites of radiolarian chert deposition (Bechennec *et al.*, 1990; Fontaine *et al.*, 1989). The tectonic ridge at the plate margin and its carbonate cover (the Bitlis-Bisitoun ridge or platform) isolated the Arabian Plate interior, and restricted intrashelf basins, from the open-marine waters of Neo-Tethys (e.g. Fontaine *et al.*, 1980; Fontaine, 1981). Extensive evaporites were deposited in the restricted intrashelf basin in Iraq in Triassic time (Fig. 3.28).

The Bitlis-Bisitoun ridge was the site of megalodontid limestone deposition in the Mid to Late Triassic (Fig. 3.28; Plates 3.8-3.12). The megalodontid facies is characteristically associated with alkali basalts. Platform carbonates were also deposited on top of volcanic seamounts within Neo-Tethys (Pillevuit *et al.*, 1997); these Triassic carbonates are now present only as thrust sheets and exotic blocks in the Zagros suture zone (Neyriz and Oman exotics) (Plates 3.10, 3.11, 3.12).

Deposition of open-marine shallow-water carbonates occurred along the northern and NE margin of the Arabian Plate. Similar carbonates are recorded in the Taurides, Bitlis Massif, Avroman/Bisitoun thrust sheets, and in the Neyriz Exotics of Iran (Jassim and Goff, 2006b).

The development of a large-scale intrashelf basin in Iraq as a result of differential subsidence in Mid Triassic – Carnian time is reviewed in Chapter 5 and Fig. 5.15. Local rapid subsidence and deposition of thick, restricted carbonates and slumped evaporites in the Kand area of northern Iraq (Fig. 5.1) indicate that the basin may have formed due to subtle tectonic extension. Further south, the western margin of the Triassic intrashelf basin may have been controlled by the Abu Jir Lineament (Fig 3.7). In Norian – Early Jurassic time, subsidence rates slowed markedly and deposition of widespread and uniform shallow-water sediments of relatively constant thickness occurred.

For additional interpretation of the palaeotectonic setting of Iraq in Late Triassic *(and younger)* time, the reader is referred to the maps published by Barrier and Vrielynck (2008).

Middle Jurassic – early Tithonian (AP7)

During this interval (corresponding to Megasequence AP7 of Sharland *et al.*, 2001), the Arabian Plate reversed its northward movement (Al-Fares *et al.*, 1998) (Fig. 3.23).

Jassim and Goff (2006b) reviewed evidence for an important phase of tectonic extension in Mid-Late Jurassic time around the southern margin of Neo-Tethys extending from Oman (Rabu *et al.*, 1990; Pratt and Smewing, 1990), to the Mediterranean (Schettino and Scotese, 2002). The palaeotectonic setting of Iraq along the northern margin of the Arabian Plate is shown in Fig 3.30. Deposition of platform carbonates continued on the Bitlis-Bisitoun ridge (Plate 3.13).

In the central and eastern Mediterranean, the onset of rifting in the Toarcian resulted in the collapse and drowning of pre-Toarcian platforms

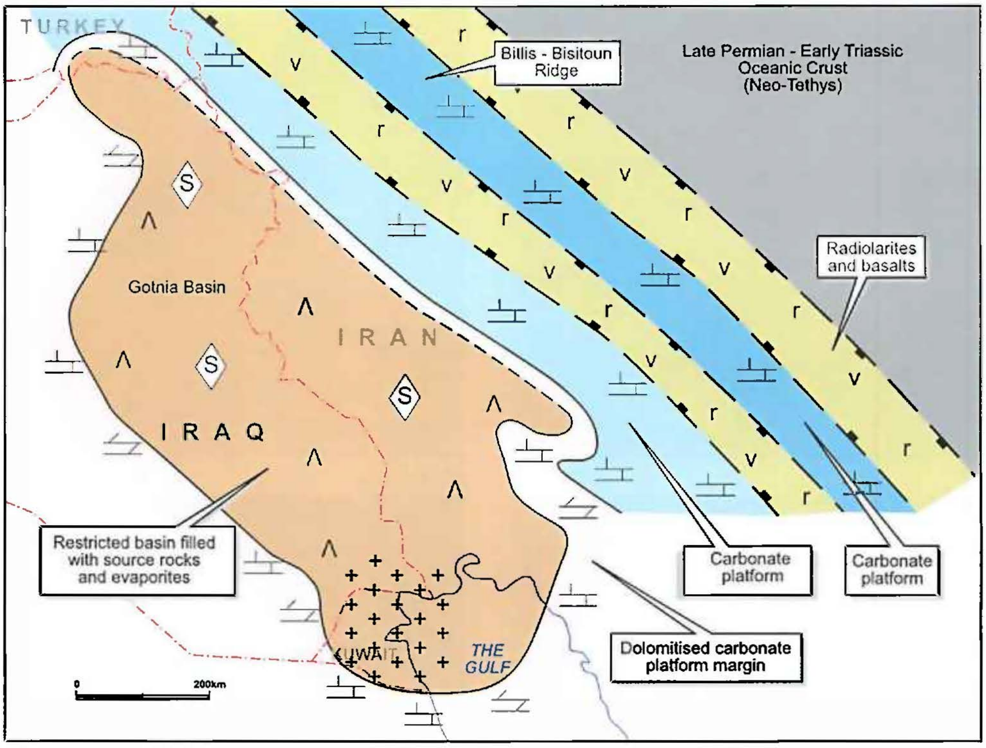


Fig. 3.30. Mid Late Jurassic palaeotectonic setting of Iraq and the SW margin of Neo-Tethys. Modified from Goff *et al.*, 2004c.

(Bernouilli and Jenkyns, 1974). Extension also occurred along the SE margin of the Arabian Plate in Late Jurassic time. NW-SE trending transtensional salt basins developed in Yemen (Maycock and Galbiati, 2001).

In Iraq, a large-scale intrashelf basin termed the Gotnia Basin formed at the end of the Early Jurassic (Figs 6.3, 6.4). The basin occupied most of southern, central, northern and NE Iraq and was relatively isolated from the open-marine waters of Tethys. It was highly restricted in mid- to Late Jurassic time resulting in the deposition of rich source rocks and evaporites. The margins of the basin were probably controlled by a system of conjugate NW-SE and SW-NE trending lineaments. A phase of faulting (and possibly structural growth) may have occurred in Late Kimmeridgian time, by analogy with the extension of the basin in Kuwait (Carman , 1996). This may have "compartmentalized" the basin with the deposition of thin evaporites taking place in northern Iraq (Fig 6.4), while thick halite and anhydrite units were deposited in SE Iraq (Fig 6.5). By the end of deposition of Megasequence AP7, only the margins of the Gotnia Basin had been filled, leaving considerable unfilled accommodation space in the sediment-starved centre (Fig 6.4).

Cretaceous

Late Tithonian - late Cenomanian (AP8)

The Arabian Plate continued to migrate southwards during late Tithonian to Aptian time, but had begun to move northwards by the Albian (110 Ma) (Al-Fares *et al.*, 1998) (Fig. 3.23). Significant regional tectonic events at this time included a major period of subsidence and passive margin sedimentation in the Eastern Mediterranean (Beydoun, 1991), the onset of rifting of India from SE Oman, and uplift of the Arabian Shield in response to thermal doming, rifting and eventual opening of the South Atlantic.

There is evidence for widespread basic volcanism of Tithonian – Albian age along the NW (Levant) margin of the Arabian Plate, and in imbricated thrust sheets in the late Campanian thrust belt of SE Turkey and NE Iraq (Jassim and Goff, 2006b). The age of the deep-water passive margin sediments (radiolarites, pelagic limestones and carbonate turbidites: Plates 3.18, 3.19) in the imbricated thrust sheets ranges from Tithonian to Cenomanian (Jassim and Goff, 2006b).

A narrow ocean ("Southern Neo-Tethys") may have opened along the northern and eastern margins of the Arabian Plate in late Tithonian time (Jassim and Goff, 2006b). This led to the rifting-away from the Arabian Plate of a narrow microcontinent or a series of continental fragments comprising the Bitlis-Bisitoun Block or ridge (Fig 3.31).

Opening of this "ocean" may have occurred by mantle exhumation during extension rather than true seafloor spreading, forming a continent-ocean transition zone similar to the southern Australian continental margin (c.f.Direen *et al.*, 2004; Beslier *et al.*, 2004).

Plate 3.8.

Plate 3.9.

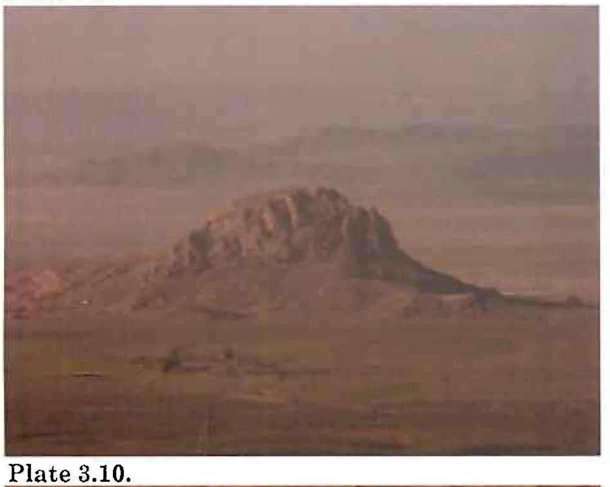


Plate 3.10.

Plate 3.11.

Plate 3.12.

Plate 3.13.

Plates 3.8- 3.19. Field photographs of allochthonous Neo-Tethyan margin and oceanic rocks from the Kermanshah, Bisitoun and Neyriz areas of SW Iran. These units are equivalent to the Avroman Limestone, Qulqula Group, Khwaqurk Series, and ophiolites of NE Iraq described by Jassim *et al.*, 2006b, c. Photos by J. Goff.

Plate 3.8. Massive megalodontid-bearing Triassic platform carbonate. Bisitoun, SW Iran.
Plate 3.9. Megalodontid bivalves from locality in Plate 3.8.
Plate 3.10. Exotic block of Triassic limestones embedded in a mélange of radiolarite and basalt. Neyriz area, SW Iran.
Plate 3.11. Contact of the exotic block of Plate 3.10 with the mélange matrix.
Plate 3.12. Megalodontid bivalves in the exotic block of Plate 3.11.
Plate 3.13. Jurassic platform carbonates, Bisitoun, SW Iran. Cliff is about 300 m high.

Plate 3.14.

Plate 3.15.

Plate 3.16.

Plate 3.17.

Plate 3.18.

Plate 3.19.

Plate 3.14. Lower Cretaceous – Cenomanian platform carbonates, Bisitoun, SW Iran. Cliff is about 1000 m high. The carbonates are in thrust contact with an ophiolitic mélange in the foreground containing radiolarites and basalts.
Plate 3.15. Huge exotic block of marble embedded in peridotite. Neyriz area, SW Iran.
Plate 3.16. Tectonic contact of marble block of Plate 3.15 with peridotite. Skarn mineralisation occurs along the contact.
Plate 3.17. Large block of serpentinised peridotite from an ophiolitic mélange, Kermanshah area, SW Iran.
Plate 3.18. Deformed stratigraphic units of cherty limestones interbedded with radiolarites, Kermanshah area, SW Iran.
Plate 3.19. Radiolarites, Neyriz area, SW Iran.

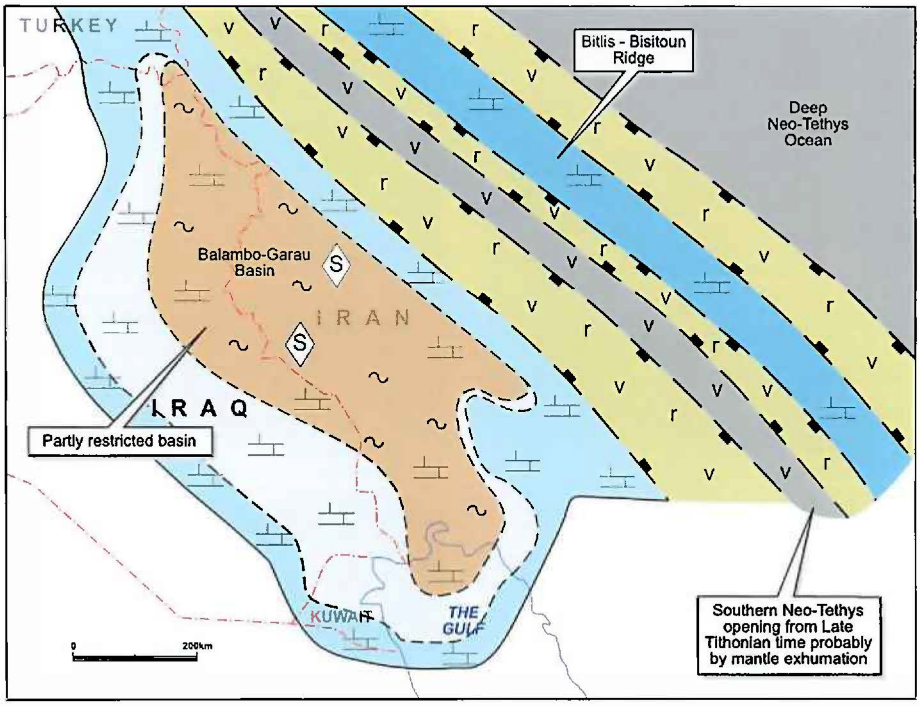


Fig.3.31. Early Cretaceous palaeotectonic setting of Iraq and the SW margin of Neo-Tethys. Modified from Goff *et al.*, 2004c.

In Oman, there is well documented Tithonian collapse of the Tethyan continental margin and SW retreat of the continental slope by several hundred km (Rabu *et al.*, 1990). This indicates major extension of the continental margin at this time.

The late Tithonian extension may have been driven by the formation of a NE-dipping intra-oceanic subduction zone within the southern part of Neo-Tethys (Jassim and Goff, 2006b)(Fig. 3.32). Intra-oceanic subduction is required to explain the geochemical signature of the Cenomanian oceanic crust which was obducted onto the leading edge of the Arabian Plate in the late Campanian. Intra-oceanic subduction must therefore have begun before the Cenomanian.

All the massive ophiolite sheets (comprising peridotites and other ultrabasic rocks, gabbros, local dykes, pillow basalts, and overlying calc-alkaline volcanics), which outcrop around the Arabian Plate from Troodos in Cyprus to Semail in Oman, have a supra-subduction zone signature. Where dated, these ophiolites also have a narrow age range (Cenomanian). They are thus younger than the Tithonian – Albian volcanics which occur in a structurally lower ophiolitic mélange containing serpentinites (Plate 3.17), radiolarites, pelagic carbonates and carbonate turbidites (Jassim and Goff, 2006b).

Deposition of thick, shallow-water platform carbonates on the Bitlis-Bisitoun ridge continued in Early Cretaceous to Cenomanian time (Fig. 3.31, 3.32; Plate 3.14).

In Iraq, evaporite deposition in the Gotnia Basin ceased in mid Tithonian time, probably associated with the opening of the Southern Neo-Tethys (Jassim and Goff, 2006b). The Gotnia Basin was succeeded in late Tithonian time by the Balambo-Garau Basin (Fig 3.31). Passive subsidence in this basin, aggradation and progradation of carbonate platform margins, and subtle tectonic controls on sedimentation are reviewed in Chapter 7. The margins of the basin were probably controlled by NW-SE and north-south trending basement lineaments e.g the Abu Jir Lineament (located on Fig 3.7).

The thickness of Megasequence AP8 increases from west to east across Iraq, reaching 2000 m in the axis of the Balambo-Garau Basin (Jassim and Buday, 2006e). Minimum thicknesses of Megasequence AP8 occur in western Iraq over the Mosul Block and Khleisia High (Fig 3.7), and in the Western Desert and SW Iraq (Jassim and Buday 2006e).The megasequence had a ramp-like geometry in late Tithonian – late Albian time (Figs 7.5, 7.16, 7.28).

Differential subsidence resulted in the development of a subtle intrashelf basin between two north-south trending palaeohighs (on which carbonate platforms developed) in SE Iraq in late Albian – Cenomanian time (Figs 3.32).

Turonian - early Campanian (lower AP9)

Deformation of the passive margin of the Arabian Plate is recorded by the deposition of limestone conglomerates in the Qulqula Group in Iraqi Kurdistan (Jassim *et al.*, 2006b). Jassim and Goff (2006b) attributed this deformation to a Turonian tectonic event along the intra-oceanic subduction zone in Neo-Tethys to the east. This involved the collision of the NE-facing margin of the Bitlis-

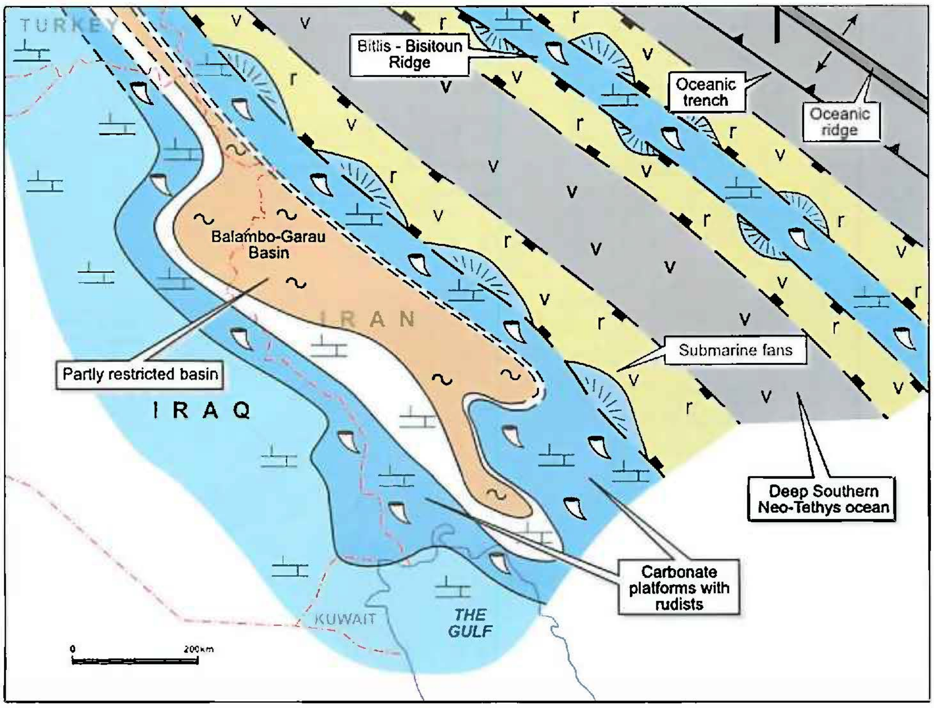


Fig. 3.32. Cenomanian palaeotectonic setting of Iraq and the SW margin of Neo-Tethys. Modified from Goff *et al.*, 2004c.

Bisitoun Block with the oceanic plate above the subduction zone. The position of the Bitlis-Bisitoun ridge relative to the subduction zone just prior to collision is shown in Fig. 3.32. Growth of important north-south trending anticlines in SE Iraq may have occurred in response to this collision during Turonian - early Campanian time.

Imbrication of the north- and east-facing passive margin of the Bitlis-Bisitoun ridge occurred, with westerly transport of thrust sheets of Late Permian – Cenomanian oceanic and slope sediments (Jassim and Goff, 2006b). The SW-facing passive margin of the Bitlis-Bisitoun ridge, the sedimentary cover of the Southern Neo-Tethys Ocean and the continental slope of the Arabian Plate were also progressively imbricated to form thrust sheets of radiolarites, pelagic limestones and carbonate slope deposits.

In Iraq, up to 500 m of mainly basinal sediments of the lower part of Megasequence AP9 were deposited in the Balambo-Garau Basin in Turonian – early Campanian time (Jassim and Buday, 2006f) (Fig. 7.45). Diverse facies were initially deposited following a period of uplift and localised extensional faulting.

Tectonic extension gave rise to the Sinjar Trough in NW Iraq (located in Fig 3.7) and other narrow, fault-controlled basins. Sediments of Turonian – early Campanian age are absent on the Mosul, Khleisia and Rutbah Highs which were emergent during this time interval.

Late Campanian – Maastrichtian (upper AP9)

In late Campanian – early Maastrichtian time, ophiolites were obducted onto the Arabian Plate. Flexural loading by the ophiolitic thrust sheets created a narrow foreland basin that extended around the eastern and northern margin of the Arabian Plate from Oman through SW Iran and NW Iraq to SE Turkey. The obducted ophiolites and associated deep-water sedimentary rocks were elevated above sea-level (Jassim and Goff, 2006b). The uplifted ophiolites and associated sedimentary rocks were eroded and re-deposited in the foredeep basin as flysch up to 2000 m thick (Fig. 3.33). Ophiolite obduction ceased at the end of the early Maastrichtian. The ophiolites were partially onlapped along the NE margin of the foreland basin by Upper Maastrichtian shallow-water conglomerates and carbonates containing *Loftusia.*

By the end of the early Maastrichtian, Southern Neo-Tethys had completely closed (Jassim and Goff, 2006b). Southern Neo-Tethyan oceanic crust is preserved as imbricates of pillow lavas, basalts, gabbros and serpentinitised ultramafic rocks. To the north and NE of the late Campanian to early Maastrichtian thrust belt lay the deformed oceanic crust of the Central Neo-Tethys. These deformed ophiolitic rocks were not emplaced onto the Arabian Plate until the late Miocene. They include an ophiolite of Early Cretaceous age in NE Iraq which was probably derived from the northern part of Central Neo-Tethys (close to the Sanandaj-Sirjan Zone of Iran) (Jassim *et al.*, 2006c).

The leading edge of the continental crust of the Arabian Plate was subducted, as indicated by early Campanian high pressure metamorphism in Oman with the formation of blueschists and eclogites (Warren *et al.*, 2003; Searle *et al.*, 2004).

Tectonic controls on subsidence and sedimentation in Iraq in late Campanian –

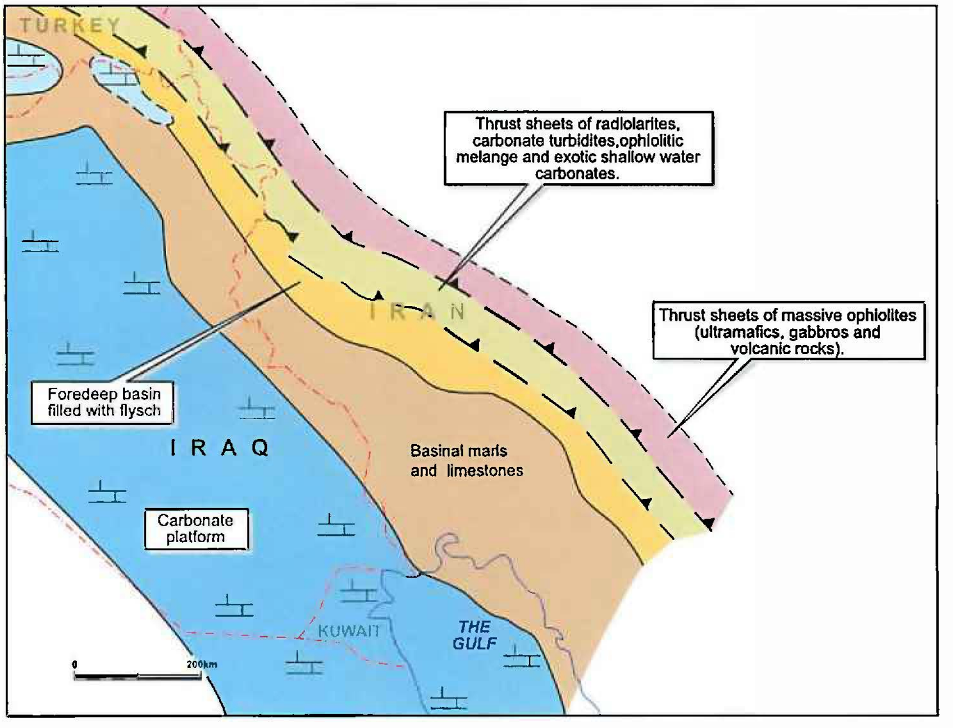


Fig. 3.33. Late Campanian - early Maastrichtian palaeotectonic setting of Iraq. Modified from Goff *et al.*, 2004c.

Maastrichtian time are discussed in Chapter 7, and illustrated in Fig 7.53A. The narrow foredeep in NE Iraq formed a prominent basin (Fig 3.33). Fault-controlled transtensional basins formed at this time including the Anah Trough, together with NW-SE wrench-related structures such as the East Baghdad Lineament (located in Fig 3.7). Up to 2000 m of sediment were deposited in both the foredeep basin and in the Anah Graben (Jassim and Buday, 2006f). Prominent palaeohighs (e.g. the Khleisia High) were onlapped in late Campanian time. Mild inversion occurred at the end of the Cretaceous with widespread partial erosion of Maastrichtian sediments, and the formation of a regional unconformity at the base of the Tertiary.

Tertiary (AP10)

In Paleocene- Eocene time, Arabia continued to move northwards (Fig 3.23). A new NE-dipping intra-oceanic subduction zone formed in the Neo-Tethys (Jassim and Goff, 2006b). The products of this subduction in Iraq are the volcanics of the Walash Group in Iraqi Kurdistan which formed in an island-arc setting, and the clastic-dominated Naopurdan Group which was deposited in a forearc basin (Jassim *et al.*, 2006). The subduction zone extended westwards into eastern Turkey and to the SE into Iran. In Turkey, the Hakkari Complex (Perincek, 1990) is a tectonic mélange formed in an accretionary prism; the Maden Complex and Helete Volcanics formed in a back-arc basin and in an island-arc, respectively (Yilmaz, 1993a,b). Similar active-margin type volcanics and sediments have been mapped in adjacent parts of Iran (Geological Survey of Iran 1:100,000 Map Series).

On the NE edge of the Arabian Plate, the Suwais Red Beds in Iraqi Kurdistan were deposited in a molasse basin overlying the thrust sheets that had been emplaced in the late Campanian – early Maastrichtian. The molasse and flysch of the Red Beds were derived from these thrust sheets (Jassim *et al.*, 2006), and comprise conglomerates containing pebbles of chert and limestone, siltstones and shales, and nummulitic limestones. As subduction continued to the NE, the molasse basin merged with the accretionary prism of the Paleogene subduction zone. The fill of the Naopurdan forearc basin was eventually thrust to the SW onto the Suwais Red Beds in the late Miocene (Jassim and Goff, 2006b).

Two observations suggest that the Neo-Tethys Ocean adjacent to Iraq closed in the early late Eocene. Firstly, collision of the Bitlis-Bisitoun Block with the Sanandaj-Sirjan Zone is indicated by a thrust fault of early late Eocene age at the eastern end of the Bitlis Massif, which is sealed by unconformably-overlying late Eocene-Oligocene siliciclastics derived from the Sanandaj Sirjan Zone (Perincek, 1990). Secondly, in Western Iran, the upper part of the volcaniclastic succession equivalent to the Naopurdan Group of Iraq passes eastwards into molasse containing large boulders derived from the advancing thrust sheets of the Sanandaj-Sirjan Zone (Geological Survey of Iran 1:100,000 Map Series).

In NE Iraq, the proximal (NE) part of the Late Cretaceous foredeep basin was uplifted in Paleocene

– Oligocene time. A NW-SE trending basin, referred to here as the Mesopotamian Basin, was established to the SW in which up to 2000 m of sediment was deposited (Fig 8.9). The basin was bordered by carbonate shelves on both sides (Fig 8.6); the axis of the basin was frequently starved of sediment. Periodic uplift of the thrust sheets that had been emplaced in Late Cretaceous time in NE Iraq led to progradation of clastic wedges to the SW (Figs 8.10, 8.11). By Oligocene time, the influx of siliciclastics from the NE had ceased and very limited subsidence occurred (Fig 8.17). Uplift of the NE margin of the basin resulted in an offlapping geometry for Eocene and Oligocene units, and the formation of a regional unconformity at the base of the Miocene across much of Iraqi Kurdistan.

In Oligocene time, the Arabian Plate began to migrate NE-wards in response to the start of sea-floor spreading in the Gulf of Aden and the Red Sea (Burke and Whiteman, 1973; Al-Fares *et al.*, 1998). The plate was tilted towards the NE due to thermal doming on its SW margin. Sea-floor spreading began in the Gulf of Aden in the Oligocene and in the Red Sea in the Miocene. Left-lateral strike slip occurred along the Dead Sea Fault.

In early to early Mid Miocene time, limited tectonic subsidence occurred on the Arabian Plate. Subsidence rates were low and shallow-water carbonates and evaporites were deposited. However in late mid to early late Miocene time, renewed compression occurred between the NE margin of the Arabian Plate in Iraq and the Sanandaj-Sirjan Zone. The accretionary prism which had formed in the Paleogene to the SW of the Sanandaj-Sirjan Zone was uplifted and exhumed (Jassim and Goff, 2006b). Huge volumes of fine silt and mud were rapidly eroded and transported to the SE during renewed subsidence of the Mesopotamian Basin in NE Iraq and SW Iran.

With progressive sea-floor spreading in the Red Sea and Gulf of Aden in late Miocene time, accompanied by further left-lateral strike-slip along the Dead Sea Fault, further collision occurred between the Arabian Plate and the Sanandaj-Sirjan Zone. Advancing thrust sheets of the Sanandaj-Sirjan Zone then overrode the accretionary prism and shed clastic debris into the Late Miocene foreland basin in NE Iraq (Bakhtiari Formation: page 277). Locally, by the end of the late Miocene, the thrust sheets of the Sanandaj-Sirjan Zone had advanced across the Southern Neo-Tethys suture onto the Arabian Plate (Jassim and Goff, 2006b).

Following the formation of a regional unconformity and the influx of fine-grained sediments from the NE, rapid subsidence began in the Mesopotamian Basin in late Mid Miocene time continuing into the early Late Miocene. Intense compression began in northern Iraq in late Late Miocene time, synchronous with rapid tectonic subsidence in the foreland basin between actively growing anticlines. This compression formed the present-day Folded Zone in Iraq (Fig 3.7). Growth of the NE–SW trending "Zagros" anticlines in NE Iraq, and inversion anticlines in NW Iraq (Plates 3.1- 3.7, cross-sections 5 -8) occurred at this time. Regional uplift in western Iraq reactivated the Mosul and Khleisia Highs (Fig 3.7) and formed the regional-scale Hauran Anticline in the Western Desert (Jassim and Buday, 2006a).

By the beginning of the Pliocene, the Arabian Plate and the Sanandaj-Sirjan Zone had become sutured, and the Bitlis-Bisitoun Block was completely overridden except in Eastern Turkey. At the eastern end of the Bitlis Massif, the Bitlis Block plunges to the SE beneath the Yuksekova Melange and is overlain by klippen of the Mordag Metamorphics; outcrops of these latter units can be traced via the Turkey-Iran border into the Sanandaj-Sirjan Zone of Iran. The Bitlis Block may thus be underplated to the Sanandaj-Sirjan Zone (Jassim and Goff, 2006b).

During the Pliocene, a change in plate motion occurred along the collision zone between the Arabian and Eurasian / Iranian Plates. Up to 70 km of deep-seated (33-70 km) right-lateral strike-slip movement occurred in the Plio-Pleistocene between the Arabian Plate and the Sanandaj-Sirjan Zone (Talabian and Jackson, 2002).

Pliocene compression initially resulted in progradation of large-scale alluvial fans into the foreland basin, while the growth of anticlines occurred with onlap and rotation of flanking sediments. Deformation then changed from predominantly compressional to predominantly strike slip. As a result, foreland basin subsidence in Iraq ceased and much of the country became an area of net erosion. A major regional unconformity thus occurs at the base of the Quaternary. Seismicity and active folding indicate that deformation continues at the present day (Ghalib, 1977; Mann and Vita-Finzi, 1982; Ayar and Al-Salim, 1986; Hessami *et al.*, 2001).

During the Pleistocene, Iraq became an area of net erosion with the development of the Tigris and Euphrates river systems. These drain from Southern Turkey and transport sediment to the SE into the Mesopotamian Plain (Aqrawi, 1993c; Aqrawi and Evans, 1994). Quaternary – Holocene sediments were deposited on a regional unconformity surface following intense deformation along the collision zone between the Arabian and Iranian Plates. A thickness of up to a few hundred metres of sediment overlies this unconformity.

Localised Plio-Pleistocene volcanism in various plate-interior locations is related to north-south to NNW-SSE extension. The nearest igneous centres to Iraq are those in SE Turkey (Karacadag Cone) and the Drouz/Azraq area of Syria and Jordan (Lovelock, 1984).

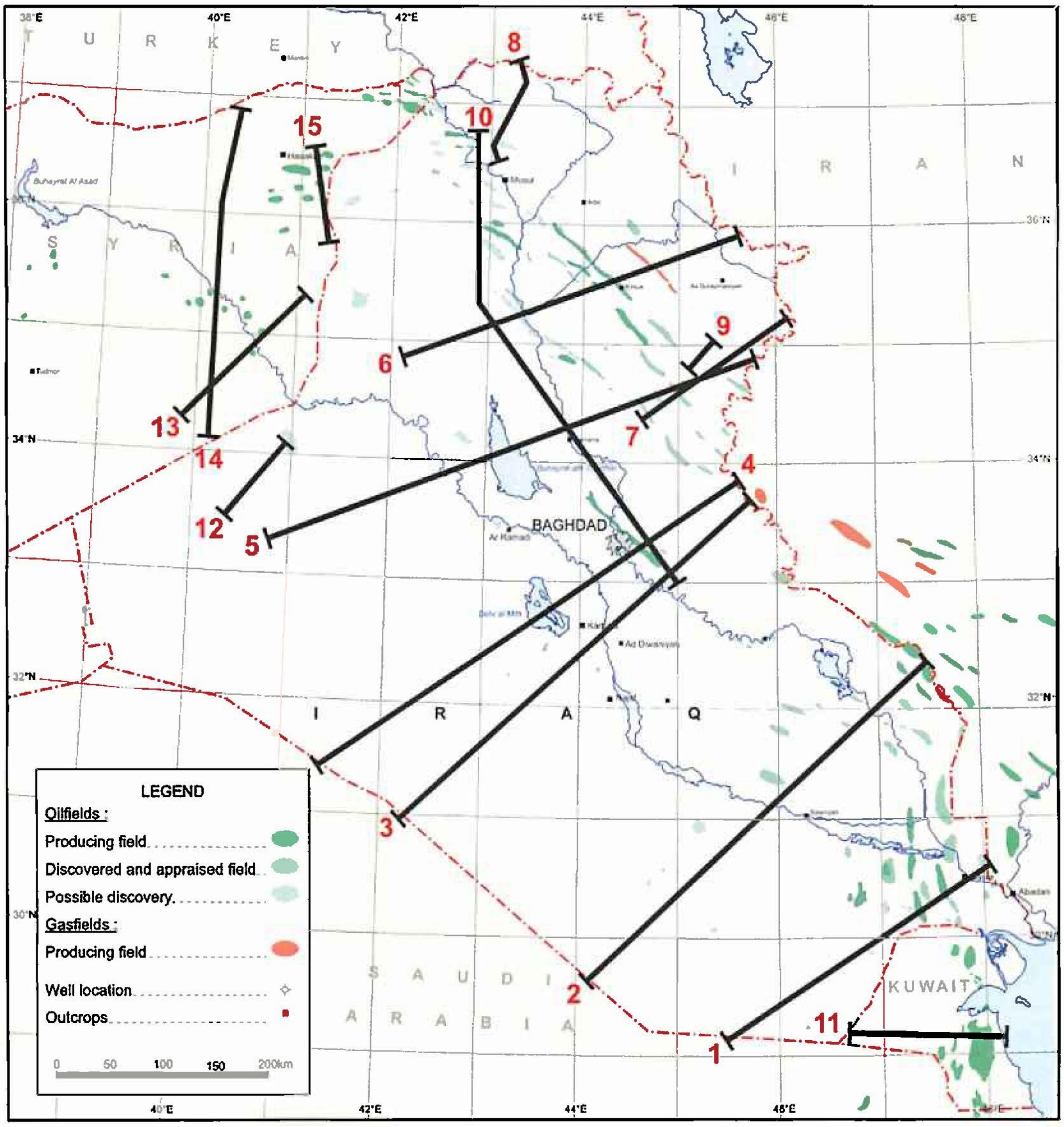
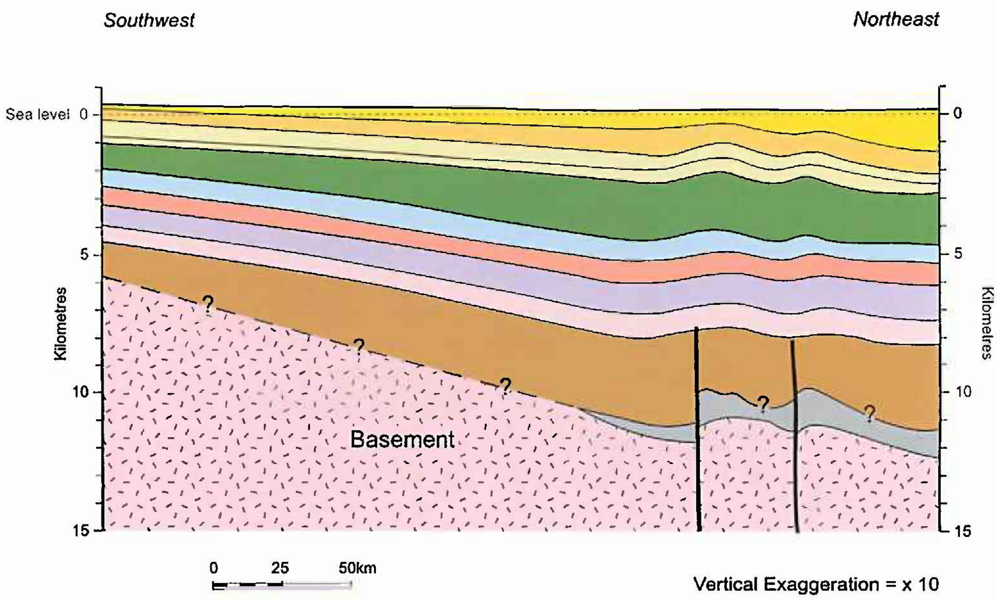
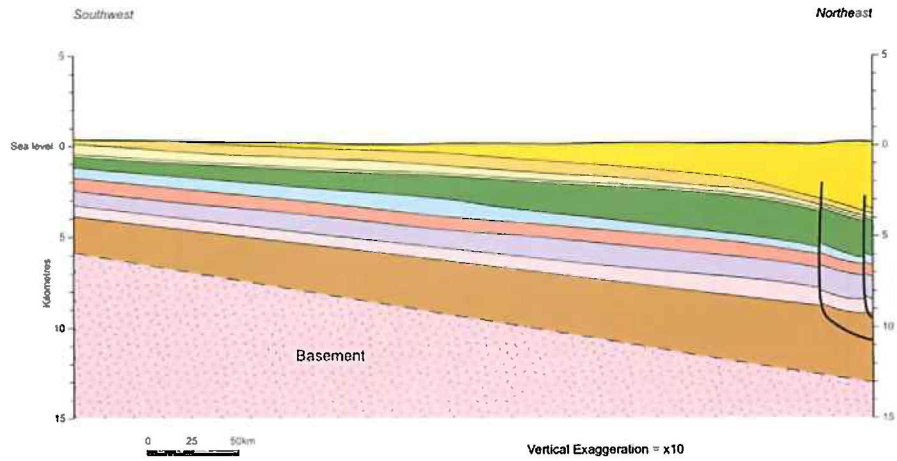


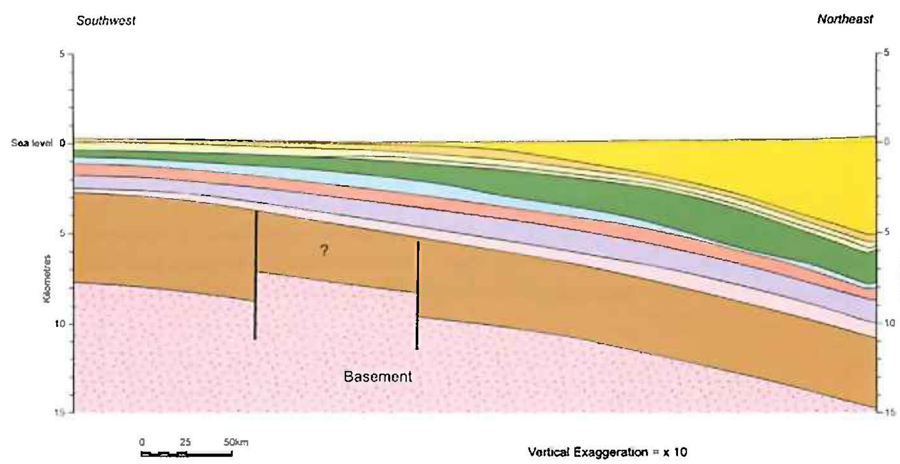
Fig. 3.34. Map of Iraq showing the locations of geological cross-sections 1-15.



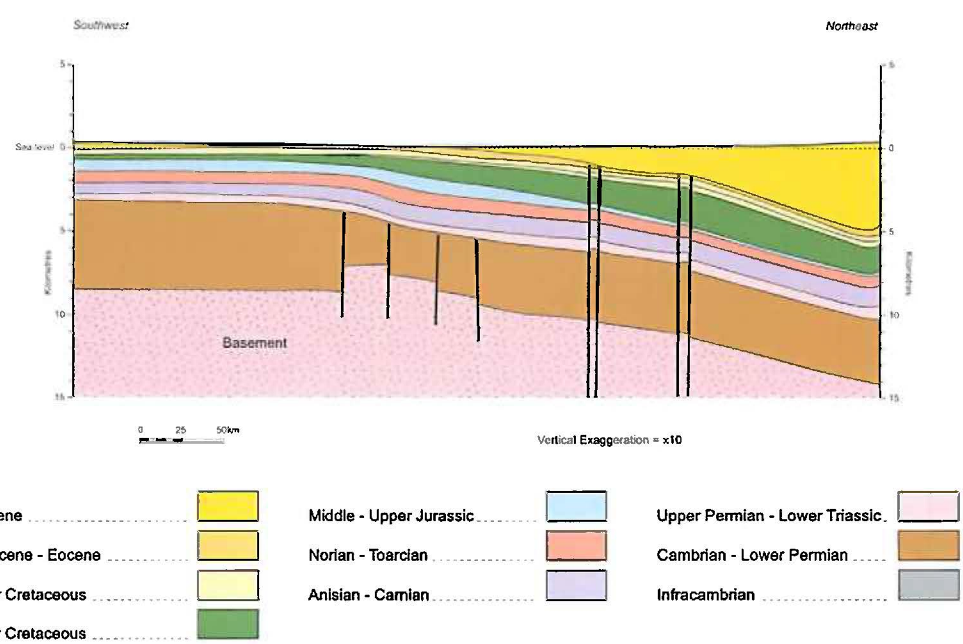
Cross-section 1. SW-NE structural cross-section across SE Iraq (see profile location in Fig. 3.34). Note the large-scale north-south trending anticlines which grew in early Late Cretaceous and late Miocene time, with an earlier phase of movement in the Late Carboniferous. See key on page 59.



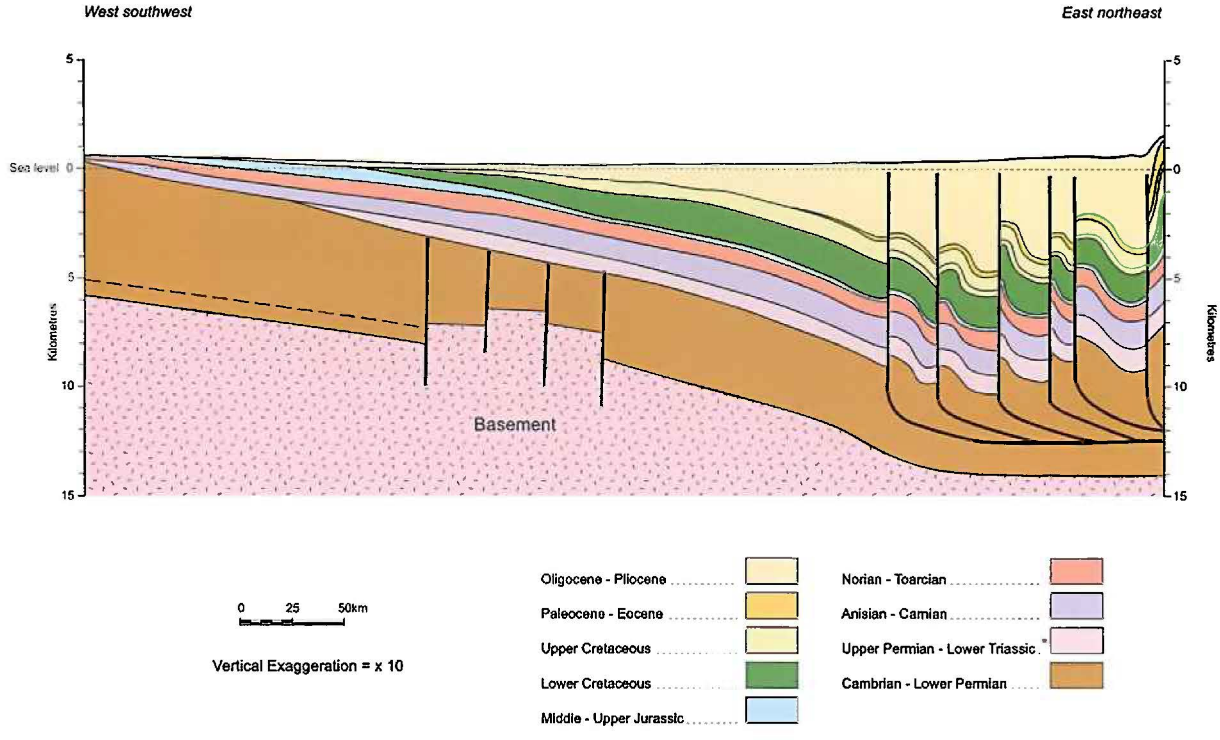
Cross-section 2. SW-NE structural cross-section across southern Iraq (see profile location in Fig. 3.34). Note the "front" of late Miocene deformation in the NE of the section.



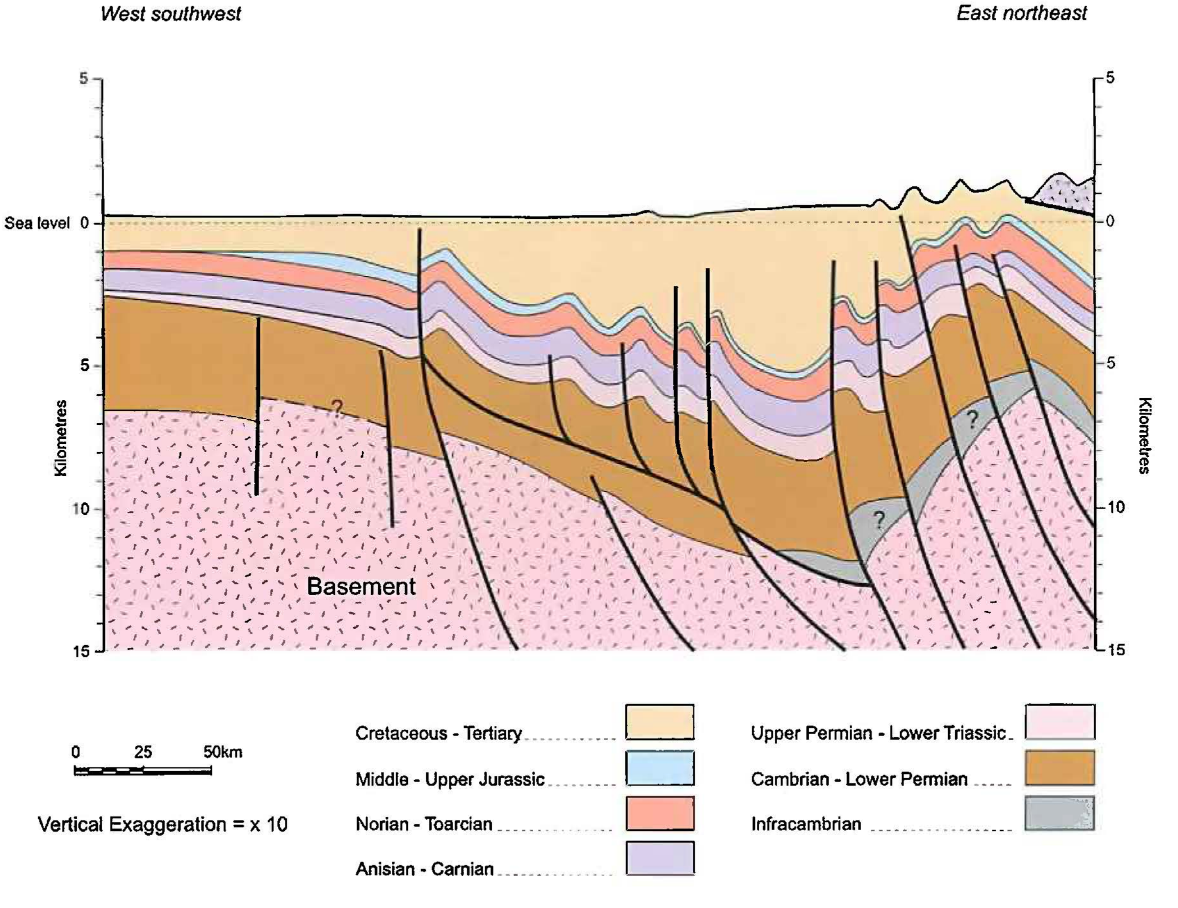
Cross-section 3. SW-NE structural cross-section across Central Iraq (see profile location in Fig. 3.34). Note the possible basement-involved structure (formed by ?Late Carboniferous deformation).



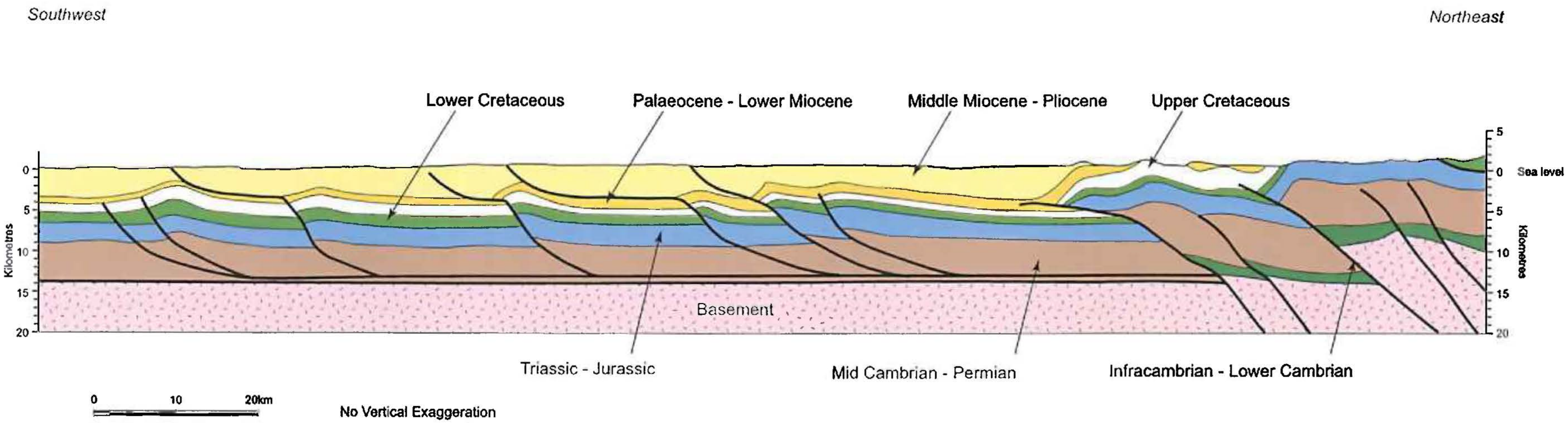
Cross-section 4. SW-NE structural cross-section across Central Iraq (see profile location in Fig. 3.34). Note the narrow, "wrench related" structures along the East Baghdad trend, and older possibly Late Carboniferous structures to the west.



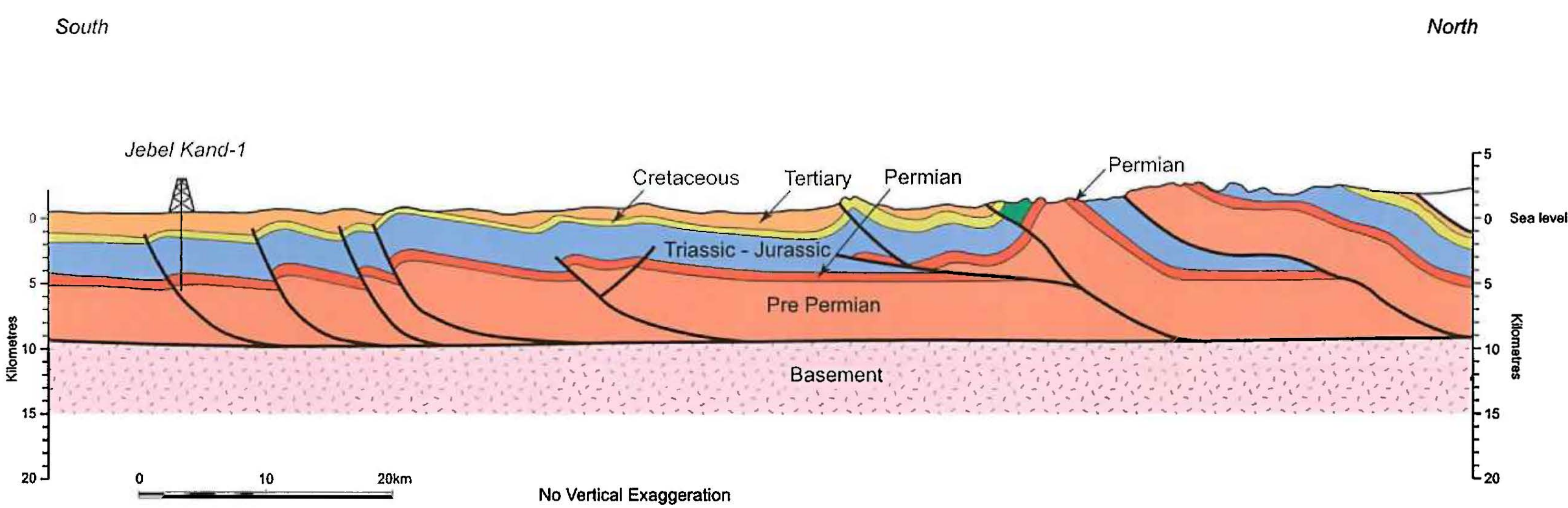
Cross-section 5. WSW-ENE structural cross-section across central-northern Iraq (see profile location in Fig. 3.34). Note the closely spaced "Zagros" folds controlled by thrusts which are shown schematically detaching in Lower Palaeozoic shales. An alternative model for this cross-section and cross-section 6 would involve thrust detachment in phyllites in the uppermost part of the basement.



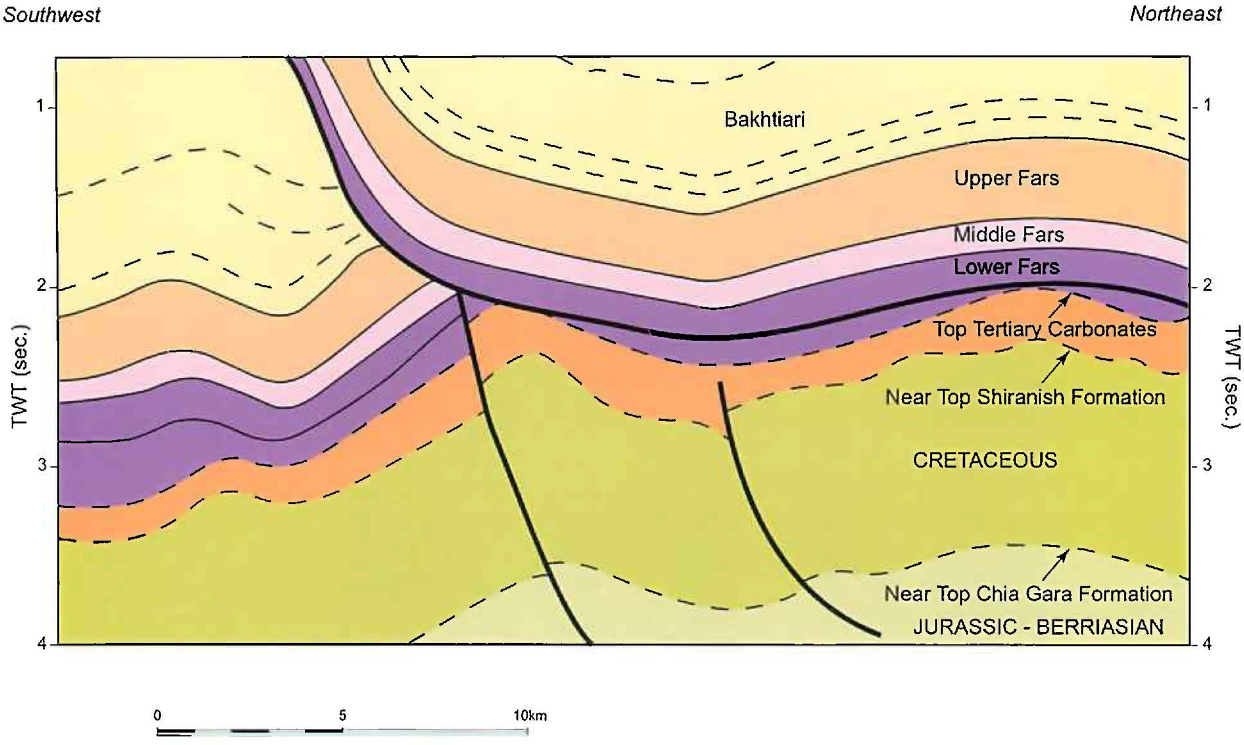
Cross-section 6. WSW-ENE structural cross-section across Northern Iraq (see profile location in Fig. 3.34). This interpretation shows steeply-dipping faults cutting the basement.



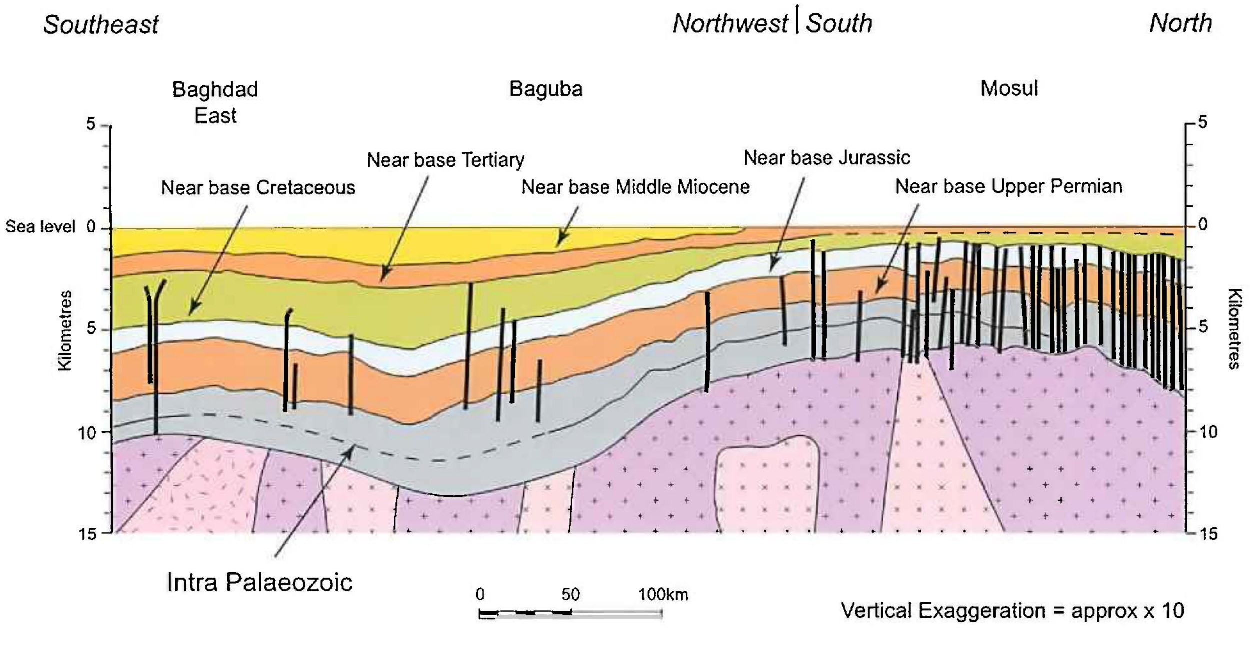
Cross-section 7. SW-NE structural cross-section across NE Iraq (see profile location in Fig. 3.34). The balanced cross-section shows a detachment near the base of the Lower Palaeozoic section beneath the foreland basin, and in the basement beneath the High Folded Zone.



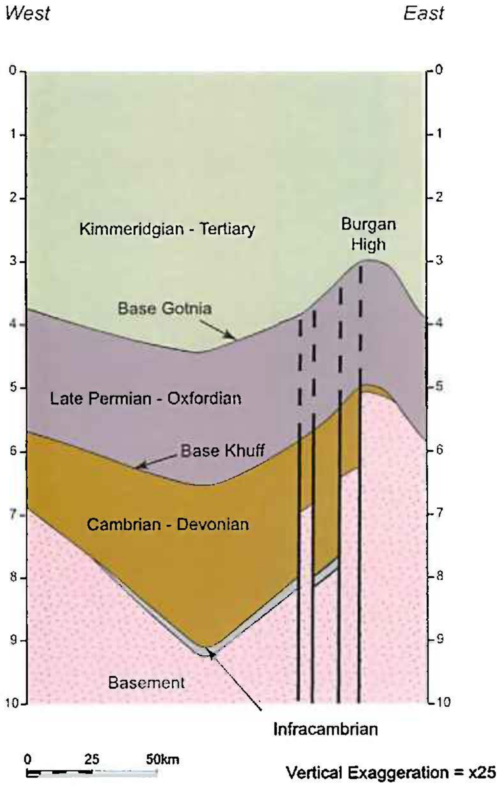
Cross-section 8. North-south structural cross-section across Northern Iraq (see profile location in Fig. 3.34). In this interpretation, the elevated ramp anticlines in the north do not include the basement.

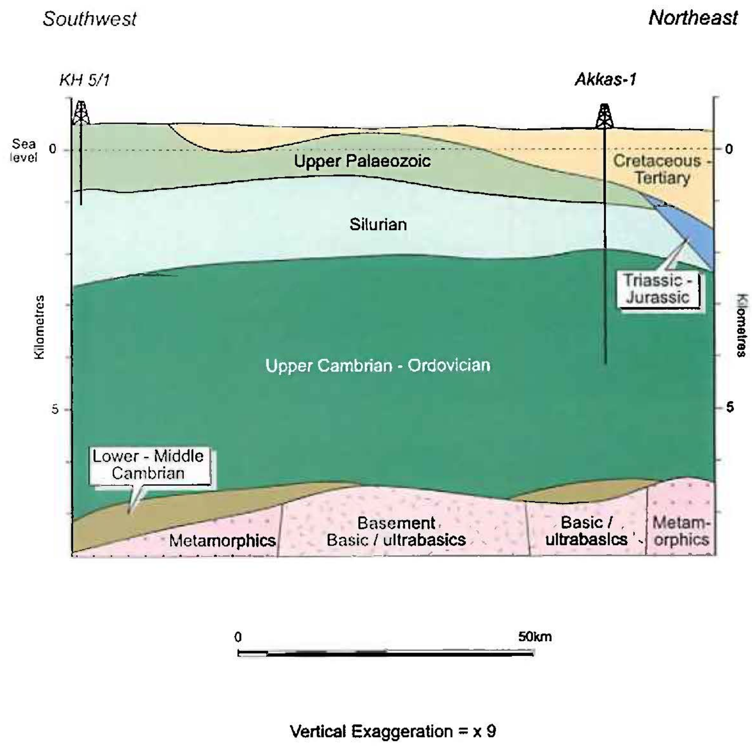


Cross-section 9. Local SW-NE stuctural cross-section across NE Iraq (see profile location in Fig. 3.34). The cross-section is based on a published seismic line and shows shallow deformation in the Miocene section, and major structural growth post-dating deposition of the Upper Fars Formation. Modified from Western Zagros (corporate presentation), March 2008.



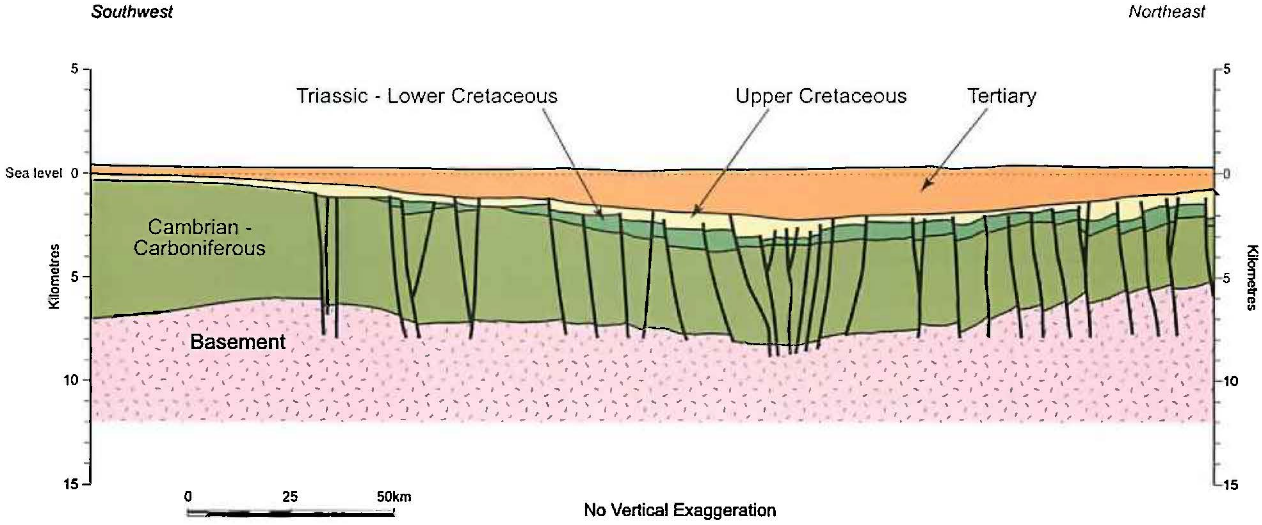
Cross-section 10. SE-NW – north-south structural cross-section across Central and Northern Iraq from East Baghdad to the Mosul High (see profile location in Fig. 3.34) (after Al-Saigh *et al.*, 1993). Note the multiple faults affecting the Mosul High.



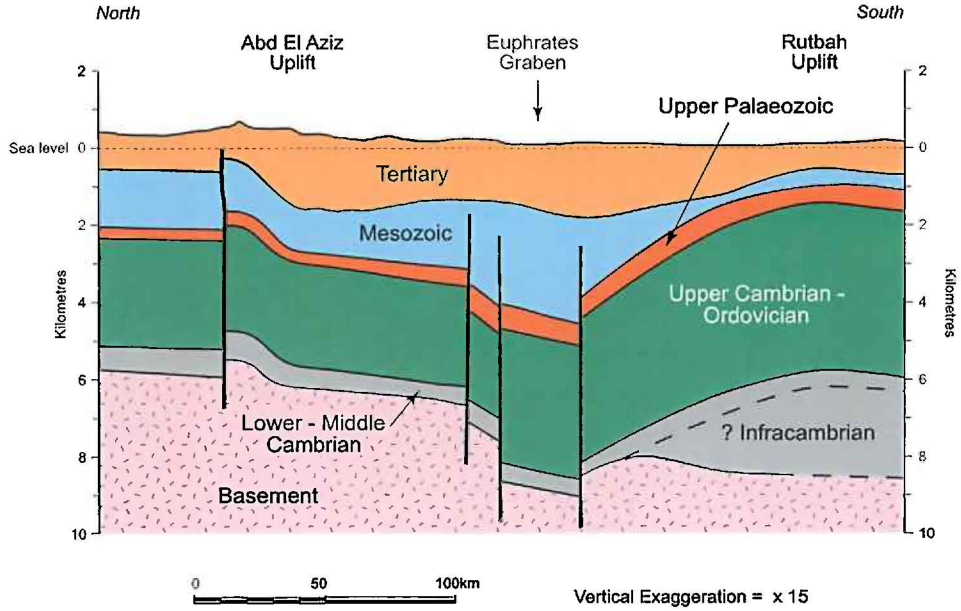


Cross-section 11(above left). Local east-west structural cross-section across the Burgan High in Kuwait (see profile location in Fig. 3.34) (after Strohmenger *et al.*, 2003). Depth to basement in the Burgan High is constrained by well data. Depth in km.

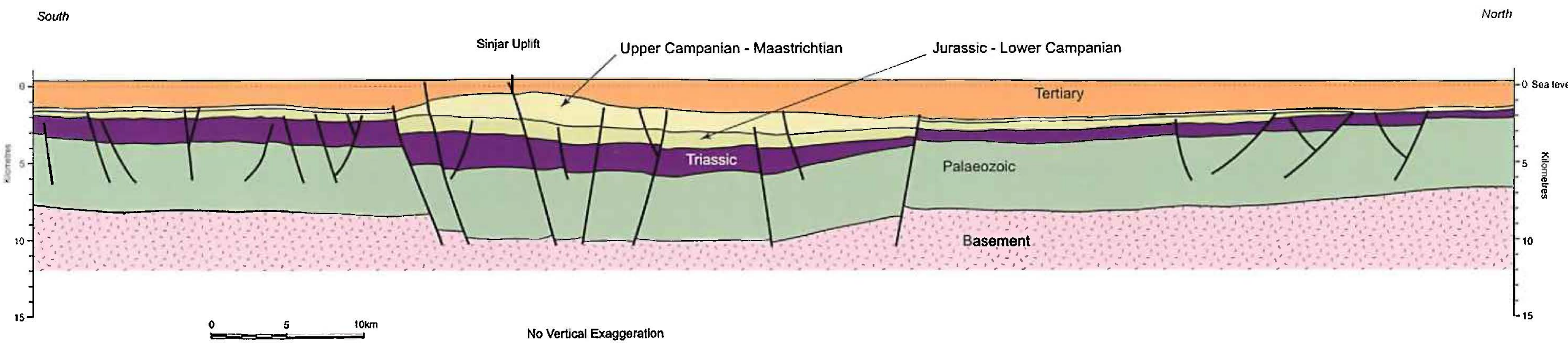
Cross-section 12 (above right). Local SW-NE structural cross-section across Western Iraq (see profile location in Fig. 3.34) (after Al-Hadidy, 2007). The cross-section traverses the Western Iraq Palaeozoic basin adjacent to the *Akkas* location.



Cross-section 13. SW-NE structural cross-section across the Euphrates Graben of Eastern Syria (see profile location in Fig. 3.34) (after Litak *et al.*, 1998). Note the closely-spaced extensional faults (uninverted).



Cross-section 14.North-south structural cross-section across Eastern Syria (see profile location in Fig. 3.34) (after Brew *et al.*, 1997).



Cross-section 15. North-south structural cross-section across NE Syria (see profile location in Fig. 3.34) (after Brew *et al.*, 1999). The cross-section passes through the inverted Sinjar Trough.

4. PRECAMBRIAN AND PALAEOZOIC

The Precambrian and Palaeozoic succession in Iraq is here divided into six megasequences (AP1–AP6) following the scheme of Sharland *et al.* (2001 and 2004) (Fig. 4.1). Relatively little is known about this succession due to the very limited outcrop and subsurface data available. Precambrian sequences have been interpreted from geophysical data calibrated against nearby areas (Buday and Jassim, 1987; Jassim, 2006b). The Palaeozoic stratigraphy has been reconstructed using the limited well and outcrop data from Iraq, and by extrapolating the more abundant well and geophysical data from adjacent parts of Jordan, Saudi Arabia, Syria, Turkey and Iran (see the location of data control points in Fig. 4.2).

During much of the Palaeozoic, Iraq lay in the outer (NE) part of an intracratonic basin centred on the Risha area of NE Jordan (Konert *et al.*, 2001; Jassim, 2006b,c). The total thickness of Palaeozoic strata in Iraq ranges from 1.5 to 6 km (Jassim, 2006b). The proven, though incomplete AP1-AP3 stratigraphic succession in Jordan is over 6 km thick (Fig. 4.3).

Pre- Megasequence AP1: Precambrian

The crystalline basement in Iraq is interpreted to consist of Upper Precambrian metamorphic rocks and partly metamorphosed and granite-intruded Lower Infracambrian rocks (Buday, 1980; Jassim, 2006b).

Six Precambrian terranes have been identifed in Iraq (Jasim, 2006b). These are the Western Arabian, Afif, Ad Dawadimi, Ar Rayn, Eastern Arabian and Zagros Terranes. Their recognition is based on detailed gravity-magnetic studies calibrated with regional data from the Arabian Plate (Fig. 3.4). The brief description of these terranes below follows the interpretations in Jassim (2006b).

The **Western Arabian Terrane** in westernmost Iraq near the boundary with Jordan is formed of island-arc volcanics and associated calc-alkaline plutons (Nehlig *et al.*, 2001).

The **Afif Terrane** has a weak aeromagnetic signature in exposed parts of the Arabian Shield (Nehlig *et al.*, 2001). In Iraq it contains north-south oriented magnetic highs and lows. The terrane comprises basal gneisses intruded by large granodiorite bodies (Johnson and Stewart, 1994). These units are overlain by up to 6500 m of Halaban Group ultrabasics (pyroxenite and harzburgite), diorite, andesite and associated volcaniclastic sediments interpreted as a fore-arc complex (Brown *et al.*, 1989; Al-Husseini, 2000; Nehlig *et al.*, 2002). The rocks are metamorphosed to greenschist facies (Delfour, 1978). Basal schistose amphibolites form magnetic highs in Iraq. Magnetic lows are interpreted to correspond to molasse successions of the Murdama Group (Jassim, 2006b). At outcrop, the Murdama Group includes sediment wedges and internal unconformities typical of foreland deposition (Nehlig *et al.*, 2001). The Murdama basins are separated by intrusive gabbros, diorites and granodiorites and post-tectonic alkali granites (Jassim, 2006b).

The **Ad Dawadimi Terrane** in Iraq has a characteristically low gravity/ magnetic signature probably due to the presence of thick phyllites (Jassim, 2006b). Analogous sericite-chlorite phyllites (Abt Phyllites) outcrop in Saudi Arabia and are underlain by imbricated ophiolites (Brown *et al.*, 1989). Intrusions of post-tectonic diorite and granite also occur (Johnson and Stewart, 1994). The fine-grained sediments from which the phyllites were derived are interpreted to have been deposited in the Amar fore-arc basin (Mitchell, 1976; Al-Shanti and Gass, 1983). This basin closed during the Amar collision (640-620Ma) and is thus younger than the terranes on either side.

The **Ar Rayn Terrane** extends from the Southwestern Desert into the Khleisia High to the NNW. In Iraq this unit is characeterized by north-south trending gravity and magnetic anomalies which can be traced beneath the Phanerozoic cover (Jassim, 2006b). It is thought to contain Amar Group volcano-sedimentary rocks cut by syntectonic gabbros and post-tectonic granites (Jassim, 2006b). On exposed areas of the Arabian Shield, the terrane comprises tholeiitic to calc-alkaline volcanics, related pyroclastic rocks and subordinate calcareous sediments containing arc-related intrusions older than 650 Ma, and plutonic rocks dated at 640-620 Ma (Vaslet *et al.*, 1983; Al-Husseini, 2000). The terrane is interpreted to have originally formed as an island arc or at an active continental margin (Al-Shanti and Mitchell, 1976).

The **Eastern Arabian Terrane** (Fig. 3.4) has a generally weak magnetic character. This terrane contains north-south trending structures in the south; north of 32°, structures trend NW-SE (Jassim, 2006b). Jassim (2006b) suggested that in Iraq, it is composed dominantly of gneiss intruded by granite plutons. However, data from Saudi Arabia and Kuwait suggest that the terrane contains low-grade, imbricated metamorphosed sediments. To the south in the Summan Platform, wells *El-Haba-2* and *Khabb-1* (locations in Fig. 4.2) both intersected steeply-dipping slates. Metasediments in well *Khabb-1* were dated at 636 to 605 Ma (Al-Husseini, 2000). Further east, Precambrian rocks consist of low-grade metasediments; at TD in the *Burgan-A* well, steeply-dipping phyllites occur (Khan, 1989). Steeply-dipping metamorphosed shales are recorded in well *Jauf-10* while folded sandstones and shales occur in well *Ain Dar-196*; the latter are dated at 671 to 604 Ma (Al-Husseini, 2000). Radiometric dates in well *Khabb-1* are similar to those of suture zone rocks in the Ad Dawadimi Terrane.

The **Zagros Terrane** to the NE is characterized by relatively large-scale magnetic anomalies that indicate basement composed of basic volcanic and plutonic rocks. These may represent an imbricated NW-SE orientated ophiolite belt (Jassim, 2006b).

Petroleum System Components

No hydrocarbon potential is expected to occur in the crystalline basement of Iraq.

Megasequence AP1: Infracambrian and Lower Cambrian

During the Infracambrian (610-545 Ma), the Arabian Plate was affected by lithospheric thinning following the Amar Orogeny. Calc-alkaline igneous activity and transtensional shearing along left-lateral NW-SE oriented "Najd" faults occurred (Nehlig *et al.*, 2002) (Fig 3.24). The faults are associated with "Najd Basins" of pull-apart origin (Coleman, 1972; Hadley, 1974; Stern, 1985; Husseini, 1988, 1989; Andrews *et al.*, 1991) which contain sedimentary rocks assigned to Megasequence AP1 of Sharland *et al.* (2001).

Infracambrian and Lower Cambrian rocks infilling these basins have not yet been drilled in Iraq. They are predicted to be up to 1500 m thick from gravity and magnetic interpretations (Buday and Jassim, 1987; Jassim, 2006c). Jassim (2006c) suggested that four Infracambrian depocentres occur in southern Iraq (Fig. 4.4). The westernmost of these basins is inferred to contain volcanic rocks and tuffs overlain by coarse fluvial siliciclastics with subordinate intermediate to acid lavas and tuffs. Sabkha-like carbonates and evaporites may be present in the other basins (Fig. 4.4).

Plate 4.1. Boulder conglomerates of the Precambrian Saramuj Conglomerate Formation exposed at Ghor as Safi, Jordan. Photo by A. Aqrawi.

The fill of the westernmost basin may be similar to the metamorphosed Saramuj Conglomerate Formation/Araba/Aqaba Complex of Jordan (Figs 4.5, 4.6), and the Fatima/J'bsia and Jubaylah (J'bala) Groups (Umm Al-Asiah and Jifn Formations) of Saudi Arabia (Fig. 3.24)(Jassim, 2006c). These units include up to 400 m of basalts and tuffs in addition to andesites, dacites and rhyolites alternating with coarse- and medium-grained siliciclastics (Powell, 1989; Andrews *et al.*, 1991) (Fig. 4.7). The latter sediments (Plate 4.1) are interpreted to have been deposited as alluvial fans and in shallow lacustrine settings (Powell, 1989). Associated volcanics from Saudi Arabia have been dated at 520-500 Ma (Delfour, 1970).

The Infracambrian grabens on the Arabian Plate contain thick synrift successions (Husseini, 1989; Andrews *et al.*, 1991). In Saudi Arabia, over 3000 m of similar strata are present in the An Nuqra area (Al-Laboun, 1986), 600-780 m in Wadi Fatima (Nerbert *et al.*, 1974), and 875 m in the Mashhad area (Hadley, 1974). Some 3000 m of Infracambrian rocks are predicted to occur in the western Rub' Al Khali (Dyer and Husseini, 1991) (Fig. 3.25). At least 1500 m of Saramuj Formation and equivalent units, interpreted from seismic data, occur in Jordan (Andrews *et al.*, 1991) (Fig. 4.6); up to 5000 m have been reported in parts of Egypt (Stern, 1985).

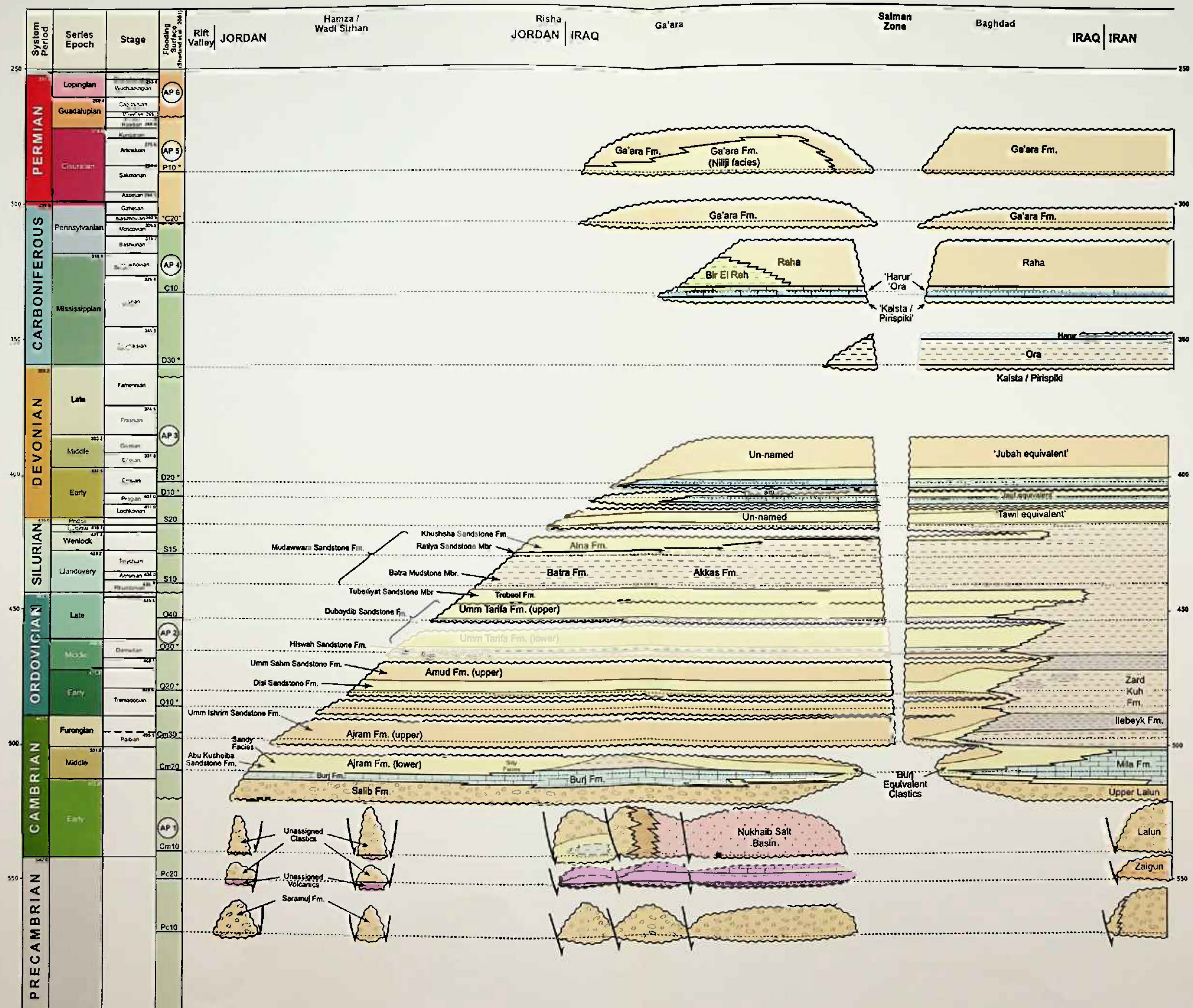


Fig. 4.1. Chronostratigraphy of the Infracambrian and Palaeozoic succession of Iraq, including data from Jordan for purposes of calibration. Subsurface names in black from Andrews *et al.*, 1991; outcrop names in blue from Powell, 1989; flooding surfaces from Sharland *et al.*, 2001.

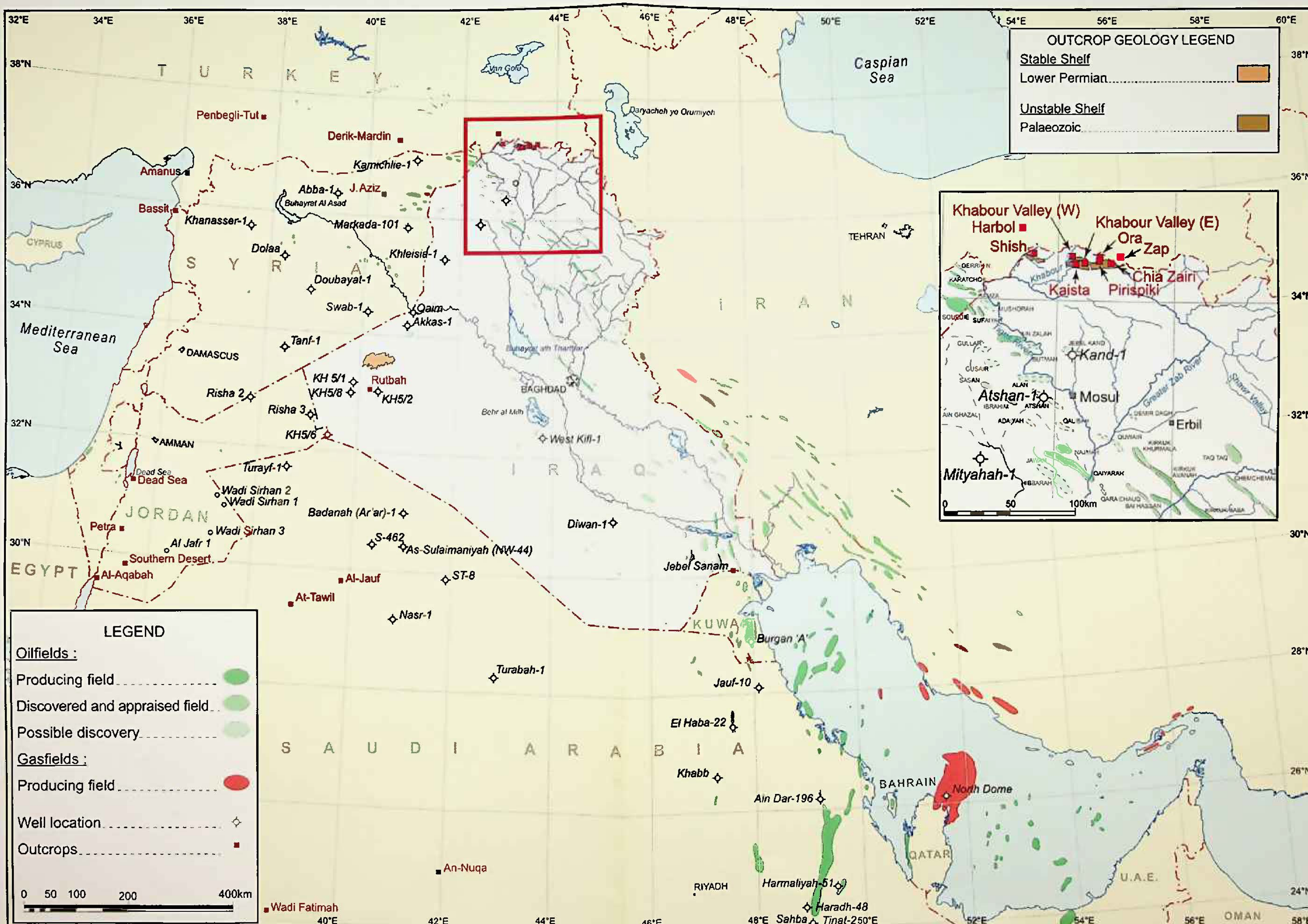


Fig. 4.2. Map of Iraq and adjacent countries with the location of data control points referred to in this chapter. Wells (marked in black) include the *"Keyhole" (KH)* boreholes in western Iraq and the nearby *Risha-3* well in Jordan. Important outcrop areas (labelled in red) include locations in northern Iraqi Kurdistan and SE Turkey (see inset box).

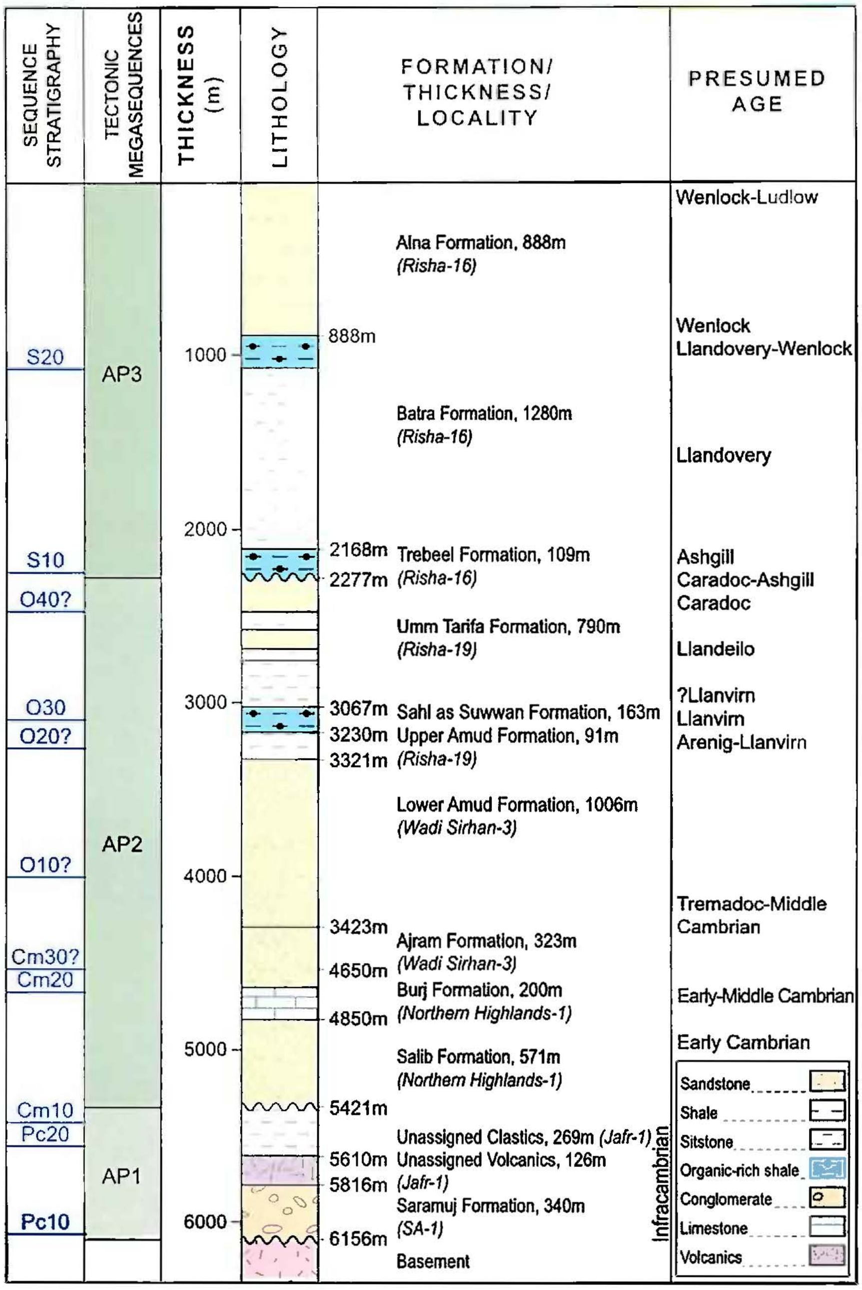


Fig. 4.3. Composite Infracambrian – Early Palaeozoic subsurface stratigraphy of Jordan. After data and nomenclature in Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001. Stratigraphy at outcrop has a different terminology (see Fig. 4.1).

In SW Iraq, the Nukhaib Basin (Fig. 4.4) is interpreted to contain a thick salt sequence (Bassam *et al.*, 1992), based upon the presence of a gravity low. A domal structure is present on seismic sections at the Cambrian level and may indicate movement of underlying salt (Jassim, 2006c; Jassim and Buday, 2006b).

Infracambrian evaporites of the Hormuz Series probably occur in the Basra region (Buday, 1980; Jassim, 2006c). Most oilfields in southern Iraq are associated with negative gravity residuals which may indicate salt (Jassim, 2006c). In addition, Jebel Sanam, a hill about 120 m high located near the border with Kuwait, is interpreted to be a salt dome (location on Fig. 4.2). It contains dolerites dated by the K-Ar method at 570±10 to 580 ± 10 Ma (Buday and Jassim, 1987), together with black algal dolomite and anhydrite (Jassim, 2006b). These features suggest continuity with the Hormuz - Soltanieh Series of Iran (as described by Kent, 1970). Similar Lower Infracambrian evaporites may have been deposited in basins elsewhere in the Arabian Plate by analogy with the Hormuz Series evaporites in the Gulf States (Delfour, 1966, 1970; Basahel *et al.*, 1984; Husseini, 1989; Husseini and Husseini, 1990; Beydoun, 1993). In northern Kuwait, deep drilling has demonstrated that Upper Carboniferous – Lower Permian clastics unconformably overlie an unfossiliferous carbonate unit which may be of Infracambrian age (Tanoli *et al.*, 2008). The depth of the contact was not reported but is probably at about 5855–6000 m.

The Infracambrian stratigraphy of northern Iraq is probably similar to that of SE Turkey. Here,

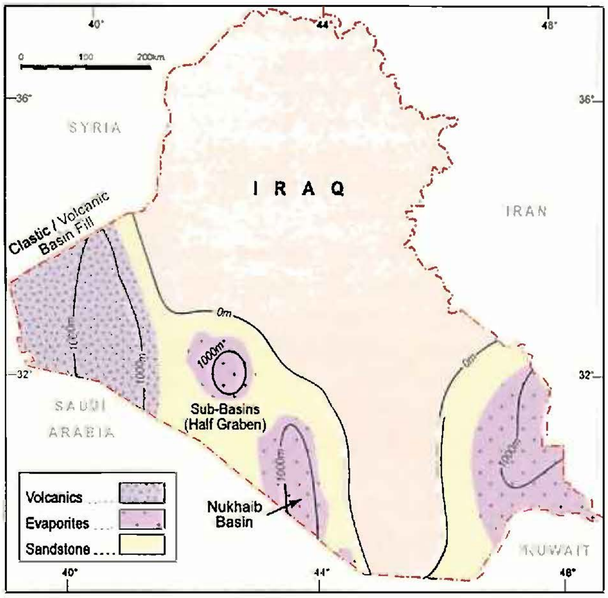


Fig. 4.4. Map of Iraq showing the possible extent of Infracambrian basins and their infills. Simplified and modified after Jassim, 2006c.

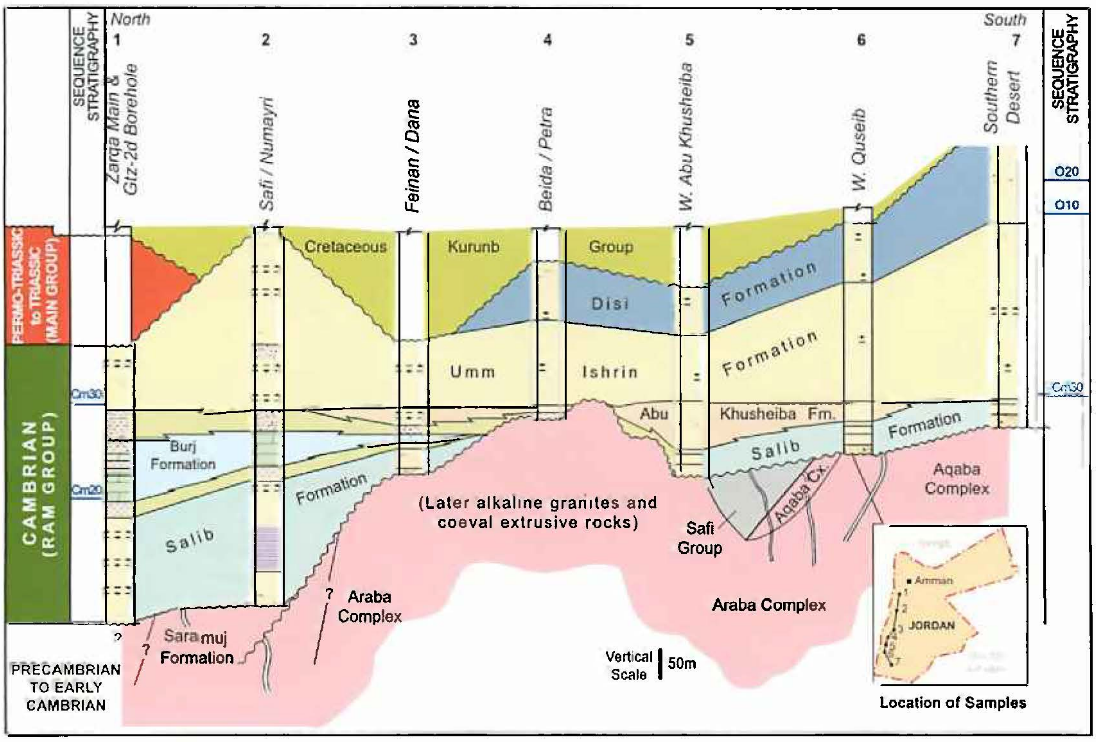


Fig. 4.5. North-south cross-section showing Palaeozoic onlap onto Precambrian basement in Jordan as defined from localities on the Dead Sea Rift margin. Note the prominent Angundan (Pre-Siq/Saq) unconformity at the top of the Infracambrian succession. It is onlapped by the Salib Formation, the Burj carbonates and coastal clastics of the Abu Khusheiba Formation. After Powell, 1989; flooding surfaces after Sharland *et al.*, 2001.

the succession comprises mixed metasedimentary and volcanic rocks assigned to the Sadan, Meryemusagi and Derik Formations (Dean *et al.*, 1997: Fig. 4.8; and Janvier *et al.*, 1984: Fig. 4.9), up to 2500 m thick (Flügel, 1971). Igneous rocks predominate in the Derik-Mardin area near the border with Iraq (Dean *et al.*, 1997). Felsite porphyries and rhyolites with basaltic dykes overlain by sandstones, conglomeratic sandstones and recrystallised limestones occur near Mardin (van der Kaaden, 1978). Similar rocks are present in Iran (Zaigun and Lalun Formations: Setudehnia,1975) (Fig.4.10). However, Infracambrian rocks are locally absent from the Hakkari area in SE Turkey, where fossiliferous Cambrian rocks unconformably overlie crystalline Precambrian basement (Altini, 1966).

Jassim (2006c) proposed that the Infracambrian basins in Iraq were largely landlocked. Positive areas of non-deposition correspond to structural highs in the Ar Rayn Terrane which were deformed and uplifted during the Amar Orogeny (Al-Husseini, 2000).This is consistent with observations of significant uplift of older rocks in a deep well on the *Burgan* structure in Kuwait (Khan, 1989). Here, fossiliferous Palaeozoic rocks rest directly on basement metasediments.

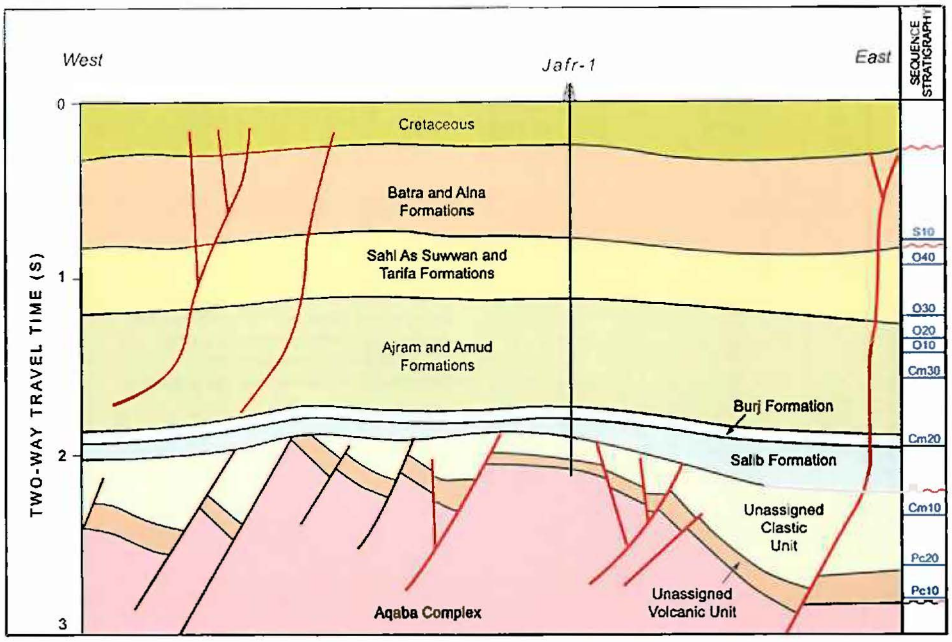


Fig. 4.6. West-east cross-section through the Jafr area of SE Jordan. The Infracambrian – Lower Cambrian rift fill succession comprises unassigned clastics and volcanics. It is bounded above by the Angundan (Pre-Siq/ Saq) unconformity at the base of the Salib Formation. Overlying units include Middle Cambrian carbonates (Burj Formation) and clastics. After Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

In Saudi Arabia, Megasequence AP1 is bounded above by the Early Cambrian Angundan/Pre-Siq (Saq) unconformity (Fig. 4.5) (Al-Laboun, 1986; Al-Husseini, 2000).

Petroleum System Components

No significant hydrocarbon reservoir rocks are predicted to occur within the AP1 Megasequence where it comprises clastic facies in western Iraq, as a result of deep burial and low-grade metamorphism similar to that recorded in Jordan (Pickard, 1941; Jarrar *et al.*, 1991). However hydrocarbon potential may be associated with the salt basin system. In Oman, reservoirs in analogous salt basins consist of overpressured fractured silicilytes (cherts) or carbonate "stringers" (Amthor *et al.*, 2005). Organic-rich source intervals are present in the silicilytes, sealed within the evaporitic Ara Formation (Grantham *et al.*, 1988; Terken and Frewin, 2000), together with sapropelic limestones (Amthor *et al.*, 2005).

The Infracambrian petroleum system in Oman was studied by Gorin *et al.* (1982). Infracambrian (Huqf-sourced) oils consist of "X" branched hydrocarbons with high proportions of C_{29} or C_{27} steranes, a low content of rearranged steranes, $\delta^{13}C$ values of about -30‰ to -36‰, and pristane/phytane ratios of <1 (Grantham *et al.*, 1988; Sykes and Abu Risheh, 1989). These oils may leak up into much shallower reservoir intervals (Al-Marjeby and Nash, 1986). Sykes and Abu Risheh (1989) estimated that some 80% of oils in Mesozoic reservoirs in Oman have an Infracambrian (Huqf) source. Interbedded thick evaporites form the seal.

Megasequence AP2: Lower Cambrian – Upper Ordovician (Ashgill)

Overlying the Angundan unconformity, the deepest seismic reflector that can confidently be identified in western Iraq and adjacent parts of Syria and Jordan corresponds to the mid-Cambrian Burj Limestone (Fig. 4.6). Cambrian rocks do not outcrop in Iraq and have not yet been penetrated by drilling.

The Mid-Cambrian – Middle Devonian sedimentary succession (Megasequences AP2 and AP3 of Sharland *et al.*, 2001) was deposited during a phase of post-rift thermal subsidence (Al-Husseini, 2000). A broadly NW-SE oriented Early Palaeozoic basin is apparent on the depth-to-basement map of Konert *et al.* (2001) in the Saudi Arabia/ Jordan/ West Iraq area (Fig. 3.2).

Jassim (2006c) inferred that over 3000 m of sedimentary rocks are present in Megasequence AP2. Najar (1999) modelled the depth to basement in Western Iraq from gravity, magnetic and seismic data, and determined a thickness of 4000 m of Cambro-Ordovician sedimentary rocks. The megasequence is very thin or absent in central and eastern Iraq (Fig. 4.11); this is thought to have been due to the elevation of the Ar Rayn Terrane, including the Salman Zone, and the Eastern Arabian Terrane (Jassim, 2006c).

Over the Salman Zone, Lower Palaeozoic rocks thin due to erosion at the Late Carboniferous unconformity; to the north, they thin due to erosion at the Late Devonian unconformity.

Ordovician strata near the top of Megasequence AP2 include the oldest rocks which have been

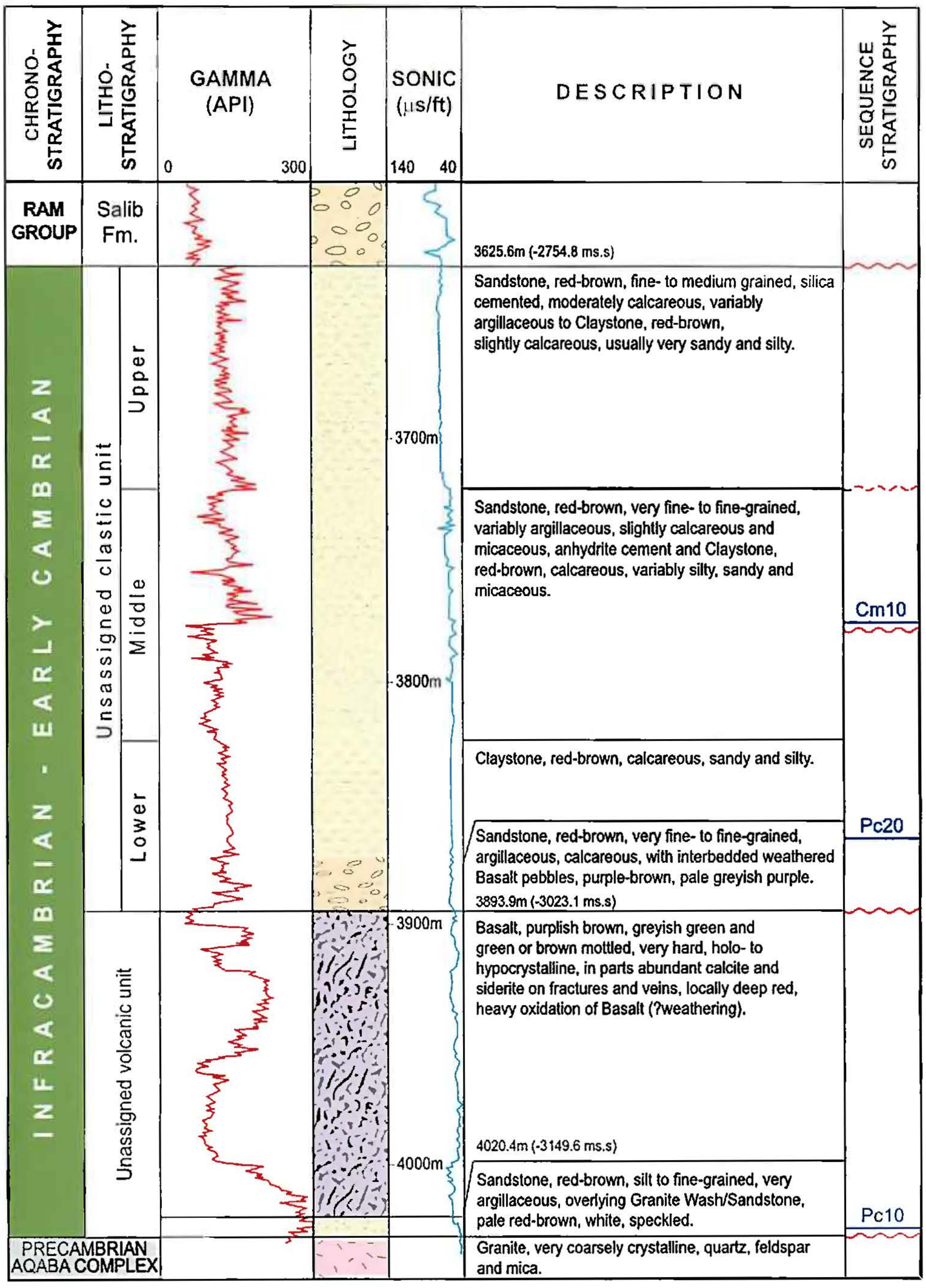


Fig. 4.7. Infracambrian and Lower Cambrian stratigraphy of the *Jafr-1* well in SE Jordan (location in Fig. 4.2). After Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

described at outcrop in northern Iraq (e.g. Dunnington *et al.*, 1959) and in the subsurface (Al-Haba *et al.*, 1994; Al-Hadidy, 2007).

Cambrian

Following intense peneplanation of AP1 and older rocks (Plate 4.2), Central Arabia was dominated by uplifted and emergent parts of the Ar Rayn and Eastern Arabian Terranes. These extend into southern Iraq, and northwards through Baghdad and Baquba in central Iraq.

Throughout the western margin of the Arabian Plate, coarse red, brown and purple arkosic sandstones with occasional micaceous red mudstones have been interpreted as braided alluvial channel deposits (Powell, 1989; Andrews *et al.*, 1991). These sandstones are assigned in Jordan to the Early Cambrian Salib Formation (Plates 4.2, 4.3), and are up to 750 m thick in the subsurface (Selley, 1970; Andrews *et al.*, 1991) (Figs.4.5,4.6). Jassim (2006c) predicted that the Salib Formation may be up to 1250 m thick in the Western Desert of Iraq, and is thin or absent in northern Iraq and over the Salman Zone. Similar sandstones are assigned to the Siq Formation in Saudi Arabia (Al-Laboun, 1986; Al-Hajri and Owens, 2000). The equivalent Sadan (Flügel, 1971) or Zabuk Formation in SE Turkey (about 270 m thick) consists of sandstones with dolomite and chert beds (Dean *et al.*, 1997; Al-Juboury and Al-Hadidy,

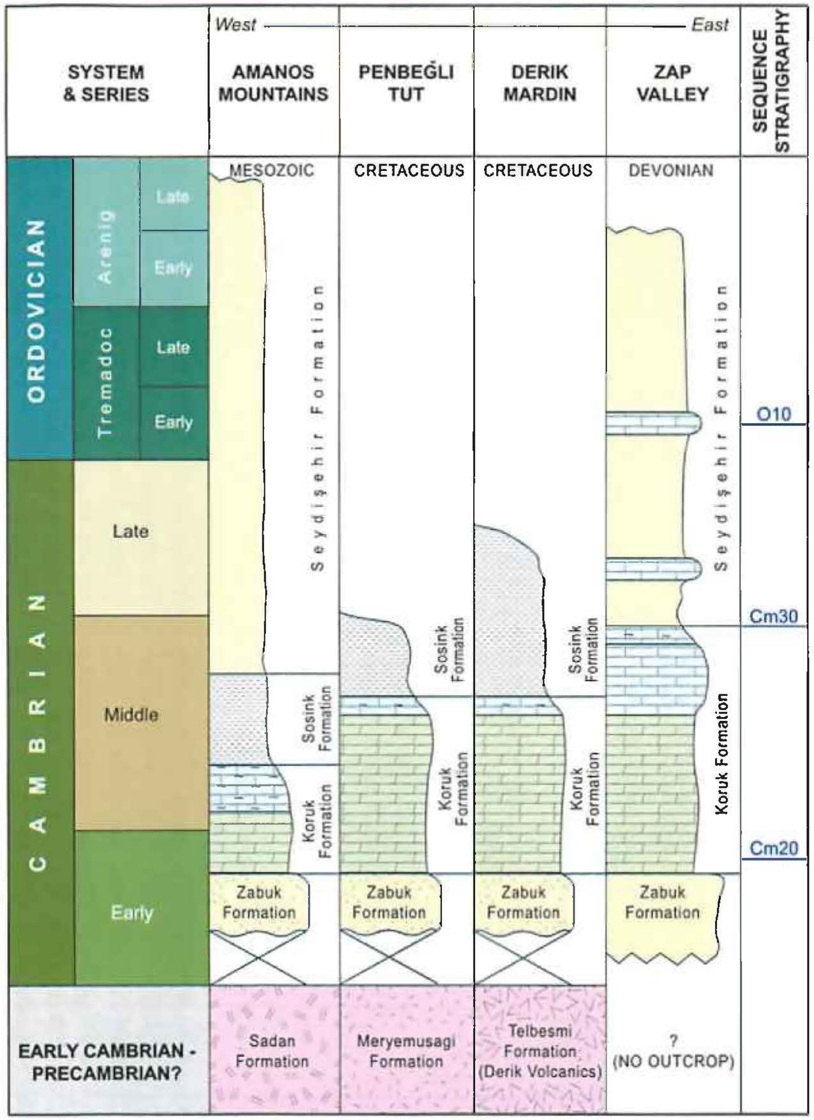


Fig. 4.8. Infracambrian – Lower Palaeozoic chronostratigraphic columns at locations in SE Turkey showing eastward backstepping of the Koruk carbonate platform (locations in Fig. 4.2). After Dean *et al.*, 1997; flooding surfaces after Sharland *et al.*, 2001.

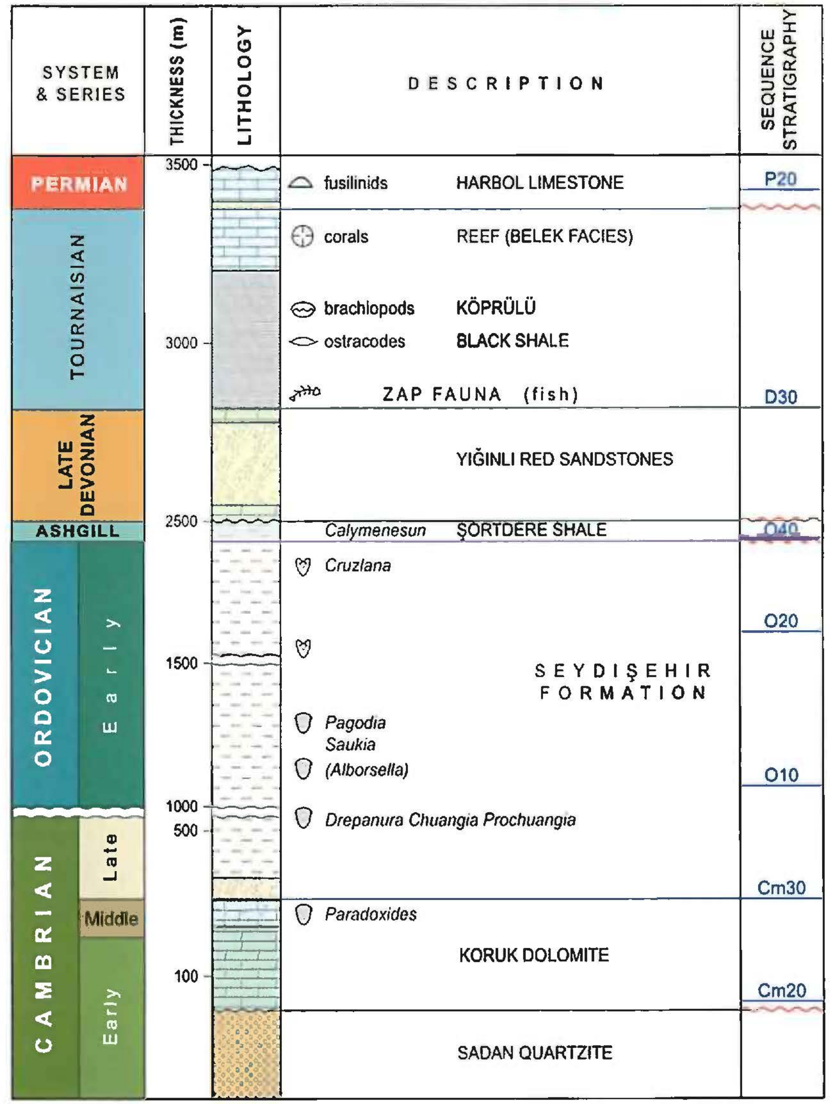


Fig. 4.9. Palaeozoic stratigraphy in the Zap area of SE Turkey ("Zab" in Arabic), near the border with Iraq (location in Fig. 4.2). Note the unconformity at the top-Ashgill due to the Late Devonian tectonic phase (see Fig. 4.20). After Janvier *et al.*, 1984; flooding surfaces after Sharland *et al.*, 2001.

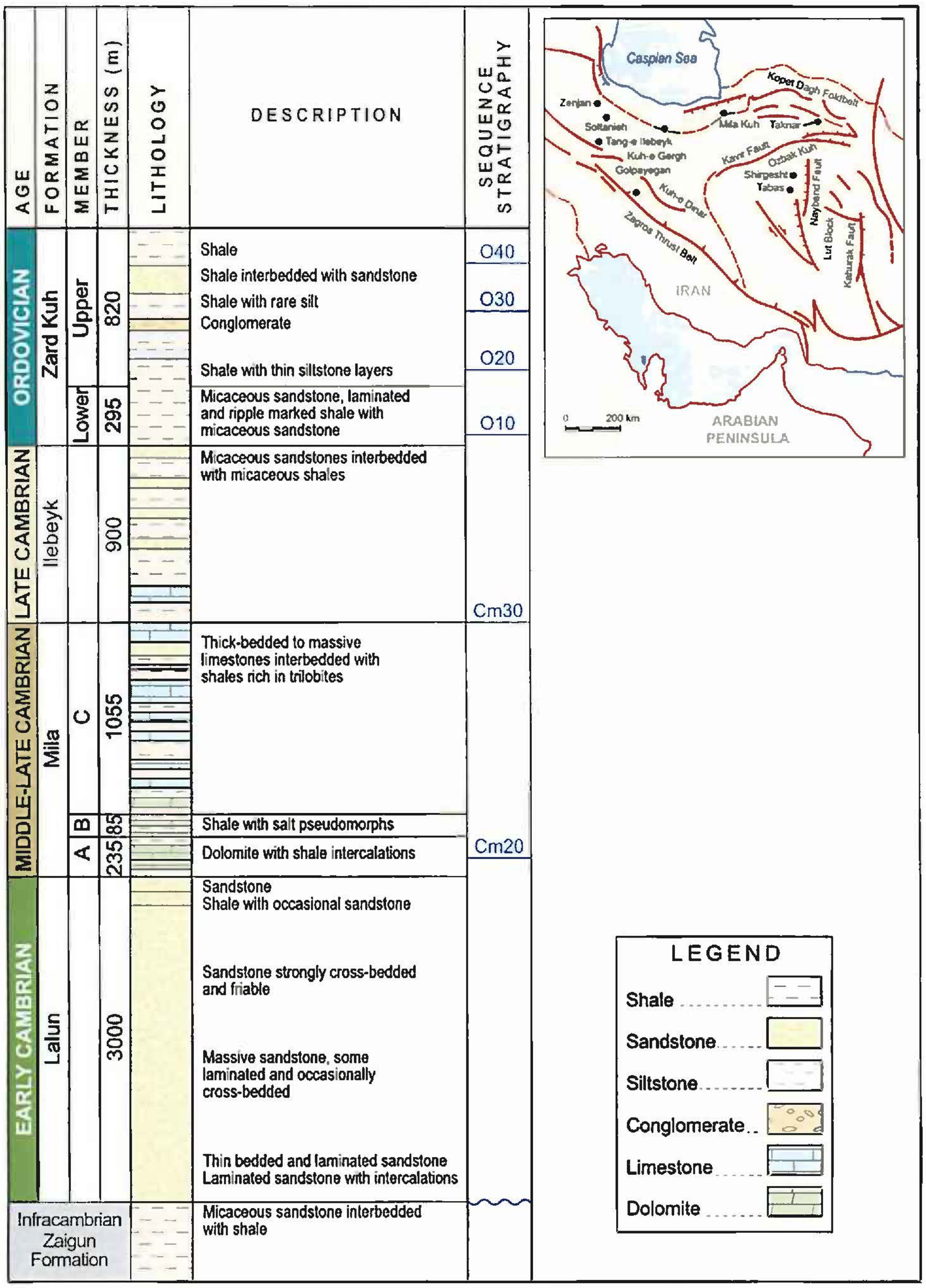


Fig. 4.10. Composite Lower Palaeozoic stratigraphy of Iran. After Setudehnia, 1975; flooding surfaces after Sharland *et al.*, 2001.

2008a) (Fig. 4.8). The formation also occurs in Syria, for example as the basal 13 m of the section penetrated at the *Khanasser-1* well (Best *et al.*, 1993; Barazangi *et al.*, 1993). Equivalent units in Iran are the Zaigun and Lalun Formations (Fig. 4.10) (Davoudzadeh *et al.*, 1986).

Mid-Cambrian marine transgression across the northern part of the Arabian Plate (Konert *et al.*, 2001) led to widespread deposition of a limestone unit (Fig. 4.12) within the otherwise siliciclastic-dominated Cambro-Ordovician succession. This unit is known as the Burj Formation in Jordan (Andrews *et al.*, 1991) (Fig. 4.13; Plate 4.4) and also in Syria, where it is 225 m thick at well *Khanasser-1* (Best *et al.*, 1993). In Turkey, it is referred to as the Koruk Formation (Janvier *et al.*, 1984; Dean *et al.*, 1997) (Figs. 4.8, 4.9). In Iran, the carbonates are assigned to the Mila Formation (Setudehnia, 1975; Ghavidel-Syooki, 1997) (Fig. 4.10). There is a strong velocity contrast between these carbonates and the over- and underlying siliciclastics; the carbonate unit thus forms a seismic marker (e.g. in Syria: Best *et al.*, 1993). A similar reflector has been recognised in seismic sections from the Western Desert in Iraq (e.g. Al-Haba *et al.*, 1994) and can be tied to the Burj Formation in the *Risha-2* well, Jordan (Jassim, 2006c). The carbonates may be very thin or absent in the Southwestern Desert of Iraq. Similarly, in Jordan and western Iraq, the formation thins southwards from about 200 m in the Risha/Rutbah area to 60 m in the southern part of Wadi Sirhan (Andrews *et al.*, 1991; Jassim, 2006c). Further south, the facies pass into marine siliciclastics

Fig. 4.11. Map of Iraq showing the thickness of Megasequence AP2. Interpretation is based mainly on gravity-magnetic data with very little well or outcrop control. Simplified after Jassim, 2006c.

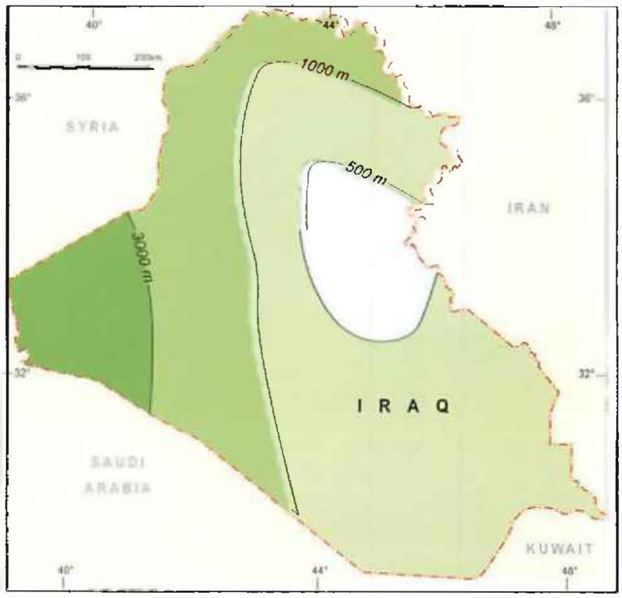


Plate 4.2. Dashed white line indicates onlap of pebbly sandstones of the Lower Cambrian Salib Formation (basal AP2) and other Lower Palaeozoic rocks onto peneplaned Precambrian basement. Location: near Aqaba, southern Jordan, at the road junction with Wadi Rum. Photo by A. Aqrawi.

Plate 4.3 (above). Pebbly arkosic sandstones of the Lower Cambrian Salib Formation at Wadi Numaira, Dead Sea — Aqaba road, southern Jordan. Photo by A. Aqrawi.

within the continental deposits of the Abu Khusheiba Formation (Powell, 1989). In Saudi Arabia, these coastal siliciclastics are recorded as the "spoor" zone of the Saq Formation with *Skolithos* (Powers *et al.*, 1966; Helal, 1968; Al-Laboun, 1986; McGillivray and Husseini, 1992). They onlap the margins of areas uplifted during the Amar collision.

The carbonates comprise tidal flat to lagoonal and occasional oolitic shoal facies (Powell, 1989; Andrews *et al.*, 1991) (see Plate 4.12, page 83). In SE Turkey (and probably also in northern Iraq), the Koruk carbonates are succeeded diachronously by deep-water facies of the Sosink/Seydisehir Formations (Figs 4.8, 4.9). The carbonate shelf was drowned in early Middle Cambrian time in the Amanos Mountains, and in the latest Middle Cambrian in the Zap Valley in SE Turkey (Dean *et al.*, 1997) (Fig. 4.8). The thickness of the carbonates thus increases from 100 m in the Amanos region, to 240 m in the Mardin area, to over 400 m at Hakkari close to the Iraqi border (Cater and Tunbridge, 1992; Dean *et al.*, 1997).

Jassim (2006c) suggested that the Burj/Koruk Formation is approximately 400 m thick in northern Iraq and 200 m thick in the Western Desert. However, he proposed that the Cambrian is absent in Central and Southern Iraq due to onlap over the uplifted Rayn anticlines of the Ar Rayn and Eastern Arabian terranes. It is absent from the Burgan High in Kuwait (based on data in Khan, 1989) (Fig. 4.12).

Siliciclastic-dominated deposition was re-established in the Late Cambrian, with the fluvial sandstones of the Umm Ishrin/Ajram Formations in Jordan (Powell, 1989; Andrews *et al.*, 1991; Makhlouf and Abed, 1991; Amireh *et al.* 1994; Beydoun *et al.*, 1994) (Figs 4.3, 4.5), the Quweira

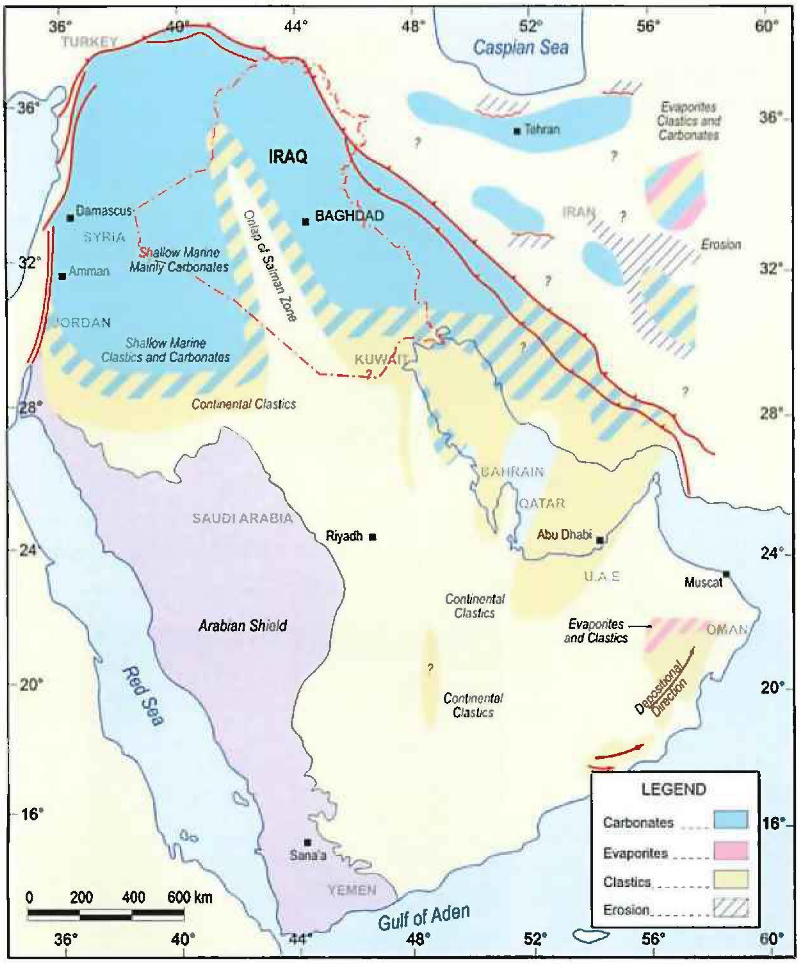


Fig. 4.12. Regional map showing the distribution of Middle Cambrian facies in Arabia. Modified after Konert *et al.*, 2001. Note the widespread carbonate platform facies in northern Arabia with clastics surrounding high areas.

Plate 4.4. Mixed siliciclastics and carbonates of the mid-Cambrian Burj Limestone Formation, exposed in a cutting on the Amman-Aqaba highway, about 50 km from Amman. Photo by A. Aqrawi.

Formation of Saudi Arabia (Al-Laboun, 1986), the lower 473 m of Palaeozoic siliciclastics ("Tabuk Unit") in the *Burgan-A* well, Kuwait (Khan, 1989), and the lower 170 m of the Mila Formation in Iran (Setudehnia, 1975; Davoudzadeh *et al.*, 1986) (Fig. 4.10). The Umm Ishrin/Ajram Formations comprise red- to dark brown, cream and purple to pale green sandstones with streaks of red shale in the west, becoming fine-grained and silty with acritarchs, *Cruziana* and oolites towards the NE (Powell, 1989; Andrews *et al.*, 1991). This unit is of middle Late Cambrian age and was deposited in a braided river setting with marine incursions (Makhlouf and Abed, 1991), and on an inner and outer subtidal shelf towards the NE (Andrews *et al.*, 1991). These deposits pass up into thick (up to 1400 m), coarse-grained sandstones of the Lower Amud Formation in the Wadi Sirhan and Risha areas of Jordan (Fig. 4.3), which are interpreted as paralic/shallow-marine deposits of Late Cambrian age (Andrews *et al.*, 1991).

Fine-grained deltaic siliciclastics of the Sosink Formation in Turkey thicken from 200 m in the west to 800 m in the east near Mardin (Fig. 4.8), and pass into the 1000 m thick Seydisehir Formation in the Hakkari region (Tunbridge, 1988; Cater and Tunbridge, 1992). Deeper-water facies near Zap are dominated by shales with trilobites (Janvier *et al.*, 1984; Dean *et al.*, 1997) (Fig. 4.9).

In western Iraq, Jassim (2006c) predicted that the early Late Cambrian succession includes an interval 450 m thick equivalent to the shelfal Ajram Formation, and a second unit about 1500 m thick equivalent to the Lower Amud Formation of Jordan.

In northern Iraq, lowermost Upper Cambrian deposits are predicted to be about 1000 m thick and

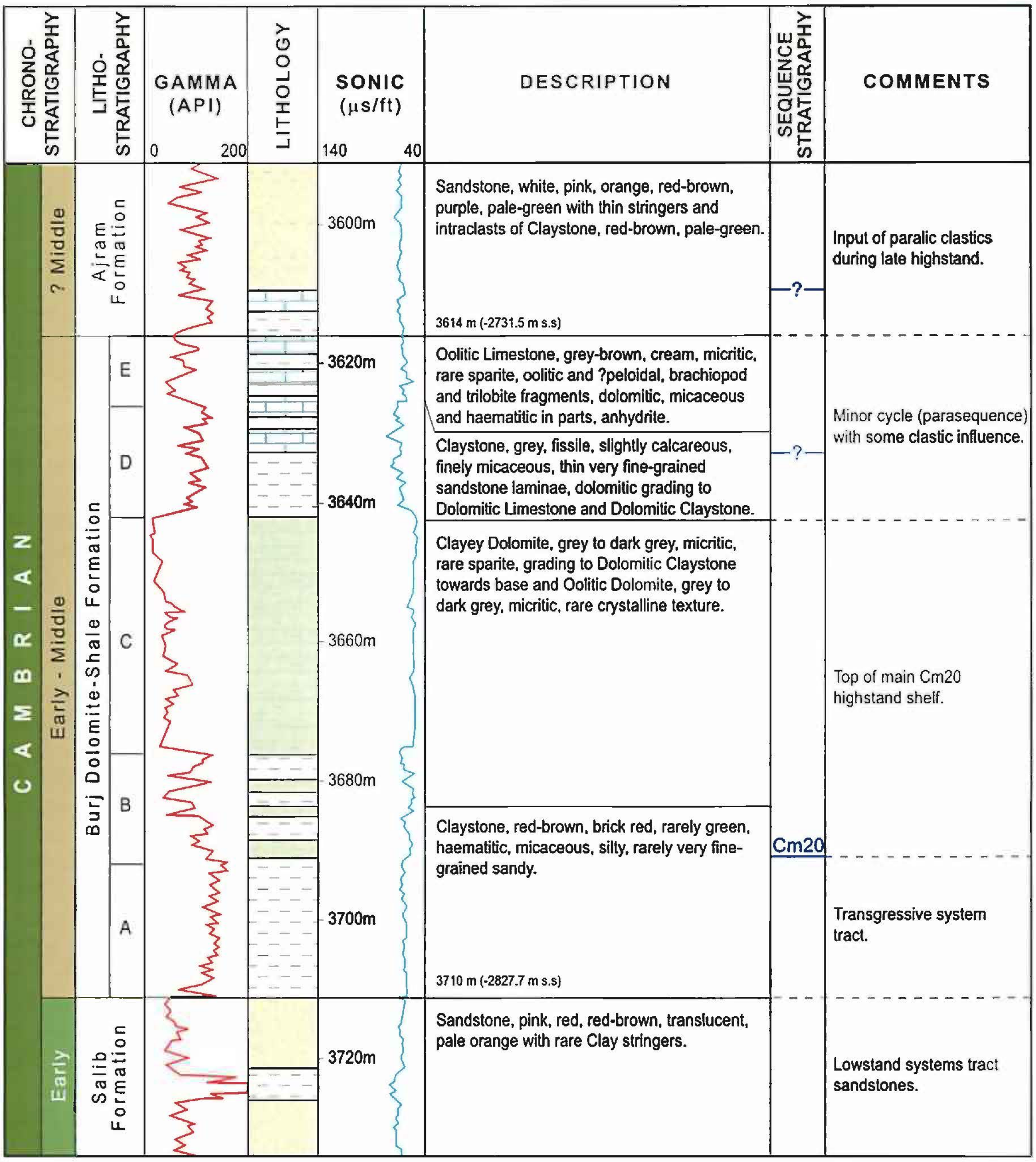


Fig. 4.13. Logs through the Burj Formation in well *Jafr-1*, SE Jordan. After Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

to include argillaceous and turbidite deposits similar to the Seydisehir Formation of SE Turkey (Jassim, 2006c). In NW Iraq, the succession is expected to be similar to that in well *Khanasser-1* in western Syria which penetrated 582 m of sandstones, siltstones and black shales (Best *et al.*, 1993).

Jassim (2006c) suggested that final flooding of the uplifted north-south trending Summan Zone in Central Arabia, and of the uplifted Ar-Rayn Terrane in southern Iraq, occurred in the Late Cambrian.

Ordovician

The oldest Palaeozoic sedimentary rocks exposed in northern Iraqi Kurdistan (Dunnington *et al.*, 1959; Seilacher, 1963) comprise sandstones and shales assigned to the Ordovician **Khabour Formation** (Plate 4.5). This unit is also known from wells *Khleisia-1* (Buday, 1980), *Akkas-1* (Aqrawi, 1998) and *Qaim-1* (Al-Hadidy, 2007). Al-Ameri and Baban (2000) and Al-Hadidy (2007) dated the Khabour Formation as Ordovician in well *Khleisia-1* (Fig. 4.14) where the succession is at least 1500 m thick; and also in well *Akkas-1*, where a thickness of at least 1910 m has been recorded (Fig. 9.2.10).

Baban (1996) and Al-Ameri and Baban (2000; 2002) divided the subsurface Khabour succession into Ashgill to Tremadoc intervals based on acritarchs, chitinozoa and spores. However, Al-Hadidy (2007) suggested that the oldest intervals penetrated are younger (probably Llanvirn–Llandeilo). He identified two upward-coarsening

Plate 4.5. Ordovician Khabour Formation exposed at the Ora anticline, northern Iraq. Photo by Eric Blanc, reproduced with permission of CASP.

cycles. The uppermost Members K1-K4 correlate with the O40 MFS of Sharland *et al.* (2001, 2004) and overlying HST sediments; while the lowermost Members K5-K7 correlate with the O30 MFS and subsequent HST. Increasing rates of subsidence in the Middle to Late Ordovician are suggested by deposition of deeper-water units associated with these O30 MFS ("Hanadir") and O40 MFS ("Raan") flooding events of Sharland *et al.* (2001).

Al-Ameri and Baban (2002) and Al-Hadidy (2007) showed that the Khabour Formation thins to the north from *Akkas-1* to *Khleisia-1* (Fig. 9.2.10). The formation consists predominantly of siliciclastics; dolomite and limestone also occur (Fig. 9.2.4), but may represent diagenetic concretions. Al-Ameri and Baban (2000) and Al-Hadidy (2007) interpreted the depositional environment as being outer neritic at the base, shallowing up to inner neritic and lagoonal.

At outcrop in the Shish-Sinat – Khabour and Ora areas of northern Iraq, the Khabour Formation consists of thin-bedded, fine-grained sandstones, greywackes and silty micaceous shales (Plate 4.5) (Dunnington *et al.*, 1959; Seilacher, 1963). Basal deep-water turbidites pass up into littoral/intertidal deposits with eurypterid plates, linguloids and *Orthoceras* (Dunnington *et al.*, 1959; Seilacher, 1963). The top of the formation at outcrop is Llandeilo and latest Ordovician in the subsurface (Dunnington *et al.*, 1959; Seilacher, 1963; Al-Ameri and Baban, 2000, 2002; Al-Hadidy, 2007). Outcrop sections in Iraqi Kurdistan are similar to the shales and siltstones (overlain by sandstones) of the Sosink and Seydisehir Formations in SE Turkey (Upper Cambrian to Arenig; Janvier *et al.*,1984; Dean *et al.*, 1997) (Figs. 4.8, 4.9), and to poorly described facies in Syria (Best *et al.*,1993).

Hiatuses (possible unconformities) often occur in this shale-dominated succession along the NE margin of the Arabian Plate. The deepwater Ashgill Sortdere Shale Formation rests unconformably on the Lower Ordovician Seydisehir Formation in the Zap area of SE Turkey (Janvier *et al.*, 1984) (Fig. 4.9). Similarly, the "Caradocian" Sinat Shales locally overlie the Khabour Formation in the Shish area of northern Iraq (Seilacher, 1963).Upper Ordovician sedimentary rocks thin eastwards from 600 m (Bedinan Formation) near Mardin, to 25 m (Sort Tepe Formation) in the Hakkari region of Turkey (Dean, 1980; Cater and Tunbridge, 1992). The hiatuses/unconformities may have developed due to condensed deposition on distal palaeohighs.

In well *Akkas-1* in western Iraq, Khabour Formation sandstones are mainly quartzarenites with subordinate lithic arenites and sub-arkoses. They are cemented by calcite and Fe-dolomite, secondary silica and clay minerals. Diagenetic changes include dissolution of carbonate cements, leaching and dissolution of feldspars and other unstable grains, and mica alteration (Al-Juboury and Al-Hadidy, 2008a).

The shales in the Khabour Formation are composed of illite, kaolinite, chlorite, and illite-smectite mixed layer clays (Al-Juboury, 1999). The main change in clay mineralogy with depth is in the composition of illite-smectite due to burial diagenesis. The change from random to regular mixed layering occurs at about 2400 m in *Akkas-1* between the Silurian (inner neritic) and Ordovician (outer neritic) successions at an equivalent vitrinite reflectance of about 0.6% (Al-Juboury, 1999).

The quartzites and shales of the Khabour Formation are comparable to the 3000 m thick Cambro-Ordovician Ram and Khreim Groups in Jordan. These comprise the Umm Ishrin, Umm Sham, Disi, Hiswa, Dubaydib and Ammar Formations at outcrop, and the Ajram, Amud, Sahl as Suwwan, Umm Tarifa and Trebeel Formations in the subsurface (Selley, 1970; Powell, 1989; Andrews *et al.*, 1991; Abed *et al.*, 1993; Beydoun *et al.*, 1994; Powell *et al.*, 1994) (Figs 4.5, 4.6; Plates 4.6, 4.7). The Upper Amud Formation in the Risha area of NE Jordan is 100 m thick and is considered to be of Early Ordovician age; it is succeeded by the shaly Sahl as Suwwan Formation (Andrews *et al.*, 1991). These formations are equivalent to the Ram and Umm Sahm Members of the Saq Formation (and overlying Hanadir Shale), the un-named sandstones and the Ra'an Shale Member of the Tabuk Formation in Saudi Arabia (e.g. Al-Laboun, 1986; McGillivray and Husseini, 1992; Alsharhan and Nairn, 1997), and the 835 m thick mixed carbonate clastic succession which underlies

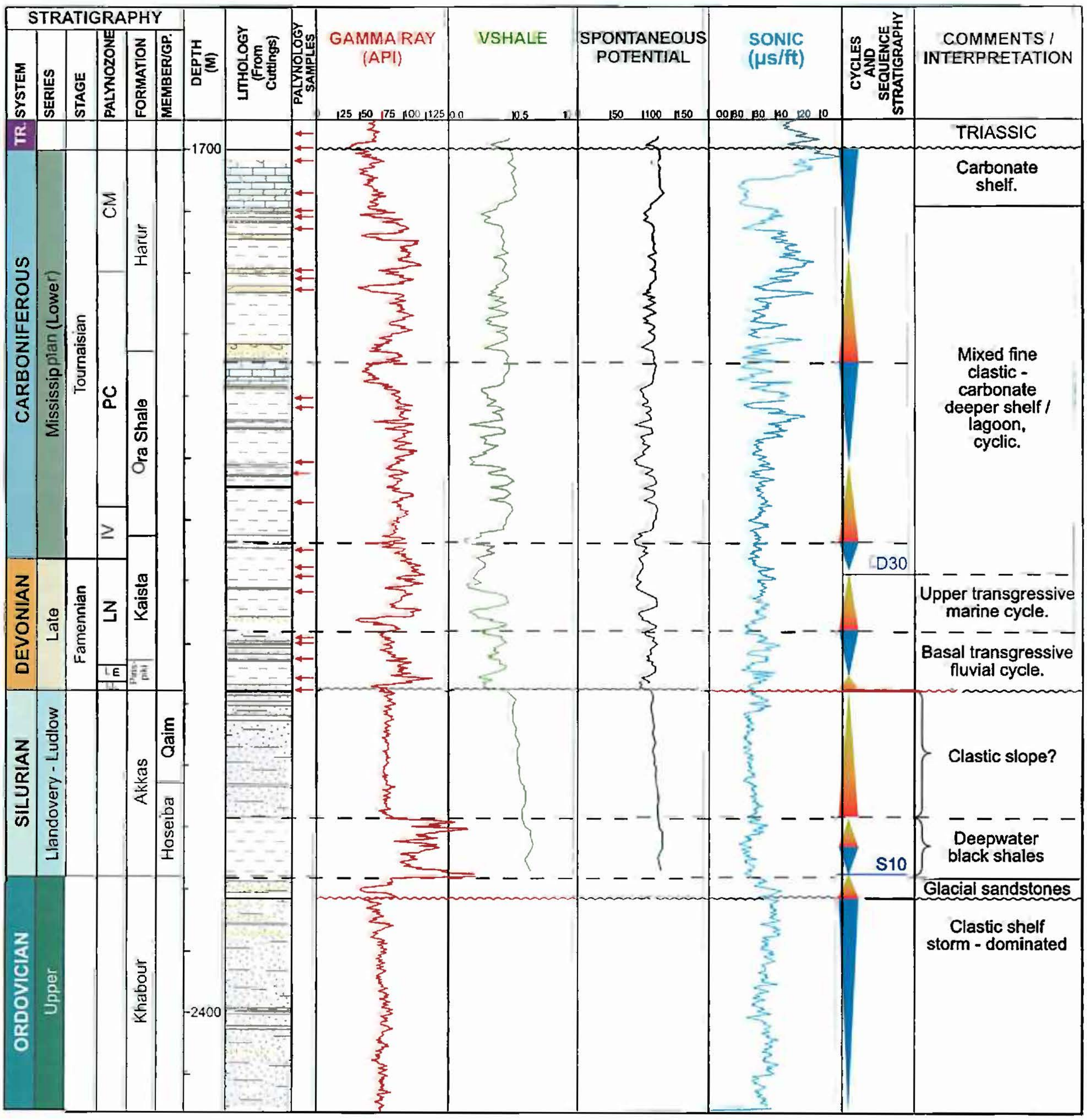


Fig. 4.14. Log through the Palaeozoic succession at well *Khleisia-1* showing Upper Devonian (Famennian) deposits resting unconformably on the Lower Silurian succession, including source rocks. Note the top-Ordovician includes a sandstone unit which is interpreted as the "glacial clastic" unit equivalent to the Trebeel Formation of Jordan. The late Tournaisian Harur Formation is older in this well than in *Akkas-1*. Red arrows indicate palaeontological control points. Log adapted after original in Al-Hadidy (2007, courtesy of *GeoArabia*). Flooding surfaces after Sharland *et al.*, 2001.

Permian rocks in the *Burgan A* well in Kuwait (Khan, 1989). In Syria, the 1025 m thick shales of the Swab Formation and the overlying 1500 m thick Afendi Formation are equivalent to the Khabour (Jassim, 2006c). In Iran, the Zard Kuh Formation represents the Middle to Upper Ordovician and Silurian, and is >1000 m thick (Fig. 4.10) (Setudehnia, 1975; Davoudzadeh *et al.*, 1986).

Middle – Late Ordovician transgressions occurred in the Ordovician intracratonic marine shelf basin. Updip littoral sandstones with *Cruziana* and downdip graptolitic outer-shelf shales represent major flooding surfaces (Helal, 1964a; Jassim, 2006c). The Hanadir Member shales of the Qasim Formation in the NE of the Nafud Basin of Northern Saudi Arabia (e.g. Helal, 1964a; Aoudeh and Al-Hajiri, 1995; Al-Hajri and Owens, 2000), the Sahl as Suwwan Formation shales in the subsurface of Jordan (Andrews *et al.*, 1991) (Fig. 4.6), and the Hiswah Shale known from Jordanian outcrops (Plates 4.8a,b) (Powell, 1989), representing the O30 MFS of Sharland *et al.*, (2001), are all of "Llanvirn" age. These have been correlated with Khabour Member K7 by Al-Hadidy (2007). The stratigraphically higher Ra'an and Batra shales are of early Caradoc age and contain the O40 MFS of

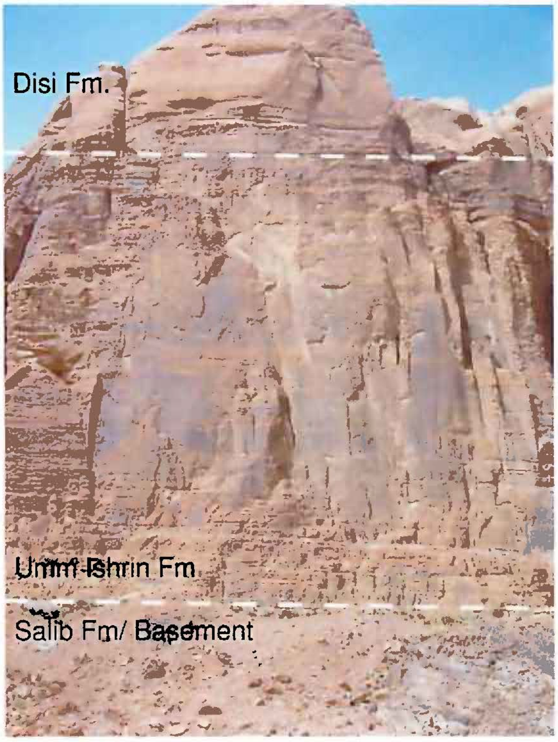


Plate 4.6 (left). Cliff face dominated by the Upper Cambrian Umm Ishrin Formation, which rests on the Salib Formation with basement rocks below. At the top is the Lower Ordovician Disi Formation. Location: near the town of Wadi Rum. Photo by A. Aqrawi.

Plate 4.7 (above). Cross-bedding in the Lower Ordovician Disi Formation, near Disi Village, SE Jordan. Photo by A. Aqrawi.

Plate 4.8a (left). Outcrop photograph of the fissile graptolitic shales of the Lower Ordovician Hiswah Formation (O30 MFS), southern Jordan. In Plate 4.8b (above), a graptolite is marked by the red box. Photos by A. Aqrawi.

Sharland *et al. (ibid.),* as do the shales in Khabour Members K2-K4 of Al-Hadidy (2007).

Jassim (2006c) proposed a tide- and storm-dominated shallow-marine depositional setting for the Khabour Formation in southern Iraq, similar to the Qasim Formation of Saudi Arabia, and a deep-marine environment in northernmost Iraq. The boundary between the more sandy "shelfal" and the more argillaceous "basinal" facies may run approximately along the eastern margin of the Salman Zone and then follows the general line of the present-day River Euphrates into Syria, finally following the SW margin of the Palmyra Basin. Seilacher (1963) noted that littoral facies are present in the Ora anticline of northern Iraq; while at the Kaista anticline some 20 km to the west, deeper-marine turbidite facies are present, suggesting a westerly-facing shelf system in northern Iraq. However, these outcropping units may be of different ages.

Late Ordovician glaciation

Regional glaciation affected the Arabian Plate during the Late Ordovician due to its near-polar location (Vaslet, 1990; Husseini, 1991; Mahmoud *et al.*, 1992; McGillivray and Husseini, 1992; Jones

Plate 4.9 a, b (above and right). Clasts to boulder grade in diamictites of the Ordovician Zarqa Formation, Tabuk Basin, NE of Tabuk, NW Saudi Arabia. Photos by A. Aqrawi.

and Stump, 1999; Sutcliffe *et al.*, 2000a,b; Monod *et al.*, 2003) (Fig. 3.26b). Studies in North Africa indicate that this glaciation was confined to a relatively short period of time during the Hirnantian ("latest Ashgill") (Abed *et al.*, 1993; Brenchley *et al.*, 1994; Sola and Worsley, 2000; Sutcliffe *et al.*, 2000). At least three glacial advances over the Arabian Plate have been recorded (McClure,1978; Vaslet, 1989; Andrews *et al.*, 1991; Husseini, 1990; McGillivray and Husseini, 1992). These were mapped in Jordan and NW Saudi Arabia by Konert *et al.* (2001) and have been identified in SE Turkey (Monod *et al.*, 2003). The whole of Iraq may therefore have been glaciated. These glacial advances led to sea-level falls of 150-200 m (Haq *et al.*,1987).

Glacial deposits in Iraq include "coarse sandy and polymictic basal beds" of the Akkas Formation. These are about 85 m thick in well *Akkas-1*, and are interpreted as diamictites (Jassim, 2006c). Al-Hadidy (2007) reinterpreted the top-most 2 m of the Khabour Formation in well *Akkas-1* as the basal Silurian transgression which followed the glacially-driven Hirnantian regression. The "low-API" sandstones in the uppermost Khabour Formation Member K1 are around 30 m thick in well *Akkas-1* (Al-Hadidy, 2007). They appear to correspond closely in their log character (Fig. 4.14) to periglacial sandstones of Latest Ordovician age in the *Risha* wells in Jordan (Andrews *et al.*, 1991) (Fig. 4.15). Texturally immature "glacial" sandstones of the Trebeel Formation in Jordan, as described by Andrews *et al.* (1991), have lower GR API signatures than the heavy-mineral dominated sandstones of the underlying Umm Tarifa Formation (Fig. 4.15).

Fluvial out-wash debris is typical of the Trebeel Formation in the Risha area of Eastern Jordan (Andrews *et al.*, 1991). In Saudi Arabia, the similar Zarqa/Sarah Formations also represent glacial/periglacial deposits and fluvio-glacial sandstones infilling incised valleys (Al-Laboun, 1986) (Plate 4.9a,b). Glacial erosion together with the effects of isostatic rebound led to the development of palaeo-valleys at least 600 m deep which were infilled by glacial moraine (McGillivray and Husseini, 1995).

Elsewhere in Iraq, the Late Ordovician glaciation may be represented by a sequence boundary (or lowstand systems tract in basinal areas) between pre-glacial facies and post-glacial transgressive Silurian deposits, as identified in the *Akkas-1* well.

Petroleum System Components

Proven and Potential Reservoir Rocks

Ordovician quartzites dominate potential reservoir systems in northern Arabia. These quartzites are generally more strongly cemented in the subsurface than they are at the equivalent Disi and Umm Sahm outcrops in Jordan. Comparison with the Dubaydib Formation of Jordan suggests that the Ordovician Khabour Formation may contain quartzite-rich intervals with reservoir potential, particularly towards the top of the unit.

The stratigraphically deepest Palaeozoic hydrocarbon accumulation in Iraq (*Akkas*) occurs in gas-bearing sandstones (up to 100 m thick) at the top of the Khabour Formation (Al-Haba *et al.*, 1994). The field has now been appraised by at least six wells and is considered to be commercial (Al-Hadidy, 2007). Sweet gas is reservoired in the K1-K4 Members. The uppermost "glacial" sandstones in Member K1 have an average porosity of 7.6% and permeability of 0.13 mD. The K2 Member sandstones (probably shallow-marine deposits) have average porosities of 6.9% and permeabilities of 0.08 mD at depths of about 2400 m (Al-Hadidy, 2007). Although these sandstones may be tightly cemented by quartz overgrowths, they have reservoir potential where fractured. Similar marine sandstones (Trebeel Formation) are gas-bearing at *Risha* in NE Jordan (Andrews *et al.*, 1991; Tamar-Agha, 2009).

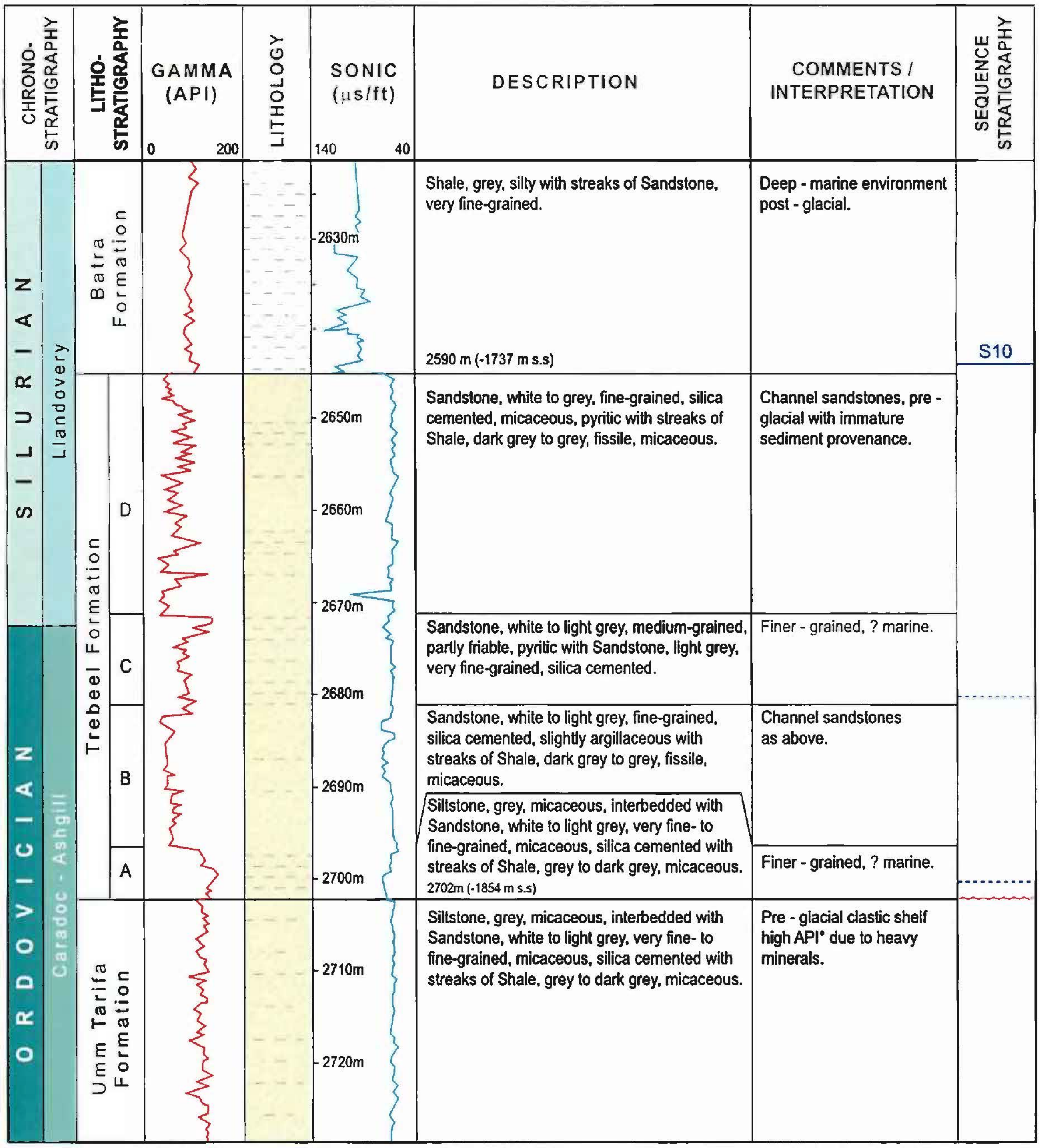


Fig. 4.15. Well logs through the Upper Ordovician glacial and interglacial siliciclastics (Trebeel Formation) in the *Risha* field, Jordan. After Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

Aqrawi *et al.* (2006b) described porosity preservation in Trebeel/ Upper Dubaydib sandstones (Plate 4.11). Primary intergranular porosity is only preserved where quartz grains are coated with clays, primarily chlorite, preventing the development of silica overgrowths. Similar chlorite-cemented sandstones may be present in the equivalent Khabour Formation in western Iraq.

In the Euphrates Graben, Syria, Ordovician sandstones of the Afendi Formation are low-porosity gas reservoirs (de Ruiter *et al.*, 1995).They have poor reservoir qualities (Konert *et al.*, 2001) due to deep burial, compaction and quartz overgrowths; a porosity of 6% was quoted by Frijhoff (2006)*. Reservoir quality is also poor due to low net : gross (de Ruiter *et al.*,1995), but may be enhanced by dissolution of carbonate cements (Konert *et al.*, 2001) or fracturing. Analogous glacial and interglacial sandstones occur at the *Elephant* field in Libya (Sola and Worsley, 2000).

The Burj Formation is unlikely to form a good reservoir rock because of extensive calcite cementation (Plate 4.12), unless secondary porosity has been created for example during dolomitisation. However, if isolated build-ups developed during drowning of the Burj platform, the potential for porosity preservation may be increased, by analogy with isolated Silurian build-ups in the Great Lakes

* *oral presentation*, Geo2006 Conference, Bahrain.

Plate 4.10. Stacked channel sandstones in the Mid– Upper Ordovician Dubaydib Formation resting on sandstones of the Hiswah Formation, southern Jordan. Geologists are inspecting the contact. Photo by A. Aqrawi.

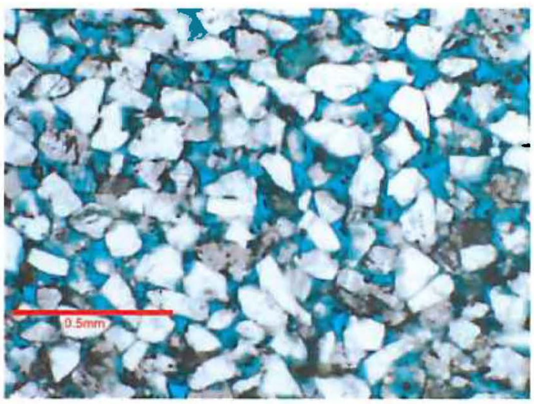


Plate 4.11. Photomicrograph of a sandstone sample from the Dubaydib Formation (Upper Ordovician), southern Jordan. Note dissolution of feldspar grains and development of overgrowths on quartz grains. Scale bar: 0.5mm. Photo by A. Aqrawi.

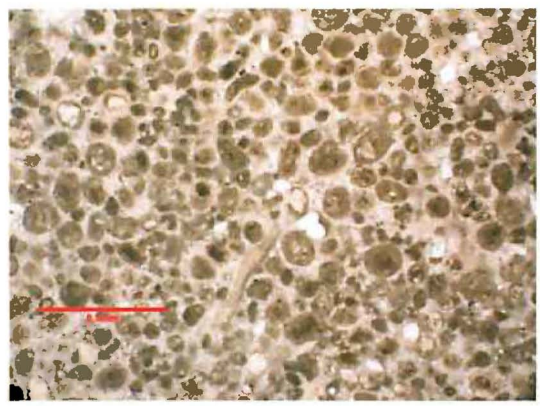


Plate 4.12. Tightly cemented oolites in the Middle Cambrian Burj Formation. Scale bar: 0.5 mm. Photo by A. Aqrawi.

area (Sears and Lucia, 1980; Bay, 1983) and Devonian build-ups in the Western Canada Basin (Schmidt *et al.*, 1985; Qing and Mountjoy, 1989).

Proven Source Rocks

Al-Ameri and Baban (2002) described source rocks in the Upper Ordovician Khabour Formation in the *Akkas-1* well. Overmature marine shales typically have 0.5-1% TOC (up to 2%: Al-Haba et *al.*, 1994). They may locally generate light hydrocarbons (Al-Hadithi, 1994; Al-Ameri and Baban, 2002) (Fig. 9.2.3). TOCs are lower in *Khleisia-1* (below 0.3%; Fig. 9.2.4). These source rocks are correlative with the "Llanvirn" Hiswah Formation shales in Jordan (O30 MFS of Sharland *et al.*, 2001), and with the Hanadir Member of the "Caradoc" Qasim Formation in Saudi Arabia (O40 MFS of Sharland *et al.*, *ibid.*) (Al-Ameri and Baban, 2000, 2002; Al-Hadidy, 2007). Ordovician source rocks are present in the *Risha* gasfield of NE Jordan (Armstrong *et al.*, 2005) and similar source potential may extend into western Iraq. Geochemical analyses of the Hiswah shales at outcrop and in the subsurface in Jordan indicate that the shales have little source potential (Aqrawi *et al.*, 2006b). The source rock potential of these basin margin facies may improve towards the basin centre.

Shelfal Burj carbonates have not been recorded as potential source rocks in wells in Jordan (Beydoun *et al.*, 1994). However, the formation may have source potential where deposited in basinal conditions towards Iraq (Aqrawi *et al.*, 2006b).

Proven Seals

Widespread shaly beds representing maximum flooding surfaces probably form local seals to the south and west of Iraq. Thicker and more extensive shales (Ra'an and Hanadir and their equivalents) are potential Ordovician seals. Sealing shales have been recorded in the Khabour Formation in the

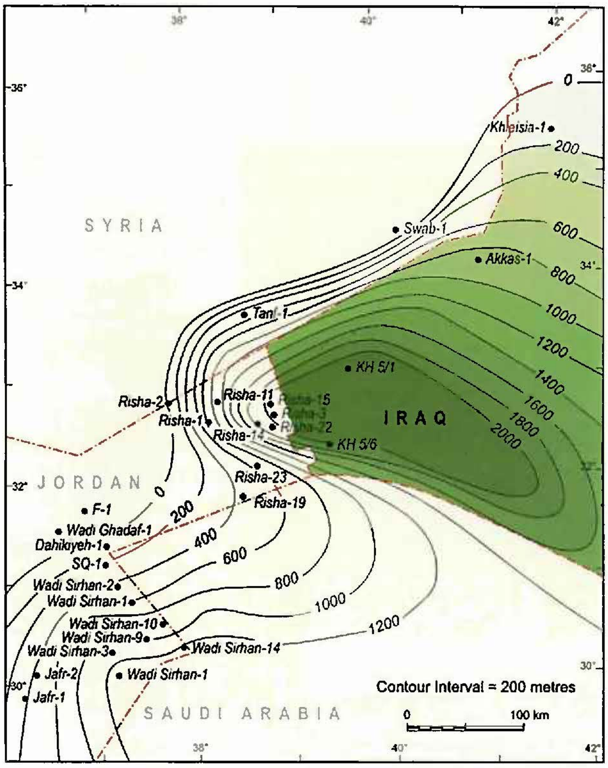


Fig. 4.16. Map of western Iraq and neighbouring areas showing the thickness of Silurian strata. Thicknesses away from well control are speculative. The trend of the area of thick Silurian sediments in western Iraq is poorly constrained. Modified after Aqrawi (1998) and Al-Haba *et al.* (1994).

Akkas field (Al-Hadidy, 2007). These shales will probably be better developed towards the north and NE of the Arabian Plate as clastic systems pass into more basinal facies. Ordovician shales probably do not seal intra-Ordovician sandstone reservoirs in Syria (de Ruiter *et al.*, 1995), which suggests that it is unlikely that these units will act as valid seals in Iraq, particularly in up-systems tract areas.

Locally at outcrop in Jordan (e.g.Plate 4.4), the Burj Formation is argillaceous and has potential as a seal rather than as a reservoir.

Megasequence AP3: Silurian – Middle Devonian (Frasnian)

Silurian

Latest Ordovician (late Ashgill)* to Middle Devonian rocks are assigned to Megasequence AP3 (Sharland *et al.*, 2001). Deglaciation accompanied by continued gentle intracratonic thermal subsidence resulted in a plate-wide transgression in the early Llandovery (earliest Silurian). The associated deepwater siliciclastics overlie Upper Ordovician shelf and glacial deposits. McClure (1988a,b) did not record a regionally significant depositional hiatus at the contact in Saudi Arabia. The Silurian interval is about 2000 m thick in west Iraq adjacent to the Risha area of Jordan (Fig. 4.16) (Al-Ameri and Baban, 2000; Jassim, 2006c; Aqrawi, 1998).It is absent at outcrop in Iraqi Kurdistan, where Upper Devonian clastics unconformably overlie Ordovician clastics.

Silurian sedimentary rocks assigned to the **Akkas Formation** were first formally reported in Iraq by Al-Haba *et al.* (1994) and Al-Ameri *et al.* (1991). Al-Ameri and Baban (2000, 2002) and Al-Hadidy (2007) also identified Silurian rocks based on palynological data in the lowest 570 m of well *KH 5/6* (Fig. 4.17), located just south of Traibeel on the Jordan/Iraq border (location: Fig. 4.2).

At well *Akkas-1* in western Iraq, the Akkas Formation is 864 m thick (depth 1463-2327 m), as indicated by well logs and palynology (Al-Hadidy, 2007). Black shales (see pp. 89-91) pass up into shales with occasional thin sandstone intervals (Al-Haba *et al.*, 1994). However, only 152 m of the lowermost shales of the Akkas Formation are present (depth 2139- 2291 m) in well *Khleisia-1* (Al-Hadidy, 2007) (Fig. 4.14). In well *KH5/6*, the succession comprises sandstones of Llandovery or younger age (Al-Naqshabandi, 1988). In this well (depth 560-1240 m: Fig. 4.17), sandstones are mostly quartz arenites and subarkoses interlaminated with siltstones and shales, deposited in a continental environment with brief marine incursions. Kaolinite is the main clay mineral with lesser chlorite and illite. Sandstones contain stable heavy minerals (zircon, tourmaline and rutile) with opaques and subordinate kyanite, staurolite and leucoxene. Petrographic and heavy mineral data indicate derivation from acid igneous, metamorphic and sedimentary rocks (Al-Jouboury, 1996; Al-Jouboury and Hassan, 1996).Well *KH5/1* penetrated 270 m of Ludlovian rocks between 1330 m and 1660 m (TD) (see Fig.4.27 below), comprising shales with occasional 10 m thick sandstone intervals (Kaddouri, 1992; Aqrawi, 1998; Al-Hadidy, 2007).

Lower Silurian rocks known from the subsurface in Iraq can be correlated with equivalent units in surrounding countries. These include the Qusaiba Shale and Sharawra Sandstone Members (Al-Laboun, 1986) of the Qalibah Formation in Saudi Arabia (Mahmoud *et al.*, 1992; Miller and Melvin, 2005). The Qusaiba Shale may reach a thickness of about 2000 m in the Turayf area near the Iraq border (Aoudeh and Al-Hajiri, 1995). Aqrawi (1998) and Armstrong *et al.* (2005) correlated the Akkas Formation in Iraq with the Mudawwara and Khusha Formations at outcrop in Jordan (Powell, 1989) (Plate 4.13), and with the subsurface Batra and Alna Formations in Jordan. These have a combined thickness of 2300 m near the Iraqi border (Fig. 4.3) (Andrews *et al.*, 1991). The Batra Formation (Figs 4.18, 4.19) is a black, micaceous shale with streaks of sandstone; it thickens to the NE from 100 m in the Wadi Sirhan area to 1300 m in the Risha area (Andrews *et al.*, 1991).

* *included here in Megasequence AP3.*

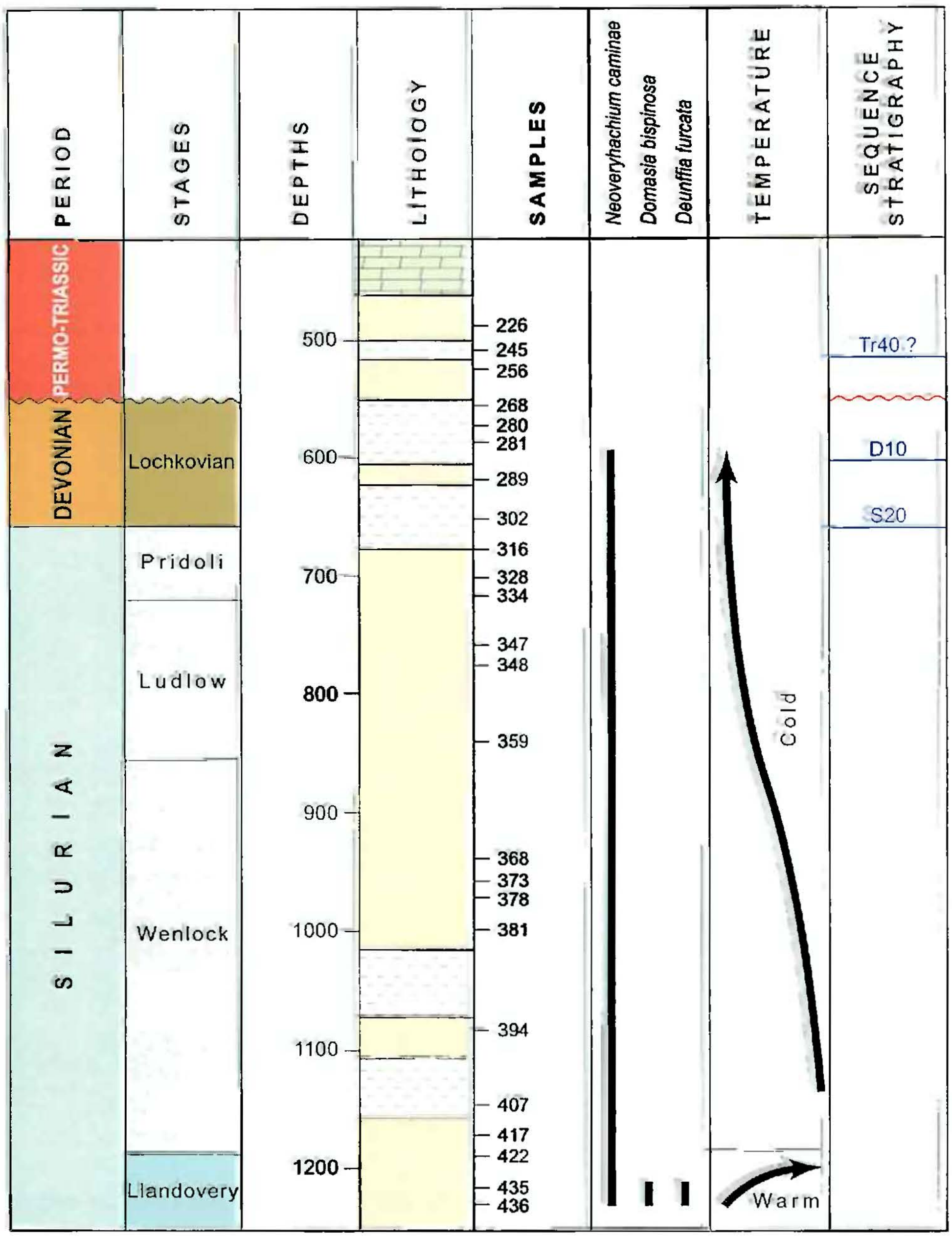


Fig. 4.17. Well log for the top of the Akkas Formation in well *KH 5/6*, showing the presence of Devonian sediments. Water temperatures are speculative and are based on palynological data. After Al-Ameri *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

In the Palmyra area of Syria, the Silurian Tanf Formation is approximately 800 m thick from seismic data (Best *et al.*, 1993). The formation has also been recorded in the Euphrates Graben (de Ruiter *et al.*, 1995; Frijhoff *et al.*, 2006), for example in well *Markada-101* where 413 m of Silurian sedimentary rocks are present. In the *Tanf-1* well near the border with Iraq, the Silurian is 530 m thick comprising graptolitic black shales interbedded with thin beds of siltstone and sandstone (Jassim, 2006c). However, Silurian sedimentary rocks are absent in the *Swab-1* well on the SW flank of the Euphrates Graben (Best *et al.*, 1993).

Later Silurian deposits are assigned to the Qaim Member of the Akkas Formation in Iraq (Al-Hadidy, 2007). Equivalent units in the Risha area of Jordan comprise the Alna Formation of Wenlock age and overlying shales, siltstones and sandstones (Andrews *et al.*, 1991). These siliciclastics in Jordan have been divided into three units: a lower mudstone/siltstone, 140 m thick, is overlain by a 600 m thick sandstone, and an upper 55 m thick black mudstone unit which probably represents the S20 MFS of Sharland *et al.* (2001). The middle sandstone member may be correlated with the Akkas Formation of Iraq as penetrated in well *KH5/6* (Al-Ameri *et al.*, 1991; Jassim, 2006c) (Fig. 4.16). The lower part of the Alna Formation corresponds to the section in well *KH5/1* in which the upper sandy part has been eroded (Jassim, 2006c). At Hazro in Turkey, the top of the Dadas Formation is a blue-green shale with phosphatic limestones of latest Silurian (Ludlow) age (Fontaine, 1981; Fontaine *et al.*, 1980). Silurian rocks are

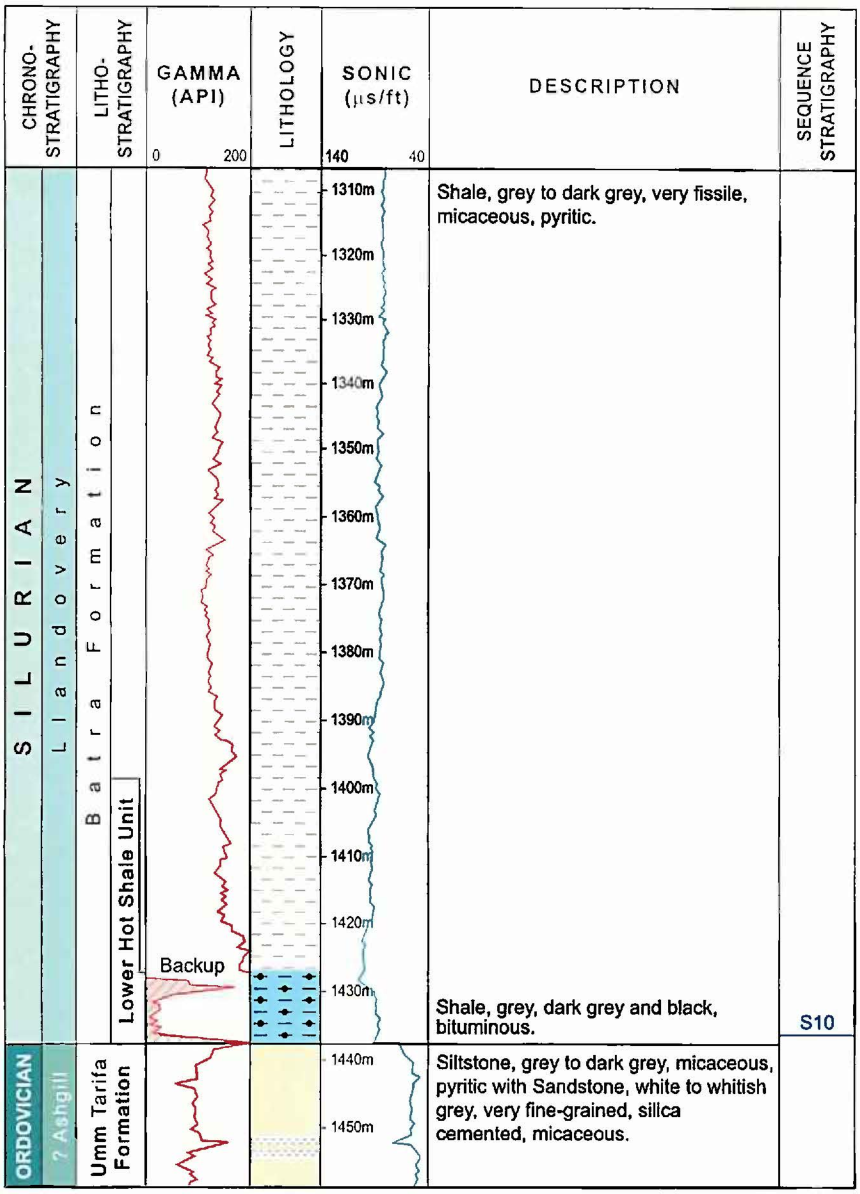


Fig. 4.18. Well logs through the lower part of the Batra Formation in well *Wadi Sirhan-8* (Jordan). Lowermost Llandovery "hot shales", which are interpreted to have source rock potential, occur at the base of the formation. Note that the glacial Trebeel Formation appears to be absent at this locality. After Andrews *et al.*, 1991; flooding surfaces after Sharland *et al.*, 2001.

absent in the Hakkari area north of the Iraqi border (Cater and Tunbridge, 1992).

Silurian deposition in Iraq began in pelagic to hemipelagic environments which evolved into an outer-shelf environment, followed by proximal shelf, inner and outer clastic shelf environments, and finally by intertidal to shoreface environments (c.f. Andrews *et al.*, 1991; Mahmoud *et al.*, 1992; Jassim, 2006c). The top of the Akkas Formation is interpreted to have been deposited in shallow-marine, inner neritic to tidal settings (Al-Ameri, 2000; Al-Ameri and Baban, 2002). The base of the formation is a deeper water deposit.

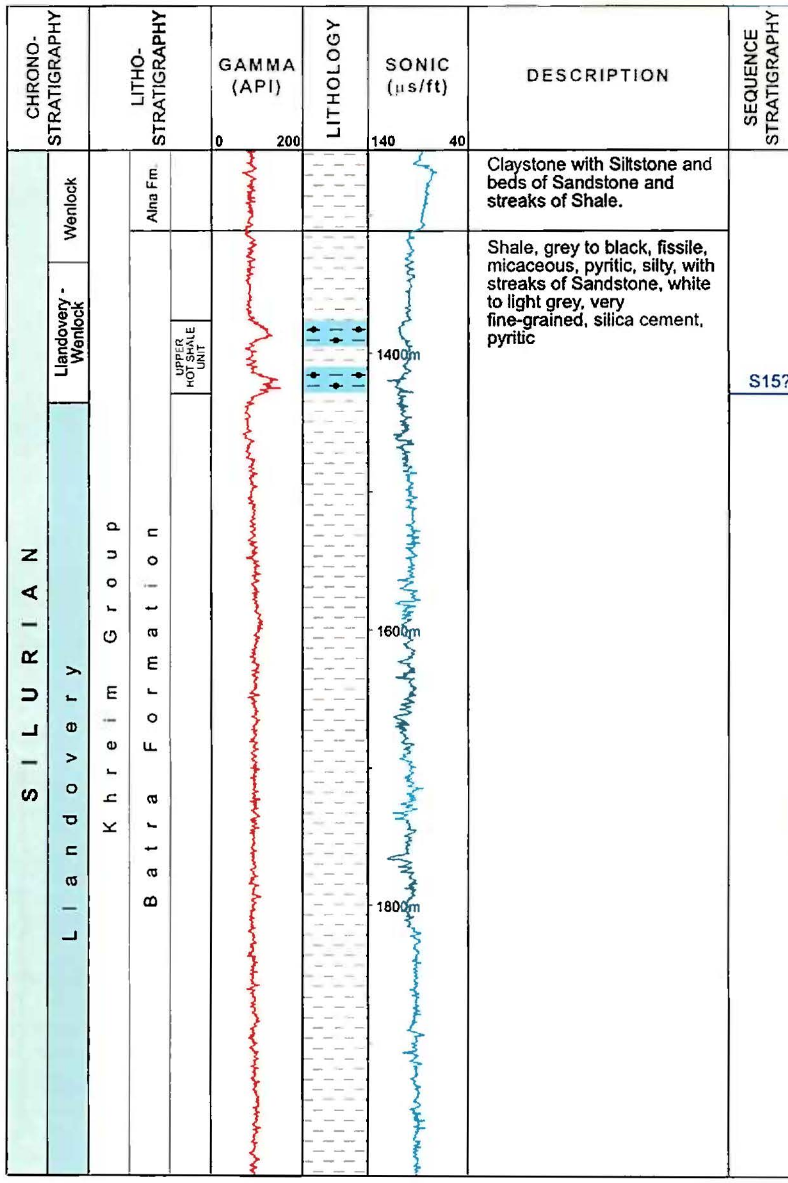
Lower – Middle Devonian

During the Early-Middle Devonian, shallow-water carbonates and clastics were deposited in the north of the Arabian Plate during relatively slow subsidence. Sediments of this age are probably absent in northern Iraq (Fig. 4.20). They are preserved in the Tabuk-Widyan areas of Saudi Arabia (Al-Laboun, 1986; Al-Hajri *et al.*, 1999). They are probably present in southern Iraq as suggested by palaeontological data and geophysical modelling (Al-Ameri *et al.*, 1991; Aqrawi, 1998; Jassim, 2006c) (Fig. 4.20). At well *KH5/6* in Western Iraq, Al-Ameri *et al.* (1991) and Al-Haba *et al.* (1994) reported 80 m of sandstones and shales conformably overlying uppermost Silurian sedimentary rocks, and dated them as Early Devonian (Gedinnian; now Lochkovian, Fig.4.17). Jassim (2006c) suggested that this interval may thicken to 700 m in the Southwestern Desert, although it is probably thin in western and central Iraq and is absent in NW and northern Iraq (Dunnington *et al.*, 1959; Seilacher, 1963; Al-Hadidy, 2007).

A "Silurian Hiatus" with minor erosion is reported in Saudi Arabia beneath the 230 m thick Tawil Formation (Al-Hajri *et al.*, 1999) (Fig. 4.21); this break may extend into the Southwest Desert of Iraq. It is also reported in the Dadas Formation in the Hazro area of SE Turkey (Fontaine, 1981; Fontaine *et al.*, 1980, 1989) where it occurs in the uppermost Ludlovian.

The Tawil Formation, which straddles the Silurian – Devonian boundary in Saudi Arabia (Al-

Fig. 4.19. Well logs through the upper part of the Llandovery succession at well *Risha-3*, NE Jordan (location: Fig. 4.2). "Hot shale" intervals, interpreted as possible flooding surfaces, occur at c.1400 m within a monotonous shale succession. After Andrews *et al.*, 1991.



Hajri and Owens, 2000), shows a shallowing-upwards signature; it is mostly marine (Plate 4.14) but passes up into aeolian dune deposits (Plate 4.15). Overlying Lower to Middle Devonian rock units may be up to 1220 m thick in NW Saudi Arabia (Al-Hajri *et al.*, 1999) (Fig. 4.21). They consist of the Jauf Formation (including the Shaibah Shale, Qasr Limestone, Subbat Shale and Hammamiyat Limestone Members; 240 m thick), and the 650 m thick Jubah Formation. These formations crop out extensively in the At-Tawil, Turaif and Al-Jauf areas of Saudi Arabia and have been closely studied (Helal, 1964a; 1965; 1968; Bahafzallah *et al.*, 1981; Boucot, 1984; Boucot *et al.*, 1988, 1989; Al-Laboun, 1986; Al-Hajri *et al.*, 1999). They occur in wells near the Iraq border including *Turabah-1* (Al-Laboun, 1986), *Nasr-1* (Al-Hajri *et al.*, 1999) and *S-462* (Loboziak, 2000) (Fig. 4.21). This succession is interpreted to represent a paralic siliciclastic to shallow-marine carbonate environment, as indicated by the presence of abundant stromatolites (Plate 4.16) and fish debris (Forey *et al.*, 1992; Lelièvre *et al.*, 1994). These units (in particular

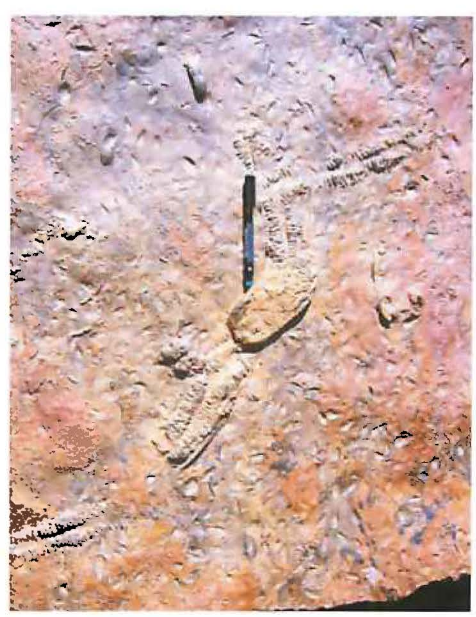


Plate 4.13. Silurian trilobites and trails *(Cruziana)* within shelfal sandstones of the Mudawwara Formation, southern Jordan. Photo by A. Aqrawi.

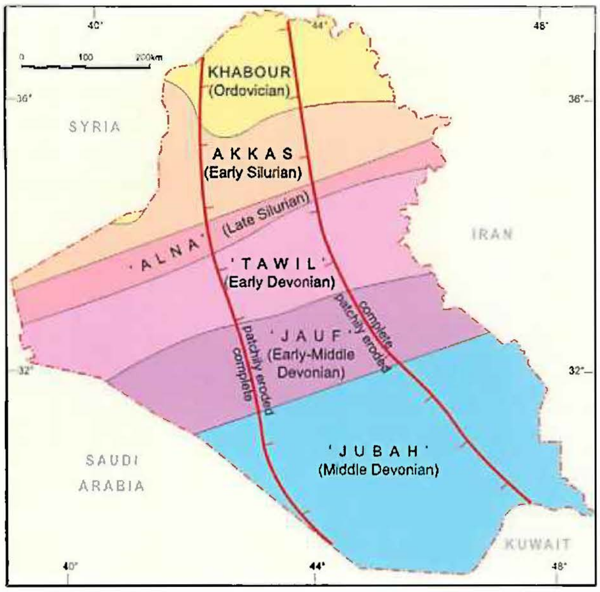


Fig. 4.20. Map of Iraq showing the subcrop beneath the Late Devonian unconformity. After Jassim, 2006c. Note that this map is based on very limited subsurface data.

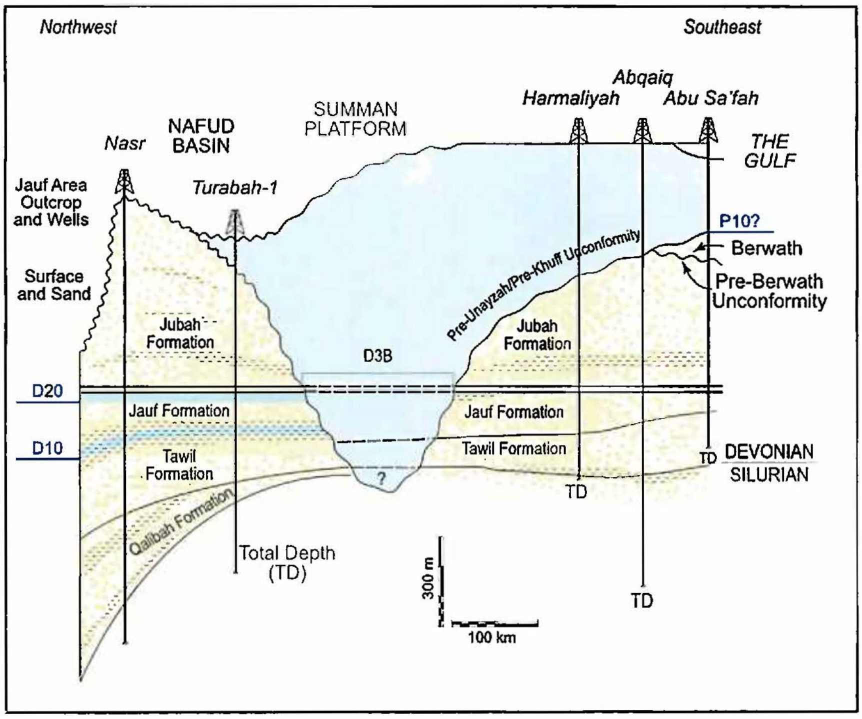


Fig. 4.21. Schematic NW-SE cross-section through Saudi Arabia (locations in Fig. 4.2) showing the Late Silurian - mid-Devonian. This interval was severely incised during the Late Carboniferous tectonic phase. After Al-Hajri *et al.*, 1999; flooding surfaces after Sharland *et al.*, 2001.

the Jauf Formation) cross the Summan Platform basement high without significant facies or thickness changes (Fig. 4.21). Lateral facies changes are thus unlikely to occur in adjacent parts of SW Iraq despite the presence of the Salman Zone.

Elsewhere, Lower – Middle Devonian units occur locally. Correlative units may include part of the Sayad Formation in the Palmyra area of Syria; while the coarser siliciclastics of the Dadas Formation in the Hazro region are of Early – Middle Devonian age (Fontaine *et al.*, 1980a,b; Cater and Tunbridge, 1992; Jassim, 2006c). These units are considered to be part of the upper AP3 Megasequence of Sharland *et al.* (2001). Eifelian to Frasnian ages have been established for the Jauf Group from miospore data (Loboziak, 2000).

The Late Devonian unconformity

The Lower – Middle Devonian succession, and part of the Silurian, was eroded over much of northern Arabia during the Middle Palaeozoic (Ruban *et al.*, 2007. The unconformity was referred to by Buday (1980) as "Caledonian", although it has no connection with the Caledonian orogenic belt of NW Europe. Jassim (2006c) interpreted an angular unconformity to be present at the base of the Upper Devonian in Iraq with progressive subcrop of older Lower Palaeozoic units to the north (Fig. 4.20).

Plate 4.14 (above left). Wave ripples in the Tawil Formation near Sakaka, NW Saudi Arabia. Photo by A. Aqrawi.
Plate 4.15 (above right). Cross-bedding in aeolian deposits at the top of the Tawil Formation, near Sakaka, NW Saudi Arabia. Photo by A. Aqrawi.

Silurian rocks are interpreted to be absent because of erosion at this unconformity in northern Iraq approximately to the north of lat. 36°N.The occurrence of basalts above the Late Devonian unconformity in northern Iraq (Dunnington *et al.*, 1959) suggest that it may have formed during a phase of thermal uplift. This unconformity is not well developed in Saudi Arabia where siliciclastics assigned to the Jubah Formation contain a nearly complete Middle –Upper Devonian succession, e.g. in well *Abu Safah-29* (Al-Hajri and Owens, 2000; Owens *et al.*, 2000).

Because of the unconformity, Lower Carboniferous sedimentary rocks unconformably overlie Ordovician sediments in well *Swab-1* on the Syria-Iraq border (Best *et al.*, 1993). In the Ora and Shish outcrop areas of Iraqi Kurdistan, unmetamorphosed Upper Devonian rocks unconformably overlie metamorphosed Ordovician quartzites containing stress micas (Dunnington *et al.*, 1959; Seilacher, 1963; Al-Hadidy, 2007). In the Zap area of SE Turkey, the Ashgill Sort Dere Shale Formation is overlain by Devonian redbeds (Janvier *et al.*, 1984) (Fig. 4.9).

Petroleum System Components

Proven and Potential Reservoir Rocks

Al-Haba *et al.* (1994) reported oil reservoired within Lower Silurian fractured sandstones and siltstones assigned to the Qaim Member of the Akkas Formation in well *Akkas-1* in western Iraq. Cores 6 to 9 from this well had an average porosity of 6.5% and permeability of 0.2 mD (Al-Sammari *et al.*,1994; Al-Hadidy, 2007). Silurian sandstones may have reservoir potential elsewhere in the Western and SW Deserts of Iraq (Aqrawi, 1998). Possible Upper Silurian – Devonian reservoir rocks include sandstones (e.g. the Tawil and Jubah Formations) and carbonates (e.g. the Jauf Formation). In Saudi Arabia, shallow-marine sandstones assigned to the Jauf Formation are proven gas reservoir rocks and have porosities of up to 25-30% (Al-Hajri *et al.*, 1999; Konert *et al.*, 2001). Oil shows occur in both the Tawil and Jubah Formations (e.g. Abu Ali *et al.*, 1999).

Oil-stained Lower Devonian sandstones (Dadas Formation) occur in the Hazro area of Turkey (Tasman and Egeran, 1952). A Devonian reservoir sandstone is known from the *Barbes Deep* well in Turkey (Beydoun, 1988b), while oils in the Hazro area are thought to have been sourced from Silurian shales (Beydoun, 1991).

Proven and Potential Source Rocks

Two organic-rich high-API "hot shales" totalling 61 m in thickness are recorded in the GR log in the lower part of the Akkas Formation (Hoseiba Member of Al-Hadidy, 2007) in the *Akkas-1* well, separated by 61 m of low-API section (Aqrawi, 1998; Al-Hadidy, *ibid.*) (Fig. 9.2.6). The shales occur between depths of 2205 m and 2327 m in this well (Al-Hadidy, 2007).

At well *Wadi Sirhan-8* in Jordan, a similar lower Llandovery "hot shale" is present at the base of the Batra Formation (Fig. 4.18). Another "hot shale" occurs at the top of the formation (upper Llandovery/ Wenlock) at well *Risha-3* (Fig. 4.19) (Andrews *et al.*, 1991; Lüning *et al.*, 2005). This shale may extend into Iraq but has not been recorded to date. "Hot shales" also occur at the base of the Tanf Formation in Syria (Frijhoff *et al.*, 2006).

The early Llandovery transgression was due in part to deglaciation (Vaslet, 1990; Mahmoud *et al.*, 1992; Armstrong *et al.*, 2005). The transgression created salinity-stratified water columns with anoxic conditions, lasting only some tens of thousands of years, throughout most of Arabia and North Africa. This led to the widespread deposition of organic-rich shales (Beydoun, 1993; Cole *et al.*, 1994a,b; Macgregor, 1996; Lüning *et al.*, 2005a,b; Dardour *et al.*, 2004). The lower Llandovery shales have high TOC contents, particularly within areas characterised by high phytoplankton productivity (Al-Ameri, 2000; Al-Ameri and Baban, 2002). High

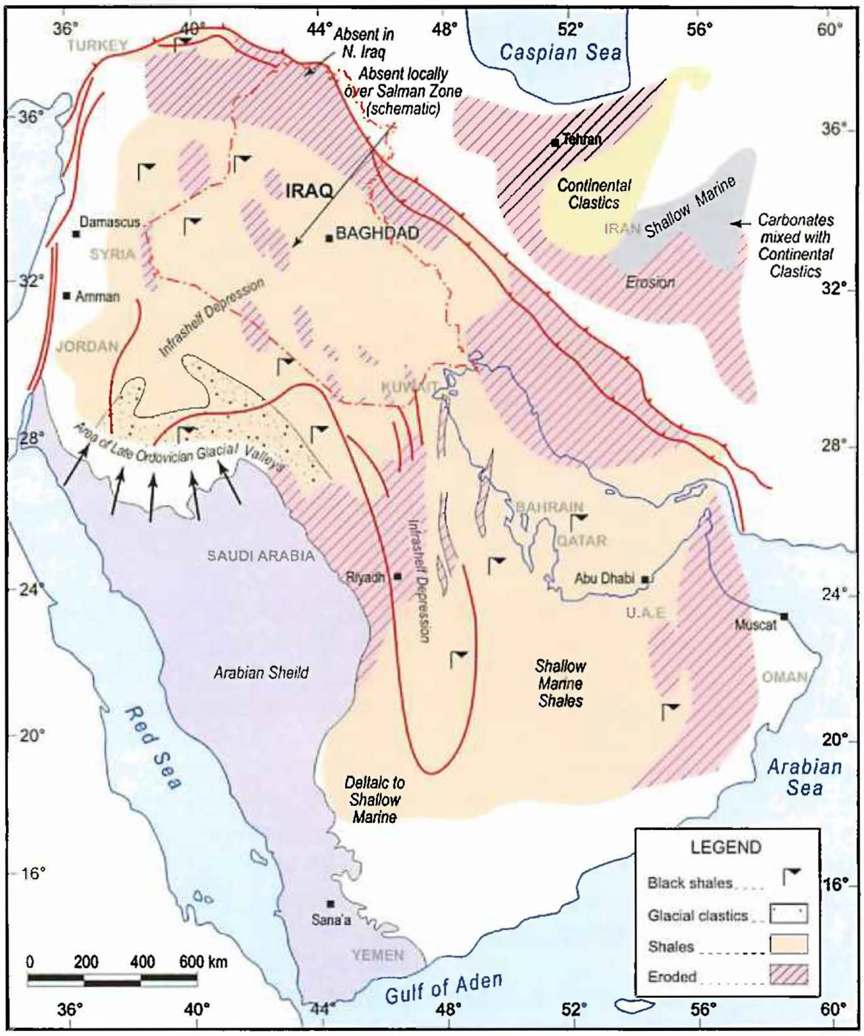


Fig. 4.22. Regional map showing the distribution of the Lower Silurian source rock system throughout Arabia. After Konert *et al.*, 2001.

Fe^{2+} contents resulted in the formation of early diagenetic pyrite (Aqrawi, 1998). Abu-Ali *et al.* (1991) recorded that pyrite can represent up to 25 wt% of the rock in Central Saudi Arabia. Very high pyrite contents are also observed in the Wadi Sirhan area of NE Jordan (*pers. obs.*, A.H., 1989). Loydell *et al.* (2009) suggested that one of the "hot shales" in the Batra Formation in southern Jordan may have formed by rapid early burial of organic carbon associated with a minor (i.e. higher-order) regression.

Shales of Early Silurian age are the main source for Palaeozoic plays throughout the Arabian Plate and North Africa (e.g. Abu-Ali *et al.*, 1991; Mahmoud *et al.*, 1992; Macgregor, 1996) (Fig. 4.22). A functioning Silurian source rock system has been proven to occur: (i) in Jordan (Aqrawi *et al.*, 2006b); (ii) in the Euphrates Graben area of Syria, where organic-rich marine shales occur at the base of the Abba Formation as identified from distinctive geochemical signatures in a number of accumulations (de Ruiter *et al.*, 1995); (iii) in many fields in Central Saudi Arabia (e.g. Abu Ali *et al.* 1999), and (iv) in the Levant, where Silurian sourced oils have recently been found in Triassic reservoirs (Pierce, 2004).

Al-Haba *et al.* (1994) first reported the presence of Lower Silurian "hot shales" in Iraq, in wells *Akkas-1* (Fig.9.2.6) and *Khleisia-1*. The shales are rich in amorphous algal, graptolitic and chitinous material (Aqrawi, 1998). XRD and SEM analyses of a shale sample from well *Khleisia-1* (Aqrawi, 1998) showed that clay minerals are dominated by illite and chlorite with some mixed-layer illite-smectite. The shales are also rich in pyrite, quartz and carbonates (particularly dolomite).

In *Akkas-1*, the TOC in the "hot shales" ranges from 0.96% to 16.62% with an average of about 6%. The hydrocarbon potential is up to 49 kg HC/ton rock (Al-Haba *et al.*,1994; F. H. Jaboury *in* Al-Sammari *et al.*, 1994; Salleh and Mokhtar, 1995; Al-Hadidy 2007). In well *Khleisia-1*, TOC ranges up to 9.94% (Al-Haba *et al.*, 1994; Aqrawi, 1998). Petroleum phases present in the associated reservoirs indicate expulsion products. They include sweet gases and light oils. Saturated and aromatic hydrocarbons form >96% of the liquid components, and are characterised by low molecular weights (C_3-C_{20}) with low contents of asphaltic materials (about 3.9%). Associated light (42-49°API) oils occur in the *Akkas* field (Al-Haba *et al.*, 1994). These are very similar to extracts of the Silurian "hot shales" from Saudi Arabia and North Africa (e.g. Abu Ali *et al.*, 1991; Cole *et al.*, 1994a,b; Macgregor, 1996); and to the hydrocarbons produced from Palaeozoic reservoirs in Saudi Arabia (McGillivray and Husseini, 1992). An immature sample of Silurian shale had a *Rock-Eval* T_{max} of 419°C and a Hydrogen Index of 469 mg/g TOC (Mahmoud *et al.*, 1992).

In Jordan, similar oils derived from Silurian "hot shales" with TOCs of up to 10% are reported to occur in the Wadi Sirhan area (Andrews *et al.*, 1991; Beydoun *et al.*, 1994; Armstrong *et al.*, 2005). Ala *et al.* (1980) and Bordenave (2008) noted that the Silurian Gakhum Formation of Iran is at an advanced stage of maturity, and is the most likely source rock for the gas in the Khuff Formation. At Kuh-e Gakhum in SE Fars, Bordenave and Burwood (1990) described over 100 m of black Silurian shales with residual TOCs of up to 4.3%. These shales may have reached a maximum burial depth of 6000 m (Beydoun, 1991). El-Bishlawy (1985) and Ali and Sildawi (1989) similarly proposed that the Silurian was a likely source of gas in the Khuff Formation in Abu Dhabi.

The predicted distribution of Silurian sedimentary rocks in Iraq (Jassim, 2006c) (Fig. 4.22), and correlation of Iraqi well-log data and source potential with well data from Jordan and Saudi Arabia (c.f. Andrews *et al.*, 1991; Cole *et al.*, 1994a,b; Sharland *et al.*, 2001), suggests that these Lower Silurian source rocks occur extensively within the Western and Southwestern Deserts of Iraq. They were eroded during Late Devonian uplift in northern Iraq (Dunnington *et al.*, 1959), where Upper Devonian sedimentary rocks unconformably overlie the "Llanvirn" Khabour Formation. They were also eroded during Late Carboniferous uplift along the Salman Zone (Jassim, 2006c). Their present-day distribution is indicated in Fig. 4.23. This suggests gradual cut-out of the source-rock interval northwards and eastwards from *Khleisia-1*, where the Upper Devonian Pirispiki Formation unconformably overlies the Lower Silurian Akkas Formation (Al-Haba *et al.*, 1994; Al-Hadidy, 2007).

Upper Silurian and Lower–Middle Devonian strata are scarce in Iraq and are poorly described in Saudi Arabia. Source rocks are unlikely to be present in the shallow-water carbonate and paralic to fluvial siliciclastics of this interval.

Proven and Potential Seals

Lower Silurian shales seal uppermost Ordovician light oil and gas reservoirs in the Akkas, Risha and Wadi Sirhan areas of NE Jordan / western Iraq (Aqrawi, 1998; Aqrawi *et al.*, 2006b), in central Saudi Arabia (Abu-Ali *et al.*,1999; Abu-Ali and Littke, 2005) and in North Africa (Macgregor, 1996). In Iraq, shales in the Hoseiba Member of the Akkas Formation form caprocks to the K1 reservoir of the Khabour Formation, while intra-Qaim shales seal reservoirs in the Qaim Member of the Akkas Formation (Al-Hadidy, 2007). Seal capacity will probably increase to the north and NE of the Arabian Plate as clastic systems pass into more basinal facies.

Plate 4.16. Algal (stromatolite) structures in the Hammamiyat Member of the Jauf Formation, NW Saudi Arabia. Photo by A. Aqrawi.

Megasequence AP4: Upper Devonian (upper Famennian) – Carboniferous (Westphalian 'C')

Upper Devonian (uppermost Famennian: "Strunian") and Carboniferous (Tournaisian to Westphalian 'C') deposits occur in Iraq. They rest on the Late Devonian unconformity. They have been recorded in the subsurface in wells *Khleisia-1, Akkas-1, Qaim-1, Jebel Kand-1* and *Atshan-1*, and in several *Keyhole* wells in the Western Desert (Buday, 1980; Kaddouri, 1992; Al-Hadidy, 2007).

Jassim (2006c) revised the age of the AP4 / AP5 Megasequence boundary in Iraq downwards into the Westphalian, from the late Stephanian as had been suggested by Sharland *et al.* (2001). Jassim (2006c) prepared an AP4 isopach map which indicates the presence of isopach thicks in the Khleisia High, Western Desert and Central Iraq areas with evidence of strong erosion over the Salman Zone (Fig. 4.24). The stratigraphic organization of this interval is complex and may not adequately have been addressed by previous litho- and chronostratigraphic schemes (e.g. Dunnington *et al.*, 1959; Sharland *et al.*, 2001; Jassim, 2006c; Al-Hadidy, 2007). In particular, there appear to be many more discontinuities (and sequences) than hitherto recorded, particularly if regional data from Saudi Arabia is taken into acount (e.g. papers in Al-Hajri and Owens, 2000). In general, the oldest units are confined to the northernmost parts of Iraq, while progressively younger units are preserved further south and west.

Recent work on wells *KH 5/1* and *Akkas-1* has led to confusion concerning the ages of the lithostratigraphic units in Megasequence AP4. For example, the Harur Limestone Formation at its

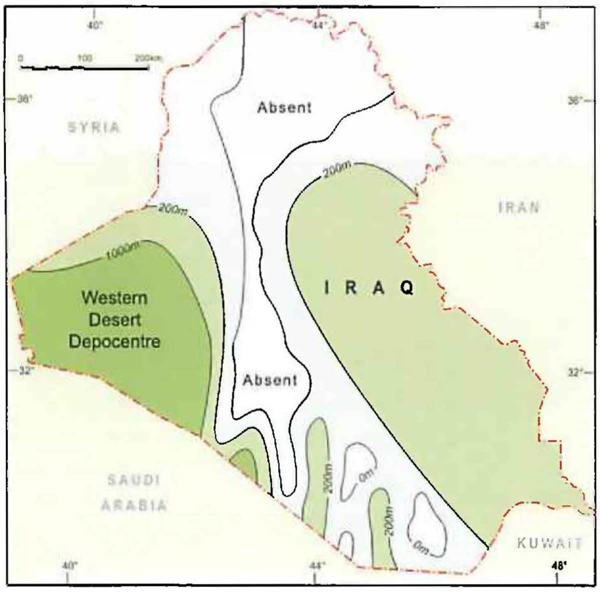


Fig. 4.23. Map of Iraq showing the isopach of Silurian – Middle Devonian strata (AP3 Megasequence) including at its base the Silurian source rock system. Based on gravity-magnetic modelling, after Jassim, 2006c.

Fig. 4.24. Map of Iraq showing the distribution of the Upper Devonian - Carboniferous (AP4) Megasequence. Based on gravity-magnetic modelling, after Jassim, 2006c.

type locality in Iraqi Kurdistan is early Tournaisian (Dunnington *et al.*, 1959; Buday, 1980), as is the equivalent Belek reef facies in SE Turkey (Janvier *et al.*, 1984) (Fig. 4.25). In well *KH 5/1,* it is mid-Tournaisian (Al-Moula, 2002; Al-Hadidy, 2007), but elsewhere it is considered to be latest Tournaisian (Al-Hadidy, 2007). In well *Khleisia-1,* the unit is also late Tournaisian (Al-Hadidy, 2007). In *Akkas-1,* the formation is still younger at its top, and a Tournaisian to early Viséan age was suggested by Kaddo (1997, in Al-Hadidy, 2007).

In northern Iraq, only the lower part of the Upper Devonian – Tournaisian succession is present (e.g. Dunnington *et al.,* 1959). It extends into adjacent parts of SE Turkey (Janvier *et al.*, 1984) (Fig. 4.25) and NE Syria (Fairbridge and Badoux, 1960; Al-Youssef and Ayed, 1992; Ravn *et al.*, 1994). Upper Devonian sedimentary rocks in Northern Iraq unconformably overlying the Lower Palaeozoic succession belong to the Pirispiki Red Beds, Chalki Volcanics and Kaista Formations (Buday, 1980; Al-Hadidy, 2007), and are assigned to the lower part of Megasequence AP4 of Sharland *et al.* (2001).

The **Pirispiki Red Beds Formation**, 83 m thick at its type locality, consists of quartz arenites, marly sandstones, siltstones, shales and conglomerates (Dunnington *et al.*, 1959) (Plates 4.17, 4.19), interpreted by Seilacher (1963) and Al-Hadidy (2007) to be continental deposits. Sandstones were probably derived from local reworking of fine-grained clastics and volcanics. In well *Khleisia-1*, the formation occurs between 2116 m and 2139 m, giving a thickness of only 23 m (Al-Hadidy, 2007). The formation was dated at outcrop as Ordovician or Devonian by Dunnington *et al.* (1959) and as Late Devonian by Seilacher (1963) and Buday (1980) based on stratigraphic context. Jassim (2006c) suggested that the basal part of the formation is Ordovician in age. Al-Hadidy (2007) presented palynological data collected by Al-Hasson (1999) which demontrates a late Famennian (Strunian: palynozones LL, LE and LN) age for the Pirispiki and overlying Kaista Formations in *Khleisia-1*, as indicated by the presence of *Retispora lepidophyta* (J. Keegan, *pers. comm.* to A.H., 2007).

The formation can be correlated with the Yiginli Formation of the Hakkari area of SE Turkey (Janvier *et al.*, 1984) (Fig. 4.25) and the Arras Basin (Altini, 1966), and partly with Upper Devonian – Tournaisian fluvial siliciclastics of the Jubah Formation in Saudi Arabia (McGillivray and Husseini, 1992; Al-Hajri and Owens, 2000; Owens *et al.*, 2000). In Syria, part of the Sayad Formation as present in well *Markada-101* may be equivalent to it (Al-Youssef and Ayed, 1992).

The Pirispiki Formation sandstones are lithic arenites with carbonate cements, and were derived from precursor sedimentary rocks as indicated by well-rounded heavy mineral grains and the absence of unstable minerals (Sinjary, 2006). Petrographic and geochemical analyses also indicated that the formation was deposited under semi-arid climatic conditions (Sinjary, 2006).

The **Chalki Volcanics** were classified as a formation by Al-Hadidy (2007) although they were previously considered to be part of the Pirispiki Red Beds Formation (Dunnington *et al.*, 1959; Buday, 1980). They comprise 2-5 m thick flows of altered olivine basalts (Dunnington *et al.*, 1959) with intercalations of tuff, ash, shales and siltstones (Buday, 1980). The volcanics are less than 20 m thick in northern Iraq at the type locality at Chalki,

Plate 4.17. Pirispiki Red Beds exposed in a road cutting near Dohuk, Iraqi Kurdistan. Photo by Eric Blanc, reproduced with permission of CASP.

and are absent some 20 km to the east at Ora (Dunnington *et al.*, 1959; Al-Hadidy, 2007).

The **Kaista Formation** at outcrop in northern Iraq comprises siltstones and silty shales with quartzites passing up into argillaceous limestones (Dunnington *et al.*, 1959). The limestones contain the brachiopod *Spirifer verneuilli* which together with other brachiopods and crinoids indicates a Famennian age (Buday, 1980).The formation was originally identified in well *Khleisia-1* (Buday, 1980). However, revision of the *Khleisia-1* stratigraphy (Al-Haba *et al.*, 1994; Al-Ameri and Baban, 2000) has now placed this interval within the Ordovician. Work by Al-Hasson (1999, *in* Al-Hadidy, 2007) shows that the top of the formation (as identified by Al-Hadidy: 2012-2116 m in *Khleisia-1*) is Tournaisian in age. However, it is more likely that its log-defined top (Fig. 4.14) is at 2078 m, thus making the entire formation Late Devonian, consistent with the outcrop stratigraphy. The formation would then be 38 m thick at that locality. In outcrops in northern Iraq, the formation is up to 70 m thick (Buday, 1980) (Plates 4.18, 4.19).

The Kaista Formation is divided into an upper dolomitic limestone and a lower black shale to fine-grained sandstone with occasional mudstone units (Barzinjy, 2006). The upper carbonate unit contains brachiopods, echinoids, algae, pelecypods, ostracods and calcispheres in addition to ooids and pellets, and was probably deposited in subtidal to intertidal environments (Barzinjy, 2006).

The sandstones are mostly quartz arenites and lithic arenites interpreted to have been deposited in a mixed fluvial-marine system. These sediments were probably derived from the Ordovician Khabour and Devonian Pirispiki Formations (Al-Juboury and Al-Hadidy, 2001). Patchy dolomite and quartz overgrowths are the main pore-filling cements (Al-Juboury and Al-Hadidy, 2008b).

The lower part of the unit passes up from continental facies (i.e. mixed Kaista and Pirispiki Formations) into shallow-marine deposits (Buday, 1980). It has thus been suggested that the use of the term "Kaista Formation" should be abandoned, and that the lower part of the formation should be reassigned to the Pirispiki Formation, and the upper part to the overlying Ora Shale Formation (Buday, 1980).

The widespread **Ora Shale Formation** in northern Iraq is up to 220 m thick. It comprises black calcareous to micaceous shales interbedded with silty marls, thin lenses of bioclastic and fine-grained limestones and occasional fine-grained sandstone beds (Dunnington *et al.*, 1959) (Plates 4.18, 4.19). Buday (1980) and Al-Hadidy (2007) noted that the formation in well *Khleisia-1* comprises shales (as in the Iraqi Kurdistan outcrops) with thin beds of limestone and dolomite and some sandstones and siltstones towards the base. The formation is estimated to be 213 m thick at this locality based on data in Al-Hadidy (2007) and using the re-picked base. The Ora Formation at outcrop contains brachiopods, echinoids, bryozoans and peloids. Fossils include *Spirifer verneuilli* in the basal part and *Avonia praelongus* and *S. julii* above (Dunnington *et al.*,1959). Palynology indicates that it is of Late Devonian – Early Carboniferous (early Strunian – early Tournaisian) age (Barzinjy, 2006). It was probably deposited in shallow-marine to near-shore environments.

The formation can be correlated with the Köprülü Shales in the Zap area of Turkey, which are dated as latest Devonian – earliest Carboniferous on the basis of their vertebrate and ostracod faunas (Janvier *et al.*, 1984) (Fig. 4.25). The Athar Formation of Syria is also equivalent although it is sandier except at the *Tanf-1* well (Al-Youssef and Ayed, 1992; Jassim, 2006c).

At outcrops in northern Iraq, the **Harur Limestone Formation** (lower Tournaisian) consists of 62 m of thick-bedded bioclastic (reefal and fore-reef) limestones interbedded with thin black calcareous/micaceous shales (Dunnington *et al.*, 1959). Buday (1980) reported that in well

Plate 4.18. Bedded calcareous marine sandstones of the Kaista Formation overlain by more massive, shelfal shales of the Ora Shale Formation at outcrop in northern Iraq. Photo by Eric Blanc, reproduced with permission of CASP.

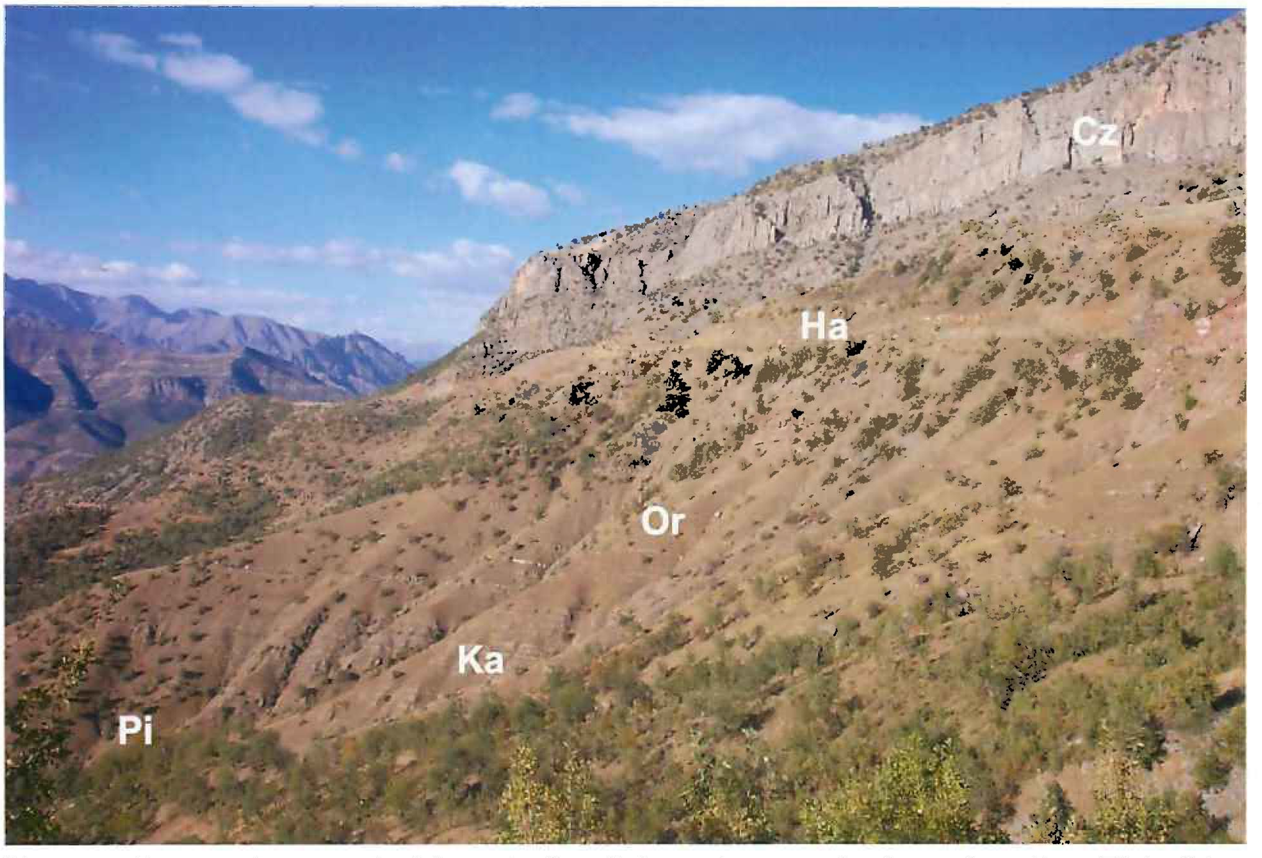


Plate 4.19. Outcrop photograph of the entire Late Palaeozoic succession in northern Iraq (Pirispiki, Pi; Kaista, Ka; Ora, Or; Harur, Ha; and Chia Zairi, CZ, Formations). Photo by Eric Blanc, reproduced with permission of CASP.

Khleisia-1, the Harur Limestone comprises dolomites and frequent interbedded shaly and silty intervals. Al-Hadidy (2007) picked the top of the formation at 1700 m, giving a total thickness of 165 m although the basal log contact is indistinct (Fig. 4.14); Buday's (1980) estimate of 120 m may be more reasonable. The Harur Formation conformably overlies the Ora Shale Formation (Plate 4.19). However, the top of the formation is marked by an abrupt break in sedimentation over most of Iraq (Dunnington *et al.*, 1959). The formation is also recorded at the base of the *Jebel Kand-1* well (Jassim, 2006c).

The Harur Formation in well *Akkas-1* is composed of lower and upper dolomitic units separated by shales. Dolomite is commonly coarsely-crystalline and consists of dolo-wackestone/packstone and dolo-peloidal wackestone/grainstone microfacies. Bioclasts include crinoids, echinoderms, red algae, bryozoans and brachiopods, interpreted to have been deposited in open-marine conditions. The middle shale unit is 5-10 m thick in the *Akkas* field and alternates with intervals of sandstone (Al-Juboury and Al-Hadidy, 2008b).It may be equivalent to 80 m of black foetid, partly oolitic and cavernous limestones of late Tournaisian

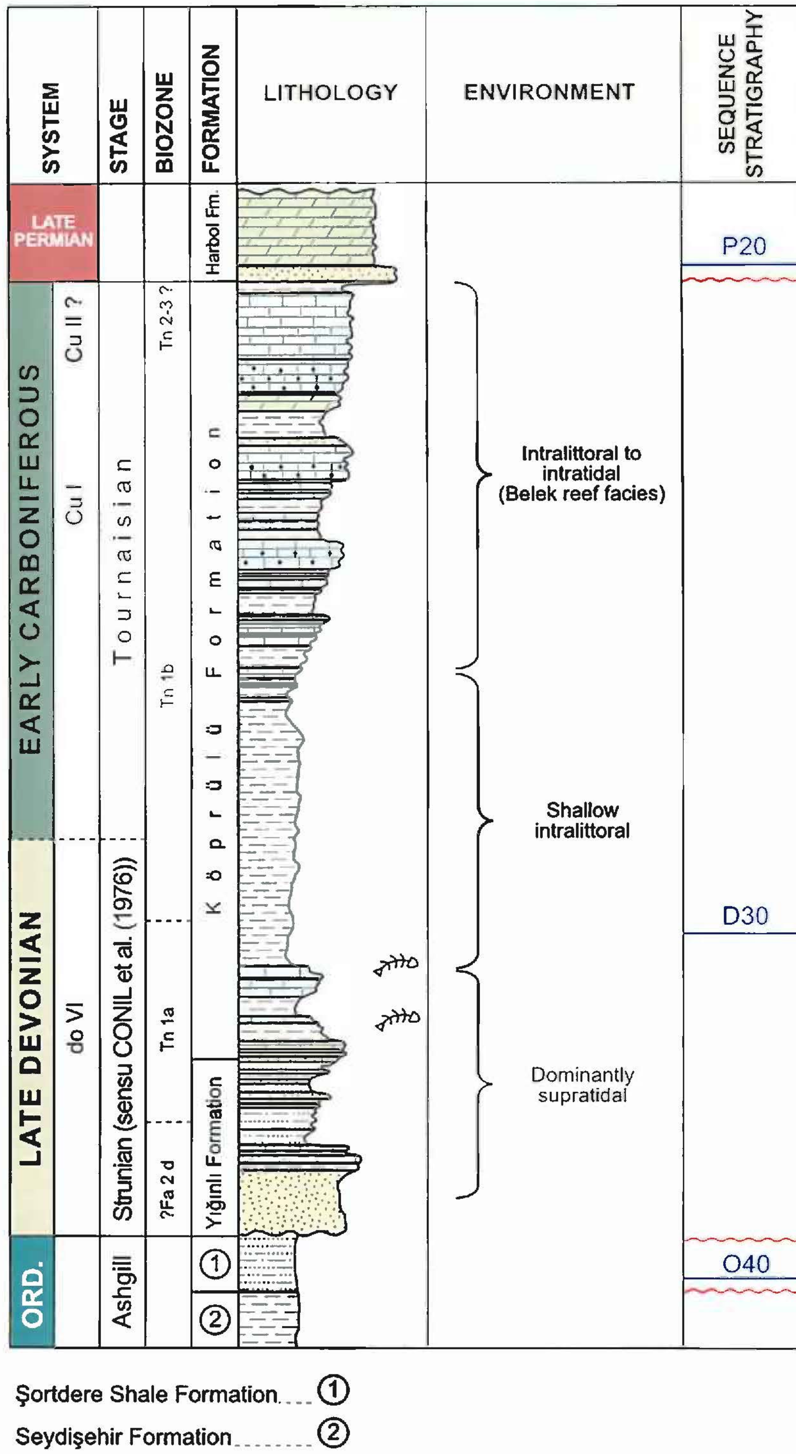


Fig. 4.25. Stratigraphic column and faunal control for the Late Devonian and Tournaisian of SE Turkey (Zap area). After Janvier *et al.*, 1984; flooding surfaces after Sharland *et al.*, 2001.

(latest PC biozone) age in *KH5/1* (Al-Moula, 2002; Jassim, 2006c).

In Jebel Abd El Aziz in Syria, Tournaisian limestones occur as olistoliths within Late Cretaceous basinal facies (Fairbridge and Badoux, 1960). The Haloul Formation comprises a 90 m thick unit of black carbonaceous limestones and mudstones of Tournaisian–Viséan age in central Syria (Al-Youssef and Ayed, 1992). The Belek Formation in SE Turkey (Janvier *et al.*, 1984) (Fig. 4.25) is also a correlative unit.

Kaddouri (1992), Al-Haba *et al.* (1994), Aqrawi (1998) and Al-Hadidy (2007: Fig. 4.26) reported sandstones, shales and carbonates from wells in the Western Desert including *Akkas-1* and well *KH 5/1* (about 600 m thick). These strata have generally been assigned to the "Suffi Formation" (Kaddouri, *ibid.*) (Fig. 4.27) or the Kaista, Ora and Harur Formations of supposed Late Devonian (Famennian) to Early Carboniferous (early Tournasian) age (Al Haba *et al.*, *ibid.*; Jassim, 2006c). Re-analysis of the palaeontological data presented by Kaddouri (1992) and Al-Hadidy (2007) indicates a late Tournaisian – Viséan or younger age for the AP4 succession in the Western Desert. The diagnostic Famennian spore *Retispora lepidophyta* has not been recorded from the *KH* wells or from *Akkas-1* (J. Keegan, *pers comm.* to A. H., 2006). Similarly, palynological and log data for well *Khleisia-1* (Fig. 4.14) suggest that many

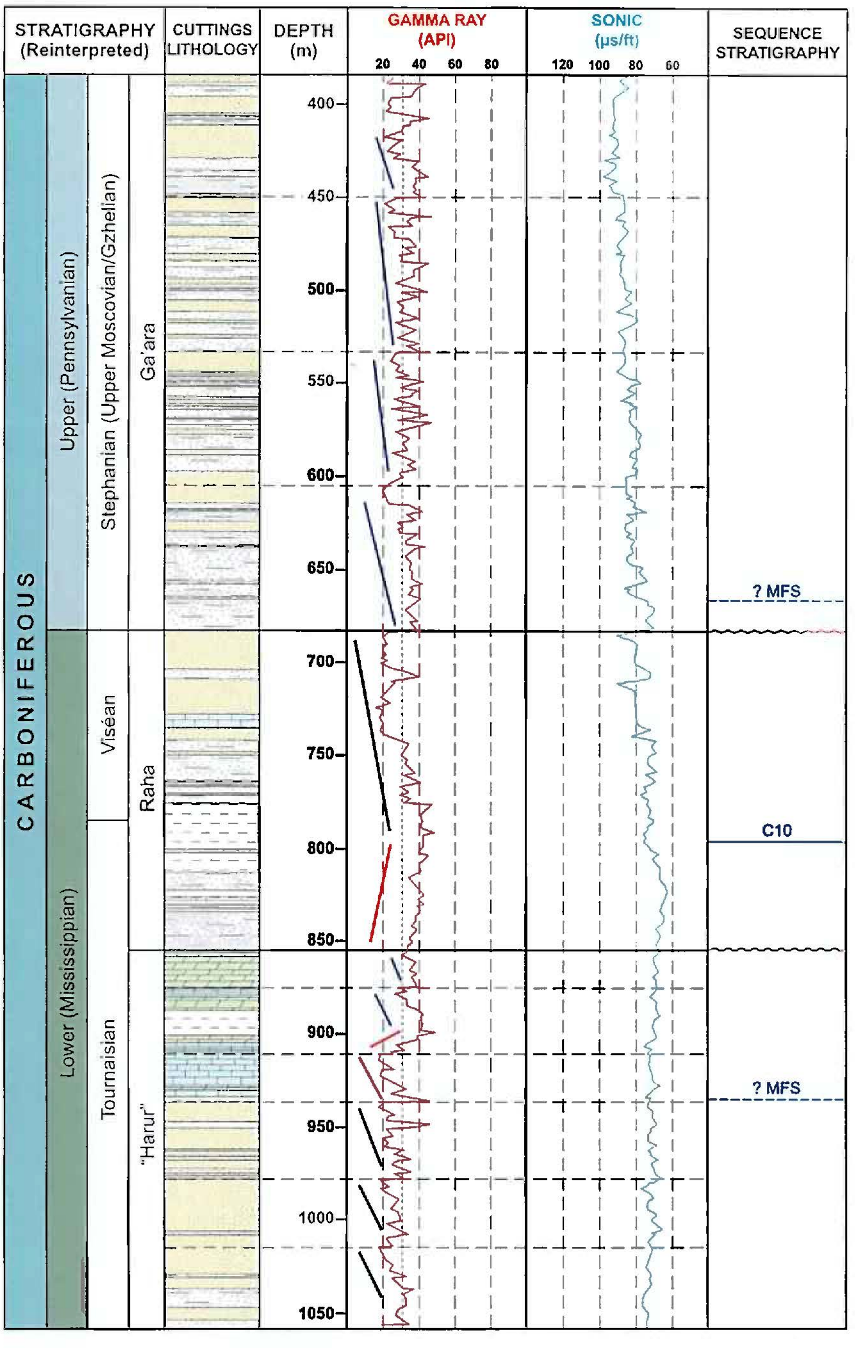


Fig. 4.26. Log through the Upper Palaeozoic succession in well *KH 5/1*. In the Tournaisian succession, parasequence cyclicity in the GR log appears to be small-scaled and deposits consist mainly of coarse clastics. A partial Viséan stratigraphy is present (the lacustrine Raha Formation), overlain erosionally by the Upper Carboniferous Ga'ara Formation. Coarser parasequence cyclicity is apparent. Log adapted after original in Al-Hadidy (2007), courtesy of *GeoArabia;* C10 flooding surface after Sharland *et al.*, 2001; the other flooding surfaces are previously undescribed.

more sequences and flooding surfaces than just the D30 MFS of Sharland *et al.* (2001) may be present in the lower part of the AP4 Megasequence.

Al-Hadidy (2007), after palynological work by Kaddo (1997) and Al-Moula (2002), re-assigned units of Viséan–Serpukhovian age in the Western Desert into a new formation, the **Raha Formation.** This supercedes the upper part of the Suffi Formation of Kaddouri (1992) and the lower part of the Bir El Rah Formation of Jassim (2006c). The Raha comprises black limnic claystones and shales with thin (<10 m thick) intervals of cross-bedded sandstones and occasional fossiliferous limestones. Numerous plant-rich shales passing into occasional immature (fusinite-grade) argillaceous coal horizons occur in the lower part of the formation above basal sandstones and shales — for example, between depths of 683 m and 856 m in well *KH5/1* (Jassim, 2006c) (Fig. 4.26). The Raha Formation is present in well *Akkas-1* where it subcrops the Ga'ara Formation (Al-Hadidy, 2007) (Fig. 4.28), and in well *KH5/2* (Jassim, 2006c) (Fig. 4.27). The upper Tournaisian–Viséan is 286 m thick in *Akkas-1*, 320 m thick in *Qaim-1* and 479 m thick in *KH5/1*. The Raha Formation is 77 m thick in *Akkas-1* and 184 m thick in *KH 5/1* (Al-Hadidy, 2007).

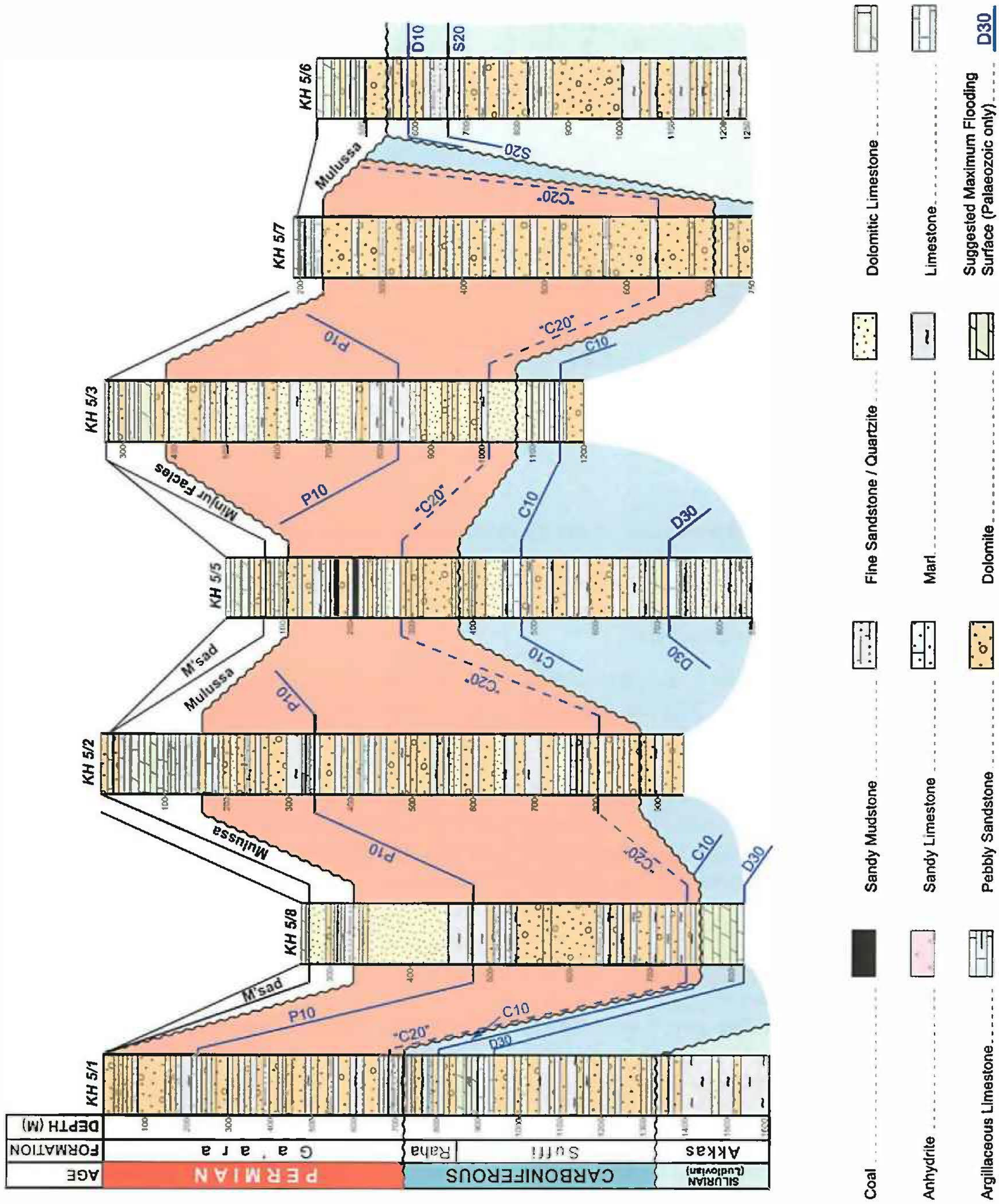


Fig. 4.27. Correlation of Upper Palaeozoic units in the Western Desert of Iraq. The "Suffi" approximates to the "Kaista Formation" and Akkas Formation of other publications. After Kaddouri (1992) and calibrated against Figs 4.16 and 4.26; flooding surfaces after Sharland *et al.*, 2001.

The succession in the Western Desert thus resembles the Markada Group in Central and Eastern Syria (cf. Daniel, 1963; Al-Youssef and Ayed, 1992; Best *et al.*, 1993; Ravn *et al.*, 1994), and the Berwath Formation of Saudi Arabia (Al-Hajri and Owens, 2000).Upper Tournaisian – Serpukhovian rocks overstep eroded upper Devonian – lowest Tournaisian strata near the Euphrates River (Fig. 4.28) and to the west in Syria (Ravn *et al.*, 1994).

The Carboniferous stratigraphy in adjacent areas of Saudi Arabia is complex. In wells *Ar'ar-1* and *ST-8* near the Iraq border (locations in Fig. 4.2), the lower part of the Berwath Formation is dated as latest Viséan – early Serpukhovian (Clayton, 1995; Owens *et al.*, 2000; Al-Hajri and Owens, 2000). This sequence (often referred to as the "pre-Unayzah clastics") also occurs in wells *NW-44* and *Turabah-1* and at outcrop at At-Tawil (Al-Laboun, 1986). It contains reworked Late Devonian and Tournaisian palynoflora at *Abu Safah-29* (Clayton *et al.*, 2000). An uppermost lower Serpukhovian – ?Moscovian sequence (the upper part of the Berwath Formation) occurs in well *Haradh-601* in Saudi Arabia (Al-Hajri and Owens, 2000; Owens *et al.*, 2000). In this well, the early Namurian to pre-late Westphalian 'D' succession contains reworked late Famennian to Tournaisian

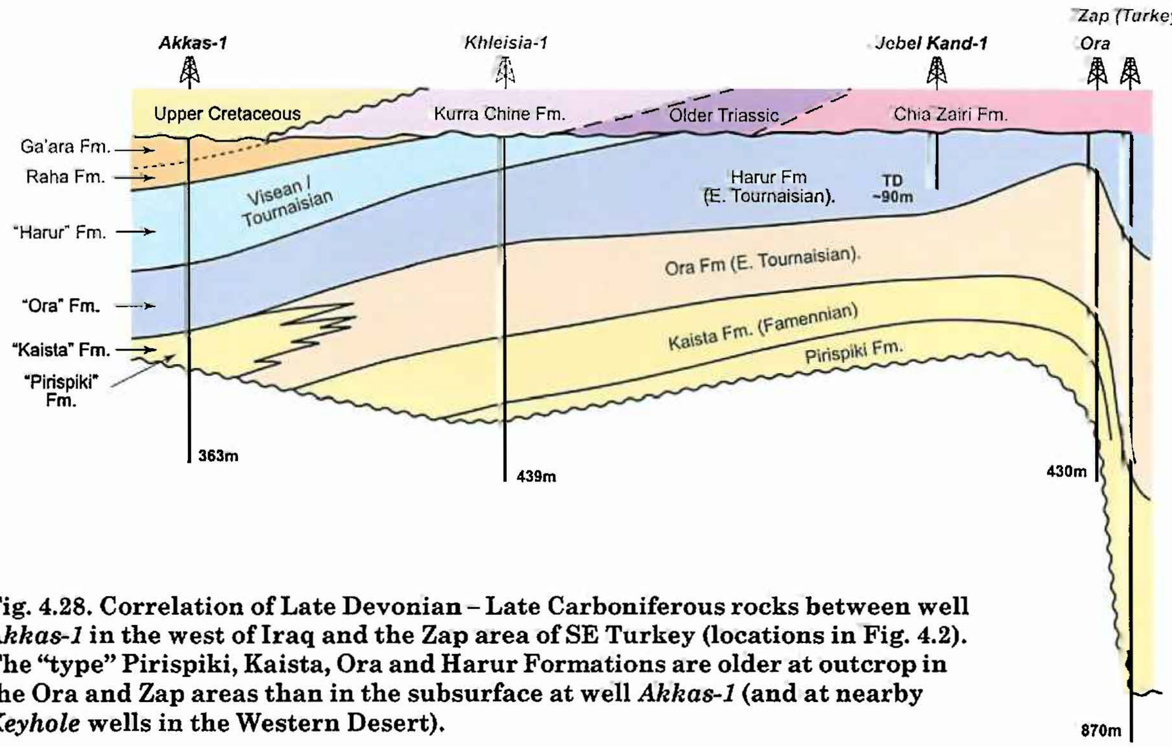


Fig. 4.28. Correlation of Late Devonian – Late Carboniferous rocks between well *Akkas-1* in the west of Iraq and the Zap area of SE Turkey (locations in Fig. 4.2). The "type" Pirispiki, Kaista, Ora and Harur Formations are older at outcrop in the Ora and Zap areas than in the subsurface at well *Akkas-1* (and at nearby *Keyhole* wells in the Western Desert).

palynomorphs (Owens *et al.*, 2000), indicating mid-Carboniferous uplift and erosion. The stratigraphy in southern Iraq is likely to resemble that found in northern Saudi Arabia.

No evidence has yet been found in Iraq for the Late Palaeozoic glacial event recorded in Saudi Arabia and Oman (Helal, 1964b; McClure, 1980; Levell *et al.*, 1988; Heward, 1990; Stump and van der Eem, 1995a, b).

Petroleum System Components

Proven and Potential Reservoir Rocks

Megasequence AP4 lacks proven reservoir rocks in Iraq, and its reservoir potential is therefore speculative and relies on analogues in neighbouring countries. Reservoir intervals in Carboniferous sandstones and leached dolomites in the Markada Formation occur in a few fields in the Euphrates Graben of Syria. However reservoir quality is often poor with low net-to-gross ratios (de Ruiter *et al.*, 1995; Litak *et al.*, 1998).

Pirispiki Formation sandstones appear to have a mature provenance and thus probably have reasonable reservoir qualities, since some second- or third-cycle quartzites described by Al-Hadidy (2007) may be derived from Early Palaeozoic sandstones. The Kaista Formation marine sandstones are believed to have good reservoir potential as they are moderately sorted. They have common carbonate cement and lesser amounts of quartz cement (Al-Juboury and Al-Hadidy, 2008a,b) due to their high content of brachiopod and coral debris. Younger Harur Formation reefal limestones may also have reservoir potential, particularly if karstified beneath the base-Permian unconformity. Facies of the Viséan and Serpukhovian siliciclastics of the Suffi / Raha Formation in the Western Desert (Kaddouri, 1992) are similar to those of the Berwath Formation in Saudi Arabia (Al-Hajri and Owens, 2000); equivalent sandstones may form reservoirs in the intervening Southwestern Desert of Iraq. The Raha Formation in *Akkas-1* has an average porosity of 20% and permeability of 58 mD in core *5* (1135-1144 m) (Al-Hadidy, 2007). Markada Formation siliciclastic reservoirs in the Hayan area of central Syria may be commercially viable, with reported flow rates of about 1800 b/d possibly rising to 3000 b/d (Hips and Árgyelán, 2007).

Proven and Potential Source Rocks

Organic-rich shales occur in the Ora Shale Formation. Their mean TOC is 1.48% in well *Akkas-1* and 3.45% in well *Khleisia-1*. The organic matter consists of woody fragments, lignin, chitin, pollen and spores mostly of continental origin (Al-Haba *et al.*, 1994), constituting gas-prone Type III kerogen. "Ora Shale" equivalents are known from SE Turkey (Köprülü Black Shales; Janvier *et al.*, 1984) and Syria (Ravn *et al.*, 1994). A Silurian or Carboniferous (Markada Formation) source has been proposed for Permo-Carboniferous – Triassic gas discoveries in the Palmyra area (Beydoun, 1991). In the Western Desert, the Ora Shale Formation appears to be absent (Kaddouri, 1992). The formation was probably removed by erosion during Late Carboniferous uplift of the Salman Zone. In Saudi Arabia, the equivalent Jubah Formation is dominated by coarse clastics with no source potential (Al-Hajri and Owens, 2000; Owens *et al.*, 2000).

Proven and Potential Seals

The Ora Shale Formation may act as a seal in Iraq. It conformably overlies potential sandstone and limestone reservoirs of Late Devonian age, and unconformably overlies older units on the margins of the Upper Palaeozoic basin. In Syria, shales of the Markada Formation (Viséan and younger) are insufficiently extensive to seal the associated intra-Carboniferous sandstone reservoirs in the Euphrates Basin (de Ruiter *et al.*, 1995).

The Late Carboniferous Unconformity

A "Late Carboniferous Tectonic Event", defined by Ruban *et al.* (2007), marks the end of Megasequence AP4 of Sharland *et al.* (2001). The associated unconformity was termed the "Pre-Unayzah Unconformity" by Al-Laboun (1986, 1987) and Al-Husseini (2000). Late Carboniferous deformation in the Arabian Plate was originally termed "Hercynian" (Buday, 1980) and was attributed to the influence of the Hercynian Orogeny (Husseini, 1991, 1992). The term "Hercynian" is more often used to describe the orogeny caused by the collision of the North American and Africa-European Plates. This created an orogenic belt extending from the Mauritainides via the Atlas Mountains into Central Europe. "Hercynian deformation" has also been used to describe time-equivalent north-south compression in Morocco and Algeria (Haddoum *et al.*, 2001), major north-south arching in Libya and Egypt (Guiraud and Bellioh, 1995), and synchronous deformation in Arabia (McGillivray and Husseini, 1992; Wender *et al.*, 1998). Formation of the associated unconformity is discussed on page 42.

The north-south trending "Rayn Anticline" structures of *Burgan*, *Ghawar* and *Khurais* were elevated or re-activated in Late Carboniferous time (Wender *et al.*, 1998; Al-Hajri *et al.*, 1999; Al-Husseini, 2000). Late Permian rocks unconformably overlie probable Cambrian and Precambrian basement metasediments (Khan, 1989; Al-Husseini, 2000) as a consequence of the uplift on the Burgan High (Kuwait) and Summan Platform (Saudi Arabia). At *Ghawar*, the Llandeilo Khafa Member of the Qasim Formation subcrops the unconformity surface; over 1000 m of sediment was probably eroded (Wender *et al.*, 1998). The Lower Palaeozoic section on the east-west trending Mardin High in SE Turkey was also deeply eroded during Late Carboniferous uplift (Cater and Tunbridge, 1992).

Late Carboniferous uplift and erosion created a regional unconformity in Iraq (Figs. 3.20, 4.29). Upper Permian limestones in Northern Iraq unconformably overlie Lower Carboniferous limestones. In both southern Iraq and the Western Desert (Al-Hadidy, 2007), Upper Carboniferous continental sandstones of the lower part of the Ga'ara Formation unconformably overlie Upper Devonian — Serpukhovian stratigraphy.

In Saudi Arabia, rock units unconformably overlying the unconformity consist of the Pre-Unayzah (Al-Khlata) and Unayzah clastics (Al-Laboun, 1986, 1988; McGillivray and Husseini, 1992; Owens and Turner, 1995; Al-Hajri and Owens, 2000). Since the Unayzah Formation covers the stratigraphic interval of the unconformity in wells in northernmost Saudi Arabia (e.g. *ST-8*, *Turabah-1*, *NW-44* and *Ar'ar-1*, close to the Iraqi border: Al-Laboun, 1986, 1988; Owens and Turner, 1995), maximum erosion and uplift on this unconformity probably occurred in present-day Jordan or Iraq.

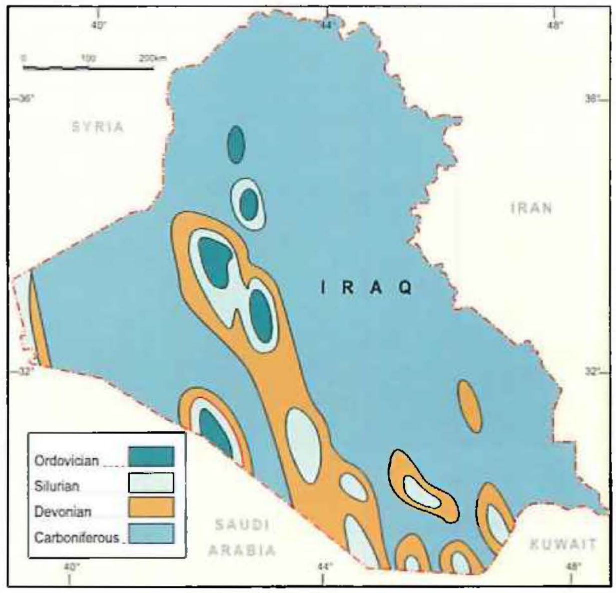


Fig. 4.29. Map of Iraq showing the subcrop to the Late Carboniferous ("Hercynian") unconformity. Based on gravity-magnetic modelling. After Jassim, 2006c.

Megasequence AP5: Upper Carboniferous (Westphalian) – Lower Permian (Kungurian)

This megasequence overlies the Late Carboniferous unconformity surface and is dominated by siliciclastic sedimentary rocks. These include the upper part of the Bir El Rah Formation (as defined by Jassim, 2006c) and most of the Ga'ara Sandstone Formation in the Western Desert of Iraq (Buday, 1980). Jassim (2006c) interpreted a major north-south trending depocentre (the Rutbah Basin) in the Western Desert, containing over 500 m of sedimentary rocks; and another basin, with up to 300 m of sedimentary rocks, in the Mesopotamian-Zagros area (Fig. 4.30). The basins formed between uplifted sectors of east and west Arabia. The western basinal area extended from NW Saudi Arabia through western Iraq and into central East Syria, where 1000 m of sedimentary rocks are present in wells *Dolaa-1* and *Doubayat-2* (Al-Laboun, 1988; Jassim, 2006c). The western uplift (an easterly-dipping monocline) covered the whole of Jordan and western Syria. The eastern uplift covered eastern and central Saudi Arabia, SW Iran and most of

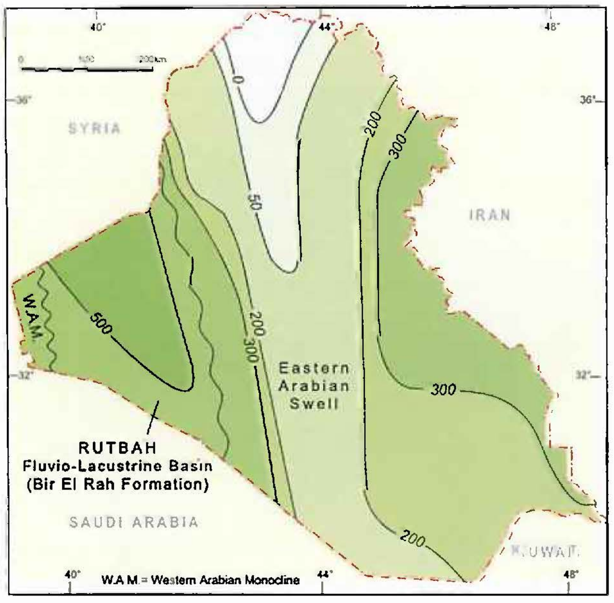


Fig. 4.30. Map of Iraq showing the isopach of Megasequence AP5 (Westphalian - Lower Permian) (after Jassim, 2006c). The presence of the depocentre in eastern Iraq is speculative because of lack of well control.

central and eastern Iraq (the Salman Zone) (Jassim, 2006c).

Sedimentary succesions in these basins have been divided into the fluvio-deltaic upper part of the Bir El Rah Formation of Westphalian to Stephanian age (Al-Haba *et al.*, 1994; Jassim, 2006c), and the overlying Ga'ara Formation red beds of Early Permian and younger age (Nader *et al.*, 1993a; Jassim, 2006c; Al-Hadidy, 2007).

Detailed palynology by Kalibova-Kaiserova (1989) from well *KH 5/2* indicated Westphalian-Stephanian to Early Permian (Autunian) ages. Upper Carboniferous sandstones and shales (Westphalian - early Stephanian) have been recorded (but were initially assigned to the Ga'ara Formation) both at outcrop in Wadi Al Sufi in the centre of the Ga'ara depression on the basis of decortified *Sigillaria* sp. (*Syringodendron*) stems, and from palynology in well *KH 5/1* (Ctyroky, 1973; Al-Najdi and Al-Jumaily, 1993). Similar results have been obtained from other palynological studies (Nader *et al.*, 1993a). In NW Saudi Arabia, part of the Unayzah Formation (Al-Laboun, 1986, 1988; Senalp and Al-Duaiji, 1995; Heine, 2000) may be equivalent.

The **Ga'ara Formation** can be subdivided into Lower and Upper units, similar to its time-equivalents in Saudi Arabia (the Al-Khlata and Unayzah Formations)(Al-Laboun, 1988; Aqrawi, 1998). Its thickness, with inclusion of the Niliji Formation as recommended by Buday (1980) and Jassim (2006c), is at least 120 m at Tlul Afyef and Wadi Duwaikhla, and 450 m in well *KH 5/1* (Fig.4.27). It is also present in shallow boreholes and trenches in the Western Desert (Jassim, 2006c). The Ga'ara Formation is generally assigned an Early Permian age at its base. Autunian ages were obtained from the lowermost 70-80 m in shallow wells including one located 10 km NNE of Bir El Rah village in Ga'ara (Nader *et al.*, 1993a; Al-Haba *et al.*, 1994). In *West Kifl-1*, a 50 m thick section of siliciclastic rocks assigned to the Ga'ara Formation underlies the Chia Zairi Formation (Fig. 5.8) and is dated as Kungurian (Al-Haba *et al.*, 1994).

The formation is highly diachronous; in the Western Desert, it extends up into the Anisian–Ladinian in well *KH 5/8* (Al-Ameri, 1990). It contains abundant plant remains (Jassim, 2006c), but further palynological work is required to subdivide the formation with greater confidence.

The Ga'ara Formation consists of cross-bedded sandstones (formerly the Ga'ara Sandstone Formation) overlying mottled mudstones with occasional thick cross-bedded sandstone beds (formerly the Nijili Formation) (Fig. 4.31). Both facies contain red mudstones that are conspicuously absent in the underlying limnic Raha/ "lower Bir El Rah" Formation (Jassim, 2006c; Al-Hadidy, 2007). Stacked sandstone channels, often with sigmoidal (point bar) cross-bedding and ironstone pebble lags, pass up into siltstones, green kaolinitic mudstones and mottled red-green mudstones, overlain by purple to red, locally pisolitic ironstones (ferricrete palaeosols) (Tamar-Agha *et al.*, 1984). Thin (a few cm thick) oxidized coal seams also occur.

These facies are interpreted as fluvio-lacustrine sediments and channels of a large meandering river system. Channel systems dominate the western part of the Ga'ara depression and flood-plain facies predominate in the east; within the channel system, rivers probably flowed from south to north (Tamar-Agha, 1986). Marsh deposits probably formed in abandoned oxbow lakes; prolonged periods of desiccation are indicated by the ferricrete palaeosols, and the climate was therefore significantly more arid than during the Westphalian (Tamar-Agha *et al.*, 1984; Jassim, 2006c). In well *KH 5/1*, cycles can clearly be defined in the GR log traces (Fig. 4.26). These may represent glacio-eustatic fourth-order parasequences. In this well, the Ga'ara sandstones are mostly highly mature quartz arenites, and are interpreted to have been deposited in a hot, humid climate (Al-Juboury and Al-Hadidy, 2005).

In wells *Atshan-1* and *West Kifl-1*, sandstones and shales beneath the carbonates and high GR API shales of the Chia Zairi and uppermost Ga'ara Formations (see Al-Hadidy, 2007) are of either Saxonian or Kungurian age. They may be correlated with the lower part of the Ga'ara Formation (Al-Haba *et al.*, 1994; Aqrawi, 1998; Melvin and Sprague, 2006).

The oldest AP5 rocks in Saudi Arabia are dated as Westphalian 'D'. The Al-Khlata Formation at well *ST-8* near the border with SW Iraq rests unconformably on the Serpukhovian Berwath Formation (Owens and Turner, 1995; Al-Hajri and

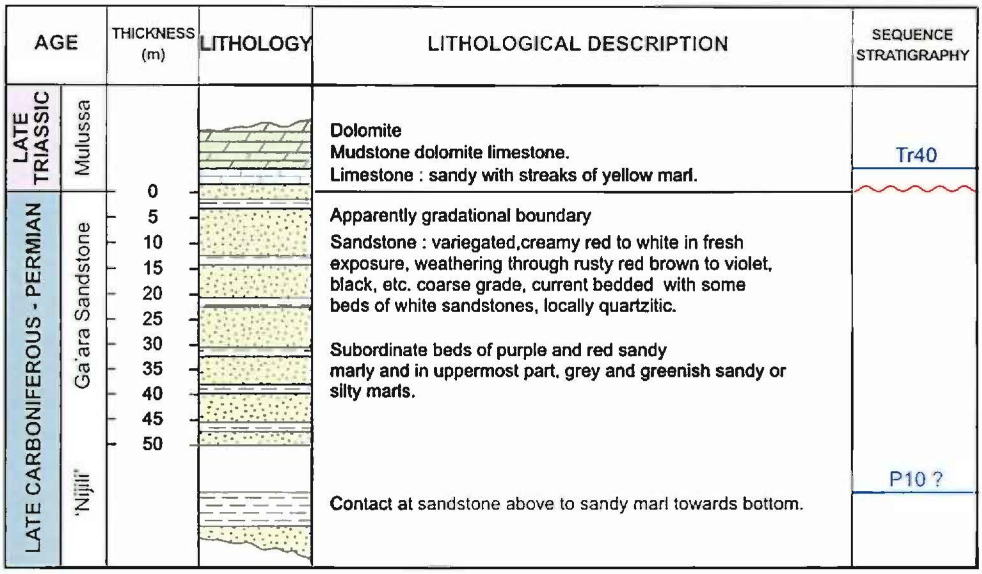


Fig. 4.31. Type section of the Ga'ara Formation in the Western Desert of Iraq. After Al-Hadidy, 2007; flooding surfaces after Sharland *et al.*, 2001.

Owens, 2000; Owens *et al.*, 2000). Wender *et al.* (1998) noted that the basal glaciogenic Unayzah Formation member 'B' is of Asselian – early Sakmarian age and onlaps the basal unconformity. The succeeding member 'A', of late Sakmarian–Kungurian age, comprises alluvial, fluvial and aeolian to shallow-marine sandstones above red-grey playa siltstones (Wender *et al.*, 1998; Konert *et al.*, 2001). Palynological data from well *ST-8*, where the Unayzah is 150 m thick, shows mixed European and Gondwanan floras. Further south in well *Haradh-601*, the floras are fully Gondwanan (Owens *et al.*, 2000) while data from the Western Desert suggests Cathaysian floras (Nader *et al.*, 1993a).The present-day border between Saudi Arabia and Iraq may thus mark the approximate position of a significant Permian floral province boundary (Owens *et al.*, 2000).

In Syria, the equivalent upper part of the Markada Formation was deposited in shallow-marine to fluvio-deltaic settings (Lucic *et al.*, 2003). Correlative units also include the Heil Formation (680 m thick in well *Doubayat-2*) which is considered to include the Amanus Sandstone as a 105 m thick upper member (Jassim, 2006c).

Upper unconformity

The unconformity at the top of Megasequence AP5 probably represents a break-up unconformity. Neo-Tethyan rifting probably began at the end of the Early Permian. However, the poorly dated and uncertain geometry of the Late Carboniferous – Permian sedimentary succession makes it difficult to date the onset of rifting in Iraq. Rifting would have been accompanied by uplift and erosion of intrabasinal highs. Sediment reworking within the megasequence further complicates the stratigraphic interpretation.

By the end of Megasequence AP5 deposition, the structural setting of the Arabian Plate had changed significantly. Rifting occurred at the northern margin of the Arabian Plate with the separation of a series of continental blocks (page 49).

Petroleum System Components

Proven and Potential Reservoir Rocks

The Ga'ara Sandstone Formation is sufficiently coarse-grained to be a promising exploration target. It may locally directly overlie Silurian source rocks, particularly within the basins bordering the Salman Zone. Westphalian–Sakmarian sandstones of the Unayzah Formation in the Widyan Basin of Saudi Arabia are potential targets for stratigraphically trapped gas reservoirs (Al-Laboun, 1986, 1988), and may extend into the Southwestern Desert of Iraq (Aqrawi, 1998). Further south, these sandstones are proven regional reservoirs (McGillivray and Husseini, 1992; Al-Husseini, 2004). They include the Unayzah 'A' reservoir that has tested "premium oil" in the *Tinat* structure in northern Saudi Arabia, and gas in the *Haradh, Sahba* and *Harmaliyah* culminations in the southern part of the *Ghawar* field (Wender *et al.*, 1998). These reservoir rocks have porosities of 5 to 25% (with an average of 12% in the pay zone) yielding flow rates of less than 5 to over 40 million scfg/d (Wender *et al.*, 1998). The Unayzah 'B' sandstones have tested gas in the *Haradh* culmination at *Ghawar*. They have average porosities of 6%, although flow rates are improved locally due to fracturing (Abu-Ali *et al.*, 1991; Wender *et al.*, 1998).

The "Basal Khuff clastics" cored in a deep well in northern Kuwait (Tanoli *et al.*, 2008) comprise about 22 m of sandstones and carbonaceous shales deposited in a coastal plain environment.

In Syria, the *Jazal* field in the Palmyra Basin contains oil in the Markada Formation sandstones with recoverable reserves of about 9 MM brls and production rates of about 3000 b/d. Another recently discovered field (*Mustadira*) tested 17.7. MM scf/d and about 150 b/d of liquids*. Porosity in the Markada Formation sandstones in the Hayan area of Syria is reduced due to compaction and early cementation by haematite, pyrite, quartz overgrowths, kaolinite and smectite-chlorite. Later diagenetic modifications included dolomitisation and transformation of clay minerals to illite-chlorite. Secondary porosity formed due to the action of acidic formation waters and was followed by late carbonate cementation (Maric-Durekovic *et al.*, 2004)

Proven and Potential Source Rocks

The Ga'ara Formation in Megasequence AP5 has little or no source potential on acount of its generally continental deposition. Minor gas potential may be associated with coaly horizons.

Proven and Potential Seals

Interbedded mudstones within the Ga'ara Sandstone Formation may locally act as effective seals. An analogue is the intra-Unayzah siltstone unit that forms a local seal within the southern part of the *Ghawar* structure (Wender *et al.*, 1998).

Concluding Remarks

The Cambrian – Lower Permian succession in Iraq consists of Megasequence AP1-5. Megasequence AP1 (Infracambrian – Lower Cambrian) is only known directly from rocks brought to the surface in the Jebel Sanam salt plug in SE Iraq. The distribution of AP1 in Iraq can be inferred from geophysical modelling. Stratigraphic data from adjacent countries suggests it may contain synrift clastics and volcanics, restricted marine evaporites and carbonates. Megasequence AP2 contains Middle Cambrian – Upper Ordovician clastics which probably include regionally extensive sandstone reservoirs and seals, and low-TOC marine source rocks.

A regional unconformity separates Megasequences AP2 and 3. Megasequence AP3 (Silurian – Lower Devonian) contains an important Lower Llandovery (Lower Silurian marine source rock which has been recognised in well *Khleisia-1* and in the *Akkas* field. The original depositional extent of this source rock outside the *Khleisia* and *Akkas* areas is unknown at present. Overlying Silurian – Lower Devonian sedimentary rocks comprise marine mudstones with beds of sandstone and carbonates. Very thin oil-bearing Silurian sandstones occur at Akkas. Uppermost Ordovician sandstones at *Akkas* contain the only commercial Palaeozoic discovery so far made in Iraq.

A major regional unconformity of Late Devonian age (separating Megasequences AP3 and 4) has been identified in northern Iraq. The subcrop of older Palaeozoic units beneath this unconformity, and the facies distribution of the overlying onlapping sediments are poorly understood. Megasequence AP4 (Upper Devonian – Upper Carboniferous) comprises shallow-marine clastics and carbonates. Reservoirs have not been described from this megasequence, which may locally act as a seal preventing the upward migration of hydrocarbons generated by the Lower Silurian source rocks into Megasequence AP5.

A major unconformity occurs at the base of Megasequence AP5 (Upper Carboniferous - Lower Permian). This megasequence is only known from outcrops and water wells in the Western Desert, where it comprises sandy fluvial and lacustrine clastics. The subcrop pattern at the basal-AP5 unconformity is poorly understood. Gravity and magnetic data suggest that deep erosion has occurred at this unconformity on north-south trending structures in the Salman Zone of central and southern Iraq, at which Ordovician sediments may locally subcrop Megasequence AP6.

The correct use of lithostratigraphic terminology in the Palaeozoic of Iraq is problematic, particularly in the Upper Palaeozoic. The authors recommend that the terms Pirispiki, Kaista, Ora and Harur Formations should be used only for Famennian – lower Tournaisian stratigraphic units. The term "Suffi Formation" should be restricted to upper Tournaisian mixed carbonates and clastics. The terms "Raha" and "Bir El Rah" Formations should be applied to Viséan – lower Moscovian and upper Moscovian – Gzhelian lacustrine to deltaic clastics, respectively. The Ga'ara Formation can be retained for overlying continental red beds.

The Palaeozoic petroleum system of Iraq is described in Chapter 9ii (pp. 293-306). It is poorly known because of limited pre-Mesozoic exploration; only six wells (*Khleisia-1, Akkas-1, Qaim-1, Atshan-1, Jebel Kand-1* and *West Kifl-1*) have penetrated the Palaeozoic interval. The Palaeozoic succession is expected to become an important exploration objective, particularly in west and SW Iraq where the Mesozoic and Tertiary cover is relatively thin. The Palaeozoic petroleum system of the Arabian Plate is better known in the countries adjacent to Iraq. Here, organic rich regionally extensive Lower Silurian source rocks have charged Upper Ordovician and Devonian sandstones, as well as Upper Carboniferous – Permian sandstones and Upper Permian carbonate reservoir units of Megasequence AP6 (described in Chapter 5).

The Cambrian – Lower Permian succession in Iraq is one of the few remaining onshore frontier exploration plays in the world. Acquisition of new high- resolution seismic data and deep drilling is required to better understand the stratigraphy of megasequences AP1-5 in Iraq, and the corresponding petroleum potential.

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* *Times Online*, 17.7.08.

5. MIDDLE PERMIAN TO MIDDLE JURASSIC

This chapter is based on high quality data from Northern Iraq and regional information. Palaeontological control is scarce. Only in Northern Iraq is there sufficient data to discuss the prospectivity of the Middle Permian to Lower Jurassic succession confidently. Available data comes from outcrop descriptions and from IPC wells *Alan-1, Butmah-2* and *Adaiyah-1* (summarised by Dunnington *et al.*, 1959), and INOC wells *Sufaiya-1* and *Abtakh-1* (Kaddouri, 1986; Sadooni, 1995) (see Fig. 5.1 for well locations). Outcrop data from the Western Desert obtained during regional studies by the Iraq Geological Survey in the 1970s was summarized by Buday (1980), Jassim *et al.* (1984), Kaddouri (1992) and Jassim *et al.* (2006a).

Little palaeontological data for the Middle Permian to Middle Jurassic succession in Iraq has been published. A range chart for palynomorphs in the Kurra Chine and Baluti Formations is presented in Fig. 5.2; selected palynomorphs are illustrated in Plate 5.1. However, there are discrepancies with equivalent units in neighbouring countries to the west (e.g. Hirsch and Gerry, 1974; Eicher and Mosher, 1974; Cameron, 1974; Imam *et al.*, 1980; Bandel and Khoury, 1981; Imam and Sigal, 1985; Eshet and Cousminer, 1986; Bebeshev *et al.*, 1988; Andrews, 1992a). For example, formation names in Syria have been borrowed from Iraqi stratigraphic terminology, but have in some cases been assigned to rock units of different ages (see Sharland *et al.*, 2001; Sadooni and Alsharhan, 2004; and Al-Husseini and Mattner, 2007).

Sharief (1982a,b; 1983) and Alsharhan and Kendall (1986) noted that Middle Permian – Middle Jurassic carbonates and evaporites in the Arabian Basin were deposited on an epeiric shelf which was affected by abrupt transgressions and regressions. The succession forms a single Megasequence (AP6) which was divided into twelve sequences (P20-J10) by Sharland *et al.* (2001). Maximum flooding surfaces (MFSs) are indicated by pelagic thin-shelled bivalves referred to as "paper pectens"(c.f. Schatz, 2005), or by laterally-extensive, thin beds of open-marine carbonates overlying unconformity surfaces. The succession in Iraq can be correlated with similar successions in Jordan and Iran (Fig. 5.3) (Andrews, 1992a; Sadooni and Alsharhan, 2004). It outcrops locally in western Iraq as shown in Fig. 5.4 (this map also shows key locations referred to in this chapter).

The Middle Permian to Middle Jurassic succession in Iraq (Megasequence AP6) is here divided into nine separate units, each bounded by a major unconformity (Fig. 5.3). An improved scheme could be created when more palaeontological and wireline log data becomes available. Each unit constitutes either a "supersequence" containing several third-order sequences identified by Sharland *et al.* (2001), or a single third-order sequence. No attempt has been made here to divide the supersequences due to the very limited log and palaeontological data currently available; however, some intra-supersequence correlations are shown in Figs 5.8 and 5.9 (pp. 111-112). Units which are considered here as sequences may eventually prove to be supersequences.

The nine unconformity-bound units are as follows (ages are approximate):

i. Upper Middle Permian – lowermost Triassic (Induan);
ii. Lower Triassic (Olenekian);
iii. Middle Triassic (Anisian);
iv. Middle Triassic (Ladinian);
v. Upper Triassic (lower – middle Carnian);
vi. Upper Triassic (upper Carnian – lower Norian);
vii. Uppermost Triassic – Lower Jurassic (upper Norian – Sinemurian);
viii. Lower Jurassic (Pliensbachian – lower Toarcian);
ix. Middle Jurassic (middle Toarcian – lower Aalenian).

Structural controls: basins and structural highs

The thickness of the upper Middle Permian – Triassic succession in Iraq varies significantly within intrashelf basins due to onlap onto (and drape over) Palaeozoic palaeohighs. The uppermost Triassic – lowermost Middle Jurassic stratigraphy also thins onto these palaeohighs. The succession thins westwards in Iraq (Fig. 5.5).

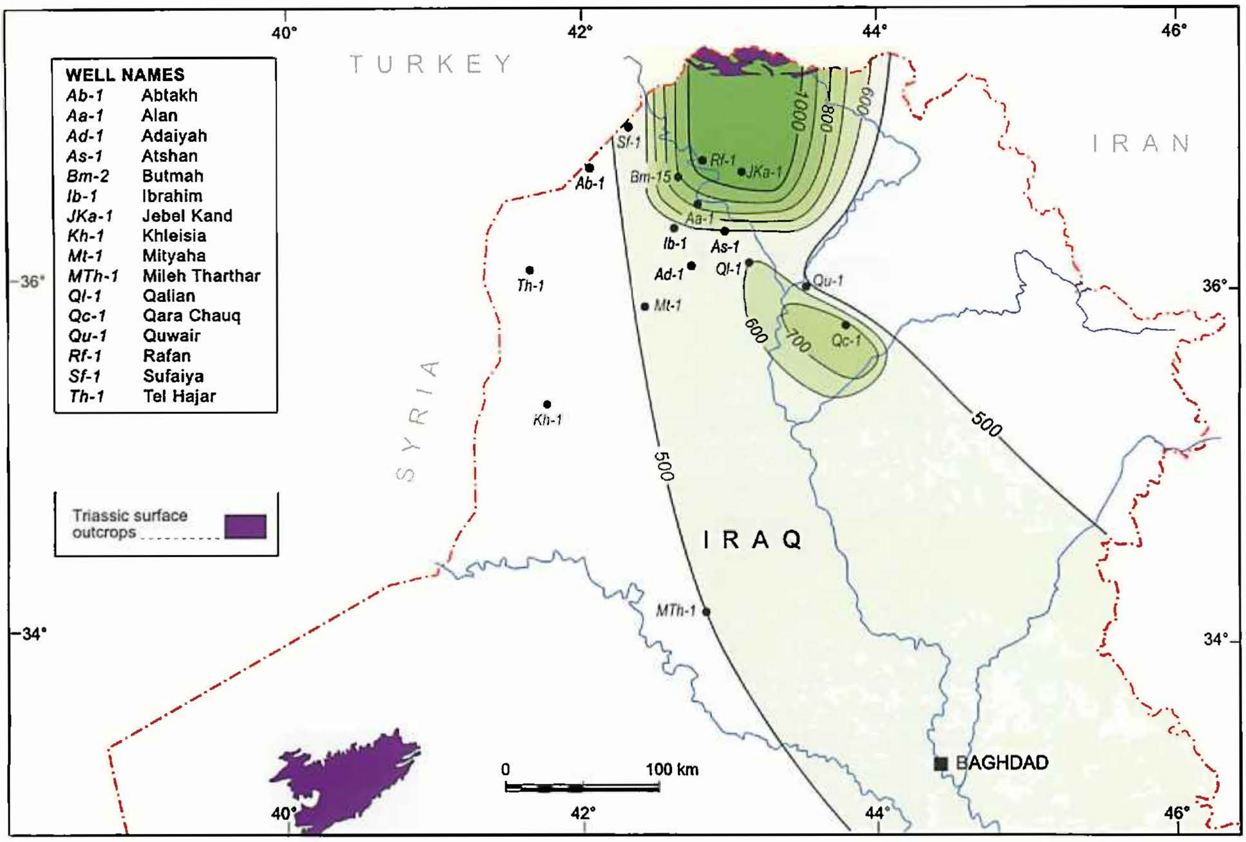


Fig. 5.1. Map of central-northern Iraq showing well locations referred to in this chapter and isopach (metres) of the Carnian-Norian Kurra Chine Formation. After Sadooni, 1995. Thicknesses are greatest in the Kand Basin centred on well *Jebel Kand (Ka)-1*. Also shown are Triassic outcrops.

The thickness of the Middle Permian – Lower Jurassic succession in Iraq can be estimated by adding together measured type sections (data in Dunnington *et al.*, 1959). Upper Middle Permian – Triassic sedimentary rocks comprise: 834 m of the Kurra Chine Formation; 575 m of the Geli Khana Formation; 64 m of the Beduh Formation; 200 m of the Mirga Mir Formation; and 811 m of the Chia Zairi Formation. This gives a total of about 2500 m. In addition, some 676 m of Lower Jurassic strata are present: approximately 530 m of the Butmah Formation, 90 m of the Adaiyah Formation and 56 m of the Mus Formation (Dunnington *et al.*, 1959). Jassim *et al.* (2006a) estimated a maximum thickness of over 3000 m for Megasequence AP6 in NW and SE Iraq (Fig. 5.5).

Patterns of deposition in Iraq were significantly influenced by the NE-projecting Rutbah High, which is the inverted expression of the former Lower Palaeozoic basin system extending from northern Saudi Arabia into western Iraq (Fig. 3.7). Over the Rutbah High, the AP6 Megasequence is incomplete and includes a high proportion of siliciclastic sedimentary rocks. Its continuation to the north is known as the Khleisia High (Fig. 3.7). Other highs may have been present in NE Iraq. They may have controlled Permian sedimentation by analogy with the Iranian Zagros at Kuh-e Dinar where Upper Permian strata onlap rocks as old as Ordovician (Szabo and Kheradpir, 1978) (Fig. 5.7). Upper Permian rocks similarly rest on Lower Palaeozoic strata at the Burgan High, Kuwait (Khan, 1989).

In the Stable Shelf of SW Iraq, Roychoudhury and Nahar (1980) tentatively identified several highs and basins which may have controlled facies patterns in the pre-Cretaceous section corresponding to Megasequences AP6 and AP7. These include from west to east the Sirhan-Turayef Basin, the Hail-Rutbah Arch, the Widyan-Awasil Basin, the Safawi to Samawa Arch (i.e. the southern part of the Salman Zone), and the Basra-Kuwait Basin. The significance of these structural elements in controlling subsurface facies distributions in Triassic and Jurassic times requires further study.

The nine (super)sequences can be grouped into four units deposited during four successive phases of subsidence. These phases (mid Permian– Early Triassic; Anisian – Ladinian; Carnian – Norian; and Rhaetian – early Aalenian) are described below.

Mid Permian – Early Triassic

The regional unconformity at the base of Megasequence AP6 is interpreted as the break-up unconformity associated with the opening of Neo-Tethys (Jassim and Goff, 2006b) (page 49). Neo-Tethys began to open at the end of the Early Permian (Angiolini *et al.*, 2003). There was a marked regression towards the west (Hirsch, 1992). In Iraq, Lower Palaeozoic rocks were initially

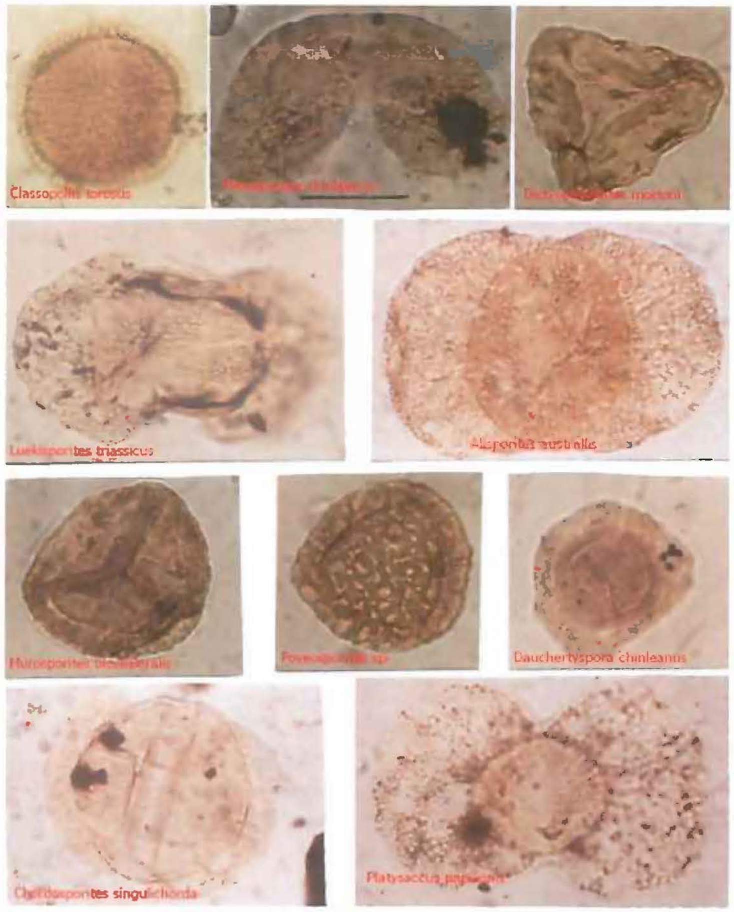


Plate 5.1. Selected palynomorphs from the Upper Triassic of western Iraq. Plate reproduced courtesy of T. K. Al-Ameri (Al-Ameri *et al.*, 2009).

1. *Classopollis torosus;*
2. *Pityosporites chinleanus;*
3. *Dictyophyllidites mortoni;*
4. *Luekisporites triassicus;*
5. *Alisporites australlis;*
6. *Murasporites bicollateralis;*
7. *Foviosporites sp.*
8. *Dauchertisporites chinleanus;*
9. *Chordosporites singulichorda;*
10. *Platysaccus papilionis.*

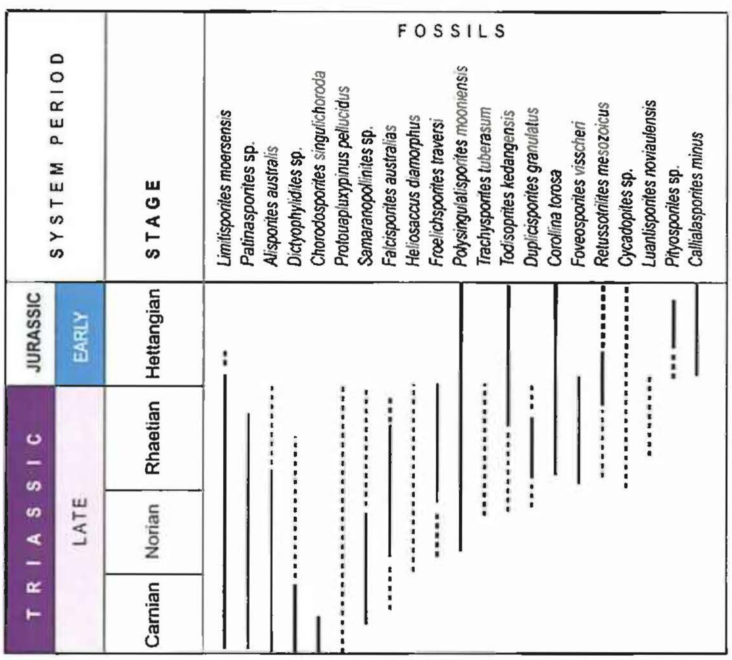


Fig. 5.2. Range chart of selected palynomorphs in the Kurra Chine and Baluti Formations, NW Iraq. (Unpublished figure reproduced with permission of T. K. Al-Ameri).

onlapped by fluvial siliciclastics of Middle Permian age, and then by overstepping carbonates of Late Permian age (Jassim and Goff, 2006a).

In Syria, the Palmyra Basin began to subside during the Middle Permian (Lovelock, 1984; Best *et al.*, 1993). Subsidence throughout the northern passive margin of the Arabian Plate led to the formation of an eastward thickening wedge of Upper Permian – Lowermost Triassic shallow-water carbonates, clastics and local anhydrites. This succession (254–247 Ma) is predicted to be up to 1000 m thick in eastern Iraq (Jassim *et al.*, 2006a). The Late Permian shoreline with zero deposition was located along the eastern flank of the Rutbah High and can be traced into Saudi Arabia (Al-Laboun, 1986). Maximum compacted sediment accumulation rates were about 150 m/Ma in NE Iraq, decreasing to 50 m/Ma in central Iraq consistent with relatively rapid thermal subsidence. The rate decreased to <20 m/Ma in the Early Triassic, indicating reduced thermal subsidence. Condensed deposition is suggested by thin oolitic units with mixed Permo-Triassic faunas which occur in Iraqi Kurdistan (Gayara, 1992), and by a distinctive thrombolitic facies in Iran (Insalaco *et al.*, 2006).

Anisian-Ladinian

During the Middle Triassic, the northern margin of the Arabian Plate became strongly differentiated as a result of renewed extension which can be traced from the Eastern Mediterranean to Oman. Extension is indicated, for example, by the occurrence of basic igneous rocks of Anisian–Ladinian age in well *Abba-1* in Syria (cf. Daniel, 1963). A deep rift basin (Fig. 3.29) developed along the northern and NE plate margin with an outer ridge of thinned continental crust (Fontaine *et al.*, 1989). At the same time, a series of extensional basins developed inboard of, and parallel to, the plate margin. The basins extended from northern Egypt via the Syrian Arc system in Sinai and Palestine into Palmyra-Sinjar-Kand-Mesopotamia and Iran (May, 1990; Brew *et al.*, 1999; Sadooni and Alsharhan, 2004). To the west, the basins may be traced into Algeria and the Atlas Mountains of Morocco (Guiraud and Bellion, 1995). The coeval basin in Iraq was located several hundred km south and west of Neo-Tethyan oceanic crust (Fig. 3.28).

The only area of Iraq where there is sufficient published data to confirm a tectonic control on sediment thickness is in the NW. Here, a significant increase in subsidence rate began in Anisian time. Some 600 m of Geli Khana Formation sediments were deposited, indicating average compacted sediment accumulation rates of 60 m/Ma.

A transgression in the early Anisian led to the deposition of platform carbonates which contain Tethyan and endemic faunas in the Eastern Mediterranean (Eshet and Cousminer, 1986; Andrews, 1992a). The Anisian transgression (Tr40 of Sharland *et al.*, 2001), and the more extensive Ladinian transgression (Tr50 of Sharland *et al.*, 2001) resulted in onlap of basin margins (Druckman *et al.*, 1982; Hirsch, 1992; Jamal *et al.*, 2000).

Jassim *et al.* (2006a) identified two basins in the Middle Triassic in Iraq (Fig. 5.5). The northern depocentre (Fig. 5.1) extends from the Amadia area of Iraqi Kurdistan southwards through Kirkuk to Makhul. Well and seismic data indicates that this basin extends westwards into the Palmyra-Sinjar area of Syria and beyond into the eastern Mediterranean (Ponikarov, 1967; Bein and Gvirtzman, 1977; Best *et al.*, 1993). Best *et al.* (1993) interpreted the Palmyra Basin as a Triassic aulacogen situated on a Precambrian plate suture. The depressions have also been described as downwarps above extensional fault zones in the basement (Sadooni and Alsharhan, 2004). The second depocentre in SE Iraq extends from Amara to the Fao Peninsula and eastwards into SW Iran (Szabo and Kheradpir, 1978). This basin appears to be bounded in Central Iraq by the Salman Zone to the SW and by the Makhul-Hamrin Lineament to the NE (Fig. 3.7).

Lovelock (1984) and Sadooni and Alsharhan (2004) noted that Triassic basins in northern Arabia are sag-like, and were controlled by blind faults at depth rather than by discrete surface-penetrating faults. Triassic extension in the Ghawar area (Saudi Arabia) is interpreted as "re-activation" of the downthrown flanks of the Ghawar structure (Wender *et al.*, 1998).

The sag basins had an initial tectonic control but their topography was maintained by surface processes associated with low carbonate productivity and local anoxia. Thin euxinic carbonates (highstand facies) were deposited in basin centres. During highstands, underfilled accommodation space developed in these basins. Lowstand evaporites were deposited in basin centres.

Carnian-Norian

The Carnian-Norian Kand Basin, first defined by Sadooni (1995) in Northern Iraq, covered an area of 50 km by 200 km (Fig. 5.1). Well data indicate that Carnian-Norian sediments are up to 1000 m thick (Sadooni, 1995). They are 850 m thick at outcrop in Kurdistan (Dunnington *et al.*, 1959), the difference probably due to dissolution of evaporite beds in surface exposures.

Within the Kand Basin, compacted sediment accumulation rates reached 230 m/Ma during deposition of the Lower Kurra Chine Formation, declining to 120 m/Ma during deposition of the Upper Kurra Chine Formation. This indicates a period of renewed tectonic extension followed by strong regional thermal subsidence. Basinal areas in Syria expanded in the Carnian as indicated on seismic profiles (de Ruiter *et al.*, 1995; Jamal *et al.*, 2000). At the Khleisia High in Iraq, Carnian-Norian carbonates onlap the Tournaisian Harur Limestone Formation in well *Khleisia-1* (Sadooni, 1995; Jassim *et al.*, 2006a).

Upper Triassic facies belts in northern Iraq are illustrated in Fig. 5.6. Widespread Carnian evaporites (halite) occur throughout northern Arabia (Sadooni, 1995; Jamal *et al.*, 2000; Sadooni and Alsharhan, 2004). The presence of halite rather than anhydrite indicates the development of relatively landlocked basins in which humidity was below about 75% (Kinsman, 1976).

Sequence boundaries usually occur at the base of evaporite units. Formation tops (for example, the evaporitic upper boundary of the Kurra Chine Formation) do not coincide with sequence boundaries but instead represent transgessive systems tracts.

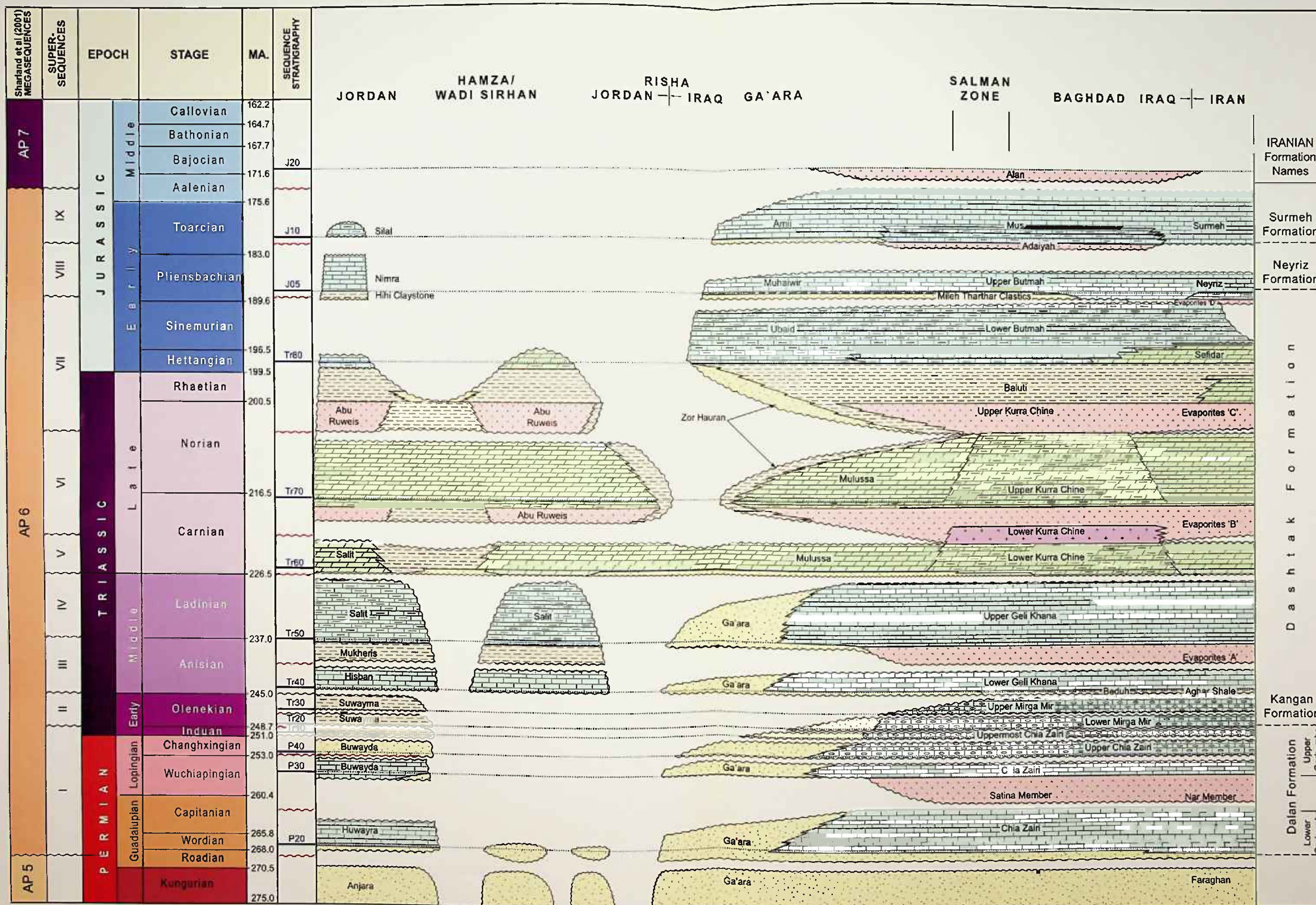


Fig. 5.3. Chronostratigraphy of the Middle Permian to Middle Jurassic succession in Iraq. The line of section extends from the Iran-Iraq border through Baghdad and via the Western Desert into Jordan.

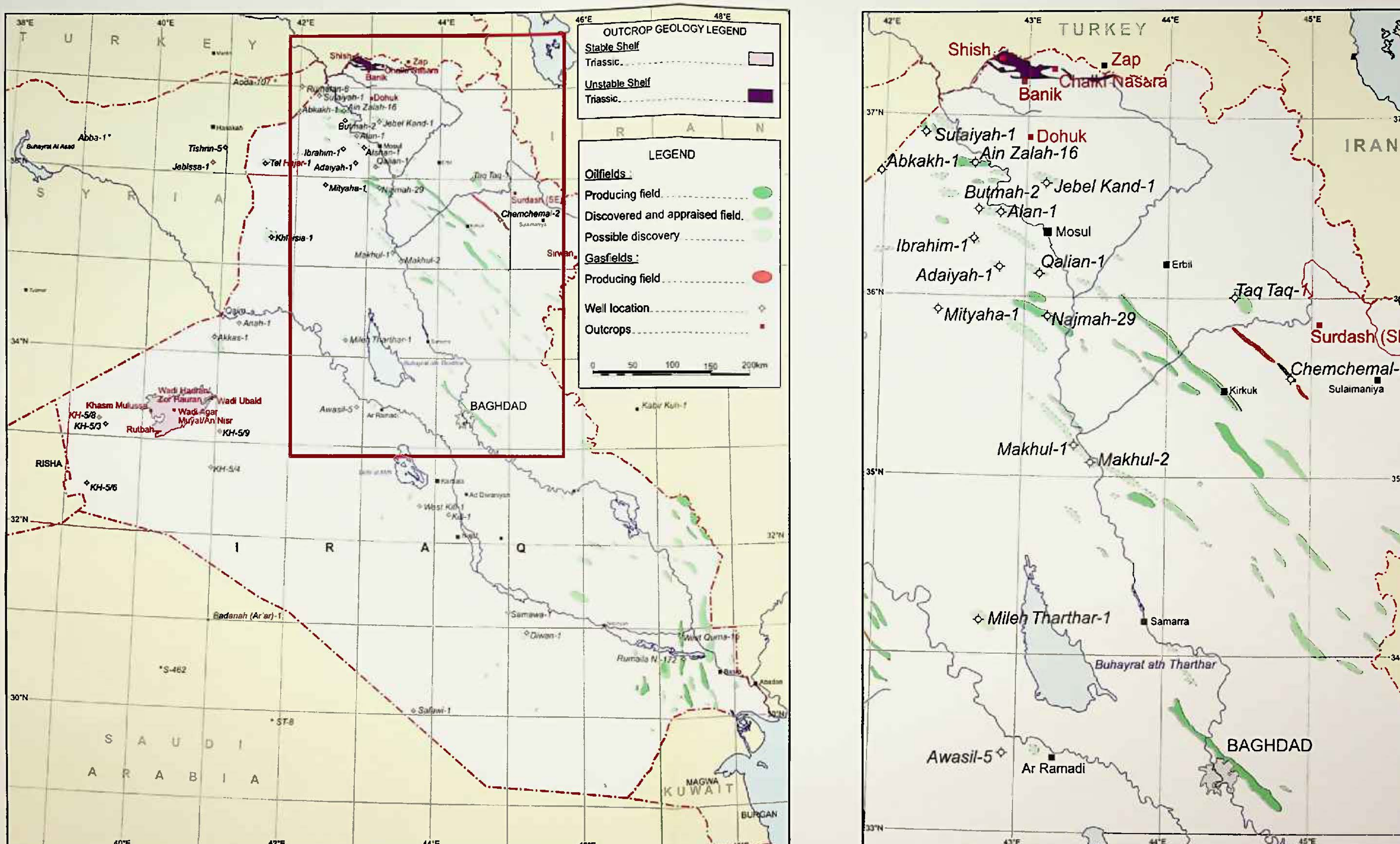


Fig. 5.4. Map of Iraq and adjacent areas showing key wells (labelled in black), fields and other localities mentioned in this chapter together with areas where Triassic rocks are exposed at the surface. Important outcrop areas are labelled in red.

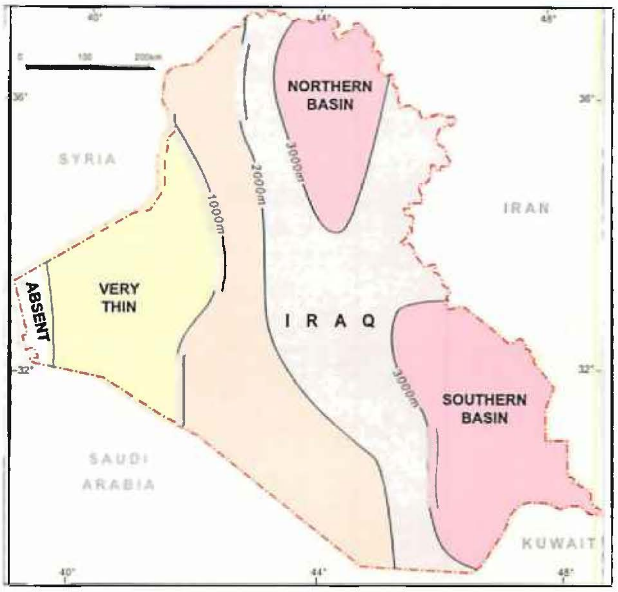


Fig. 5.5. Isopach of Upper Permian to Lower Jurassic sedimentary rocks in Iraq as interpreted from gravity modelling, well and outcrop data. Modified after Sadooni, 1995, and Jassim *et al.*, 2006a. Note that the location of the northern basin does not correspond to Sadooni's (1995) Kand Basin (Fig. 5.1) which was defined from well data.

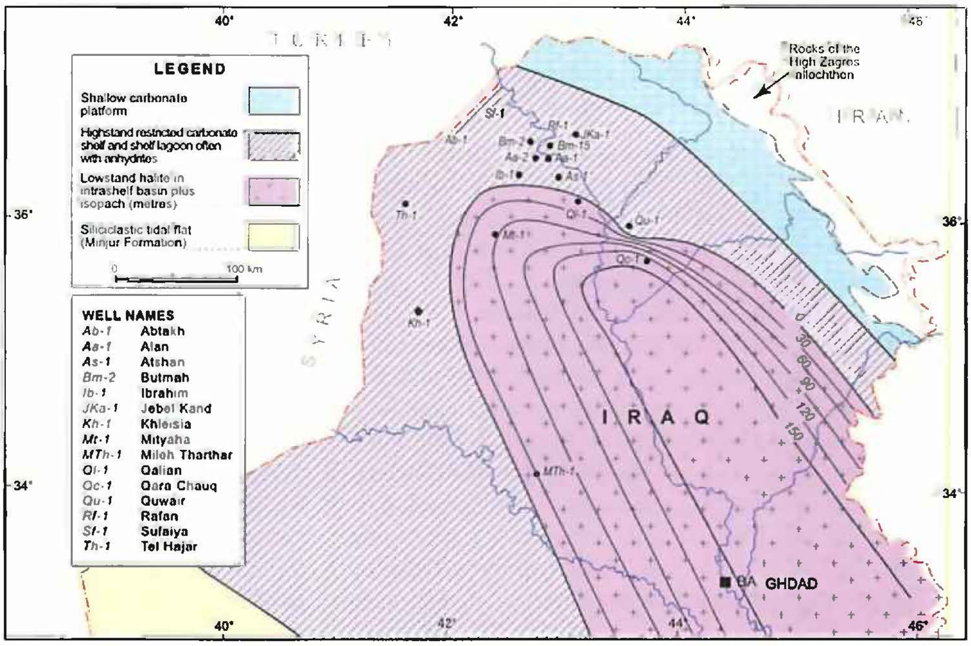


Fig. 5.6. Map of northern Iraq and adjacent areas showing first-order distribution of Upper Triassic facies belts. After Sadooni, 1995.

Rhaetian – early Aalenian

In Rhaetian – early Aalenian time, the subsidence rate in Iraq was significantly reduced. About 600–900 m of sediments were deposited in the basin in southern Iraq in about 40 Ma, indicating a sediment accumulation rate of 15-20 m/Ma. Individual stratigraphic units extend for several hundred km, indicating very uniform depositional conditions. Passive deposition of restricted lagoonal carbonates, evaporites and fine-grained siliciclastics occurred. There is no evidence for either significant uplift of the western margin of the southern basin or structural growth in Iraq in Rhaetian – early Aalenian time.

The upper Middle Permian – lowermost Triassic (Induan) Supersequence

This supersequence has been recorded in deep boreholes in western and southern Iraq. Data in Kaddouri (1992) and Al-Hadidy (2007) indicate that it thickens from 83 m in well *KH 5/2* in western Iraq, to 442 m in well *Atshan-1*, 514 m in well *West Kifl-1*, and 631 m in well *Jebel Kand-1* (locations in Fig. 5.4). Wells *Mityaha-1* and *Diwan-1* partially penetrate this unit (Al-Hadidy, 2007). A well at *Burgan* in Kuwait penetrated a thickness of 586 m (Khan, 1989). The supersequence is absent in wells *Akkas-1, Qaim-1* and *Khleisia-1* and in most deeper Western Desert *Keyhole (KH)* wells (Kaddouri, 1996; Aqrawi, 1998; Al-Hadidy, 2007).

Rocks in this supersequence are assigned to the upper part of the Ga'ara Formation (late Middle Permian to earliest Triassic) and the overlying Chia Zairi Formation (Late Permian to earliest Triassic) (Fig. 5.8) (Al-Hadidy, 2007).

There is a disconformity at the base of the **upper part of the Ga'ara Formation** which is marked by a sharp log break between massive clean siliciclastics below and fine-grained siliciclastics above (e.g. in well *West Kifl-1*: Al-Hadidy, 2007). Locally, the upper part of the formation onlaps the

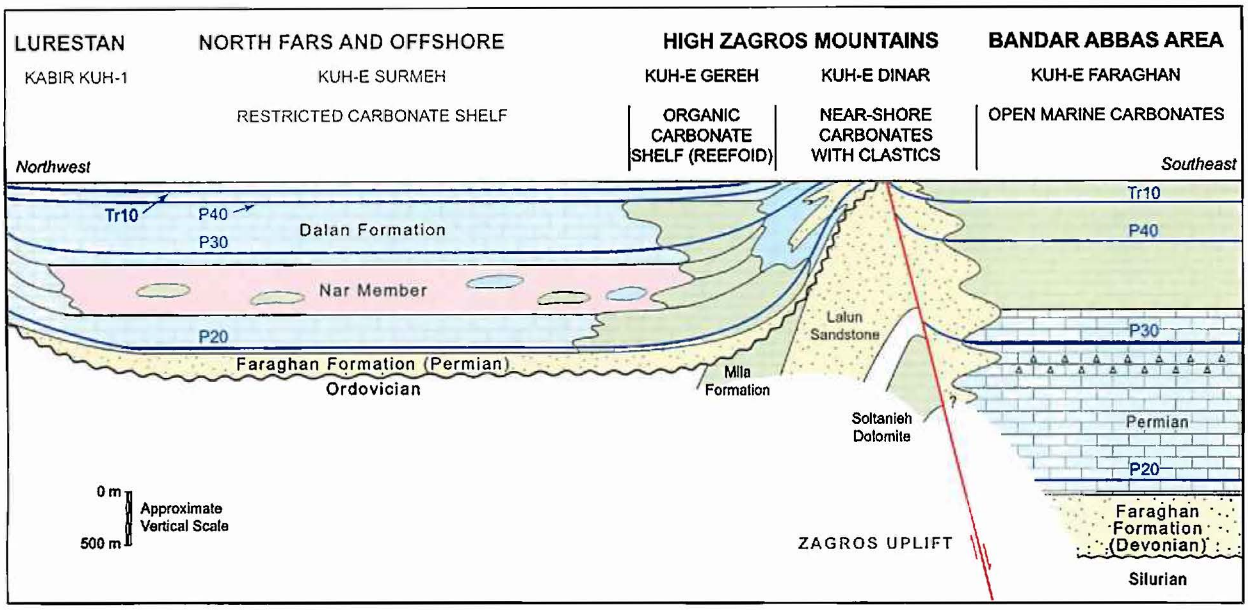


Fig. 5.7. NW-SE cross-section through the Upper Permian platform in Iran showing facies changes with respect to Upper Palaeozoic palaeohighs. Based on Szabo and Kheradpir, 1978, and taking subsequent work into account.

Tournaisian Harur Formation, for example in well *Jebel Kand-1* (Fig. 5.9) (Al-Hadidy, 2007). Its upper contact with the Chia Zairi Formation is gradational, and siliciclastic rocks in the Chia Zairi could probably be re-assigned to the Ga'ara Formation or to pre-Chia Zairi Clastics.

The upper part of the Ga'ara Formation ranges in thicknesses from 14 m (at *West Kifl-1*) to 68 m (at *Atshan-1*), as calculated from re-picked log data presented by Al-Hadidy (2007) (Figs. 5.8, 5.9). Very limited information is available for the Ga'ara Formation. Shales and sandstones are recorded in the subsurface. Silty argillaceous limestones, silty dolomites, some shales and sandstones occur near the base of the penetrated section in *Atshan-1* (Singh, 1964; Buday, 1980), and in wells *Jebel Kand-1* and *West Kifl-1* (Al-Hadidy, 2007) (Figs. 5.8, 5.9). The basal interval of the upper part of the formation is shaly as illustrated by GR log data. Upwards-cleaning cycles occur in the upper part of the formation (Al-Hadidy, 2007) (Figs 5.8, 5.9). In the Western Desert at Wadi Dwaiklah, the Ga'ara Formation consists of white to red claystones (Ctyroky, 1973) while the Upper Permian section in well *KH 5/2* consists of sandstones (pebbly, calcareous or argillaceous) and shales (Kaddouri, 1992).

Singh (1964) described shales in a core from well *Atshan-1* with a diverse palynological assemblage including 32 genera (49 species) indicating a late Middle Permian age. In the Western Desert well *KH 5/2*, the upper part of the Ga'ara Formation (from a sample at 227-228 m) yielded bisaccate spores indicating a Late Permian (Zechstein) age (Kalibova-Kaiserova, 1984, *in* Jassim *et al.*, 2006a). The Ga'ara Formation at Wadi Dwaiklah contains a Cathaysian flora (including *Lobatannularia heianensis*, *Pteridophyta* fam. indet., *Plagiozamites oblongifolius*, *Pecopteris* sp., *Taeniopteris* sp., and *Protoblechnum* sp.) of Middle-Late Permian age (Ctyroky, 1973).

Onlap occurred across the Late Carboniferous unconformity (Ruban *et al.*, 2007) (page 99), particularly in the Western and Southwestern Deserts (Al-Haba *et al.*, 1994; Aqrawi, 1998; Jassim *et al.*, 2006a). The Salman Zone may have divided Iraq into western and eastern basins. Coarse-grained sediments are probably thickest near to the uplifted sediment source areas, although total sediment thicknesses will be greatest in flanking basins. Internally, the uppermost Ga'ara Formation probably consists of prograding cycles of fluvio-deltaic siliciclastics, deposited prior to the P20 maximum flooding surface of Sharland *et al.* (2001).

In Saudi Arabia, correlative basal clastics are known as the Basal Khuff Clastics and are composed of alluvial, fluvial and aeolian sandstones (Konert *et al.*, 2001). Upper Permian redbeds similar to those in the Western Desert also occur in the Umm Irna Formation in the Zarqa Ma'in area of Jordan, and are interpreted as braided fluvial facies (Makhlouf *et al.*, 1991). In the Zap area of SE Turkey, thin siliciclastics underlie the Upper Permian Harbol Limestone Formation (Fig. 4.9) (Janvier *et al.*, 1984). The Faraghan Formation of the Iranian Zagros represents a similar onlapping marginal - shallow marine siliciclastic system. It is best developed near palaeohighs from which clastic sediment was probably derived (Szabo and Kheradpir, 1978) (Fig. 5.7).

At its type locality in northern Iraqi Kurdistan near the Turkish border, the **Chia Zairi Formation** is 800 m or more thick (Hudson, 1958). A subsurface type-section in well *Jebel Kand-1*, 579

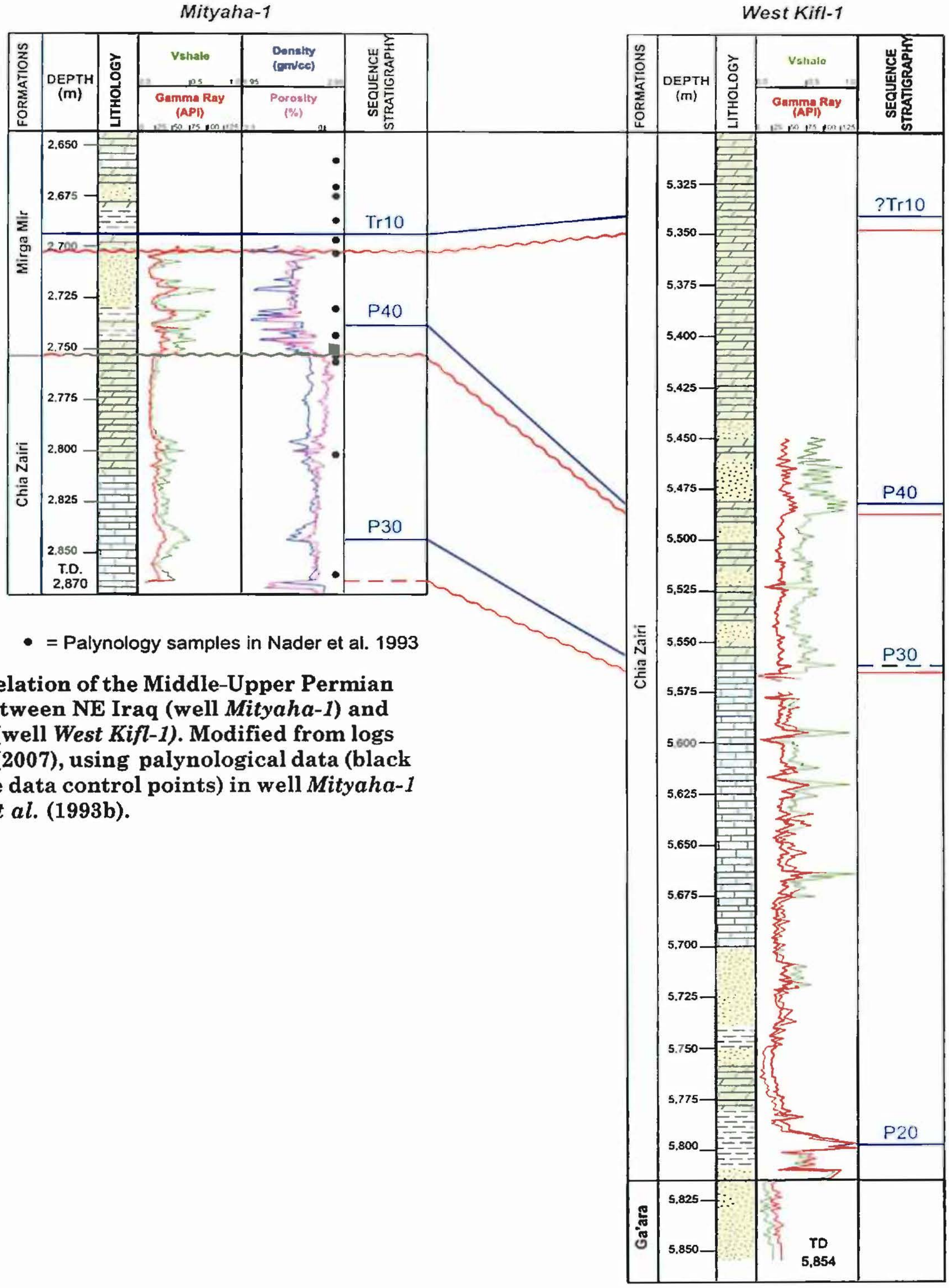


Fig. 5.8. Correlation of the Middle-Upper Permian succession between NE Iraq (well *Mityaha-1*) and Central Iraq (well *West Kifl-1*). Modified from logs in Al-Hadidy (2007), using palynological data (black spots indicate data control points) in well *Mityaha-1* from Nader *et al.* (1993b).

m thick (Fig. 5.9), was chosen by Al-Hadidy (2007). The formation is 502 m thick in well *West Kifl-1* (Fig. 5.8) (Al-Haba *et al.*, 1994; Al-Hadidy, 2007). It was deposited following major rifting and opening of Neo-Tethys (Al-Juboury and Al-Hadidy, 2008a).

At its original type section, the Chia Zairi Formation comprises limestones (sometimes cherty), dolomitic limestones and dolomites (Hudson, 1958; Dunnington *et al.*, 1959). A rich coral and algal biota, indicating a Mid-Late Permian age, was recorded by Hudson (1958). A breccia-dominated unit (the Satina Member) occurs in the middle of the formation at the type section A thin oolite unit is present at the top containing a mixed Late Permian and Early Triassic *"marginifera"* fauna (Dunnington *et al.*, 1959; Buday, 1980; Gayara, 1992) (probably *Spinomarginifera*: L. Angiolini, *pers. comm.* to A.H., 2008). These units cannot easily be identified in the subsurface, although the middle of the formation is commonly dolomitic rather than evaporitic (Al-Hadidy, 2007) (Fig. 5.9).

The log responses presented by Al-Hadidy (2007) indicate stacked depositional cycles that may contain the P20, P30, P40 and Tr10 maximum flooding surfaces of Sharland *et al.* (2001) (Figs 5.8, 5.9). Logs presented by Al-Hadidy (2007) show that

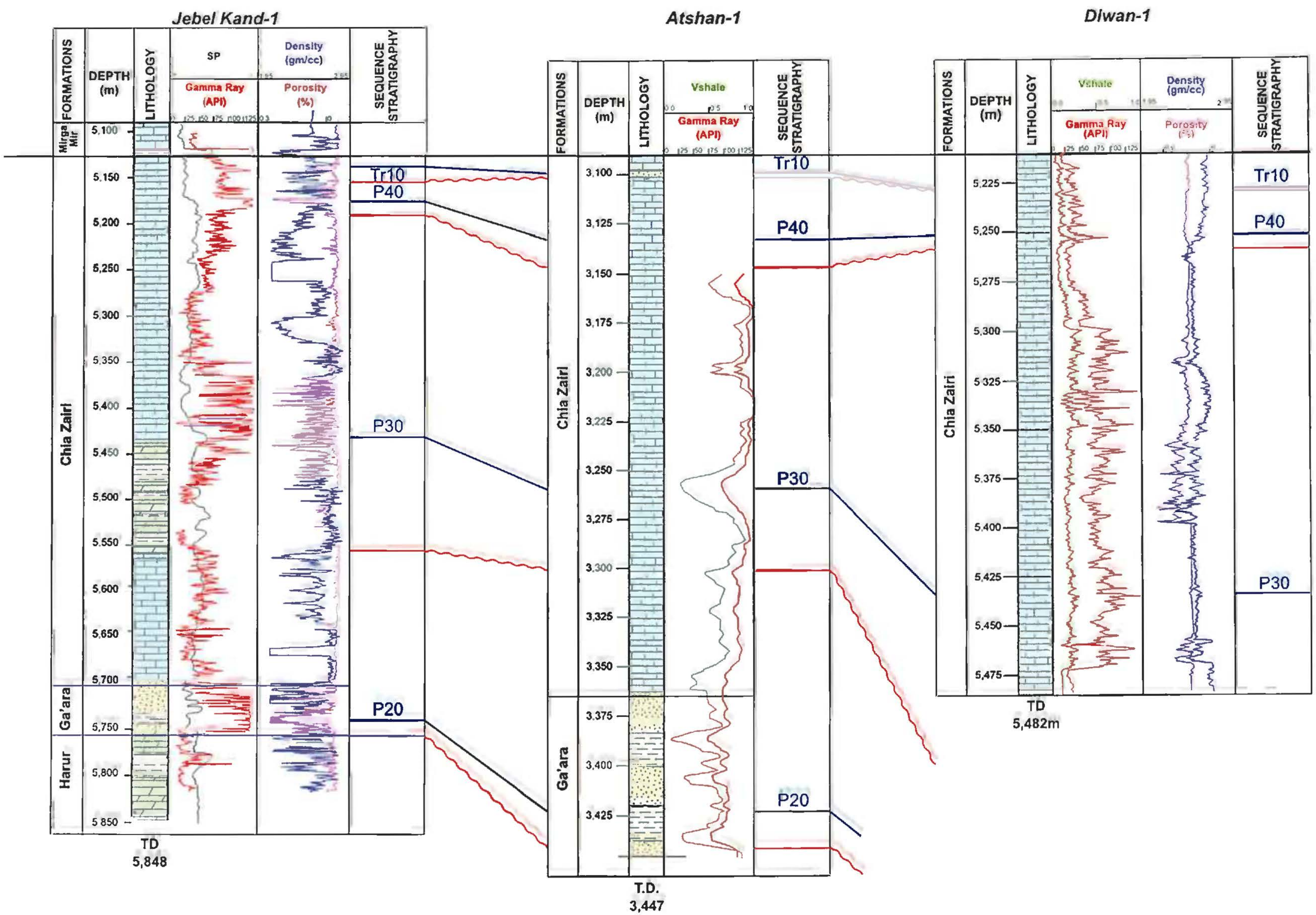


Fig. 5.9. Correlation of the "downdip" Middle–Upper Permian succession between wells *Jebel Kand-1, Atshan-1* and *Diwan-1*. After data in Al-Hadidy, 2007.

the proportion of siliciclastics increases away from the type sections southwestwards, from the Iraqi Kurdistan outcrops towards well *Mityaha-1* to the SW of Mosul, and well *West Kifl-1* near Najaf (Fig. 5.8). This was also noted by Buday (1980), Nader *et al.* (1993b) and Al-Juboury and Al-Hadidy (2008a). The thick and massive sandstone units in wells *Mityaha-1* and *West Kifl-1* should probably be reassigned to the Ga'ara Formation.

In outcrops in northern Iraq, the Chia Zairi Formation unconformably overlies the Carboniferous Harur Limestone Formation (Dunnington *et al.*, 1959) (Plate 4.19). Elsewhere, the formation conformably overlies the Ga'ara Formation (as indicated by data in Al-Hadidy, 2007).

The formation is interpreted to have been deposited on a homoclinal carbonate ramp. Shales and mudstones represent outer ramp deposits. Dolomitic facies with relicts of fusilinids, bryozoans and algae represent mid-ramp deposits. An inner ramp is represented by lime wackestone and sandstones (Al-Juboury and Al-Hadidy, 2006).

The breccias of the Satina Member are interpreted to be collapse breccias after original evaporites (Hudson, 1958; Dunnington *et al.*, 1959). These may represent the highly restricted late HST to early TST infill of an intrashelf basin that developed prior to the P30 MFS of Sharland *et al.* (2001). The intrashelf basin itself may be bordered on all sides by reefal facies (e.g. in central and southern Iraq).

The Satina Member can be correlated with the Nar Member of the Dalan Formation in Iran which was deposited in an intrashelf basin developed behind a tectonic sill on the Tethyan margin (Szabo and Kheradpir, 1978) (Fig. 5.7), and with the "C" evaporite of the Khuff Formation (Sharland *et al.*, 2001). An evaporitic unit in the Permian succession in Kuwait (Khan, 1989) is probably equivalent to the Satina Member. The succession is thickest closest to the thrust front in Iran (1500 m of Dalan Formation is present in Lurestan: Szabo and Kheradpir, 1978). Thick anhydrites occur along the axis of the Arabian Gulf, for example in the vicinity of Lavan Island, offshore Iran (Szabo and Kheradpir, 1978). The evaporitic member is absent in condensed, updip settings e.g. in well *Kabir Kuh-1* in the Lurestan area (Fig.5.7) and in Saudi Arabia (e.g. Sharland *et al.* (2001), their figure 2.17). Dolomitic limestones and evaporites of the Khuff Formation occur in northern Saudi Arabia in wells *Ar'ar-1, ST-8* and *S-462* (Al-Hajri and Owens, 2000). Similar facies probably occur along strike in the Southwest Desert of Iraq (Sharief , 1983; Kashfi, 1992; Alsharhan *et al.*, 1993; Aqrawi 1998).

Petroleum System Components

Reservoir rocks

In Iraq, no reservoir rocks of Middle Permian – earliest Triassic age have been reported; both dolomites and limestones appear to be tight (Jassim *et al.*, 2006a; Al-Hadidy, 2007). No reservoir quality data have been reported for the underlying siliciclastics. However, as noted above, only a few wells have penetrated the supersequence.

Middle–Upper Permian carbonates of the Khuff Formation are important reservoir rocks in the Middle East. The first Khuff discovery was *Awali* in Bahrain in 1949 (Alsharhan and Nairn, 1997), and this was followed by discoveries in Saudi Arabia, Abu Dhabi, Iran and Oman (Dunnington, 1967a). The giant *North Dome* gasfield, Qatar, was discovered in 1971; its extension in Iranian waters is known as *South Pars*. The Khuff Formation produces gas from up to four separate pay zones consisting of oolitic grainstones and intertidal dolomudstones, which are capped by intra-formational anhydrites (Al-Jallal, 1995). Reservoir quality is heterogeneous both laterally and vertically due to diagenesis including dolomitisation, anhydrite cementation, leaching and local fracturing. Oomouldic porosity is the most important pore type recorded in the Khuff Formation in Saudi Arabia (Kamal, 2000).

In Saudi Arabia, the uppermost parts of the Unayzah Formation contain Early Permian (Kungurian) sandstones (Abu Ali *et al.*, 1991). The sandstones are interbedded with mudstones and siltstones (MacGillivray and Husseini, 1992) and have porosities of up to 30% and permeabilities of up to 1 Darcy. Reservoir properties vary because of quartz overgrowth development and kaolinite or illite/smectite cementation (Polkowski, 1997; Konert *et al.*, 2001). The Unayzah Formation was recently cored in a deep well in northern Kuwait (Tanoli *et al.*, 2008). Here it comprises sandstones, siltstones and shale deposited in braided fluvial, floodplain, coastal plain and possibly aeolian environments. It is overlain by the Basal Khuff clastics.

The Upper Permian Amanus Formation in the Palmyra area of Syria comprises shales, sandstones and thin limestones, deposited in a fluvio-deltaic to littoral setting (Hips and Árgyelán, 2007).

Source rocks

The lowest 20 m of the supersequence in wells *Jebel Kand-1, Atshan-1, West Kifl-1* and *Diwan-1* may have source potential (Al-Haba *et al.*, 1994). This is suggested by the gamma-ray log data presented by Al-Hadidy (2007), which indicates high-API mudrocks in the uppermost Ga'ara Formation. In Kuwait, Khan (1989) described a "highly radioactive shale" from the middle part of the evaporite member of the Upper Permian carbonates. This shale may be a source rock, as evaporitic environments can be favourable sites for source-rock deposition (Kirkland and Evans, 1981). Moreover, Khan (*op. cit.*) described this unit's excellent marker status,

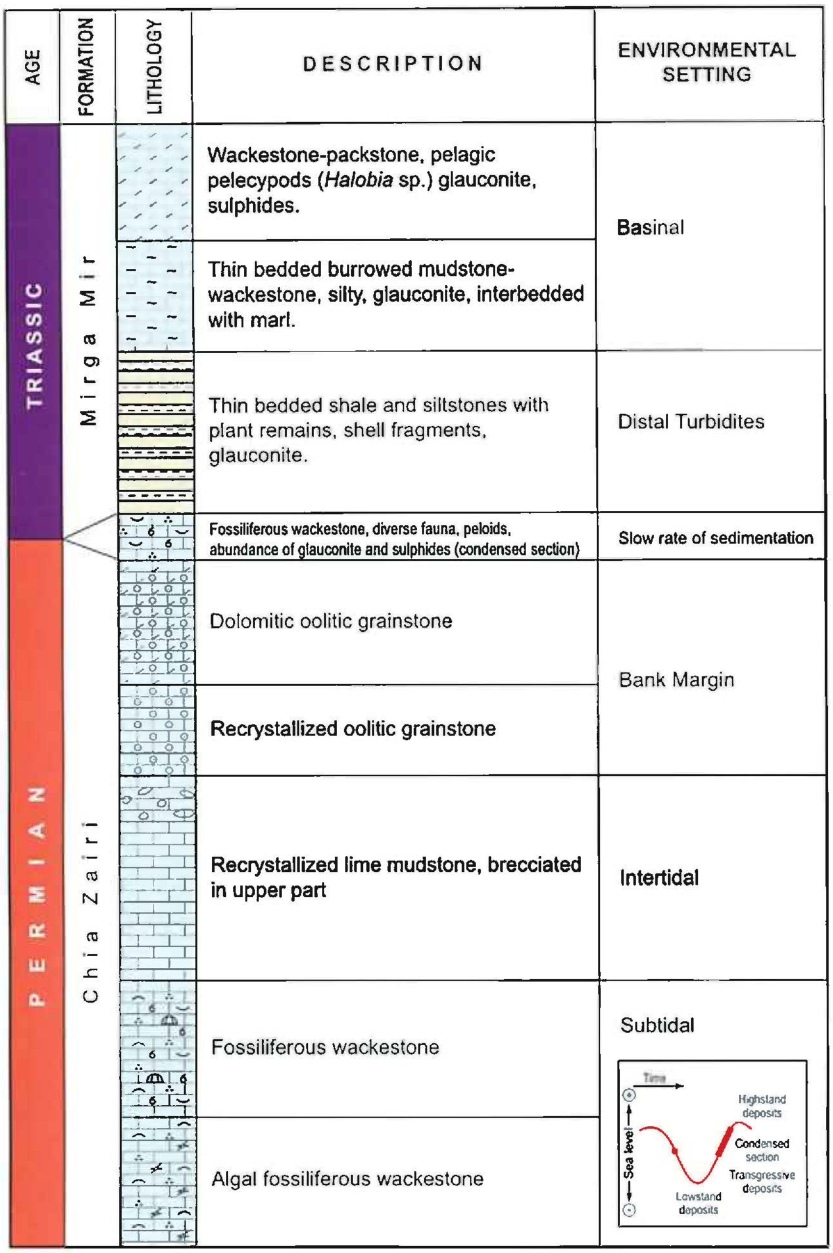


Fig. 5.10. Stratigraphy of the Permo-Triassic boundary section near Shish, NW Iraqi Kurdistan. After Gayara, 1992. Note the condensed horizon at the Permian-Triassic boundary.

implying that it may well extend into southern Iraq.

Seals

Aqrawi (1998) suggested that the "Satina Evaporite Member" of the Chia Zairi Formation may be a regional seal. However, recently published well data (Al-Hadidy, 2007) suggests that this unit is not widely distributed. At outcrop, it is represented by collapse breccias of uncertain origin and/or timing (i.e. the brecciation may be due to early as opposed to late dissolution).

Amanus Formation shales form an effective seal for coeval reservoirs in the Palmyra area of Syria (Hips and Árgyelán, 2007). In the southern culmination of the *Ghawar* field, the basal Khuff Formation shales and carbonates seal the underlying Unayzah "A" reservoirs (Wender *et al.*, 1998). The P20 MFS of Sharland *et al.* (2001) is regionally extensive, and GR log data in Al-Hadidy (2007) indicates that it is shaly. It may occur over much of Iraq and seal pre-AP6 reservoirs in stratigraphic and structural traps.

The Lower Triassic (Olenekian) Supersequence

Lower (but not lowermost) Triassic sedimentary rocks in Iraq are assigned to the Mirga Mir and overlying Beduh Formations (Fig. 5.3), present in Iraqi Kurdistan and in well *Atshan-1* (Dunnington *et al.*, 1959). The Mirga Mir formation also occurs above the Chia Zairi Formation in wells *West Kifl-1*, *Diwan-1*, *Jebel Kand-1* and *Mityaha-1* (Jassim *et al.*, 2006a; Al-Hadidy, 2007).

The Lower Triassic Supersequence is probably absent from most of the Stable Shelf area of west Iraq. In well *Khleisia-1*, the Upper Triassic Kurra Chine Formation unconformably overlies the Tournaisian Harur Limestone Formation (Sadooni, 1995). In well *Akkas-1*, Upper Cretaceous rocks directly overlie the Palaeozoic (Aqrawi, 1998; Al-Hadidy, 2007). Lower Triassic sedimentary rocks have not been described in the Ga'ara area (Al-Ameri, 1990; Kaddouri, 1992).

The **Mirga Mir Formation** was first described from the Ora area in the Northern Thrust Zone of Iraqi Kurdistan by Dunnington *et al.* (1959). At its type locality the formation is about 200 m thick and consists of sandy deposits overlain by oolitic limestones and solution/recrystallized breccias with thin-bedded argillaceous limestones and shales (Dunnington *et al.*, 1959). Bivalves (typically "paper pectens": Schatz, 2005) frequently occur on maximum flooding surfaces. Gayara (1992) described a bed near the base of the formation at outcrops at Shish in NW Iraqi Kurdistan containing *Halobia* and glauconite (Fig. 5.10). This bed was used as the type section for the Tr20 maximum flooding surface of Sharland *et al.* (2001). At well *Atshan-1*, there is a higher proportion of siliciclastics compared to the outcrop, and anhydrite also occurs (Dunnington *et al.*, 1959). At *Jebel Kand-1*, anhydrite is also present at the top of the formation (OEC, 1989).

Fossils at the type locality include *Pseudomonotis (Claraia) claraia, C. aurita, Anodontophora fassaensis, A. fassaensis* var. *bittneri, Myophoria cf. ovata* and *Spirorbis valvata.* This assemblage indicates an "early Werfenian" age (Dunnington *et al.*, 1959; Buday, 1980). Gayara (1992) interpreted the bed containing *Halobia* more specifically as middle Olenekian. "Werfenian" faunas are typically endemic to the eastern Mediterranean area (c.f. Hirsch, 1992).

The Mirga Mir Formation gradationally overlies the Chia Zairi Formation. Its upper contact with the Beduh Shale is conformable. At outcrop, an abrupt colour change to the characteristic purple and red strata of the Beduh occurs with an upwards decline in the proportion of limestones.

The formation is interpreted to be a shallow-water to paralic deposit. Oolitic limestones are interpreted to have been deposited on a shallow, high-energy shelf. Anhydrite and solution breccias indicate the existence of sabkhas or salinas. Coarse-grained siliciclastic material indicates nearby emergent land areas, probably to the west as indicated by data from wells *Khleisia-1* and *Akkas-1* and in the Western Desert. Concentrations of thin-shelled bivalves such as *Halobia* within black shales indicate periods of dysoxia and soft substrates (Schatz, 2005) rather than a true epiplanktonic (deeper-water) habitat (c.f. Wignall, 1994). The endemic nature of the fauna indicate a restricted depositional environment. The Mirga Mir was thus probably deposited in a restricted shallow-water environment, perhaps in an intrashelf basin.

The Mirga Mir Formation is equivalent to the Amanus Shale Formation of Syria (Jamal *et al.*, 2000) and probably to the Goyan Formation of southern Turkey (Altinli, 1966). It is also equivalent to the Kangan Formation (Szabo and Kheradpir, 1978) (Fig. 5.11), and the lower part of the Khaneh Kat Formation, in SE Iran (Furst, 1970). In Saudi Arabia and southern parts of the Arabian Plate, the equivalent unit is the Sudair Shale Formation (e.g. in wells *ST-8* and *Ar'ar-1* close to the Iraqi border) (Powers, 1968; Al-Laboun, 1986; Alsharhan and Nairn, 1997).

The **Beduh Shale Formation** is 64 m thick at its type locality in the Amadia district of northern Iraqi Kurdistan. It consists of red-brown and purplish weathering shales and marls, some silty, with subordinate "ribs" of limestone with sandy streaks, and forms an excellent field marker (Dunnington *et al.*, 1959). In well *Atshan-1*, the formation is more arenaceous and calcareous, and is thicker than at outcrop (Dunnington *et al.*, 1959).

A fauna of *Anodontophora fassaensis, A. fassaensis* var *bittneri, Myophoria* cf. *praeorbicularis, M. balatonis, Gervillia* sp., *?Palaeoneilo distincta, Nucula* sp. and *Gonodon* sp. indicates a "probable late Werfenian" age (Dunnington *et al.*, 1959).

The formation was deposited in continental, occasionally paralic conditions. It contains condensed marine intervals indicated by the "paper pecten" fauna. The formation probably represents the lowstand and the TST beneath the Tr40 MFS of Sharland *et al.* (2001).

Equivalents of the Beduh Shale are the Aghar Shale Member of the Dashtak Formation in Iran (Szabo and Kheradpir, 1978) (Fig. 5.11) and the Sudair Shale of Saudi Arabia (Powers, 1968; Al-Laboun, 1986).

Petroleum System Components

Reservoir rocks

The Lower Triassic succession contains several potential reservoir units. In the Mirga Mir Formation, basal sandy oolites may be thickly developed in the subsurface, particularly close to onlap margins where the sandstone content may be higher. The Beduh Formation is locally sandy at outcrop (Dunnington *et al.*, 1959) but the proportion of sandstone is probably low, especially in central Iraq where the unit becomes more marine, as implied by facies changes detailed by Dunnington *et al.* (1959).

Source rocks

The correlative Amanus Shale Formation in Syria, equivalent to the Mirga Mir Formation, is the source of the Triassic oil and gas discoveries in the NE

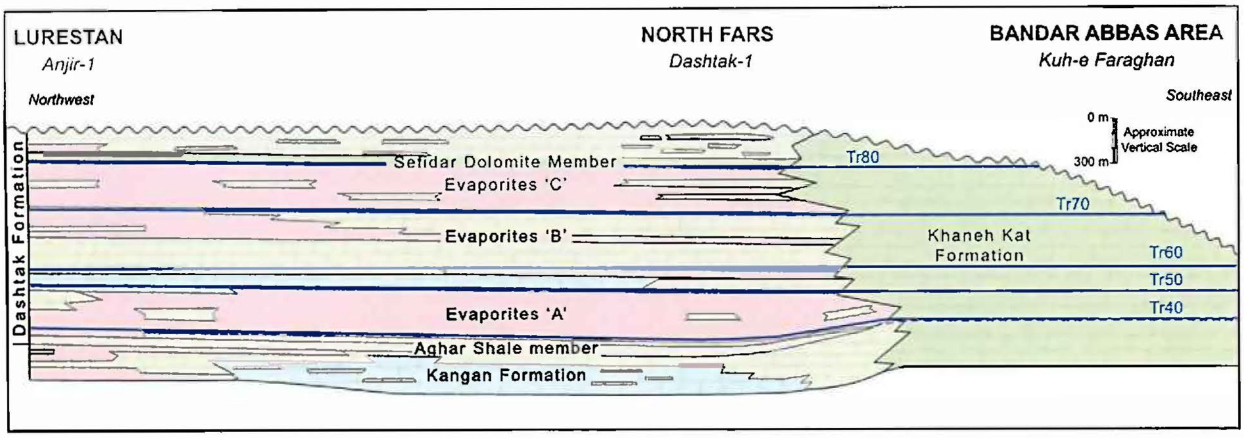


Fig. 5.11. Schematic NW-SE cross-section showing Triassic facies patterns in Iran. After Szabo and Kheradpir, 1978.

Palymra region, as indicated by biomarker correlations between source rocks and oils (Abboud *et al.*, 2005). It comprises alternating dark laminated shales, grey argillaceous finely-crystalline limestones, and fine-grained quartzitic sandstones, up to 300 m thick (Abboud *et al.*, *ibid.*).

Shales, marls and argillaceous limestones in the Mirga Mir Formation and possibly thin bivalve-rich beds in the Beduh Formation may have source rock potential; no geochemical data is available for these formations in Iraq. However, Bernasconi (1994) and Bernasconi and Riva (1993) noted that similar Triassic bivalve-rich black shales of the Grenzbitumenzone Formation in Switzerland may be very organic rich.

Seals

By analogy with the Sudair Formation of Gulf countries, shales, marls and argillaceous limestones in the Mirga Mir Formation may form intraformational seals for underlying sandstones and oolites, and for uppermost Chia Zairi Formation carbonates. The Beduh Formation may act as a seal for potential reservoirs in the uppermost Mirga Mir Formation. The correlative Lower Triassic Sudair Shale and Aghar Formations are an excellent regional seal, for example for the super-giant Khuff gas reservoirs at the *North Dome/ South Pars* fields of Qatar/Iran (Alsharhan and Nairn, 1997; Insalaco *et al.*, 2006).

The Middle Triassic (Anisian) Sequence

The Middle Triassic (Anisian) sequence in northern Iraq contains the Tr40 maximum flooding surface of Sharland *et al.* (2001). Data in Eshet and Cousminer (1986), Andrews (1992a), Hirsch (1992) and Shinaq (1996) suggest that the Tr40 MFS represents a regional-scale transgression which resulted in the deposition of carbonates on Lower Triassic and older strata. These carbonates are dated as early (but not earliest) Anisian.

The unit is here interpreted as a third-order sequence represented by the **lower member of the Geli Khana Formation**. It is 221 m thick at its type locality near Ora in northern Iraqi Kurdistan (Dunnington *et al.*, 1959), about 200 m thick in well *Atshan-1* (Buday, 1980), and 300 m thick in the Sirwan Valley (Dunnington *et al.*, 1959). The formation has been well documented in the subsurface in eight wells: *Ibrahim-1, Alan-1, Atshan-1, Mileh Tharthar-1, Jebel Kand-1, Mityaha-1, West Kifl-1* and *Diwan-1* (Dunnington *et al.*, 1959; Buday, 1980; OEC, 1989; Jassim *et al.*, 2006a). At Ora, the unit consists of greyish, thin-bedded limestones and hard calcareous shales with streaks of ripple-marked sandstones, passing up into 65m of greyish and yellowish, thin-bedded limestones and shales with bands of "recrystallisation breccias" (probably collapse breccias) (Dunnington *et al.*, 1959). In wells in northern Iraq, the basal parts of the formation have a high siliciclastic content and include anhydrite intervals (Buday, 1980); a thick anhydrite bed occurs in well *Jebel Kand-1* (OEC, 1989).

At Ora, the Geli Khana Formation has yielded, apparently from the base (Buday, 1980), a fauna including *Myophoria* sp., *Spiriferina* sp., *Trocholina* sp. and *Glomospira* sp. possibly indicating an Anisian age. The Geli Khana Formation conformably overlies the Beduh Shale Formation. In well *Khleisia-1*, a thin limestone unit assigned to the Geli Khana Formation rests unconformably on the Harur Limestone Formation (Jassim *et al.*, 2006a). The upper contact is poorly described. It may be a sequence boundary across which late highstand evaporites pass up into deeper-water euxinic limestones. The presence of collapse breccias beneath the contact suggest that it was subaerially exposed.

The lower member of the Geli Khana Formation represents a prograding highstand carbonate platform which ended with local evaporite deposition. It has been interpreted as a nearshore and occasionally lagoonal deposit (Buday, 1980).

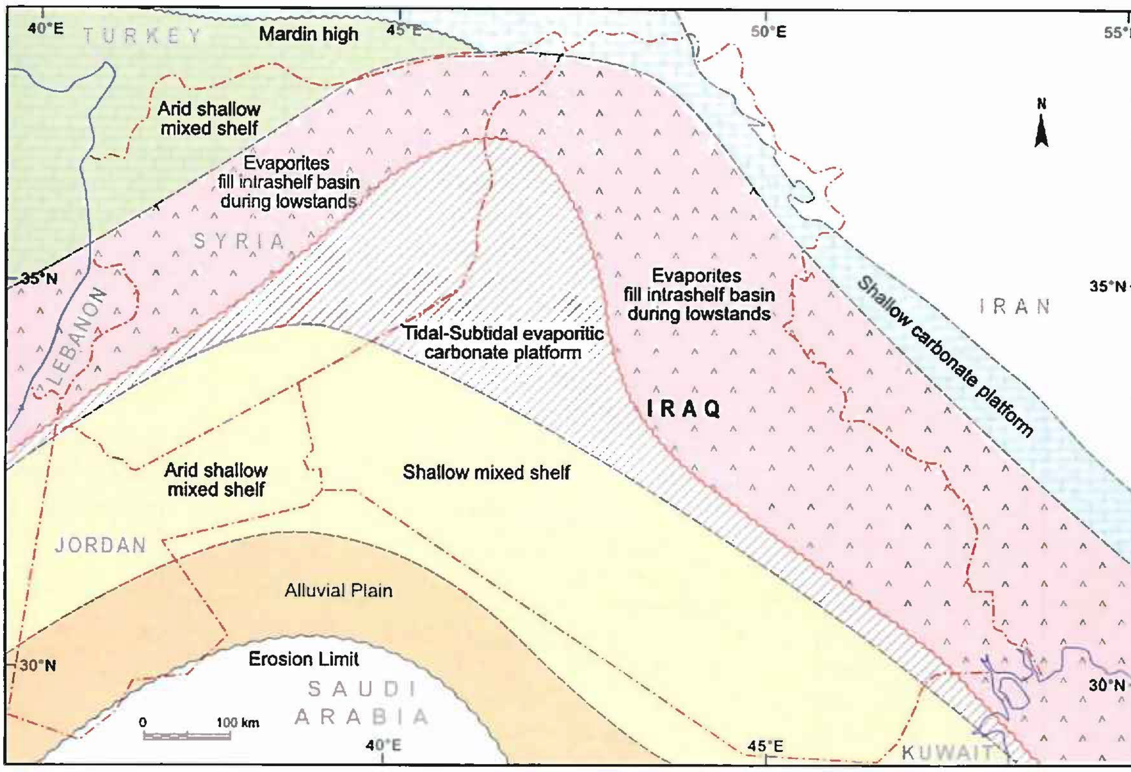


Fig. 5.12. Map of Iraq and adjacent areas showing Anisian – Ladinian palaeogeography. Modified after Sadooni and Alsharhan, 2004.

The Geli Khana platform may have formed part of an Anisian basin system which extended westwards into the Eastern Mediterranean region and Turkey (Sadooni and Alsharhan, 2004; Fig. 5.12). The Anisian sequence contains a distinctive (endemic) biota. In Syria, the equivalent Middle Triassic formation is the mis-named "Kurrachine Formation" (Abboud *et al.*, 2005). Anisian volcanics are reported from the *Dolaa-1* and *Abba-1* boreholes in Syria (Dubertret, 1966; Ponikarov (Ed.), 1967), indicating tectonic extension. An equivalent of the Geli Khana Formation in Iran is the Dashtak Formation "A" Evaporite of Szabo and Kheradpir (1978) (Fig. 5.11).

Palynological data from well *KH 5/8* in the NW corner of the Western Desert of Iraq indicates that deposition of the **Ga'ara Formation** continued into the Anisian (Al-Ameri, 1990). This formation is interpreted to be a fluvial deposit. It resembles the undated clastic succession in nearby well *KH 5/3* (Kaddouri, 1992) (Fig. 4.27), as mapped by Sadooni and Alsharhan (2004) (Fig. 5.12). However, other wells nearby (e.g. *KH 5/2, KH 5/6*) (Fig. 4.27) only contain the Mulussa Formation of later Triassic age (Kaddouri, 1992). Large areas of the Western Desert were thus probably emergent during the Early–Middle Triassic and are represented by an unconformity (Fig. 3.17).

Petroleum System Components

Reservoir rocks

Reservoir intervals may occur within the lowermost Geli Khana Formation, which includes shallow-water (locally oolitic) carbonates with associated evaporite collapse breccias and/or karstic fabrics at the top of the sequence.

Source rocks

No proven source rocks are known from this interval in Iraq. However, the equivalent "Kurrachine Formation" is recognized to be a source rock in the Palmyra Basin of Syria (Abboud *et al.*, 2005), suggesting that some source potential may exist in Iraqi wells containing thicker, shalier and more evaporitic successions (e.g. perhaps *Jebel Kand-1*; OEC, 1989).

Seals

Basal argillaceous units and uppermost evaporitic units in the lower Geli Khana Formation are potential seals. The equivalents of the evaporitic units are the anhydritic "A Evaporites" of the Dashtak Formation in Iran (Szabo and Kheradpir, 1978). These may provide seals in SE Iraq.

The Middle Triassic (Ladinian) Sequence

Ladinian rocks throughout most of Iraq are assigned to the **upper member of the Geli Khana Formation** (Fig. 5.3). Thicknesses range from 353 m at the type locality at Geli Khana (from data in Dunnington *et al.*, 1959) to 150 m in the Sirwan Valley and 260 m in well *Atshan-1* (Buday, 1980).

At the type locality, the upper Geli Khana Formation commences with 154 m of bluish shales intercalated with yellowish limestones and occasional sandy bands. These pass up into 138 m of hard, fine-grained cliff-forming limestones with alternating thin and thick beds, with intercalations of olive-green shales and yellow-brown marls in the lower part, and occasional bands of chert nodules near the top. These are followed by 58 m of dark, foetid dolomites with bands of grey dolomitic limestones containing abundant recrystallised gastropods; and finally a 3.5 m thick, laminated ferruginous dolomite with streaks of black chert and nodular haematite (Dunnington *et al.*, 1959). At the base of the Upper Geli Khana is the Tr50 MFS of Sharland *et al.* (2001).

In the Sirwan Valley section, basal argillaceous limestones contain the "paper pecten" bivalves *Daonella indica, D.* cf. *indica, D. lomelli* and *D. lomelli-taramelli* (Dunnington *et al.*, 1959; Buday, 1980). These suggest a Ladinian age (Dunnington *et al.*, 1959). The top of the Geli Khana Formation is a prominent disconformity marked by haematization, silicification and dissolution. In the Sirwan area, it is covered by a red marlstone bed with ferruginous crusts and limonitized pisolites. In the Chalki (Nazdur) area in northern Iraqi Kurdistan, ferruginous staining and patches of weathered saccharoidal dolomite occur (Dunnington *et al.*, 1959).

At Geli Khana, the upper member of the Geli Khana Formation was deposited in a deeper-water environment than the lower member (Buday, 1980). The lithological succession (and faunal data from the Sirwan Valley) indicate that it was deposited as an upwards-shallowing, possibly prograding, carbonate ramp that developed following establishment of deepwater conditions (c.f. Ahr, 1973).

Bandel and Khoury (1981), Bandel and Waksmundzki (1985) and Eshet and Cousminer (1986) noted that an earliest Ladinian transgression (well-dated regionally by conodonts, ammonites and palynological data) occurred to the west of Iraq. To the SE in Iran, carbonate units equivalent to those in the upper Geli Khana occur above the "A Evaporites" of the Dashtak Formation (Szabo and Kheradpir, 1978; Fig. 5.11); these facies may also be present in SE Iraq.

In the NW of the Western Desert at well *KH 5/8*, deposition of the fluvial siliciclastics of the **Ga'ara Formation** continued in Ladinian time, as indicated by palynological data (Al-Ameri, 1990). The undated clastic stratigraphy in nearby well *KH 5/3* may be similar (Kaddouri, 1992) (Fig. 4.27). However, other wells nearby (e.g. *KH 5/2, KH 5/6*) (Fig. 4.27) contain only the Mulussa Formation of later Triassic age (Kaddouri, 1992). These areas were therefore probably emergent during the Middle Triassic and are represented by an unconformity, as in the Anisian (Fig. 3.17). The Ga'ara Formation in the Western Desert is overlain by the Mulussa Formation. The contact between the two formations was described as *"possibly disconformable but apparently gradational and concordant"* by Dunnington *et al.* (1959).

Petroleum System Components

Reservoir rocks

Reservoir rocks may occur within the shelfal carbonates in the uppermost part of the Geli Khana Formation. Karstic porosity has been described from both outcrop and subsurface studies at the upper contact of the formation (Dunnington *et al.*, 1959).

Source rocks

Source rocks have not been recorded in this interval in Iraq. The mid-Triassic "Kurrachine Formation" may have source potential in the Palmyra Basin, Syria (Abboud *et al.*, 2005).

Seals

Intra-Geli Khana Formation flooding surface Tr50 (Sharland *et al.*, 2001) may seal potential reservoirs in the lower part of the formation.

The Upper Triassic (lower–middle Carnian) Sequence

The lower-middle Carnian succession in Iraq was initiated by the Tr60 MFS of Sharland *et al.* (2001). The Carnian-Norian succession is assigned to the **Kurra Chine Formation** (Fig. 5.13, 5.14), which is some 834 m thick in NE Iraq (Dunnington *et al.*, 1959) and over 1000 m thick at several well locations (Buday, 1980; Sadooni, 1995) (Fig. 5.1). The Kurra Chine Formation passes laterally into the **Mulussa Formation**, which is an order of magnitude thinner in the Western Desert (Dunnington *et al.*, 1959) (Fig. 3.17). Both the Kurra Chine and Mulussa Formations represent two sequences (Fig. 5.13), which are probably of early–middle Carnian and late Carnian to early Norian ages, respectively.

At the type section outcrop near Ora in Iraqi Kurdistan, the Kurra Chine Formation is poorly described. It consists of dark brown and black limestones alternating with papery shales and thick-bedded dolomites showing slump structures (Dunnington *et al.*, 1959). Dunnington *et al.* (1959) considered that breccia beds at the type section were formed by recrystallization and dissolution of evaporites by meteoric waters. This interpretation is confirmed by the presence of thick evaporite intervals in the subsurface, where the Kurra Chine Formation consists of alternating limestones and dolomites, shales, anhydrites and some halite (Buday, 1980; Kaddouri, 1986; Sadooni, 1995; Sadooni and Alsharhan, 2004) (Fig. 5.14). Two carbonate units and two overlying evaporite members are known from the subsurface (Fig. 5.13). Carbonates represent the Tr60 and Tr70 MFSs of Sharland *et al.* (2001) and their subsequent

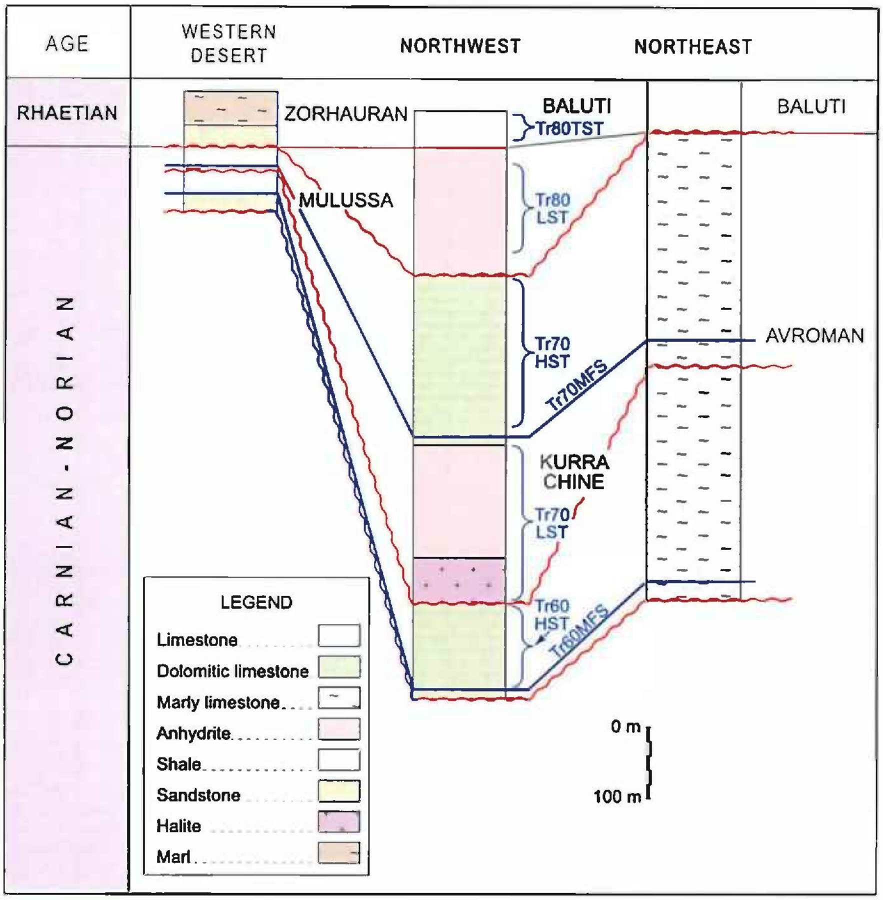


Fig. 5.13. Generalized Upper Triassic stratigraphy in west, NE and NW Iraq. Modified after Sadooni, 1995. Positions of the MFS and SB in the Avroman Formation are uncertain. The Avroman Limestone only occurs in Tethyan allochthonous units.

highstands. Anhydrites represent lowstand deposits at the base of sequences Tr70 and Tr80. Microfacies include oolitic wackestone-packstones, stromatolitic limestones and the *"Paleotrix"* facies (of IPC geologists) consisting of packed "paper pectens" and dolomite (Sadooni, 1995; Sadooni and Alsharhan, 2004). Hay and Algawi (1958, *in* Buday, 1980) described "relatively thick" sandstone beds from the lower part of the formation in well *Mileh Tharthar-1*. A sandstone unit occurs in wells *Awasil-5* (Buday, 1980) and *Mityaha-1* (Sadooni, 1995) (Fig. 5.14).

At well *Tel Hajar-1*, the formation contains a relatively diverse biota including *Simeonella brotzenorum*, *Involutina* sp. 1., *Sinous sinous*, *Trocholina* sp., radiolaria and ostracods suggesting a Carnian-Rhaetian? age (Kaddouri, 1986). Other characteristic fossils include *Posidonia wengensis*, *P. altior*, *P. idriana* and *Estheria minuta* (Dunnington *et al.*, 1959). Palynomorphs indicate a Late Triassic age (Fig. 5.2). The Kurra Chine Formation rests disconformably on the Geli Khana Formation (Dunnington *et al.*, 1959).

The Kurra Chine Formation was probably deposited on an epeiric platform (Fig. 5.15), dominated by subtidal to supratidal cycles with local development of sabkhas; this occurs for example at carbonate-dominated basin-margin wells such as *Khleisia-1*. However, thicker evaporitic units in depocentres (as in *Jebel Kand-1*) and black shales containing abundant "paper pectens" may represent third-order late highstand to early lowstand infills of a starved intrashelf basin (Fig. 5.16). The provenance of the sandstones at the base of the succession is also important in the interpretation of the formation. According to Buday (1980), the presence of these sandstones *"indicates both the transgressive nature of the formation and the proximity of the land"*. In a carbonate-dominated succession, the abrupt appearance of siliciclastic sediments may indicate the proximity of an exposed basin margin. A major stratigraphic break may thus occur between the Geli Khana and Kurra Chine Formations.

The **Mulussa Formation** (Fig. 5.17) is the most prominent Triassic rock unit exposed in the Western Desert. It contains the "i" marker. This is a conspicuous oolitic-peloidal, locally limestone clast conglomerate; only the sub-"i" marker member is considered to occur within the Tr60 (early–middle Carnian) sequence. The Mulussa Formation varies in thickness due to Cretaceous erosion. Where the entire thickness of the lower member is preserved between Wadi Agar Muyat and Al-Alaif, it is 107 m thick (Dunnington *et al.*, 1959). It consists of massive to thin-bedded, crystalline or micro-crystalline, oolitic to "pseudo-oolitic" (?peloidal) and

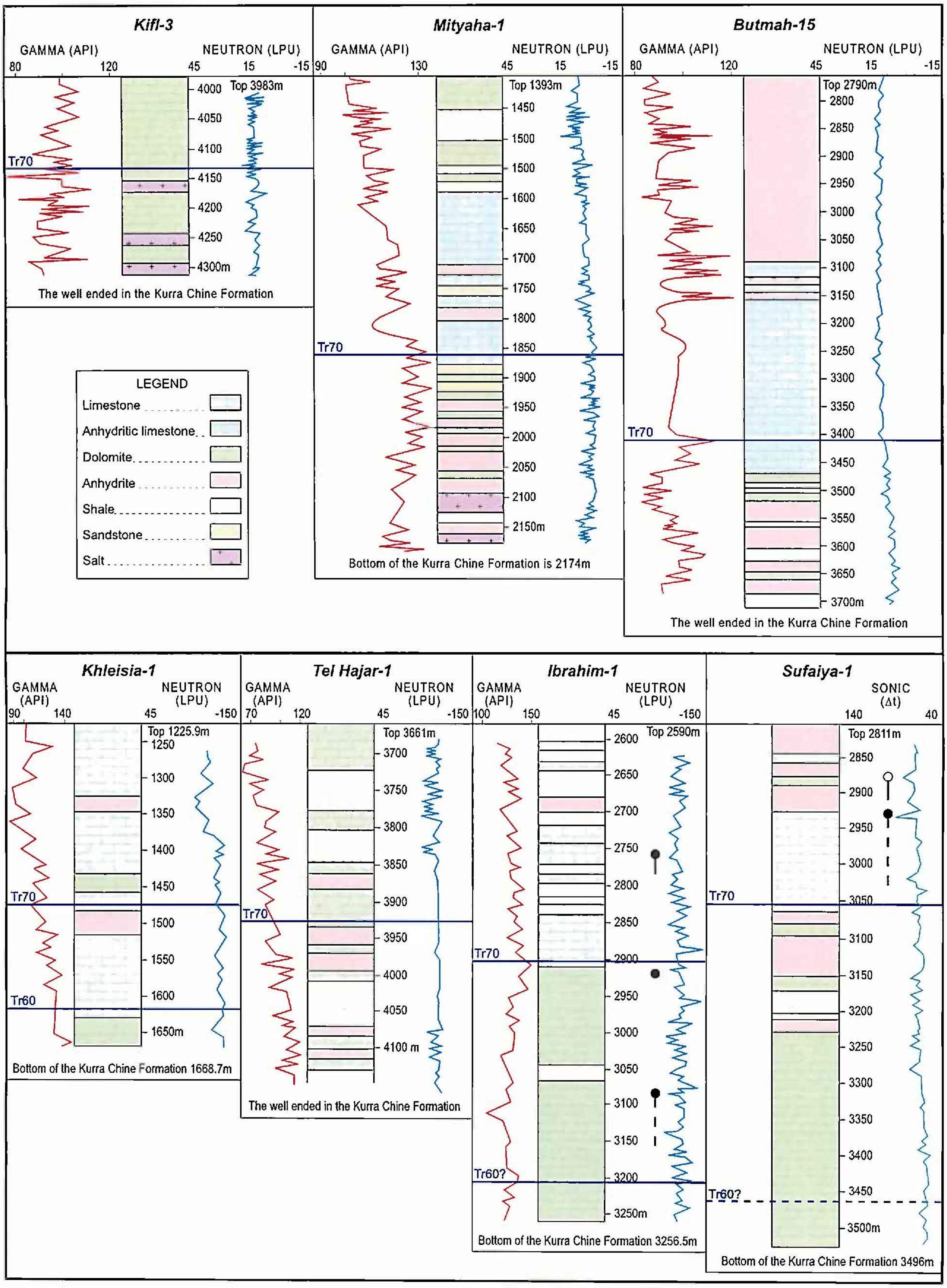


Fig. 5.14a, b. Stratigraphic columns for the Kurra Chine Formation from wells in Iraq. After Sadooni, 1995. Figure modified to show likely positions of MFSs and hydrocarbon shows (oil: black dots; gas: unfilled dots) (from data in Sadooni, 1995 and Sadooni and Alsharhan, 2004).

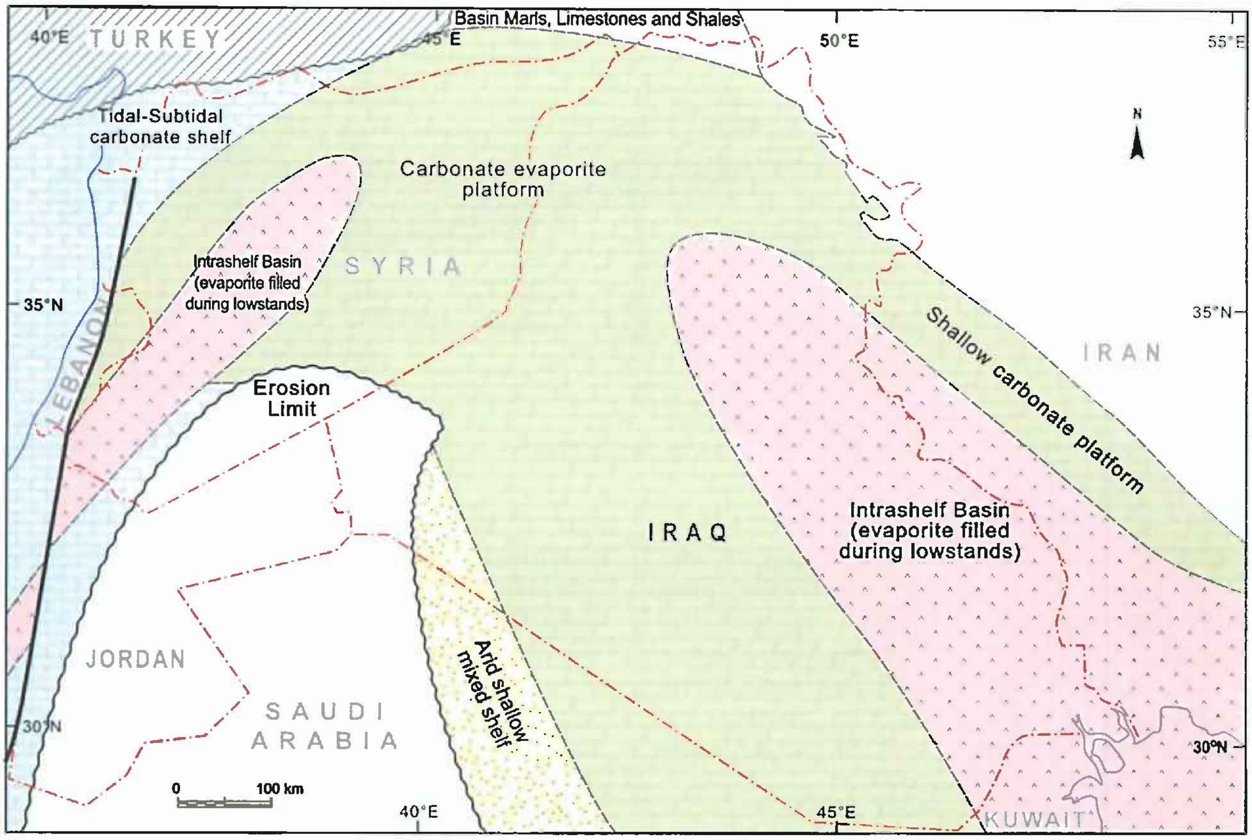


Fig. 5.15. Map of Iraq and adjacent areas showing generalized Carnian - Norian palaeogeography. Modified after Sadooni and Alsharhan, 2004.

sandy limestones with subordinate yellow marlstones and marly limestones (Dunnington *et al.*,1959. It is extensively dolomitised and partly silicified. The Mulussa Formation is generally more sand-rich in the west than in the east (Sadooni, 1995). Buday (1980) suggested that it passes into the Minjur Sandstone Formation of Saudi Arabia. Kaddouri (1992) recorded that a sandy "Minjur" facies of Triassic age occurs in wells *KH 5/3* and *5/8.*

The basal part of the formation in well *KH 5/8* is of Carnian age (Al-Ameri, 1990); Jassim *et al.* (2006a) also dated the formation as Carnian. In wells *KH 5/4* and *5/9*, the lower part of the Mulussa Formation carbonates have been assigned to the Anisian - Ladinian (Kaddouri, 1986) based on sparse palaeontological data (Fig. 5.17).

The Mulussa Formation is interpreted to indicate a relatively near-shore and higher energy, more littoral environment than the generally low-energy Kurra Chine Formation.

The basal units of the Kurra Chine equivalents in the eastern Mediterranean (Abu Ruweis and Mohilla Formations) have been accurately dated from palynological, conodont and ammonite studies (Bandel and Khoury, 1981; Bandel and Waksmundzki, 1985; Eshet and Cousminer, 1986; Abu Hammad, 1994). These confirm the Carnian age of the maximum flooding surface which was originally (but poorly) defined in Iraq (c.f. Sharland *et al.*, 2001). A Late Triassic age has been assigned to the undifferentiated Ramtha Group carbonates in the *Risha* area of Jordan. These carbonates unconformably overlie Palaeozoic sedimentary rocks (Andrews, 1992a) and are lithologically similar to the Mulussa Formation. In adjacent parts of Syria, Iran and the eastern Mediterranean, anhydrite beds thicken and pass into halite facies towards depocentres (Druckman, 1977; Jamal *et al.*, 2000).

In summary, a transgression at the base of the lower–middle Carnian sequence covered the Khleisia and Rutbah Highs, which then became sites of carbonate deposition for the first time since the Early Carboniferous. This established a broad carbonate platform. The varied lithologies and often great thicknesses of Carnian units in Iraq and nearby countries indicate high overall sediment productivity. Thick platforms built up around intrashelf basins into which there was only minor progradation and infilling during HST conditions (Fig. 5.16). During lowstands, the basins became restricted and were infilled or partially infilled by anhydrite and halite (Fig. 5.16). Locally slumped anhydrite units occur in well *Tel Hajar-1* and may indicate synsedimentary fault activity. Meanwhile, clastic sediment entered the basin from onlap margins (Fig. 5.16) located to the SW, probably in southern Jordan and NW Saudi Arabia.

Petroleum System Components

Reservoir rocks

Reservoir intervals may occur in the lowermost carbonate-dominated member of the Kurra Chine

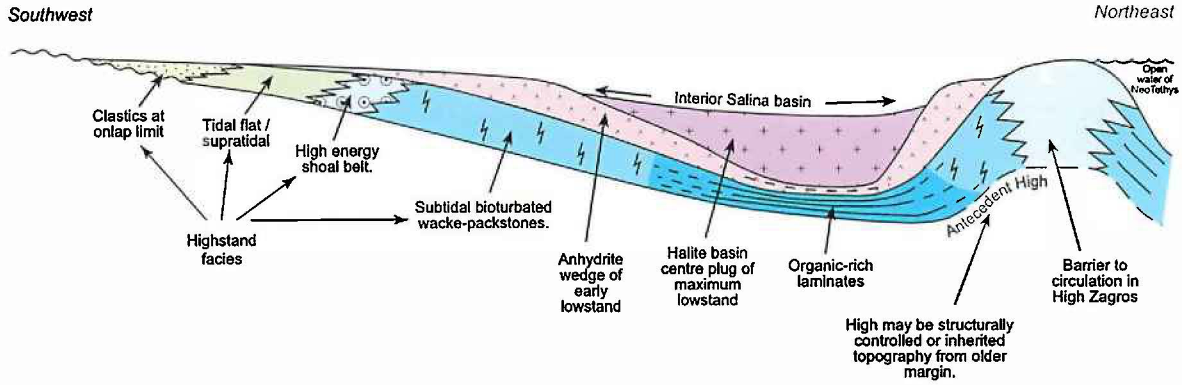


Fig. 5.16. Schematic SW-NE section showing the development of third-order Triassic intrashelf basin sequences in Iraq.

Formation, although most successful tests of the formation in Iraq are reported to be from carbonates in the upper part. In Syria, however, most production comes from the top of the equivalent "Kurrachine Dolomite", for example at *Souedie, Hamza, Rumelan, Jebissa* and *Tishreen* fields in the NE (May, 1991; Sadooni, 1995; Sadooni and Alsharhan, 2004), and north of *Shamal Alhosin* in NE Palmyra (Abboud *et al.*, 2005).

Source rocks

No source rocks are known to occur in the Lower Kurra Chine carbonates, although some potential may exist in the centre of the intrashelf basin.

Seals

No sealing facies appear to be present in this sequence, perhaps explaining the lack of discoveries in the uppermost karstified part of the Geli Khana Formation.

The Upper Triassic (upper Carnian – lower Norian) Sequence

The upper Carnian – lower Norian succession is up to 600 m thick along the palaeo-Sinjar fault zone and in the Kand Basin in northern Iraq (Sadooni, 1995) (Fig. 5.1). It contains the lower evaporite and upper carbonate members of the **Kurra Chine Formation** in the subsurface, and the upper member of the **Mulussa Formation** in the Western Desert outcrops and subsurface (Fig. 5.13, 3.17). Where it can be identified, MFS Tr70 was located in strata at the base of the carbonate succession by Sharland *et al.* (2001) (Fig. 5.13); this MFS is not well-dated in Iraq.

The above members of the **Kurra Chine Formation** are 350-400 m thick in wells *Tel Hajar-1* and *Jebel Kand-1* (from data in Kaddouri, 1986; OEC, 1989). In the Sirwan area, the Kurra Chine formation contains lenses of gypsum (Dunnington *et al.*, 1959). In the subsurface, the formation contains significantly more anhydrite than at outcrop (Sadooni, 1995), particularly in the middle part of the unit at wells *Mileh Tharthar-1* (Dunnington *et al.*, 1959) and *Mityaha-1* (Sadooni, 1995) (Fig. 5.14). Halite occurs locally at the base of the evaporite units in well *Mityaha-1* (Fig. 5.14). The halite was deposited in an intrashelf basin (Fig. 5.6). Anhydrite beds thicken and pass into halite facies towards depocentres, although the thickest anhydrites (some 800 m in well *Jebel Kand-1*) are not associated with interbedded halites (OEC, 1989). These occur in the Kand Basin as defined by the isopach map of Sadooni, 1995) (Fig. 5.1).

At the base of the upper carbonate member are dolomites and dolomitic and oolitic limestones, generally occurring as alternating (metre-scale) beds, for example in wells *Sufaiya-1* and *Ibrahim-1* (Sadooni, 1995).

Hassan (1986) and Kaddouri (1986) dated the uppermost Kurra Chine Formation carbonates as Norian-Rhaetian, based on the foraminifera present in overlying units. This is consistent with recent palynological studies (Fig. 5.2).

The upper carbonate-dominated part of the Kurra Chine Formation was initially deposited on an epeiric platform dominated by shallow subtidal to supratidal cycles with local sabkhas (for example in basin margin locations e.g. *Khleisia-1)*. In other wells, there are well-developed black shales with abundant "paper pectens". These were probably deposited in restricted intrashelf basins such as the Kand Basin (Sadooni, 1995).

The **upper part of the Mulussa Formation** is 52 m thick at its type section near Mulussa in Wadi Hauran. It has a higher marl content than the lower member (Dunnington *et al.*, 1959). Oolitic facies occur in the basal part of this sequence, in the interval known as the "i" marker (Dunnington *et al.*, 1959). Fossils recovered from this interval include *Myophoria* aff. *postera, Mytilus minus trus, Gervillia* sp., *Archaediscus* sp. and *Trocholina* sp., with frondicularids, textulariids and ostracods (Dunnington *et al.*, 1959; Buday, 1980). Palynological studies of the Mulussa Formation yield a Carnian date at its base (Al-Ameri, 1990), and by inference, a probable Norian or Rhaetian

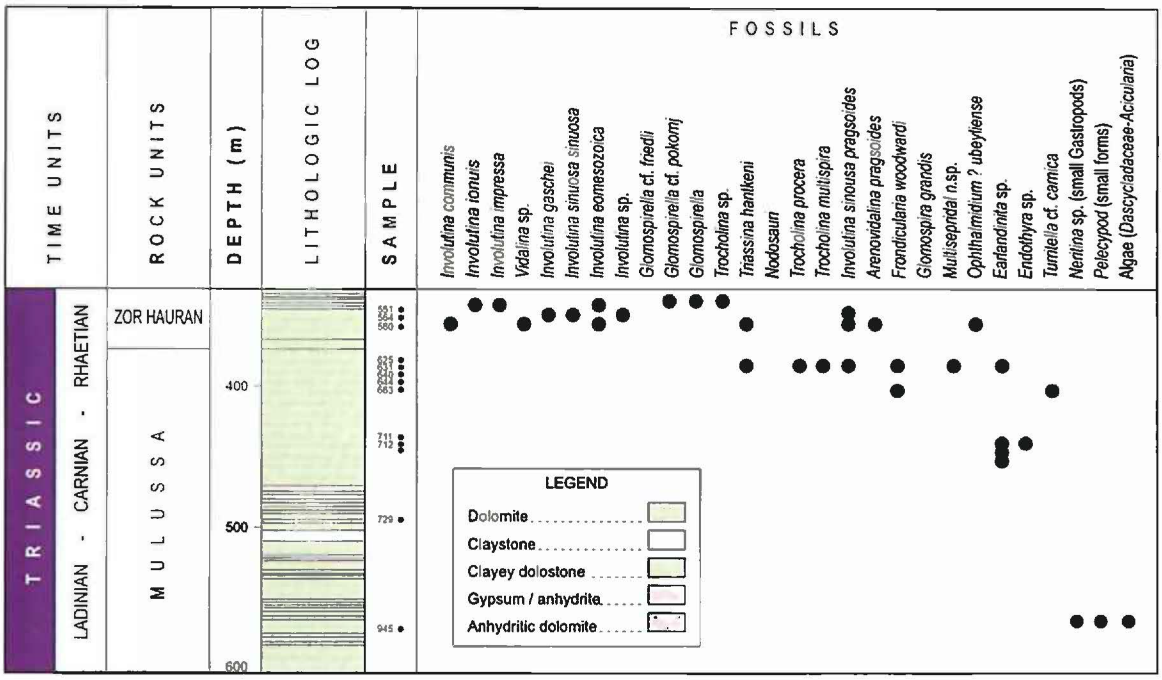


Fig. 5.17. Fossil distribution in the Mulussa Formation, well *KH 5/8*. After Al-Ameri, 1990. Note that **the Ladinian age is not supported by the palaeontological data presented.**

age for its upper member. The Mulussa Formation is overlain conformably and gradationally by the Zor Hauran Formation (Dunnington *et al.*, 1959; Kaddouri, 1992) (Figs. 5.17, 3.17).

The upper carbonate-clastic member of the Mulussa Formation was probably deposited in a restricted inner-shelf environment. The "i" marker represents more open-marine and relatively deeper-water conditions.

Deposition of carbonates associated with the basal MFS of this sequence records a major Late Triassic transgression throughout the eastern Mediterranean region (Hirsch, 1992). Reliable dates have been obtained from carbonates resting on middle Carnian evaporites from palynology, conodonts and ammonites (Eshet and Cousminer, 1986; Hirsch, 1992). In the later stages of platform development, restricted intrashelf basins with remnant accommodation space were infilled by thick evaporites in both Iraq (Sadooni, 1995) and Iran (Szabo and Kheradpir, 1978). At Hazro in SE Turkey, equivalent units contain megalodontid bivalves (Fontaine, 1981). Restricted carbonate platform facies occur in the Kaneh Kat Formation of Iran (Szabo and Kheradpir, 1978) (Fig. 5.11).

A major erosional surface at the top of the Upper Triassic sequence separates the Neyriz and Dashtak Formations in Iran at well *Kuh-e Siah-1* (Szabo and Kheradpir, 1978). To the west, the end-Triassic to earliest Jurassic was marked by uplift, erosion, emplacement of intrusive rocks and volcanism (Zak, 1963; Dvorkin and Kohn, 1989; Hirsch, 1992). Equivalent units in Kuwait (Yousif and Nouman, 1997) (Fig. 5.18) and NE Saudi Arabia (Powers *et al.*, 1966) are assigned to the Minjur Formation, which consists of clastic facies associated with coastal onlap.

Petroleum System Components

Reservoir rocks

The uppermost Triassic succession may include the most prospective reservoir rocks in Megasequence AP6 in Iraq, although very little data is available. Reservoir rocks include porous and fractured Triassic carbonates (dolomites and oolitic limestones) in northern Iraqi Kurdistan and Syria, which are up to 350 m thick in *Butmah-15* (Fig. 5.14) (Sadooni, 1995; Sadooni and Alsharhan, 2004; Jassim and Al-Gailani, 2006). Al-Ameri *et al.* (2009) recorded channel, vuggy and intergranular porosity in rocks with reservoir potential. Jassim and Al-Gailani (2006) reported porosities ranging from 4 to about 12% at approximately 3500 m in *Butmah-15* (Fig. 5.14).

The Kurra Chine Formation contains oil in northern Iraq at *Butmah*, *Sufaiya* and *Alan*. In NE Syria,the equivalent "Butma" Formation contains oil at *Twinan* (Palmyra) and *Ouda* (Abboud *et al.*, 2005). The lower "Mulussa Formation" carbonates (members A-C) in the Euphrates Graben, which are equivalent to the Kurra Chine Formation in Iraq, includes low net:gross reservoir rocks with low porosities and permeabilities (de Ruiter *et al.*, 1995). In Jordan, the age-equivalent Abu Ruweis Formation has porosities of up to 25% and permeabilities of up to 1000 mD (Sadooni and Dalqamouni, 1998) (Fig. 5.19).

Siliciclastic reservoir intervals may occur locally in the Kurra Chine Formation. Dunnington *et al.* (1959) and Sadooni (1995) reported that the lower

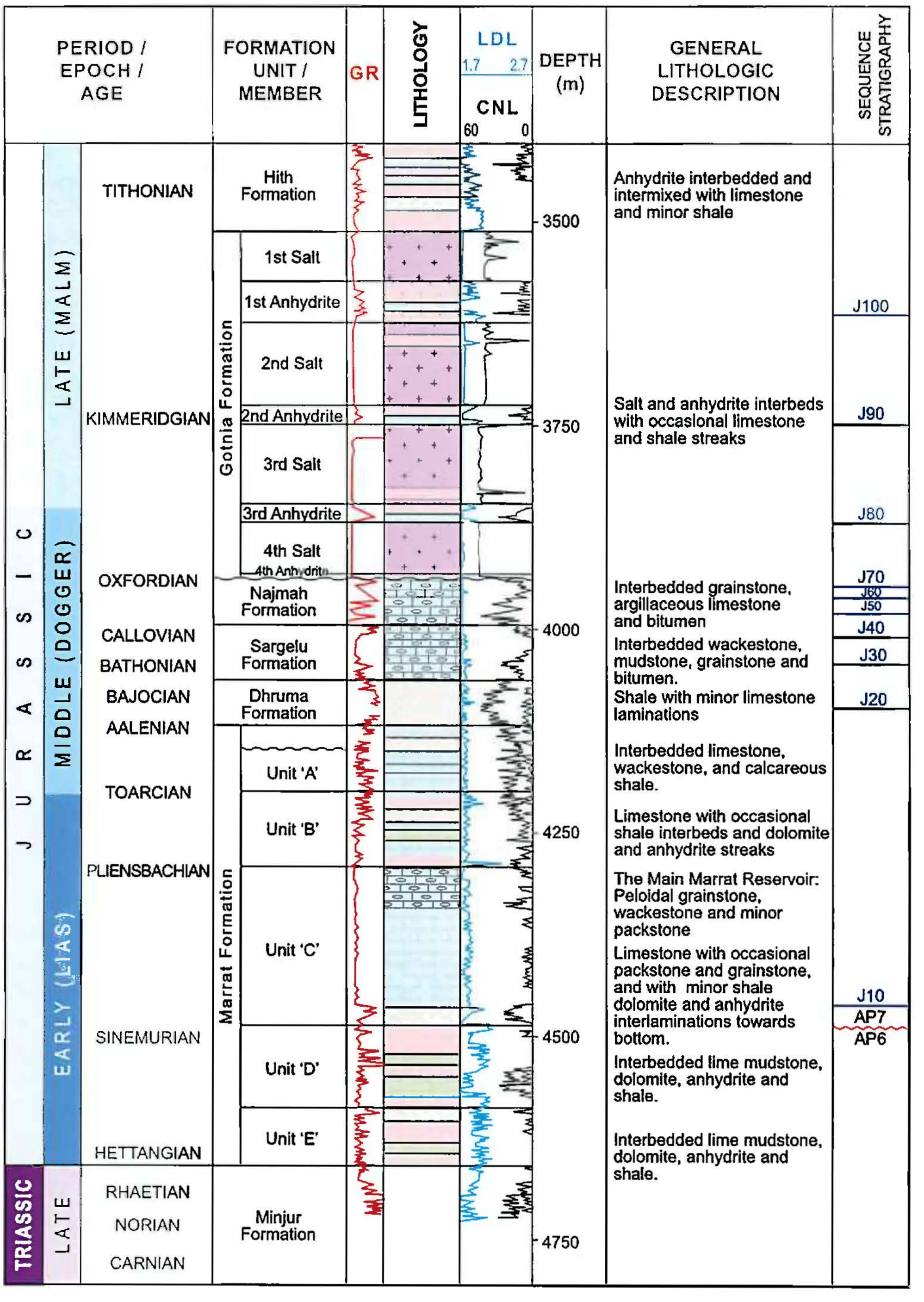


Fig. 5.18. Stratigraphy of Jurassic units in Kuwait, based on well *Minagish-27*. After Yousif and Nouman, 1997.

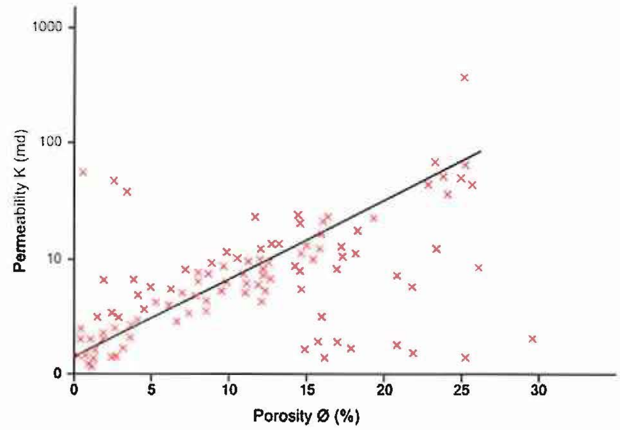
part of the formation becomes increasingly siliciclastic towards central Iraq. However, reservoir quality will probably be poor to moderate by comparison with the slightly younger "Mulussa F" reservoirs of the Euphrates Graben (de Ruiter *et al.*, 1995).

Source rocks

Oils in Triassic reservoirs in Iraq have different sulphur isotope ratios compared to oils in younger Mesozoic and Tertiary reservoirs (Thode and Monster, 1970). Metwalli *et al.* (1972) analysed crude oils from *Jebissa* field in NE Syria. They showed that Triassic reservoired oils have different characteristics (lower densities, and low-sulphur and low-asphaltene contents) compared to oils in Cretaceous and Tertiary reservoirs. May (1991) suggested that Triassic oils in Syrian and Iraqi oilfields could have been sourced from Middle to Lower Triassic or Permian shales and limestones.

Beydoun (1988b,1993) favoured sourcing by thin shales which occur within the Triassic carbonate succession, for example in the Euphrates graben. Sadooni (1995) suggested that the Kurra Chine Formation contains source and reservoir rock intervals in northern Iraq. The source potential of

Fig. 5.19. Porosity versus permeability plot for carbonate reservoirs in the Abu Ruweis Formation, Jordan. From Sadooni and Dalqamouni, 1998. The Abu Ruweis is an equivalent of the Kurra Chine Formation.



the formation has been confirmed by recent geochemical studies (Al-Ameri *et al.*, 2009) (see pp. 307-309). TOCs of up to 5% occur in *Jebel Kand-1*. Maximum TOCs occur in the middle of the Kurra Chine and the Baluti Shale Formations in *Ain Zalah-29*. Al-Ameri *et al. (ibid.)* noted that organic matter is Type II/III, deposited under suboxic-anoxic lagoonal conditions. Potential source rocks are probably best developed in the mudstones which are interbedded with the Kurra Chine Formation evaporites.

Shales and argillaceous carbonates in the Abu Ruweis Formation of Jordan (equivalent to the lower evaporites of the Kurra Chine Formation of Iraq) may be effective source rocks. The shales mostly occur in the basal part of the formation (Shinaq, 1996). Beydoun *et al.* (1994) reported that argillaceous Triassic source rocks in Jordan contain mixed oil-prone Type II and gas-prone Type III kerogen, and have low-to-moderate organic contents. In well *Northern Highlands-1*, shaly and carbonate intervals (AR-4 unit) have TOC contents of 0.5-1.9 % and may be oil-prone source rocks (Shinaq, 1996). Abboud *et al.* (2005) noted that the equivalent "Butma Formation" at the *Ouda* field, Syria, has source rock characteristics.

Seals

Evaporites in the lower part of the Kurra Chine Formation seal reservoir intervals in underlying carbonates in the Alan/Adaiyah/Ibrahim area of NW Iraq (Sadooni, 1995; Sadooni and Alsharhan, 2004). However, towards Iraqi Kurdistan, this seal capacity may be compromised due a reduction in the anhydrite content of the formation.

The Uppermost Triassic – Lower Jurassic (upper Norian – Sinemurian) Sequence

Upper Norian – Sinemurian rocks comprise the uppermost evaporitic part of the Kurra Chine Formation, the Baluti Formation, and the lower part of the Butmah Formation in the subsurface. Outcrop equivalents are the Zor Hauran and Ubaid Formations in the Western Desert (Fig.3.17), and the Sarki Formation in Iraqi Kurdistan (Dunnington *et al.*, 1959; Kaddouri, 1986; Hassan, 1986). The basal part of this succession comprises evaporitic and mostly continental deposits of late Norian to Rhaetian age. The lower part of the post-Rhaetian succession in Iraq comprises thick, clean low-energy carbonates. These pass up into more heterolithic facies,terminated by a sequence boundary, overlain by clastic units and heterolithic facies. The Tr80 MFS was not precisely dated by Sharland *et al.* (2001). On the basis of the Rhaetian age of the underlying Zor Hauran Formation (Kaddouri, 1986), the MFS may be very earliest Jurassic rather than latest Triassic.

A transition from oolitic grainstones which are assigned to the Tr70 HST up into massive to laminated, locally slumped anhydrite with some graded beds is recorded at well *Tel Hajar-1* in the Sinjar Graben (Sadooni, 1995). Anhydrites are thickest in depocentres but are absent or poorly developed in basin margin settings such as *Khleisia-1*. Halite has not been recorded in this sequence.

Uppermost parts of the **Kurra Chine Formation** include sabkha and salina deposits (Sadooni, 1995) (Figs. 5.13, 5.14). The anhydrite may represent maximum restriction, isolation and high salinity conditions in the intrashelf basins during the late highstand of Tr70 to early TST of Tr80. The laminated fabrics, graded beds and slumps in anhydrites at well *Tel Hajar-1* (Sadooni, 1995) suggest development of depositional slopes and perhaps synsedimentary tectonic activity within a relatively deep-water setting (c.f. Sharland *et al.*, 2001). Dunnington *et al.* (1959) suggested that the Kurra Chine Formation passes conformably and gradationally up into the Baluti Shale Formation.

The **Baluti Shale Formation** is 58.5 m thick at the Sarki locality in Iraqi Kurdistan (Dunnington *et al.*, 1959). At its type section south of Amadia City, it consists of grey and green, calcareous and dolomitized shales. It contains intercalations of thin-bedded (less than 10 cm thick) finely-crystalline dolomitized limestones with solution brecciation probably formed by the dissolution of anhydrite (Dunnington *et al.*, 1959).

Fossils in the Baluti Shale include *Glomospira* sp., ostracods and indeterminate molluscs. A Rhaetian age has been suggested for this unit (Dunnington *et al.*, 1959). The upper contact appears to be sharp although conformable.

The Baluti Shale Formation probably represents the latter part of a lowstand to early transgressive sequence. Most of the formation was deposited in a continental setting and may include aeolian (loess) deposits. The dolomite may have been deposited in a peritidal to sabkha environment.

The Baluti Shale Formation can be correlated with the **Zor Hauran Formation** (*sensu* Buday, 1980) at outcrop in the Western Desert. It consists of 27 m of variegated gypsiferous marls and shales (Dunnington *et al.*, 1959) and contains foraminifera dated as Rhaetic (Kaddouri, 1986, his chart 1; Kaddouri, 1992) (Fig. 5.17). Carbonates beneath the upper contact of the Zor Hauran Formation are reddened. Local erosion and the presence of siliciclastics in the overlying Ubaid Formation indicate a disconformity at its upper surface (Jassim *et al.*, 2006a) (Fig. 3.17), suggesting that the Zor Hauran is a latest highstand to early lowstand deposit. The depositional environment of the Zor Hauran Formation is interpreted to have been similar to that of the Baluti Formation.

The **Butmah Formation** comprises 450-600 m of limestones, dolomites, shales, traces of sandstone and locally well-developed anhydrites (Dunnington *et al.*, 1959). The formation can be divided into five members. The lower two members (Lower Butmah Formation) are here assigned to the upper Norian – Sinemurian Sequence. The upper three members (Upper Butmah Fomation) are assigned to the overlying Pliensbachian – lower Toarcian sequence.

The lower Butmah Formation comprises 146 m of a distinctive massive dolomite at the type well *Butmah-2,* overlain by 150 m of thin beds of green-grey to black mudstones, argillaceous dolomites, dolomitised wackestones and packstones, and nodular anhydrites (Dunnington *et al.*, 1959). It becomes increasingly anhydritic towards Syria; cyclic beds of evaporites occur in well *Sufaiya-1* (Kaddouri, 1986).

No detailed palaeontological data for the Butmah Formation is available. Dunnington *et al.* (1959) recorded gastropod debris in bioclastic limestones, macrofossil debris, sponge spicules, fish debris, ostracods and coprolithic pellets (*Favreina* sp.) together with *Glomospira* sp., *Archaediscus*, *Problematina* sp. and small textulariids. An Early Jurassic age was suggested for the formation by Kaddouri (1986).

The lower Butmah Formation was probably deposited during a marine transgression across Iraq. It passes up into restricted, cyclic sediments containing tidal flat and sabkha deposits with a restricted biota.

The **Ubaid Formation** in the Western Desert is 75 to 125 m thick (Dunnington *et al.*, 1959; Jassim *et al.*, 2006a). It is composed of a clastic-carbonate pair (Jassim *et al.*, 2006a) (Fig. 3.17). The basal clastic member is absent in the Rutbah area. It thickens to the east to about 40 m by onlap onto an unconformable basal contact (Buday, 1980; Kaddouri, 1986). It contains narrow channels infilled with ferruginous limestone clast conglomerates in the Wadi Hauran area (Jassim *et al.*, 2006a). The basal part of the overlying clean carbonate unit (*sensu* Buday, 1980; formerly asigned to the upper part of the Zor Hauran Formation of Dunnington *et al.*, 1959), is dominated by oolitic facies (Jassim *et al.*, 2006a). It comprises argillaceous limestones, and *"oolitic and pseudo-oolitic limestones and dolomitised limestones with thin beds of mudstone and yellow/green gypsiferous marl"* (Dunnington *et al.*, 1959). The clean carbonates represent a maximum flooding surface (the MFS Tr80 of Sharland *et al.*, 2001), which is succeeded by shallow-water HST strata which were initially deposited in relatively open-marine conditions and then become more restricted. Ubaid Formation carbonates include locally dolomitic, sandy and marly limestones (Dunnington *et al.*, 1959; Kaddouri, 1986), overlain by crystalline limestones with chert nodules (Jassim *et al.*, 2006a). The uppermost part of the formation is gypsiferous.

Microfauna in the Ubaid Formation are dominated by ostracods and foraminifera including *Involutina* sp. Larger fossils include *?Neomegalodon* sp. and *?Grammatodon* sp. of the genus *Protodiceras* (Kaddouri, 1986) and *?Mytilus* sp., *?Modiolus* sp. and *?Cardita* sp. (Jassim *et al.*, 2006a). *Spiriferina muensteri* and *S. walcotti* (Jassim *et al.*, 1984) occur in the formation and are dated as Sinemurian – late Pliensbachian (Hassan, 1986; Kaddouri, 1986). The upper contact of the Ubaid Formation with the Hussainiyat Formation is a ferruginous surface (Jassim *et al.*, 2006a). It is a highly karstified disconformity with dolines up to tens of metres wide and 50 m deep containing infills of laterite, bauxite and siliciclastic material.

The former presence of evaporites is indicated by abundant dissolution features. Skoceck and Hussein (1980, *in* Jassim and Goff, 2006a) suggested that the Ubaid Formation was deposited in shallow hypersaline conditions with separate shoal, lagoonal, supratidal pond and marsh environments. The presence of brachiopods indicates temporary open-marine environments.

In Iraqi Kurdistan, the **Sarki Formation** is 303 m thick at its type locality (Dunnington *et al.*, 1959). The lower 122 m comprises dolomites or dolomitic limestones with beds of marlstone, often with chert and collapse breccias (Dunnington *et al.*, 1959; Kaddouri, 1986). A thin, massive, dark brown dolomite occurs at the base of the formation (Dunnington *et al.*, 1959; Kaddouri, 1986) (Fig.

5.20). The middle division of the Sarki Formation consists of thin-bedded cherty and dolomitic limestones, cherty shales and sucrosic dolomites, with thin bands of shell-breccia, oolitic limestone and breccia (Dunnington *et al.*, 1959; Kaddouri, 1986). The upper 121-180 m of the formation consists of extensively weathered and cavernous dolomites alternating with cherty dolomite and shales and blocky marlstones (Dunnington *et al.*, 1959; Kaddouri, 1986).

The basal dolomites ("Cyrenia" beds) contain *Eomiodon indicus, Spongiostroma, ?Trocholina* sp. and *?Glomospira* sp. (Dunnington *et al.*, 1959). The upper part of the formation contains *Archaediscus, Problematina*, fish debris and algae (Jassim *et al.*, 2006a). The contact of the formation with the overlying Sehkaniyan Formation is sharp and conformable (Dunnington *et al.*, 1959).

Jassim *et al.* (2006a) noted that the transition from the evaporitic Butmah Formation into the less evaporitic Sarki Formation occurs over a palaeohigh (their "Taq Taq-Dohuk" palaeohigh), which may have promoted restriction in the basin to the SW. The high may be controlled by a lineament in the Chemchemal area, also identified from Cretaceous data by Haddad and Ameen (2007).

The massive dolomites at the base of the Butmah Formation are probably equivalent to the Sefidar Member of the Dashtak Formation in Iran (Szabo and Kheradpir, 1978). This represents the MFS and early highstand to Tr80. Overlying "D Evaporites"represent the subsequent early lowstand (from data in Szabo and Kheradipir, 1978). Low-GR carbonates in the Mulussa "D" interval in the Euphrates Graben and the "Muss Formation" in Palmyra (Jamal *et al.*, 2000) are also probably equivalent to the basal clean carbonates of the Butmah Formation of Iraq. Neither the Syrian or Iraqi successions are well dated. In Jordan, rare thin clean carbonates occur at the top of the Abu Ruweis Formation (Andrews *et al.*, 1992a) (Fig. 5.3). These may also be equivalent to the basal Butmah Formation.

A major erosional surface was identified in the Euphrates Graben where the Mulussa "F" clastics unconformably overlie older Mulussa units (Jamal *et al.*, 2000). In the Levant, the ?Pliensbachian Asher Volcanics rest on older strata with an angular unconformity, and locally overstep rocks of Carnian age (Dvorkin and Kohn, 1989). Uplift associated with this basal unconformity may be due to doming resulting from volcanism. The associated erosion may be the source of the siliciclastics present above this sequence boundary in eastern Syria and Iraq.

Petroleum System Components

Reservoir rocks

There are no proven reservoir rocks in this interval. Clean carbonates at the base of the Butmah Formation may locally have reservoir potential. Basal sandstones in the Ubaid Formation at outcrop in the Western Desert may act as reservoirs, by analogy with the Mulussa 'F' reservoir units in Syria. Roychoudhury and Nahar (1980) suggested that the Butmah Formation clastics may form good reservoirs over tectonic highs in southern Iraq. Significant reservoirs associated with karst and collapse breccias may also be present beneath the upper boundary of the unit.

Source rocks

Possible upper Carnian–Rhaetian source rocks were reviewed as part of the previous section. Younger (Hettangian–Sinemurian) source rocks have not yet been identified in Iraq or neighbouring countries. Argillaceous sediments associated with thick evaporites in the Butmah Formation may have source potential, by analogy with the "Kurrachine" Formation of Syria (Abboud *et al.*, 2005). Roychoudhury and Nahar (1980) reported the presence of oils in bituminous shales of the Butmah Formation in well *Samawa-1*.

Seals

The massive evaporites in the upper part of the Kurra Chine Formation and the associated shales and argillaceous limestone seal the Triassic reservoirs. However, de Ruiter *et al.* (1995) downgraded the Lower Mulussa plays in the Euphrates Graben area because of perceived problems with intraformational seals. The thickness of evaporite units decreases away from depocentres (Jamal *et al.*, 2000), while the proportion of coarse siliciclastic sediments increases towards palaeohighs. These factors may also reduce the effectiveness of Triassic -Lower Jurassic seals over palaeohighs in Iraq. Minor seals may also occur within the shales and anhydrites overlying the basal dolomite unit of the Butmah Formation.

The Lower Jurassic (Pliensbachian – lower Toarcian) Sequence

The upper part of the **Butmah Formation** is typically about 240 m thick in the subsurface of Iraq (Dunnington *et al.*, 1959). Regional correlation with the better-dated stratigraphy in the eastern Mediterranean suggests that it is Pliensbachian – early Toarcian. At outcrop in the Western Desert, rocks of this age are assigned to the **Hussainiyat Formation** which is up to 120 m thick and consists of lower (siliciclastic) and upper (carbonate) members (Al-Mubarek *et al.*, 1981; Jassim, 1981b; Jassim *et al.*, 2006a) (Fig.3.17). Correlative outcrops in Iraqi Kurdistan are represented by the lower division of the **Sehkaniyan Formation** (Fig. 5.20), which is 85 m thick at Surdash (Dunnington *et al.*, 1959).

The upper part of the Butmah Formation begins with a siliciclastic-dominated unit that is 51 m thick

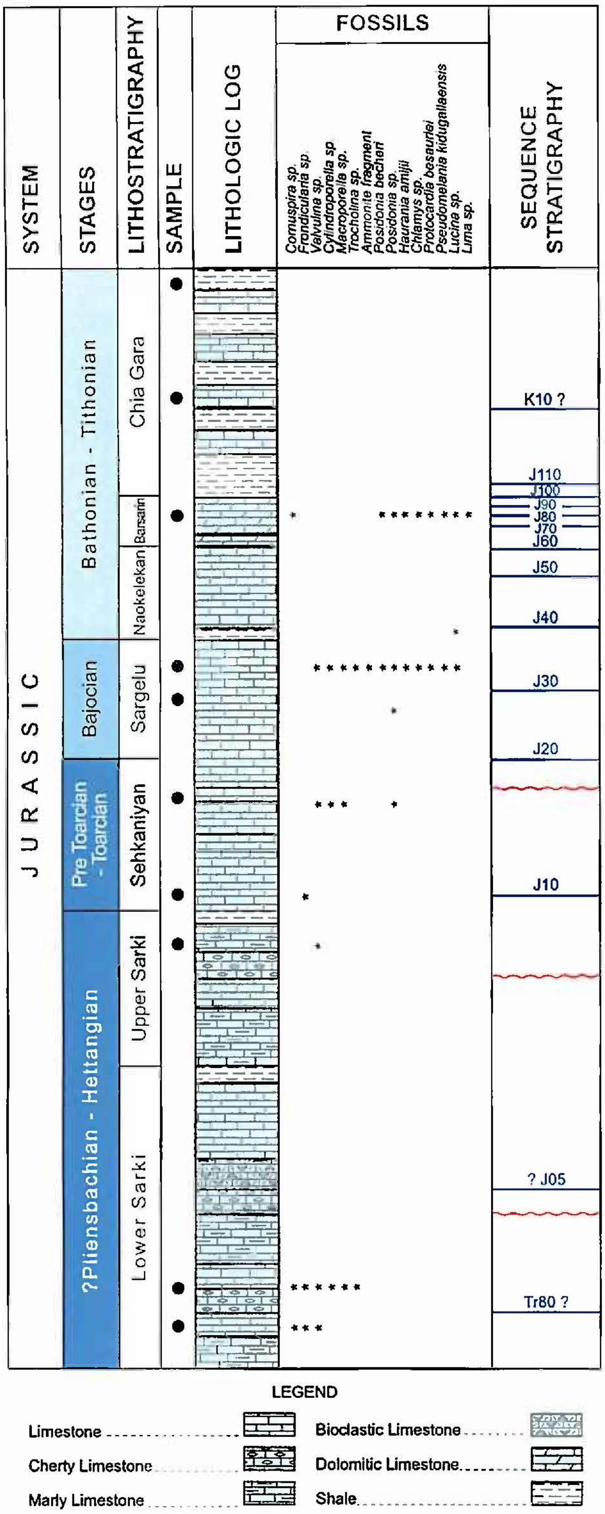


Fig. 5.20. Log of the Lower Jurassic to Neocomian succession in the Benavi area, northern Iraqi Kurdistan. The logged column represents 200 m of stratigraphy. After Kaddouri, 1986.

at the type section in well *Butmah-2* (Dunnington *et al.*, 1959). This interval is well-developed in the *Mileh Tharthar-1* well (Dunnington *et al.*, 1959) where it is known informally as the "Mileh Tharthar clastics" (Jassim *et al.*, 2006a). It occurs as far south as *Samawa-1* (Roychoudhury and Nahar, 1980); age-equivalent clastics are present in Kuwait (*Burgan* field; Al-Naqib, 1967). To the NW, siliciclastics including reddish marls, siltstones, purple shales and marls with haematitic sandstones are recorded in wells *Alan-1, Mileh Tharthar-1, Makhul-2, Qalian-1, Butmah-2, Sufaiya-1, Ibrahim-1* and *Butmah-15* (Dunnington *et al.*, 1959; Buday, 1980; Roychoudhury and Nahar, 1980; Kaddouri, 1986).

The uppermost part of the Butmah Formation, 185 m thick at its type section (Dunnington *et al.*, 1959), comprises calcareous mudstones, dolomitised argillaceous lime mudstones, pelletal wackestones, thin peloidal-oolitic packstones and bedded and nodular anhydrites. Thin beds of cherty mudstones and cherty dolomites occur throughout. It passes gradationally into the overlying Adaiyah Formation.

The upper part of the Butmah Formation probably represents stacked tidal flat to supratidal/ sabkha deposits, alternating with higher-energy oolite and peloid shoals, whose abundance depend on cycle stacking patterns. Clastics in the Butmah Formation may have been derived from the Hail-Rutbah Arch to the west / SW (Roychoudhury and Nahar, 1980).

The uppermost Butmah Formation which contains black to green dolomites overlain by heterolithic facies is probably equivalent to the Neyriz Formation in Iran (Szabo and Kheradpir, 1978).

At outcrop in Iraqi Kurdistan, the lower part of the **Lower Member of the Sehkaniyan Formation** (Fig. 5.20) is a 60 m thick, brown massive dolomite, with saccharoidal dolomites and dolomitic limestone towards the top (Dunnington *et al.*, 1959; Kaddouri, 1986; Hassan, 1986). It contains indeterminate gastropod and lamellibranch debris (Dunnington *et al.*, 1959). This unit represents a restricted carbonate platform facies, although this was probably more subtidal and less cyclic than the facies in the Butmah Formation towards the SW.

In the Western Desert, the lower (siliciclastic) Member of the **Hussainiyat Formation** is 54 m thick in Wadi Hauran; it is absent in the Rutbah area (Fig. 3.17). This unit is the most extensive siliciclastic unit of Early Jurassic age in western Iraq. It contains stacked fluvial channel sandstones, channel lag deposits with ironstone pebbles, silicified tree trunks, plant stems, prints of leaves and ferruginous mudstones (Jassim *et al.*, 2006a). The upper (carbonate) member of the Hussainiyat Formation comprises dolomitised limestones with relict pellets, intraclasts and bioclasts.

Fossils in the Hussainiyat Formation carbonates include five gastropod species and eleven bivalve species together with ostracods, valvulinid, textulariid and nodosarid foraminifera, and occasional "algal structures" (Jassim *et al.*, 2006a) that may be microbialites. These are tentatively dated as Toarcian–Bajocian (Hassan, 1986; Kaddouri, 1986). The presence of *Cyas* sp. indicates tropical climatic conditions (Jassim *et al.*, 2006a). The siliciclastic basal member of the Amij Formation rests disconformably on the Hussainiyat Formation (Kaddouri, 1986; Jassim *et al.*, 2006a).

Close to the onlap margin in the SW, the basal clastic member of the Hussainiyat Formation was deposited in a flood-plain environment. To the NE, it is interpreted to have been deposited in a deltaic environment (Kaddouri, 1986). The carbonate member of the formation was probably deposited in a lagoonal environment, although the upper part appears supratidal.

Siliciclastic facies also occur at the base of the Lower Jurassic sequence in well *Anah-2* (Jassim *et al.*, 2006a) and can be correlated with the Mulussa "F" Formation of the Euphrates Graben, Syria (Jamal *et al.*, 2000). Siliciclastic input may have been related to uplift of Palaeozoic rocks, probably associated with rifting in NW Syria (Delaune-Mayere, 1984) and basaltic volcanism in the Levant (Dvorkin and Kohn, 1989). A transgression following the deposition of these basal siliciclastic units has been identified in the eastern Mediterranean, where the well-dated Nirim Formation (Pliensbachian) overlies the ?Pliensbachian Asher Volcanics (Dvorkin and Kohn, 1989).

Petroleum System Components

Reservoir rocks

Sandstone-rich intervals in the upper part of the Butmah Formation may locally have reservoir potential in southern Iraq (Roychoudhury and Nahar, 1980). Fluvial and coastal sandstones in the basal Hussainiyat Formation are potential exploration targets in the Western and SW Deserts. Correlative Mulussa "F" fluvial siliciclastics are a secondary pay in the Euphrates Graben with a net:gross ratio of 25% and porosities of up to 20% (de Ruiter *et al.*, 1995). Similar sandstones may occur in extensions of the graben system in western Iraq.

Carbonates within the uppermost Butmah, Hussainiyat and lower Sehkaniyan Formations may have reservoir potential, particularly when oolitic and/or dolomitised. Reservoir potential may also be associated with collapse breccias in the upper parts of these formations.

Source rocks

No source rocks have yet been identified in this sequence in Iraq or neighbouring countries. Argillaceous sediments associated with evaporites in the Butmah Formation may have source potential by analogy with the Kurra Chine Formation. Oil has been recorded in bituminous shales in the Butmah Formation in well *Samawa-1* (Roychoudhury and Nahar, 1980).

Seals

Evaporite and shale seals occur within the upper part of the Butmah Formation.

The Middle Jurassic (middle Toarcian – lower Aalenian) sequence

This sequence consists of the **Adaiyah** and **Mus Formations** in the subsurface (130-150 m thick; Dunnington *et al.*, 1959; Jassim *et al.*, 2006a), the upper part of the lower and the middle division of the **Sehkaniyan Formation** (Fig. 5.20) at outcrops in Iraqi Kurdistan (120 m thick; Dunnington *et al.*, 1959), and the **Amij Formation** in the Western Desert, which is up to 80 m thick (Kaddouri, 1986) (Fig. 3.17).

The **Adaiyah Formation** consists at its type section in well *Adaiyah-1* of 90 m of bedded and nodular anhydrites with limestones and shales (Dunnington *et al.*, 1959). Halite occurs at well *Makhul-2* (Jassim *et al.*, 2006a). The formation contains *Nodosaria* sp, *Glomospira* sp., lituolids, ostracods, small-shelled gastropod debris and echinoid elements (Dunnington *et al.*, 1959). The formation is interpreted to be of late Early Jurassic age based on regional considerations (Dunnington *et al.*, 1959).

The Adaiyah Formation probably represents sabkha-salina deposition in an arid environment (Dunnington *et al.*, 1959; Kaddouri, 1986), possibly within a shallow intrashelf basin. The contact at the top of the formation is generally conformable and sharp. It is overlain by the Mus Formation.

The upper 25 m of the **Lower Division of the Sehkaniyan Formation** includes breccias, probably formed by the dissolution of evaporites (Dunnington *et al.*, 1959; Kaddouri, 1986).

The **Mus Formation** is on average 40 m thick but reaches 56 m in its type section at well *Butmah-2* (Dunnington *et al.*, 1959). It is dominated by dolomitic peloidal limestones with marly limestones, shales and rare anhydrites. It is early Toarcian – Aalenian (Dunnington *et al.*, 1959).

The formation has a distinctive microfacies and a limited foraminiferal fauna, and contains abundant algal-encrusted grains (oncolites). The fauna also includes gastropods (locally abundant), bivalve debris (uncommon) and ostracods, together with textulariids, *Glomospira* sp, nodosarids and *Ammodiscus* sp. (Dunnington *et al.*, 1959). Roychoudhury and Nahar (1980) noted that the Mus Formation contains oolites and sandstones in southern Iraq.

The upper contact of the Mus Formation with the overlying Alan Formation is generally sharp. However, locally the Sargelu directly overlies the Mus Formation (Dunnington *et al.*, 1959). In the *Mileh Tharthar-1* well, the Mus is dolomitised and is unconformably overlain by sandy conglomerates of the basal Alan Formation containing clasts of

Mus Formation limestone (Dunnington *et al.*, 1959). This indicates that an important sequence boundary ocurs at the base of the Alan Formation (see page 139).

The Mus Formation is interpreted as a subtidal low- to moderate energy shelf deposit. Moderate hydraulic energies are indicated by the presence of oncolites (c.f. Flügel, 2004).

Towards the High Folded Zone of NE Iraqi Kurdistan (e.g. in Sulaimaniya Province), the Mus Formation is replaced by the **Middle Division of the Sehkaniyan Formation** (Fig. 5.20). The Middle Division at its type locality consists of 44 m of highly fossiliferous, organic and peloidal limestones, locally dolomitised, with silicified fossils and some chert (Dunnington *et al.*, 1959; Kaddouri, 1986). Bed thicknesses increase from 20 cm at the base to 1 m at the top (Dunnington *et al.*, 1959; Kaddouri, 1986).

Fossils in the Middle Division include *Lithiotis* sp., *Spiriferina* sp. cf. *S. ampla*, *Zeilleria* sp., *Haurania* sp. and *Lituola* sp.; algae include *Boueina hochstetteri* var. *liasica* (Dunnington *et al.*, 1959). *Lithiotis* is locally abundant. This unit is referred to informally as the "Lithiotis Limestone". Bed thicknesses and facies of the Middle Division indicate a shallowing-upwards succession. The facies and biota suggest that it is probably slightly more open marine than the Mus Formation, although it is a similarly low energy shelf carbonate.

In the Western Desert, the **Amij Formation** (= Upper Butmah Formation of Hassan, 1986) is 42–80 m thick (Kaddouri, 1986) (Fig. 3.17). The basal siliciclastic-dominated interval comprises 20-30 m of fine-grained sandstones. Sedimentary structures include cross bedding, herringbone cross-lamination and oscillation ripple marks. Darker laminae contain heavy mineral grains (zircon, ilmenite). Siltstones, red-green mudstones and thin gypsum beds also occur, overlying a red claystone unit (Jassim *et al.*, 2006a). These sediments are interpreted to have been deposited in a shallow-marine environment. The J10 maximum flooding surface of Sharland *et al.* (2001) can be placed within the basal part of the Limestone Unit of the Amij Formation, which comprises white to yellowish, argillaceous dolomites and dolomitic limestones, with laminated to domal microbialites (Jassim *et al.*, 2006a).

A rich assemblage of endemic molluscs in the basal carbonates includes *Grammatodon* sp., *Oxtyoma* sp., *Pinna* sp., *Corulomya* sp., *Tancredia*? sp., *Pleuromya* sp., *Plagiostoma* sp. and *Mytilus* sp. (Jassim *et al.*, 2006a). According to Jassim *et al.* (*ibid.*), the Amij Formation is the basal part of an uppermost Toarcian – Callovian interval. The age of the formation is considered (Jassim *et al.*, 2006a; Hassan, 1986) to be "older than Bajocian". However, a Bajocian age cannot be excluded. The Amij Formation is sharply overlain by the basal sandstones of the Muhaiwir Formation (Jassim *et al.*, 2006a).

The fauna and associated microbialites, recrystallised algae and plant debris indicate a restricted brackish-water depositional environment, which contrasts strongly with the open-marine fauna of the overlying Muhaiwir Formation carbonates (Hassan, 1986). Sharland *et al.* (2001) placed the boundary of Megasequences AP6 and AP7 at the contact of the Amij and Muhaiwir Formations.

Time-equivalent deposits in nearby areas include the Marrat "C" Member in Kuwait, which comprises up to 200 m of peloidal oolitic wackestone to grainstones (Yousif and Nouman, 1997) (Fig. 5.18). The thickness of the Marrat 'C' increases by about 25% compared to off-structure areas. It represents barriers and shoals passing into lower energy subtidal deposits (Yousif and Nouman, 1997). Buday (1980) suggested that the Adaiyah Formation passes laerally into the Marrat Formation in extreme SW Iraq. Yousif and Nouman (1997) proposed that the Adaiyah is equivalent to the evaporitic Marrat "D" and "E" Members in Kuwait (Fig. 5.18).

Petroleum System Components

Reservoir rocks

In the 1980s, deep exploration for Jurassic targets was conducted in the *Rumaila* area. Well *West Qurna-15* produced gas condensate from the Najmah Formation. However, Samarrai (1988, *pers. comm.* to F. S.) suggested that the productive reservoir unit in this well may be equivalent to part of the Lower Jurassic Mus Formation. The equivalent unit in Kuwait, the Marrat "C", is a significant oil reservoir, particularly where dolomitized (Yousif and Nouman, 1997; Singh *et al.*, 2006). The Marrat "C" produces 8000 b/d oil from six wells in the *Humma Marat* field (Kumar *et al.*, 2006); single well production and tests show rates of 2400-5700 b/d oil and 4-18 MM scf/d of gas (Singh *et al.*, 2006), with 70-75% of the production from the lowermost "C" Member at *Humma Marat*. Average porosities are 12- 22% and permeability 1- 10 mD (Meddaugh *et al.*, 2006).

Source rocks

In well *Jebel Kand-1*, Al-Haba (1988 , *in* Al-Sakini, 1992) found that the Mus Formation has a low organic matter content. Oil occurs in bituminous shales in the Mus Formation in well *Samawa-1* (Roychoudhury and Nahar, 1980).

Seals

The massive evaporites in the Adaiyah Formation, and the associated shales and argillaceous limestones, are probably effective seals. However, they are not known to seal any hydrocarbon accumulation in the region.

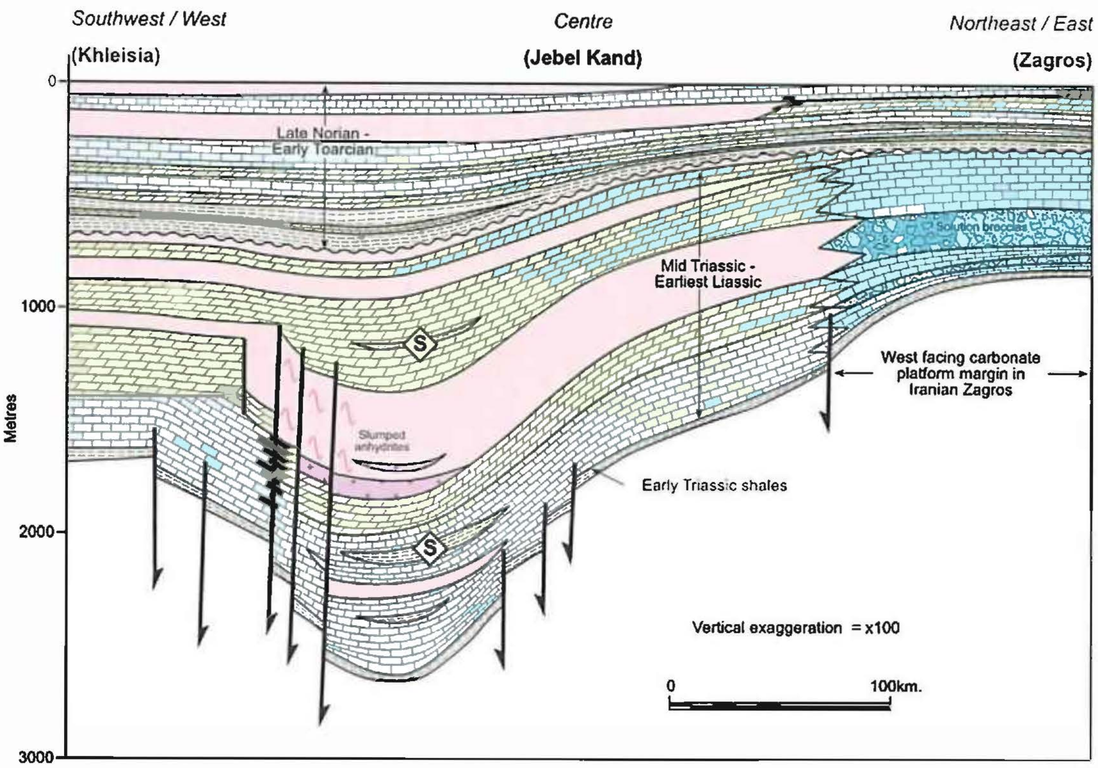


Fig. 5.21. Schematic cross-section through the Triassic succession in northern Iraq and the Iranian Zagros. Modified after Goff *et al.*, 2004c.

The Mus Formation has been suggested as a seal in southern Iraq (Roychoudhury and Nahar, 1980).

Concluding Remarks

The Middle Permian – Middle Jurassic Megasequence AP6 in Iraq can be subdivided into nine stratigraphic units bounded by unconformities. This stratigraphy has only been proven by deeper wells in Iraq. A maximum thickness of just over 3 km is present to the east of the Salman Zone.

Megasequence AP6 onlaps westwards onto the Khleisia and Rutbah Highs. Clastic sediments are restricted to updip areas which have Palaeozoic sediment source terranes. The lowest unit, of Middle Permian – Earliest Triassic age, comprises a poorly known basal clastic interval and an overlying carbonate ramp. It overlies a breakup unconformity related to the opening of Neo-Tethys. The distribution of clastic reservoirs in this unit will be better understood through acquisition of high resolution seismic and well data. Reservoir quality rocks have not yet been identified in the Upper Permian carbonates of the Chia Zairi Formation in Iraq. This contrasts with the presence of carbonate reservoirs in the Khuff Formation in the Gulf region to the south. Lower Triassic clastic/carbonate sediments form a gently-dipping ramp.

Middle Triassic – Early Norian sediments were deposited in a series of broad, restricted, evaporitic intrashelf basins probably affected by localised extensional faulting (Fig. 5.21), bounded to the west by a carbonate-evaporite platform. Late Norian – Toarcian sediments were deposited in a more slowly subsiding shallow-water basin and platform. Each basin contains a major evaporite unit in Iraq and the adjacent countries (e.g. the upper anhydrite member of the Kurra Chine Formation). Between the evaporite units are epeiric carbonates that show remarkably little lateral variation in thickness or facies. These basins were probably bounded to the east by poorly-described shallow-water carbonate platforms that faced into Neo-Tethys. They includes a restricted carbonate platform known along strike in Iran (Fig. 5.21), and megalodontid-bearing limestones known only from allochthonous Tethyan units (*see pp. 49-50 for further discussion of the Tethyan margin in Triassic – Early Jurassic time*).

Shelfal areas on palaeohighs are not prospective because they are dominated by low-energy, low-porosity platform interior carbonates. Reservoir, seal and source rocks are absent. Transgressions resulted in the deposition of thin, higher-energy and relatively open-marine porous carbonate beds. These form a reservoir in the *Butmah* field. Relatively restricted depositional conditions occurred during late highstands and continued through the following lowstand. Thin organic-rich carbonates were deposited and have source rock potential. During lowstands, thick evaporites (mostly anhydrite) were deposited. Halite is present in the Salman Zone. Evaporites and argillaceous carbonates form effective seals.

Micropalaeontological analysis of Megasequence AP6 deposits has not been successful in Iraq due to the abundance of dolomite and anhydrite. The detailed stratigraphic characteristics of this interval will probably only be revealed by the application of palynological and possibly conodont-based dating techniques. These techniques have been applied in basins to the west of Iraq.

Effective source rocks in the Middle Permian – Middle Jurassic megasequence in Iraq appear to be confined to thin bituminous Triassic carbonate units deposited in intrashelf basins (Fig. 5.21). These have charged thin, porous carbonate beds in the Triassic petroleum system. Much of the Triassic – basal Middle Jurassic section in Iraq consists of sealing lithologies (fine-grained carbonates, and argillaceous carbonates and evaporites). Reservoir, source and seal rocks of the Triassic petroleum system in Iraq are discussed in more detail in Chapter 9iii (pp. 307-314).

6. MIDDLE TO UPPER JURASSIC

In the Gulf countries to the south of Iraq, the Middle–Upper Jurassic succession (Megasequence AP7 of Sharland *et al.*, 2001) contains one of the world's most important hydrocarbon systems. However in Iraq, despite the presence of rich source rocks, the limited exploration of this megasequence has been unsuccessful. The evaluation in this chapter is based on data from a few well penetrations and from Jurassic outcrops (Fig. 6.1) together with data from adjacent countries, particularly those to the south and east (Kuwait, Saudi Arabia and Iran).

In Iraq, Megasequence AP7 can be divided into three unconformity-bound supersequences (Fig. 6.2). The basal supersequence (upper Aalenian–Bathonian) is composed of the Alan, Sargelu and Muhaiwir Formations. The overlying Callovian – Oxfordian Supersequence is dominated by the lower or main part of the Najmah Formation, and the Naokelakan Formation in Iraqi Kurdistan. Above is a Kimmeridgian–Tithonian Supersequence consisting of the evaporitic Gotnia Formation and the Barsarin Formation limestones and breccias.

Structural setting

Little tectonic activity took place on the NE Arabian Plate between the Norian and the mid-Aalenian. During the late Aalenian, a restricted intrashelf basin (known as the Gotnia Basin: Jaber, 1975) developed and covered most of eastern Iraq (Figs. 3.30, 6.3) (Goff, 2005). Other intrashelf basins developed in the Gulf region to the south. Intervening high areas were covered by shallow-marine carbonates which were frequently oolitic.

Initial basin development was probably related to renewed extension along the NE plate margin (Jassim and Goff, 2006b). Thick volcanic units in the eastern Mediterranean area, emplaced both immediately prior to and during deposition of Megasequence AP7, indicate rifting at this time (Dvorkin and Kohn, 1989; Mouty, 2000).

The margins of the Gotnia Basin are not well known because of subsequent erosion. The margins may approximate to those of an older Triassic intrashelf basin (see Chapter 5). The SW basin margin was aligned roughly parallel with the frontier between Iraq and Saudi Arabia (Fig. 6.3). The western basin margin follows the eastern side of the Rutbah High, probably along the western margin of the Salman Zone. To the north, this margin then changes course and approximately follows the line of the River Euphrates, although its precise location is again obscured by post-Jurassic erosion. The eastern basin margin is not known in northern Iraq since it was overthrust during convergent margin tectonics in the Late Cretaceous. Large areas of the western basin margin around the Khleisia High were uplifted during the Neocomian. Ponikarov *et al.* (1967) indicated that Upper Jurassic sedimentary rocks are also absent in adjacent parts of NE Syria; the nearest age-equivalent rocks occur in the Palmyra area.

It can be inferred that a barrier must have separated the euxinic Iraqi portion of the Gotnia Basin from the open-marine waters of Neo-Tethys, which lay to the NE (Jassim and Goff, 2006b). This is consistent with the presence of silt and plant debris in outcrops of the Bajocian – Bathonian Sargelu Formation in Iraqi Kurdistan, and with shallow-water Middle Jurassic facies now only known from clasts in Paleogene conglomerates (Gerçus Formation: van Bellen, 1959) along the NE margin. This barrier was probably formed by thick Jurassic neritic carbonates on the edge of the Arabian Platform (Fig. 3.29).

Basin evolution

Evolution of the Gotnia Basin during the Middle – Late Jurassic has some similarities with that of age-equivalent basins in Gulf countries to the south. The relatively undifferentiated and possibly epeiric Lower Jurassic shelf (the upper part of Megasequence AP6) evolved into a strongly differentiated intrashelf basin in the Middle Jurassic. The Rutbah-Khleisia High in western Iraq was re-activated in the Middle Jurassic. Its continuation in SE Syria, the Al-Hamad Uplift, similarly underwent uplift in the Kimmeridgian (Caron *et al.*, 2000). Lovelock (1984) suggested that the Palmyra and Sinjar troughs in Syria were uplifted and peneplained from the Late Jurassic until the Aptian-Albian.

At the base of the AP7 Megasequence in Iraq is a major sequence boundary overlain by sandstones of the Muhaiwir Formation and conglomerates at the base of the anhydritic Alan Formation. The Alan Formation passes up gradationally into the Sargelu Formation (Dunnington *et al.*, 1959). In Iraq, an early deeper-water depositional phase in a probable ramp setting (Muhaiwir/Sargelu Formations) was followed by aggradation of high energy shelf-margin shoal carbonates (Najmah Formation) (Fig. 6.4).

SW-NE and NW-SE oriented lineaments may have controlled the limits of carbonate platforms at this time. The SE limit of the Najmah Limestone Formation in the Mosul-Najmah area of northern Iraq (c.f. Dunnington, 1958) is marked by the central strand of the Hadhr-Bekhme lineament of Jassim and Goff (2006). The NE limit of the age-equivalent platform in southern Iraq (data in Sadooni, 1997) suggests a conjugate orientation.

The presence of constructional highs around the margins of the Gotnia Basins resulted in restriction and periodic isolation of the basin from the open-marine waters of Neo-Tethys (page 51). Shallow-water open-marine carbonates were deposited throughout the mid- to Late Jurassic around the margins of the Gotnia Basin. However, the detailed geometry of these margins and their underlying tectonic control is poorly understood. Platform margin facies are overridden in Iraq by Late Cretaceous and Tertiary thrust sheets. Their presence in Iraq can only be inferred from reworked pebbles of Middle Jurassic oolites which are present in the Eocene Gerçus Formation (van Bellen, 1959). The basin-margin platform is, however, exposed in the High Zagros of Iran as the Surmeh Formation (James and Wynd, 1965; Setudehnia, 1978).

Euxinic marine source rocks and evaporites were deposited in the Gotnia and other intrashelf basins due to continued but subtle subsidence of extensional origin (Goff, 2005). Deposition of these source rocks and evaporites indicates periodic isolation of the basins from the open-marine waters of Neo-Tethys. The local accumulation of up to 500 m of evaporites in 2 Ma in latest Kimmeridgian – early Tithonian time suggests that a brief pulse of tectonic subsidence occurred at this time. Jassim and Goff (2006b) related this event to a further phase of tectonic extension along the Tethyan margin that immediately preceded the onset of the opening of a narrow, slow-spreading ocean ("Southern Neo-Tethys") in the late Tithonian (Fig 3.32). This event may have created significant structures along the margins of (and within) the Gotnia Basin. Faulting and folding along basement lineaments occurred at the same time as late Kimmeridgian evaporite deposition, as demonstrated by seismic data in Kuwait (Carman, 1996).

In southern Iraq and Kuwait (Yousif and Nouman, 1997; Goff, 2005) (Fig.6.5), little or no accommodation appears to have remained by the end-Jurassic, and evaporites largely fill (by onlap) the topography developed during the previous aggradational phase of rimmed platform development. In northern and central Iraq (Fig. 6.4), a thick anhydrite wedge (Gotnia Formation) developed and onlapped against the former platform margin (c.f. wells *Jebel Kand-1* and *Tikrit-1:* Jassim and Buday, 2006d). This wedge passes into condensed basin-centre deposits (Barsarin Formation), recorded for example in well *Taq Taq-2* (Kaddouri, 1986) and at outcrop (Dunnington *et al.*, 1959; Kaddouri, *ibid.*).

The reasons for north-south variation in the proportions, thicknesses and types of evaporites deposited in the Gotnia Basin are not fully understood, but may relate to the elevation of the northern part of the basin and the consequent southerly tilt of the basin floor during the Late Jurassic. Differential uplift is also demonstrated by the absence, due to erosion, of Middle–Upper Jurassic shelfal sediments in NW Iraq, Syria and SE Turkey (c.f. Caron and Mouty, 2007), where hundreds of metres of section may have been removed before Cretaceous onlap.

Stratigraphy

Many authors (e.g. Ditmar *et al.*, 1971 *in* Jassim and Buday, 2006d; Jaber, 1975; Roychoudhury and Handoo, 1980; Roychoudhury and Nahar, 1980) have recognized a basic three-fold geographical division of the Middle–Upper Jurassic succession in Iraq (Figs 6.2, 6.4):

(i) a western "clastic-carbonate inner shelf" succession, with thin Muhaiwir and Najmah Formations;

(ii) a central platform / platform-margin succession, comprising Alan Formation overlain by thick Sargelu and thick Najmah Formations, overlain but only in southern Iraq by thin Gotnia Formation; and

(iii) an eastern basin-centre succession characterised by either Alan Formation then thin Sargelu/basinal Najmah/thick Gotnia and/or Barsarin Formations; or in the Kurdistan region, by the uppermost Sehkaniyan Formation overlian by thin (condensed) Sargelu, Naokelekan and Barsarin Formations.

These stratigraphic successions (partly represented in Fig. 6.4) reflect the structural configuration of the Gotnia Basin. The relative thicknesses of the formations show the progression of the basin infill and changes in basin geometry.

Biostratigraphy

The biostratigraphy of the Jurassic section in Iraq is poorly calibrated. Palaeontological studies have

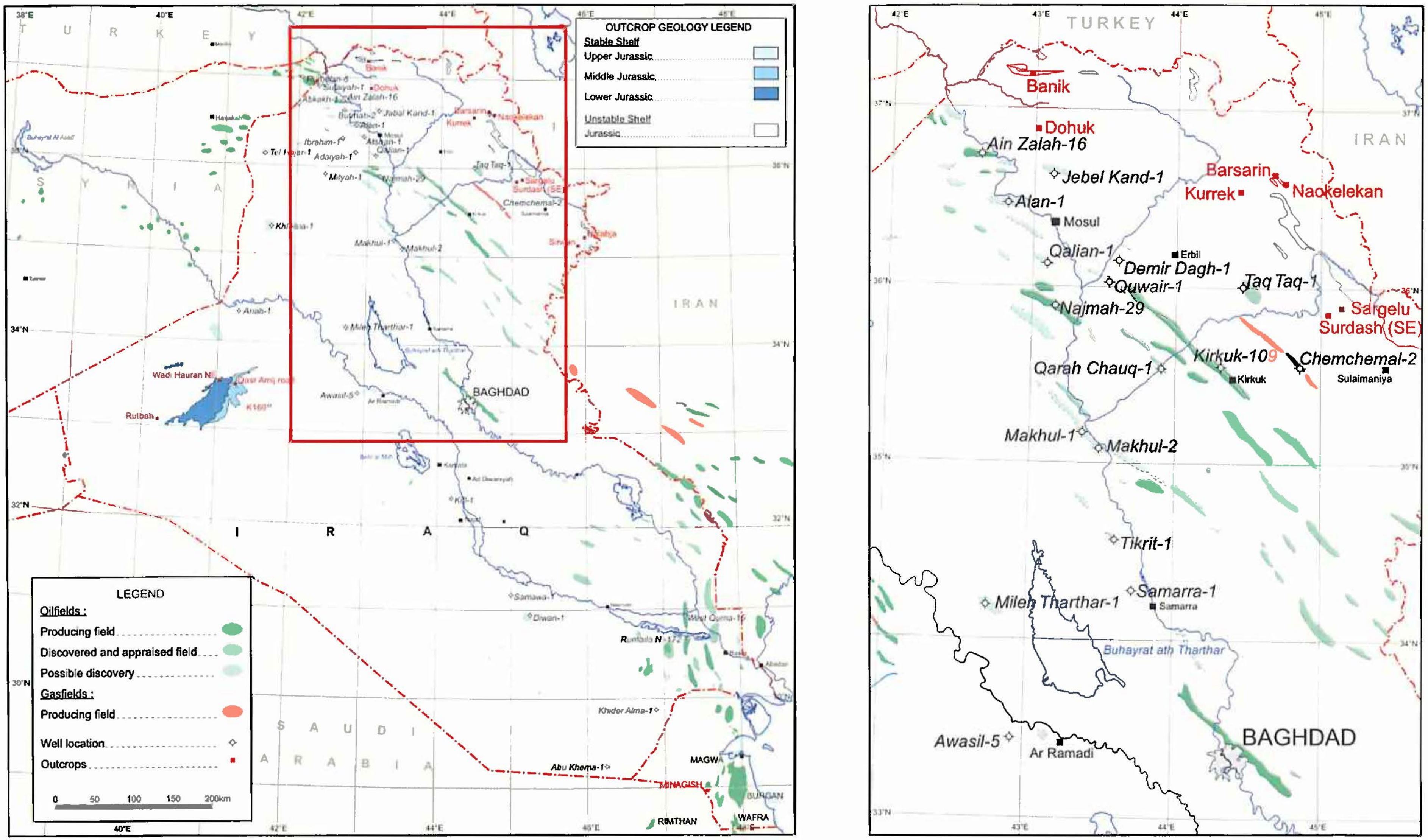


Fig. 6.1. Map of Iraq and adjacent areas, showing key wells (labelled in black), fields and other localities mentioned in this chapter, together with areas where Jurassic rocks are exposed at the surface. Important outcrop areas are labelled in red.

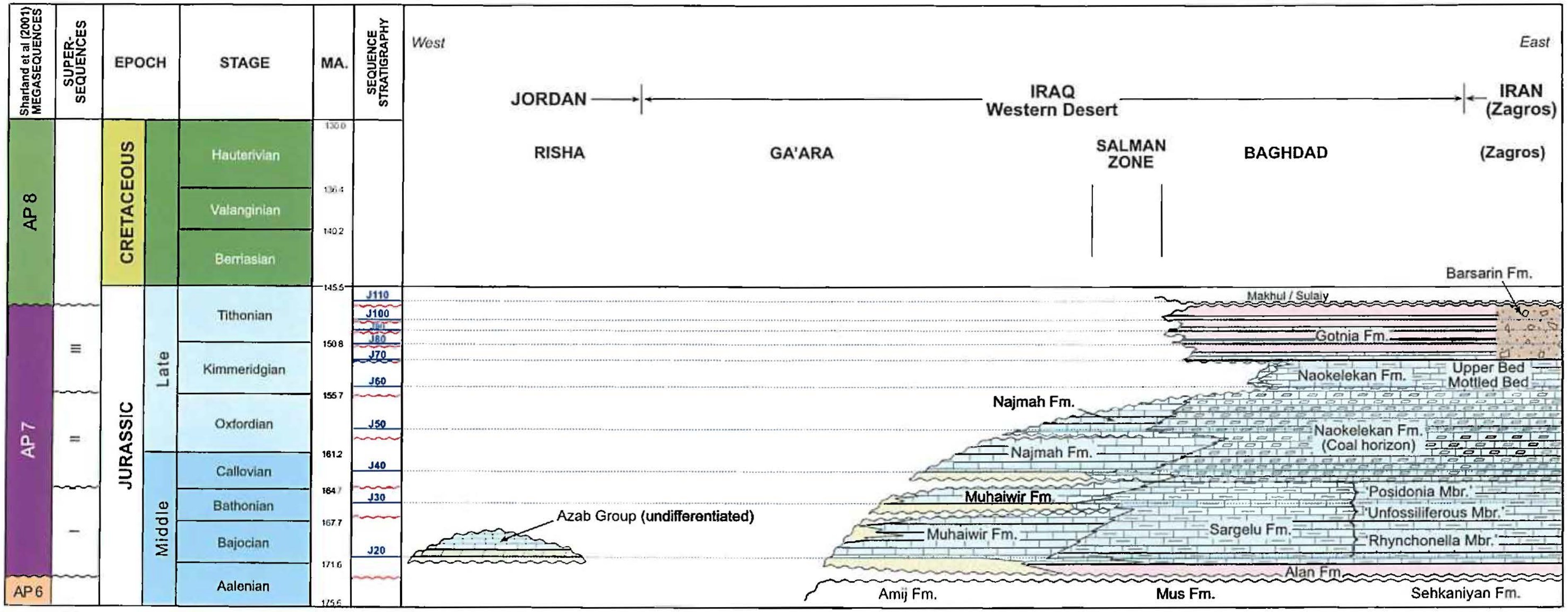


Fig. 6.2. Chronostratigraphy of the Middle-Late Jurassic in Iraq. The line of section runs from Jordan and the Western Desert through Central Iraq and Baghdad, towards the Iranian Zagros.

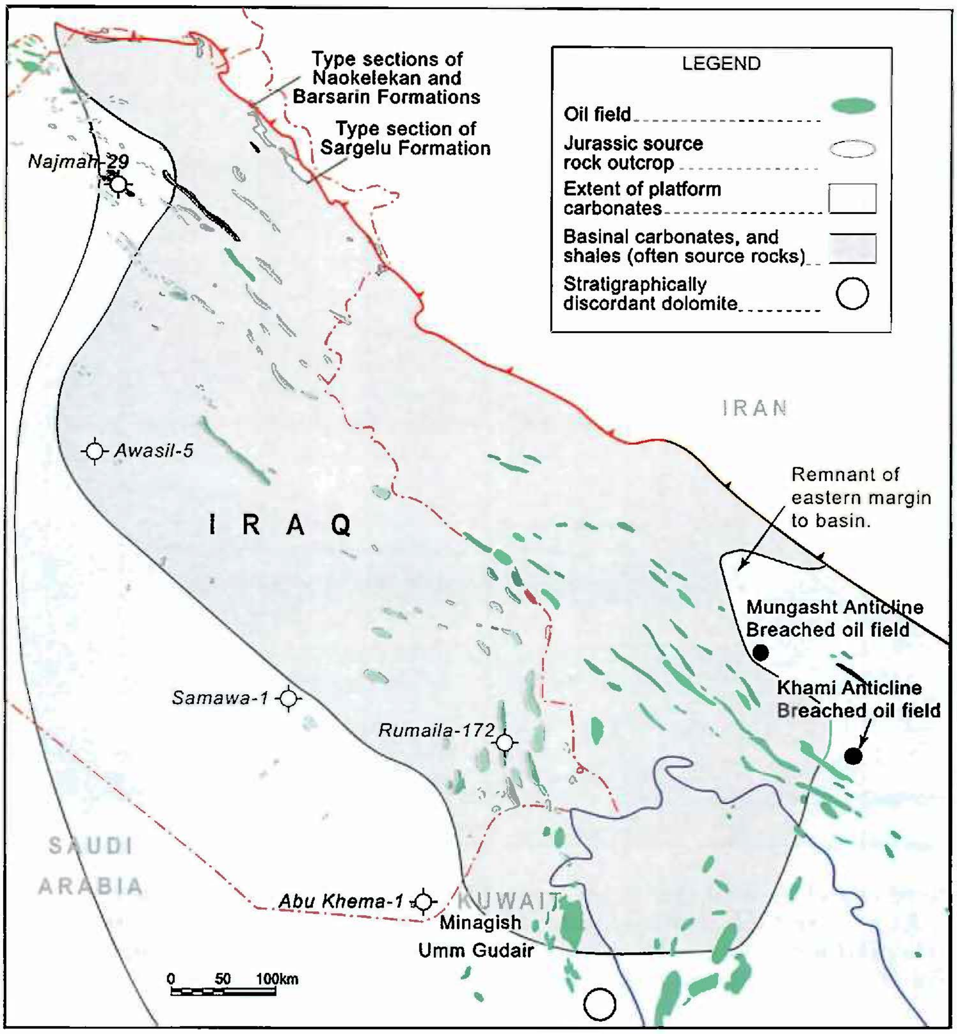


Fig. 6.3. Location map showing the extent of the deeper-water parts of the Gotnia Basin. Adapted from Goff, 2005.

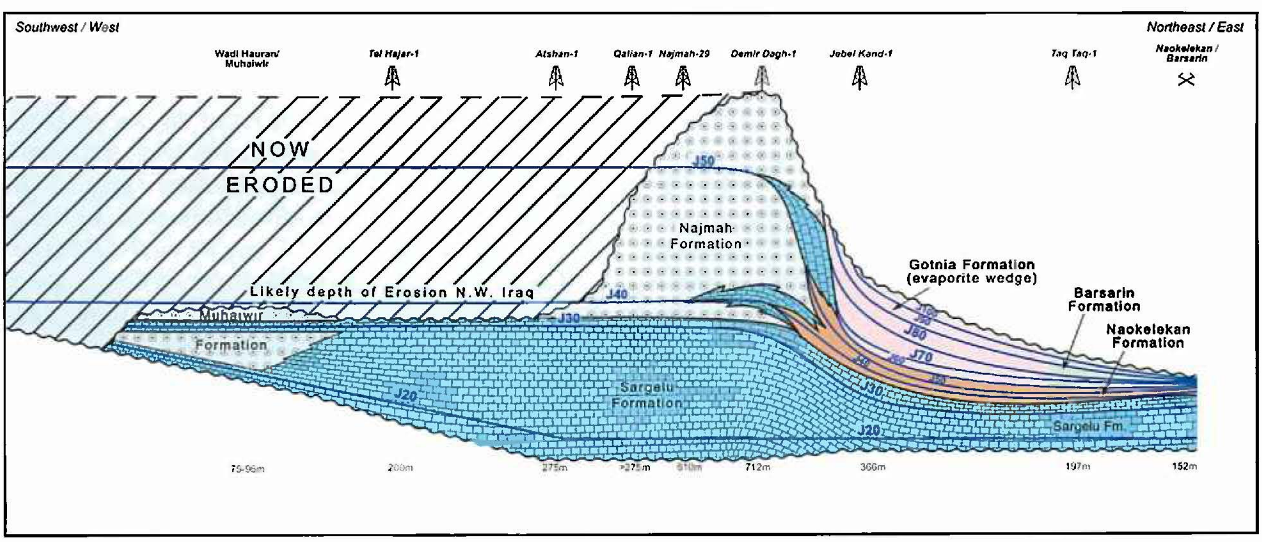


Fig. 6.4. Generalized depositional profile across the western margin of the Gotnia Basin in central and northern Iraq showing maximum flooding surfaces, formations and facies. The extent of erosion on the AP7/8 boundary in the west is shown, as is the progressive but incomplete lateral infill of the basin by (a) ramp carbonates, (b) rimmed shelf carbonates, (c) an evaporite wedge, and (d) condensed basin centre facies. The section runs from the Syrian frontier in western Iraq to the Iranian border. Data after Dunnington *et al.* (1959), Kaddouri (1986) and Jassim and Buday (2006d). Note that an equivalent system was present on the eastern (Zagros) margin of the basin.

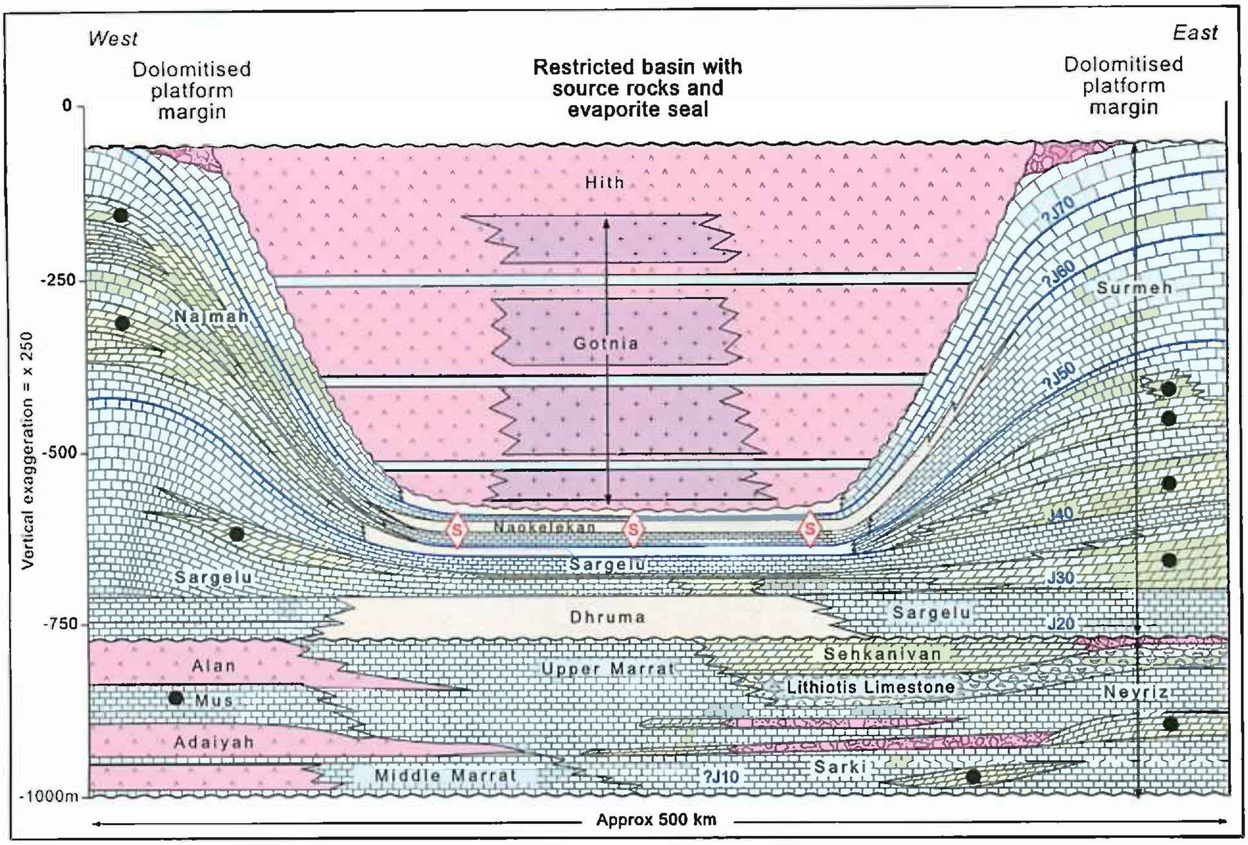


Fig. 6.5. Idealised model for basin fill in the Gotnia Basin incorporating stratigraphic information from NW Iraq, Kuwait and the Mungasht area of SW Iran. It shows the evolution of the Lower Jurassic epeiric platform into a ramp- and then rimmed-shelf-bounded basin, with subsequent onlap and infill of accommodation by evaporites. Modified after Goff, 2005.

focused on macrofossils and generic-level identification of microfossils (e.g. Dunnington *et al.*, 1959; Hassan, 1986), although more recent work has included improved calibration and speciation (e.g. Iraqi data in Whittaker *et al.*, 1998). Recent studies of well-calibrated nearby areas in Saudi Arabia (Hughes, 2004) and the Levant (Mouty, 2000) are based on species-level micropalaeontological identification, although Hughes *(ibid.)* noted that *"the stratigraphic ranges of Middle East Jurassic benthic foraminiferal species are relatively poorly known"*. In addition, Hughes *(ibid.)* proposed that there was strong water-depth (i.e. facies) control on microfossil distribution. The first and last occurrences of many microfossils may therefore be controlled by sequence stratigraphy and basinal location rather than evolutionary processes.

Given these difficulties, interpretations of the ages of Jurassic units in Iraq are often tentative. Chronostratigraphic divisions are relatively arbitrary because key stratigraphic contacts and shelfal successions in Iraq are poorly dated. However, the durations of each supersequence may be calibrated against better-understood areas to the south including Saudi Arabia (both at outcrop: Enay and Mangold, 1994; and in the subsurface: Hughes, 2004), Qatar (Droste, 1990), and Abu Dhabi (de Matos and Hulstrand, 1995; Azer and Peebles, 1998).

Stratigraphic organization

The contacts between Megasequence AP7 in Iraq and the over- and underlying successions are well defined. At the base, the conglomeratic base of the Alan Formation rests disconformably on regionally-extensive Lower Jurassic carbonate facies of the Mus Formation (Dunnington *et al.*, 1959). At the top, the succession is bounded by an angular unconformity of great magnitude (Fig. 6.2), with progressive onlap of mid-Tithonian units in the basin centre and Aptian/Albian onlap on the basin margins in the extreme NW (e.g. in well *Tel Hajar-1*; Kaddouri and Al-Shaibani, 1993). Both Neocomian and Jurassic stratigraphy may have been modified or even entirely removed by erosion in the Late Cretaceous and Cenozoic.

The Sargelu-Najmah contact, described as unconformable by Dunnington *et al.* (1959), can be correlated with an unconformity which cuts out the upper Bathonian – lower Callovian in the UAE and Oman (de Matos, 1997). The relationship between the Najmah and Gotnia Formations has always proved controversial. Many authors (e.g. Jaber, 1975) have proposed that these formations are lateral facies equivalents. However, the onset of evaporitic lowstand deposition within intrashelf basins in Arabia (i.e. at the beginning of Arab-Gotnia deposition) followed an Oxfordian –

Kimmeridgian boundary lowstand which is well-dated elsewhere, for example in the intrashelf basins of Abu Dhabi (de Matos and Hulstrand, 1995).

Sharland *et al.* (2001) identified nine maximum flooding surfaces (MFSs J20 to J100 inclusive) in Megasequence AP7, which can be divided between the three supersequences as follows (Figs. 6.2, 6.4):

(i) the J20 and J30 MFSs are in the upper Aalenian – Bathonian Supersequence;

(ii) MFSs J40 (mid-Callovian) and J50 (mid-Oxfordian) are in the Callovian–Oxfordian Supersequence;

(iii) five MFSs are in the terminal supersequence – J60 (lower Kimmeridgian), together with J70, J80, J90 and J100.

Accommodation (of several hundred metres) was created early in basin development as indicated by deposition of the deep-water, euxinic *Bositra* shales of the Sargelu Formation during the Bajocian, immediately above sabkha / salina anhydrites of the Alan Formation. The Sargelu Formation also thins and becomes more condensed into the basin centre (Fig. 6.4, 6.5). The basin subequently shallowed. Shallow-water units overlie deeper-water units due to downstepping during forced regressions (Fig. 6.4). Remnant accommodation space was inherited in the late Tithonian and Neocomian in NE Iraq and Lurestan in Iran.

Early-formed accommodation space is also recorded in the Eastern Mediterranean area. There, 1250 m of Aalenian to lower Callovian platform carbonates are overlain by a condensed Oxfordian – Kimmeridigan stratigraphic succession only 250 m thick (Mouty and Zaninetti, 1998; Mouty, 2000).

The upper Aalenian – Bathonian Supersequence

This supersequence (Figs 6.4, 6.5) is represented by the Alan and Sargelu Formations throughout most of Iraq, by the Muhaiwir Formation in the west and by the Upper Division of the Sehkaniyan Formation in Iraqi Kurdistan. The basal beds of the Sargelu Formation (containing *Bositra, Gryphaea* and *Rhynchonella*) have been dated as latest Toarcian – early Bajocian (Dunnington *et al.* 1959). An abundant ammonite fauna including *?Thamboceras* sp. (late Bajocian) and *Micromphalites* sp. (Bathonian) was recorded by Jassim and Buday (2006d). Sharland *et al.* (2001) located the well-dated J20 maximum flooding surface (lower Bajocian) associated with shales bearing the ammonite *Shirbuirnia fastigata* of the *Witchellia laeviuscula* Zone of the Bajocian, near the base of the lowest unit of the Dhruma Formation in Central Saudi Arabia (c.f. Enay and Mangold, 1994). Sharland *et al. (ibid.)* suggested that this flooding surface correlates with the base of the Sargelu Formation in both Iraq and Kuwait. The Dhruma and Sargelu Formations represent deposition of deeper-water, open-marine to euxinic carbonates on top of shallow-water and restricted platform carbonates. In the Levant, equivalent thick open-marine carbonates (Jandal, Ouyoun and "unit B" of the Dodo Formation, Syria) are of Aalenian age based on the presence of *Timidonella sarda* (Mouty and Zaninetti, 1998; Mouty, 2000). The AP6/AP7 Megasequence boundary may thus be located within the Aalenian.

At the end of the Bathonian, a regional unconformity formed with widespread erosion. Dunnington *et al.* (1959) recorded an unconformable contact between the Sargelu Formation and the overlying Najmah Formation. This contact is probably the same unconformity at which lower Callovian and upper Bathonian strata have been eroded from the Musandam Group in Oman (de Matos, 1994,1997). Further palaeontological studies of the Sargelu Formation will be required to calibrate its lower and upper contacts more precisely, particularly in the subsurface.

Alan Formation

The **Alan Anhydrite Formation** is 59 m thick at its type locality at well *Alan-1* (Dunnington *et al.*, 1959), and represents the lowest part of the supersequence in the subsurface. The formation comprises 60 to 200 m of bedded anhydrites, locally with peloidal and pseudo-oolitic limestones (Dunnington *et al.*, 1959; Kaddouri, 1986). In the *Ain Zalah* field, an uppermost Lower Jurassic unit with evaporites is described as brecciated and conglomeratic with polymict clasts (Daniel, 1954). The basal Alan Formation is also conglomeratic, containing clasts of the underlying Mus Formation limestones in *Mileh Tharthar-1* (Dunnington *et al.*, 1959).

No fossils have been reported from the Alan Formation (Dunnington *et al.*, 1959). A latest Early Jurassic age was suggested by Dunnington *et al.* (1959). The contact with the overlying Sargelu Formation was taken as the AP6 / AP7 Megasequence boundary in Iraq by Sharland *et al.* (2001). However this contact is redefined here at the base of the basal conglomerates, i.e. the Alan —Mus contact. The Alan Formation thus represents early restricted infill of the Gotnia Basin.

The Alan Formation probably represents deposition of dominantly subaqueous evaporites in a shallow, arid intrashelf basin. The stratigraphic relationships of the formation suggests that it is part of a transgressive systems tract, comparable to the uppermost parts of the upper evaporites of the Kurra Chine and Baluti Formations (c.f. Fig. 5.13).

In Kuwait, the Alan Formation is represented by the slightly evaporitic argillaceous carbonates of the Marrat "A" and "B" Members (Yousif and Nouman, 1997) (Fig. 5.18).

Upper Division of the Sehkaniyan Formation

The Upper Division at its type locality at Sehkaniyan near Sargelu (location: Fig. 6.1) comprises 51 m of dark, foetid saccharoidal dolomite and dolomitic limestone, locally with chert (Dunnington *et al.*, 1959). It may be a collapse breccia after dissolution of evaporites similar to those seen in the Alan Formation. The original conditions of deposition were thererfore probably similar to those of the Alan Formation.

Muhaiwir Formation

The Muhaiwir Formation is the oldest Middle Jurassic formation in the Western Desert of Iraq (Fig. 3.17). Dunnington *et al.* (1959) defined the Muhaiwir Formation at an incomplete section and recognised three units. The upper unit in Wadi Hauran (location: Fig. 6.1) comprises 14 m of limestones and marly limestones with brachiopods, gastropods, bivalves and echinoids. The middle unit comprises 12 m of interbedded sandstones, marly limestones and oolitic limestones with corals; this overlies 9 m of marls and micritic limestones with chert nodules at the base. The lower unit is exposed along the road cutting between Muhaiwir and Qasr Amij. It comprises 4 m of sandy oolitic limestones and sandstones, overlying 9 m of argillaceous, sandy oolitic limestones with corals, sponge debris and brachiopods capped by a micritic limestone with chert nodules. Allowing for a few metres of overlap between the two sections, the total exposed thickness of the Muhaiwir Formation in Dunnington *et al.'s* original description is about 45 m.

Radosevic and Lesevic (1980) assigned all the Jurassic sedimentary rocks (70–250 m thick) penetrated in boreholes drilled by the Geological Survey in the Western Desert to the Muhaiwir Formation. Hassan (1986) noted that the Muhaiwir Formation at outcrop near the 160 km marker on the Rutbah – Baghdad highway (K 160: Fig. 6.1) is only 38 m thick, although this may partly be due to erosion. The formation was redefined by Jassim and Buday (2006d), who reported it to be 75–141 m thick and to comprise two units, each with a basal siliciclastic member and an upper carbonate member. Jassim and Buday's (2006d) data suggest that both the basal and upper carbonate members identified at Wadi Hauran contain flooding surfaces, separated by a middle clastic member that defines the regressive and transgressive systems tract beneath the J30 MFS. This definition is followed here.

The lower unit comprises quartz arenites and sandy limestones overlain by coral-bearing limestones, marls, and cherty limestones with beds of siltstone and fine-grained sandstone. The upper unit comprises conglomerates and pebbly sandstones and dolomitic cherty limestones with corals overlain by beds of marly limestones and sandstones.

The Muhaiwir Formation contains a diverse (cosmopolitan) macrofauna of 56 bivalve and eight gastropod species with similarities to both Mediterranean and Indo-African faunal provinces; of these, a total of 32 species are also found outside Iraq (Hassan, 1986). Species known from Europe and from continental Iran and Turkey are typically absent, suggesting the development of a faunal sub-province which includes Western Iraq, Arabia, East Africa, India and Madagascar (Hassan, 1986). In addition to bivalves and gastropods, the ammonite *Bullatimorphites* sp. (identification by H.S. Torrens *in* Hassan, 1986) is present suggesting a Bathonian–Callovian age, although it is not known from which part of the formation this ammonite was recovered.

The microfauna of the formation is characterised by *Haurania deserta, Amijiella (Haurania) amijii* and *Pfenderina* sp. (Jassim and Buday, 2006d). The fauna has been interpreted as Bathonian (Dunnington *et al.*, 1959). However, the association of *Haurania deserta* and *Amijiella amijii* elsewhere in the region (e.g. on Mount Hermon: Mouty and Zaninetti, 1998) is now considered to indicate the late Bajocian to early Bathonian. Therefore, the Muhaiwir Formation at its type section is likely to be correlative with the sequence containing the J20 MFS of Sharland *et al.* (2001) rather than with that containing the younger J30 MFS (as originally suggested by Sharland *et al., ibid.*). Sediments attributable to the sequence containing the J30 MFS probably consist of the upper clastic-carbonate pair as described by Jassim and Buday (2006d) with a microfauna of *Amijiella (Haurania) amijii, Nautiloculina* sp., *Trocholina elongata, T. alpinus, Trocholina* sp., miliolids and textulariids.

A change occurs from the underlying, endemic but restricted molluscan fauna of the Amij Formation (= "Upper Butmah Formation" of Hassan, 1986), in which only 30% of species are known outside Iraq, up into the more diverse and cosmopolitan Muhaiwir facies. This confirms that a significant maximum flooding surface is located at the base of Muhaiwir Formation. Hassan (1986) described this as a "rapid transgression in the southern Tethyan region". This interpretation is consistent with the proposed J20 (early Bajocian) MFS marking the base of the AP7 Megasequence.

The Muhaiwir Formation is overstepped from east to west by the Najmah Formation, Saggar Formation and Rutbah Sandstone Formation (at the type locality) (Fig. 3.17) (Dunnington *et al.*, 1959; Jassim and Buday, 2006d).

Unpublished reports by Ctyroky and Karim (1981) and by Al-Mubarek (1983), cited in Jassim *et al.* (1984), Kaddouri (1986) and Jassim and Buday (2006d), recorded the "Najmah Formation" at outcrop at the NE end of Wadi Hauran in the Western Desert, with a fauna of *Nautiloculina oolithica, Pfenderina salernitana, Protoglobigerina* sp., *Amijiella (Haurania) amijii,* and *H. deserti.*

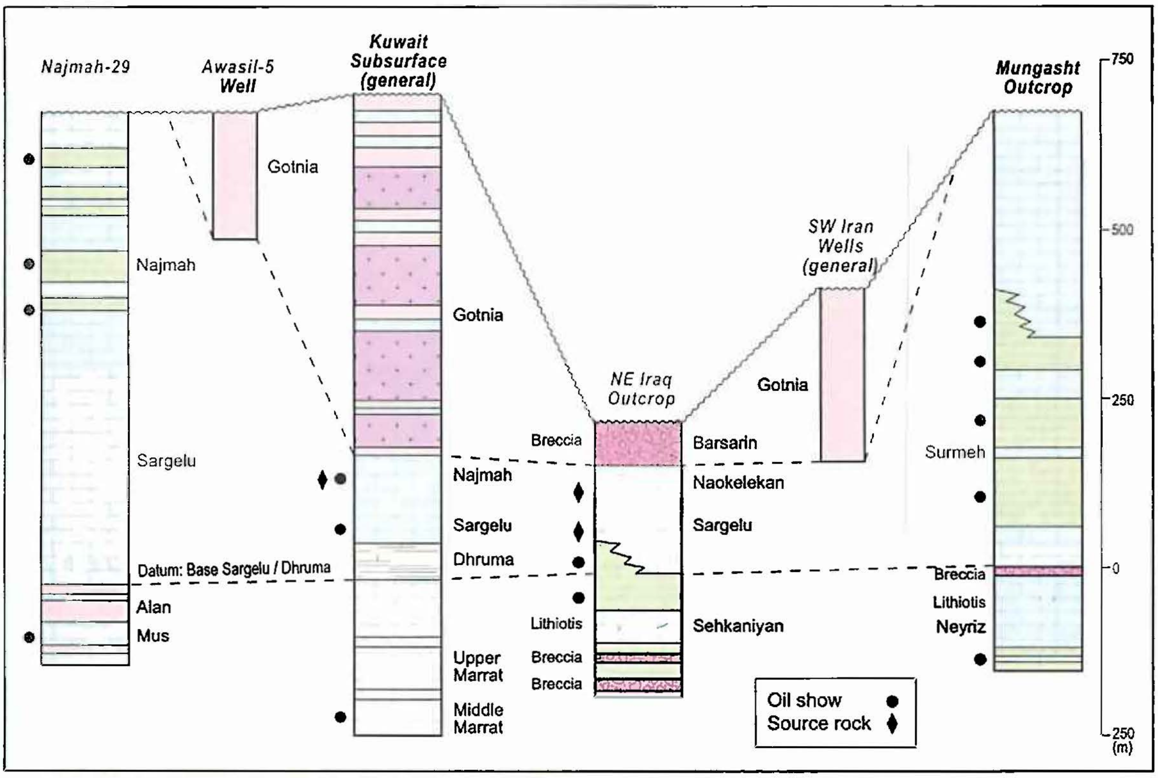


Fig. 6.6. Stratigraphic columns for measured sections in the Gotnia Basin. Data control points are marked on Fig. 6.3. Adapted from Goff, 2005.

As noted above, the *Haurania* species when occurring together are considered to indicate a Bajocian — early Bathonian age (c.f. Mouty and Zaninetti, 1998; Mouty, 2000). *Pfenderina salernitana* is long-ranging through the Saudi Arabian stratigraphy (Hughes, 2004), but in the Levant, it is most abundant in the lower Bathonian (Mouty and Zaninetti, 1998). The microfossils cited by Ctyroky and Karim probably indicate a unit older than the Najmah Formation *sensu stricto*, but of similar facies (Muhaiwir Formation). Kaddouri (1986) suggested that stratigraphic confusion has arisen because of the over-importance that Ctyroky and Karim (*op. cit.*) attached to *Protoglobigerina* sp. as a Late Jurassic marker. The outcrop of "Najmah Formation" is at least 38 m thick. It consists of a basal sandstone overlain by 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 which is argillaceous and sandy in part; and an upper 8 m thick unit of greyish-white to buff recrystallised limestone which has burrows and is partly argillaceous and partly oolitic. The "Najmah Formation" thins to only a few metres near Rutbah (Jassim *et al.*, 1984).

Interpretation

The Muhaiwir Formation is interpreted here as an inner ramp, high energy open-marine deposit. During lowstands, it was karstified with clastic bypass into the deeper Gotnia Basin. During the early part of subsequent transgressions, fluviatile to shallow-marine sandstones were preserved beneath maximum flooding surfaces.

Based upon their interpretation of the Muhaiwir Formation, Radosevic and Lesevic (1980) suggested that the east-facing shallow-water Middle Jurassic carbonate platform margin (i.e. the transition from the Muhaiwir into the Sargelu Formations) trended NW-SE between Anah and Najaf.

During later transgression and early highstand, deposition was carbonate-dominated. The increasing influence of siliciclastics and higher organic contents are probably related to lowstands when there was increased restriction and stratification in the basin. Basinal deposits pass updip into the shoals and coastal clastics of the Muhaiwir Formation. Deposition over active highs in the SW Desert, for example along the Salman Zone, may have resulted in shallower-water conditions (Roychoudhury and Nahar, 1980). The clean-washed and sandy coarse-grained limestones of the Muhaiwir Formation may therefore have been deposited over an extensive area (Roychoudhury and Nahar, 1980).

Sargelu Formation

The Sargelu Formation is the eastern basinal equivalent of the Muhaiwir Formation and occurs throughout most of Iraq (Dunnington *et al.*, 1959; Jassim and Buday, 2006d). At its type locality in the Surdash anticline near Sulaimaniya in NE Iraqi Kurdistan (Fig. 6.1, 6.3), it is about 115 m thick (Dunnington *et al.*, 1959). Balaky (2004) described three relatively condensed sections in the Naokelekan (49 m), Chia Gara (65 m) and Banik (18 m) areas. The formation is thicker in the subsurface; it is reported to be 350 m thick at well *Najmah-29* (Dunnington *et al.*, 1959) (Fig. 6.6). Al-Haba (1988, *in* Al-Sakini, 1992) reported that the Sargelu Formation at well *Jebel Kand-1* is about 150 m thick.

At outcrop, the Sargelu Formation comprises thin-bedded, black bituminous and dolomitic limestones, and black, papery organic-rich shales with chert. The fauna is characterized by *Posidonia* (now *Bositra)* (Dunnington *et al.*, 1959; Jassim and Buday, 2006d), as in age-equivalent units throughout the Arabian Plate and most of the Tethys region (e.g. the Surmeh Formation of Iran: James and Wynd, 1965). Jassim and Buday (2006d) noted that subsurface sections contain more shale beds, with occasional very fine-grained sandstones. The uppermost beds of the Sargelu Formation and the lowermost beds of the Najmah Formation are locally highly silicified (Dunnington *et al.*, 1959).

At outcrop in Iraqi Kurdistan, Balaky (2004) recognised four lithofacies in the Sargelu Formation:

(i) *Dolomite*: massive bedded, with calcite veins and a foetid odour, overlain by thin- to medium-bedded (10 – 20 cm) dolomite with thin laminations of brown shale. The dolomite is saccharoidal and intercrystalline porosity is filled by bitumen.

(ii) *Bositra Limestone*: thin- to medium- bedded, dark grey bituminous limestones rich in *Bositra, Globigerina*, ammonites and ostracods, with thin (1 cm) intervals of black shale without chert. The limestone is calcite veined and contains stylolites.

(iii) *Cherty Limestone*: thin- to medium- bedded (10–40 cm), dark grey bituminous limestones and dolomitic limestones with thin beds of fractured black chert (1–6 cm thick); lenses and nodules of chert and thin-bedded argillaceous limestones and thin- to medium-bedded black shales. The chert beds are rich in *Bositra,* radiolaria and "calcispheres".The limestone beds contain abundant *Bositra* and ammonites. The abundance of *Bositra* and the thickness of the shale beds increase upwards, while the abundance of calcispheres and the thickness of limestone beds decrease upwards.

(iv) *Argillaceous Limestone*: thin- to medium-bedded, brownish-black papery shales, and thin-bedded (10 cm) bituminous dolomitic limestones with thin beds of argillaceous limestone with poorly preserved *Bositra,* ostracods and calcitised radiolaria.

The deeper-marine trace fossils *Zoophycos* and *Nereites* occur in most of these facies.

Microfacies, fossils and deposition

The Sargelu Formation comprises lime mudstones, dolomitised lime mudstones, wackestones with *Bositra,* foraminifera or calcispheres, dolomitised wackestones, and packstones with *Bositra* or radiolaria (Balaky, 2004). Deeper-water bioclasts present include *Saccocoma, Cadosina* and ammonite aptychi, together with abundant ammonite debris (Jassim and Buday, 2006d). Shallower-water indicators locally occur towards the top of the formation including miliolids, *Orbitammina* sp., *Haurania* sp., *Pfenderina* sp. and the alga *Thamuatoporella vesiculifera* (now *parvovesiculifera* (Jassim and Buday, 2006d).

Kaddouri (1986) recorded a fossil assemblage from the Sargelu Formation near Benavi in Iraqi Kurdistan (Fig. 5.20) which includes *Chlamsa* sp., *Protocardia besauriei, Pseudomelania kidugallaensis, Lucina* sp., *Lima* sp., *Trochopsidea* sp., *Ataparu* sp., *Thracia lens, Pictaria* sp. and *Protocardia* sp., considered to be of Bajocian age. In basin centre locations such as tectonic windows in the High Folded Zone of Iraqi Kurdistan, *Bositra buchi* is found in the uppermost part of the Sargelu Formation (Jassim and Buday, 2006d). This species was most abundant during the Bajocian–Bathonian (Jassim and Buday, 2006d). However it also occurs in Saudi Arabia in both the upper part of the Dhruma Formation and the Tuwaiq Mountain Formation of middle-late Callovian to earliest Oxfordian age, and shows a strong facies control, being confined to deeper-water sediments (Hughes, 2004). This suggests that the top of the Sargelu Formation may be younger in Kurdistan than it is in the subsurface when it is succeeded by the "thick" (i.e. platformal) Najmah Formation; supporting ammonite data are not available. In Kuwait, the Sargelu Formation also extends up into the Callovian (Yousif and Nouman, 1997); the uppermost part of the Sargelu Formation in Kuwait corresponds to the basal Najmah Formation of Iraq. Sharland *et al.* (2001) placed the J40 (middle Callovian) maximum flooding surface within the Sargelu Formation in Kuwait (as defined by Yousif and Nouman, 1987), although they acknowledged that the original data is not well calibrated.

The Sargelu Formation in Iraq was probably deposited under stratified, anoxic marine conditions within the euxinic Gotnia Basin (Hallam, 1975; Murris, 1980; Beydoun, 1988b, 1991). The formation is equivalent to the lower and middle parts of the Dhruma Formation of Saudi Arabia (c.f. Enay and Mangold, 1994).

The Callovian – Oxfordian Supersequence

The Callovian–Oxfordian Supersequence is characterised by downstepping of platform deposits into the basin. The basal J40 flooding surface is poorly dated in Iraq, and both the Najmah and Naokelekan Formations in which it occurs are probably of Callovian age at their base (Dunnington *et al.*, 1959). It is best defined by ammonites

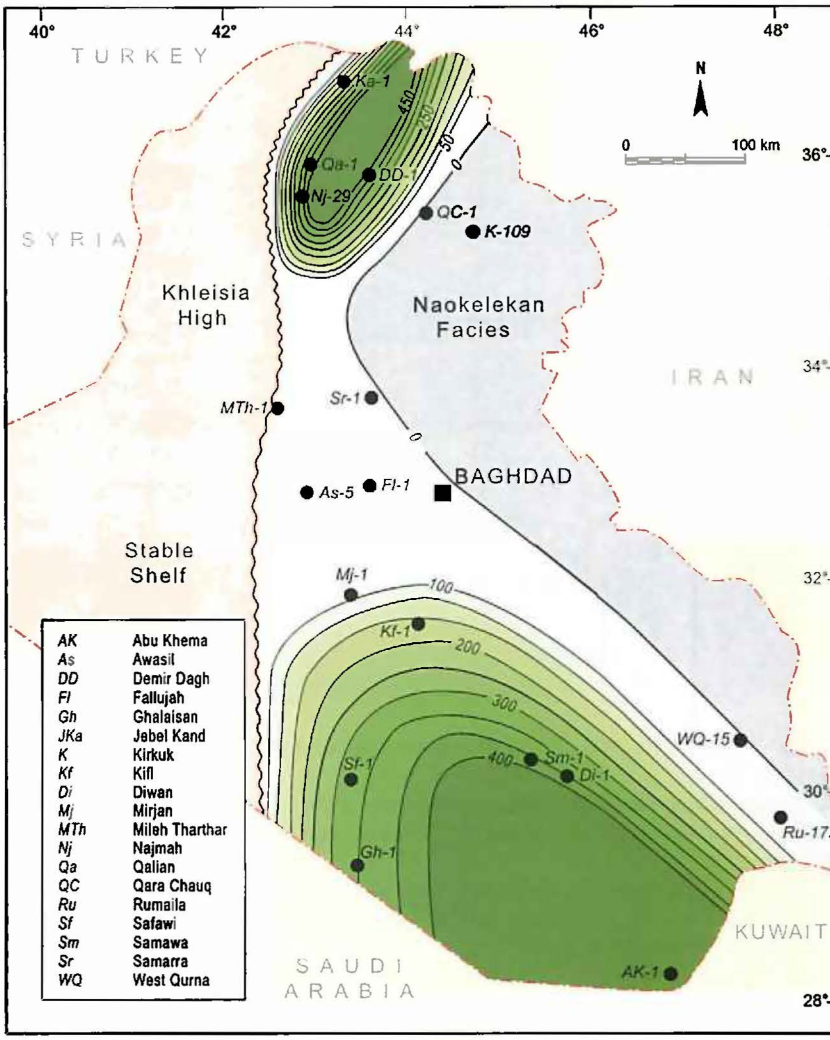


Fig. 6.7. Isopach of the Najmah Formation showing two depocentres – in northern and SW Iraq. Modified after Sadooni (1997), incorporating data from Al-Naqib (1967) and Roychoudhury and Handoo (1980).

(*Erymnoceras coronatum, Grossouvria* cf. *kontkiewiczi* of the *Erymnoceras coronatum* Zone of the Callovian) as in the uppermost Dhruma Formation of Saudi Arabia (Le Nindre *et al.*, 1990; Enay and Mangold, 1994).

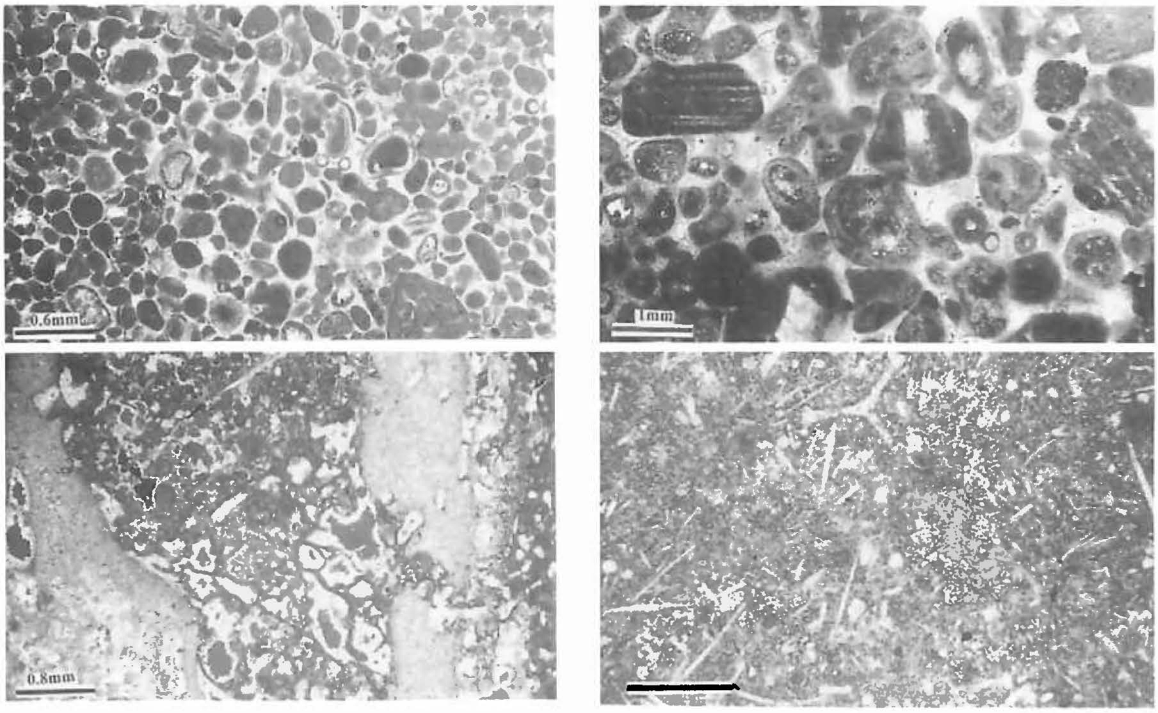
Callovian – Oxfordian transgressions are prominent in western Syria; a very well-constrained ammonite fauna documents the onlap of the Majdal Chams Formation marls onto the Hermon Limestone (Mouty, 2000). At a larger scale, Callovian – Oxfordian transgressions were the most widespread Jurassic transgressive events and extended from Europe to East Africa (Cox, 1935). They introduced for the first time significant European faunas into the Mediterranean area and beyond (Hallam, 1969; Ager, 1981).

Oxfordian deposition was terminated by a major regression. The top of the Najmah Formation in northern Iraq is dated as Oxfordian or younger by poor palaeontological control, but regional considerations suggest that the formation does not extend into the Kimmeridgian. The Callovian – Oxfordian platform margins of the Arabian intrashelf basins to the south were folllowed by a major lowstand system. The early Kimmeridgian transgression (J60 MFS of Sharland *et al.*, 2001) onlapped the slopes of the Oxfordian platforms but did not cover the former platform tops (c.f.Fig.6.4). Therefore many of the platforms show a major stratigraphic break at the Oxfordian–Kimmeridgian boundary, e.g. in Saudi Arabia (Enay and Mangold, 1994) and in the subsurface of Abu Dhabi (de Matos and Hulstrand, 1995).

Najmah Formation

The Najmah Formation in Iraq (Fig. 6.7) is of "Late Jurassic age" (Dunnington *et al.*, 1959). *Kurnubia (Valvulina) jurassica* is reported to be abundant in the upper part of the Najmah Formation at well *Najmah-29*, associated with a fauna of *Trocholina, Nautiloculina* and *Pfenderina*. Corals, algae, sponges and "*Paleotrix*" (= *Bositra)* are present towards the base of the formation (Dunnington *et al.*, 1959). This faunal assemblage is insufficiently detailed to be dated more accurately. However in the Eastern Mediterranean, *Pfenderina* species associated with "*Valvulina*" *(Kurnubia) jurassica* occur in the Middle Jurassic (Bathonian – lower Callovian) (Mouty, 1997a,b; Mouty and Zaninetti, 1998; Mouty, 2000).

The Najmah Formation is 341 m thick at its type section in well *Najmah-29* (Fig. 6.7) The thickest section known (443 m) occurs in well *Demir Dagh-1* in Iraqi Kurdistan (Sadooni, 1997).



Plates 6.1-6.4. Najmah Formation microfacies (photomicrographs by F. Sadooni):

Plate 6.1 (above left). Oolitic packstone grainstone microfacies, consisting mostly of spherulites with peloids and micritized bioclasts, typical of shoals and platform-margin barriers. Well *Samawa-1*, 2695 m.
Plate 6.2 (above right). Pelletal (faecal pellet) grainstone; this is a slightly lower-energy microfacies than the oolitic grainstone in Plate 6.1 and indicates a restricted platform interior environment. Well *Samawa-1*, 2689 m.
Plate 6.3 (below, left). Algal boundstone dominated by coralline and red algae with dissolution porosity. Similar facies form reservoirs in the US Gulf Coast (Jurassic Cotton Valley Formation). Well *Kifl-1*, 3119 m.
Plate 6.4 (below right). Sponge spicule wackestone-packstone, a deeper-water shelf facies. Well *Najmah-29*, 1532 m.

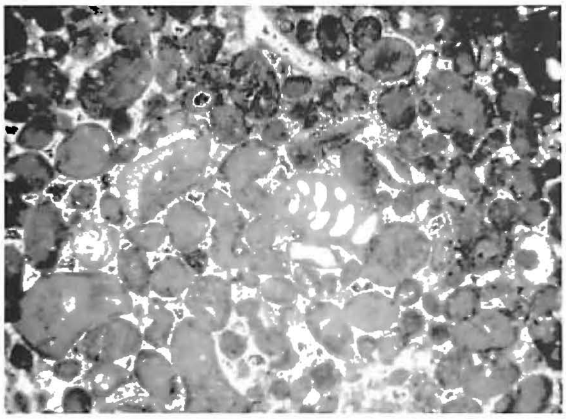
To the west in well *Qalian-1*, its thickness is reduced to about 275 m by the loss of the uppermost part (about 70 m) beneath the base-Cretaceous unconformity (Dunnington *et al.*, 1959) (Fig. 6.4). The formation generally thins to the west due to erosion. Local erosional remnants of the Najmah Formation are reported to crop out in the Western Desert (Sadooni, 1997; Jassim and Buday, 2006d).

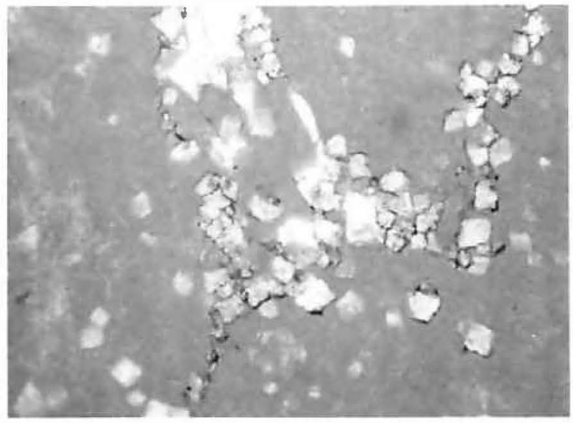
Sedimentology

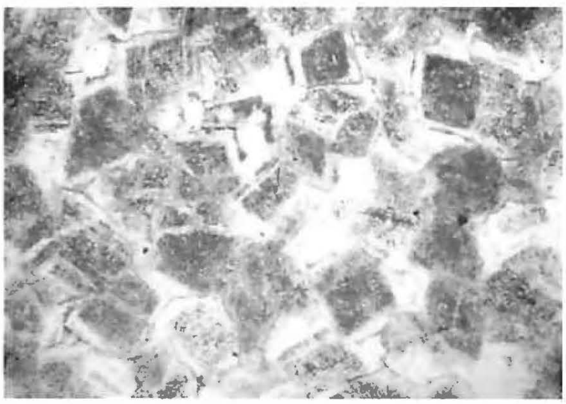
Sadooni (1997) recognised the following lithofacies in the Najmah Formation: oolitic packstones and grainstones (Plate 6.1); pelletal packstones and grainstones (Plate 6.2); algal boundstones (Plate 6.3); foraminiferal wackestones and packstones; sponge or sponge-spicule bearing wackestone-packstones, locally with "calcispheres" (Plate 6.4); and bioturbated lime mudstones.

In well *Samawa-1*, the Najmah Formation comprises porous detrital limestones passing up into alternating oolitic, peloidal and aphanitic limestones with upwards increasing proportions of anhydrite; a thick anhydrite bed occurs in its upper part (Roychoudhury and Nahar, 1980; Roychoudhury and Handoo, 1980). Platform-basin transitions typically comprise fine detrital limestones interbedded with dark coloured, basinal limestones, with an upward increase in anhydrite (Jaber, 1975). Interbedded limestones and anhydrites occur in well *Samawa-1* (Bhasin, 1982).

Ibrahim (1981a) recorded *Clypeina jurassica, Trocholina palastiniensis* and *Kurnubia (Valvulina) jurassica* in the upper parts of the Najmah Formation in wells *Kifl-1* ("basinal Najmah": *see below*) and *Samawa-1* ("platformal Najmah"). The presence of *Clypeina jurassica* indicates a Kimmeridgian–Tithonian age (Bassoulet *et al.*, 1978), while *Trocholina palastiniensis* occurs in the late Kimmeridgian Jubaila Formation in Saudi Arabia (Hughes, 2004). These observations suggest an assemblage in central and southern Iraq which is younger than that of the type section (which is no younger than Oxfordian) given by Dunnington *et al.* (1959). Other conflicting but older dates given for the Najmah Formation were cited by Jassim and Buday (2006d), who noted the co-occurrence of *Amijiella (Haurania) amijii* (Sinemurian—Bajocian) and *Pfenderina salernitana* (Bathonian—Tithonian) from un-named localities. This suggests that the platformal Najmah Formation (*sensu*







Plates 6.5-6.7. Najmah Formation microfacies *(cont.)*. (Photomicrographs by F. Sadooni):
Plate 6.5 (above left). Peloidal grainstone with mouldic and dissolution porosity and isopachous cements; these are marine early diagenetic fabrics. Well *Samawa-1*, 2706 m.
Plate 6.6 (above). Selective dolomitisation, with fine (150-200 μm) crystals along a stylolite. Well *Najmah-29*, 1664 m.
Plate 6.7 (left). Extensive dolomitisation – coarse (500μm) crystals with cloudy centres; note the good intercrystalline porosity. Well *Najmah-29*, 2695 m.

stricto) may locally have been mis-identified. More palaeontological studies are required if the chronostratigraphic control in Iraq is to be as good as that in Saudi Arabia, Qatar and Abu Dhabi (c.f. Wilson, 1985; Droste, 1990; Enay and Mangold, 1994; Al-Silwadi *et al.*, 1996; Hughes, 2004).

In southern Iraq, the Najmah Formation is 485 m thick in well *Khider Alma-1* (Jassim and Buday, 2006d) and comprises dolomitised chalky to pelletal anhydritic limestones (Kadhim and Nasir, 1971). The upper contact of the Najmah Formation with the Gotnia Formation in Central and Southern Iraq has been described as both "conformable" (Dunnington *et al.*, 1959) and strongly diachronous (Roychoudhury and Nahar, 1980).

Interpretation

The Najmah Formation facies described by Sadooni (1997) permit a simple depositional model to be constructed (Fig. 6.8). Deeper-water shelf deposits which represent 3rd and 4th order flooding surfaces comprise sponge-spicule and "calcisphere"-bearing facies. Algal and sponge boundstones are interpreted as initial shallow-water deposits, while foraminiferal-algal packstones and wackestones are interpreted as low energy subtidal deposits. The shallowest-water facies consist of oolitic pack-grainstones (high energy shoals), pelletal packstones and grainstones (back-barrier washover in a restricted lagoon), and lime mudstones (restricted low-energy subtidal to intertidal deposits). Roychoudhury and Nahar (1980) and Sadooni (1997) studied the distribution and origin of oolite shoals which occur throughout the Najmah Formation. They suggested that the shoals were "basement-controlled" and were associated with the basin margin. In this respect, it is likely that the "Rayn anticlines" (Al-Husseini, 2000), which control structures such as that at *Ghawar* in Saudi Arabia, also control facies patterns in Iraq. Perhaps the most significant of these palaeohighs in Iraq is the Salman Zone (see page 36).

Variations in thickness of the Callovian–Oxfordian Supersequence (Dunnington *et al.*, 1959; Sadooni, 1997) demonstrate that the Najmah Formation was deposited along the western margin of a basin. Basin-centre deposits are represented by the thinner Naokelekan Formation in the Zagros region of Iraqi Kurdistan.

Diagenesis

Najmah Formation grainstones are strongly cemented by isopachous marine phreatic cements (Plate 6.5), followed by meniscus cements formed in the meteoric vadose zone. Blocky cements with large calcite crystals probably formed in the freshwater phreatic zone (Sadooni, 1997). Porosity was destroyed by this early diagenesis.

On the western carbonate platform margin of the Gotnia Basin, wells penetrating the Jurassic section (*Najmah-29, Samawa-1* and *Abu Khema-1*) indicate that significant dolomitisation of the Najmah Formation has occurred (Sadooni, 1997) (Plate 6.6). In the type section at *Najmah-29*, petrographic studies indicate that about 100 m of dolomites are present (Sadooni, 1997). At *Samawa-*

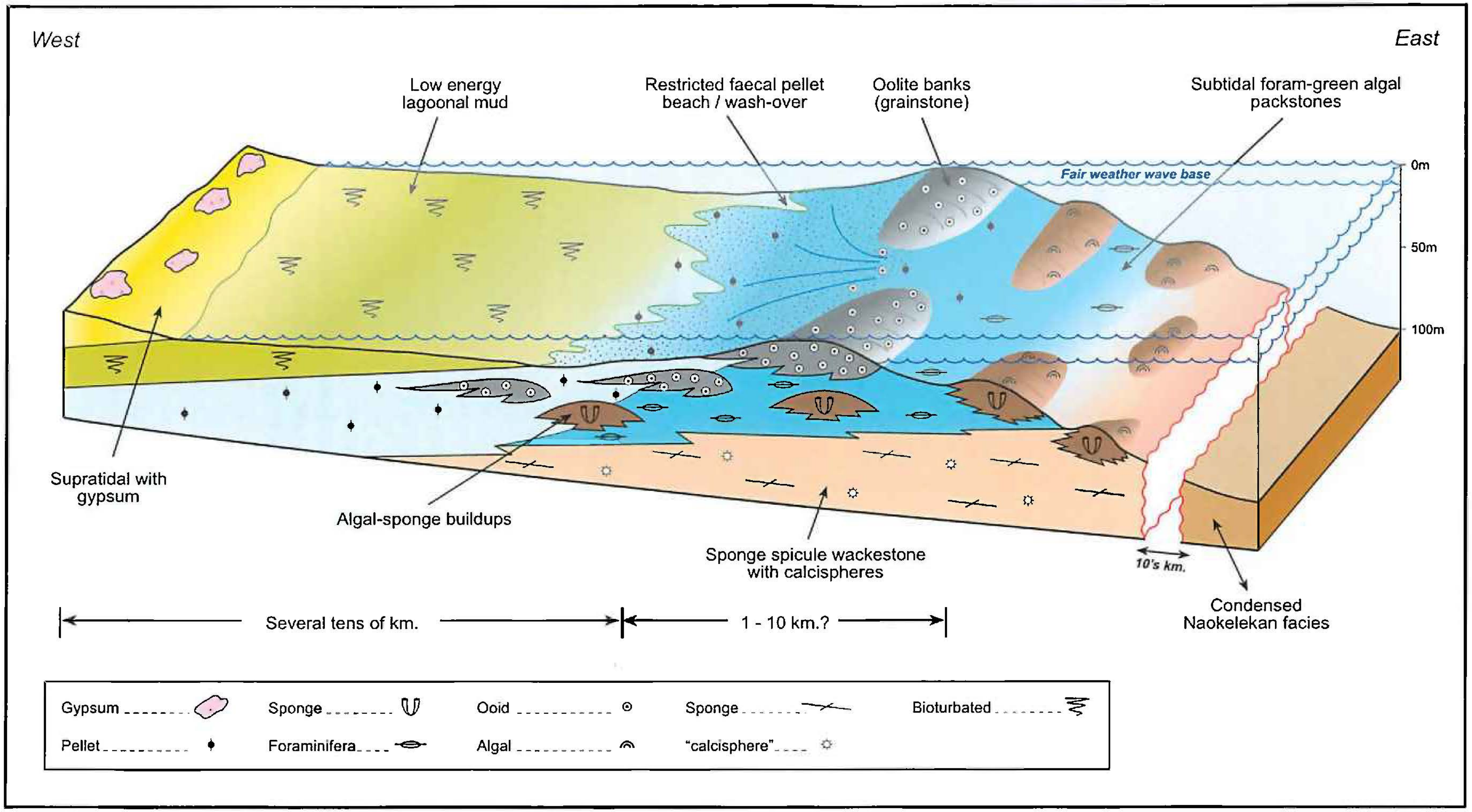


Fig. 6.8. Generalized depositional model for the western margin of the Gotnia Basin during the Oxfordian. Updip Najmah Formation carbonate ramp to high energy rimmed shelf facies pass into euxinic basin centre facies. Updip facies represent potential reservoir rocks; downdip facies are potential source rocks and seals. An equivalent system was present on the eastern (Zagros) margin of the basin.

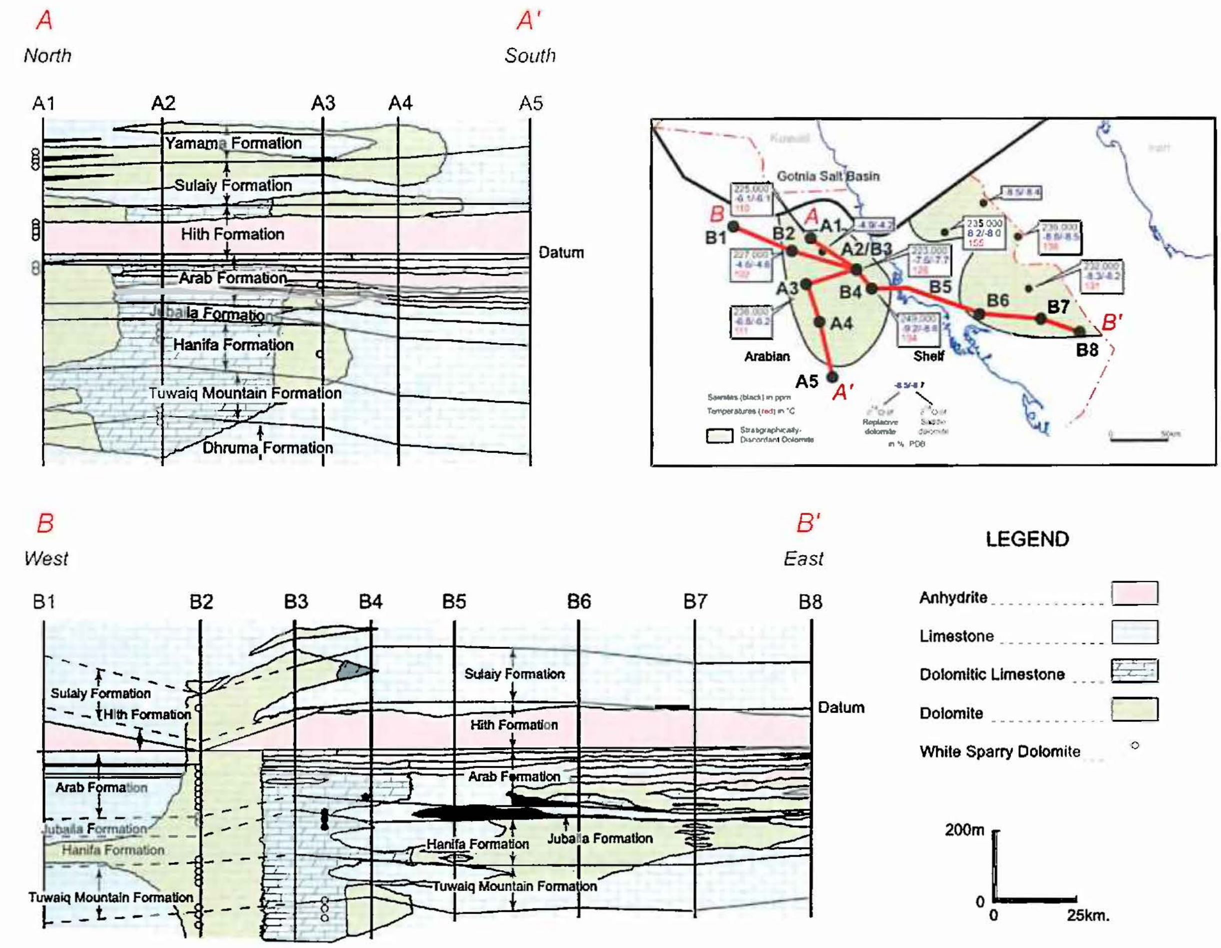


Fig. 6.9. North-south (above) and east-west (below) cross-sections through stratigraphically discordant dolomite bodies along the southern margin of the Gotnia Basin. After Broomhall and Allan, 1987.

1, the limestones of the Najmah Formation are tightly cemented; by contrast, the massive dolomite units are porous and contain hydrocarbons (Roychoudhury and Handoo, 1980). Dolomitisation is generally pervasive, replacing both lime mudstones and grainstones, but is sometimes localized along stylolites and fracture networks. At *Abu Khema-1*, only the dolomite beds form significant reservoir units in the Najmah Formation (Bhasin, 1982).

Dolomites are typically of burial origin; where dolomitisation is partial and selective, the rhombs are between 150 μm and 200 μm in size, and either replace micrite or clearly follow stylolites (Plate 6.6). Extensive dolomitisation is typified by coarser (500 μm) crystals (Plate 6.7) that replace all carbonate lithologies from micrite to oolitic grainstone, leaving only ghosts of allochems (Dunnington *et al.*, 1959; Sadooni, 1997).

Goff (2004a) investigated exposures of Middle – Upper Jurassic carbonates in the forelimb of the Kuh-e Mungasht anticline in the Zagros Mountains, SW Iran. Large-scale dolomitisation of the Late Jurassic Surmeh Formation in the eastern carbonate platform margin of the Gotnia Basin has occurred here, creating dolomite bodies which are about one hundred metres thick (Goff 2005) (Plate 6.8). Fluid-inclusion data from these dolomites indicates that they were precipitated at temperatures of 90-120°C from fluids with salinities of 150,000 to 240,000 ppm NaCl equivalent, synchronous with oil migration. This dolomitisation is analogous to the dolomitisation which is recorded in the subsurface of Iraq. Reservoir quality is best in coarsely crystalline dolomites with inter-crystalline porosity and in vuggy dolomites (Goff, 2005). Field and petrographic studies indicate the widespread occurrence of both sucrosic and saddle dolomite. The dolomites preferentially replace deeper-water bioturbated wacke-, pack- and grainstones.

In northern Saudi Arabia and southern Kuwait to the south of the evaporitic Gotnia Basin, dolomitising fluids of similar composition to those which created the Mungasht dolomite reservoirs have enhanced porosities in shelfal carbonates, and have caused large-scale destruction of Upper Jurassic and Lower Cretaceous seals. Secondary porosity has been created in a 150-200 km wide belt around the southern margin of the Gotnia Basin (Broomhall and Allan, 1987) (Fig. 6.9). Dolomite bodies, many tens of metres thick, are distributed

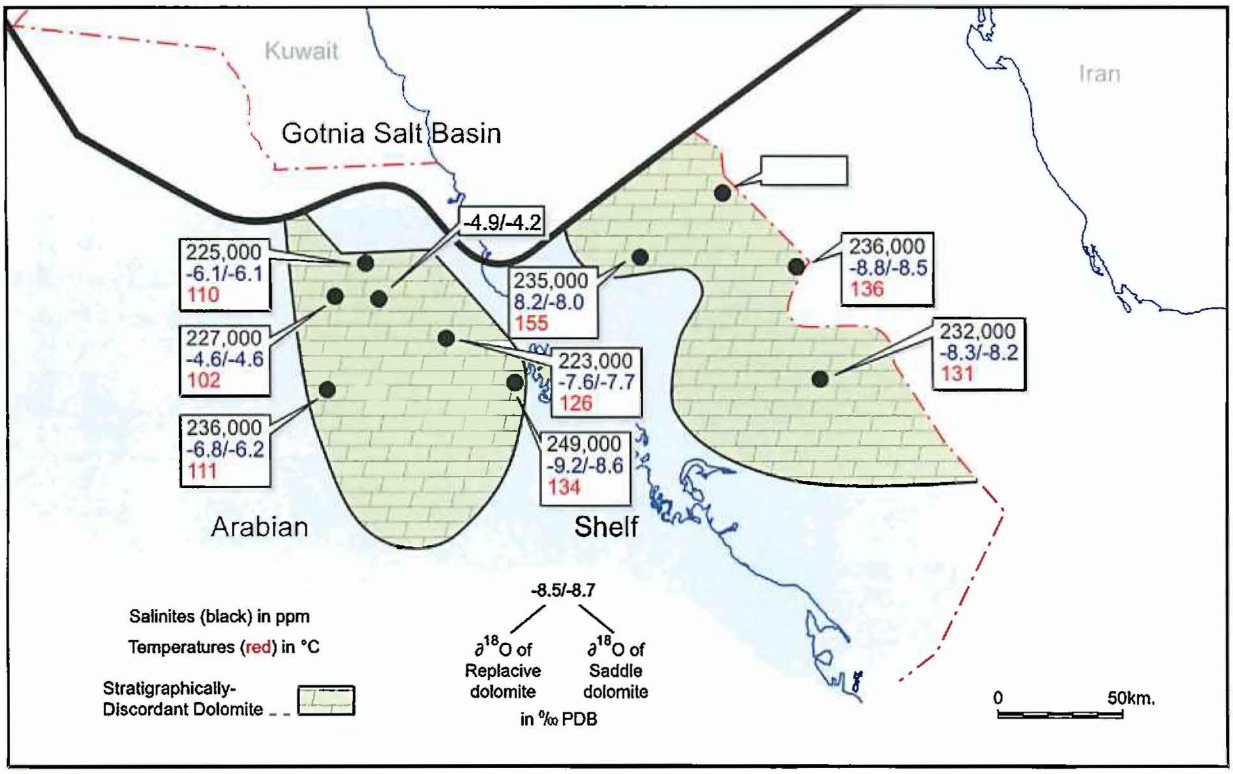


Fig. 6.10. Distribution of stratigraphically discordant dolomite bodies in northern Saudi Arabia, together with temperature and salinity data from fluid inclusion studies. After Broomhall and Allan, 1987.

over a wide area. Two regional-scale "dolomite plumes" have been identified: the first on the border between Saudi Arabia and Kuwait, and the second offshore Saudi Arabia (Fig. 6.10).

This stratigraphically discordant dolomite is locally associated with breccias due to dissolution of the Hith and Arab Formation anhydrites. Dolomite is present in the Tuwaiq Mountain, Hanifa, Jubaila, Arab, Hith and Sulaiy Formations (Fig. 6.11). It is best-developed in the Hanifa Formation. The dolomite shows enhanced porosities and permeabilities compared to host limestones (Broomhall and Allan, 1987).

Fluid inclusion data from the dolomites indicate that precipitating fluids were both hot (temperatures between 102 and 155°C) and saline (at least six times seawater salinity — values of 225,000 to 249,000 ppm NaCl equivalent were recorded) (Fig. 6.10) (Broomhall and Allen, 1987). Both replacive and saddle dolomites are present. They show similar oxygen isotope ratios suggesting that they were derived from the same parent fluid, although the western salient dolomites have a lower temperature, more positive $\delta^{18}O$ signature suggesting that they were precipitated slightly earlier and at shallower depths. Fluid inclusions indicate that oil migration took place at the same time as dolomitisation. There is abundant evidence of dead heavy oil in the pore systems. This may be due to failure of seal integrity due to dolomitisation (Broomhall and Allan, 1987).

Stratigraphically concordant non- fabric-preserving dolomites and stratigaphically-discordant baroque dolomite also occur in the Arab-D carbonate reservoir in the *Ghawar* field, some 500 km to the south of the Gotnia Basin. These dolomites precipitated at temperatures of 85–114°C from pore waters with a salinity of 195,000 – 230,000 ppm NaCl equivalent (Cantrell *et al.*, 2004). Stratigraphically discordant dolomitisation of Middle Jurasic rocks has also been reported to occur in Lebanon, where it is attributed to penecontemporaneous igneous activity (Nader and Swennen, 2004).

The dolomitisation of Middle Jurassic carbonates, and also perhaps of overlying intervals (in the Qamchuqa and Shiranish Formations and the Asmari/Kirkuk Group) thus appears to be largely hydrothermal in character (e.g. Al-Aasm *et al.*, 2009). The movement of dolomitising fluids may have been associated with the onset of Late Neogene compression in the Gotnia Basin, which caused rupturing of Jurassic and deeper evaporite seals and therefore permitted the large-scale mobilization of overpressured Mg-rich formation waters. Broomhall and Allan (1987) interpreted the dolomites to have been formed by brines migrating from the Gotnia Basin as a result of burial.

Naokelekan Formation

The Naokelekan Formation was first described from outcrops in NE Iraqi Kurdistan. It is a highly condensed formation, 9 to 34 m thick (typically less

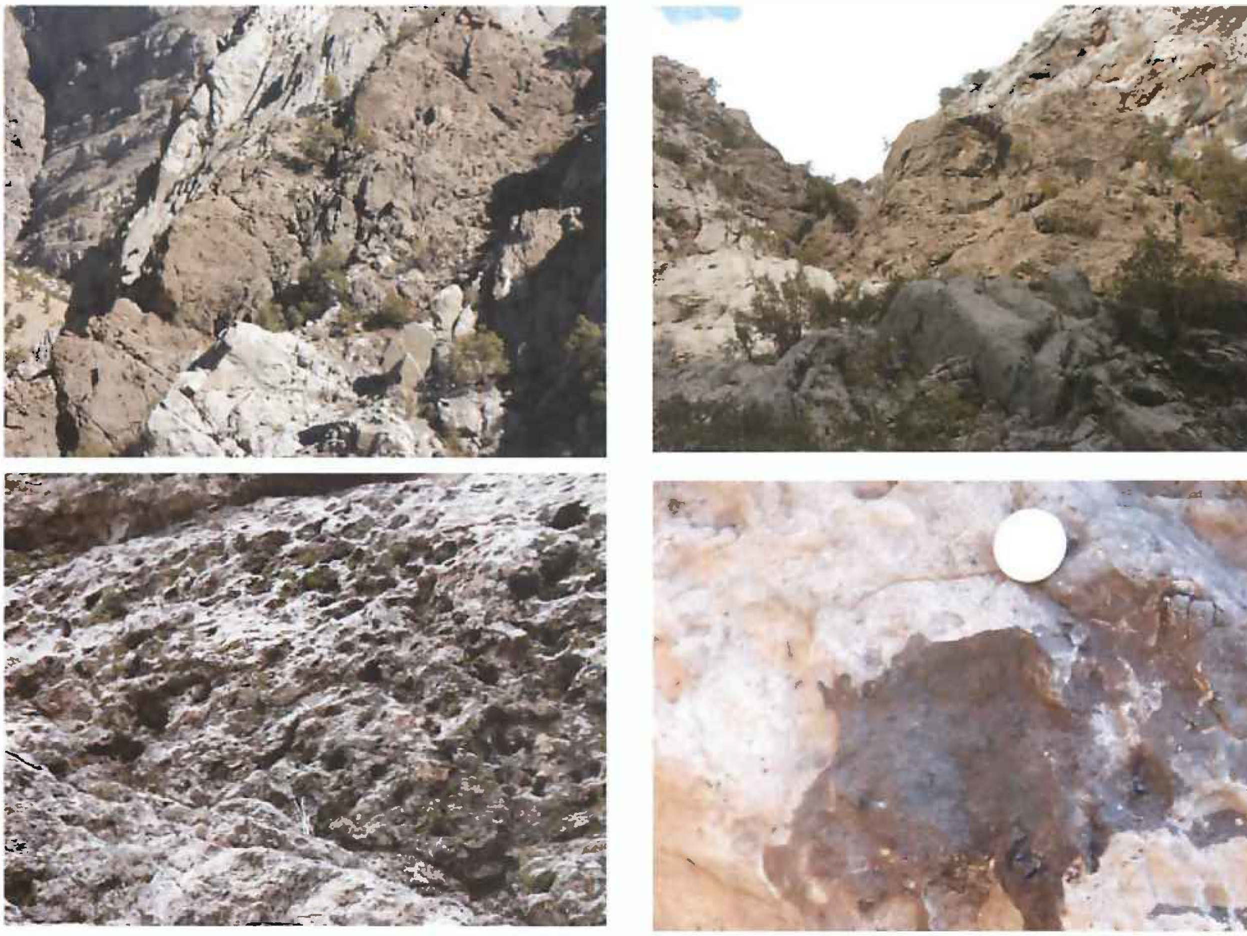


Plate 6.8. Field photographs of the Upper Jurassic Surmeh Formation at the Mungasht anticline on the eastern margin of the Gotnia Basin in the Iranian Zagros. Bituminous dolomite units are dark brown in the field and contrast with the intercalated pale grey, tightly cemented limestone units. Bitumen-filled vugs (bottom right) are frequently 5-10 cm in diameter. Photos by J. Goff.

than 20 m). The formation can be divided into three units at its type locality (see Fig. 6.3 for location) (Dunnington *et al.*, 1959):

(i) an upper 3 m of laminated argillaceous limestones;

(ii) a middle 4 m of "Mottled Limestone Beds", comprising hard, calcite-veined limestones which contain ammonites indicating a "probable early Kimmeridgian" age (Dunnington *et al.*, 1959);

(iii) a lower 7 m, referred to as the "Coal Horizon", which comprises thin-bedded bituminous limestones and dolomites with beds of bituminous calcareous shale. The unit has slump structures and weathers into nodular "phacoids". Its top is dated as late Oxfordian on the basis of possible identifications of the ammonite *Reineckia* at Naokelekan in Iraqi Kurdistan; the nearby occurrence of *Choffatia* at Kurrek suggests a Callovian age for its base (Dunnington *et al.*, 1959).

The formation conformably overlies the Sargelu Formation (Jassim and Buday, 2006d); the upper contact with the Barsarin Formation is often marked by a ferruginous horizon, e.g. in the north Thrust Zone (Hamza and Isaac, 1971, *in* Jassim and Buday, 2006d). Kaddouri (1986) noted a 1.4 m thick pisolitic limestone at this horizon.

The Naokelekan Formation contains a mainly deepwater fauna (Dunnington *et al.*, 1959). Buday and Suk (1978) *in* Kaddouri (1986) and Jassim and Buday (2006d), noted that at Halabja and elsewhere in Sulaimaniya Province in Iraqi Kurdistan, deeper-water fauna are present including *Protoglobigerina* sp., *Cadosina* sp. and the Callovian–Oxfordian belemnite *Hibolites semihastatus*. Shallower-water microfossils also occur such as *Kurnubia palastinensis* Henson, *Ammobaculites* sp., Textularidae sp., *Nautiloculina oolithica*, and the algae *Cladocoropsis*, *Thaumatoporella* sp. and *Cayeuxia doerflesiana*. Indeterminate dascycladaceans together with the stromatoporoid *Shuqraia "heybroeki"* (now *zuffardi*) also occur, indicating a Callovian–Kimmeridgian age (Buday and Suk, 1978, *in* Kaddouri, 1986).

Basinal Najmah Formation

An equivalent of the Naokelekan Formation is the informally-defined "basinal Najmah Formation" in wells in central and southern Iraq and also in Kuwait. This unit includes basinal organic-rich limestones with shelf and slope carbonates (Goff, 2005). Other examples of the "basinal Najmah Formation" occur between Awasil and Makhul, comprising black calcareous shales, oolitic and micritic limestones and so-called "chemical" limestones (Dunnington *et al.*, 1959), which are probably clotted peloidal fabrics.

Argillaceous limestones and shales occur between Mosul and Samarra (Kadhim and Nasir, 1971). The shallower-water allochems in this "basinal Najmah" Formation may be present as a result of *in situ* shallow-water deposition during phases of drawdown. The "basinal Najmah" facies resemble the Naokelekan Formation more than the "true" Najmah Formation as described at its type locality. Ideally, the term "Najmah Formation" should be dropped for these units, which should either be re-assigned to the Naokelekan Formation (c.f. Sadooni, 1997) or referred to a new unit.

Interpretation

The Naokelekan and basinal Najmah Formations represent highly condensed, basin-centre deposits. During highstands, deposition was mostly of condensed deeper-water carbonates, with organic content increasing as restriction increased. Lowstands resulted in almost total desiccation of the basin and deposition of thin, restricted, very shallow water carbonates.

Regional correlation

The Najmah Formation at its type section in well *Najmah-29* is equivalent to the 290 m thick Upper Dhruma, Tuwaiq Mountain and Hanifa Formations of Central Saudi Arabia (c.f. Enay and Mangold, 1994). The micropalaeontological characterisation of the Najmah Formation at its type section is poor (Dunnington *et al.*, 1959; Sadooni, 1997). The age of the formation can be inferred by comparison with the better-dated Saudi Arabian stratigraphy (cf. Hughes, 2004). In Central Saudi Arabia, both the Upper Dhruma Formation (equivalent to the Lower Fadhili Reservoir in the subsurface) and the overlying Lower Tuwaiq Mountain Formation (Upper Fadhili Reservoir in the subsurface) are dated as mid-Callovian (Hughes, 2004). These formations contain a similar fauna (with *Trocholina, Nautiloculina* and *Pfenderina*, corals and sponge debris) to the undifferentiated Najmah Formation in well *Najmah-29*. *Kurnubia* is recorded in the Upper Dhruma Formation and in the Lower Tuwaiq Mountain Formation (Hughes, 2004), and also in the uppermost part of the Najmah Formation at well *Najmah-29* (Sadooni, 1997). *Valvulina* sp. is recorded both in the middle of the Najmah Formation at *Najmah-29* (Sadooni, 1997) and in the Upper Dhruma Formation (Hughes, 2004). Both the Upper Najmah Formation of Iraq in its shelfal facies and the Upper Tuwaiq Mountain Formation (Hadriyah Reservoir in the subsurface) of Saudi Arabia (El Asa'ad, 1989; Hughes, 2004) are dated as late Callovian to perhaps Oxfordian. They are therefore equivalent to the Lower Najmah source rock of Kuwait (and possibly the "basinal Najmah" in southern Iraq), as dated by Sharland *et al.* (2001).

The lowermost part of the Naokelekan Formation (the "Coal Horizon") was deposited during a period of major shelf carbonate aggradation in the Callovian. It can be correlated with the lowermost Najmah Formation of Iraq (Jassim and Buday, 2006d) and the Upper Dhruma / Lower Fadhili, Lower Tuwaiq Mountain / Upper Fadhili (mid-Callovian) Formations of Saudi Arabia (Enay and Mangold 1994; Hughes, 2004).

The top of the "Coal Horizon" in Iraqi Kurdistan is of late Oxfordian age, broadly equivalent to the lowest shaly beds of the Hanifa Formation at outcrop in Saudi Arabia. These are mid-Oxfordian since they lie in the *plicatilis* Biozone (Enay and Mangold, 1994) and thus contain the J50 maximum flooding surface of Sharland *et al.* (2001). These units overlie the early – mid-Oxfordian Upper Tuwaiq Mountain / Hadriya Formation in Saudi Arabia (Enay and Mangold, 1994). In Kuwait, the J50 MFS has been placed within the lower part of the (basinal) Lower Najmah source rock. Therefore, during middle-late Oxfordian time, the upper part of the "Coal Horizon" was deposited at the same time as the platforms around the intrashelf basins were being drowned, at least temporarily.

Thick platform deposits pass into condensed basin-centre deposits in other Arabian intrashelf basins of this age. In Abu Dhabi, the Oxfordian is represented by about 120 m of platform-margin limestones that pass to the SW into about 18 m of basinal limestone source rocks (Al-Suwaidi and Aziz, 2002). In the *Berri* field in Saudi Arabia, the 70 m thick Hadriya reservoir (Upper Tuwaiq Mountain Formation) passes basinward into 15 m of organic-rich lime mudstones.

The dolomitised part of the Surmeh Formation at the Kuh-e Mungasht section in Iran lies below the estimated position of the J50 maximum flooding surface of mid-Oxfordian age (Goff, 2005). The dolomitised Surmeh Formation almost certainly corresponds in age and sometimes facies to the Sargelu and Najmah Formations of Iraq between the J30 and J50 maximum flooding surfaces (Goff, 2005).

Over the Rimthan Arch in northern Saudi Arabia, shallow-water oolitic and peloidal grainstones, probably equivalent to the Callovian Tuwaiq Mountain and the Oxfordian Hanifa Formations, have extensive early marine cements (Koepnick *et al.*, 1995). A broad facies belt of cemented skeletal packstones with benthic foraminifera and echinoderm debris is also present. This facies is extensively burrowed with hardgrounds and stylolites; very thin beds of skeletal grainstones occur. This facies has very low porosity and permeability and is considered non-reservoir. It underlies and passes updip into the Hadriya reservoir facies.

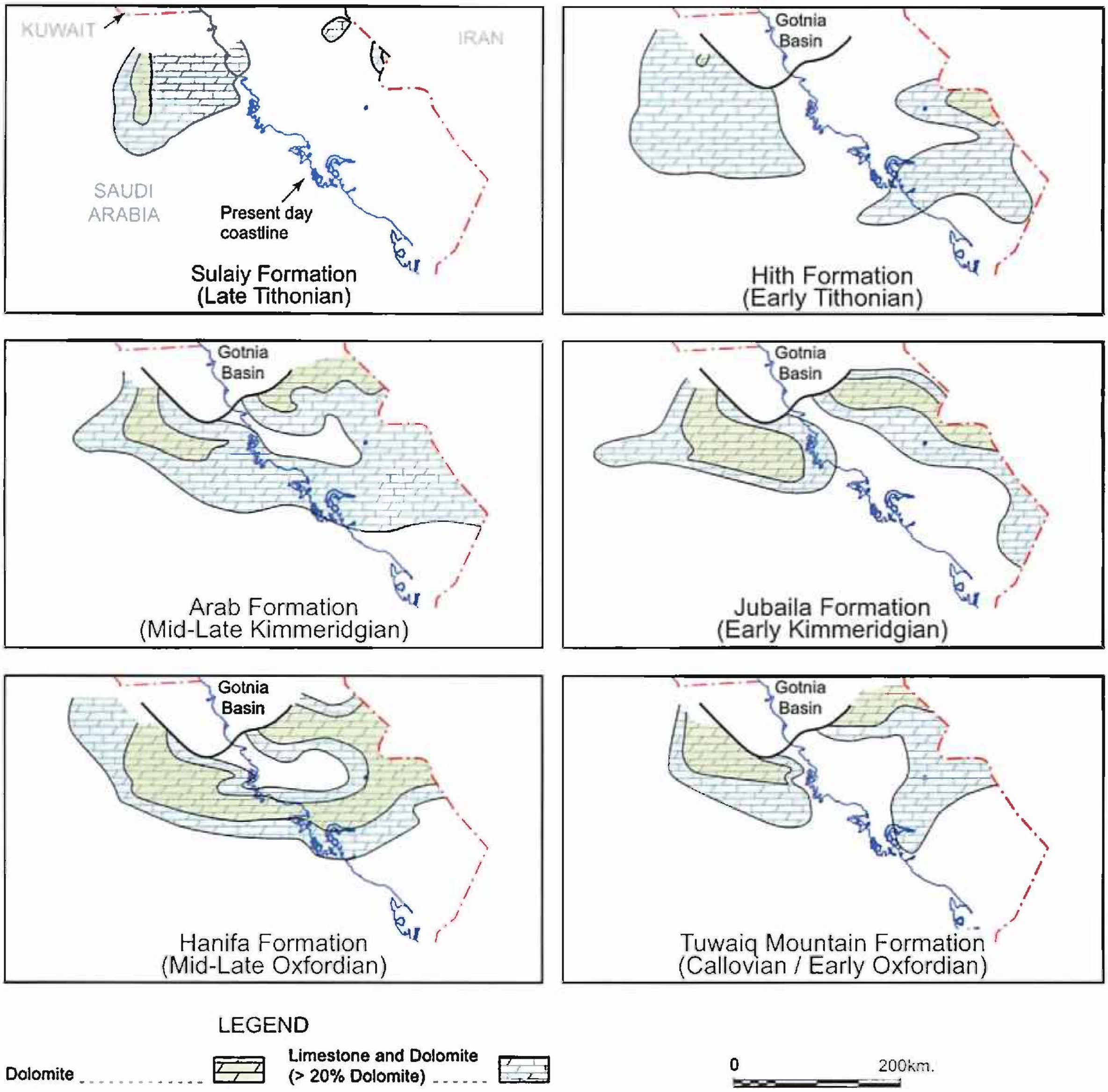


Fig. 6.11. Evolution of stratigraphically discordant dolomite bodies around the southern margin of the Gotnia Basin. After Broomhall and Allan, 1987.

The Kimmeridgian – lower Tithonian Supersequence

The Kimmeridgian – lower Tithonian Supersequence is characterised by onlap back onto the platform margins following the end-Oxfordian lowstand, and is typified by evaporite deposition. The J60-J100 flooding surfaces occur within 3.25 Ma (Sharland *et al.*, 2001) and indicate the presence of fourth-order parasequences rather than third-order sequences. Roychoudhury and Nahar (1980) suggested that the supersequence were deposited in two informally-defined sub-basins (the Widyan-Awasil and Basra-Kuwait sub-basins). Areas outside the basins were probably emergent or contain only very thin platform-top facies; for example in western Syria and Lebanon, Kimmeridgian sediments are only about 40 m thick (Mouty, 2000).

Within the supersequence, two formations are recognised. The evaporitic Gotnia Formation is recorded in northern and southern Iraq and in adjacent parts of Kuwait. This passes to the north and NE into the carbonates and breccias of the Barsarin Formation.

Gotnia Formation

The type locality of the Gotnia Formation is well *Awasil-5* in central Iraq (see Fig. 6.7 for location) (Dunnington *et al.*, 1959). Here the formation is 193 m thick and consists predominantly of massive anhydrites with thin interbeds of brown calcareous shales, black bituminous shales and "pseudo-oolitic" limestones; the shales contain fish remains. A restricted fauna of dwarf foraminifera (textulariids and miliolids) is present and ostracods occur in the limestones (Dunnington *et al.*, 1959). In northern Iraq, the formation is also present in wells *Makhul-1* and *-2* and *Mileh Tharthar-1* (Dunnington *et al.*, 1959), and in *Qarah Chauq-1* (Sadooni, 1997). It is 466 m thick at *Tikrit-1*. The combined Gotnia and

Barsarin Formations are 216 m thick at well *Jebel Kand-1* (Jassim and Buday, 2006d).

At the time the *Iraq Lexicon* was published in 1959, the Gotnia Formation had not been drilled in Southern Iraq. Descriptions of the formation by Al-Naqib (1967), Roychoudhury and Handoo (1980), Roychoudhury and Nahar (1980) and Bhasin (1982) indicate that a thin Gotnia stratigraphy overlies thick Najmah Formation in SW Iraq. The Gotnia was described as an anhydritic chalky limestone (Roychoudhury and Handoo, 1980).

Calcarenitic interbeds occur in the Gotnia Formation in well *Abu Khema-1*. They resemble cyclical facies in the Arab Formation in Saudi Arabia (Roychoudhury and Handoo, 1980). It is thus possible that equivalent Arab Formation carbonate reservoirs may occur in SW Iraq similar to those in Saudi Arabia and Abu Dhabi.

A thick Gotnia succession with halite is known from well *Rumaila North-172* in southern Iraq (OEC, 1989); a thicker (460 m) section of halite and anhydrite in the *Burgan* field, Kuwait, was correlated with the formation (Dunnington *et al.*, 1959). Ali (1995) and Yousif and Nouman (1997) (Fig. 5.18) reviewed the Gotnia Formation in Kuwait. In west Kuwait the Gotnia is 240-470 m thick (Ali, 1995).

Dunnington *et al.* (1959) and Kadhim and Nasir (1971) suggested a Callovian – early Tithonian age for the formation. This is too broad an age-range considering the better-constrained Callovian, Oxfordian and early Kimmeridgian ages obtained from the Naokelekan Formation (Dunnington *et al.*, 1959) which underlies the coeval Barsarin Formation. An age-range for the Gotnia Formation in Kuwait and the southern Gulf of Kimmeridgian – early Tithonian, as suggested by Alsharhan and Kendall (1986), seems more reasonable.

The secondary type section of the Gotnia Formation in Kuwait is in the Minagish area (Yousif and Nouman, 1997). Here, it has been divided informally into eight units: four halite and four anhydrite (Fig. 5.18). The formation is overlain by the Hith Formation which consists of about 100 m of anhydrite with thin limestone beds. Sharland *et al.* (2001) recognised four maximum flooding surfaces corresponding to limestone horizons within the anhydrite units separating the four halite units in Saudi Arabia and the Southern Gulf. These were located beneath the Arab-D, and near the base of the Arab-C, Arab-B and Arab-A carbonates respectively (MFSs J70, J80, J90 and J100). In the Gotnia Formation, the halite units may wedge out around the margins of the Gotnia Basin. Halite was probably deposited during maximum lowstands of sea level when the basin was completely isolated from Neo-Tethys.

Up to 600 m of Gotnia Formation evaporites were deposited in Kuwait during a brief period of about 2 million years (152–150 Ma). In Kuwait, localised structural growth occurred during deposition of the lower part of the Gotnia Formation; the lowest halite units (the 3rd and 4th Salt) are absent in North Kuwait near the Iraq/Kuwait border. The basal 4th Salt is also absent in the Magwa area of the *Greater Burgan* structure. The Gotnia Formation thins over narrow NNE-SSW and NNW-SSE trending structural highs in west Kuwait (Ali, 1995). Seismic lines flattened on the top of the Hith Formation indicate that structural growth during deposition of the sequences containing the J70 and J80 MFSs created the topography onto which the evaporites onlapped (Carman, 1996). The sequences that contain the J90 and J100 MFSs and the 2nd and 1st Salt Units are regionally extensive, overstepping the 3rd and 4th Salt and onlapping the basin margins. Similar updip wedge-out of anhydrite units occurs in Abu Dhabi (Al-Silwadi *et al.*, 1996) (Fig. 6.12).

The stratigraphic relationship between the shelfal carbonates of the Najmah Formation and the basin-fill evaporites of the Gotnia Formation is uncertain in Iraq. Studies of the stratigraphic successions in other intrashelf basins (e.g. in Abu Dhabi: Al-Silwadi *et al.*, 1996) suggest that during evaporite deposition, transgressive to highstand systems tracts developed and resulted in the deposition of shelf carbonates on the basin margins (Fig. 6.12). During subsequent lowstands, drawdown resulted in almost complete evaporation of water in the basin centre, such that the evaporites onlap the basin margins. It is notable that the evaporites often appear to be thickest near to the platform margins. This may be because subaqueous evaporites (particularly anhydrite) often form thick wedges close to onlap margins (c.f. the Permian Hartlepool Anhydrite of the North Sea Zechstein: Tucker, 1991). Isostatic loading of the margins of the condensed basin by thick platform carbonates may have produced a depression in front of the margin in which lowstand evaporites were preferentially deposited (N. Pickard, *pers comm.* to A.H., 2006). This may explain the presence of relatively thick anhydrite at wells *Tikrit-1* and *Jebel Kand-1*. The complex relationships developed during these high-frequency and high-amplitude changes of sea-level may have resulted in the Najmah Formation of southern Iraq (*sensu stricto*: platformal facies) correlating in part with the Gotnia Formation evaporites. This was originally suggested (but erroneously based on northern Iraqi data) by Dunnington *et al.* (1959) and Dunnington (1967a).

Barsarin Formation

This formation is relatively thin at outcrop. It is 17 m thick at its type locality at Barsarin (Dunnington *et al.*, 1959), and 10-59 m thick at Ru Kuchuk in NE Iraqi Kurdistan (Dunnington *et al.*, 1959). Subsurface sections are thicker, and 407 m of this formation, in a facies gradational with the Gotnia

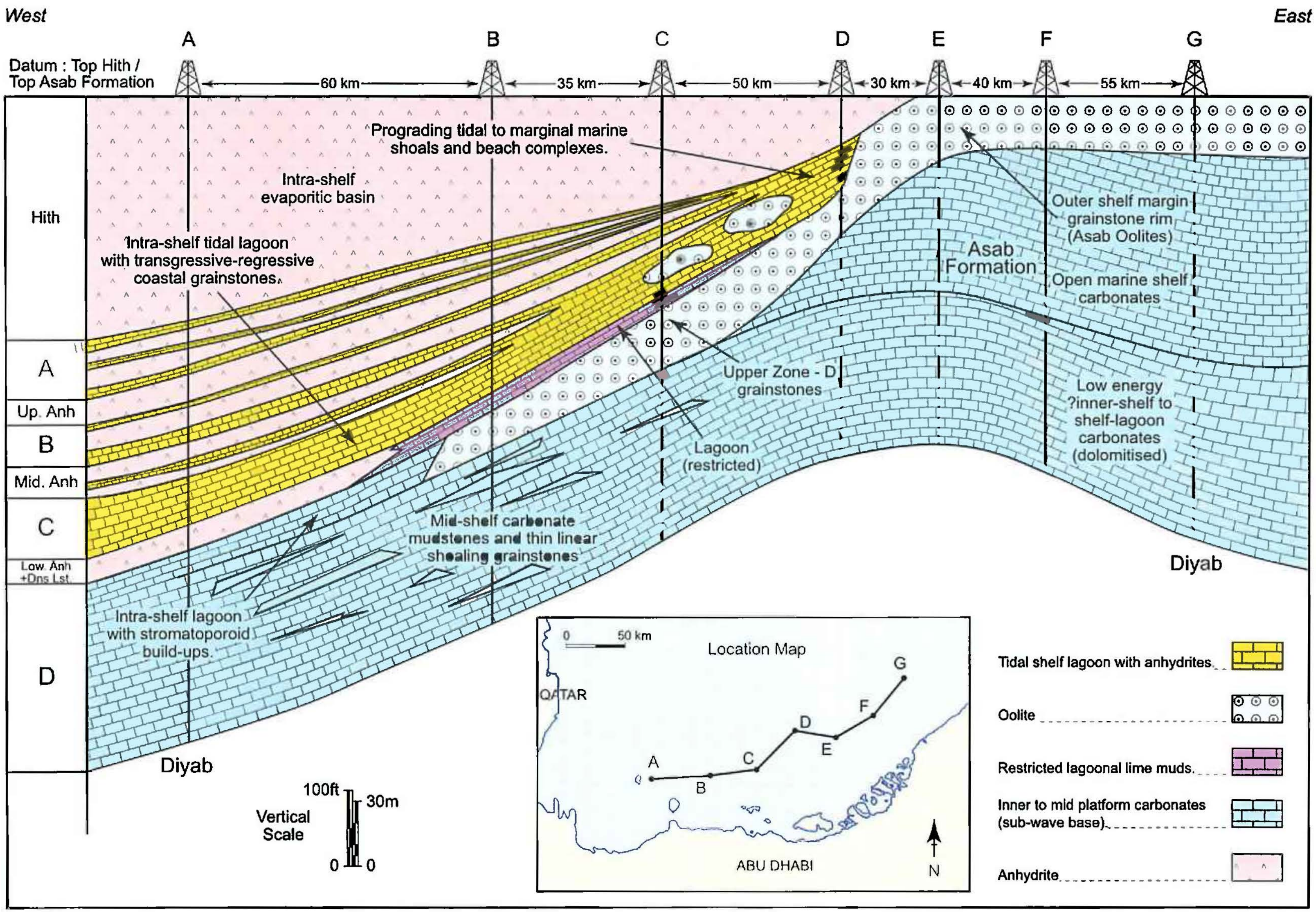


Fig. 6.12. Geometry of the Middle — Upper Jurassic shelf margin in Abu Dhabi, showing early rimmed shelf to basinal carbonates onlapped by younger cyclic evaporites and carbonates. Modified following suggestion by C. Toland, after Al-Silwadi *et al.*, 1996.

Formation, were penetrated at well *Kirkuk-109* (Dunnington *et al.*, 1959). Some 214 m of the Gotnia / Barsarin were recorded at well *Jebel Kand-1* (Jassim and Buday, 2006d). Similar (breccia) facies extend into the High Zagros of Lurestan (Iran) (Setudehnia, 1978).

The Barsarin Formation comprises limestones and dolomitic limestones (or dolomites with anhydrite in the well sections) which show evidence of deposition in a resticted environment. The limestones are laminated or fluffy-textured and cherty (Jassim and Buday, 2006d). These alternate with beds of carbonate breccia containing angular blocks of limestone and dolomite in an argillaceous or marly matrix, and locally black calcareous shales (Dunnington *et al.*, 1959; Kaddouri, 1986). The breccias have been interpreted as solution features formed by the dissolution of anhydrite and the collapse of overlying carbonates, although no angular discordance with the overlying Chia Gara Formation has been reported. Some beds contain bipyramidal quartz crystals and chert nodules. Beds of gypsum occur locally at outcrop in Ser Amadia and Kurrek (Dunnington *et al.*, 1959).

The undated microfauna of the Barsarin Formation has been described as "*very restricted, confined to forms which are tolerant of high salinities and which are associated with anhydrite deposits in other areas*" (Dunnington *et al.*, 1959). Kaddouri (1986) reported that the Barsarin Formation consists predominantly of foraminiferal limestones with *Clypeina jurassica* and *Nautiloculina oolithica* in the Benazi area, and *Kurnubia palastiniensis* at well *Quwair-1*. This fauna indicates a Kimmeridgian-Tithonian age.

The timing of evaporite dissolution has not been determined and the original thickness of the formation prior to evaporite dissolution has not been estimated. The formation may have been deposited in a separate and perhaps structurally elevated sub-basin that was partially isolated from the "Gotnia Basin" of southern Iraq, as proposed by Ditmar *et al.* (1971) (*in* Jassim and Buday, 2006d). This sub-basin was restricted and starved of clastic sediments; the underlying highly-condensed Naokelekan Formation and overlying Chia Gara Formations were both mostly deposited in deep-water euxinic environments. The breccias in the formation may have formed during periodic relative falls of sea level as a result of eustatic variations, followed by drawdown associated with salt deposition further south. Tectonic processes are unlikely to have produced the breccia facies, both because the facies is regionally extensive and because there is no apparent relationship between it and local structural elements.

Regional correlation

The Gotnia-Barsarin Formations of Iraq are correlatives of the Arab Formation which was also deposited in an intrashelf basin. The Arab-D grainstone belt (in which > 25% of the stratigraphy is grainstone) occupies an area of about 75,000 sq. km in northern Saudi Arabia between the Arabian Shield and the Qatar High (Wilson, 1975). It probably results from a unique combination of geological factors, and a similar facies belt is unlikely to occur at the same scale in western Iraq.

In the north of Saudi Arabia close to the Iraq border, cyclic "Arab" facies occur and may extend across SW Iraq. The Jubaila Formation in well *Safaniya-17* is overlain by a 25 m thick anhydrite unit, which may be the equivalent of the basal 4th Anydrite of the Gotnia Formation in Kuwait. This anhydrite unit is overlain by 55 m of Arab-D carbonates, consisting predominantly of lime mudstones with packstones and thin anhydrite intervals. To the NW (SW of *Wafra* field), the carbonates laterally equivalent to the Arab-D are reported to be almost completely dolomitised.

Azer and Peebles (1998) described the sequence stratigraphy of the Arab A–D Members offshore Abu Dhabi comprising 140 m to over 180 m of anydrites, dolomites and limestones. They recognised 19 sedimentary cycles (parasequences) in the Arab Formation, and five cycles in the overlying Hith Formation. A typical Arab parasequence consists of a shoal grainstone (transgressive systems tract) passing up into lagoonal lime mudstones and wackestones (maximum flooding surface), overlain by bioclastic grainstones capped by laminated algal limestones and anhydrites (highstand systems tract). Hardgrounds occur at the tops of cycles and at maximum flooding surfaces. The carbonates consist mainly of dolomite at the present day.

Strontium isotope ratios indicate a mid-late Kimmeridgian age for the Arab A-D and an early Tithonian age for the Hith Formation (Azer and Peebles, 1998). However, the isotope ratios are so similar that it is likely that there has been considerable homogenization and resetting of original values; also, the Hith value may have been affected by the presence of clay minerals (Azer and Peebles, 1998). Palaeontological calibration suggests a middle Kimmeridgian – middle Tithonian age for the whole system (Al-Silwadi *et al.*, 1996; Al-Saad and Ibrahim, 2005). The latter ages were used as a basis for the chronostratigraphic panel in Fig. 6.2, partly because of the problems acknowledged by Azer and Peebles (1998), and partly because thicknesses of comparable cyclic carbonate-evaporite successions, such as the Khuff or the Zechstein of the end-Permian, yield cycle durations of approximately 1 Ma. The anhydrite beds are interpreted to have been formed subaqueously in large hypersaline lagoons and ephemeral lakes (Azer and Peebles, 1998). One of these beds, the lowermost 4th Anhydrite, is an important drilling marker that is used to pick a casing point at the base of the Gotnia Formation in Kuwait.

Petroleum system components in the Middle – Upper Jurassic

Because petroleum systems data relating to each sequence are infrequent and scattered in Iraq, the Middle – Upper Jurassic Megasequence AP7 is considered in its entirety in the following section. Important aspects include source rock potential, the development of overpressuring, and the enhancement of reservoir potential by dolomitization and fracturing.

Reservoirs with matrix porosity

Interest in the reservoir potential of mid-Jurassic sedimentary rocks in Iraq followed the discovery of significant oil accumulations in equivalent units in the south of the Arabian Plate. However, no proven reservoirs of this age are known in Iraq, although they constitute one of the world's greatest reservoir systems in adjacent parts of Saudi Arabia. Thus, Jurassic reservoirs produce oil at *Dibdibah* (4250 b/d) and at *Rimthan*, 65 miles SE of well *Abu Khema-1*, where six full-to-spill reservoirs in the Arab and Jubaila Formations flowed 5000-10,000 b/d (Roychoudhury and Nahar, 1980). At *Ghawar*, the largest oilfield in the world, the main reservoir is in the Arab "D" (Halbouty *et al.*, 1970; Ayres *et al.*, 1982), and production comes from oolitic grainstones and dolomitised oolitic grainstones. Similar reservoir facies also occur at *Qatif* (Wilson, 1985). Porous Middle – Upper Jurassic calcarenites may have reservoir potential in adjacent parts of Iraq (Roychoudhury and Nahar, 1980).

Coarse-grained Middle Jurassic calcarenites of the Muhaiwir Formation are predicted to occur on structural highs developed between, and to the west of, wells *Abu Khema-1* and *Samawa-1* (Roychoudhury and Nahar, 1980). This lithofacies may be comparable to the calcarenites of the Dhruma Formation which have produced oil in Saudi Arabia at the *Ghawar, Abqaiq, Dammam, Fadhili* and *Rimthan* fields, where reservoir facies were also deposited on growing structures (Roychoudhury and Nahar, 1980).

Kadhim and Nasir (1971) studied the hydrocarbon potential of the Jurassic sedimentary rocks in Iraq, and considered that the Najmah Formation had reservoir potential. Braithwaite (unpublished 1981, *in* Jassim and Buday, 2006d) investigated the hydrocarbon system of the entire geologic section in the west Baghdad area, including the Upper Jurassic, but classified the formation as a non-porous carbonate. Bhasin (1982) and Sadooni (1997) reviewed the petroleum potential of the Upper Jurassic succession, and considered the Najmah Formation to have promising reservoir potential in southern and central Iraq.

The Najmah Formation includes potential reservoir intervals comprising oolitic-peloidal grainstones and packstones, with intergranular porosity which is enhanced in some cases by ooid dissolution, together with dolomitic limestones with intercrystalline porosity (Sadooni, 1997). The *Samawa-1* well was drilled in southern Iraq in the early 1960s and penetrated what was considered to be the Najmah Formation from which 330 brl/day of heavy oil were produced from a drill stem test (Roychoudhury and Nahar, 1980). Well *Kifl-1*, drilled to delineate the hydrocarbon potential of the Najmah Formation, encountered oil shows in intervals with oomouldic porosity (Sadooni, 1997). *Abu Khema-1*, drilled by the Indian Oil and Natural Gas Commission, found oil shows in the Najmah and Gotnia Formations (Roychoudhury and Nahar, 1980; Roychoudhury and Handoo, 1980). These disappointing results were thought to be due to seal failure, and exploration for Najmah targets by INOC moved further east to locations where the Gotnia Formation seal was expected to be thicker. The *Diwan-1* well, to the east of *Samawa-1*, was thus intended to examine the possibility of better oolite development in the Najmah Formation and a better seal in the Gotnia (Sadooni, 1997). However, the well failed because although it encountered both a thick oolitic succession and a seal, the reservoir was highly cemented (Sadooni, 1997).

The importance of dolomitization in creating porous reservoirs in the Najmah Formation was discussed on pp. 145-148. The petrophysical characteristics of the Najmah Formation in Iraq have not been investigated in detail, although porosity is known to be present in some dolomites (Sadooni, 1997). Bhasin (1982) recorded secondary porosities of 8.5%, S_w of 20-45%, and pore throats of 5-20μm in clean, coarse dolomites at well *Abu Khema-1*. Hydrothermal dolomites in Lebanon comparable to those in Iraq have porosities of 6 to 10% (measured by point-counting), with values of <3% in early diagenetic dolostones and <5% in limestones (Nader and Swennen, 2004). By contrast, Goff (2005) cited data from Kuwait which showed that non-source rock basinal limestones have porosities of 2.3% and permeabilities of less than 0.01mD.

In shelf-to-basin transitional areas, porous reservoir units may also be associated with microbial-, sponge- or coral-dominated pinnacle build-ups (Sadooni, 1997) located outboard of the shelf margins. These may be analogous to the gas reservoirs in the Cotton Valley Formation (Oxfordian-Kimmeridgian) in Texas (Montgomery, 1996).

New reservoir data for the Jurassic will be obtained during future exploration drilling and will be important for evaluation of Jurassic plays. Failure analysis of existing wells should show whether wells drilled on surface closures have tested closures at top-Jurassic level, given the asymmetry of many Zagros-related structures. For example, wells such as *Demir Dagh-1* are reported to have found heavy oils in the Najmah Formation (Al-

Table 6.1. Geochemical data for Middle to Upper Jurassic source rocks of the Gotnia Basin in northern Iraq (from Al-Haba and Abdullah, 1989, translated by Sadooni, 1997; and Odisho and Othman, 1992). Note that the samples analysed range from immature to overmature.

Well Name	Formation	TOC %			Primary production potential (kg/tonne)			Production index %		
		N=	Mean	Range	N=	Mean	Range	N=	Mean	Range
Jebel Kand-1	Sargelu	1	3.1	n/a	1	14.17	n/a	1	0.07	n/a
Kirkuk-109	Barsarin	13	3.09	1.43 - 7.79	13	4.6	0.95 - 9.34	13	0.23	0.15 - 0.37
	Naokelekan	5	4.01	2.43 - 5.34	5	3.46	2.39 - 4.56	5	0.22	0.20 - 0.26
Qara Chauq-1	Gotnia	5	3	0.4 - 6.85	5	4.95	0.89 - 11.91	5	0.21	0.10 - 0.37
	Naokelekan	13	4.31	0.58 - 13.25	13	n/a	1.36 - 40.9	13	0.18	0.04 - 0.35
	Sargelu	10	4.94	1.71 - 7.59	10	n/a	14.14 - 24.9	10	0.13	0.06 - 0.19

Gailani, 1996a), but it is not clear if the well tested a valid closure at Jurassic depths. These deeper-water facies are unlikely to have good matrix porosity. Both primary (intergranular) and secondary (intercrystalline) porosity is more likely to have developed in shelfal facies (oolitic limestones and dolomites, respectively).

The above discussion suggests that the Najmah Formation, and to a lesser extent the Muhaiwir Formation and the calcarenites in the Gotnia Formation, may constitute significant reservoir targets, particularly over palaeohighs in central and southern Iraq. The Najmah Formation also offers possibilities in the vicinity of well *Demir Dagh-1*, which penetrated the greatest thickness of this formation in Iraqi Kurdistan.

Fractured Reservoirs

In the Upper Jurassic succession of Arabia, fractured reservoirs are generally of less importance than reservoirs with matrix porosity (Roychoudhury and Nahar, 1980). However, where fracture networks are present in source rock intervals, they may confer reservoir potential. In Kuwait, the Sargelu and basinal Najmah Formations locally constitute fractured reservoirs. This reservoir system was recently investigated by Goff (2005) in a review which forms the basis of the discussion in the following paragraphs. Similar reservoir intervals may be present both in these formations and in the Naokelekan Formation in Iraq. The discovery of 21-22° API oil in the Sargelu Formation has recently been reported* in well *Shaikhan-1* in Iraqi Kurdistan; preliminary tests indicate flow rates of 5000-8000 b/d.

Fractures in the Najmah and Sargelu Formations occur at all scales from microfractures visible in thin sections, to hairline fracture networks visible in cores, to bed-confined vertical fractures observed in core and on image logs, and to large, widely-spaced fractures which cut across bed boundaries (Strohmenger *et al.*, 1998; Goff *et al.*, 2004b; Needham *et al.*, 2004). Vertical fractures in cores in the Najmah Formation are usually short, cemented or partly cemented, with low width:length ratios. Many fractures have an outer rim of calcite cement which encloses residual hydrocarbon inclusions. The Sargelu Formation is characterized by uncemented and partly cemented hairline fractures. These fractures can have spacings of less than 2 cm and some have visible oil staining. Longer throughgoing fractures have been identified on borehole image logs, but are only rarely reported in cores. First-generation fractures have low temperature calcite cements and lack oil inclusions, and are thought to be associated with Late Jurassic deformation. The presence of a second phase of fracturing, with calcite cementation and oil inclusions, suggest that pre-existing fractures reopened, probably during mid-Cretaceous (Turonian) folding, synchronous with the onset of oil generation in the basin. Reopening of the fractures would have been facilitated by a reduction in horizontal stresses during folding and by increased pore pressure gradients during oil generation. Saturation of fracture porosity with oil may have led to the cessation of carbonate cementation and the preservation of effective permeability. Later hairline fractures observed in non-source intervals cross-cut older diagenetic features, and probably formed during Late Tertiary uplift.

Source rocks

In Iraq, Megasequence AP7 contyains rich oil source rocks. Inhabitants of Iraqi Kurdistan have long quarried oily bituminous shales from the "Coal Horizon" of the Naokelekan Formation for local use as a fuel (Dunnington *et al.*, 1959). Dunnington (1958, 1967) drew attention to these shales' potential as a source of oil throughout the Arabian Basin. Intervals with source-rock potential occur within the Sargelu, Gotnia, Naokelekan and Barsarin Formations, and also in the overlying Chia Gara Formation of Sharland *et al.*'s (2001) Megasequence AP8.

Mid – Upper Jurassic source rocks in Iraq are typical of carbonates deposited in deep-marine, restricted basinal conditions. It is not clear why

* *Upstream Newsletter*, 6.8.09.

Table 6.2. Further geochemical properties of Middle – Upper Jurassic source rocks from the northern part of the Gotnia Basin. After Odisho and Othman (1992).

Well Name	Formation	TOC %	Depth (m)	S_1	S_2	HI	PI	PP or P_2	T_{max}°C
Jebel Kand-1	Sargelu	3.1	2374	0.94	1	426	0.07	14.17	441
Taq Taq-1	Naokelekan	4.66	3236	0.47	5	22	0.31	1.51	568
Taq Taq-1	Sargelu	0.49	3308	0.06	10	102	0.11	0.56	515

these conditions developed on what is conventionally thought of as a passive margin formed after Permo-Triassic rifting (Murris, 1980). A possible explanation is that an outer basement high, similar to that known further south in Iran, extended along the NE margin of the Arabian Plate and acted as a barrier preventing open-oceanic circulation from reaching shelfal areas. Restriction would have been enhanced by carbonate platforms forming on the barrier and building up to sea level along its entire length (for an analogous example, see Fig. **3.29**). Development of the restricted, shallow intrashelf Gotnia Basin behind the barrier (Fig. 3.30) would have been created conditions suitable for the deposition of organic-rich source rocks.

The Gotnia Basin covers eastern Iraq and extends into Lurestan Province of Iran, across Kuwait and into parts of northern Saudi Arabia (Fig. 6.3). Many authors (e.g. Murris 1980; Ayres *et al.* 1982; Lehner, 1984; Wilson,1984; Alsharhan and Kendall, 1986; Al-Sakini 1992) have suggested that euxinic conditions in this basin resulted in the deposition of black, organic-rich shales and limestones with source rock potential.

Source rock data in Iraq has been collected from wells including *Jebel Kand-1, Kirkuk-109, Ajeel-8* and *-12* (formerly *Saddam* field) and *Taq Taq-1*. However there is currently no published data for source rocks in Southern Iraq, and it is therefore difficult to assess regional variations in source rock quality. Much of the data is in Arabic-language publications (e.g. Al-Haba, 1989; Al-Haba and Abdullah, 1989); it has been reproduced by Odisho and Othman (1992) and Sadooni (1997).

Source rock quality

The source rock quality of the Sargelu, Naokelekan, Barsarin and Gotnia Formations is summarised in Tables 6.1 and 6.2 with additional data briefly reviewed below. The Tables show that the mean Total Organic Carbon (TOC) content of Jurassic source rocks in Iraq typically ranges from 0.5 to 5%, reaching a maximum of just over 13% in the Naokelekan Formation at well *Qarah Chauq-1* in Northern Iraq (Al-Haba and Abdullah, 1989; Odisho and Othman, 1992). The Sargelu Formation shows the greatest variation in TOC content. TOCs in the fold belt, measured in cores and cuttings, are 2-6%, including some values of over 20% in the basal part of the formation (PGA, 2000 *in* Pitman *et al.*, 2004). In the thrust belt, reported TOCs are under 2% probably due to oermaturity (Al-Haba and Abdullah, 1989; PGA, 2000 *in* Pitman *et al.*, 2004).

TOC contents in equivalent Jurassic source rocks in west Kuwait are up to 19% (Moore *et al.*, 1998). TOCs in the subsurface, measured from cores and cuttings, are 3-9%, including some values of over 15% (Al-Haba and Abdullah, 1989; PGA, 2000 *in* Pitman *et al.*, 2004). At outcrop, TOCs are up to 11% (Al-Haba and Abdullah, 1989; PGA, 2000 *in* Pitman *et al.*, 2004), but typically range up to 8 or 9%.

Odisho and Othman (1992, quoting Al-Jiboury, 1989) noted that in the *Ajeel-8* and *-12* wells, both the Sargelu and Naokelekan Formations have similar TOC contents to those reported for the *Kirkuk* area. In well *Qarah Chauq-1*, TOCs were particularly high in the upper argillaceous zone (around 30 m) of the Upper Jurassic sedimentary succession. They were also high in the lowermost shaly 5 m of the Gotnia Formation. Hydrocarbon potential for the Upper Jurassic of *Qarah Chauq-1* is up to 40 kg/ton (Al-Haba and Abdullah, 1989).

Original HI values of the Sargelu and Naokelekan Formations were around 600 mgHC/gTOC, based on average compositions of kerogen in source rock intervals. Present-day values range from <100 to >600. Samples from wells *Kirkuk-109* and *Taq Taq-1* are overmature. In well *Kirkuk-109*, HI is 69 mg/g and T_{max} is 450°C at 3396 m, while in *Taq Taq-1*, HI values are 22 mg/g, with a T_{max} of 568°C at 3236m (Al-Haba and Abdullah, 1989; Sadooni and Alsharhan, 2003; PGA, 2000 *in* Pitman *et al.*, 2004).

In well *Jebel Kand-1*, Al-Haba (1988 unpublished and cited by Al-Sakini, 1992) found that the Alan Formation is mature but has a low organic content and is thus a poor-quality source rock. Organic material in the Alan Formation is of continental origin and is gas-prone. Liquid oils have been recorded in bituminous shales in the Alan Formations in well *Samawa-1*, and in some wells which penetrated the Marrat Formation in Saudi Arabia (Roychoudhury and Nahar, 1980).

Kerogen types

Petrographic studies showed that the kerogen in the Naokelekan, Barsarin and Gotnia Formations at well *Qarah Chauq-1* was mostly amorphous and of marine origin. In well *Kirkuk-109*, the kerogen in the Barsarin Formation was of mixed marine-continental type, while that in the Naokelekan Formation was mainly amorphous and marine. Odisho and Othman (1992) noted that a sample from the Sargelu Formation at well *Jebel Kand-1* had Type III characteristics, with an H/C of 0.87 and an O/C of 0.18, although *Rock-Eval* data suggested an oil-prone Type II kerogen. Additional analyses gave a pristane/phytane ratio of 0.4, a pristane/nC_{17} ratio of 0.1, and a phytane/nC_{18} ratio of 0.2.

Hydrocarbon potential

Mean primary production potential varies between 0.56 and 14.10 kg/tonne (Tables 6.1, 6.2). The Sargelu Formation shows the widest variation in hydrocarbon potential; the Gotnia/Barsarin Formations consistently have higher production potentials than the Naokelekan Formation. Al-Haba and Abdullah (1989) suggested that the present-day hydrocarbon potential of the Upper Jurassic is generally around 40 kg of hydrocarbons per ton. At well *Kirkuk-109*, although the remaining hydrocarbon potential reached nearly 10 kg of hydrocarbons per ton in the Barsarin Formation (Table 6.1), the original potential was estimated to be more than 100 kg/ton for some samples (Al-Haba and Abdullah, 1989). A petroleum yield greater than 100 kg/ton, as recorded in West Kuwait, would require an initial Hydrogen Index exceeding 700 mgHC/gmTOC (Moore *et al.*, 1998).

Production indices generally range from 0.07-0.13 for the Sargelu Formation, to 0.18-0.22 for the Naokelekan Formation and 0.21-0.23 for the Gotnia-Barsarin Formations (Odisho and Othman,1992; Sadooni, 1997) (Table 6.1).

Analogues

In Iran, argillaceous limestones of the Sargelu Formation are over 150 m thick and have TOCs of 3.1 - 4.4%, comprising Type IIs kerogen with *Rock-Eval* S2 of 18 kg/tonne and $\delta^{13}C$ of -28.7 ± 0.5 ‰ for both kerogen and kerogen pyrolsate (Bordenave and Huc, 1995). However, oils in Asmari and Bangestan Group reservoirs in Lurestan do not have the same carbon isotope signatures as the Sargelu oil, indicating that the latter oil is separate from those in the post-Jurassic petroleum system. This is probably because the thick evaporites of the Gotnia Formation sealed the Sargelu source rock and isolated it from overlying reservoirs (Bordenave and Burwood, 1990; Bordenave and Huc, 1995).

The Sargelu source rock system therefore continues into the Lurestan area of Iran. This indicates that risk associated with the presence of Middle – Upper Jurassic source rock in border areas is probably minimal.

Proven and Potential Seals

Thick anhydrites in the Gotnia Formation represent an effective regional seal for the Jurassic petroleum system in central and southern Iraq (although this was disputed by Pitman *et al.*, 2004), but they usually occur above non-matrix porosity reservoir facies (Naokelekan or basinal Najmah Formations). Where they are thin, anhydrites may be located directly above the Najmah Formation shelfal facies and could represent lower quality seals (Al-Naqib, 1967). These anhydrites may then play a similar sealing role to that of the Hith Anhydrite Formation above Arab reservoirs in the southern Gulf. In Iraq to the north of Makhul, the Gotnia Formation is replaced by the collapse breccias of the Barsarin Formation, which probably do not form such an effective seal. The upper contact of the Najmah Formation in northern Iraq is erosional, and the Gotnia or Barsarin Formations have never been reported above shallow-water Najmah Formation facies; therefore, valid Najmah-Gotnia reservoir-seal combinations are only present in very limited areas. A top-seal for the Najmah interval in northern Iraq will have to rely on the presence of suitable lithologies in the Cretaceous succession. Lateral and bottom sals will have to be provided by older Jurassic limestones. The risk associated with trap integrity is therefore significant. Cretaceous erosion of the uppermost Jurassic (Kimmeridgian – Tithonian) highstand carbonates from the western and southern basin margins (Fig. 6.4) may have breached the top seal. This is probably the main reason why the Middle–Upper Jurassic in central and northern Iraq has failed as a major petroleum system.

Potential top and lateral seals may be developed where pinnacle build-ups (Najmah/Muhaiwir equivalents) were abandoned and then sealed by either basinal shales or evaporites of the Gotnia Formation, analogous to the Silurian Niagara reefs (e.g. Sears and Lucia, 1980; Bay, 1983). The massive evaporites of the Alan Formation and associated shales and argillaceous limestones potentially provide good bottom seals for the Sargelu Formation. Similar lithologies in the upper Marrat Formation in Kuwait seal middle Marrat carbonate reservoir units.

Close to platform margins, anticlinal structures may involve some element of stratigraphic trapping, and single crestal wells on large anticlines may not necessarily have tested optimum reservoir conditions.

Concluding Remarks

The Middle to Late Jurassic history of Iraq is dominated by the formation of the intrashelf Gotnia Basin containing Megasequence AP7 sediments (Fig. 6.5). This basin formed during the late Aalenian to early Bajocian by differential subsidence of the epeiric Early Jurassic shelf. It covered most of Iraq, Kuwait and the Lurestan area of Iran. However, the basin fill and the flanking carbonate platform to the west are poorly described because of a lack of well and seismic control over large areas. The eastern margin of the basin is not seen in Iraq as a result of later overthrusting. An important phase of faulting may have occurred in Kimmeridgian time. This may have been related to tectonic extension along the NE margin of the Arabian Plate, although the relative roles of tectonics and inherited topography in controlling the margins of the basin require further study.

Megasequence AP7 comprises three supersequences: upper Aalenian – Bathonian; Callovian – Oxfordian; and Kimmeridgian – lower Tithonian. The detailed stratigraphic architecture of the platform margins that formed during the deposition of these supersequences is unknown. The supersequences correspond to major phases in basin evolution. Initial infill of the basin in the Mid Jurassic was by lateral accretion due to progradation of the carbonate platform margins. The margins then aggraded in Callovian – early Kimmeridgian time with very condensed deposition in the basin centre. Finally the basin was partly plugged by evaporites in late Kimmeridgian – early Tithonian time (Fig. 6.5). Thus, an early carbonate ramp phase (Sargelu and Muhaiwir Formations) is followed by an "early restricted" and locally high-energy rimmed shelf phase represented by the Najmah and Naokelekan Formations. Finally a "late, very restricted" phase is represented by the Gotnia and Barsarin Formations. At the end of deposition in the Tithonian, considerable accommodation space remained in the basin and was carried over into AP8.

Porous Middle-Upper Jurassic limestone reservoir intervals analogous to the Arab Formation of Saudi Arabia have not yet been described from Iraq. To date, the only reservoirs described are dolomitised shelf carbonates of the Najmah Formation. Condensed, high-quality, organic-rich oil source rocks were deposited in the basin centre throughout its evolution. Major lateral facies changes occur along the margins of the Gotnia Basin (Fig. 6.5). Basinal source rocks and limestones pass updip into dolomitised platform carbonates.

Thick evaporites were deposited in southern and central Iraq and form an important regional seal. The distribution of equivalent evaporites and associated solution breccias in northern Iraq is poorly known. The seal potential at the top of Megasequence AP7 in northern Iraq is thus not understood, and large-scale vertical migration of Jurassic oil into the overlying megasequence may have occurred.

The infill of the Gotnia Basin thus includes organic-rich carbonate source rocks, potential dolomite reservoirs and evaporite caprocks. However, in the centre of the basin, evaporites directly overlie source rocks and conventional carbonate reservoirs may be absent. This stratigraphic organization has not resulted in major play fairways in Iraq. In contrast, in the intrashelf basin in Saudi Arabia to the south, the Hith anhydrite directly overlies Arab Formation carbonate reservoirs charged by underlying Jurassic source rocks. There, vertical instead of lateral accretion of equivalent stratigraphic units has resulted in the favourable stacking of source, reservoir and seal facies.

Jurassic plays in the Gotnia Basin of Iraq include naturally fractured basinal carbonates and source rocks sealed by evaporites, and dolomitised platform margin dolomites. Stratigraphic traps may be present in the Gotnia Basin, such as build-ups or isolated platforms; these are not known elsewhere in Arabia. The Jurassic petroleum system of Iraq is discussed further in Chapter 9iv (pp. 315-326).

7. CRETACEOUS

The Cretaceous succession* in Iraq (Figs 7.1, 7.2) is up to 3000 m thick (Sadooni and Aqrawi, 2000) and comprises Megasequences AP8 and AP9 of Sharland *et al.* (2001). H.V.Dunnington recorded in the introduction to the *Iraq Lexicon* (van Bellen *et al.*, 1959) that the succession has three principal characteristics:

Firstly, he observed that as many as 44 of the 75 pre-Tertiary formations in Iraq were of Cretaceous age, while another four formations spanned the Cretaceous – Jurassic boundary. As a result of more recent studies, 53 Cretaceous units are now recognised. The formations are lithologically diverse indicating a complex depositional history.

Secondly, Dunnington observed that while Palaeozoic to Jurassic strata consist of relatively homogeneous, regionally extensive formations, many Cretaceous formations were deposited in localised environmental settings.

Thirdly, he noted that the Cretaceous succession contains at least five major unconformities, contrasting with the Jurassic which contains only one.

The Cretaceous succession has been extensively studied because it contains abundant reservoir intervals. It is the most productive interval in Iraq and contains about 80% of the country's oil reserves (Al-Sakini, 1992). The Mishrif Formation contains the largest volume of undeveloped and underdeveloped oil in Iraq.

The map in Fig. 7.3 shows locations referred to in this chapter.

Structural setting

Three major periods of Cretaceous basin development and tectonic activity can be identified in Iraq: late Tithonian – early Turonian; late Turonian – early Campanian; and late Campanian – Maastrichtian. The palaeotectonic setting of Iraq during these three time periods is discussed in Chapter 3.

**For the purposes of this book, the "Cretaceous" succession includes the lower part of Megasequence AP8 which is uppermost Jurassic (upper Tithonian).*

Late Tithonian - early Turonian

The nature of the Cretaceous – Jurassic boundary varies from conformity to marked unconformity (IPC, 1956). A regional unconformity at the base of the Cretaceous in western Iraq (Fig. 7.1) can be dated at 149 Ma. The unconformity is subcropped by Jurassic and locally Triassic sequences (Dunnington, 1958; Dunnington *et al.*, 1959). The Rutbah-Khleisia-Mosul palaeohighs in the north and west of Iraq were onlapped from late Tithonian time onwards.

In the mid-Tithonian, evaporitic sedimentation in the Gotnia Basin abrubtly ceased; deposition of very condensed, deep shelfal and basinal organic-rich shales, marls and micritic limestones occurred in the late Tithonian. The Cretaceous basin which succeeded the highly restricted Gotnia Basin is referred to here as the "Balambo-Garau Basin"(Figs 3.31, 3.32). The NE portion adjacent to Iran was termed the "Permanent Basin" or "Kirkuk Embayment" by IPC geologists (e.g. Dunnington, 1958). Neocomian regional subsidence was most intense in the centre of the Balambo-Garau Basin (Jassim and Buday, 2006e),where late Tithonian sedimentary rocks are preserved. The western depositional limit of Tithonian source rocks may have been controlled by the NW-SE trending Abu Jir Fault Zone (Fig. 3.7) and a north-south trending fault system to the west of Tikrit.

During passive Early Cretaceous (Berriasian–Albian) subsidence, carbonate platform margins aggraded and locally prograded into the Balambo-Garau Basin. Up to 1500 m of carbonates with significant late Neocomian and Albian siliciclastic intervals were deposited (Jassim and Buday, 2006e). The locations of the basin margins may have had an underlying tectonic control.The NE margin was located to the NE of present-day Iraq. It can be identified in the Iranian Zagros (Setudehnia, 1978).

In the Early Cretaceous, two phases of thermal doming and rifting occurred in eastern Africa (Burke and Whiteman, 1973; Giraud and Maurin,

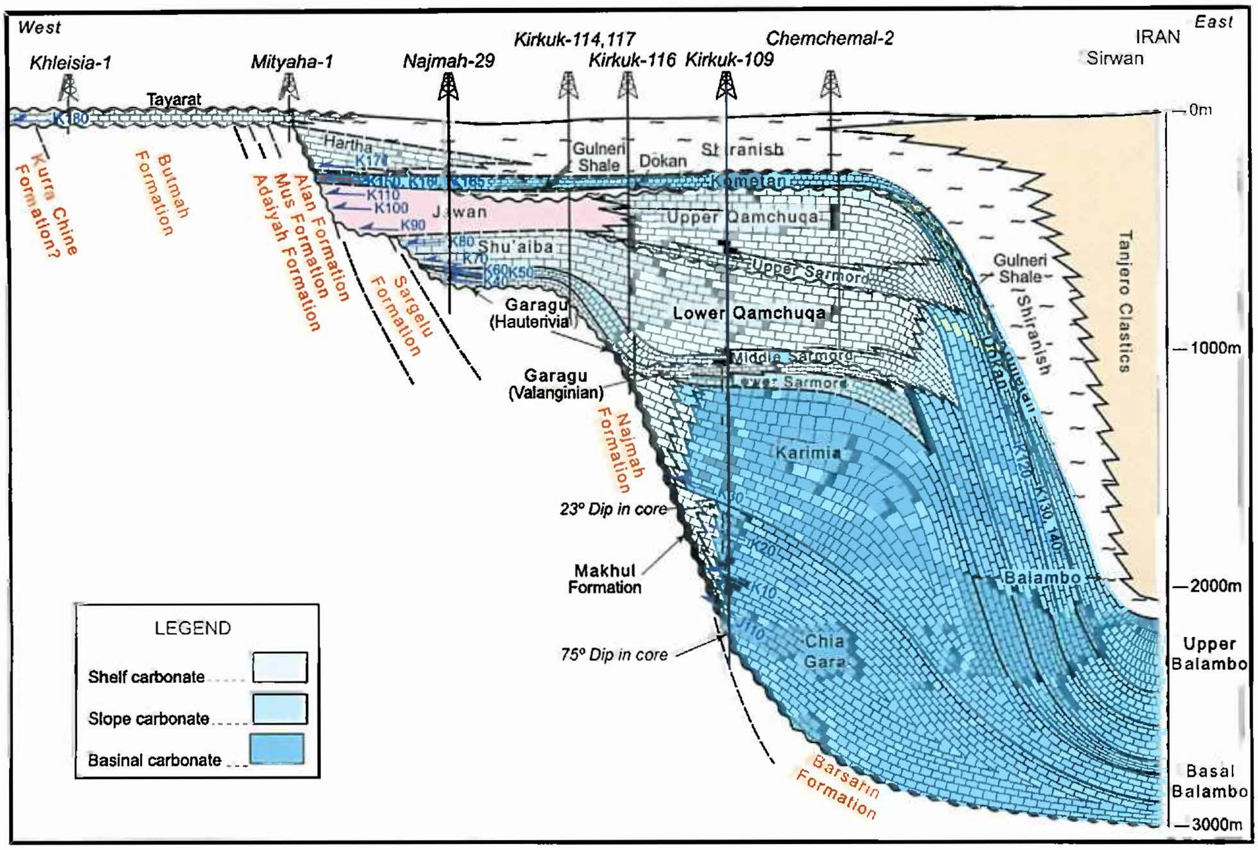


Fig. 7.1. Schematic west-east cross-section across northern Iraq showing onlap of Cretaceous units onto Jurassic and older stratigraphy. Local stratal dips have been removed. Based on data in IPC (1956), Dunnington *et al.* (1959), Wilson (1975), Buday (1980) and Jassim and Buday (2006e,f). Note the composite erosional unconformity at the base of the Cretaceous succession. Lower Jurassic and Upper Triassic formations subcrop the base of the Cretaceous on the Khleisia High in the west.

1992). This led to the uplift and erosion of the western Arabian Shield with the eastward progradation of clastic wedges into Arabia (Al-Fares *et al.*, 1998). These wedges form important sandstone reservoirs (Zubair and Nahr Umr Formations). They pass eastwards into open-marine deposits which consist of globigerinal shales, marls and limestones (IPC, 1956). Progradation of these siliciclastic systems pushed back the platform carbonates which only developed in more distal areas (Davies *et al.*, 2002).

A major sequence boundary occurs between the Aptian and the Albian. This corresponds to a change in Arabian Plate motion from the slow southward drift which had taken place since the end of the Jurassic, to northwards drift coincident with the opening of the Equatorial Atlantic (Al-Fares *et al.*, 1998) (Fig. 3.23). Subtle structural growth controlled by movement on basement faults may have begun in the late Albian in Iraq (c.f. Sadooni and Aqrawi, 2000). In the Euphrates Graben area of eastern Syria, the isopach of the Albian Upper Rutbah Shales indicates the onset of extension (Caron *et al.*, 2000). Rifting in the Euphrates Graben was accompanied by basaltic volcanism, dated by the K/Ar method at 95 Ma (late Albian – early Cenomanian) (Caron *et al.*, 2000). In the Abd El Aziz trough of NE Syria, the first pulse of extension occurred in the Early Cretaceous (Kent and Hickman, 1997). The oldest Cretaceous sediments known in Western Iraq, from the Sinjar Trough (Kaddouri and Al-Shabani, 1993) and Western Desert (Kaddouri, 1989; Jassim and Goff, 2006) are of Barremian age.

The end of the Albian is marked by a major sequence boundary (Dunnington, 1958; Buday 1980). Subsequent increased regional subsidence led to onlap of palaeohighs, progressive backstepping of carbonate platforms, and widespread deposition of deep-water carbonates.

Arabia continued to migrate northwards during the Late Cretaceous (Al-Fares *et al.*, 1998), partly as a consequence of the opening of the Atlantic (Sharland *et al.*, 2001). Differential subsidence in the Cenomanian formed an intrashelf basin in the Awasil-Nafatah-Fallujah area of central Iraq (Sherwani and Aqrawi, 1987), referred to here as the Najaf Intrashelf Basin (Fig. 7.34). This mainly contains marly oligosteginal limestones (Aqrawi, 1983; Sherwani, 1983; Aqrawi *et al.*,1998). In SE Iraq to the east of the Najaf Intrashelf Basin, a broad carbonate platform developed on which thick shallow-water rudist carbonates were deposited (Figs 3.32, 7.34). Rudist shoals and build-ups

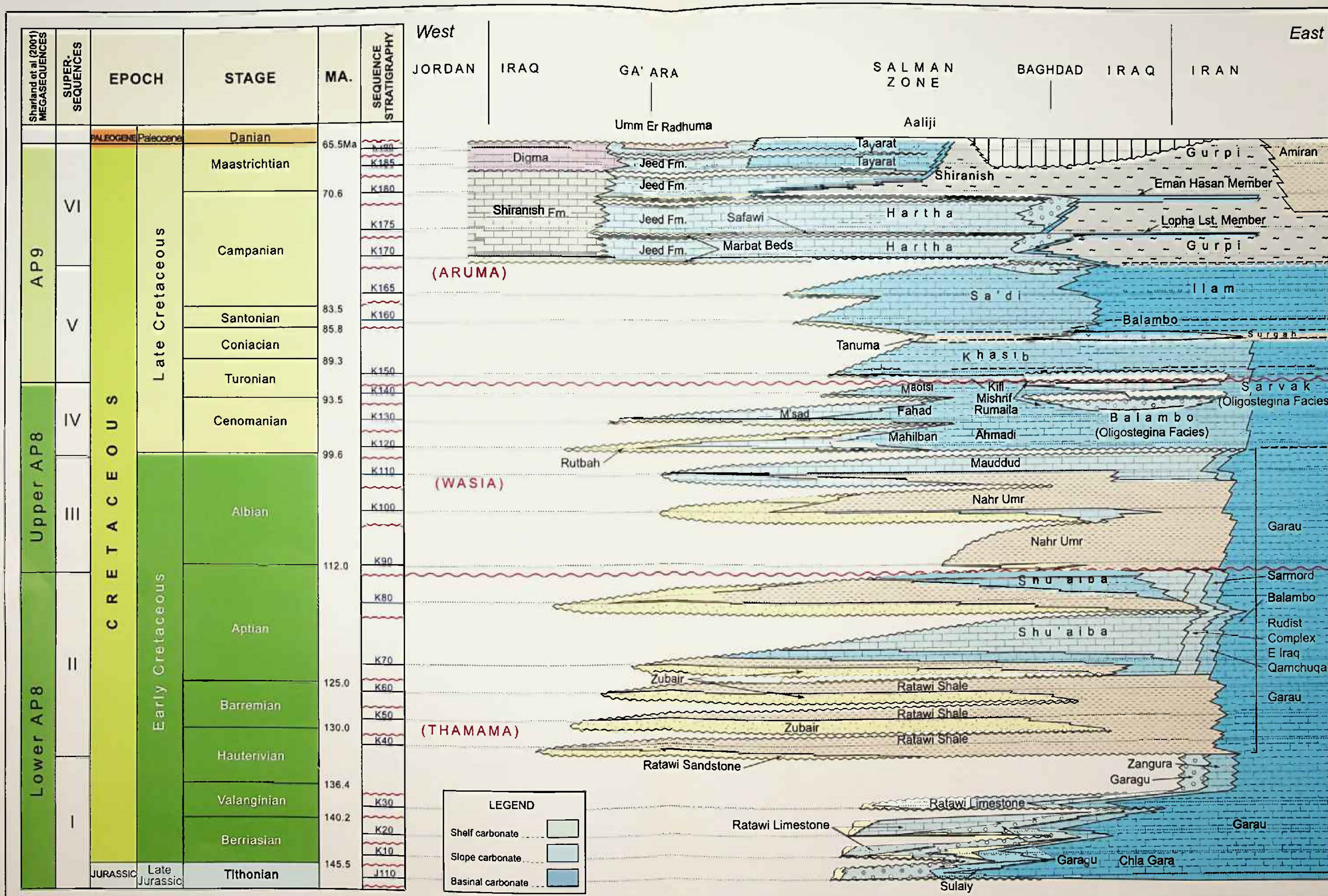


Fig. 7. 2. Cretaceous chronostratigraphy of Iraq; the profile runs from the Western Desert through central Iraq and the Baghdad area to the border with Iran. A similar stratigraphic organization is present in southern Iraq.

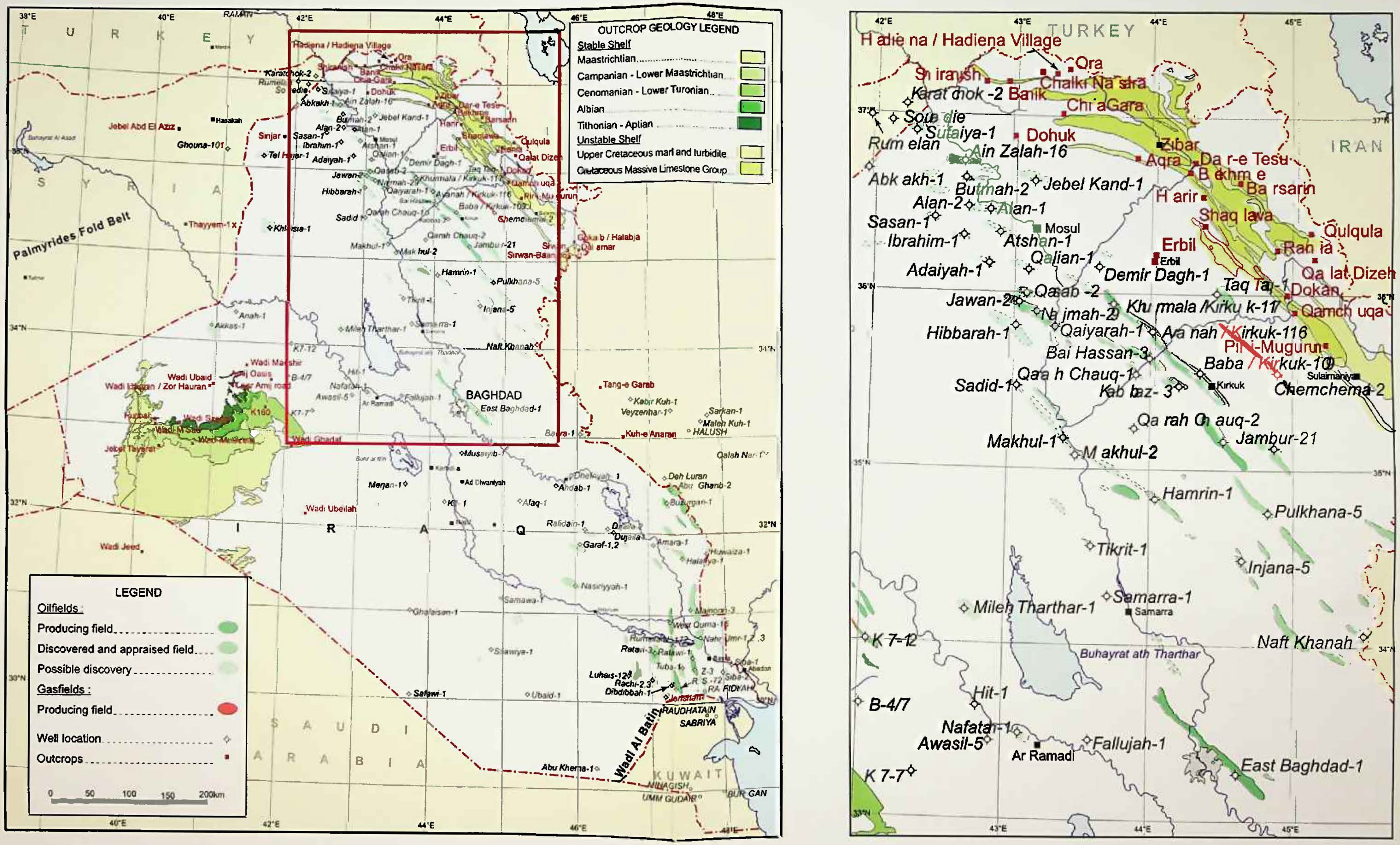


Fig. 7. 3. Map of Iraq and adjacent areas showing key wells (labelled in black), fields and other localities mentioned in this chapter, together with areas where Cretaceous rocks are exposed at the surface. Important outcrop areas are labelled in red.

developed locally on north-south trending palaeohighs (Sadooni and Aqrawi, 2000). Faulting may have begun along the Tikrit-Samarra-East Baghdad lineament,with initial deposition of the Mishrif Formation. A submarine palaeohigh in Iraqi Kurdistan to the NE of Kirkuk(Dunnington, 1958;Kaddouri,1982b) also developed in the Cenomanian.

Late Turonian - early Campanian

Important tectonic activity occurred in Turonian – early Campanian time in Iraq, possibly related to the subduction of the southern branch of Neo-Tethys (Jassim and Goff, 2006b). In SE Iraq, reactivation of basement lineaments resulted in the formation of large-scale north-south trending anticlines. These anticlines contain important Lower Cretaceous and Cenomanian oil reservoirs. They are asymmetric; their western limbs dip more steeply than their eastern limbs (Al-Gailani, 2003). Growth of similar anticlines began in the Turonian in Kuwait, Saudi Arabia and Qatar. Formation of narrow, wrench-related, NW-SE trending faulted anticlines occurred in west-central Iraq, and regional extension began in NW Iraq. At the same time, uplift occurred on the Rutbah and Khleisia Highs over which Turonian – early Campanian sediments are absent.

In the Euphrates graben system in Syria and adjacent parts of western Iraq, block-faulting and graben formation began in the Turonian – Coniacian, with a period of tectonic quiescence in the Santonian (Litak *et al.*, 1998; Caron *et al.*, 2000). Narrow NW-SE trending structural corridors formed in Central Iraq (Tikrit, Balad and East Baghdad: Al-Jawadi, 1990; Sadooni, 2004;).

Late Campanian – early Maastrichtian

Plate motion changed from north- to northeastward drift in the late Campanian (Al-Fares *et al.*, 1998). In late Campanian – early Maastrichtian time, a narrow, deep foreland basin formed in NE Iraq in front of advancing thrust sheets and ophiolites (Jassim and Goff, 2006b) (Fig. 3.33). Further west, a significant pulse of rifting occurred during the late Campanian with the formation of a series of "troughs" in Syria and Iraq including the Khleisia, Tayarat, Anah, Turayf and Tinif troughs in western Iraq (Fig. 3.7), and the Sinjar trough in NW Iraq (Fig. 3.5). These troughs contain thick successions of upper Campanian – Maastrichtian basinal marls and carbonates (Jassim and Buday, 2006e). Up to 2000 m of sediments were deposited between 80 and 65 Ma, corresponding to a compacted sediment accumulation rate of up to 130 m/ Ma. Tilted fault blocks and horsts developed, and wrench-related faulted anticlines formed in areas affected by related strike-slip faulting. Major extensional faults were oriented perpendicular or oblique to the axis of regional compression.

NW-SE trending extensional basins elsewhere on the Arabian Plate include the Euphrates and Azraq-Sirhan grabens (Lovelock, 1984; de Ruiter *et al.*, 1995; Kent and Hickman, 1997). In the Euphrates Graben, major NE-vergent listric faults developed at the SW margin of the basin (Caron *et al.*, 2000). A narrow, inverted, fault-controlled basin may underlie the NW-SE trending Makhul-Hamrin anticlinal trend as indicated by a gravity anomaly (Fig. 3.19). Similarly oriented fault-controlled features occur along the *East Baghdad* lineament, and possibly along the Adab-Rafedain lineament in SE Iraq (Fig. 3.7).

The Balambo-Tanjero Zone, Mosul High and Rutbah-Jezira High (Fig. 3.7) were uplifted with erosion of upper Turonian – lower Campanian strata (Dunnington, 1958; Jassim and Buday, 2006f). Footwall highs were significantly eroded and locally supplied olistoliths as old as Palaeozoic into the adjacent basins, e.g. at Jebel Abd El Aziz in Syria (Kent and Hickman, 1997).

Plate motion by Maastrichtian time reverted to northward drift (Al-Fares *et al.*, 1998) (Fig. 3.23). Subtle structural growth occurred in northern Iraq in latest Maastrichtian time. Upper Maastrichtian sediments are absent on many anticlines including Jebel Sinjar (Dunnington, 1955; Kennedy and Lunn, 2000), probably due to a phase of inversion. At Jebel Sinjar, Paleogene Sinjar Limestone Formation shelf carbonates unconformably overlie Shiranish Formation basinal carbonates (van Bellen, 1959). North-south compression in the late Maastrichtian also terminated rifting in the Euphrates Graben and resulted in inversion, particularly where the graben joins the Palmyride Fold Belt (Caron *et al.*, 2000).

Structural versus constructional "highs"

Constructional "highs", often with relief of several hundreds of metres, have influenced the Cretaceous stratigraphic succession. These highs are lithified platform margins which pass on either side into thinner and/or less consolidated and more compacted deposits (lagoonal or basinal).

The Barremian – Albian Qamchuqa Formation represents a platform margin which formed a positive feature in NE Iraq in the Kirkuk, Chemchemal and Jambur areas. It was referred to by Jassim and Buday (2006e) as the "Qamchuqa ridge". During the Cenomanian to early Campanian, condensed, relatively deep-water but shelfal facies (Dokan and Kometan Formations) thickened away from the "ridge" (see Fig. 7.20), indicating that it formed a submarine high. Later, the "ridge" controlled the location of the Bekhme and Aqra platform limestones, which themselves formed constructional highs in the late Campanian – Maastrichtian.

Table 7.1. Table summarising Cretaceous stratigraphic units in Iraq showing the units' distribution in time and space. Based on various sources including Dunnington *et al.*, 1959; Buday, 1980; and Sadooni and Aqrawi, 2000.

Supersequence	Age	Western Desert / SW Iraq	SE Iraq (Subsurface)	Central Iraq (Subsurface)	Northern Iraq (Subsurface)	Northern Iraq (Outcrop)
VI	Late Campanian-Maastrichtian	Tayarat Digma Pilsener Jib'ab	Tayarat Qurna / Shiranish Hartha Safawi	Shiranish Mushak Oolite Dibs Anhydrite	Shiranish Hartha	Aqra Tanjero Shiranish Bekhme Hadiena
V	Middle Turonian - Early Campanian		Sa'di Tanuma Khasib Kifl	Sa'di Tanuma Khasib Kifl	Mushorah Wajnah Kometan Lst. Kometan Shale Kometan Lst. Gulneri	Kometan Balambo Gulneri
IV	Latest Albian Early Turonian	M'Sad Rutbah	Mishrif Rumaila Ahmadi	Maotsi Fahad Mahilban	Gir Bir	Mergi Dokan Balambo
III	Latest Aptian - Late Albian	? Mauddud	Mauddud Nahr Umr	Mauddud Jawan Upper Sarmord / Batiwah	Mauddud Upper Sarmord / Batiwah Rim Siltstone	Upper Qamchuqa Upper Sarmord Sarmord Balambo
II	Late Valanginian - Late Aptian	? Shu'aiba Saggar / S'Ker	Shu'aiba Zubair Ratawi Shale	Shu'aiba Zubair	Shu'aiba Lower Sarmord	Lower Qamchuqa Sarmord Balambo
I	Late Tithonian - Middle Valanginian		Ratawi Lst. Yamama Sulaiy	Zangura Makhul	Garagu Sarmord Karimia Chia Gara	Garagu Sarmord Balambo Chia Gara

Shelf Carbonate .... Slope Carbonate .... Phosphatic Carbonate .. Basinal Carbonate and Marl .... Oligosteginal Carbonate and Marl ....

Shelf Shales .... Fluvio- Deltaic Sandstone .... Turbidite / Flysch .... Anhydritic .... Restricted Shelf ....

Condensed / Glauconitic ....

Another constructional feature is the Amara Palaeohigh in southern Iraq upon which shallow-water limestones of the Mishrif Formation were deposited (Aqrawi *et al.*, 1998) (Fig. 7.33). This palaeohigh is located above a pre-existing Barremian–Albian platform margin. Significantly greater thicknesses of Mishrif Formation limestones are present here compared to surrounding basinal areas.

Deepwater shelves with little or no structural control occur. Some of these sediment-starved areas were referred to as "migratory carbonate suppressed belts" by Davies *et al.* (2002). A possible example is the zone between the shallow-water / deltaic siliciclastics of the Zubair and Nahr Umr/Burgan Formations and the outboard Balambo Formation basin. Relatively deep-water limestones and shales were deposited in this area. They extended into Iran during the Albian, where the Kazhdumi Formation was deposited in waters about 100 m deep (Bordenave and Huc, 1995). Another example is the latest Albian – early Turonian Najaf Intrashelf Basin (Fig. 7.34).

These intrashelf basins were sometimes sites of lowstand evaporite deposition, e.g. the Kifl and Safawi Formations (Fig. 7.45, 7.53). Biogenic carbonate productivity in the basins was suppressed due to adverse environmental conditions such as freshwater plumes in front of deltas (Davies *et al.*, 2002) or increased salinities behind reefal belts. Once a basin was initiated, its topography accentuated the restricted environmental conditions, further reducing carbonate production.

These highs and basins of non-tectonic origin have previously been attributed to tectonic controls. An example is the Barremian – Albian platform margin which crosses the *Jambur* field (Fig. 7.20) and extends to the SE of *Kirkuk* and *Chemchemal* fields (Fig. 7.21).The platform may have prograded to a point where, in the Barremian, it was limited by a fault (the "Anah-Qalat Dizeh Fault" of Jassim and Buday, 2006e: Fig. 3.18). However, once platform margin progradation had ceased, it began to aggrade with no continued structural control.

It is often difficult to distinguish between active tectonic and inherited controls on carbonate platform margins.

Palaeoclimate

The palaeolatitudinal location of the Arabian Plate influenced Cretaceous stratigraphy in Iraq. Progressive northward drift placed the Arabian Plate in equatorial tropical latitudes. Prevailing winds came from the east, as indicated by the identification of high-energy windward and low-energy leeward facies in the Valanginian Yamama Formation at *West Qurna* (Sadooni, 1993b; Sadooni and Aqrawi, 2000). Climate probably became more arid from the Albian onwards. Evaporites (mainly anhydrites) were deposited in platform-top intrashelf basins during lowstands and when the supply of coarse clastic sediment decreased. Conversely, detrital illite and kaolinite in the Sa'di, Tanuma and Khasib Formations may indicate a reversion to tropical or sub-tropical climatic conditions (Aqrawi, 1996).

Stratigraphy

The Cretaceous succession in Iraq has been studied intensively but relatively little data has been published (Sadooni and Aqrawi, 2000). It has been divided into contrasting stratigraphic schemes by different authors. Some sequence boundaries were originally defined using stratigraphic breaks which are no longer considered to be important (e.g. the "intra-Berriasian break" of Dunnington, 1958), or using only lithostratigraphic criteria.

Dunnington *et al.* (1959) and Al-Naqib (1967) recognized five depositional "cycles". These cycles are capped by the upper boundaries of the Shu'aiba Formation (Albian–Aptian boundary), the Mauddud Formation (Albian– Cenomanian boundary), the Mishrif Formation (upper Cenomanian–lower Turonian), the Sa'di Formation (upper Campanian), and the top of the Cretaceous, respectively. Ditmar *et al.* (1971, 1972, *in* Buday, 1980) divided the Cretaceous stratigraphy into two intervals separated by an unconformity at the top of the Mishrif Formation and time-equivalent units. Al-Siddiki (1978a) used a three-fold subdivision equivalent to the Thamama, Wasia and Aruma Groups of the central Gulf and Kuwait. Buday (1980) identified four "cycles". Sadooni and Aqrawi (2000) proposed a sequence stratigraphic framework with seven Cretaceous sequences. They recognized large- and medium-scale accommodation cycles using available sedimentological and palaeontological data.

Abundant, easily datable shelf carbonate units in the Cretaceous succession facilitates identification of coastal onlap (Fig.7.1). Sharland *et al.* (2001) identified nineteen third-order sequences within Megasequences AP8 and AP9; these sequences were labelled J110 to K180 inclusive. They noted that "bundles" of sequences show onlap and have increasingly marine (or deeper-marine) characteristics upwards (e.g. their figure 3.28; Fig. 3 of Davies *et al.*, 2002; Godet *et al.*, 2008).

Six of these bundles (defined here as **Supersequences I-VI**) are identified in the Cretaceous succession (Table 7.1). Supersequences I-IV correspond to Megasequence AP8, and V-VI to AP9 (Fig. 7.2). The megasequences are separated by a regional unconformity of mid-Turonian age. The supersequences comprise:

Supersequence I: Upper Jurassic – lower Neocomian (late Tithonian – middle Valanginian) ("Lower Thamama"). This includes four maximum flooding surfaces (J110 to K30) and contains the Sulaiy/Makhul and Yamama/Garagu Formations.

Supersequence II: upper Valanginian – upper Aptian ("Upper Thamama"). The supersequence comprises a major siliciclastic system overlain by a carbonate platform. It includes five maximum flooding surfaces (K40-K80) and contains the Zubair and Shu'aiba (Lower Qamchuqa) Formations.

Supersequence III: uppermost Aptian – upper Albian ("Lower Wasia"). This supersequence also consists of a siliciclastic system and an overlying carbonate platform. It includes three maximum flooding surfaces (K90-K110) and contains the Nahr Umr and Mauddud (Upper Qamchuqa) Formations.

Supersequence IV: uppermost Albian – lower Turonian ("Upper Wasia").This supersequence marks the onset of carbonate platform drowning and the end of large-scale siliciclastic deposition. Within this supersequence, Sharland *et al.* (2001) identified three maximum flooding surfaces (the K120, K130 and K140 MFSs). However, four maximum flooding surfaces can be identified in Iraq. They are located at the base-Ahmadi Formation; at the base-Rumaila; and two are within the Mishrif Formation, including a new MFS at the base of the formation provisionally named K135 (see Fig. 7.33).

Supersequence V: upper Turonian – lower Campanian ("Lower Aruma"). This supersequence consists predominantly of deep shelf sediments in Iraq and includes the Khasib, Tanuma and Sa'di Formations. The supersequence includes the K150 to K160 maximum flooding surfaces of Sharland *et al.* (2001) and an additional surface (defined here as K165) in the lower Campanian.

Supersequence VI: middle Campanian – Maastrichtian ("Upper Aruma"). Ophiolite obduction along the NE margin of the Arabian Plate created a foreland basin during the late Campanian. Transtensional deformation intensified in northern and central Iraq where rift margins were often significantly uplifted and eroded. Deposition was differentiated on highs and lows, with both thick platform carbonates (Hartha, Bekhme, Aqra Formations) and basinal marls (Tanjero, Shiranish Formation). Supersequence VI includes the K170, K175 and K180 maximum flooding surfaces of Sharland *et al.* (2001); two younger surfaces (?K185 and ?K190) have been identified within the supersequence in the Zagros foldbelt.

Age Dating

Cretaceous stratigraphic units have been dated using IPC palaeontological data presented in

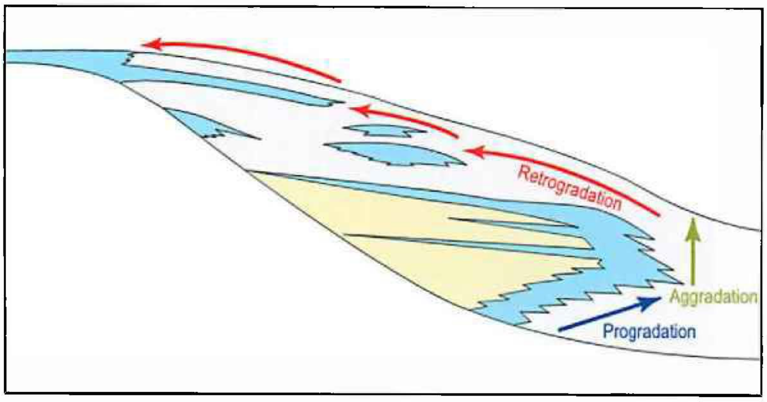


Fig.7.4. Sketch diagam showing the development of coarse detrital siliciclastic units (yellow) and shallow-marine carbonate units (blue) within the Cretaceous stratigraphy of Iraq. Basinal carbonate facies are shaded grey.

Dunnington *et al.* (1959) and by comparison with equivalent formations in the Gulf area. Data from recent publications on Iraq were also used. The data include: the review of the Upper Cretaceous in Southern Iraq by Darmoian (1975); Whittaker *et al.*'s (1998) revision of the IPC micropalaeontological collection; Al-Ameri *et al.*'s (1999) study of the palynology of the Sulaiy Formation; Ali and Aziz's (1993) description of the Zubair Formation at *East Baghdad* field; and publications by Mohammed and Al-Sayyab (1993) and Al-Ameri *et al.* (2001) on the palaeontology of the Nahr Umr and Mauddud Formations.

The ages of Early and mid-Cretaceous units in Kuwait were recalibrated by Al-Fares *et al.* (1998). Revisions to the later Cretaceous stratigraphy in Iraq were made by Kaddouri (1982a,b) and Haddad and Amin (2007) for the mid-Turonian – early Campanian. Al-Shaibani (1973), Kassab (1973, 1975a,b, 1978a), Al-Omari and Sadek, 1974, Abdel-Kireem (1983, 1986a,b), Al-Omari *et al.* (1989) and Kennedy and Lunn (2000) revised the Campanian – Maastrichtian stratigraphy. Jassim and Buday (2006e,f) reviewed the palaeontology of the Cretaceous succession, providing important data on the Western Desert.

The biostratigraphic basis for calibration of the Cretaceous succession in Iraq is improving but some horizons are still poorly dated. Future work may challenge previous assumptions concerning formation ages. For example, palynological dates from various authors appear to disagree with micropalaeontological dates established for the middle part of the Cretaceous. Both Venkatachala and Rawat (1980) and Al-Ameri and Batten (1997) revised the age of the Zubair Formation upwards into the Aptian – mid-Albian using palynology. Also, Henson (1948) and later authors (Ibrahim, 1981b, 1983; Al-Ameri *et al.*, 2001; and Sadooni and Alsharhan, 2003) suggested that the top of the Mauddud Formation is at least locally of earliest Cenomanian age, implying that it may be diachronous from north to south.

Cyclic Cretaceous stratigraphic successions have often been mis-correlated. This is usually because cycles of different ages have similar lithologies and log responses. For example, high resolution biostratigraphic studies of the Wara and Mauddud Formations of offshore Kuwait indicate that they occur in or just below nannofossil zone KN31 (Al-Fares *et al.*, 1998). However, the "Mauddud Formation" here may in fact be equivalent in age to the Dair Limestone Member of the Nahr Umr Formation in Iraq. The Iraqi Mauddud Formation may be an entirely different and much younger unit.

Stratigraphic geometries and contacts

Megasequences AP8 and AP9 onlap westwards onto palaeohighs (Figs.7.1,7.2). Shelf systems prograded eastwards during the Neocomian into the relativly open-marine Balambo-Garau Basin (Fig. 7.4). During the Aptian – Albian, the shelf systems aggraded. From the Cenomanian onwards, the shelf systems were drowned and retreated westwards onto the palaeohighs. Middle and Upper Cretaceous deposits are more heterogeneous than underlying units. They include carbonate build-ups of various types (sponge-stromatoporoid, algal and rudist) including those in the Mishrif and Aqra/Bekhme Formations.

Contacts between Cretaceous and under- and overlying units are well defined in the north of Iraq, but less so in the south. At Barsarin and Chia Gara in the Balambo – Garau Basin centre, the contact between the upper Tithonian – basal-Cretaceous Chia Gara Formation and the underlying lower Tithonian – Kimmeridgian Barsarin Formation is sharp and conformable (Spath, 1950; Dunnington *et al.*, 1959; Howarth, 1992). This sharp contact is also recorded in wells *Kirkuk-109, Demir Dagh-1* and *Jebel Kand-1* (data in Dunnington *et al.*,1959; and Jassim and Buday, 2006e). Westwards, the contact is a major regional unconformity onlapped by the Hauterivian Garagu Formation in well *Najmah-29* (Dunnington *et al., ibid.*) (Fig. 7.1), and by upper Barremian – Aptian units near to the Syrian border in well *Tel Hajar-1* (Kaddouri and Al-Shaibani, 1993). Palaeohighs at Qalian and in the Alan-Butmah area were not onlapped until the Albian (Dunnington *et al.*, 1959). In the *Khleisia-1* well on the Khleisia High (Fig. 7.1), in the *Akkas-*

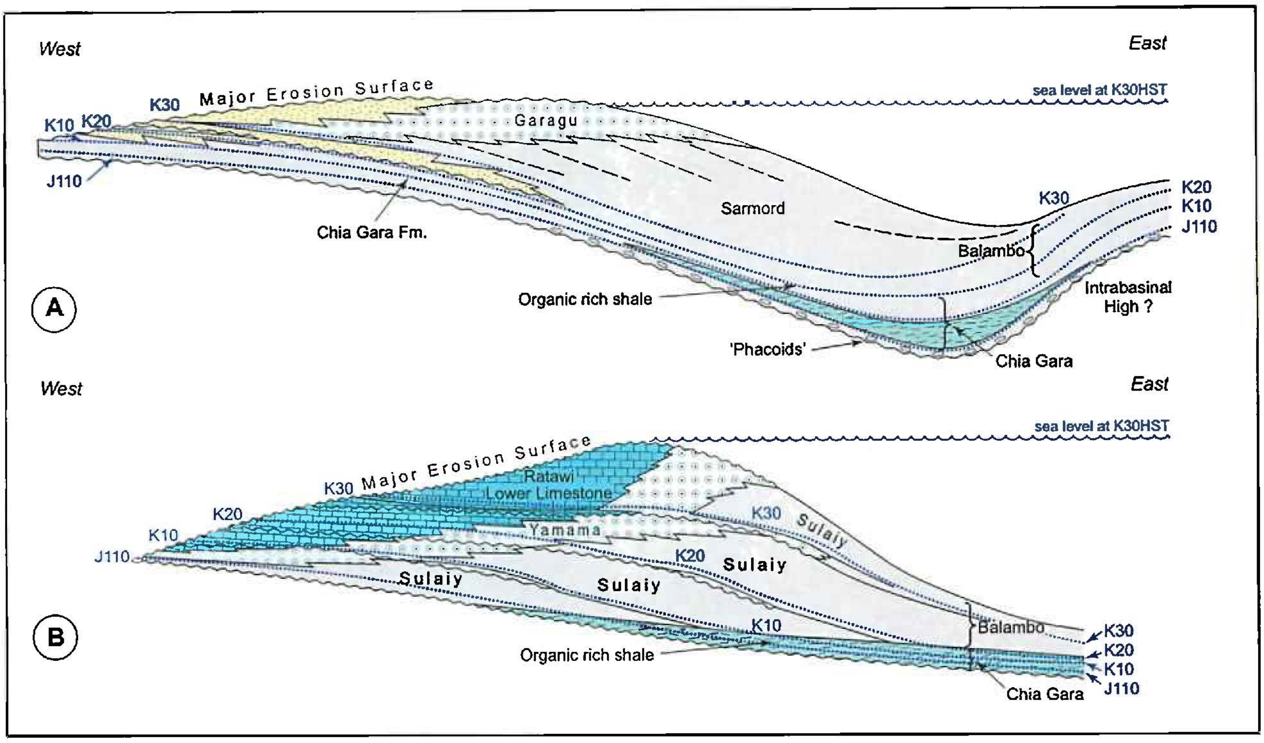


Fig. 7.5. Schematic west-east profiles across (a) northern Iraq and (b) southern Iraq, illustrating the organisation and relative thicknesses of late Tithonian – middle Valanginian stratigraphic units. The Garagu Formation in (a) is present as an oolite.

1 well and in the Western Desert (Fig. 3.17), onlap did not occur until the late Campanian or Maastrichtian (Dunnington *et al.*, 1959; Al-Naqib, 1967; Buday, 1980; Jassim and Buday, 2006e).

The upper contact of the Cretaceous succession (i.e. top-Megasequence AP9) is a significant depositional break. Several hundred metres of stratigraphy is missing at many anticlines in North Iraq (Dunnington, 1955). In addition, core descriptions of the contact as a "pot-holed", mineralised surface (Daniel, 1954 for *Ain Zalah*), together with the loss of later Maastrichtian biozones (Kennedy and Lunn, 2000), suggest a considerable submarine or even subaerial hiatus.

Supersequence I: upper Tithonian – middle Valanginian

Stratigraphic organization of this supersequence represents a simple eastwards transition from an onlap margin to a basin (Figs. 7.5, 7.6), as originally proposed by Dunnington (1958). The depocentre was located close to the Iran-Iraq border.

In northern Iraq (Fig. 7.5a), the Chia Gara Formation is gradationally overlain by the unfossiliferous Karimia Mudstone Formation, followed by the Sarmord Formation (e.g. in well *Kirkuk-109*) and the Garagu Formation (Dunnington *et al.*, 1959; Jassim and Buday, 2006e). At outcrops in northern Iraq, the Balambo Formation conformably overlies the Chia Gara Formation, e.g. to the SE of Sulaimaniya (Buday, 1980; Jassim and Buday, 2006e). The contact may be disconformable in SE Iraqi Kurdistan at *Rania, Dalamar* and *Sirwan* (Dunnington *et al.*, 1959; Jassim and Buday, 2006e).

In the south, the supersequence comprises prograding carbonate ramp deposits (Yamama Formation) overlying the upper Jurassic – lowermost Cretaceous Sulaiy Formation (Sadooni, 1993b; Al-Ameri *et al.*, 1999) (Fig. 7.5b). The Yamama Formation passes laterally into deeper shelfal facies of the Makhul Formation which in turn pass to the NE into the Chia Gara Formation (Jassim and Buday, 2006e). The Yamama Formation is overlain by the shelfal Ratawi Formation.

The upper contact of the supersequence, at the top of the Garagu and Ratawi Formations, is a regional unconformity throughout Iraq.The unconformity is overlain by the Zubair Formation in Central Iraq.

In Kuwait, a sequence boundary (marking a gap of 3 Ma) occurs at the top of the lower Valanginian Ratawi Formation, which contains the nannofossils *N. steinmannii minor, N. kamptneri minor, D. rectus* and *N. quadratus* (Al-Fares *et al.*, 1998; Douban and Medhadi, 1999). This sequence boundary is here considered to be equivalent to the contact between the Lower and Upper Members of the Ratawi Formation in Iraq (Fig. 7.13). Jassim and Buday (2006e) recommended that the Ratawi Formation should be divided into the "Ratawi Limestone" and the overlying "Ratawi Shale".

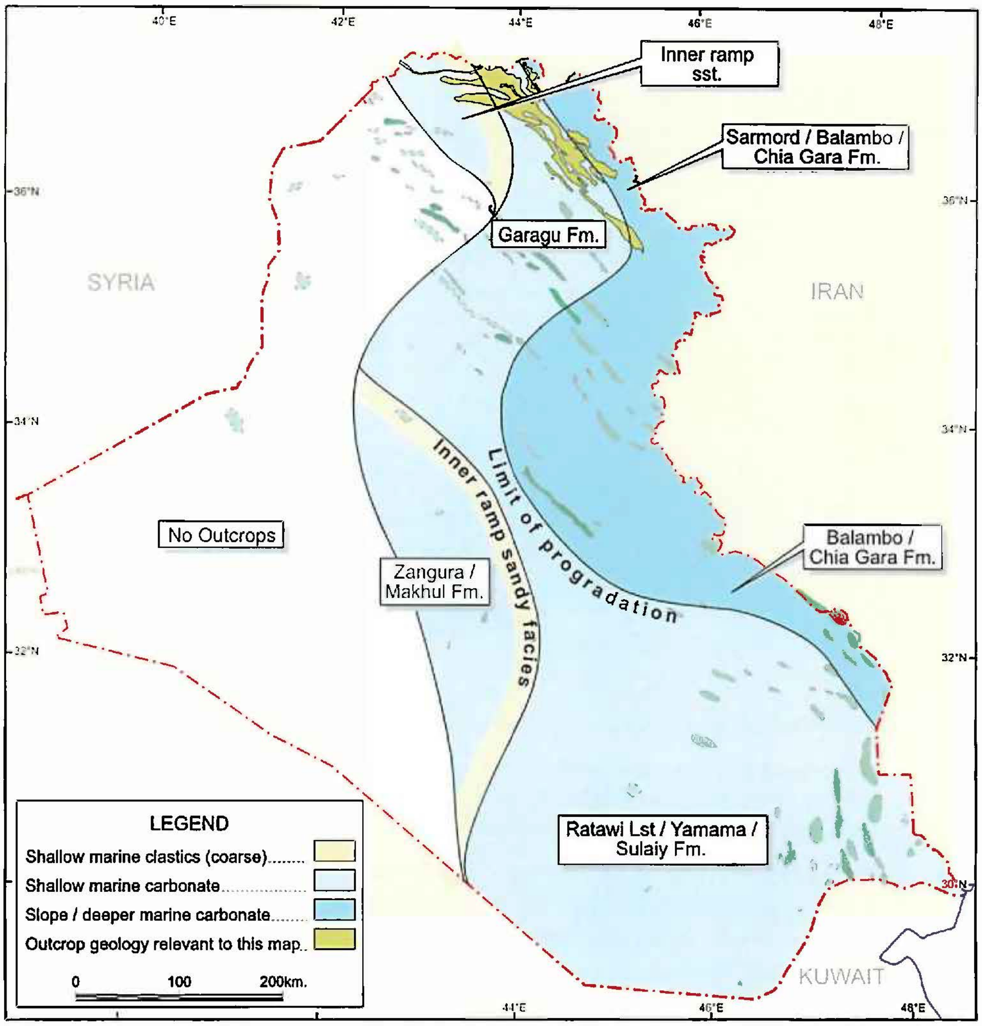


Fig. 7.6. Late Tithonian – middle Valanginian palaeogeography of Iraq. Note that these units crop out in Iraqi Kurdistan but not the Western Desert. Simplified Cambridge Carbonates Ltd map based on published data.

Formations

The **Sulaiy Formation** comprises argillaceous or marly pyritic limestones (Al-Siddiki, 1978a,b,c) grading into chalky, massive-bedded limestones with interbedded calcarenites (Jassim and Buday, 2006e). It is of late Tithonian or earliest Early Cretaceous age and contains the *Bramkampella* sp. faunizone at its base (Redmond, 1964; Al-Siddiki, 1978a,b,c). Its top may be as young as Valanginian (Al-Ameri *et al.*, 1999), particularly in the east where it grades into the overlying Yamama Formation (Fig. 7.7) (Sadooni, 1993b).

Chatton and Hart (1960 *unpublished, in* Jassim and Buday, 2006e) suggested that the Sulaiy should be defined as a "neritic limestone lithofacies". Towards the west over the Salman Zone, the formation becomes increasingly sandy; a sandstone bed marks its base (Jassim and Buday, 2006e). It was probably deposited on a distal dysoxic shelf (Al-Ameri *et al.*, 1999).

The carbonate-dominated **Yamama Formation** (Fig. 7.7–7.11) passes into and overlies the Sulaiy Formation. It is 400 m thick in the Zubair area (Sadooni, 1993b; Jassim and Buday, 2006e) (Fig.7.8). The formation is usually conformably overlain by the Ratawi Formation. Towards the west (over the Salman Zone), where the Yamama and Ratawi Formations are absent, the Zubair Formation unconformably overlies Jurassic rocks (Buday, 1980). The Ratawi Formation is also absent in Central Iraq where the Zubair Formation rests directly on the Garagu Formation (Dunnington *et al.*, 1959).

In SE Iraq, the formation comprises three depositional cycles (Sadooni, 1993b) (Fig. 7.9) later interpreted by Sharland *et al.* (2001) as equivalent to third-order sequences. Cycle tops contain oolitic grainstone inner-ramp facies which pass down into finer-grained peloidal facies and middle-ramp bioclastic/coral/stromotoporoid pack-wackestones. Outer-ramp cycle bases comprise thick grey shales with stringers of chalky micrite (Roychoudhury and Handoo, 1980). Yamama microfacies are illustrated in Plates 7.1 and 7.2.

Twelve to 14 sub-cycles may occur, bounded by lowstand horizons containing plant remains (Roychoudhury and Handoo, 1980; Sadooni, 1993b). Cycle tops (YR-A,-B,-C) and bases (YB-1, -2)

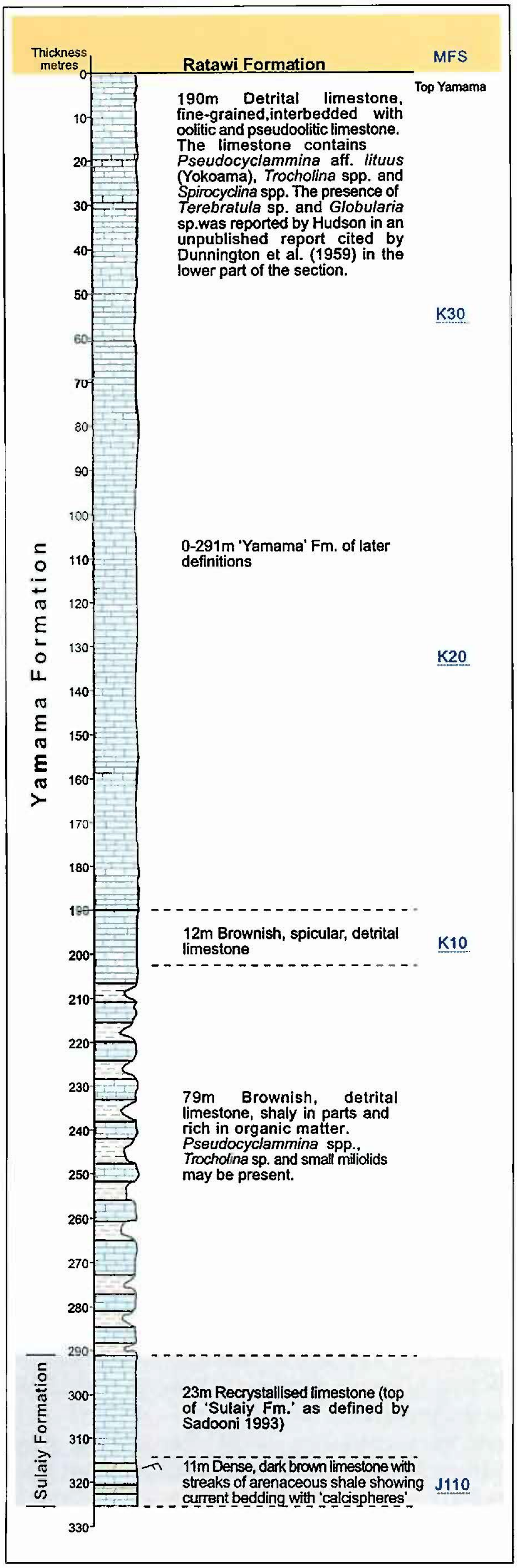


Fig. 7.7. Lithologic column for the Sulaiy and Yamama Formations at the Iraqi type locality, well *Ratawi-1*. From data in Sadooni, 1993b, after Dunnington *et al.*, 1959.

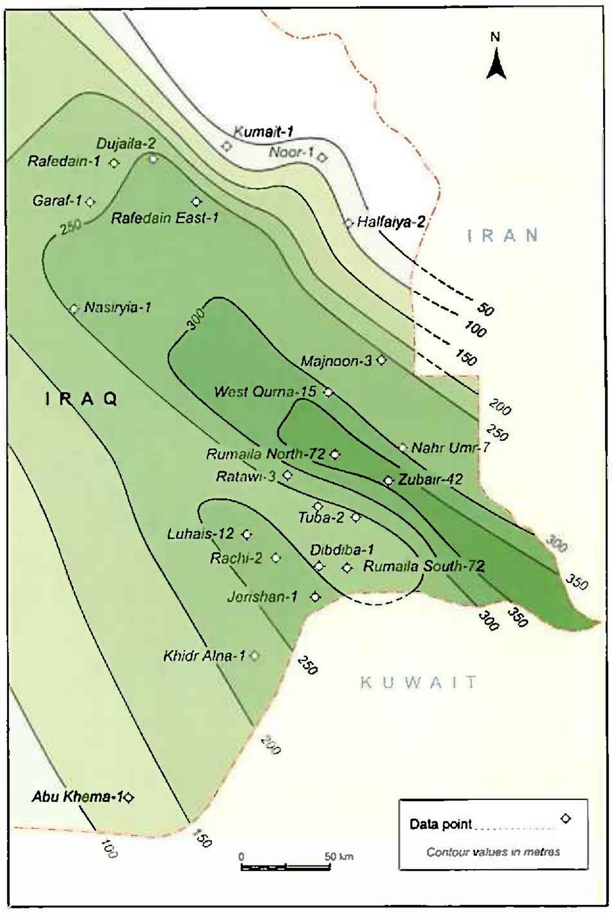


Fig.7.8. Isopach of the Yamama Formation. After Sadooni, 1993b.

represent late highstand and transgressive / early highstand systems tracts, respectively. They are organized into a series of NW-SE oriented "thicks" (Sadooni, 1993b) interpreted as "depocentres" (Jassim and Buday, 2006e) but here re-interpreted as bank complexes or build-ups.

Throughout the supersequence, cycle stacking in the Yamama Formation results in upwards facies changes. Roychoudhury and Handoo (1980) noted that "uppermost" facies are pinkish grey "intramicrites" and grey micrites which are locally chalky or contain thin, interbedded calcarenites; lower units are dominantly calcarenitic and oolitic. In well *Kifl-1* (Fig. 7.10a), the oldest sequence (highstand to the K10 MFS of Sharland *et al.*, 2001) is oolitic (Sadooni, 1993b). The middle sequence (highstand to the K20 MFS) is oolitic in the Luhais-Ratawi-Samawa area (Sadooni, *ibid.*). In the uppermost sequence (highstand to the K30 MFS), oolites prograded as far east as the *Nasiriya* area (Fig. 7.10c).

In SE Iraq, at the *Nasiriya, West Qurna, Majnoon* and *Amman* fields, probable sequence boundaries have been identified within the Yamama Formation at the top of oolite facies (G. Dhani, *pers. comm.*to F.S., 2008).

Facies belts indicate an easterly-facing ramp system (Sadooni, 1993b) (Fig. 7.6, 7.11, 7.12) with

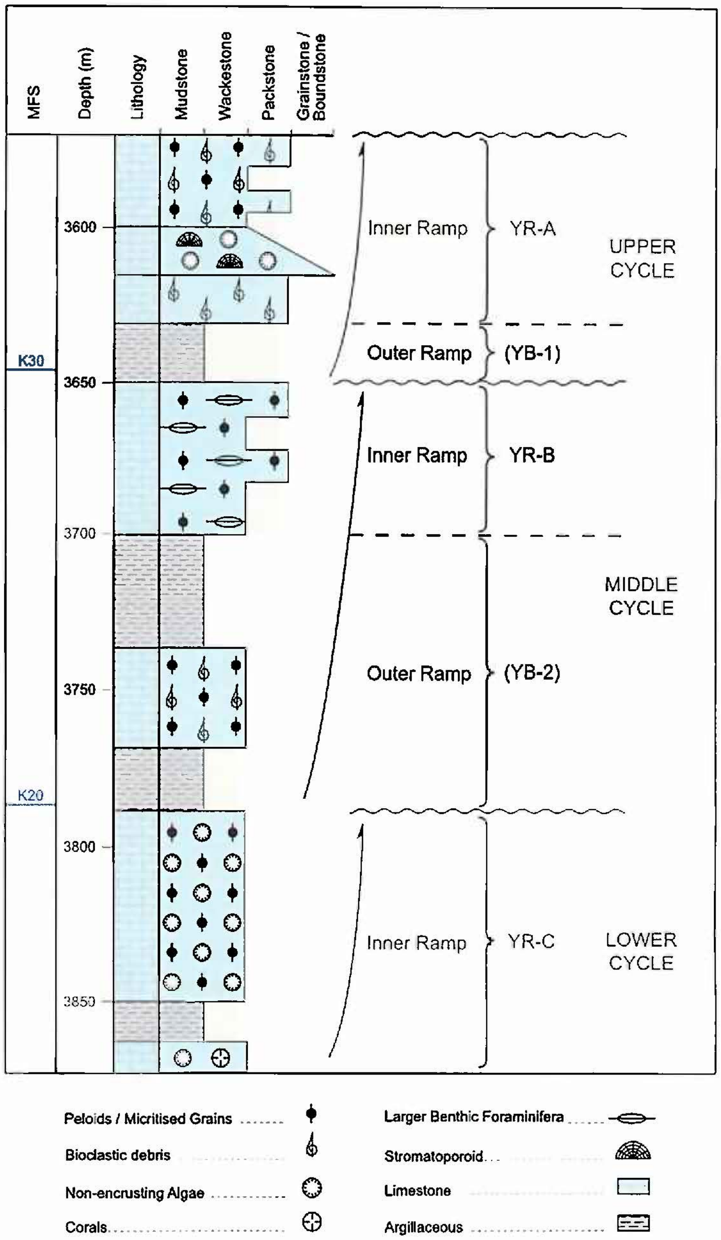


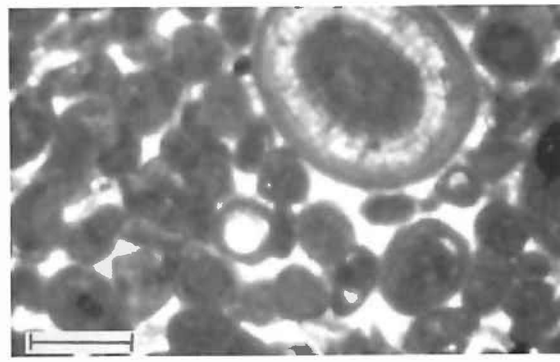
Fig. 7.9. Schematic stratigraphic log through the Yamama Formation at well *West Qurna-12* showing stacked depositional cycles. After Sadooni, 1993b.

limited development of updip marly limestones of the Lower Ratawi Formation. These Ratawi facies indicate the formation of the first Cretaceous Migratory Carbonate Suppressed Belt (MCSB), where input of clastic material has resulted in a decrease of carbonate production and hence the formation of a shallow basin (Davies *et al.*, 2002). In the Awasil area of Central Iraq (Dunnington *et al.*, 1959), siliciclastics were deposited together with high energy carbonates without producing an MCSB, indicating a more gradual clastic invasion in this area.

Low-energy stromatoporoid-algal-coral-reefal build-ups occur throughout the middle ramp facies belt of the Yamama Formation. These build-ups were probably deposited on crestal areas of growing structures, with more mud-rich facies deposited on the flanks (Sadooni, 1993b) (Figs. 7.11, 7.12).

The Lower Member of the overlying **Ratawi Formation** (Fig. 7.13) comprises calcareous shales and marly limestones interbeded with pyritic pseudo-oolitic, detrital limestones (Dunnington *et al.*, 1959; Sadooni, 1993b). This member is equivalent to the Buwaib Formation of Saudi Arabia (Powers *et al.*, 1966) and the Gadvan Formation of SW Iran (James and Wynd, 1965). In Kuwait, the Ratawi Formation is considered to be Berriasian – early Valanginian in age (Al-Fares *et al.*, 1998), and corresponds to the Lower Member of the Ratawi Formation in Iraq (Fig. 7.13). It is disconformably overlain by the Hauterivian Zubair Formation.

The **Makhul Formation** extends throughout Central Iraq (Fig. 7.14) at least as far north as the Hamrin Mountains (Dunnington *et al.*, 1959; Dunnington, 1967a; Sadooni and Aqrawi, 2000). It comprises argillaceous limestones and calcareous



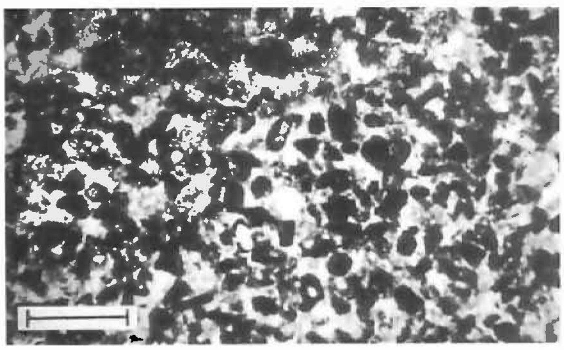
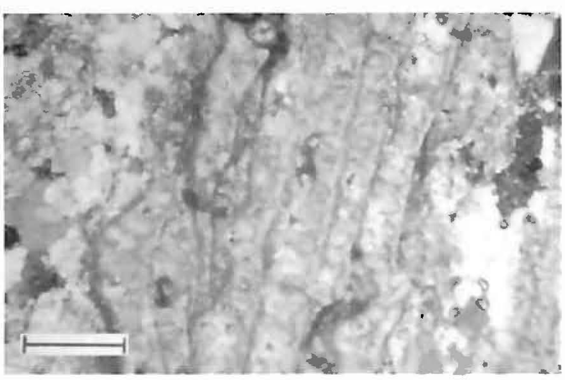
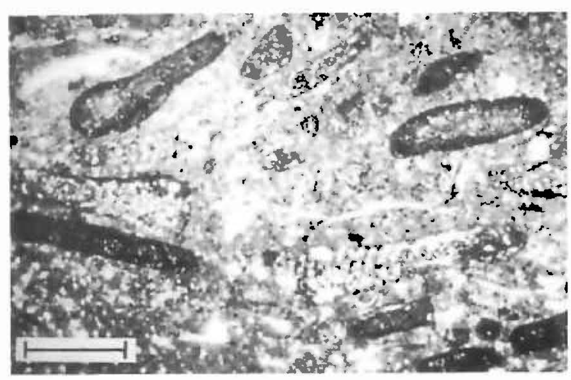


Plate 7.1. Yamama Formation microfacies (from Sadooni, 1993b). Scale bars: 1mm.

a. (left, above). Well-sorted oolitic grainstone with rare peloids. Well *Ratawi-1*, 3685 m.
b. (above). Poorly-sorted oolitic peloidal grainstone. Well *West Qurna-15*, 3670 m.
c. (left, below). Sand grade peloids probably of faecal origin. Well *Rumaila North 158*, 3869 m.





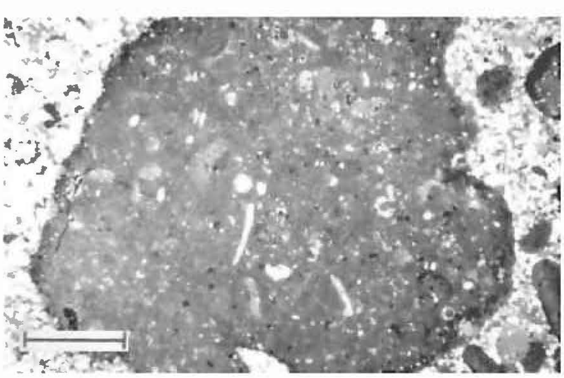


Plate 7.2. Yamama Formation microfacies (from Sadooni, 1993b). Scale bars: 1 mm.

a. (above left). Neomorphosed coral fragment. Well *West Qurna-12*, 3590 m.
b. (above, right). Packstone with variably micritized foraminifera including *Anchsipriocyclina* sp. Well *Rumaila South 72*, 3873 m.
c. (left). Intraclast of algal-debris wackestone in a micritic matrix. Well *Rumaila North 172*, 3810 m.

mudstones, locally dolomitised with beds of pseudoolitic limestone near the top and base. Marls occur in wells *Samarra-1* and *Musaiyib-1* (Dunnington *et al.*, 1959). A bed of anhydrite occurs near the base of the type section in well *Makhul-1*. In well *Awasil-5*, the formation is 145 m thick; oolitic facies may occur above the contact with the Gotnia Anhydrite (Dunnington *et al.*, 1959; Dunnington, 1967a). Sandstones and siltstones occur in wells *Fallujah-1*, *Samarra-1* and *Musaiyib-1* (Jassim and Buday, 2006e). The Makhul Formation was described as a "deep inner shelf facies" by Dunnington *et al.*, (1959) and Jassim and Buday, 2006e. It is probably chronostratigraphically equivalent to the Sulaiy Formation.

Northwards, the Makhul passes up into the **Karimia Mudstone** (Fig. 7.1) which is a poorly-fossiliferous micrite, 610 m thick in well *Kirkuk-109* (with thicknesses probably reflecting steep stratal dips), equivalent to the Sarmord Formation marls at outcrop in Iraqi Kurdistan (Dunnington *et al.*, 1959; Al-Naquib, 1960).

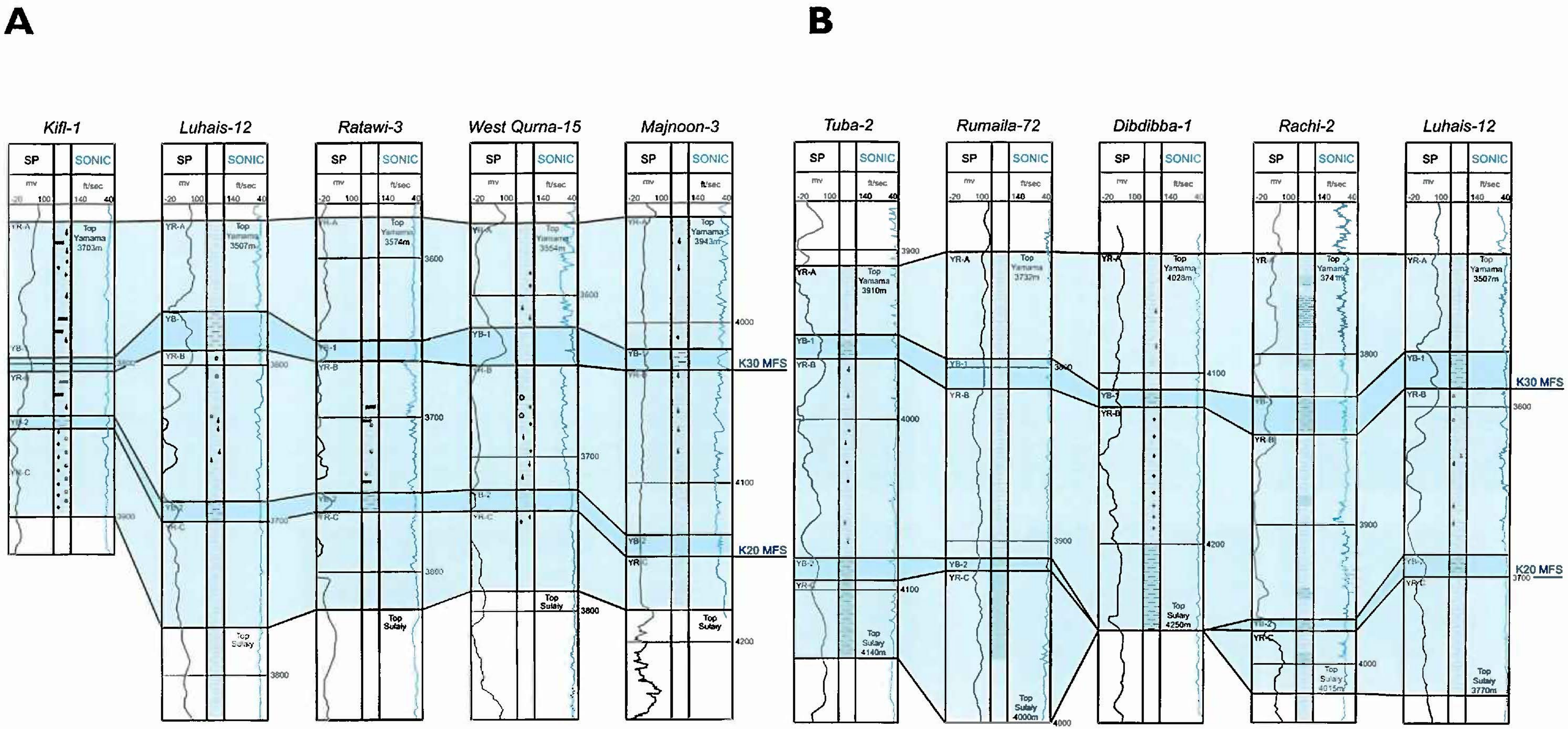


Fig. 7.10a(above left). Logs through the Yamama Formation ramp: mid-ramp wells. After Sadooni, 1993b.
Fig. 7.10b (above right). Logs through the Yamama Formation ramp: downdip wells. After Sadooni, 1993b.

Depths are in metres.

Key to colours (Figs 10a-c): grey: outer shelf; dark blue: deeper shelf limestones; pale blue: oolite shoal; yellow: sandstones; cream: shelf shales.

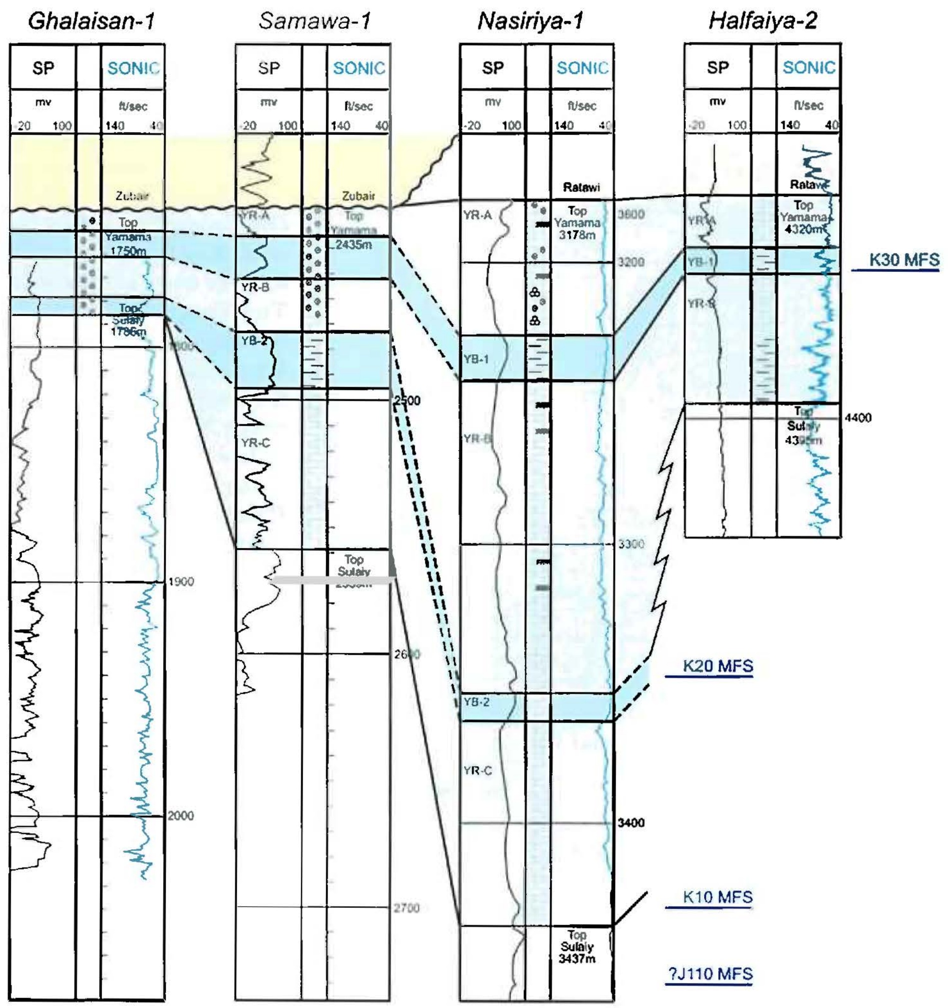


Fig. 7.10c. Logs through the Yamama Formation ramp: updip (inner ramp) wells *Ghalaisan-1* and *Samawa-1* with downdip wells *Nasiriya-1* and *Halfaiya-2*. After Sadooni. 1993b.

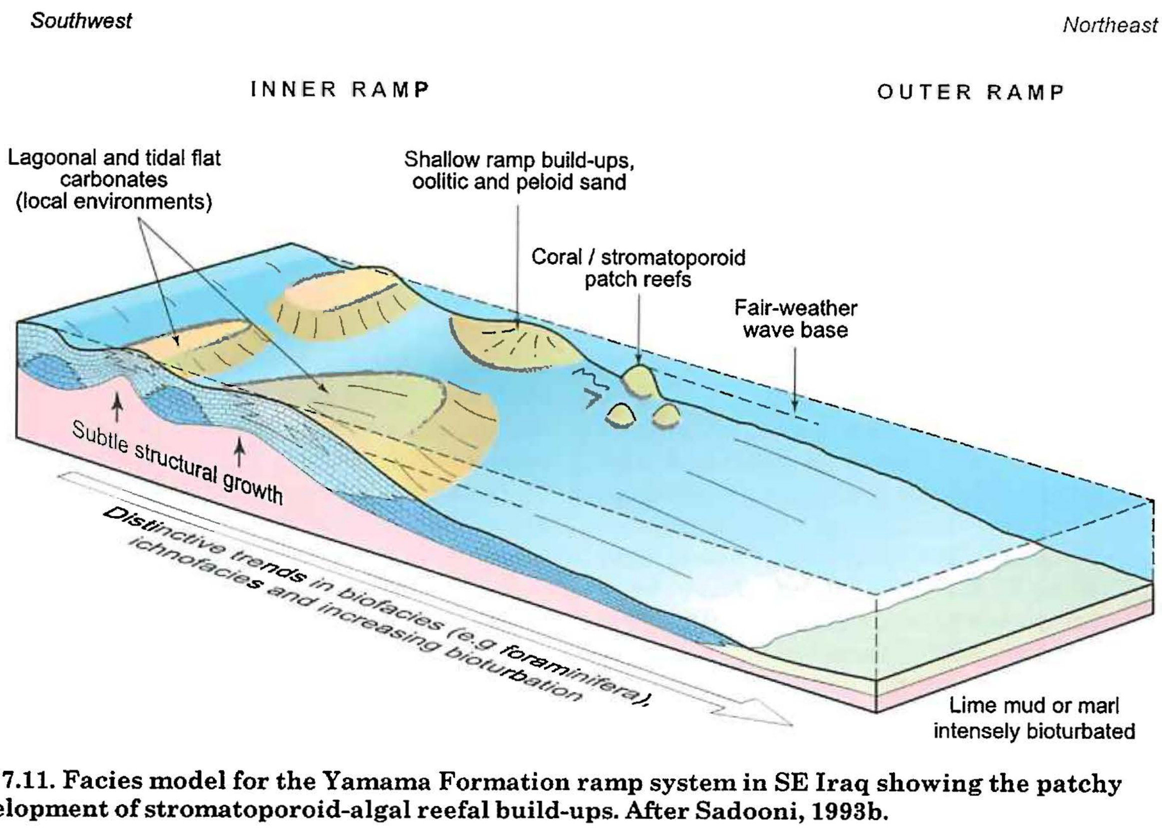


Fig. 7.11. Facies model for the Yamama Formation ramp system in SE Iraq showing the patchy development of stromatoporoid-algal reefal build-ups. After Sadooni, 1993b.

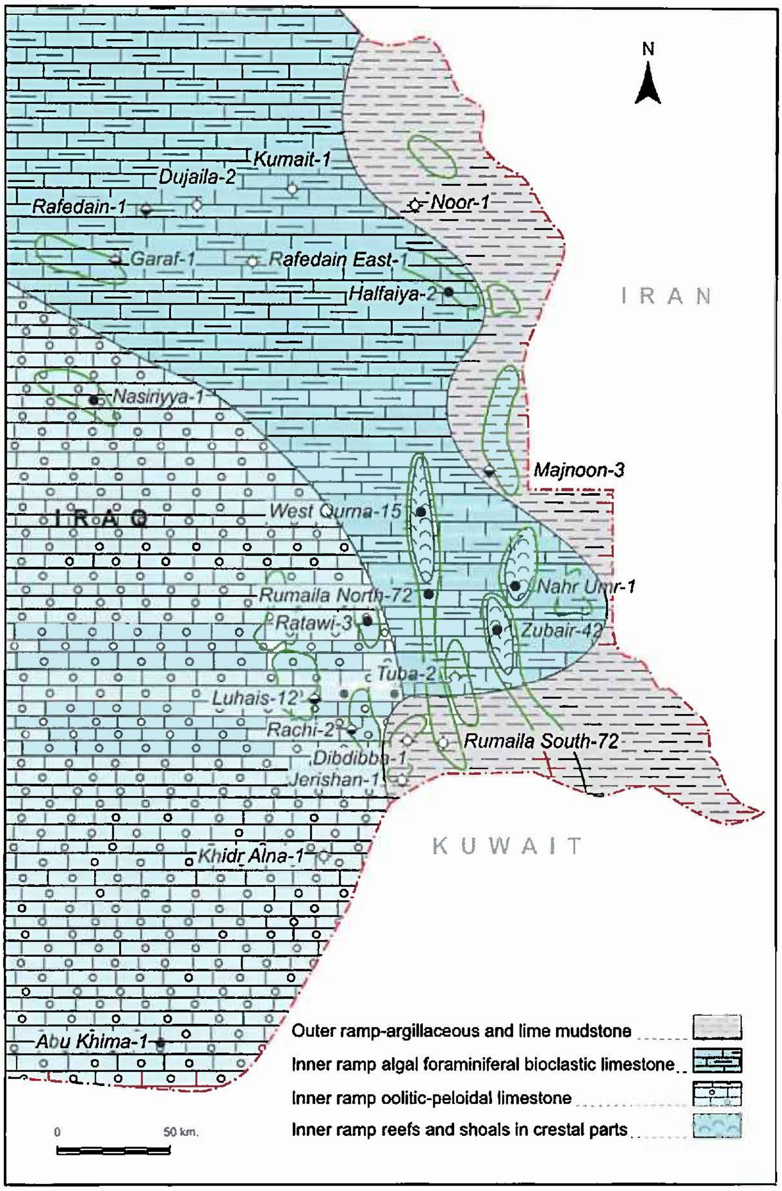


Fig. 7.12. Generalized facies distribution within the Yamama Formation ramp system. After Sadooni, 1993b. Inner ramp oolites are located in the western facies belt, and pass eastwards into deeper-water sediments of the Balambo-Garau Basin. Reefal and shoal facies were deposited locally over active structures. The Yamama Formation is oil-bearing at the *Ratawi, Rumaila, West Qurna, Zubair* and *Halfaiya* fields. Note the presence of inner ramp, reef and shoal carbonates in the *West Qurna, Zubair* and *Nahr Umr* fields. The *Ratawi* and *Rachi* fields are located along the eastern margin of the inner ramp ooidal-pelitic facies belt.

The Makhul Formation passes laterally into the **Chia Gara Formation** over the Tikrit-Amara "submarine palaeoridge" of Jassim and Buday (2006e), as demonstrated by well *Fallujah-1* (Dunnington, 1967a) (Fig. 7.14). This feature may mark a shelf-slope transition. The presence of *Calpionella alpina* and *C. elliptica* indicates a deep-water depositional environment and a latest Berriasian age (Dunnington, 1967a).

The Chia Gara Formation is 30 to 300 m thick (Jassim and Buday, 2006e). A basal bed with distinctive "phacoids" (large diagenetic concretions) occurs at its type locality in Iraqi Kurdistan (Dunnington *et al.*, 1959) (Fig. 7.5a). Phacoids may occur in well *Kirkuk-109* but have been misinterpreted as a basal conglomerate (Ditmar *et al.*,1972 *in* Buday, 1980; Jassim and Buday, 2006e).

The Chia Gara contains an abundant, diverse ammonite fauna of middle Tithonian to late Berriasian age (Spath, 1950; Dunnington *et al.*, 1959; Howarth, 1992; Balaky, 2004). Large benthic foraminifera locally occur (for example at Halabja), suggesting the formation was deposited on a moderately deep shelf (Jassim and Buday, 2006e).

In the Awasil-Makhul-Fallujah area of central Iraq, a peloidal facies equivalent of the oolitic Yamama Formation is termed the **Zangura Formation** (Dunnington *et al.*, 1959). At its base, it includes the *Psudocyclammina kelleri* Zone, indicating that it is equivalent to the lower part of the Yamama Formation (Dunnington, 1967a). It conformably overlies the Makhul Formation and is overlain by the Garagu Formation (Fig. 7.14).

The **Garagu Formation** at its type locality at Amadia in northern Iraqi Kurdistan includes sandy oolites with fossiliferous limestones (Dunnington *et al.*, 1959). In central Iraq, it comprises sandy oolites deposited on a shallow-water, high-energy shelf. It extends eastwards into the *Kirkuk, Bai Hassan* and *Jambur* fields of NE Iraq and into northern Iraqi Kurdistan (Dunnington *et al.*, 1959; Dunnington, 1967a; Al-Rawi *et al.*, 1980). The foraminifera *Pseudocyclammina lituus* indicates age-equivalence with the uppermost Yamama

Formation and the lower Ratawi Formation to the south (Dunnington, 1967a).

In the Northern Thrust Zone at Banik, the Garagu Formation unconformably overlies the Chia Gara Formation; the basal conglomerate contains pebble-sized clasts of bitumen ("*manjak*") (Dunnington *et al.*, 1959). In Central Iraq, the formation (often described as the Yamama Formation) is unconformably overlain by the Zubair Formation in *Awasil-5* and *Kifl-1* (Al-Naqib, 1967).

The **Sarmord Formation** (*sensu stricto*) comprises 455 m of pelagic marls with interbedded neritic limestones. The basal beds are slope or transitional inner ramp-basinal facies equivalents of the Garagu Formation (Dunnington *et al.*, 1959). The Zangura, Karimia Mudstone and Makhul Formations probably represent mid to outer-ramp facies of Tithonian-Berriasian age; they were grouped into the Sarmord Formation by Sadooni and Aqrawi (2000) after Chatton and Hart (1960).

Petroleum System Components

Proven and Potential Reservoir Rocks

The principal reservoir unit in Supersequence I comprises oolitic limestones of the Yamama Formation in southern Iraq (Sadooni, 1993b). Porosities range from 5 to 20% with permeabilities varying from 3 to 180 mD (Jassim and Al-Gailani, 2006). Porosities reach 22% where the oolites are leached with maximum permeabilities of about 300 mD (Sadooni, *ibid.*). Porosity is also present in recrystallised and dolomitised facies.

Oolitic limestones in well *Ratawi-3* have the highest flow rates recorded from the Yamama Formation (19,000 b/d) (Sadooni, 1993b). Good reservoir qualities also occur in the *Rumaila North* and *West Qurna* fields (Jassim and Buday, 2006e). Reservoir quality declines towards the south; in well *Rumaila South-72*, the formation consists predominantly of outer-ramp argillaceous and micritic limestones. Well *Tuba-2* had no flow from the Yamama Formation, and *Jerishan-1* had a weak unmeasurable flow (Sadooni, 1993b). The *Majnoon* structure was interpreted by Sadooni (1993b) to lie within the unproductive outer ramp facies belt of the Yamama Formation (Fig. 7.12).

A well in the *West Qurna* field tested 9000 b/d, while rates of 10,800 b/d were recorded in the *Zubair* field. Some 4000 b/d were produced at *Halfaiya* (Jassim and Al-Gailani, 2006). *Rumaila North-172* flowed 1350 b/d from inner ramp algal foraminiferal bioclastic limestones (Sadooni, 1993b). Further north at *West Qurna*, inner ramp "build-up and shoal facies" occur in the Yamama Formation; individual reservoir units have flowed at 2000–3750 b/d. High oil flow rates are also recorded from these facies in the northern *Zubair* structure (5000–5400 b/d). The *Ratawi* and *Rachi* structures are located along the eastern edge of the Yamama Formation inner ramp oolitic-peloidal facies belt.

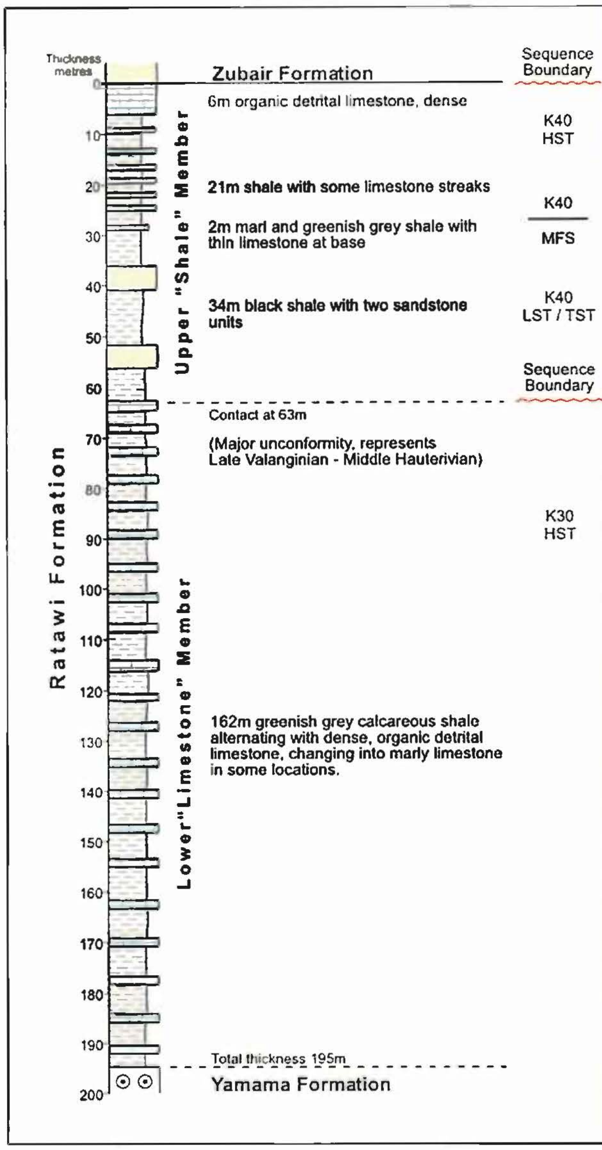


Fig. 7.13. Lithological column for the Ratawi Formation at well *Ratawi-1* (from Sadooni, 1993b, after Dunnington *et al.*, 1959).

The facies-equivalent Garagu Formation is mostly tight but is productive at the *Bai Hassan* field (Dunnington, 1967a) and also at *Jambur* (Al-Rawi *et al.*, 1980).

Equivalent units in West Kuwait (Minagish Oolite Formation) have better reservoir qualities than the Yamama Formation in Iraq, and produce oil at the *Minagish* and *Umm Gudair* fields (Abdullah and Kinghorn, 1996).

The lower, carbonate-dominated part of the Ratawi Formation forms a secondary reservoir in crestal areas of the *Rumaila North* and *Zubair* fields (Sadooni and Aqrawi, 2000). The reservoir is of generally poor quality. Oil-bearing limestones have primary porosities of 5 to 15% and low permeabilities in the *Tuba* structure (Jassim and Al-Gailani, 2006). Leached oolitic and bioclastic limestones with 50-100 m of pay may occur locally with porosities of 16-18% (Al-Sakini, 1992).

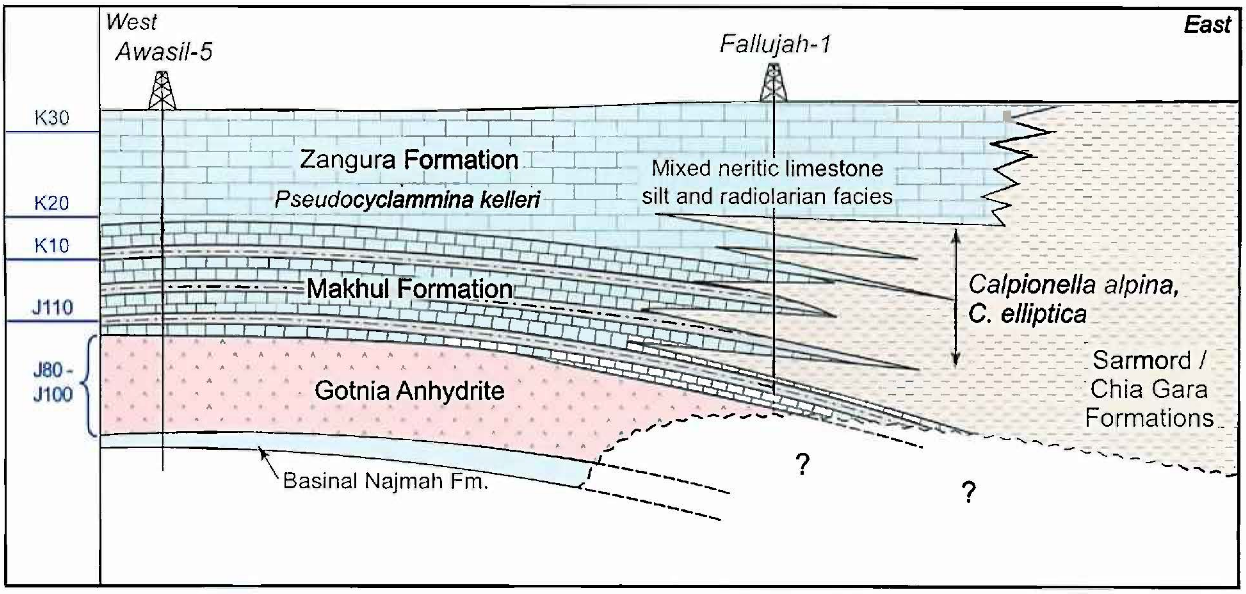


Fig. 7.14. West-east cross-section from Awasil to the Baghdad area of central Iraq illustrating the lateral transition of the Makhul and Zangura Formation carbonates into the basinal Makhul and Chia Gara Formations (basal AP8). The Gotnia/Najmah relationship below the TD of the *Fallujah* well is speculative. After Dunnington, 1967a.

Proven and Potential Source Rocks

Source rock intervals consist of organic-rich shales, deposited in the centre of the Balambo-Garau Basin. These have been analysed geochemically at wells including *Kirkuk-109*, *Ajeel-8* and *-12*, and *Taq Taq-1* (Al-Haba and Abdullah 1989; Odisho and Othman, 1992; Sadooni, 1997). Definitions of the Chia Gara, Balambo and even Makhul and Sulaiy Formations may vary from author to author. However, the Chia Gara Formation (*sensu stricto*) mainly represents the source rock facies, while the Balambo Formation (*sensu stricto*) refers to the overlying, organically-leaner carbonates.

In well *Kirkuk-109*, the Chia Gara Formation contains overmature amorphous marine organic matter with a mean TOC of 2.19% (range 0.28-6.91%) (Fig. 9.5.1) and a pyrolysis yield of 4 kg/tonne in *Kirkuk-109* (Al-Haba and Abdullah, 1989).The formation is considered to be a source rock for oil in Central Iraq (Al-Beyati, 1998). Al-Ameri and Al-Obaidi (2004) suggested that the oil reservoired in the Khasib Formation at the *East Baghdad* field was sourced by the Chia Gara Formation and the lower part of the Upper Ratawi Formation in the overlying Supersequence II.

The Sulaiy Formation is a proven oil source rock in southern Iraq (Al-Ameri *et al.*, 1999; Al-Ameri and Al-Musawi, 2009) and may be the major source of oil in Cretaceous reservoirs (Al-Sakini, 1992). It has a TOC of 0.5-1.0%, is dominated by Type II kerogen and has an HI of 200-500mgHC/g. The presence of richer oil source rocks in the lower part of the formation (Tithonian) beneath *Rumaila* field was confirmed by Al-Ameri *et al.* (2009b) (p. 327).

Al-Haba and Abdullah (1989) recorded that the Balambo Formation in northern Iraq contains a mixture of marine and terrestrial kerogen including plant, pollen and spore debris. TOC contents range from 0.14 to 8.85%; pyrolysis yields are 2-50kg HC/tonne and HI is 200-400 mgHC/g. Note however that the Balamabo Formation has a wide age-range and occurs in Supersequences I-V, and that the precise age of the samples analysed is not known.

Well-studied correlative source rocks in Iran occur in the basal parts of the Garau Formation. At the Tang-e Garau type section, the TOC content increases towards the base of the formation (Fig. 7.15). The Garau comprises 230 m of thermally mature, grey to black, thin-bedded "bituminous marls and micritic, often pyritic argillaceous limestones". Marls and limestones have residual TOC values of 4.5-9% and 1-2%, respectively (Bordenave and Huc, 1995).

The source kitchen mapped by Bordenave and Huc (1995) is located mostly within Iran. However, their maps are based on Valanginian facies distributions. The maps do not show the Balambo-Garau Basin during the period of maximum organic matter preservation in the late Tithonian/Berriasian, when the basin extended into the Sirwan area of SE Iraqi Kurdistan and eastern and SE Iraq. The Garau source rocks (and thus probably the Chia Gara Formation) were deposited in a stratified silled basin (Bordenave and Huc, 1995).

Source rocks in Kuwait were investigated by Abdullah and Kinghorn (1996). The Sulaiy Formation consists of dark argillaceous limestones and shales with TOCs ranging from 0.4 to 2.68% within an interval 122 to 274 m thick. Kerogen is Type II. Non-oolitic facies of the Minagish Formation had TOCs of 0.3-0.54%. In the Sulaiy Formation, organic material is amorphous and of marine algal

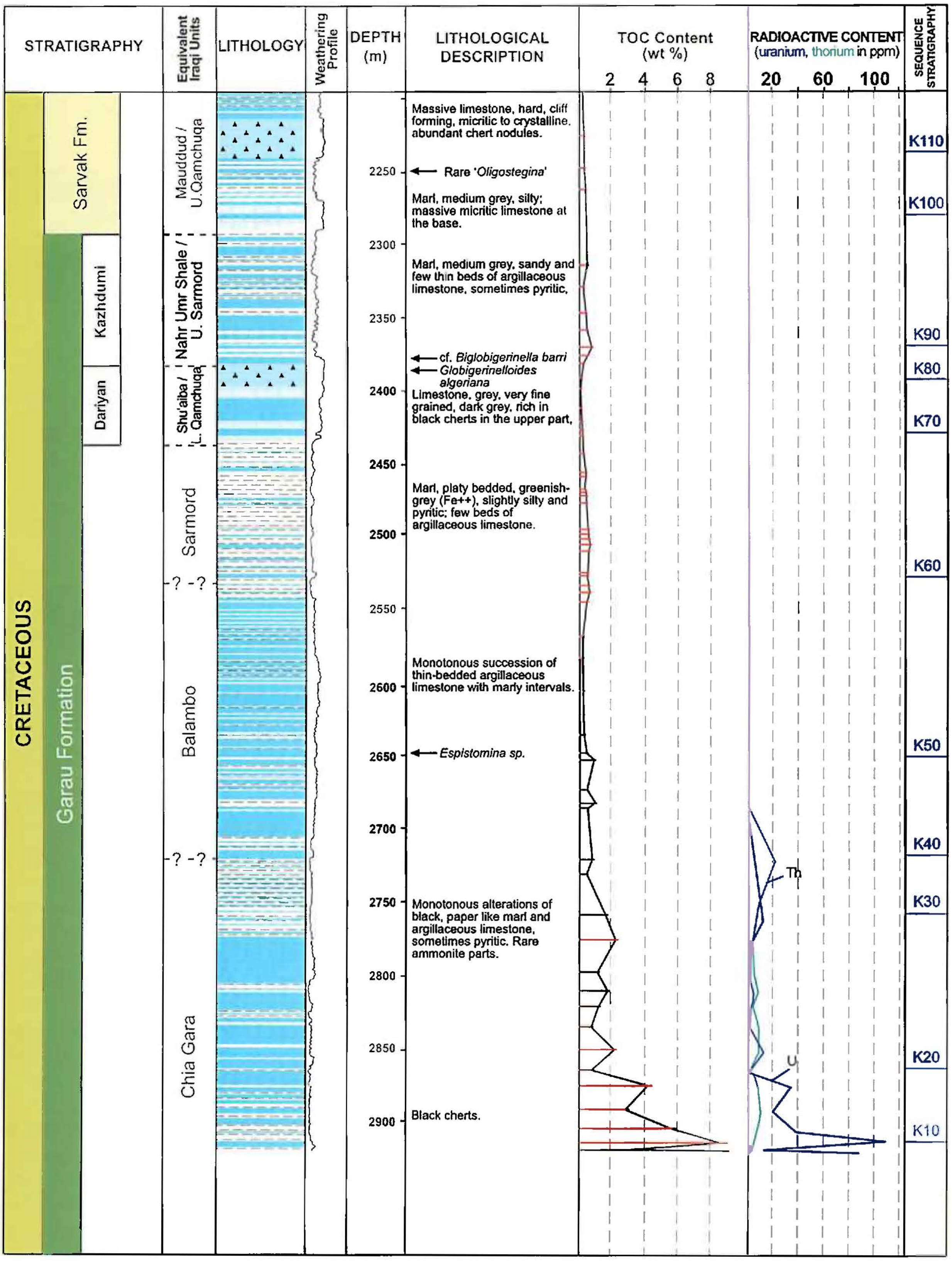


Fig. 7.15. Log through the Garau Formation, Tang-e Garau, Iran (equivalent to the Chia Gara / Balambo Formations in Iraq), showing high TOC values at the base of Megasequence AP8. The Neocomian succession in eastern Iraq near the border with Iran will probably be similar. After Bordenave and Huc, 1995.

origin. Mean HI values after the removal of contamination were 355 mgHC/gC$_{org}$. The Lower Ratawi Formation had mean TOCs of 0.55 wt %, consisting predominantly of Type III kerogen.

Poven and Potential Cap Rocks

Two intra-Yamama Formation permeability barriers (referred to as the YB-1 and YB-2 units) occur in the Basra area (Fig. 7.10). They consist of

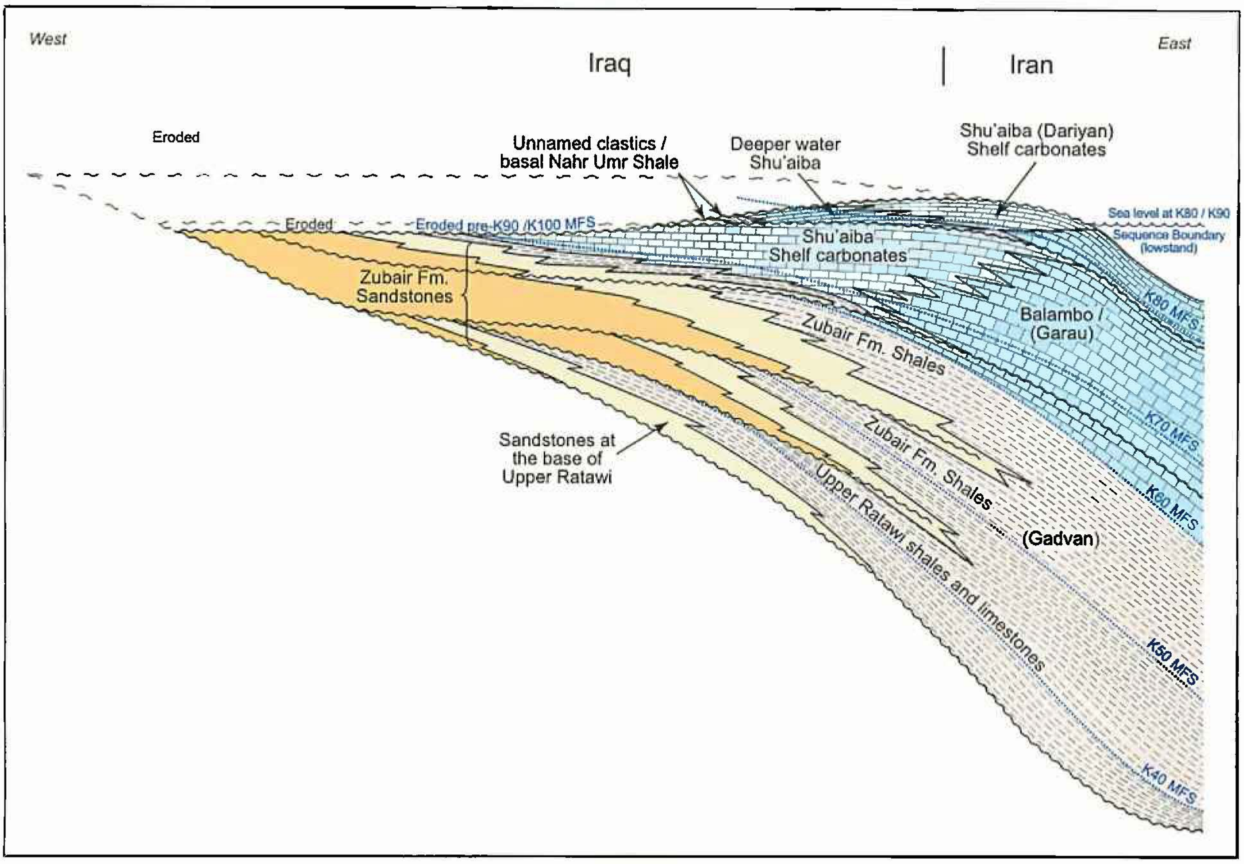


Fig. 7.16. Schematic west-east profile across southern/ central Iraq illustrating the organisation and relative thicknesses of stratigraphic units in Supersequence II (Iranian names in brackets).

outer-ramp, organic-rich argillaceous mudstones or shales (Sadooni, 1993b). Basal, thick argillaceous limestones and marls of the Sulaiy, Makhul and Chia Gara Formations may act as regional seals above the breccias of the Barsarin Formation and other units in Megasequence AP7 in northern and north-central Iraq.

Supersequence II: upper Valanginian – upper Aptian

This supersequence represents a simple eastwards transition from an onlap margin to a basin (Fig. 7.16, 7.17) (Dunnington, 1958). At the onlap margin, the Zubair Formation (or the equivalent Saggar/ S'ker Formation) may directly overlie the base-Cretaceous unconformity. ?Upper Barremian – Aptian sediments occur in *Tel Hajar-1* (Kaddouri and Al-Shaibani, 1993). They may have been deposited over the Khleisia and Rutbah Highs but were later eroded from these locations. Basinwards, the Zubair sharply overlies the upper shale member of the Ratawi Formation, which passes eastwards into the Sarmord Formation and the basal (Valanginan *Crioceras* Zone) Balambo Formation (Dunnington *et al.*, 1959; Jassim and Buday, 2006e).

The progradational Zubair/Ratawi clastic shelf was covered by the Shu'aiba Formation carbonates following backstepping of the Zubair and Ratawi Formations (Figs. 7.2, 7.16). Jassim and Buday (2006e) suggested that the Zubair Formation depocentre was located at the eastern limit of the Salman Zone, as illustrated by the isopach of the Zubair Formation (Ali and Nasser, 1989) (Fig.7.18).

Supersequence II geometries define a clastic deltaic to shallow-marine shelf passing eastwards into a low energy basin. The overlying flat-topped carbonate platform has narrow margins which accreted vertically (Fig. 7.16). The margin is spectacularly exposed in the Pir-i-Mugurun anticline near Sulaimaniya in NE Iraqi Kurdistan (Fig. 7.19) (Henson, 1950a). Similar stratigraphy is present at the *Jambur* field (Al-Rawi *et al.*, 1980) (Fig. 7.20), near *Kirkuk* and in well *Chemchemal-2* (Wilson, 1975) (Fig. 7.21).

This supersequence onlaps westwards further than any of the Cretaceous supersequences, reaching as far as Syria. The oldest Cretaceous units recorded in the Euphrates Graben (Caron *et al.*, 2000), NE Syria (Nikolaevskiy, 1972) and in the Abba / Jebel Abd El Aziz area (Kent and Hickman, 1997) are of ?Barremian – Aptian age. Throughout the Arabian Plate, the Aptian was a period of maximum transgression dominated by carbonate deposition; siliciclastic deposystems retreated towards sediment source areas in the west.

Formations

The **Zubair Formation**, the most significant sandstone reservoir in Iraq, is composed of fluvio-

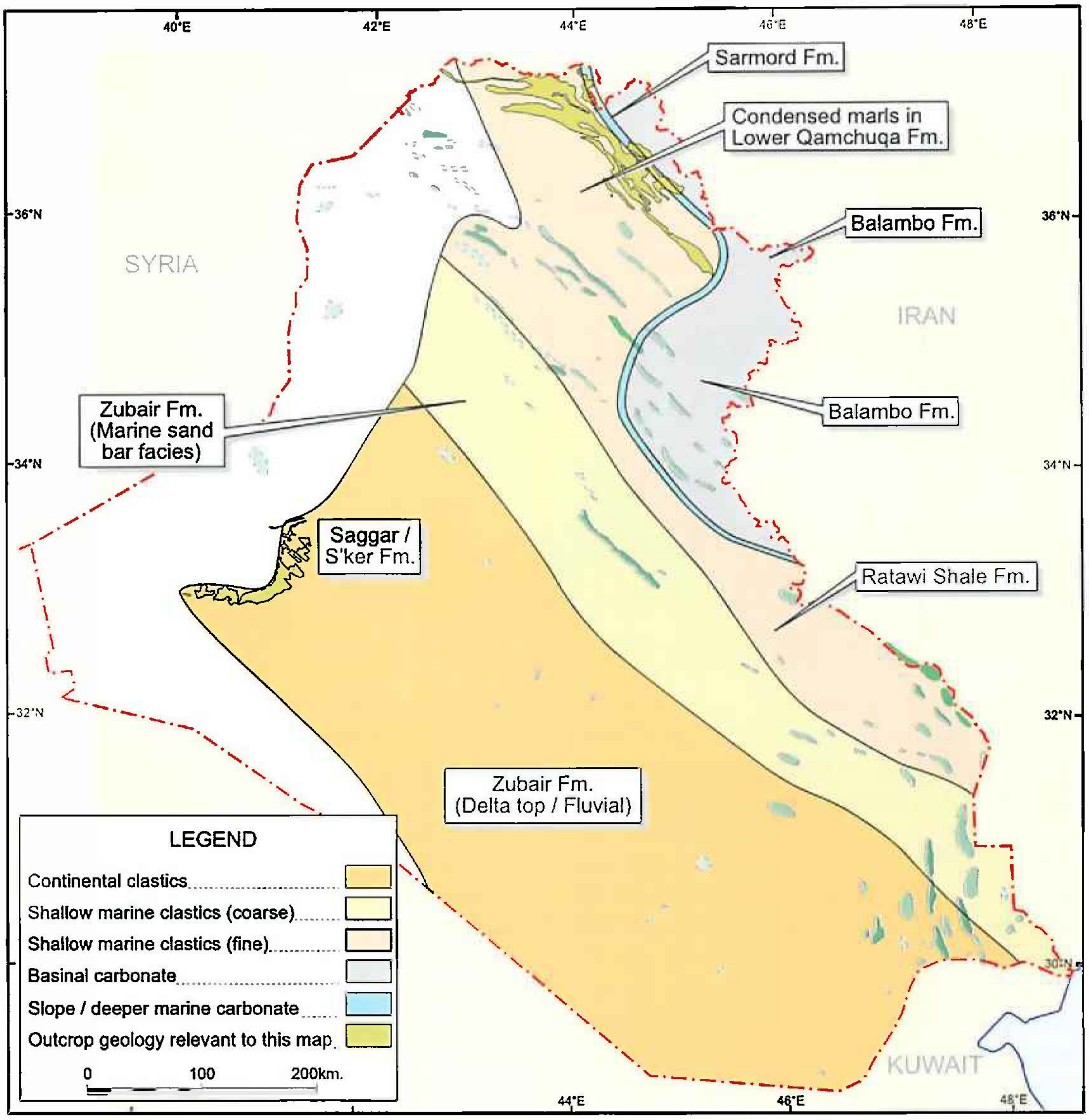


Fig. 7.17. Late Hauterivian – Barremian palaeogeography of Iraq. Units of this age crop out both in Iraqi Kurdistan and the Western Desert. Simplified Cambridge Carbonates Ltd map based on published data.

deltaic, deltaic and marine sandstones. It covers wide areas of the Arabian Plate including northern Saudi Arabia, Kuwait and most of southern and part of Central Iraq. The formation correlates with the Biyadah (Riyadh) Formation of Saudi Arabia (Powers *et al.*, 1966). In Iraq, the formation was probably most extensive in the Barremian. It is 200–500 m thick in southern Iraq (Fig. 7.18). The NE limit of the Zubair sandstone fairway is defined by a facies change from delta front or chenier sandstones into shelf mudstones.

At its type locality in the *Zubair* field, the formation is divided into five units (Owen and Nasr, 1958; Dunnington *et al.*,1959; Abbo and Safar, 1967) (Fig. 7.22a). These are (from the top): the Upper Shale (100 m thick), the Upper Sandstone (the principal reservoir or "Main Pay"), and the Middle Shale, Lower Sandstone and Lower Shale (IPC, 1956; Jamil, 1978). The Upper Sandstone is composed of cross-bedded quartz arenites with thin shale and silt intervals and lignite seams. It is interpreted here to have been deposited in a deltaic environment with wave/tide influence (Rohan, 1976). Prodelta, delta front, swamp and marsh, and transgressive facies have been identified (Ali and Nasser, 1989) and form cyclical successions. Lateral facies variations are due to delta lobe switching.The proportion and thickness of channel sandstones in the Zubair Formation increases upwards both in the *Zubair* field (Dunnington *et al.*, 1959; c.f. Ali and Nasser, 1989) and in Kuwait (Nemcsok *et al.*, 1998). At *Rumaila,* the Zubair Formation is 380-390 m thick. The reservoir here comprises sandstones of earliest Aptian to Hauterivian age (Jamil, 1978), which are coarser-grained than those at *Zubair* (IPC, 1956) (Fig. 7.22b).

Kabir *et al.* (2007) noted that there is excellent sandbody connectivity at the *South Rumaila* field. Net thickness of the Main Pay here is about 120 m (Jamil, 1978). Jassim and Al-Gailani (2006) cited a thickness of 229 m for the formation at *South*

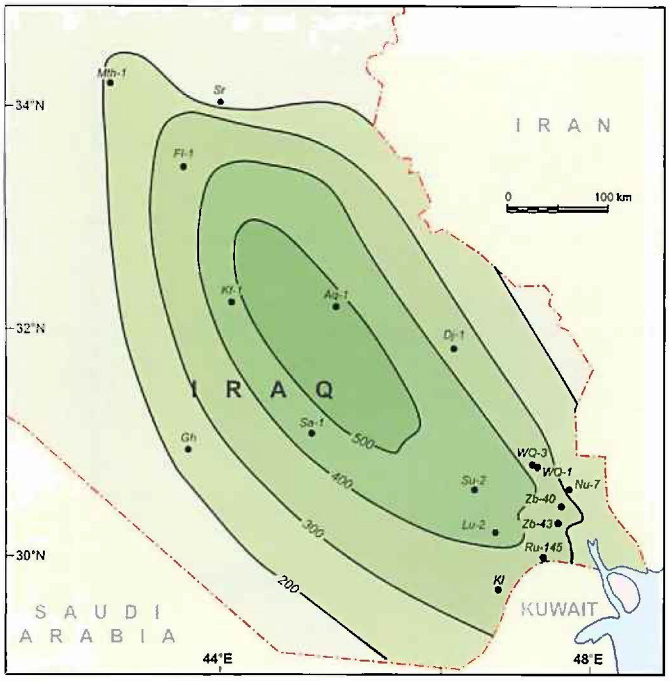


Fig. 7.18. Isopach map of the Zubair Formation; thicknesses in metres. After Ali and Nasser, 1989. The Zubair Formation thickens from 200 m in the SW near Saudi Arabia to 500 m in the depocentre. The major oilfields which produce from the Zubair Formation are located in large-scale north-south trending structures in the SE of the depocentre.

Rumaila, but this probably incorporates approximately 100 m of the underlying lower sandstones. Net:gross is estimated to be about 0.8.

Zubair Formation sandstones dominate the SW margin of the Balambo-Garau Basin and thin towards Iran (Ali and Nasser, 1989). A depocentre is located to the south of Baghdad, and here the formation is over 500 m thick (Ali and Nassr, 1989; Jassim and Buday, 2006e) (Fig. 7.18). In the Hit area (probably in well *Awasil-5)*, there are 455 m of lower and lowermost mid-Cretaceous sandstones (combined Zubair/Nahr Umr Formations) containing minor shales (IPC, 1956). The proportion of carbonate in the formation increases eastwards to 15% at *Nasiriya* and 35% at *Amara* (Jassim and Buday, 2006e), with a decrease in net sand thickness to 100 m.

In central Iraq (*Mileh Tharthar* to *Awasil*), the Zubair Formation directly overlies the Garagu/ Yamama Formation (Dunnington *et al.*, 1959). Basal shales near Basra contain *Orbitolina* cf. *discoidea*, *Chofatella decipiens*, *Cristallaria* sp., *Cuneolina* sp., *Trocholina* sp., *Exogyra* sp., *Cerithium* sp. and *Lima carteroniana* (Owen and Nasr, 1958; Dunnington *et al.*, 1959) indicating a Hauterivian/Barremian to earliest Aptian age, probably Hauterivian at its base. Shales in the Makhul area have been dated as late Hauterivian to early Barremian; *Orbitolina* is absent here (Dunnington *et al.*, 1959).

In the *East Baghdad* area, the Zubair Formation is a fine- to very fine-grained, texturally mature, well- to moderately-sorted quartz arenite. It was derived from a provenance area dominated by acid igneous rocks (Ali and Aziz, 1993). Barrier and beach facies identified are better sorted and texturally more mature than delta-top fluvial channel facies (Ali and Aziz, *ibid.*).

Palynological analyses in *East Baghdad* (Al-Ameri and Batten, 1997) suggested an anomalous late Aptian – Albian age. In Kuwait, the Zubair Formation is dated as late Hauterivian – early Aptian by nannofossils (zones KN42 to 49) and the tops of *M. obtusus/D.lehmanii* (at the top) and of *C. margerelii*, *C. margerelii grandis* at the base, with a major break of early Valanginian – mid-Hauterivian age between the Zubair and Ratawi Formations (Al-Fares *et al.*, 1998).

During the Cretaceous, siliciclastic systems including the Zubair Formation typically prograded eastwards, away from the Arabian Shield (Ali and Aziz, 1999; Ziegler, 2001). Periodic uplift of sediment source areas in the Shield controlled depositional cyclicity. Third-order eustatic variations (Sharland *et al.*, 2001) and switching of delta lobes resulted in depositional heterogeneities. The Zubair Formation sandstones may have been transported into the Basra area via the NE-SW trending Wadi Al Batin lineament (Ali and Aziz, 1993; Ali and Nasser, 1989; Jassim and Buday, 2006e) (Fig. 3.18). The transport route into Central Iraq is unclear. Jassim and Buday (2006e) suggested a sediment source area to the NW although this seems unlikely in the absence of an exposed basement terrane in that direction.

Overall, the Zubair Formation was deposited in a fluvio-deltaic to marine setting (Fig. 7.23) in humid-tropical climatic conditions (Ali and Aziz, 1993). Near Basra, regular alternations of sandstones and shales indicate stronger marine influences (Khaiwka, 1990; Al-Ameri and Batten, 1997; Sadooni and Aqrawi, 2000). Delta lobes have been identified in the *East Baghdad* field, where wave and tidal influenced facies occur together with channel, marsh, chenier and shelf lithofacies; the delta was periodically drowned with the deposition of shales on top of delta-top sandstones (Ali and Aziz,

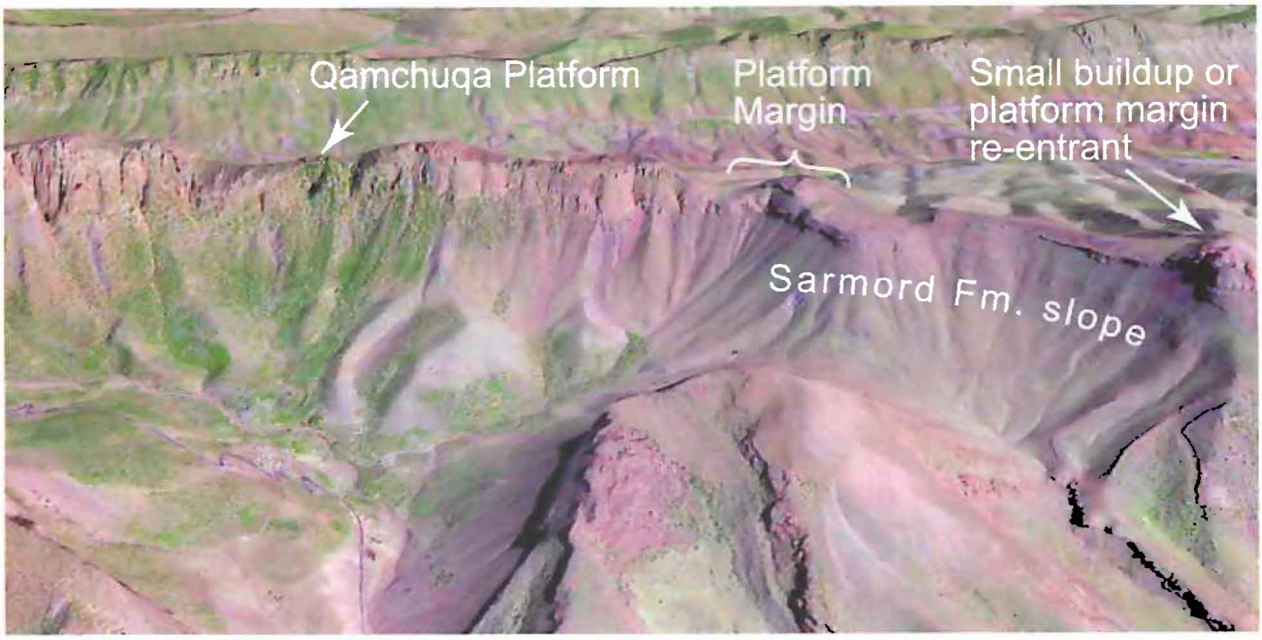


Fig. 7.19. Image of the Neocomian-Albian carbonate platform margin at Pir-i-Mugurun, NE Iraqi Kurdistan, showing massive platform carbonates at left (Qamchuqa Formation) passing downdip into thin-bedded and relatively featureless basinal marls (Sarmord Formation). A limestone knoll within the slope marls (at right, arrow) may be a lowstand build-up or reef. Image derived from 2.5 m resolution false colour SPOT imagery draped over SRTM DEM, approximating to a figure in Henson (1950a), courtesy of M. Insley and Infoterra Ltd.

1993).The bulk of the formation probably represents either prograding lowstand/ transgressive systems tract deposits (often incised into underlying sequences), or updip late highstand systems tracts. HST clastics were probably largely reworked during subsequent lowstands (see Fig. 7.16).Transgressive facies may be more carbonate rich (c.f. Davies *et al.*, 2002).

The Zubair Formation passes offshore into shelfal shales, marls and limestones of the Upper Member of the **Ratawi Formation** (Fig. 7.16). This siliciclastc-rich unit, often referred to as the "Middle Sarmord Formation" in northern Iraq (Dunnington *et al.*, 1959), extends to the *Jambur* and *Kirkuk* fields where it occurs between the Garagu and Lower Qamchuqa Formations (Wilson, 1975; Al-Rawi *et al.*, 1980) (Fig. 7.20). The Upper Member of the Ratawi Formation at well *Ratawi-1* near Basra contains *Choffatella decipiens*, *Cyclammina* sp., *Trocholina* sp. and *Pseudo-cyclammina* sp. including *P. lituus* and *P. cf. kelleri* indicating a Hauterivian age (Dunnington *et al.*, 1959).The highest bed of the Ratawi Formation is a peloidal limestone containing debris of the alga *Lithocodium aggregatum*.This limestone bed probably marks the K40 MFS of Sharland *et al.* (2001); a similar limestone is present in the Kuwaiti offshore well "*F*" (Al-Fares *et al.*, 1998) within lower Hauterivian shales of the Zubair Formation (Zone KN47 to KN49). *Cyclammina greigi* occurs near the base of this interval (Dunnington *et al.*, 1959). The biota and lithofacies indicate a deep inner to middle shelf clastic facies (c.f. Fig. 7.23).The disconformity at the base of the Upper Member of the Ratawi Formation is overlain by a 12 m thick sandstone bed in well *Samawa-1* (Al-Naqib, 1967).

The **Shu'aiba Formation** comprises neritic carbonates which gradationally overlie the uppermost shales of the Zubair Formation (Al-Naqib, 1967). These limestones thin or pinch-out completely to the SW within the fluvial clastic facies belt,e.g in well *Safawi-1* (Al-Naqib, 1967) (Fig. 7.24).

At its type locality at well *Zubair-3*, the base of the Shu'aiba Formation (including MFS K70 of Sharland *et al.*, 2001) includes a dense, whitish "pseudo-oolitic" (?peloidal) limestone with rare *Orbitolina cf. discoidea* and *Choffatella decipiens*. Owen and Nasr (1958) described similar limestones containing sand grains at the base of the formation. The upper part of the type section, containing the K80 MFS of Sharland *et al.* (2001), has a planktonic fauna in the Basra area (Dunnington *et al.*, 1959) which may indicate deepening associated with formation of an intrashelf basin (or "Migratory Carbonate Suppressed Belt", MCSB) as proposed for onshore Kuwait by Davies *et al.* (2002). At *Buzurgan-2* near the border with Iran, Al-Ani (1975) recorded chalky biomicritic limestones with chert nodules interpreted as deeper-water deposits.

In Kuwait, the Shu'aiba Formation passes up into a unit of "Unnamed Clastics" which Al-Fares *et al.* (1998) dated as Aptian (with a nannofossil assemblage of *N. circularis* and *L. houghtonii*). This interval marks siliciclastic input into the basin from the west (Davies *et al.*, 2002). These clastics have not yet been identified in Iraq.

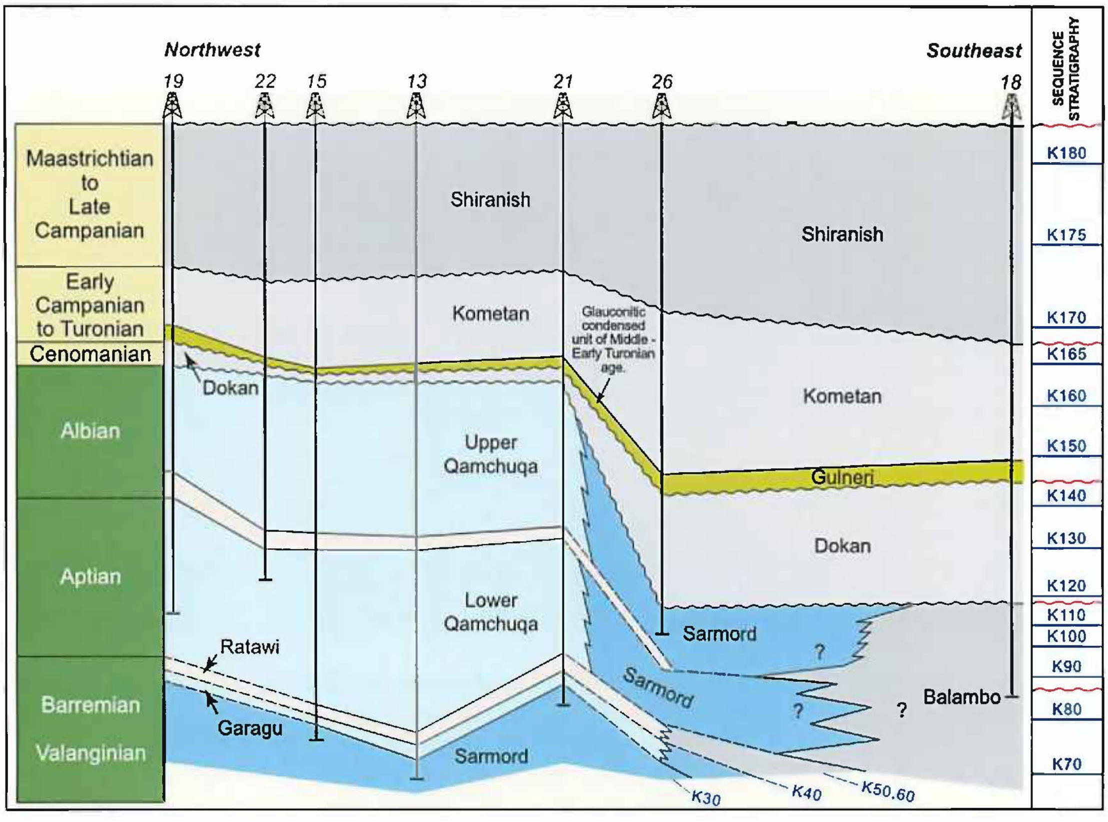


Fig. 7.20.Cretaceous stratigraphy at the *Jambur* field. After Al-Rawi *et al.*, 1980. Wells *19, 22, 15* and *13* penetrated "shelfal" stratigraphic successions. Well *21* is located at the shelf margin. Well *26* penetrated slope sediments and thicker Dokan/Kometan/Shiranish Formation which fills accommodation left after Albian deposition. Well *Jambur-18* is located within basinal facies.

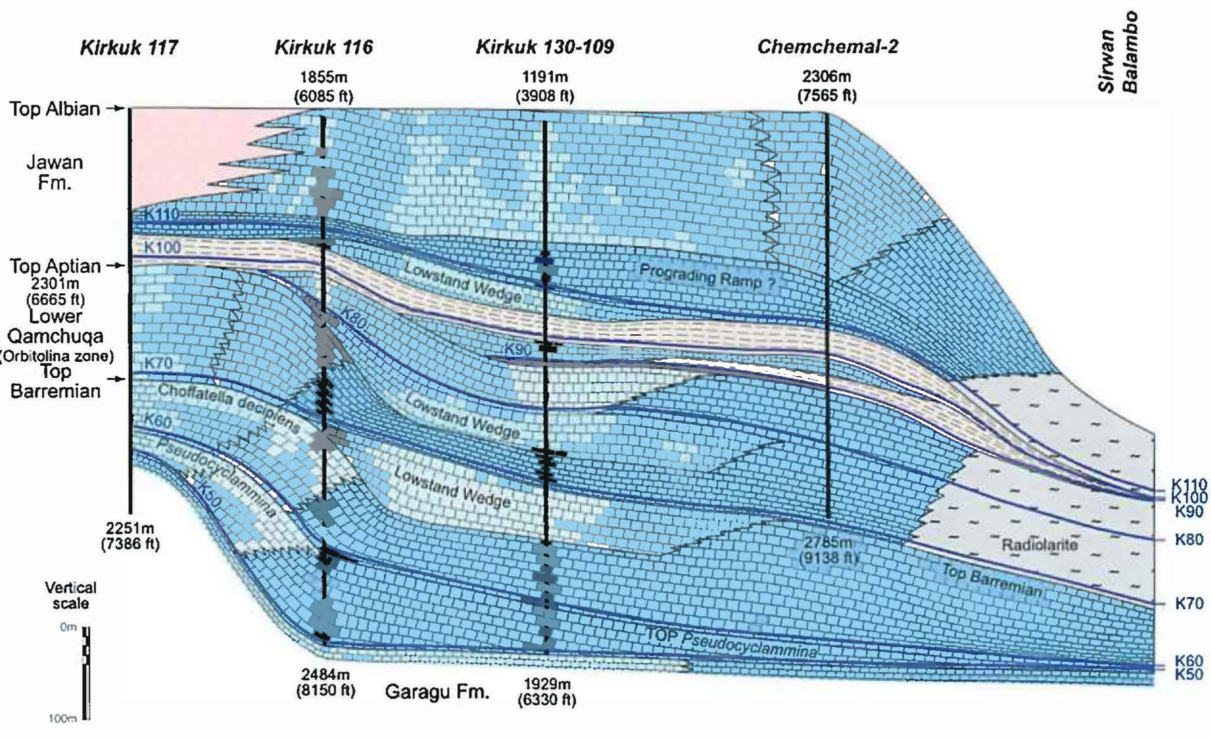


Fig.7.21. Facies relationships at the Kirkuk structure, passing via the platform margin into the Balambo-Garau Basin with both slope (Sarmord) and basinal facies (Balambo Formation). Reinterpreted after Wilson, 1975.

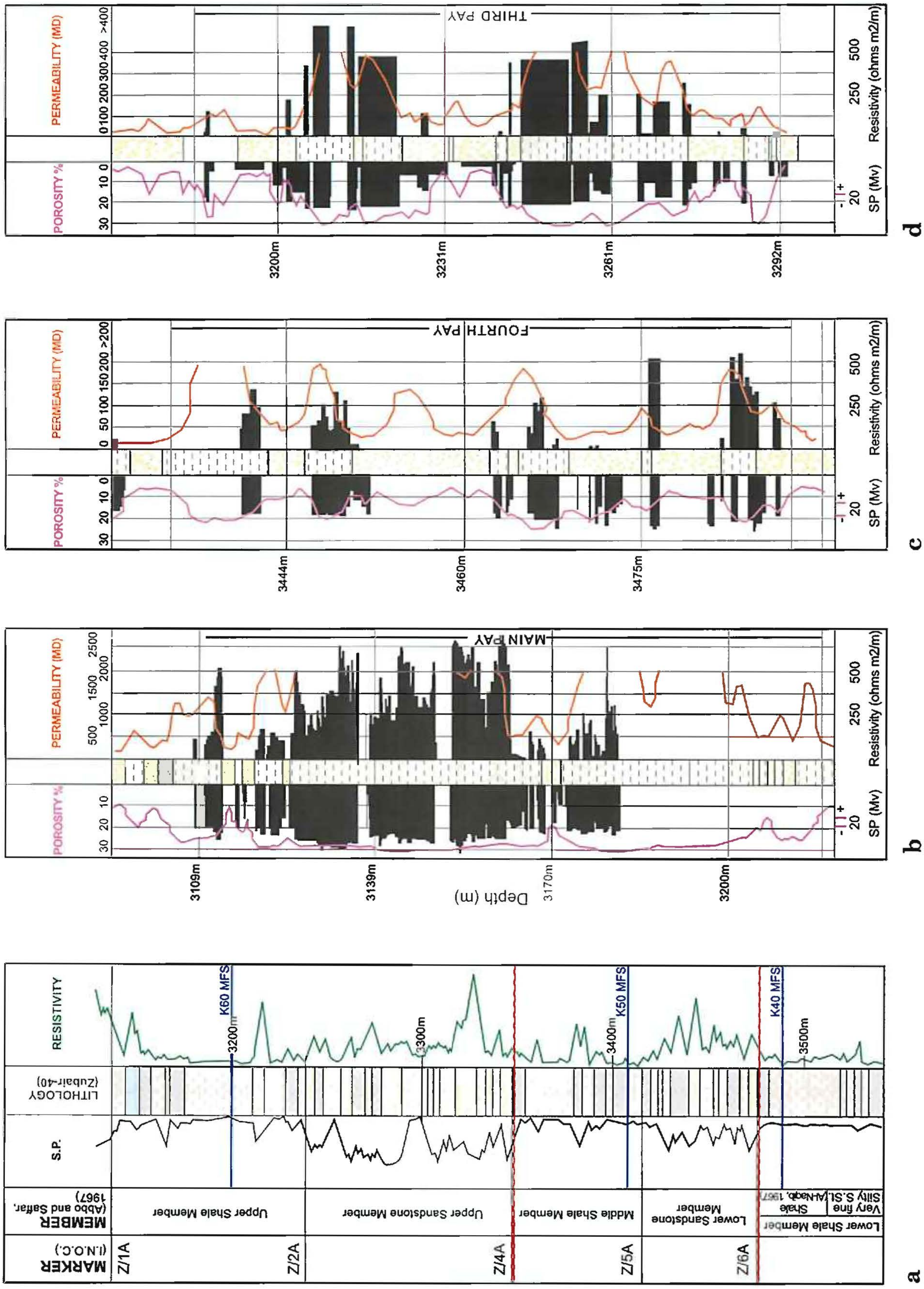


Fig. 7.22.(a) Stratigraphy of the Zubair Formation at well *Zubair-40*. After Dunnington *et al.*, 1959; Abbo and Safar, 1967; and Ali and Nasser, 1989.
(b-d). Logs through the Zubair Formation sandstones: (b) Main Pay, *Rumaila* field; (c) Fourth Pay, *Zubair* field; (d) Third Pay, *Zubair* field. Note how net : gross and overall reservoir quality improves significantly from (c) to (d) to (b). From Jassim and Al-Gailani (2006).

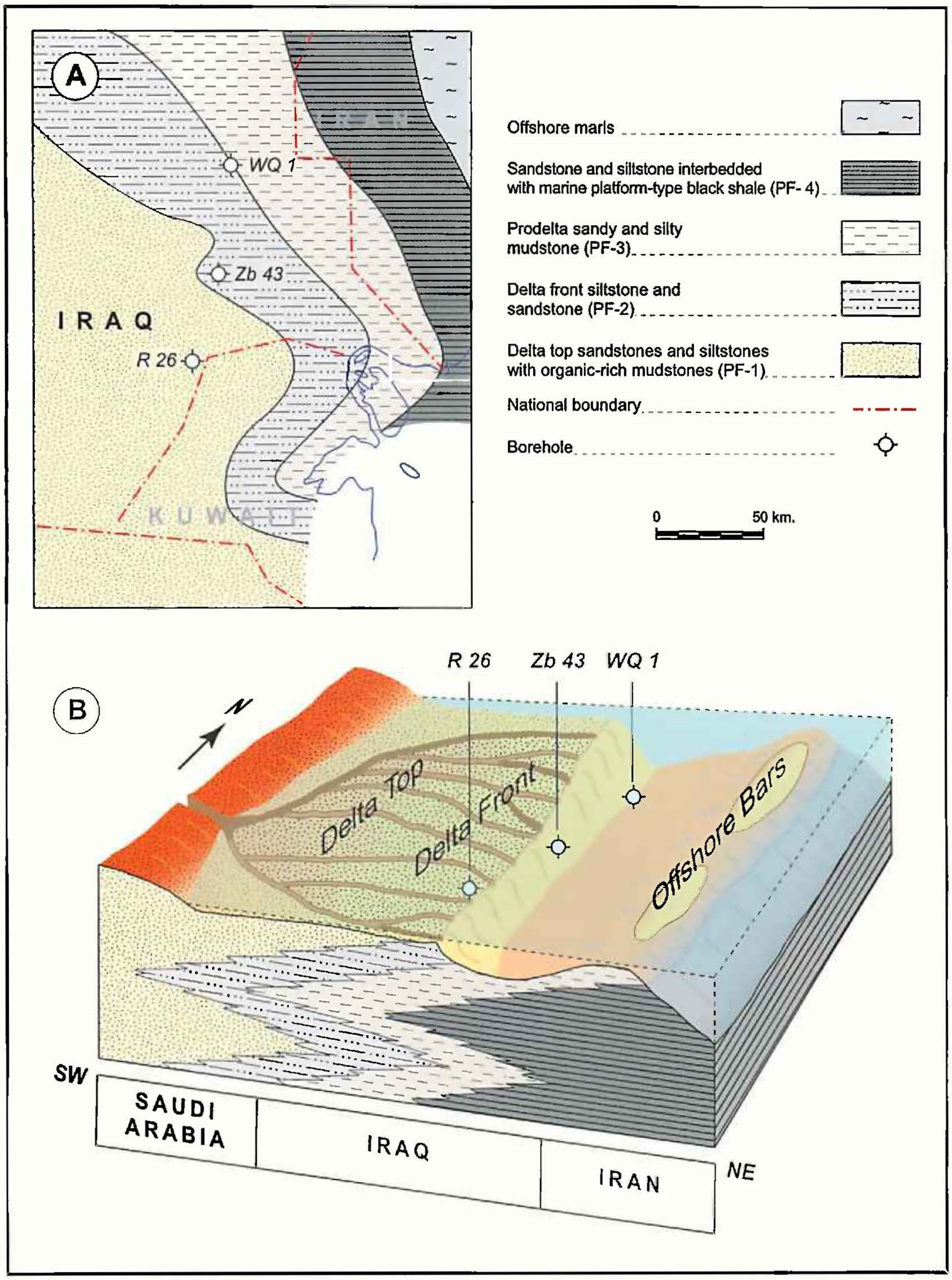


Fig. 7.23. Model for the deposition of Zubair Formation. Deltaic deposits pass laterally into shales of the Upper Member of the Ratawi Formation in southern Iraq. Coastal plain environments to the west pass into delta-front and offshore barrier bar systems. After Al-Ameri and Batten (1997).

Further NW in *Awasil-5* and *Nafatah-1*, vacuolar dolomites replace rudist limestones (Dunnington *et al.* 1959; Jassim and Buday, 2006e). These rudist-dominated facies resemble the rudist-dominated Thamama / Shu'aiba Formation of the southern Gulf (Frost *et al.*, 1983; Harris and Frost, 1984). Here, the contact between the Hauterivian-Aptian and Albian Supersequences is often unconformable (Dunnington *et al.*, 1959). In Kuwait, a 6 Ma stratigraphic break occurs between the Burgan and Shu'aiba Formations (Al-Fares *et al.*, 1998).

Where Aptian and Albian carbonates are difficult to distinguish, the unit is often referred to as the **Qamchuqa Formation** (Fig. 7.25). The Aptian – Hauterivian portion (Lower Qamchuqa Formation) comprises shoal limestones containing larger foraminifera and sucrosic dolomites (Sadooni, 1978; Al-Shdidi *et al.*, 1995). The formation is dolomitised in the *Kirkuk* field (Wilson, 1975) and the *Jambur* field (Al-Rawi *et al.*, 1980) and conformably overlies marls at the base of the formation. At Banik in NW Iraqi Kurdistan, the formation unconformably

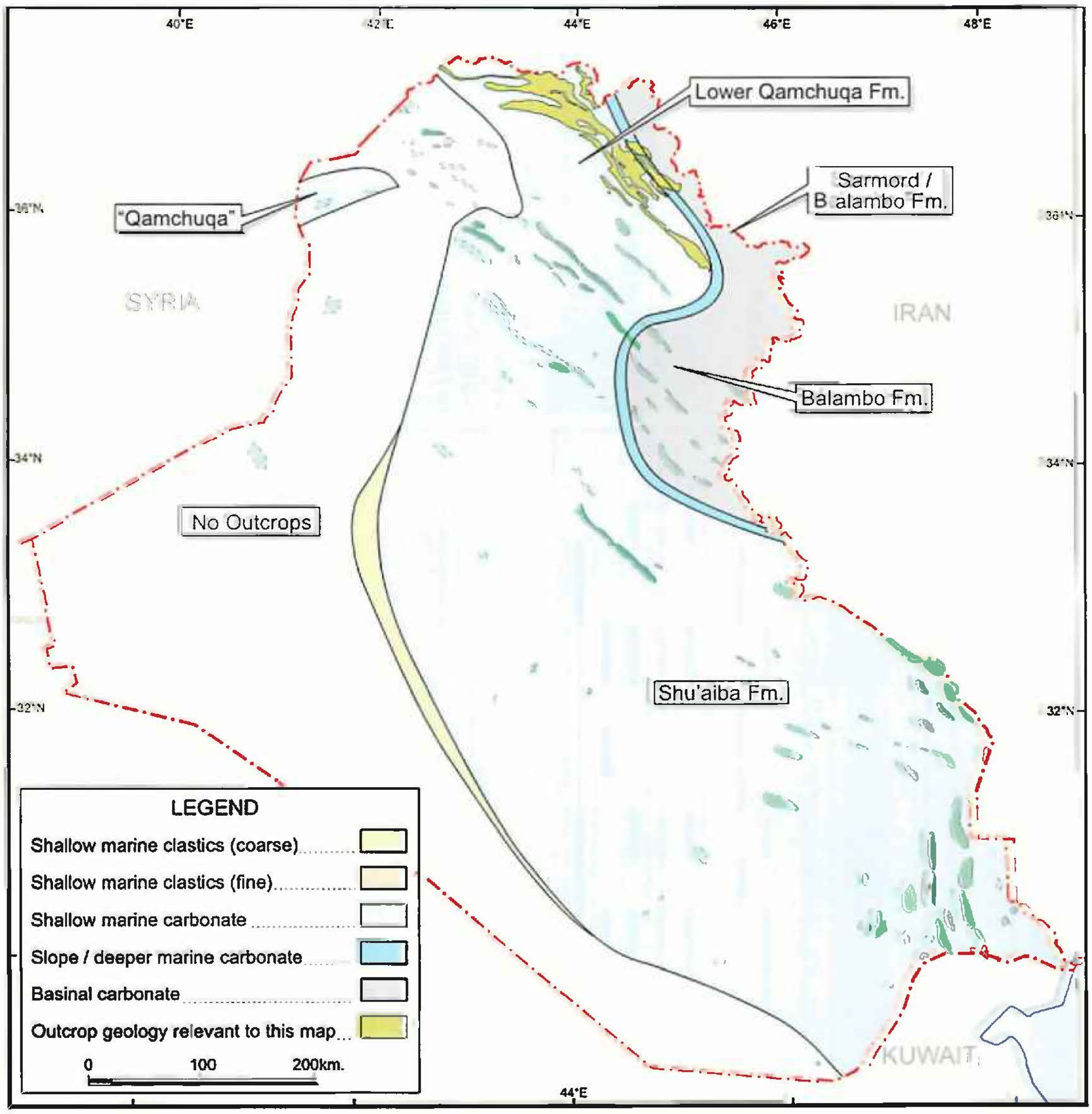


Fig. 7.24. Aptian palaeogeography of Iraq. Simplified Cambridge Carbonates Ltd map based on published data.

overlies the Garagu Formation (Dunnington *et al.*, 1959).

At *Halfaiya* and *Buzurgan* in SE Iraq, the Zubair Formation grades into offshore limestones and marly carbonates (Sadooni and Aqrawi, 2000). The younger Shu'aiba Formation is also thick along the Tikrit-Amara "palaeoridge" (Jassim and Buday, 2006e) corresponding to the Lower Qamchuqa platform margin complex.

In the Western Desert, proven Jurassic and Albian strata are separated by a siliciclastic unit termed the **Saggar Formation** (Jassim *et al.*, 1987) or **S'Ker Formation** (Kaddouri, 1989a) (Fig. 3.17). Jassim and Buday (2006e) suggested that it is Jurassic based on similarities between its dolomite cements and those in the Najmah Formation. Kaddouri (1989a) dated the formation as Hauterivian – Barremian from dinoflagellates, whose presence, however, was not confirmed in later studies (S.Jassim, *pers. comm.* to J.G.2006).

The Saggar Formation is exposed in cuttings along the Rutbah – Baghdad motorway between Rutbah and Wadi Saggar. It is about 30 m thick and was described by Jassim and Buday (2006e) as follows. The basal clastic unit comprises pebbly sandstones with rootlets overlain by gypsiferous sandstones. Overlying carbonates include sugary dolomites with zoned rhombs within a brown dolomitic matrix. Stromatolitic domes up to 50 cm in diameter occur 70 km east of Rutbah. Clastics are thickest (>15 m) in palaeo-depressions; carbonates thicken from 10 m near Rutbah to 25 m near Wadi Hauran to the NE. To the west, the basal contact is often marked by a laterite. A section on the western bank of Wadi Maeshir in the Western Desert comprises 1.7 to 8 m of red calcareous (lateritic) claystone with thin (0.3-1.4 m) interbeds of sandy, clayey carbonates, and fining-upward light grey sandstones (0.8-3.0 m), overlain by thick beds of locally fossiliferous sandy dolostones (Kaddouri, 1989a). The siliciclastics and carbonates are interpreted as fluvial and lagoonal/supratidal facies, respectively (Jassim and Buday, 2006e). Aptian siliciclastics and Shu'aiba Formation

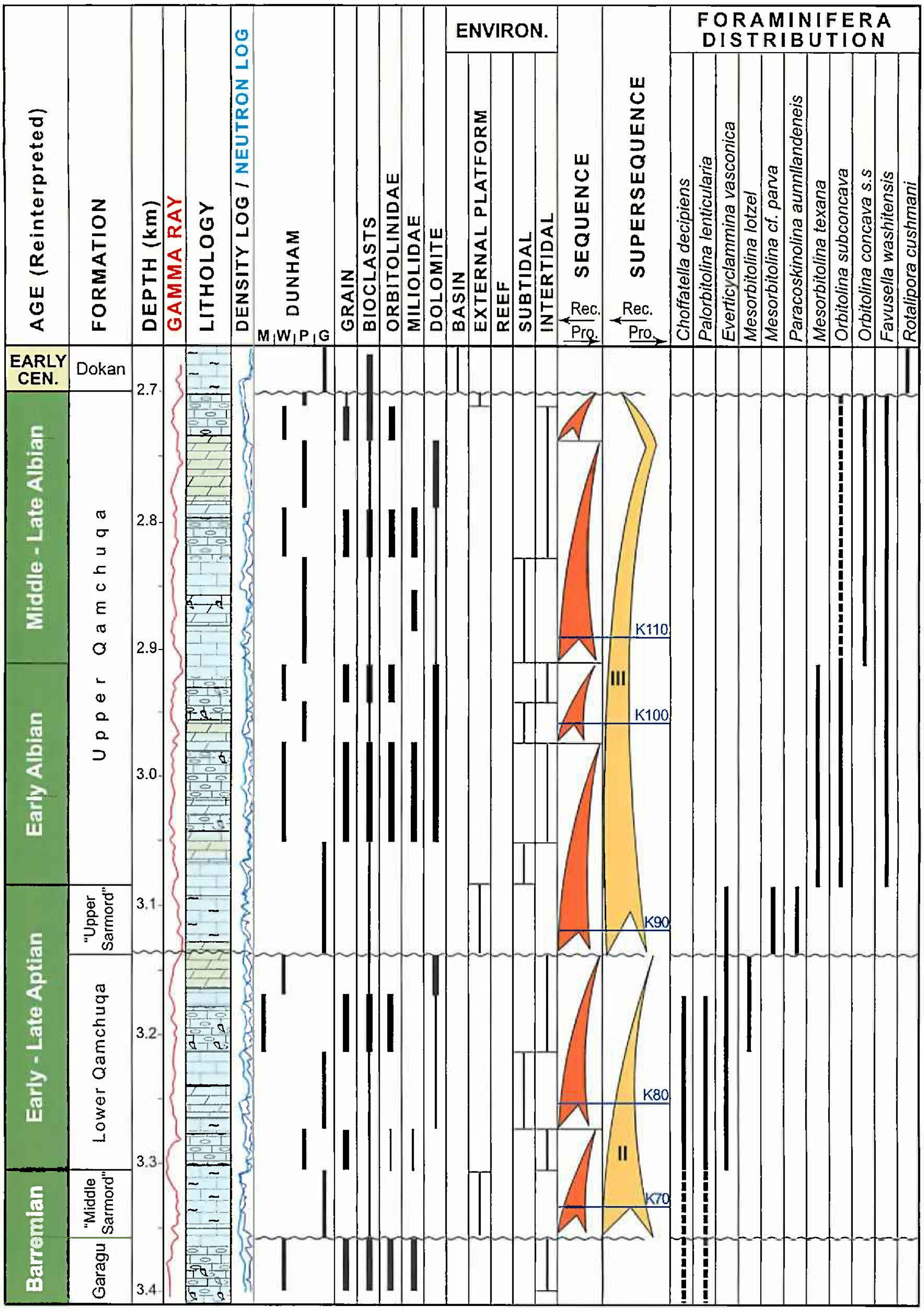


Fig. 7.25. Sequences and lithologies in the Qamchuqa Formation of the Kirkuk area, northern Iraq. The formation is relatively massive but different depositional facies can be identified and sequence stratigraphic divisions interpreted. The marly intervals are referred to here as the Middle and Upper Sarmord Formations. After Al-Shdidi *et al.*, 1995.

carbonates occur in nearby boreholes *KH7/7* and *B4/7* (Radoicic, 1986).

The Qamchuqa Formation passes downdip into slope facies marls and limestones of the **Sarmord Formation** (Fig.7.20). At Sirwan near Sulaimaniya, Supersequence II is represented by the basal part of the **Balambo Formation**, comprising thin-bedded basinal limestones with abundant ferruginous nodules. Fossils include *Crioceras* sp. and *Hoplites* sp. (Dunnington *et al.*, 1959). Balambo Formation mudstones in well *Pulkhana-5* are dated as Hauterivian –Valanginian (Jassim and Buday, 2006e). In the lowermost Balambo Formation, ammonites indicate a late Valanginian age; Berriasian sediments are often absent in the underlying Chia Gara Formation (Dunnington, 1967a). At Dalamar, the top of the underlying Chia Gara Formation (Dunnington *et al.*, 1959) is dolomitised and stained purple-brown, indicating a submarine hardground or condensed surface.

Petroleum System Components

Proven and Potential Reservoir Rocks

The main reservoir interval in this supersequence is the Zubair Formation.The Zubair sandstones are main pay zones in the *Zubair* and *Rumaila* fields and are locally important in Central Iraq (e.g. at *East Baghdad*). The Zubair is referred to as the Main Pay in *Rumaila* field, and as the 3rd and 4th Pays in the *Zubair* field (Al-Naqib, 1967).

The sand content of the Zubair Formation increases to the southwest (Ali and Nasser, 1989). In the Salman Zone, the formation consists entirely of sandstones (e.g. in wells *Awasil-5*, *Ghalaisan-1* and *Safawi-1*; Jassim and Al-Gailani, 2006). The reservoir quality (net:gross and porosity) of these sandstones declines towards the east of the Balambo-Garau Basin. Porosities of 30% in the Salman Zone decline to about 15% close to the border with Iran (Jassim and Al-Gailani, 2006). Permeabilities in the formation range from 20 to 1800 mD with a mean of 700 mD (Jassim and Al-Gailani, 2006). The Main Pay in the *Rumaila* field has an average porosity of 25% and permeability of 1000 mD (Al-Naqib, 1967).

The mean porosity at *South* and *North Rumaila* is 20% and 15%, respectively (Jassim and Al-Gailani, 2006). Permeability is higher than at *Zubair* and averages about 1000 mD (IPC, 1956). Mean aquifer permeabilities are about 600 mD on the west flank and 350 mD on the east flank (Kabir *et al.*, 2007).

At *Zubair* field, the formation comprises three pay zones (referred to by Al-Naqib (1967) as the AB, DI and LN reservoirs) with two intervening shales. Net pay reaches 100 m. Porosity averages 20% with permeabilities of 600 mD for the AB sand, 1000 mD for the DI sand, and 850 mD for the LN sand (Al-Naqib, 1967; Sadooni and Aqrawi, 2000). The 4th Pay in *Zubair* has a similar net:gross to that in the 3rd Pay but its reservoir quality is poorer.

Zubair Formation sandstones may have minor reservoir potential in NW central Iraq. The NE limit of the formation appears to lie a few km to the NE of *East Baghdad* field (Al-Ameri and Batten, 1997).

In the Upper Member of the Ratawi Formation in well *Abu Khema-1* near the border with Saudi Arabia, a 6-7 m thick sandstone interval has a porosity of 25% (Roychoudhury and Handoo, 1980).

At *Jambur*, reservoir quality in the Qamchuqa Formation is best where it is dolomitised (Al-Rawi *et al.*, 1980). Elsewhere in northern Iraq, the Lower Qamchuqa is a reservoir at the *Kirkuk* and *Bai Hassan* fields (Dunnington, 1967a; Al-Shdidi *et al.*, 1995). Porosities of 15-25% (average 20%) occur in dolomitised rudist facies in the Qamchuqa at *Kirkuk* field, decreasing to 2-3% in downdip Sarmord Formation slope facies (Al-Shdidi *et al.*, 1995). The porosity in the rudist limestones is mainly associated with rudist and bioclast moulds; algal limestones generally lack "recrystallisation" textures (Henson, 1950a). Karstification at the end of the Aptian may also contribute to reservoir porosities of 8 to 30% (average: 18%) and permeabilities of 80 to 1000 mD (average: 150 mD) (Jassim and Al-Gailani, 2006).

The Shua'iba Formation, equivalent to the Lower Qamchuqa, is an important carbonate reservoir in many Gulf countries, but is of only minor significance in southern Iraq. In the Gulf, the formation has 18-29% porosity but <100 mD permeability and is sealed by shales (Hamdan and Alsharhan, 1991; Alsharhan, 1995). Dunnington *et al.* (1959) noted "vacuolar secondary dolomite" in the Shu'aiba Formation at wells *Awasil-5* and *Nafatah-1* in Central Iraq.

Dunnington (1958; 1967a) considered that the Shu'aiba Formation acted as a sheet-like carrier bed which facilitated lateral oil migration into the *Kirkuk* palaeostructure and the Qaiyarah area fields of NW Iraq. Al-Naqib (1967) noted that the formation is a lost circulation zone. At *Nahrairan* in central Iraq, caverns encountered during drilling caused operational problems (F.S., *pers. obs.)*.

Proven and Potential Source Rocks

Only limited geochemical analyses have been performed on potential source rocks in this supersequence in Iraq. Shales within the Zubair Formation at *East Baghdad* field have TOCs of 0.5-6% (Al-Ameri and Batten, 1997). In Kuwait, Zubair Formation shales have TOCs of 0.5-3% and contain terrestrial organic matter (Type III kerogen) (Abdullah and Kinghorn, 1996).

The Ratawi Formation in Kuwait is 180 - 390 m thick. TOCs in the upper part are 0.4 to 3.2 wt% (Abdullah and Kinghorn, 1996). Kerogen macerals include spores, cuticle and woody material.

The Balambo Formation is equivalent to the middle and upper parts of the Garau Formation in Iran (see Fig. 7.15).

The Gadvan Formation in Iran (equivalent to the Upper Member of the Ratawi Formation of Iraq) was deposited in an intrashelf basin less than 100 m deep which extended SW towards Iraq

(Bordenave and Huc, 1995).It contains 20-100 m of argillaceous, sometimes pyritic and slightly bituminous limestones with TOCs locally above 1% in the basin centre. *Rock-Eval* S2 is 5 kg/tonne (Bordenave and Huc,1995).

Proven and Potential Cap Rocks

In Southern and Central Iraq, shale units within the Zubair Formation are internal seals. Argillaceous limestones of the Upper Member of the Ratawi Formation seal underlying Yamama Formation reservoirs. In northern Iraq, the only sealing facies are marly units at the base of the Lower Qamchuqa Formation. These seal the Garagu Formation; further west they may seal Jurassic reservoirs. In southern Iraq, the Shu'aiba is unconformably overlain by Nahr Umr Formation channel sandstones and thus lacks a seal.

Supersequence III: upper Aptian – upper Albian

In the latest Aptian, large parts of western and NW Iraq (emergent in the Neocomian) were onlapped, as recorded in wells *Sasan-1* and *Alan-2* (Dunnington *et al.*, 1959; Al-Jumaily and Domaci, 1976). In these wells (Fig. 7.26), the "Upper Sarmord" (Nahr Umr Shale/Batiwah Formation), and locally the Jawan Formation (e.g. in *Qalian-1*; Dunnington *et al.*, *ibid.*) unconformably overlie Jurassic formations. Further east, they overlie the Shu'aiba Formation (e.g. in well *Kirkuk-117*: Wilson, 1975) (Fig. 7.1).

In Kuwait, latest Aptian and earliest Albian sediments of nannozones KN36 to KN39 are missing (Al-Fares *et al.*, 1998); they are also probably absent from adjacent areas in southern Iraq. However in the Dezful Embayment of Iran, the Aptian Dariyan Limestone Formation is succeeded by the Kazhdumi Formation which is of latest Aptian age at its base (James and Wynd, 1965; Bordenave and Huc, 1995).

The main Albian depocentre was located to the east of the Salman Zone, south of the Takhadid-Qurna Transverse Fault (Fig. 3.18); Albian sediments are absent over parts of the Khleisia High and in Wadi Hauran in the Western Desert (Jassim and Buday, 2006e) (Fig. 7.27).

As with the underlying supersequences, stratigraphic organization in Supersequence III represents a transition from onlap margin to basin (Dunnington, 1958) (Fig. 7.28). From the onlap margin eastwards, the Nahr Umr Formation passes from sandstones into shales, which in turn pass laterally into deeper-water, carbonate-dominated facies, e.g. at *Buzurgan* (Al-Ani, 1975; Fig. 7.30). These pass into the upper part of the Sarmord Formation (*sensu stricto*), then into the middle part of the Balambo Formation. Locally in NW Iraq (Fig. 7.28a), the Nahr Umr Formation shales pass up into the anhydrites of the Jawan Formation. The shelfal system is capped by extensive carbonates of the Mauddud Formation, which pass eastwards into the upper part of the Qamchuqa Formation (Fig. 7.29).

The upper contact of the supersequence is a regional disconformity or unconformity overlain by transgressive Cenomanian marly limestones or shales (Dokan, Ahmadi and Rumaila Formations) (Fig. 7.2). Locally in northern Iraq, Albian formations are onlapped by much younger Late Cretaceous strata. In the *Butmah* field, the lower Campanian Mushorah Formation unconformably overlies the Nahr Umr Formation shales (Jassim and Buday, 2006e); it overlies the Jawan Formation in well *Sasan-1* (Al-Jumaily and Domaci, 1976) (Fig. 7.26b). The Hartha Formation overlies the Mauddud Formation at well *Alan-1* (Al-Jumaily and Domaci, 1976) (Fig. 7.26a). In the *Bekhme* area NE of Erbil, the Bekhme Limestone unconformably overlies the Qamchuqa Formation (Dunnington *et al.*, 1959) (Plate 7.3). In these locations, several erosional unconformities may be superimposed over a palaeohigh.

Formations

Supersequence III (upper Aptian – Albian) is generally less sandy than the underlying Hauterivian– upper Aptian Supersequence (Sadooni and Aqrawi, 2000). The principal siliciclastic depositional unit, the **Nahr Umr Formation**, is up to 300 m thick and thins eastwards, and becomes less sandy and more carbonate-rich towards Iran (Al-Ani, 1975; Ibrahim, 1983) (Figs. 7.30, 7.31). At its type section in the *Nahr Umr* field, it comprises black shales interbedded with medium- to fine-grained sandstones containing lignite, amber and pyrite (Owen and Nasr, 1958). A carbonate unit containing *Orbitolina* (Dair Limestone member) occurs locally in the upper part of the Nahr Umr Formation in SE Iraq, pinching out to the west and south (Dunnington *et al.*, 1959).

The Nahr Umr Formation is interpreted to be an alluvial to lower coastal plain to deltaic deposit with shallow-marine and aeolian influences (Ibrahim, 1981b, 1983; Alsharhan, 1994). Basal siliciclastics in the *East Baghdad* field (deltaic to coastal plain deposits), contain abundant palynomorphs, principally spores. These pass up into shallow-marine facies, as indicated by the appearance of carbonates and the increased abundance of foraminiferal test linings (Al-Ameri *et al.*, 2001). Palaeocurrent analysis of the correlative Burgan Formation in Kuwait suggests palaeoflow to the NE (Al-Eidan *et al.*, 2001) and this also probably applies to most of SE Iraq. At *Buzurgan*, the formation includes glauconitic and bituminous sandstones and pyritic shales with plant remains and amber (Al-Ani, 1975). These pass up into argillaceous or chalky limstones.

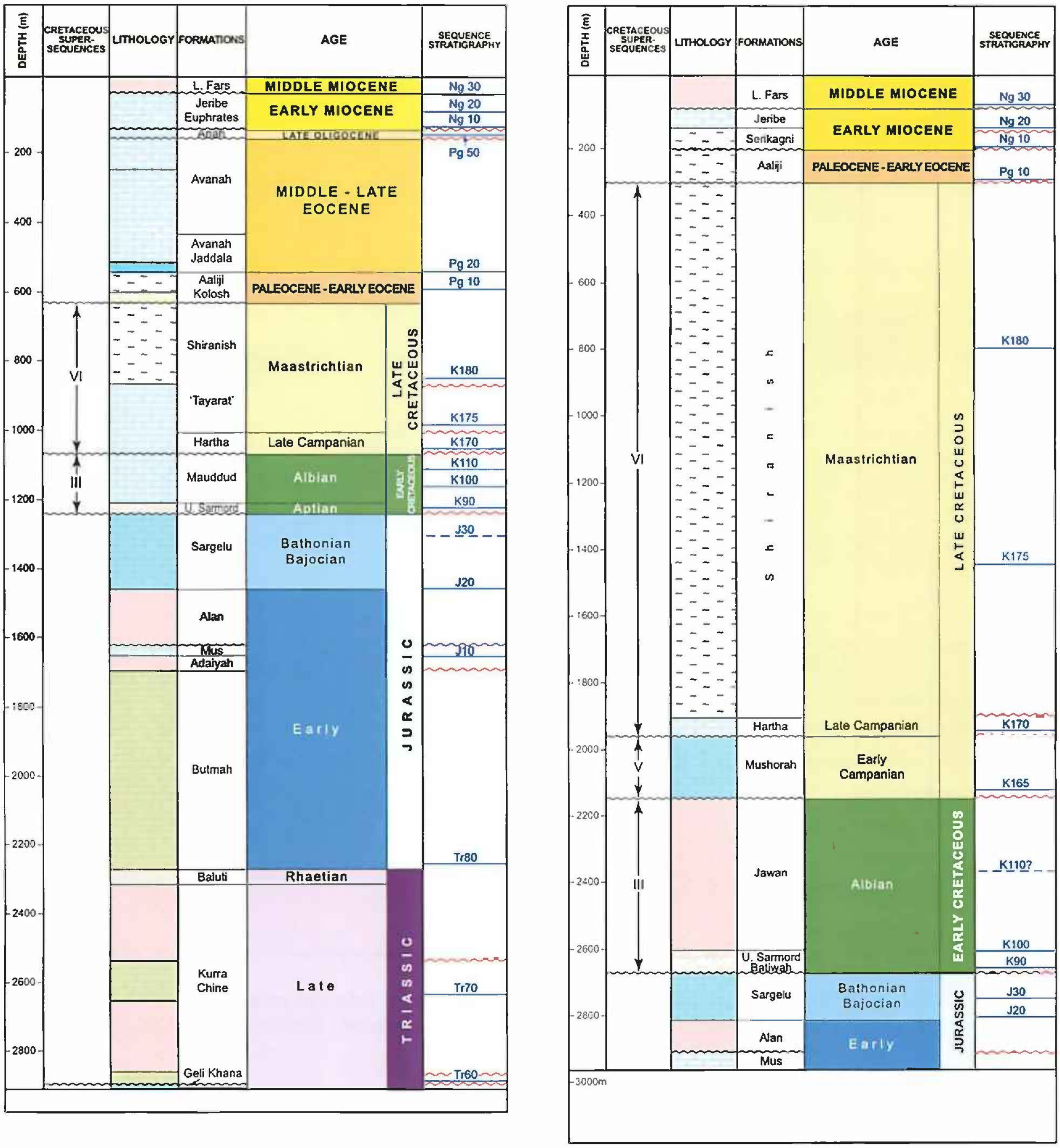


Fig. 7.26. Lithostratigraphy of wells *Alan-1* (left) and *Sasan-1* (right), showing the onlap of Jurassic units by the late Aptian – Albian Upper Sarmord / "Ratawi" Formation. Both wells penetrate a partial (mid-upper) Cretaceous stratigraphic succession. In *Sasan-1*, the thick upper Campanian - Maastrichtian section represents deposition in a graben which was subsequently inverted. By contrast, shelfal facies of the same age in *Alan-1* are thinner and are typical of deposition on a latest Cretaceous palaeohigh. After Al-Jumaily and Domaci, 1976.

In outcrops in the Western Desert, the Nahr Umr Formation unconformably overlies the Saggar Formation (Jassim and Buday, 2006e). It is 22 – 54 m thick and comprises up to 43 m of cross-bedded ferruginous sandstones and basal conglomerates, overlain by 11 m of sandstones, sandy marls and fossiliferous limestones. It is overlain by the Mauddud Formation.

In the Euphrates Graben, Syria, the correlative Rutbah Sandstone Formation (*sensu lato*) was deposited in a shallow-marine or deltaic to interdeltaic environment (de Ruiter *et al.*, 1995). These sandstones may extend into the Anah, Khleisia, Tinif and Tayarat grabens in western Iraq.

The **Nahr Umr Formation Shale** (also referred to as the **Batiwah Formation** or **Upper Sarmord Formation**: Sadooni and Aqrawi, 2000) comprises marls with interbedded limestones, laterally equivalent to the Nahr Umr Formation

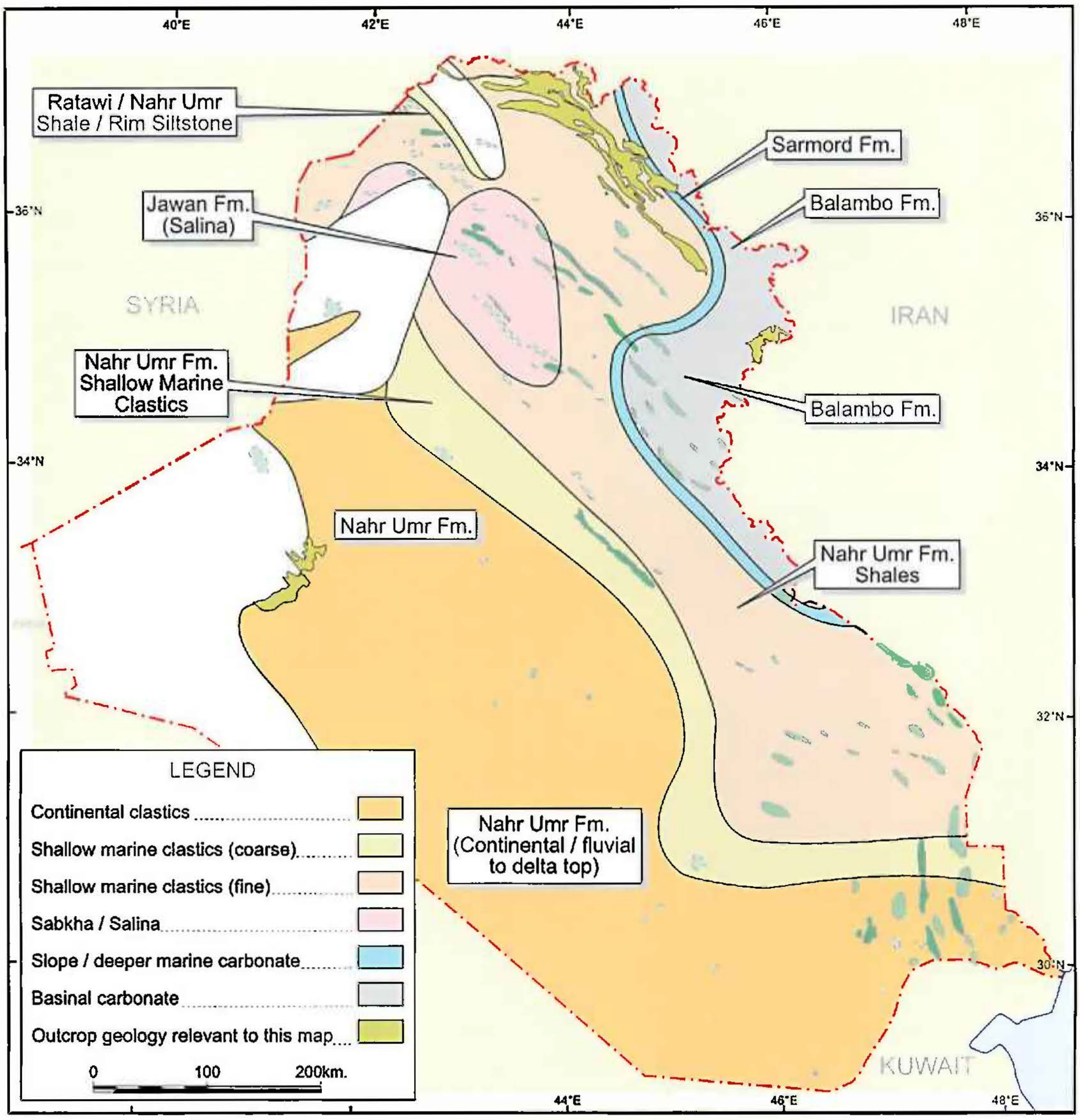


Fig. 7.27. Early – middle Albian palaeogeography of Iraq. Units of this age crop out both in Iraqi Kurdistan and the Western Desert. Simplified Cambridge Carbonates Ltd map based on published data.

sandstones. It thickens towards the NE from 11 m in well *Ibrahim-1* to 169 m at *Kirkuk* (Jassim and Buday, 2006e). The formation separates the Upper and Lower Qamchuqa carbonates at *Jambur* (Al-Rawi *et al.*, 1980; Fig. 7.20) and *Kirkuk* (Wilson, 1975; Fig. 7.21), and represents the distal clastics of the Nahr Umr delta. At *Ain Zalah*, the formation is 34 m thick and unconformably overlies Jurassic strata. It consists of recrystallised dolomitic limestones with partings of black shales and green pyritic fossiliferous shales (El Zarka, 1993).

An overlying clastic unit, the **Rim Siltstone Formation** comprises 55 to 60 m of shales, siltstones and thin sandstones in the *Butmah* area (Dunnington *et al.*, 1959). It was probably deposited on the western margin of a north-south trending palaeohigh running through Jebel Kand (Fig. 7.27).

The Nahr Umr Formation is overlain by the **Mauddud Formation** (Fig. 7.29). This is preserved in wells *Makhul-2, Awasil-5, Adaiyah-1, Atshan-1, Alan-1, Butmah-2, Qarah Chauq-1* and *Ain Zalah* (Dunnington *et al.*, 1959; Hart and Hay, 1974; Jassim and Buday, 2006e). The formation may be absent locally in NW Iraq due to intra-Cretaceous erosion.

In the Basra area, the Mauddud Formation is 19 m thick at the *Ratawi* field (Sadooni and Alsharhan, 2003). It is nearly 240 m thick near Amara and thickens towards the Iranian border (Al-Ani, 1975; Ibrahim, 1983; Mohammed and Al-Sayyab, 1993; Jassim and Buday, 2006e) (Figs. 7.28, 7.30). This isopach thick is interpreted to be a constructional high (see page 165). It was referred to as the "Tikrit-Amara palaeohigh" by Jassim and Buday, 2006e.

Lithofacies in the Mauddud Formation include rudstones and grainstones resembling the overlying Mishrif Formation (Mohammed and Al-Sayyab, 1993; Sadooni, 2005). In SE Iraq, organic detrital to pseudo-oolitic limestones occur locally with blue-

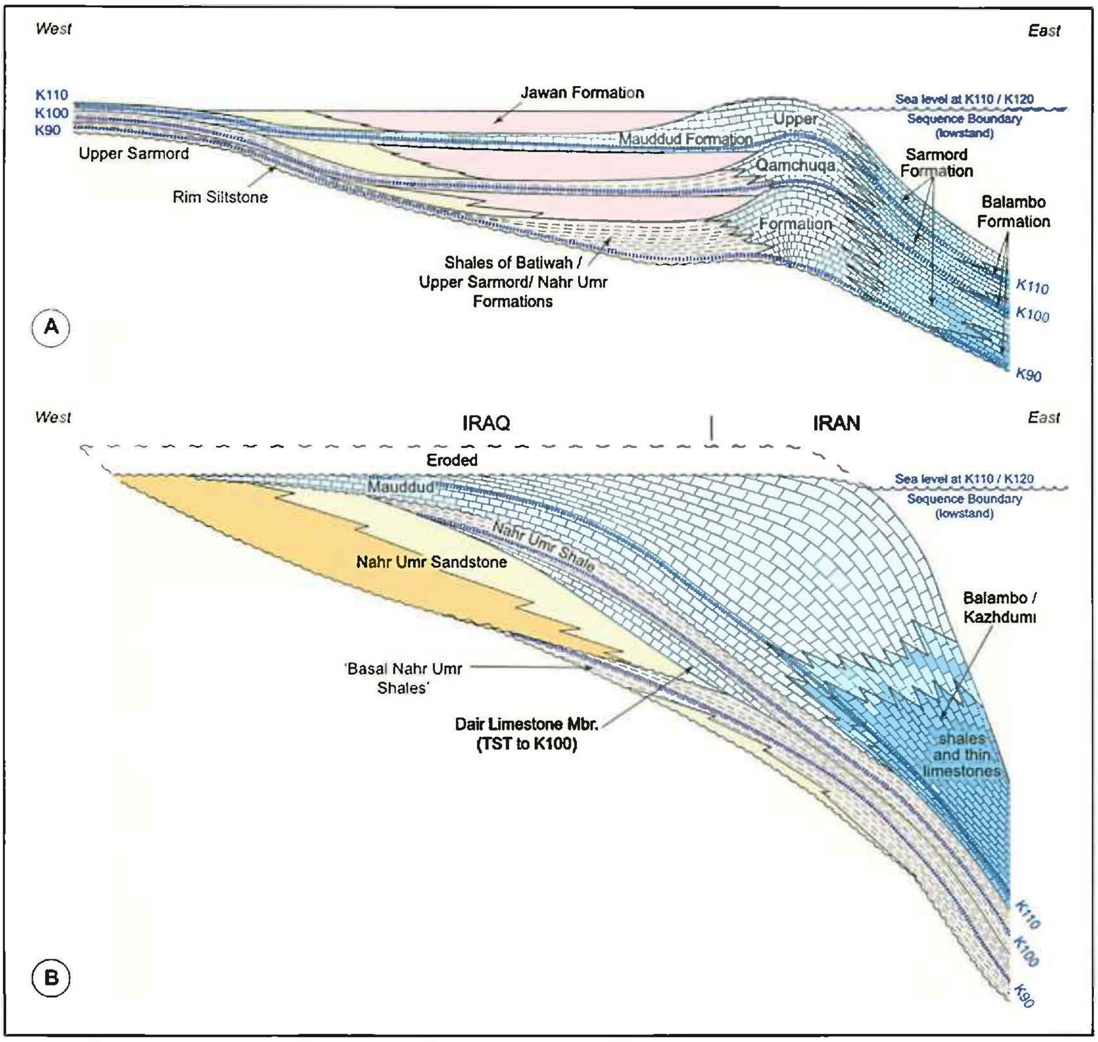


Fig. 7.28. Schematic west-east profiles across (a) northern Iraq, and (b) southern Iraq illustrating the organisation and relative thickness of stratigraphic units in Supersequence III.

Plate 7.3. Maastrichtian limestones assigned to the Aqra/ Bekhme Formations (A/B: background) resting unconformably on bedded dolomitic limestones of the Qamchuqa Formation (Q: foreground) at Geli Ali Bek, Iraqi Kurdistan. Photo: A. Aqrawi.

green shales (Owen and Nasr, 1958). Deep-water limestones occur at the base of the formation. They are overlain by marls with a planktonic fauna which represent the K110 MFS. These shallow up into shelfal facies (N. Pickard, *pers. comm.* to A.H., 2009). The formation extends westwards to the SE flank of the Hauran Anticlinorium (Jassim and Buday, 2006e). To the east, in *Buzurgan* and *Abu Ghirab*, it consists of chalky, rudist-dominated intervals at least 40 m thick similar to the Qamchuqa Formation at *Jambur*, interpreted as platform margin facies (Al-Ani, 1975; Mohammed and Al-Sayyab, 1993; Sadooni and Alsharhan, 2003).

A fauna including *Orbitolina* is recorded (Plate 7.4) in dolomitic limestones or dolomites (Sadooni and Aqrawi, 2000) interpreted as fore-reef facies. These occur to the west of the main rudist-dominated units, for example at the *Ratawi*, *Majnoon* and *Halfaiya* fields (Mohammed and Al-Sayyab, 1993), suggesting possible development of an intrashelf basin between the rudist facies and the siliciclastics to the west. At *Ain Zalah* field, the Mauddud Formation (referred to here as the Qamchuqa Formation) comprises 165 m of dolomitic

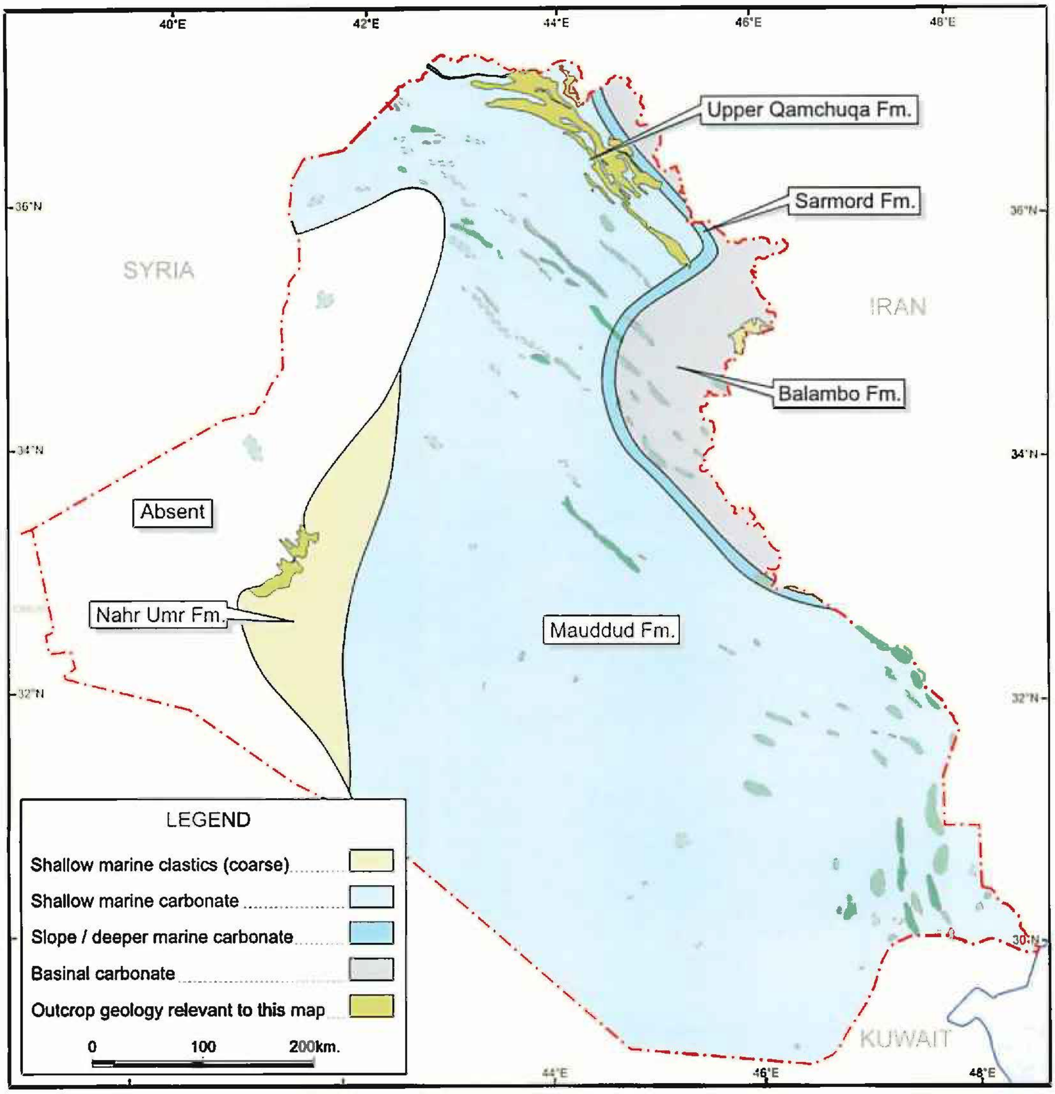


Fig. 7.29. Late Albian palaeogeography of Iraq. Simplified Cambridge Carbonates Ltd **map based on published data.**

limestones and thin, black bituminous shales; the limestones are bioclastic, peloidal and oil- saturated, while the shales are black or grey and fissile (El Zarka, 1993). The formation is often dolomitised but the dolomite content and porosity is variable and unpredictable (Henson, 1950a).

In Iraqi Kurdistan, the Mauddud passes into the upper part of the **Qamchuqa Formation** (Plates 7.5, 7.6). The terms Mauddud and Upper Qamchuqa are often used interchangeably for Albian carbonates in this area (c.f. El Zarka, 1993). They comprise alternating *Orbitolina* and rudist limestones and two or more dolomite intervals in the *Jambur* field (Al-Rawi *et al.*, 1980; Sadooni and Alsharhan, 2003) and in the *Kirkuk* area (Wilson, 1995; Al-Shdidi *et al.*, 1995) (Fig. 7.25). Up to 400 m of Albian carbonates occur in NE Iraq (Jassim and Buday, 2006e). The dolomites may be of deep-seated high-temperature (possibly hydrothermal) origin (Sadooni and Alsharhan, 2003) although Al-Shdidi *et al.* (1995) suggested that dolomitising fluids were dominantly related to burial.

In the *Sadid*, *Hibbarah*, *Jawan*, *Qalian* and *Najmah* area of NW Iraq, the Qamchuqa and Nahr Umr Formations pass into the **Jawan** and **Batiwah Formations** (Dunnington *et al.*, 1959; Buday, 1980). The Jawan Formation contains lagoonal and sabkha facies (Sadooni, 1978, 1995a). It extends into the NW part of the *Kirkuk* field (Wilson, 1975) (Fig. 7.21, 7.27). Further west, it is interbedded with platform carbonates in the *Sasan-1* and *Ibrahim-1* wells. It is thickest in the *Makhul* area (222-276 m) and contains thin siltstone beds with euryhaline fossils (Jassim and Buday, 2006e). The Jawan Formation is interpreted as a lowstand evaporite deposited in local basins between the Nahr Umr deltaic complex and the Upper Qamchuqa platform margin.

The **Batiwah Formation** includes the organic-rich shales at the base of the Jawan Formation described by Buday (1980, after unpublished work by Chatton and Hart, 1961). These shales resemble the Kazhdumi Shales of Iran (James and Wynd, 1965) and may be important source rocks.

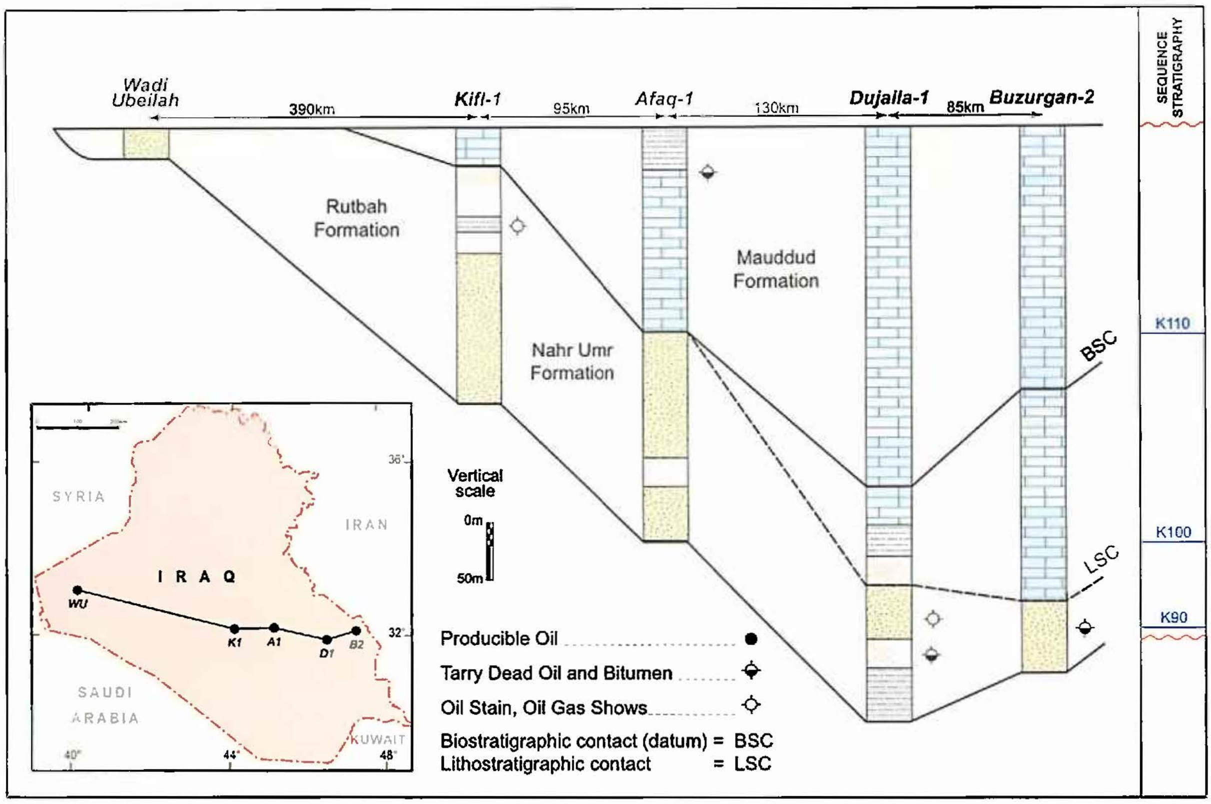


Fig. 7.30. Albian cycle in central Iraq: cross-section of the clastic-carbonate shelf showing eastwards thinning of clastics and concomitant thickening of the carbonates. Modified after Ibrahim (1983).

In deeper parts of the basin system, the Qamchuqa Formation passes eastwards into, and progrades over, slope facies (limestones and marls) of the **Sarmord Formation** *sensu stricto* (Plate 7.6; Fig. 7.19) (Henson, 1950a; Dunnington *et al.*, 1959). These slope facies pass laterally over a short distance into basinal limestones of the **Balambo Formation**, of which the Albian interval is about 90 m thick at *Sirwan* (Dunnington *et al.*, 1959). The Balambo Formation occurs in the Kirkuk Embayment to the SE of the *Kirkuk* and *Jambur* fields, and to the NE of the *East Baghdad* field. In well *Pulkhana-5* in the Kirkuk Embayment, the foraminifera *Hastingerinella subcretacea* and *Schackoina eicheli* indicate an Albian age and bathyal water depths for the Balambo Formation (Jassim and Buday, 2006e). In the *Jambur* field, transitional interbedded rudistid and "Balambo" type facies occur in the SE of the structure (Al-Rawi *et al.*, 1980) (Fig. 7.20). The *Badra* field in eastern Iraq contains a chalky limestone facies indicating deeper waters than the "typical" Upper Qamchuqa / Mauddud shelf carbonates (Sadooni and Alsharhan, 2003) (Figs 7.27, 7.29).

Petroleum System Components

Proven and Potential Reservoir Rocks

Two main reservoir facies are present in Supersequence III: (i) deltaic sandstones of the Nahr Umr Formation, which form a secondary clastic reservoir target (above the Zubair Formation) in southern Iraq (Ibrahim 1981b, 1983; Al-Ameri *et al.*, 2001); and (ii) the carbonate-dominated Qamchuqa Formation (Sadooni and Alsharhan, 2003). Minor reservoir units are also present in the Mauddud Formation.

Porosity in the **Nahr Umr Formation** ranges from 16 to 23.3% (mean: 21%) and permeability from 20 to 3000 mD (mean: 200 mD) (Jassim and Al-Gailani, 2006). The formation may have a high shale content; in the *Nahr Umr* field, the net-gross is only 0.4 (Al-Naqib, 1967; Sadooni and Aqrawi, 2000). Two Nahr Umr sandstone reservoirs (the 3rd and 4th sandstones: Owen and Nasr, 1958) are separated by a major shale unit. In Iraq, the reservoir quality of the Nahr Umr Formation is poorer than that of the underlying Zubair Formation (Al-Sakini, 1992). The equivalent Burgan Formation in Kuwait is up to 350 m thick and contains very well-sorted sandstones forming an excellent reservoir, with a net:gross of almost 1.0 (Fox, 1959; Al-Naqib, 1967; Brennan, 1990; Al-Eidan *et al.*, 2001).

The **Qamchuqa Formation** is important in the *Kirkuk*, *Jambur* and *Bai Hassan* fields (Dunnington, 1967a; Al-Rawi *et al.*, 1980) and also at *Kabbaz* (Sadooni and Aqrawi, 2000) in northern Iraq. At the *Taq-Taq* field, well *10* tested a 136 m thick interval in the Qamchuqa at 11,080 b/d oil*. In eastern Iraq, the *Badra* structure has also been

* *www.gulfoilandgas.com*, 18.3.09.

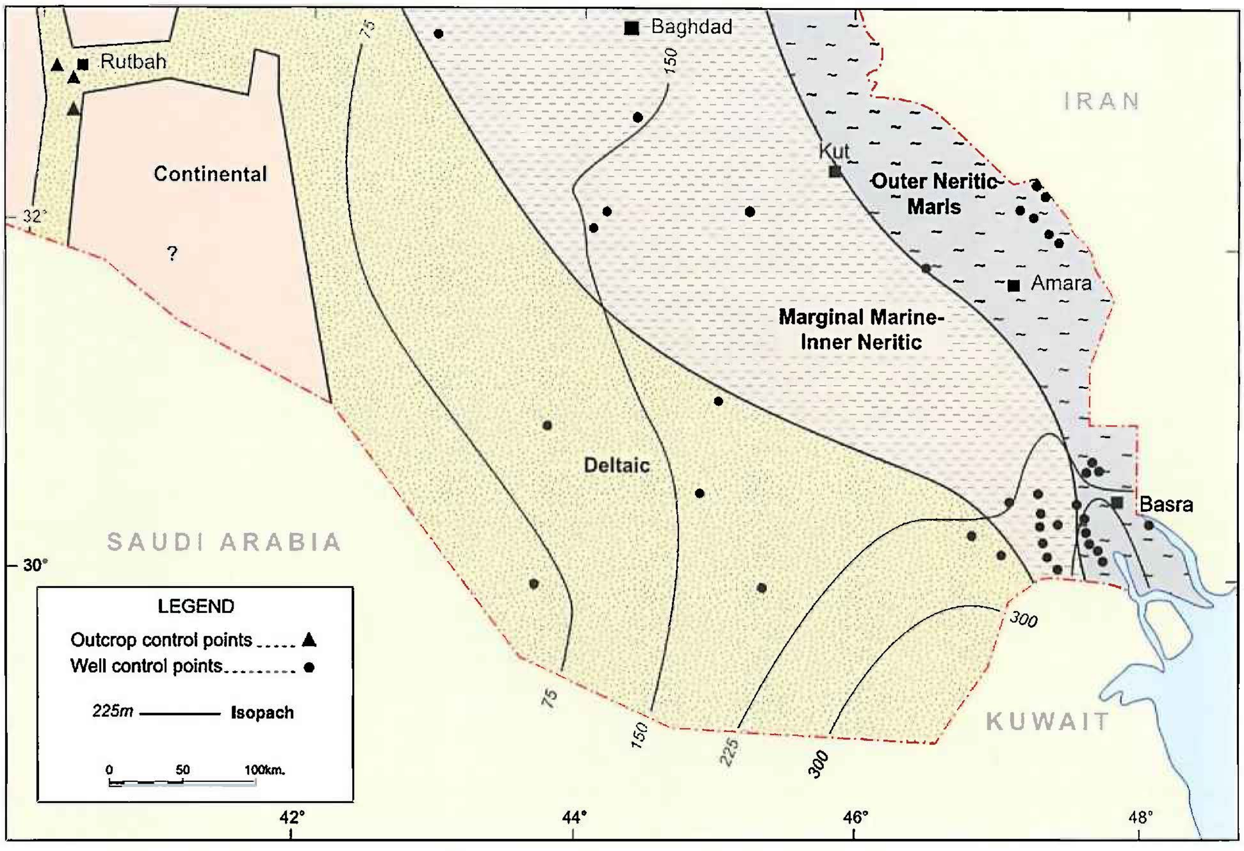


Fig. 7.31. Isopach and facies map of the early Albian in south-SW Iraq. A shale-rich facies belt occurs between the deltaic clastics and the outer-shelf marls. Modified after Ibrahim, 1983.

tested (Sadooni and Aqrawi, 2000). The formation is partly dolomitised (Dunnington *et al.*, 1959) which has enhanced its permeability although porosity may not be effected (Al-Rawi *et al.*, 1980; Sadooni and Alsharhan, 2003; Plate 7.7a; Fig. 7.32). Sadooni and Alsharhan (2003) noted widespread meteoric diagenesis at the unconformity at its upper boundary, with palaeo caves and karst at Sefin Dagh (near Shaqlawa town) in Iraqi Kurdistan (Plate 7.7b). Significant vuggy porosity also occurs in the subsurface at the *Kirkuk, Bai Hassan* and *Jambur* fields (Sadooni, 1978).

The *Bai Hassan* field produces from a fractured *Orbitolina* limestone and dolomite reservoir (Sadooni and Alsharhan, 2003). In outcrop to the NE, the fore-reef *Orbitolina* facies is often porous (Henson, 1950a). Analogous vuggy porosity occurs in Albian carbonates in Qatar (Focke *et al.*, 1986).

Dolomite units have average porosities of 18% (Al-Sakini, 1992). Al-Shdidi *et al.* (1995) recorded core porosities of 15-25% (mean: 20%) with a mean log porosity of 18% in the Qamchuqa dolomite, and 2-3% porosity in the downdip Sarmord Formation slope facies. Porosities from mercury injection data for dolomites in *Kabbaz* field range from 0.2 to 21% (Sadooni and Alsharhan, 2003). Porosities of planar-e dolomite average about 11% with permeabilities of 13 mD; permeability increases sharply at porosities >15%. The average porosity of the non-planar-e dolomite is only 6% but the average permeability is about 200 mD. Permeabilities in analysed samples peak between porosities of 10 to 15%; higher porosities are associated with large, isolated vugs which have generally low permeability. High permeabilities also occur in fractured samples (Salih and Sadooni, 1987; Sadooni and Alsharhan, 2003).

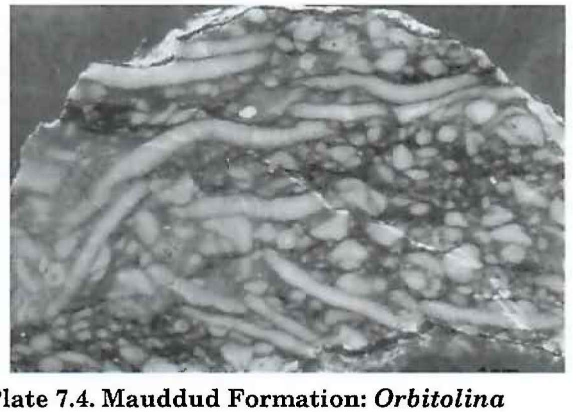


Plate 7.4. Mauddud Formation: *Orbitolina* rudstone from *Kirkuk* field, northern Iraq (from Sadooni and Alsharhan, 2003).

Mauddud Formation reservoirs produce from dolomite, leached bioclastic (rudist) limestones or *Orbitolina* limestones (Sadooni and Alsharhan, 2003).The formation comprises porous fossiliferous pack-grainstones with a mean porosity of 18% (range 10-22%) and permeabilities of 10-15 mD (Sadooni and Alsharhan, 2003). In interbedded shelf and basinal (Balambo) facies, limestones are often

Plate 7.5a, b. Qamchuqa Formation at outcrop in Iraqi Kurdistan (photos by A. Aqrawi):
(a) reefal limestones at Sefin Dagh, 5 km from Shaqlawa (around 40 km from Erbil); note the cave.
(b) ridge formed by Qamchuqa Formation limestones near Harir, about 55 km north of Erbil.

Plate 7.6. Massive limestones of the Qamchuqa Formation at the top of the cliff resting on thin-bedded marly limestones of the Sarmord Formation. Near Geli Ali Bek waterfall, about 85 km north of Erbil in Iraqi Kurdistan. Photo by A. Aqrawi.

chalky or dolomitised (e.g. *Badra* field: Sadooni and Alsharhan, 2003). In the updip part of the shelf, limestones are commonly very thin .

The *Ain Zalah* discovery well produced 8000 b/d (El Zarka, 1993). This "Second Pay" is reported to be 100-200 m thick at *Ain Zalah* with average porosities and permeabilities of 1.1% and 1 mD, respectively see further discussion on pp. 351-356). Some thin beds have porosities of up to 20% (El Zarka, 1993). The formation comprises fractured bioclastic limestones and permeable and porous dolomites (Hart and Hay, 1974; El Zarka, 1993; Sadooni and Alsharhan, 2003). It has a net thickness of 150 m in the Amara area and 50 m near *Zubair* (Jassim and Al-Gailani, 2006). The formation also forms a secondary reservoir in the *Ratawi* field (Al-Sakini, 1992; Sadooni and Aqrawi, 2000).

To the south, the Mauddud Formation is a reservoir in the *Raudhatain* and *Sabriya* fields of Kuwait. The formation also produces oil in parts of the *Burgan* field, and forms the main reservoir in the *Bahrain* field (Al-Naqib, 1967).

Medium-grained quartzose sandstones of the **Rutbah Sandstone Formation** occur in the Euphrates Graben, Syria, and probably also in graben systems in Iraq (e.g. the Anah Graben). In the Euphrates Graben, the formation produced up to 400,000 b/d from 38 pools (de Ruiter *et al.*, 1995). Well *Thayyem-1X* penetrated 200 m of sandstones with a net:gross of up to 0.95, a porosity of 20% and permeabilities of up to several Darcies at depths of approximately 3000 m (de Ruiter *et al., ibid.).* The porosity in the reservoir decreases downwards, but permeabilities do not decline significantly with depth (de Ruiter *et al., ibid.).* The Rutbah Sandstone Formation also locally contains leached limestone reservoir intervals (de Ruiter *et al.*, 1995; Caron *et al.*, 2000).

Proven and Potential Source Rocks

Oils in the Nahr Umr Formation may have been generated by source rock intervals in the thick interbedded shales (Sadooni and Aqrawi, 2000). Al-Ameri *et al.* (2001) recorded marine algal kerogen in shales in the upper part of the Nahr Umr and basal Mauddud Formations at the *East Baghdad* field, with TOC of 0.4-0.95% and a TAI of 1.8. The lower part of the Nahr Umr contains only Type III or IV kerogen (Al-Ameri *et al.*, 2001). El Zarka (1993) suggested that possible source rocks in the *Ain Zalah* area include thin beds of black bituminous shale in the "Qamchuqa" and presumably Batiwah / Nahr Umr Shale Formations.

The Balambo Formation is equivalent to the uppermost part of the Garau Formation in Iran. Bordenave and Huc (1995) recorded residual TOC values of 0.5 to 0.6% in uppermost Aptian-Albian

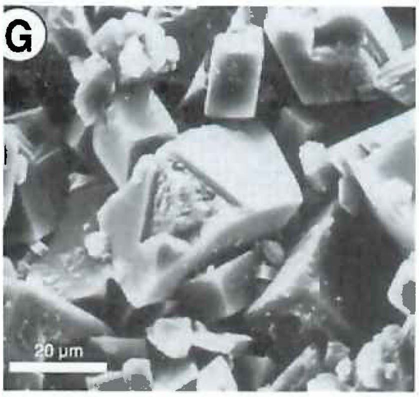


Plate 7.7a (left). Qamchuqa Formation: SEM of porosity in dolomitised limestone. From Sadooni and Alsharhan (2003).
Plate 7.7b (right). Cavernous porosity in the Qamchuqa Formation at outcrop. From Sadooni and Alsharhan (2003).

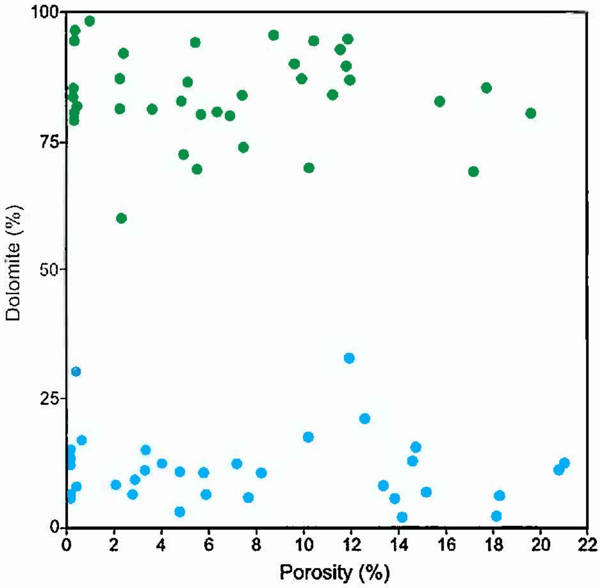


Fig. 7.32. Porosity in limestone reservoir intervals (blue dots) versus dolomite intervals (green dots) in the Mauddud/Qamchuqa Formations. Modified from Sadooni and Alsharhan (2003).

marls at the Garau Formation's type section (Fig. 7.15). Possible source rocks may also occur in the Sarmord Formation *sensu stricto* (Sadooni and Aqrawi, 2000).

Bituminous mudstones and marls in the Kazhdumi Formation are a major source rock in the Dezful Embayment (Iran), in an intrashelf basin of Albian age along-strike from, and adjacent to, the southern Iraqi basin system. Kazhdumi shales form the principal source rock system for the oil reservoired in the Asmari and Bangestan Group oilfields (Bordenave and Huc, 1995). The Kazhdumi Formation is equivalent to the Nahr Umr Shale and Batiwah Formation of Iraq.

The Dezful Embayment occupies an area of 40,000 sq. km and extends into SE Iraq (Bordenave and Huc, 1995, their fig. 14). The quality of the Kazhdumi Formation source rock is outstanding, comprising over 300 m of dark-grey marls and argillaceous limestones. In the basin centre, TOC values average 7.5% (range: 3.1 to 12.0%). Mean *Rock-Eval* S1 and S2 values are up to 3 and 53 kg/tonne, respectively in the *MLB-16* well. Within the basin as a whole, S2 generally ranges from 17 to 40 kg/tonne; HI is up to 713 kgHC/tC (Bordenave and Huc, 1995).

Source-rock quality appears to increase towards Iraq (compare wells *B* and *C* in fig. 12 of Bordenave and Huc, 1995). However, this may be due to the present-day overmaturity of the Khazdumi Formation in the basin centre (now located in the mountain front). Although it is located in front of a major clastic deposystem, Kazhdumi organic matter is composed of marine algal remains with few sphaeromorphs and "no trace of terrestrial plants" (Ala *et al.*, 1980). The kerogen is classified as Type IIc and has a high sulphur content (3 to 4% when immature, 1% when mature) and an HI of 500 to 700g HC/kgC (Bordenave and Huc, 1995).

Water depths in the intrashelf basin probably did not exceed 100 m. Source-rock deposition was probably promoted by the input of highly oxygenated fresh surface waters charged with nitrates and phosphates. Oceanic waters circulated into the basin as a counter current and density stratification developed, allowing organic preservation in the denser, anoxic marine waters (Bordenave and Huc, 1995).

Shales in the Burgan Formation of Kuwait increase in thickness towards the north and NE and have TOCs ranging from 0.64 to 3.4 wt% (mean: 2.4%) (Abdullah and Kinghorn, 1996). Organic material is terrigenous, and the HI is about 300 mgHC/gC_{org}.

Proven and Potential Cap Rocks

In southern and central Iraq, well-developed shale units within the Nahr Umr Formation act as intraformational seals. The Albian Jawan Formation anhydrite unit may form a seal but is restricted to north-central Iraq between the *Makhul* and *Kirkuk* regions.

The Nahr Umr Shale is a more efficient seal in northern Iraq than the marls at the base of the Qamchuqa Formation. It appears to seal oil accumulations in Lower Qamchuqa reservoirs in *Kirkuk Baba Dome, Bai Hassan* and *Jambur* (Dunnington, 1967a) or at least it isolates the different pays (Al-Rawi *et al.*, 1980). The Shale may not be an effective seal at the Jurassic subcrop in NW Iraq. In Syria, the correlative late Albian Rutbah Shale represents a possible sealing unit above the Rutbah Sandstone Formation (Caron *et al.*, 2000).

Supersequence IV: uppermost Albian – lower Turonian

Stratigraphic organization in Supersequence IV represents a transition from onlap margin to basin (Fig. 7.33, 7.34), as proposed by Dunnington (1958). The supersequence thickens eastwards (Fig. 7.33). In the Western Desert, the basal unit is the Rutbah Sandstone Formation, equivalent to the Wara Formation and the basal shales of the Ahmadi Formation which are present further east (Al-Naqib, 1967). The unit was termed the "third clastic front" of the Cretaceous by Sadooni and Aqrawi (2000). The overlying shelf carbonates of the M'sad Formation pass eastwards into the Ahmadi and Rumaila Formations in southern Iraq (locally referred to as the Maotsi, Fahad and Mahilban Formations in Central Iraq) (Fig. 7.34).

The Rumaila Formation passes laterally and upwards into the Mishrif Formation to the east and north (Fig. 7.33). The Mishrif passes to the NE into the Dokan and Balambo Formations in Iraqi Kurdistan to the SE of *Jambur* and *Kirkuk* fields.

Alkersan (1975) noted that the rudist-bearing facies of the Mishrif Formation only occurs to the east of the *Luhais* and *Afaq* fields. To the west, a few feet of unfossiliferous micrites in the *Samawa* and *Uba'id* wells have been assigned to the Mishrif Formation. However, they are considered here to be lowstand units resting on the Supersequence IV/V boundary. In NW Iraq, the Gir Bir Formation is equivalent to the Mishrif Formation, but directly overlies older sequences.

Cenomanian – lower Turonian sediments are absent from the Mosul High and the Khleisia and Rutbah Highs (Fig. 7.34). At the top of the supersequence, the upper bounding unconformity represents a considerable period of non-deposition/erosion (Fig. 7.2).

Supersequence IV can be correlated with the upper part of the Sarvak Formation in Iran, the Massive Limestone in NE Syria, and the Derdere Formation in Southern Turkey (Sharland *et al.*, 2001).

Formations

The **Wara Formation,** at the base of Supersequence IV (Fig. 7.33), was defined in Kuwait (Owen and Nasr, 1958). In Kuwait, the formation consists of fine-grained sandstones with siltstones and shales. The shales are light grey, lignitic and laminated, and thin towards the north (Abdullah and Kinghorn, 1996). Equivalent silty marine shales in Iraq are assigned to the basal part of the Ahmadi Formation (Chatton and Hart, 1961; Al-Siddiki, 1978 *in* Jassim and Buday, 2006e). Dunnington *et al.* (1959) and Al-Naqib (1967) considered the Wara Formation to be of earliest Cenomanian age.

The **Ahmadi Formation** is dominated by shales, but up to 160 m of carbonates rich in calcisphaerulids *(Oligostegina)* occur in the (Middle) Tuba Member. The "*Cythereis bahraini* Limestone" marker bed is present near the base of the formation (Dunnington *et al.*, 1959). These relatively deep-water deposits represent the K120 maximum flooding surface of Sharland *et al.* (2001) (Fig. 7.33).

The top of the Ahmadi Formation has been dated as early Cenomanian (Dunnington *et al.*, 1959; Al-Naqib, 1967). Ostracod faunas in Ahmadi Formation shales indicate water depths of 20 m (i.e. shallow inner shelf) to 70 m (i.e. middle shelf) (Al-Fares *et al.*, 1998).

In southern Iraq, the Ahmadi Formation is overlain by the carbonate-dominated **Rumaila Formation** (Owen and Nasr, 1958; Dunnington *et al.*, 1959) which extends northwards to Makhul and Samarra (Jassim and Buday, 2006e), where its basal contact is locally unconformable to conglomeratic. The lower member of the Rumaila comprises fine-grained chalky limestones; the upper member includes marls and fine-grained marly oligosteginal limestones (Owen and Nasr, 1958; Dunnington *et al.*, 1959; Aqrawi, 1983). The formation is of Cenomanian age (Smout, 1956). Dominant dwarf foraminifera indicate a restricted depositional environment (Jassim and Buday, 2006e). Sharland *et al.* (2001) placed the K130 MFS within the carbonate member of the formation. The Rumaila Formation grades up into the Mishrif Formation in eastern Iraq. The contact of these formations is often difficult to pick (Alkersan, 1975; Aqrawi, 1983; Sherwani, 1983; Aqrawi *et al.*, 1998). In the Najaf area, the Rumaila Formation is overlain sharply by the Kifl Formation (Al-Naqib, 1967). Towards the north, it is overlain by the Kometan or Sa'di Formations (Jassim and Buday, 2006e).

The Rumaila Formation is >100 m thick in two areas: between wells *Samarra-1* and *Kifl-1*; and from *West Qurna-1* southwards, reaching 107 m at its type locality at *Zubair-3* (Dunnington *et al.*, 1959).

Aqrawi and Khaiwka (1986, 1989) described four microfacies within the formation: lime mudstone,

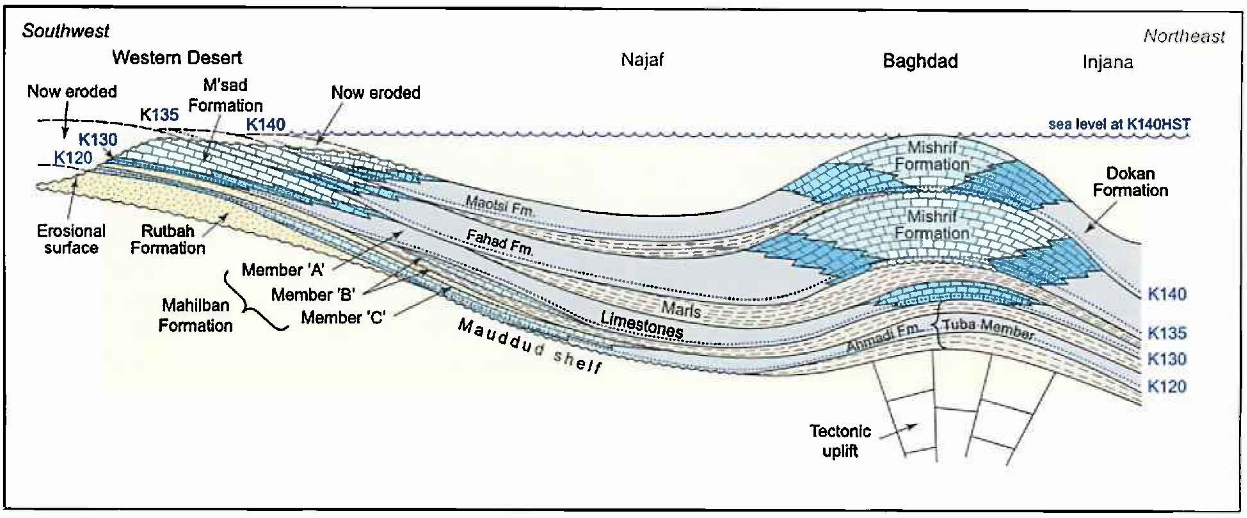


Fig. 7.33. Schematic west-east profile illustrating the organisation and relative thicknesses of stratigraphic units in Supersequence IV (after Aqrawi *et al.*, 1998, modified from Chatton and Hart, 1961).

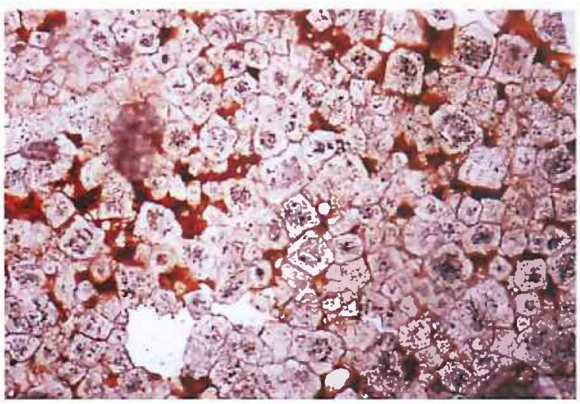


Plate 7.8. Oil residues and clear-rimmed, cloudy centred dolomite crystals in dolomitised limestones of the Rumaila Formation. Well *Shawiya-1* (SW Iraq), 1415 m depth. Photomicrograph is 3 mm wide. Photo by A. Aqrawi.

fossiliferous lime mudstone, lime wackestone and lime packstone. Planktonic foraminifera, globigerinids and oligosteginids dominate the microfauna. Sponge spicules and echinoderm debris also occur with some mollusc and intraclastic material (Dunnington *et al.*, 1959).

The Rumaila Formation is interpreted to have been deposited in an intrashelf basin (Aqrawi, 1983) referrd to here as the Najaf Intrashelf Basin (Fig. 7.34). Basinal lime mudstones occur in the *Luhais* and *Afaq* areas. Dolomitised lime mudstones occur locally in *West Qurna* field, at well *Shawiya-1* (Plate 7.8) and at *East Baghdad* (well *EB-3*), and probably extend eastwards (Aqrawi and Khaiwka, 1986, 1989). The uppermost Rumaila and lowermost Mishrif Formations are commonly silicified (Alkersan, 1975).

In the Awasil – Fallujah area, the **Mahliban, Fahad** and **Maotsi Formations**, originally defined by Dunnington *et al.* (1959), have been included in the Rumaila and Mishrif Formations (Aqrawi, 1983; Sherwani, 1983; Sherwani and Aqrawi, 1987; Sadooni and Aqrawi, 2000). The oligosteginal Mahilban Formation is of probable middle Cenomanian age. The Fahad and Maotsi Formations are probably late Cenomanian/ Turonian (Dunnington *et al.*, 1959; Aqrawi, 1983; Sherwani, 1983; Sherwani and Aqrawi, 1987; Aqrawi *et al.*, 1998). These formations contain a slightly higher proportion of shallow-water shelf benthics than the Rumaila Formation, and are interpreted as mid-outer ramp or slope deposits (Sadooni and Aqrawi, 2000). Locally-developed oolites, conglomerates, siliciclastics and glauconitic horizons (Dunnington *et al.*, 1959), probably mark lowstand systems tracts within these units (Fig. 7.33).

The Mishrif Formation

The Mishrif Formation overlies oligosteginal carbonates of the Rumaila Formation in a belt between the Iraq-Iran border and the Basra area in SE Iraq (Owen and Nasr, 1958; Dunnington *et al.*, 1959; Alkersan, 1975; Aqrawi *et al.*, 1998) (Fig. 7.35). The isopach map of the formation (Fig. 7.36), demonstrates that this belt continues northwestwards through *East Baghdad / Hamrin* (Aqrawi *et al.*, 1998) into the Tigris Valley. The formation is 350 to 400 m thick in the *Amara / Halfaiya / Majnoon / Buzurgan* area (Fig. 7.37b), but thins to the SW (Fig. 7.36). It is only 157 m thick at its type locality at well *Zubair-3* (Owen and Nasr, 1958; Dunnington *et al.*, 1959).

The Mishrif Formation was first formally described by Owen and Nasr (1958) and Dunnington *et al.* (1959) from southern Iraq. It is highly heterogeneous (Sadooni, 2005). Gaddo (1971) divided the formation into four "zones" at well *Tuba-*

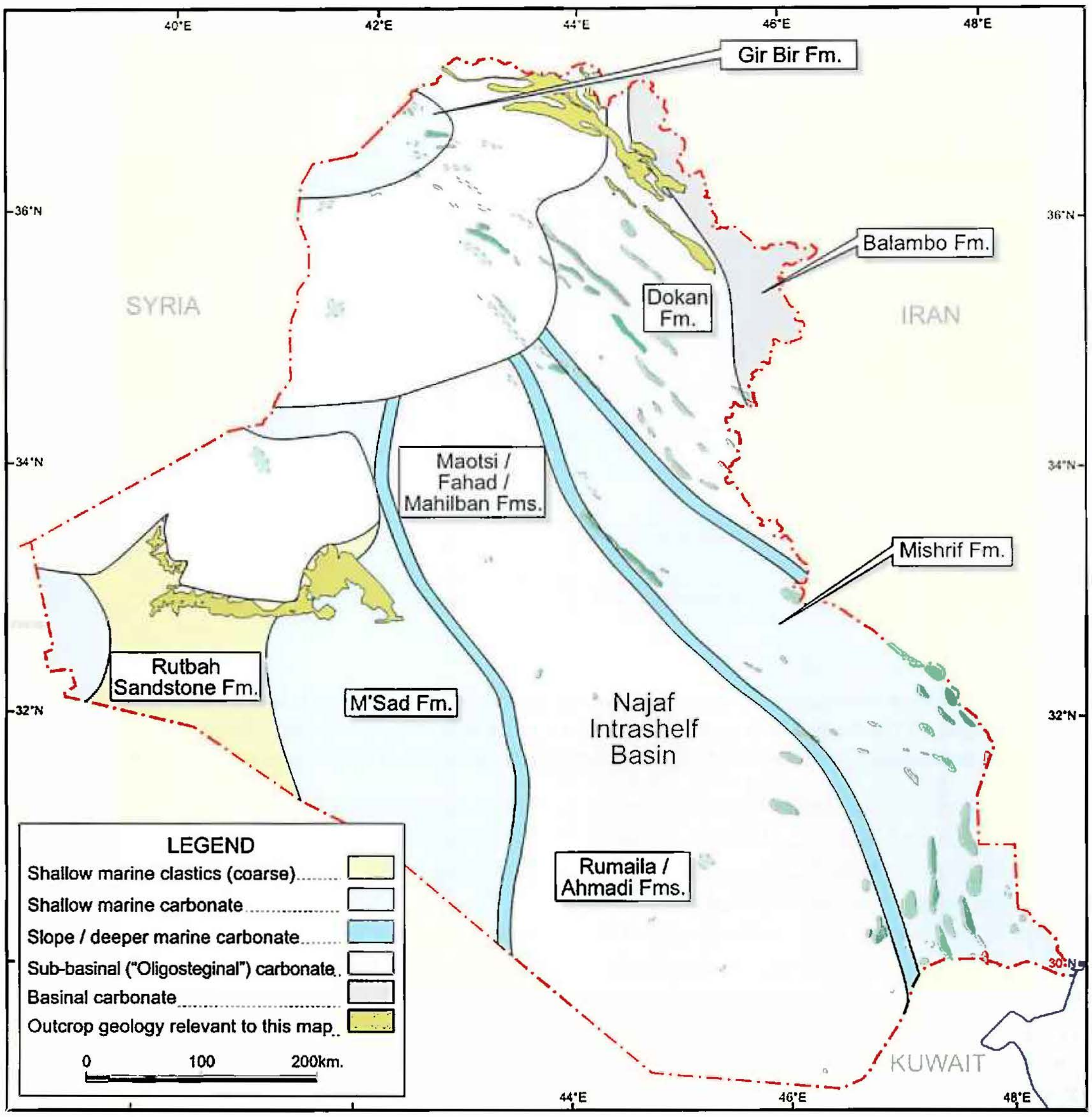


Fig. 7.34. Latest Albian – early Turonian palaeogeography of Iraq. Simplified Cambridge Carbonates Ltd map based on published data. Outcrops of these units occur both in Iraqi Kurdistan and in the Western Desert.

1 in the *Rumaila-Zubair* area (Fig. 7.37a): from the base upwards, Mi/D, C, B and A. Zone Mi/D comprises sub-basinal facies. Mi/C consists of shelf limestones containing rudist build-ups with associated restricted shelf facies. Zone Mi/B comprises compact marly (sub-basinal facies) limestones (Dunnington *et al.*, 1959; Aqrawi *et al.*, 1998). At the formation's type locality, Zone Mi/A comprises restricted shelf facies (Dunnington *et al.*, 1959; Al-Naqib, 1967; Gaddo, 1971).

Mishrif Formation facies (Plate 7.9 a-d)

Mishrif Formation facies have been given a variety of names by different authors (e.g. Gaddo, 1971; Alkersan, 1975; Sherwani and Mohammed, 1993; Aqrawi *et al.*, 1998). Four general facies can be recognised: restricted shelf, rudist build-up, open shelf and sub-basinal. Mishrif facies merge into each other and boundaries are not sharp or distinct (Sherwani and Mohammed, 1993).

Facies 1: Restricted Shelf

This facies includes porcellanous pack-wackestones (Sadooni, 2005). It was divided by Alkersan (1975) into a *subtidal sub-facies* dominated by smaller benthic foraminifera in pack-wackestone fabrics, and a finer-grained *intertidal-supratidal sub-facies* (mudstone fabrics) with unusual allochem assemblages. Log data show high resistivities where mud is absent, to low with positive SP where sediments are argillaceous (Gaddo, 1971).

Allochems in the subtidal pack-wackestones include smaller foraminifera (miliolids, alveolinids, lituolids, peneroplids, textulariids, *Nezzazata*, *Glomospira*, rotaliids, dicyclinids), gastropod and lamellibranch fragments, dascycladacean algae, ostracods, sponge spicules and echinoderms. Bioclasts are rarely sorted and usually unabraded. Peloidal-oolitic grainstones occur locally at the top of the formation in the northern dome of the *Zubair* field (Gaddo, 1971).

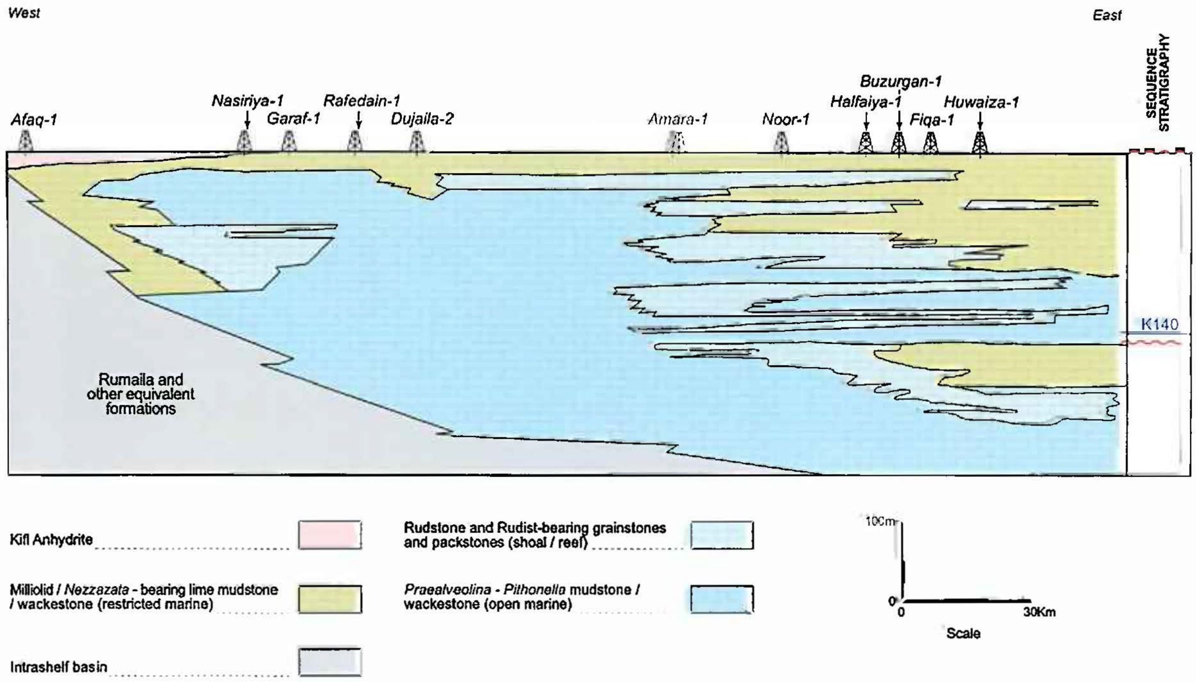


Fig. 7.35. Approximate west-east correlation panel through the Mishrif bank system in SE Iraq showing facies types. The Najaf Intrashelf Basin is to the left. The section is hung from top-Mishrif but this does not necessarily indicate a flat topography. Modified after Aqrawi *et al.*, 1998.

The intertidal – supratidal sub-facies occurs at the top of the formation (Alkersan, 1975) in Gaddo's (1971) Mi/A zone (Fig. 7.37a). It contains some of the allochem types present in the subtidal sub facies. Encrusting (blue-green) algae, pellets/peloids, intraclasts and dolomite also occur in this facies. In the *Rumaila-Zubair* area, beds of limonitic charophyte limestones overlying ostracod-rich deposits and anhydrites locally occur (e.g. in *Rumaila-35*; Gaddo, 1971). Conglomerates comprising rounded pebbles in a marly matrix occur in the upper part of the formation in the *Amara* and *Dujaila* fields (Alkersan, 1975). Some shaly streaks may occur (Gaddo, 1971). This sub-facies is well-developed in *Luhais, Ratawi, Rumaila* and *Zubair* fields but is absent from *Buzurgan* and *Afaq* (Alkersan, 1975).

Interpretation

The biota in the subtidal sub-facies indicate deposition in relatively restricted, shallow-water environments interpreted by Alkersan (1975) to be between the base of the photic zone and the normal marine wave-base (i.e. about 10 to 20 m). The presence of open-marine fauna (e.g. echinoderms) may indicate deeper waters at least locally. Algal mat, conglomeratic, charophyte and limonitic units indicate much shallower-water to lacustrine deposition. Oolitic grainstones indicate locally shallower, higher-energy conditions, perhaps on palaeohighs, within a generally low-energy, semi-restricted or lagoonal setting (Alkersan, 1975; Sherwani and Mohammed, 1993). Anhydrites indicate extreme restriction and drawdown. Shalier intervals have been interpreted as near-coastal muds deposited along the western margin of the Mishrif Formation (Aqrawi *et al.*, 1998) in the *Nasiriya* and *Gharraf* oilfields.

The restricted shelf facies with algal mats, conglomerates, charophytes, limonite and anhydrite at the top of the Mishrif Formation (particularly the intertidal-supratidal sub-facies) were probably deposited during the late K140 HST and lowstand prior to the K150 MFS. This uppermost unit probably represents a highly restricted environment and may be a lateral equivalent of the Kifl Formation. It should therefore probably be reassigned to the basal part of the overlying Supersequence V.

Facies 2: Rudist Build-up

This facies is the main reservoir rock in the Mishrif Formation (Gaddo, 1971; Alkersan, 1975; Aqrawi *et al.*, 1998). Three sub-facies are recognised (rudist packstones, rudist grainstones and rudist rudstones), distinguished by the relative content of micrite and the coarseness of the rudist-derived material (Alkersan, 1975; Aqrawi *et al.*, 1998).

Allochems are dominated by fragments of rudists, which in the rudstone sub-facies reach gravel grade (Plate 7.9a,c). They are accompanied by echinoids and corals (Plate 7.9b). Particularly large rudists occur in the *Buzurgan* field (Sadooni, 2005). Other allochems include peloids, algae, ostracods and lamellibranchs. The rudists were probably fragmented by both physical (wave/storm) activity and biological processes. Subsequent sorting and rounding of fragments occurred around fair-weather wave base (estimated to be approximately 10 m by Alkersan, 1975). On well logs, these facies

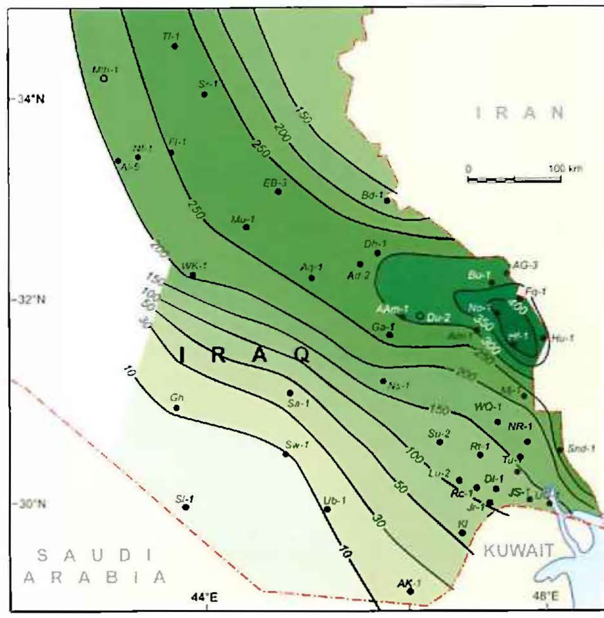


Fig. 7.36. Isopach of the Mishrif Formation (in metres). See Fig. 7.3 for well names. After Aqrawi *et al.*, 1998.

show high resistivities and strongly negative SPs, although the SP character is less pronounced where the facies have been cemented (Gaddo, 1971).

Rudist build-up facies occur in intervals about 2 ft (0.6 m) thick which can be correlated for up to 1 km between wells, to units 50 ft (15 m) thick which can be correlated for several km (Gaddo, 1971). However, true rudist reef deposits (framestones, floatstones and boundstones) only occur rarely (Aqrawi *et al.*, 1998; Sadooni and Aqrawi, 2000; Sadooni, 2005).

The rudist build-up facies alternates with open shelf facies. In the *Rumaila-Zubair* area, five stacked build-ups (Gaddo, 1971) can be recognised from well logs, for example at *Tuba-1* (Gaddo, 1971). Similar stacked facies are dominant near the Iraq – Iran border at *Halfaiya-1* (Aqrawi *et al.*, 1998) (Fig. 7.37a, b). Cycles are capped by rudist rudstones in the *Amara* area (Reulet, 1982; Aqrawi *et al.*, 1998).

Interpretation

Aqrawi *et al.* (1998) interpreted the more micritic lithologies as back-reef deposits, grainstones as reef-bank or shoal deposits and rudstones as fore-reef shoal to slope deposits.

This facies is best developed along the isopach thick passing through the *East Baghdad* field into SE Iraq, separating the "Dokan" basinal facies in the NE from the Rumaila intrashelf basin facies to the SW (Fig. 7.38).

Facies 3: Open Shelf

Open shelf limestones occur extensively in the Mishrif Formation (Aqrawi *et al.*, 1998). They comprise wackestones dominated by specific types of bioclast; larger benthic foraminifera are dominant in the middle of the formation (Plate 7.9d). These include the Cenomanian index species *Praealveolina cretacea* var. *tenuis*, together with *Multispirina iranensis*, *Cisalveolina fallax*, *C. lehneri*, *Dicyclina qatarica*, *Taberina bingistani*, *Pseudochrysalidina conica*, numerous *Begia* sp., *Coxites zubairensis* and *Trocholina* sp. (Dunnington *et al.*, 1959). Algae, echinoderms and limited planktonic foraminifera also occur. Bioclasts form 10-50% of the sediment (Aqrawi *et al.*, 1998).

The open shelf facies includes the "algal facies" identified by Gaddo (1971). Sherwani and Mohammed (1993) noted the association of algae with somewhat deeper-water deposits. Algae comprise fragmented *Permocalculus* sp. in a mudstone to wackestone fabric, contrasting with the entire (mostly dascycladacean) algae that occur in the restricted shelf facies. Gaddo (1971) described the "algal facies" as being "semi-symbiotic" with rudist reefs; the facies was common in *Zubair* but less so in *Rumaila*. Log data indicated that the "algal facies" had variable resistivities and SPs, with log responses being controlled by either clay content or porosity (Gaddo, 1971).

Interpretation

The open marine facies were deposited in inter-reef and shallow-water shelf areas. They are generally highstand deposits and occur mainly in the upwards-shallowing middle part of the Mishrif Formation, prior to deposition of the main Rudist build-up facies.

Facies 4: Sub-Basinal

This facies consists mainly of micritic lithologies. Gaddo (1971) recognised wackestone-dominated "shallower sub-basinal" and mudstone-dominated "sub-basinal" sub-facies. The former contains finely comminuted rudist material, deposited in narrow belts around rudist build-ups. Aqrawi *et al.* (1998) referred to this facies as "tongues of Rumaila Formation in the Mishrif Formation".The facies was described as "chalky" by Gaddo (1971). It is

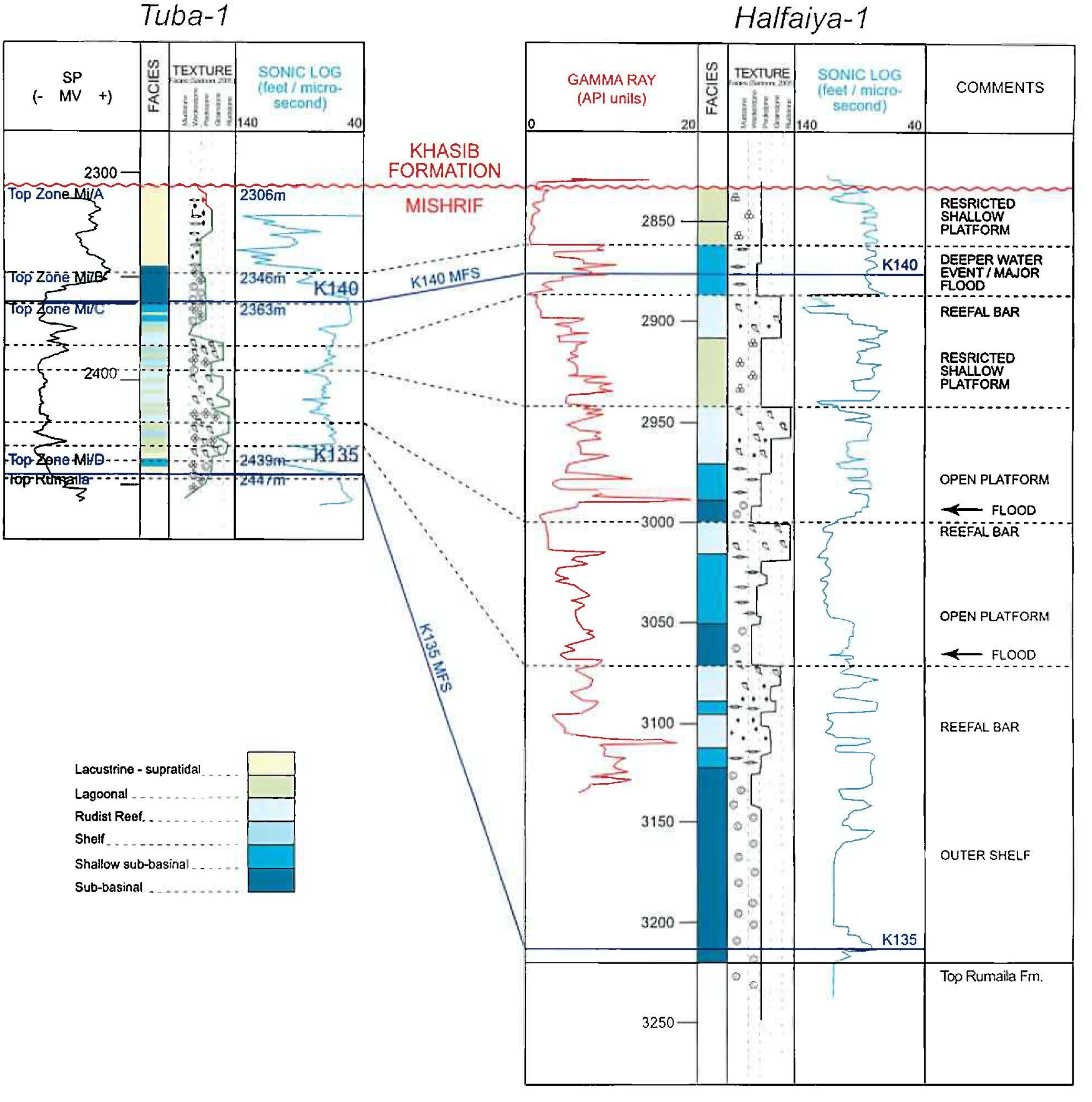


Fig. 7.37a,b. Correlation of the Mishrif Formation betwen wells *Tuba-1* (left) and *Halfaiya-1* (right), showing the marked cyclicity of the succession and thinning towards the *Tuba-1* location. These wells are typical of locations where the Mishrif is "thin" and "thick", respectively. Modified from Gaddo (1971) and Aqrawi *et al.* (1998).

best-developed in the south and SW of southern Iraq, in fields such as *Ratawi, Luhais* and *South Rumaila* (Alkersan, 1975).

Allochems are dominated by *Oligostegina* (calcisphaerulids) and other planktonic fauna including *Globigerina* sp., *Gumbelina* sp., *Heterohelix* sp., *Hedbergella washitensis*, and *Anomalina* sp., together with drifted ostracods and sponge spicules (Aqrawi *et al.*, 1998). Shallower-water conditions are indicated by echinoid debris, lamellibranchs, miliolids, *Textularia* sp., algae, brachiopods and rudist debris which fines away from build-ups. The underlying Rumaila Formation, lacks shallow-water allochems.

Interpretation

The oligosteginid biota and depositional textures indicate that the facies was probably deposited in moderate water depths ("deeper shelf": perhaps 100 to 200 m according to Adams *et al.* 1967), during maximum flooding to early highstand conditions.

Sequence Stratigraphy

Facies models show that the Mishrif Formation forms a shallowing-upwards succession. Gaddo (1971) recognised that "oscillations in sea-level" were superimposed on this trend in the *Rumaila-Zubair* area. Aqrawi *et al.* (1988) noted the difficulty of separating structural and eustatic controls on facies and sequence boundaries.

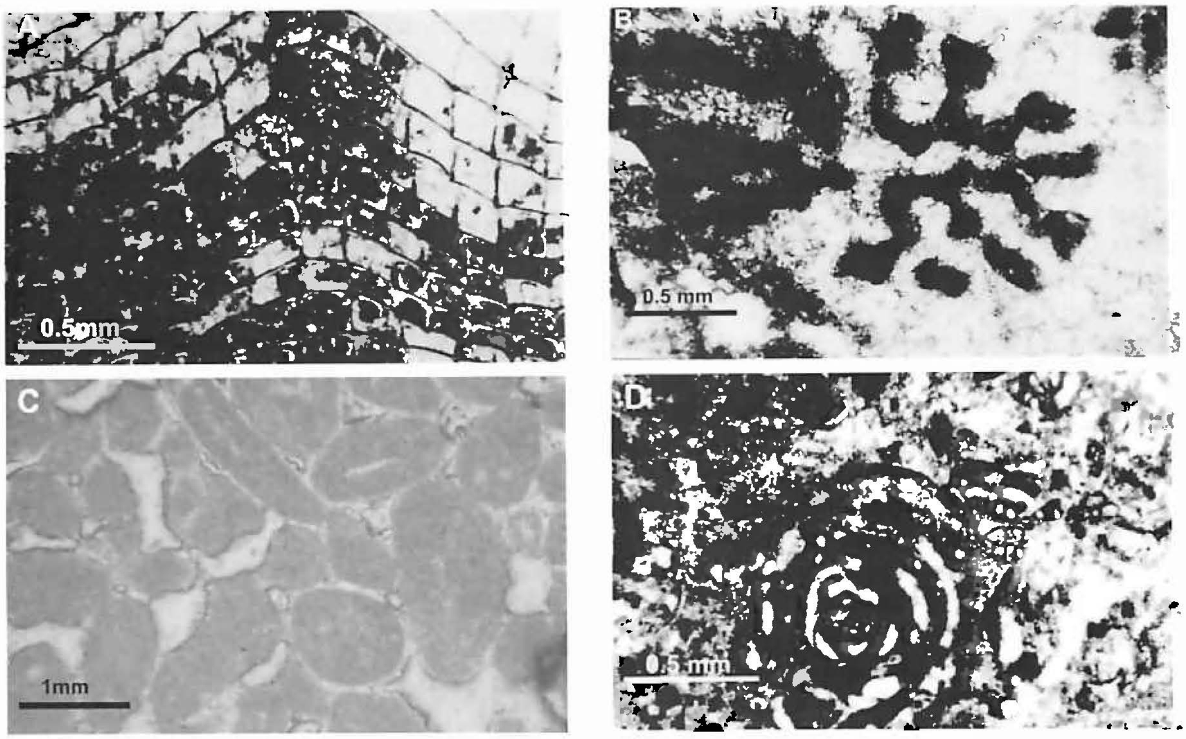


Plate 7.9. Microfacies of the Mishrif Formation, well *Dujaila-1*. From Sadooni, 2005.
(a) Large rudist fragment from a rudist build-up ca. 38 m thick. Depth 3129 m.
(b) Cemented coral fragment forming a secondary component in the rudist build-up. Depth 2876 m.
(c) Grainstone composed mainly of rudist debris. This facies is the main reservoir unit in the Mishrif Formation in this well. Depth 2865 m.
(d) Large benthic foraminifer (*Praealveolina* sp.), a significant component of the Mishrif Formation microfacies. Depth 2878 m.

The formation consists of two third-order sequences separated by an intra-formational unconformity which is recorded near the Iranian border at Amara (Reulet, 1982; Aqrawi *et al.*, 1998). Both sequences comprise three medium-scale cycles (probably fourth-order parasequences) recognised in the *Amara*, *Halfaiya* and *Rafedain* fields (Aqrawi *et al.*,1998). This cyclicity may have controlled the development of rudist biostromes.

Shale units occur above the intra-Mishrif sequence boundary in wells *Nasiriya-1* and *Rafedain-1* and in the *Gharraf* field (Reulet, 1982; Aqrawi *et al.*, 1998). Shales are coeval with the subaerial exposure surface observed within the Mishrif Formation further to the east (Aqrawi *et al.*, 1998). The sub-basinal facies developed at the base of the upper sequence corresponds to the K140 MFS of Sharland *et al.* (2001). This event has been dated in Kuwait by El-Naggar and Rifaiy (1972), where their unit Mi/B1 of the correlative Magwa Foramation is latest Cenomanian in age. In the *Rumaila* and *Zubair* fields, deposition of the main rudist-bearing unit in the Mishrif Formation (unit Mi/C of Gaddo, 1971) ceased due to drowing associated with this MFS. Rudist-dominated carbonates were not then re-established in this area.

Beds of oligosteginal limestones at the base of the Mishrif Formation (Aqrawi *et al.*, 1998) correspond to a flooding surface (?K135) intermediate between the K130 (intra-Rumaila) and K140 (top-Mishrif) MFSs of Sharland *et al.* (2001). These basal-Mishrif beds were assigned to the middle Cenomanian by Aqrawi *et al.* (1989).

Depositional models

Facies models

The Mishrif succession indicates general shallowing from open-shelf to fore-reef slope, then reef flat and finally inner-shelf conditions (Aqrawi *et al.*, 1998). Regional correlations across southern Iraq indicate variations in vertical stacking of these facies (Sherwani, 1998; Sadooni, 2005). Lateral facies variations in the formation occur at both basin and field scale (Sadooni, 2005).

Reef-building organisms in the Mishrif Formation in Iraq (rudists, sponges, corals and stromatoporoids) are similar to those in the Mishrif Formation equivalents in Oman, Iran, Saudi Arabia and the United Arab Emirates (e.g. Burchette and Britton, 1985; Jordan *et al.*, 1985; Alsharhan, 1995; Burchette, 1993; Videtich *et al.*, 1988). During the Cretaceous, rudists were important constructors of shelf mounds and shelf margins throughout Arabia (Wilson, 1975), and also occur principally in the Shu'aiba and Mauddud Formations (Alsharhan and Nairn, 1997). The dominant rudists of the Mishrif Formation in the *Basra* area are radiolitids (Sherwani, 1998). They are commonly associated with algae and shallow-water benthic foraminifera (Gaddo, 1971).

Gaddo (1971) studied the Mishrif Formation in the *Rumaila*, *Tuba* and *Zubair* fields in southern Iraq. He recorded rudist biostromes in five intervals in the middle part of the formation. He suggested that the rudists preferred unrestricted depositional environments with little input of fine-grained siliciclastic material; they are absent from lagoonal and deep-water deposits unless transported. Gaddo *(ibid.)* noted that rudist colonies within the succession tend to increase in size upwards; small reefs and banks pass up into larger biostromes.

Gaddo (1971) and Alkersan (1975) suggested that rudists were dismantled by bio-erosion and wave or current activity. Rudist shells were reworked over a broad area (Sadooni, 2005). Large, unsorted, angular rudist fragments were assumed to have been deposited in water depths of >10m.

The build-ups in Iraq probably did not form continuous complexes, unlike modern reefs. Similar rudist-dominated Albian-Cenomanian platform margin complexes are exposed in the Sierra Madre Oriental, Mexico, at Sierra de El Abra (Scott, 1990a).There, the ratio of *in-situ* rudist bank to calcarenite sands derived from physical and bio-erosion of rudists is about 1:20 (A. H., *pers. obs.*). Most of the rudists in the Mishrif were probably fragmented and similarly redeposited as rudstones.

Controls on the location of the main Mishrif margin

Rudist build-ups and deposition of associated shallow-water sediments along the main platform margin may have been controlled by synchronous growth of structural features in the Balambo-Garau Basin (Sadooni and Aqrawi, 2000) related to reactivation of basement faults (Fig. 7.38). The main platform-margin facies is associated with the isopach thick located along the Iran-Iraq border near Buzurgan (Fig. 7.36) (Alkersan, 1975). The facies appears to extend via well *Badra-1* into the Tigris area of northern Iraq (Aqrawi *et al.*, 1998; Sadooni, 2005). It is in continuity with with the Bala Rud Shoals of the Sarvak Formation in Iran (Bordenave and Huc, 1995).

The main rudist build-up facies of the Mishrif Formation appears to have developed above inherited Albian platform-margin topography in SE Iraq. Deposition of the Mishrif Formation began in the east of the Balambo-Garau Basin (Aqrawi *et al.*, 1998) rather than prograding out from the site of coastal onlap to the west. Aqrawi *et al.* (1998) suggested that the Mishrif facies belt consists of NW-SE trending western and eastern higher-energy facies belts separated by a central belt of lower-energy facies (recorded in the *Dujaila* and *Gharraf* areas) (Fig. 7.35). The Mishrif platform margin then probably prograded slightly to both NE and SW over sub-basinal facies. The limit of the rudist facies to the SW, as it passes into deeper-water open-marine facies, is near *Luhais*, *Ratawi* and *Afaq* (Alkersan, 1975).

Activation of basement faults and differential movement of fault blocks controlled lateral facies variations (c.f. Buday and Jassim,1987), particularly the new location of the main platform margin in central Iraq. The limit between the Mishrif and Dokan Formations marks the later structural boundaries of the Foothill Zone and Mesopotamian Basin. Fields to the north (*Jambur*, *Kirkuk*), where the Qamchuqa Formation is composed of platform margin deposits, were drowned during the early Cenomanian. Following deposition of the Qamchuqa Formation, it is possible that faulting in the East Baghdad – Hamrin area may have caused the NE side (in the Foothill Zone) to subside more rapidly, allowing the platform margin to re-establish itself along the Bala Rud – Baghdad axis. Jassim and Buday (2006e) also emphasised the role of reactivated longitudinal ridges and transverse blocks in controlling such changes in sedimentation.

Development of Mishrif build-ups

Buday (1980) proposed that structural features including the Samarra-Dujaila-Amara "ridge", which extended southwards into the Burgan High, influenced the distribution of shallow-water Mishrif facies. To the SW of the main "rudist build-up" facies belt, individual structural features may control development of rudist-dominated "biostromes" (Gaddo, 1971), "banks" (Alkersan, 1975) or "patchy build-ups" (Fuloria, 1976; Sadooni and Aqrawi, 2000). Biostromes are associated with the *West Qurna*, *Rumaila North* and *South, Zubair* and *Nahr Umr* anticlines (Gaddo, 1971; Alkersan, 1975; Al-Sakini, 1992; Sadooni and Aqrawi, 2000; Sadooni, 2005). Dominant facies are rudist rudstones and rudist grainstones in crestal wells at the *Zubair* and *Rumaila* fields, where isopach thicks of the rudist biostrome facies correspond to structural culminations (Gaddo, 1971; Alkersan, 1975; Sadooni, 2005) (Fig. 7.39).

Sadooni (2005) studied build-ups at locations some distance away from the main platform margin. He considered that the maximum thickness of the Mishrif Formation in the *Dujaila* area was controlled by a local uplift, the "Dujaila Shoal". Data from the *Dujaila* field suggest that build-ups also formed in locations unrelated to present-day structures. Rudist-rich facies occur in structurally low locations (well *Dujaila-1)* contrasting with the crestal positions of rudist facies in the Basra area; a structurally higher well 7 km to the NW (*Dujaila-2*) is dominated by deeper-water off-bank facies (Sadooni, 2005) (Plate 7.10). The *Dujaila* structure clearly formed *after* deposition of the Mishrif.

Chatton and Hart (1961, *in* Sadooni, 2005) implied that the "Dujaila Shoal" was a structural feature that may have extended into the Arabian Shield through Kuwait, although it is interpreted here as a bioconstructional high. The great

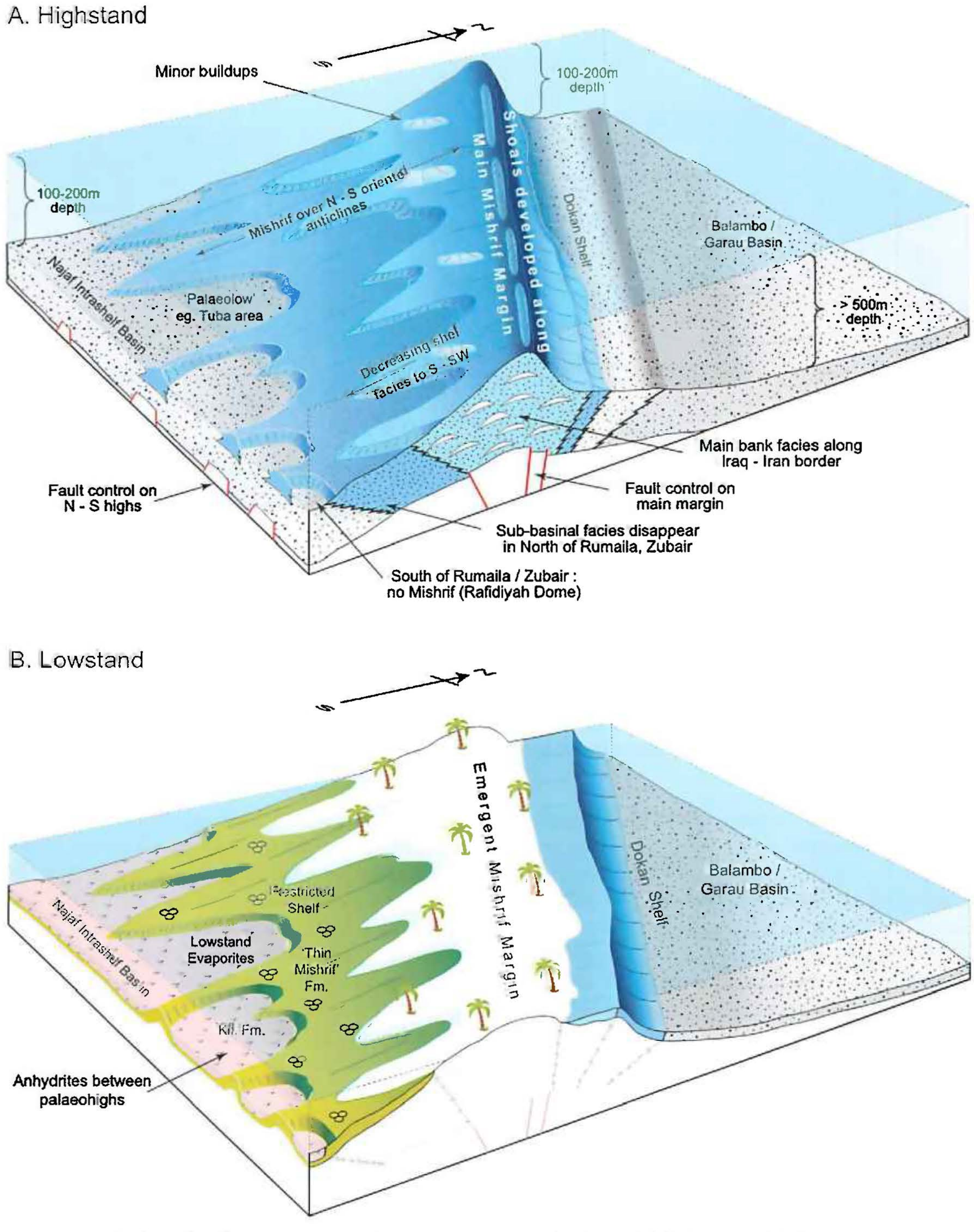


Fig. 7.38. Model of Mishrif Formation deposition during the latest Albian – early Turonian: (a, above) During relative sea-level highstand, with the Najaf intrashelf basin to the SW passing into the Dokan shelf to the NE; note the position of the main platform margin and of minor build-ups in the intrashelf basin. (b, below) During lowstands; deposition of restricted water facies occurred in the Najaf intrashelf basin while deposition of the Dokan Formation continued uninterrupted.

thicknesses of these shallow-water facies suggest that their depositional relief was largely constructional (partly inherited from the buried Albian platform margin), although controlled in the first instance by active uplift.

The movement of Infracambrian Hormuz Salt was particularly important in southern Iraq (Murris, 1980). Sadooni (2005) suggested that rudist build-ups in the Basra area nucleated on the crests of growing salt structures. When the build-ups reached wave-base, they were eroded and rudist fragments were reworked, transported and dispersed to form bioclastic packstone/grainstones. Gaddo (1971) likewise proposed that banks developed into "tabular reefs" which later spread laterally (i.e. prograded) for several kilometers in response to uplift. Such isolated platforms controlled local facies variations (Sadooni, 2005).

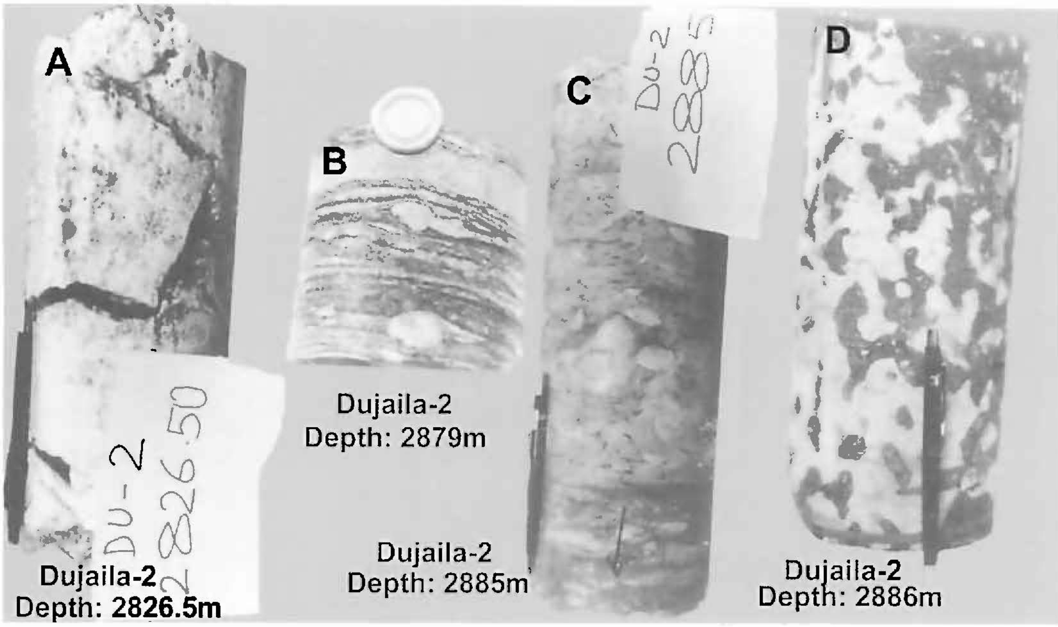


Plate 7.10. Core-scale deeper-water facies of the Mishrif Formation from well *Dujaila-2*. From Sadooni (2005). Pen: 14 cm long. Film canister lid: 3cm wide.

(a) Fractures in limestone; fractures are uncommon in the Mishrif Formation and contribute to only a small proportion of the porosity. Depth 2826.5 m.
(b) Laminated limestone; laminae are argillaceous and nodular, and are saturated with bitumen. Depth 2879 m.
(c) Bioturbated crystalline limestone. Depth 2885 m.
(d) Bioturbated limestone *(Thalassinoides)*; bioturbated volume is filled with dark sediment. Depth 2826 m.

In the *Fateh* field, Dubai, rudist build-ups are similarly associated with structural growth controlled by movement of Hormuz Salt; surrounding areas subsided due to salt withdrawal (Jordan *et al.*, 1985; Videtich *et al.*, 1988). Rudist build-ups developed preferably on the flanks of the salt high (not on structural crests as in Iraq; Sadooni, 2005); salt-withdrawal basins were filled with coeval fore-reef debris.

Mishrif deposition in palaeolows

Anticlinal growth created protrusions of the rudist margin into the Najaf intrashelf basin (Fig. 7.38). Alkersan (1975) noted that the shallowest-water, thickest and best sorted rudist facies of the Mishrif Formation in the *Rumaila* anticlinorium occur near *West Qurna*, in the present-day structurally-lowest area. Wells in the south of this structure show the most open-marine/sub-basinal character.

Variations of the succession occur locally in the *Rumaila* and *Zubair* fields (Gaddo, 1971) and at *Ratawi* and *Luhais* (Alkersan, 1975). The proportion of open-marine "sub-basinal" facies increases westwards and southwards. These facies comprise chalky planktonic foraminiferal limestones with thin shales near the top (Gaddo's unit Mi/B) and limestones with "neritic streaks" at the base of the formation (unit Mi/D). In well *Ratawi-1*, algal-benthic foraminiferal limestones with shales and argillaceous limestones occur, with scattered rudists in the lower part of the formation (Sadooni, 2005).

The Mi/A unit in palaeolows comprises algal-dominated "lagoonal facies" Gaddo (1971). It overlies *Oligostegina* limestones of the Mi/B unit and was deposited following a regression. The fauna comprises an ostracod-rich basal interval with gastropods, lamellibranchs, textulariids, algae (*Permocalculus*), miliolids, pellets in muddy intervals and *Glomospira* in the lower parts of Mi/A, and *Charophytae* at the very top (Dunnington *et al.*, 1959; Al-Naqib, 1967; Gaddo, 1971).This faunal distribution suggests progressively increasing restriction and drawdown. Conglomeratic facies described by Sadooni (2005, after Chatton and Hart, 1961) may occur locally around the flanks of the palaeolows.

Low-relief structures in palaeolows, for example *Tuba* (between *Rumaila* and *Zubair*), contain low-energy restricted lagoonal facies with few rudists (Gaddo, 1971). Lagoonal facies were deposited in locations that became cut off from the deeper-water Najaf (intrashelf) and Balambo-Garau Basins, due to the development of mantling build-ups (Alkersan, 1975).

Other formations

The **Rutbah Sandstone Formation** is the basal unit of Supersequence IV in the west of Iraq (Fig. 7.33). The formation thickens westwards (Jassim and Buday, 2006e) as it oversteps older Mesozoic units. On the western margin of the Ga'ara high, it rests directly on the Ga'ara Formation. At its type locality near Rutbah, it overlies the Mulussa Formation, but ten km to the east it overlies the Saggar Formation. Fifty-five km east of Rutbah, it unconformably overlies the Mauddud Formation (Jassim and Buday, 2006e).

The Rutbah Formation comprises fine- to coarse-grained, locally ferruginous sandstones which are equivalent to the Sakakah Sandstone Formation of Saudi Arabia (Jassim and Buday, 2006e). It is of early Cenomanian age based on its stratigraphic position between the late Albian Mauddud Formation and the early Cenomanian M'sad Formation (Dunnington *et al.*, 1959).

The overlying **M'sad Formation** (Fig. 7.33) comprises rudist reefal, shell breccia and chalky limestones, with sandy marls and sands; a thin basal sandstone unit occurs (Dunnington *et al.*, 1959). Outcrop studies demonstrate that the formation includes supratidal facies with well-developed fenestral limestones at Ga'ara (Jassim and Buday, 2006e). It is 35 m thick at its type section at Wadi M'sad, 45 m thick at Rutbah, and 97 m near the K160 settlement (location on Fig. 7.3) (Jassim and Buday, 2006e). At water wells in the Salman Zone, the M'sad Formation directly overlies the Mauddud Formation (Jassim and Buday, 2006e).The M'sad Formation is overlain at a regional unconformity by the Hartha Formation.

In NW Iraq, Supersequence IV is represented by the neritic **Gir Bir Formation**. Unlike the Mishrif Formation, the Gir Bir in general unconformably overlies Albian shelf carbonates. The Gir Bir is composed of bioclastic limestones, often recrystallised and/or dolomitised (Dunnington *et al.*, 1959). In the *Ain Zalah* field, it includes distinctive conglomeratic beds (Sadooni, 2005, after Chatton and Hart, 1961) and 45 m of dolomitic limestones (El Zarka, 1993). The formation contains a larger foraminiferal fauna including *Praealveolina cretacea* of Cenomanian age (Dunnington *et al.*, 1959; Al-Jassim, 1993). A similar unit in SE Turkey is known as the Derdere Formation (Cater and Gillcrist, 1994). It is equivalent to part of the "Massive Limestone" of NE Syria (Nikolaevskiy, 1972) (Fig. 7.40).

Throughout SE Turkey, NE Syria and NW Iraq, shelf carbonates of Supersequence IV form the middle and aggrading (thickest) part of a carbonate platform/ build-up complex of Aptian to Maastrichtian age. This complex of build-ups generally backsteps through time. The succeeding Turonian – early Campanian and middle Campanian– Maastrichtian shelf carbonates are both more restricted in area and are thinner (Fig. 7.40). In SE and eastern Syria, the coeval Judea Limestone is a sheet-like unit, 10-90 m thick, lying unconformably between the clastic Rutbah

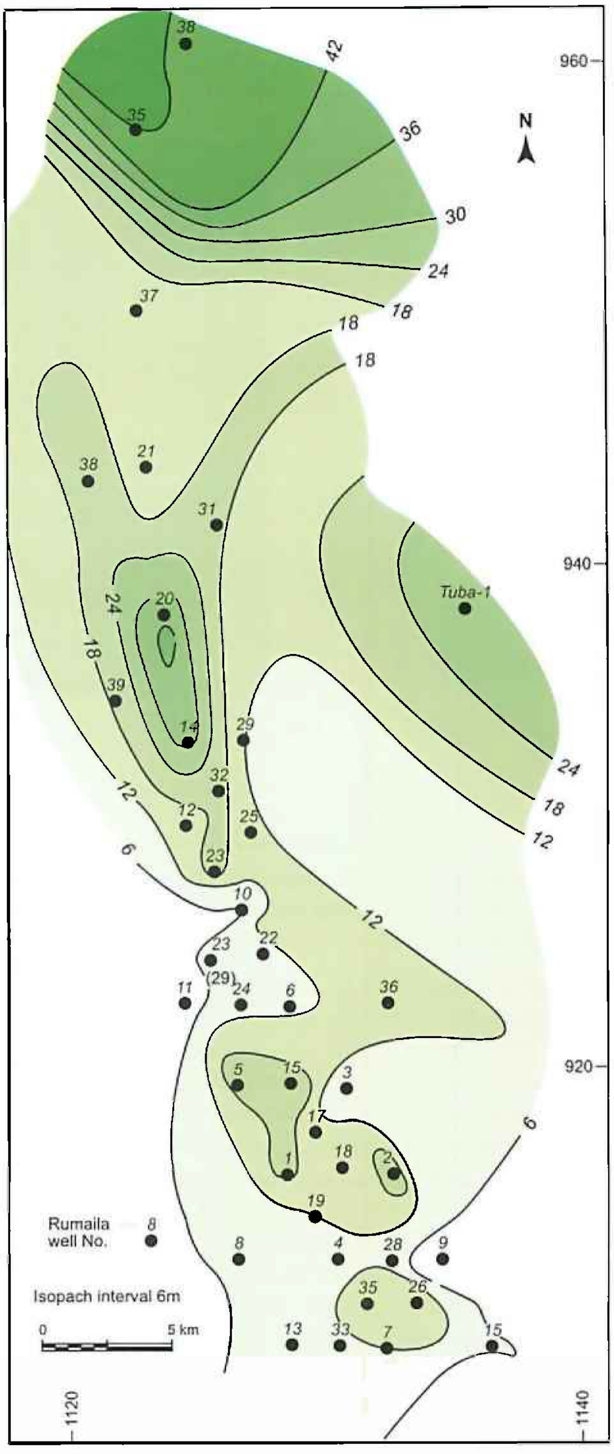


Fig. 7.39. Variations in the thickness of rudist facies along the crest of the Rumaila structure (after Gaddo, 1971).

Sandstone and the Derro Red Bed Formation (Daniel, 1963; Caron *et al.*, 2000).

In NE Iraq, the Mishrif Formation passes into the **Dokan Formation** (Figs. 7.33, 7.38), e.g. to the south of *Jambur* (Al-Rawi *et al.*, 1980). This formation comprises about 4 m of starved "inner basinal" sediments at its type locality at Dokan (Dunnington *et al.*, 1959). The Dokan Formation drapes the underlying Upper Qamchuqa Formation. A thicker wedge of the Dokan Formation

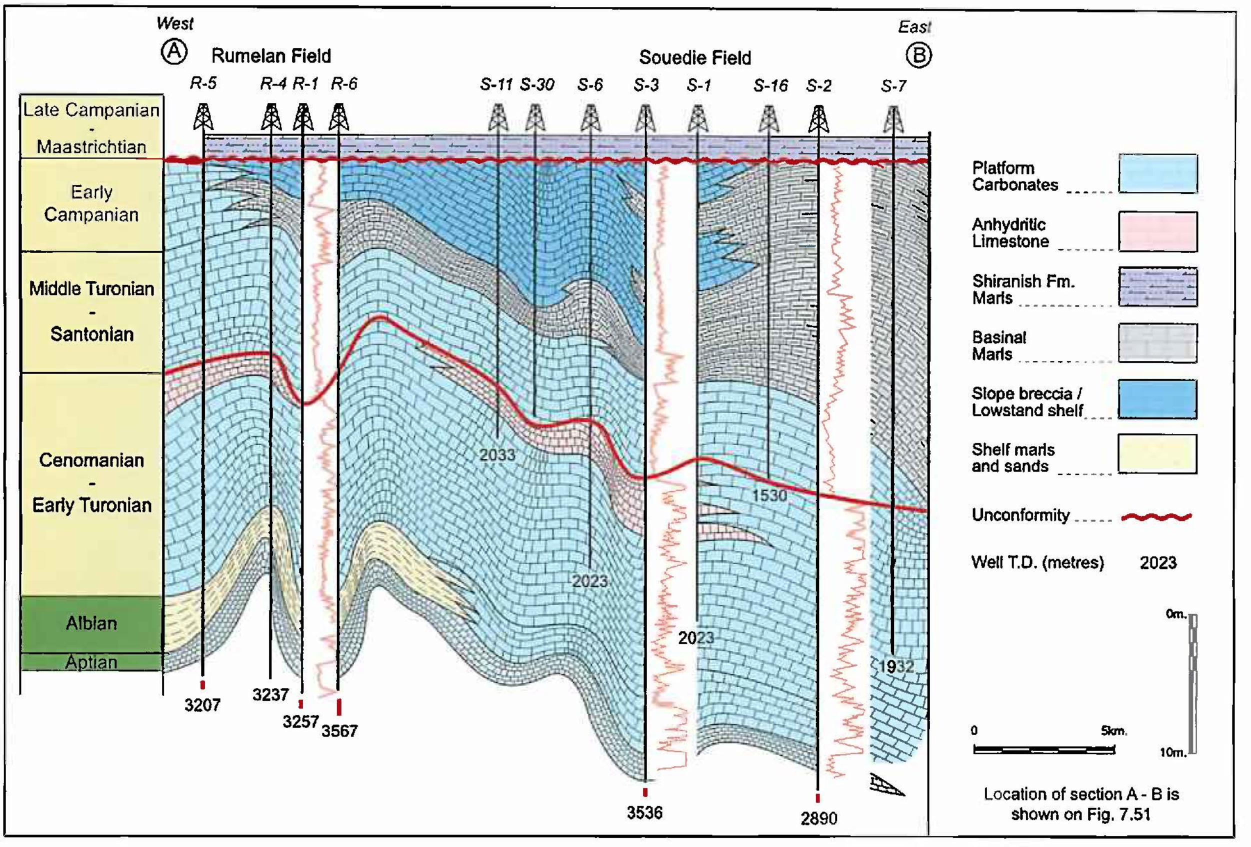


Fig. 7.40. Cross-section through the Massive Limestone in NE Syria. After Nikolaevskiy, 1972. Note that no palaeontological data were presented to support the assigned ages. The line of section is located on Fig. 7.51.

is located immediately basinwards of the former Qamchuqa shelf margin (Al-Rawi *et al.*, 1980) (Fig. 7.20). At *Chemchemal*, the Dokan Formation is up to 150 m thick (Jassim and Buday, 2006e).

The base of the Dokan Formation is glauconitic at Dokan but conglomeratic at *Bai Hassan* (Jassim and Buday, 2006e). It is interpreted to be more distal and to have a more open marine faunal content than the Rumaila Formation (Al-Naqib, 1967).

The Dokan Formation passes eastwards into the upper part of the pelagic **Balambo Formation** (Fig. 7.34) in parts of Iraqi Kurdistan and in the Kirkuk Embayment, for example in the SE of the Jambur structure (Al-Rawi *et al.*, 1980) and in well *Pulkhana-5* (Al-Naquib, 1960; Jassim and Buday, 2006e). In well *Injana-5*, the Upper Balambo consists of shales; at *Naft Khanah*, it comprises > 900 m of marls with thin limestone beds. Further to the NE, in the *Herki*, *Rikan* and *Zibar* areas of Iraqi Kurdistan, neritic limestones occur (Jassim and Buday, 2006e).

Petroleum System Components

The Mishrif play fairway in SE Iraq is one of the most important in the Gulf region. The Mishrif Formation is confined to southern and central Iraq and extends as far north as the Hamrin Mountains (Fig. 7.36). Particularly thick rudist platform facies occur close to the Iranian border (Sadooni and Aqrawi, 2000). To the west, reservoir quality in the Najaf Intrashelf Basin is poor due to the dominance of oligosteginal facies. To the NE, the Mishrif passes into tight basinal carbonates of the Dokan and Balambo Formations. Aqrawi *et al.* (1998) identified only a single rudist-bearing reservoir interval in the western Mishrif facies belt, located in the lower part of the Mishrif succession. However, in the Amara area to the east, multiple pay zones with at least three rudist-bearing intervals are present in the upper part of the succession.

The Gir Bir play fairway in northern Iraq may be confined to Late Cretaceous half grabens because it was removed from palaeohighs during Turonian–Campanian erosion of footwall highs. Consequently it may be present in anticlines which are formed by inversion of basinal features (e.g. *Ain Zalah*: Hart and Hay, 1974).

Proven and Potential Reservoir Rocks

The reservoir potential of Cretaceous rudist build-ups was recognized early in the exploration of the Arabian Basin. The **Mishrif Formation** forms the main carbonate reservoir unit in Iraq (Aqrawi *et al.*, 1998; Jassim and Al-Gailani, 2006).The formation contains about 40% of Cretaceous reserves and up to 30% of total Iraqi oil reserves (Al-Sakini, 1992). The best reservoir units have porosities of 18-25% (average: 20%) and permeabilities of 100-1000 mD (average: 200 mD) (Al-Hassan, 1979; Aqrawi *et al.*, 1998; Sadooni and Aqrawi, 2000).

Table 7.2. Average porosity and permeability of facies of the Mishrif Formation in southern Iraq (after Reulet, 1982).

Facies	Type	Av.Porosity %	Av. Perm. mD
Barrier (reefal)	Biostrome	15 – 20	10 – 100
Shoal	Shoal	20 – 25	100 – 1000
Outer shelf (moderate energy)	Slope	10 – 15	c. 10
Inner shelf (moderate energy)	Back-Shoal	10 – 15	0 – 10
Inner shelf (low energy)	Lagoon	0 – 5	0.1

Reulet (1982) summarised average values of porosity and permeability for Mishrif facies in southern Iraq (Table 7.2).

The first production from the Mishrif Formation in Iraq occurred at the *Zubair* and *Rumaila* fields, where the formation is known as the Second Pay (Al-Naqib, 1967; Gaddo, 1971). Major oil accumulations occur within or near basin-margin rudist build-ups in SE Iraq. The Mishrif is an important reservoir at *Rumaila North, West Qurna* and *Majnoon, Zubair, Rumaila South* and *Ratawi.* Significant reserves also occur at *Buzurgan, Amara, Halfaiya, Dujaila* and *Nasariya* (Gaddo, 1971; Al-Sakini, 1992; Aqrawi *et al.*, 1998; Sadooni, 2005; Jassim and Al-Gailani, 2006).

The main reservoir facies are bioclastic (rudist) pack-grainstones with primary intergranular and secondary dissolution porosity (Sadooni, 2005). Significant reservoir quality also occurs in rudist rudstones and rudist pack-grainstones representing banks and bank-margins (Alkersan, 1975; Aqrawi *et al.*, 1998) .

Reservoir quality in rudist-rich facies is enhanced by early meteoric dissolution of aragonitic rudist components. Later dissolution and coarse crystalline dolomitisation created a well-connected pore system (Gaddo, 1971; Aqrawi *et al.*, 1998). Processes which further modified porosity include: meteoric cementation beneath sequence boundaries, drusy mosaic cementation, compaction, neomorphism and stylolitisation (Aqrawi *et al.*, 1998). Secondary pores are vuggy, mouldic or channel-like (Gaddo, 1971; Aqrawi *et al.*, 1998).

In well *Halfaiya-1*, cycles representing reef bank and shoal deposits are major reservoir units (Aqrawi *et al.*, 1998) (Fig. 7.37b). Coarsening-up cycle tops generally consist of a single pay zone of rudstones and/or rudistid grainstone-packstones (Sadooni and Aqrawi, 2000).

Alkersan (1975) noted that near Basra, the reservoir quality of the rudist facies is highest in structural crests. On structural flanks, reservoir quality deteriorates due to diagenesis and the presence of lagoonal and sub-basinal facies (Gaddo, 1971). Alkersan (*ibid.*) noted that on the crest of the *Rumaila* structure, the proportion of rudist bank material decreases within the saddles between structural culminations, reducing reservoir quality. Karstification and dolomitisation may be enhanced over the crests of growing structures. Dolomitisation has improved reservoir quality in bank-margin facies (Alkersan *ibid.*)

A permeability of 1560 mD was recorded in reservoir zone "C" at the *Rumaila* field; the highest porosity (36%) occurred in biostromal carbonates. Mean porosities are 16% at *Rumaila* and 9% at *Zubair* (Gaddo, 1971). Reservoir quality deteriorates southwards (towards the intrashelf basin) due to the decreasing volume and permeability of the biostrome facies. At *Rafidiyah* in the south of the Zubair structure where biostromes are small and discontinuous, the Mishrif Formation contains no economic pay (Gaddo, *ibid.*). Lagoonal bioclastic wacke-packstones and sub-basinal planktonic foraminiferal mud-wackestones may be porous but have low permeability unless fractured. Leached, recrystallised biostrome-flanking "algal facies" with *Permocalculus* sp. and "shallower sub-basinal facies" are locally important reservoir rocks (Gaddo, 1971). The chalky algal facies contains many stylolitic horizons, resulting in low to moderate effective porosities and low permabilities. Sub-basinal facies have the poorest reservoir characteristics.

In well *Dujaila-1*, the Mishrif Formation had a mean porosity of 15%; the well produced 2000 b/d of oil from a depth of 2844-2877 m (Sadooni, 2005). In well *Nasiriya-3*, porosities of 1.8-27% and permeabilities of <0.01-73 mD were recorded (Al-Rikabi *et al.*, 1987, *in* Aqrawi *et al.*, 1998).

In Kuwait, the only example of production from the Mishrif Formation (which is up to 78 m thick) comes from bioclastic limestones (algal/rudist/coral reefal carbonates) in the offshore *Hout* field in the Neutral Zone (Abdullah and Kinghorn, 1996).

Reservoir rocks in the **Gir Bir Formation** are of similarly high quality to those in the Mishrif Formation and produce oil at *Ain Zalah* (Hart and Hay, 1974). These carbonates are often intensely recrystallised (F.S. and A.H., *pers. obs.*, 1988). In NE Syria, the equivalent Massive Limestone (Fig. 7.40) has been karstified; it lacks significant internal barriers and seals and has a very high net:gross (see data in Nikolaevskiy, 1972). Reservoir quality is best in "sucrosic" reef facies with cavernous porosity at *Rumelan, Souedie* and *Karatchok* (Dunnington, 1967a).

In SE Turkey, the Mardin Limestone/Derdere Formation forms the principal reservoir unit (Tasman and Egeran, 1952; Wagner and Pehlivan,

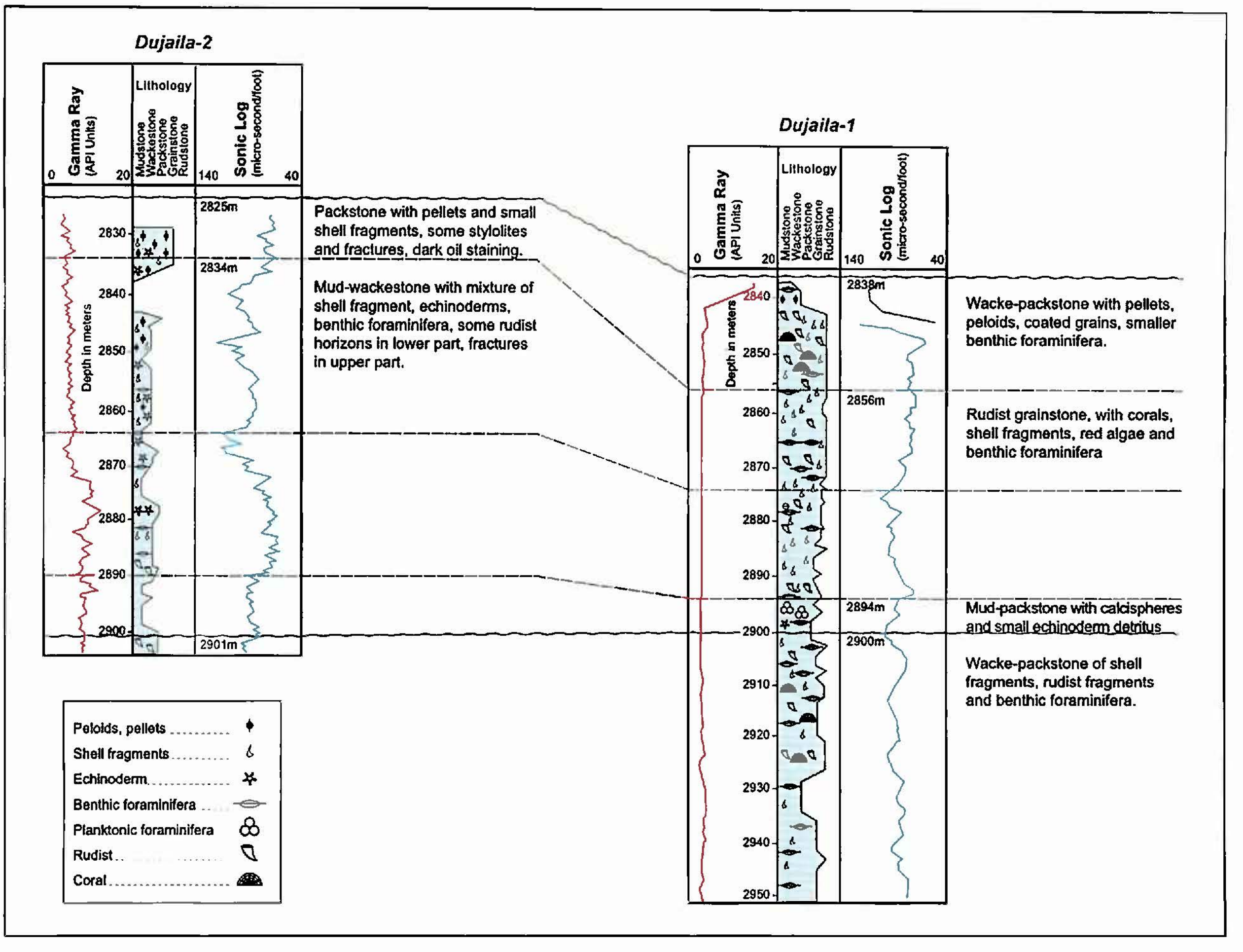


Fig. 7.41. Cenomanian – lower Turonian facies relationships at the *Dujaila* structure (after Sadooni, 2005).

1987; Cater and Gillcrist, 1994). Porosity is related to prolonged subaerial exposure during the middle Turonian – Coniacian (Wagner and Pehlivan, 1987). Macropores (vugs and caves) and well-developed joints have been detected by drill-string drops. The *Raman* field in SE Turkey contains an upper pay, 100 m thick, and a lower pay, 12 m thick, separated by an 80 m tight interval (Tasman and Egeran, 1952). Log porosities are highest (10%) at a depth of 3000 m in the upper 50 m of the carbonates where DST-derived permeabilities are 20 to 500 mD, and decrease rapidly with depth (Wagner and Pehlivan, 1987).

Karstified Cenomanian carbonates may act as a regional carrier-bed system. Dunnington (1958) noted that the Mosul High formed a focus for oil migration out of the foreland basin, and that several oilfields occur on its flanks. Hart and Hay (1974) deduced that oil was trapped in the Gir Bir and Mauddud Formations in fault blocks in the *Ain Zalah* area prior to Late Tertiary inversion, consistent with the remigration model of Dunnington (1958). Several secondary carbonate reservoirs are present. Fracture systems in the Dokan Formation produced oil in the *Baba Dome (Kirkuk)* and *Bai Hassan* and gas from *Jambur* (Dunnington, 1967a). The Rumaila Formation forms a secondary reservoir at *West Qurna* in SE Iraq (Al-Sakini, *pers. comm.* to A.A., 1989).

Proven and Potential Source Rocks

No proven source rocks have yet been identified in Supersequence IV in Iraq.

In Iran, basin-margin *Oligostegina* facies of the Ahmadi Member of the Sarvak Formation have TOC contents of up to 5% in the Binak/Bahregansar area (Bordenave and Huc, 1995). TOC contents rarely exceed 1% in more proximal *Oligostegina* facies equivalent to the Dokan Formation of Iraq (i.e. shallower-water units) which were deposited in dysoxic conditions. A few metres of marls with TOCs of 1.5 to 4% occur in the *Kabir Kuh* field (Bordenave and Huc, 1995).

In Kuwait, the Ahmadi Formation comprises creamy limestones which pass up into green-grey, pyritic shales. These thin onto the crests of anticlines. TOC contents are <1 wt% (Abdullah and Kinghorn, 1996). In Abu Dhabi, the coeval Shilaif Formation is an excellent source rock (Hassan and Azer, 1985; Bordenave and Huc, 1995).

The Rumaila Formation, which is up to 140 m thick in Kuwait, consists of fine-grained marly limestones interbedded with calcareous shales. Mean TOC values are 0.4%, and organic matter comprises marine-amorphous sapropelic Type II kerogen in the *Minagish* field (Abdullah and Kinghorn, 1996).

Proven and Potential Cap Rocks

The marly Dokan Formation may seal the underlying Aptian-Albian shelf and shelf-margin carbonates at *Kirkuk, Jambur* and *Bai Hassan* fields (Dunnington, 1967a; Al-Rawi *et al.*, 1980). Dunnington (1958) suggested that oil in the Upper Qamchuqa reservoir in NE Iraq was stratigraphically trapped (presumably by the Dokan Formation) prior to Zagros folding and fracturing.

The Ahmadi Formation locally seals the Mauddud Formation in southern Iraq (Sadooni and Alsharhan, 2003). Tight and/or muddy layers within the Mishrif Formation may locally act as intraformational seals in the *Zubair* and *Rumaila* fields. Shales overlying the intra-Mishrif sequence boundary may act as seals in wells *Rafidain-1* and *Nasiriya-1* (Aqrawi *et al.*, 1998; Sadooni and Aqrawi, 2000).

Lateral facies variations in the Mishrif result in great variation in intraformational seal capacity. Gaddo's (1971) zones Mi/B and Mi/D comprise tight calcisphaerulid limestones in the southern parts of the *Zubair* and *Rumaila* fields. Zone Mi/B separates the main productive pay (Mi/C) from porous oolitic units in the uppermost zone, Mi/A. The non-reservoir oligosteginal facies pass northwards in both fields into productive facies (Gaddo, 1971).

At *Dujaila,* Mishrif facies comprise pelletal and peloidal limestones. Rudist bank facies in downdip well *Dj-1* pass NW into argillaceous wackestones with mixed fossils in the updip well *Dj-2*. Only one metre of calcisphere-bearing limestones (of Rumaila Formation facies) is present in well *Dj-1* (Sadooni, 2005) (Fig. 7.41). *Dujaila-1* produced oil from downdip rudist build-ups, whereas *Dujaila-2* was dry because of the poor reservoir quality of the Mishrif Formation in this updip location, suggesting that the deeper-water *Dujaila-2* facies have some lateral sealing capacity (Sadooni, 2005).

Supersequence V: upper Turonian – lower Campanian

This supersequence consists of a fine-grained, mixed siliciclastic-carbonate middle shelf to sub-basinal depositional system (Aqrawi, 1996; Sadooni and Aqrawi, 2000) (Fig. 7.42). The lowermost stratigraphic units in Supersequence V are the locally-developed Kifl Formation in the Najaf Intrashelf Basin, and the Gulneri Shale Formation which overlies the Dokan Formation in NE Iraqi Kurdistan. In central and southern Iraq, the supersequence consists of three formations, from base to top: Khasib, Tanuma and Sa'di (Owen and Nasr, 1958; Dunnington *et al.*, 1959; Al-Naqib, 1967; Darmoian, 1975; Aqrawi, 1996) (Fig. 7.43, 7.44).

Supersequence V onlaps westwards onto the basal regional unconformity. Facies changes occur over subtle structural highs and in narrow grabens (Fig. 7.45). Marked overstep of earlier units is observed. In the basin centre, the Khasib Formation unconformably overlies Supersequence IV. Towards the west / SW, the Mishrif/Kifl Formation is overlain by the Tanuma Formation, for example at well *Safawi-1* (Al-Naqib, 1967). The Tanuma is overstepped towards the west and NW in the Rutbah–Jezira area by the Sa'di Formation (e.g. in *Fallujah-1, Mileh Tharthar-1, Makhul-2* and *Nafatah-1*: Jassim and Buday, 2006f). Northwards, these formations pass into the Kometan Formation (Dunnington *et al.*, 1959; Al-Naquib, 1960; Kaddouri, 1982b; Haddad and Amin, 2007). Equivalent units in NW Iraq are the Wajnah and Mushorah Formations (Table 7.1) (Hart and Hay, 1974; El Zarka, 1993). They onlap lowermost Turonian and older units on the Khleisia – Mosul High. However, on the crests of the Khleisia, Rutbah and Mosul-Bekhme Highs, this succession is absent (Dunnington, 1958; Kaddouri, 1982b). Towards the east, these formations pass into the Balambo Formation. These relationships are illustrated in Fig. 7.45.

Formations of the intra-Turonian lowstand

Supersequence V is bounded below by a major unconformity, for example at the *West Qurna* field where the Khasib Formation unconformably overlies the Mishrif Formation (Sherwani, 1983; Aqrawi, 1996). Initial facies in the supersequence are locally represented by the **Kifl** and **Gulneri Formations.**

The **Kifl Formation** (Fig. 7.45) was first described by Al-Naqib (1967) in well *Kifl-1.* The formation thickens to the north and east and is thickest at *East Baghdad* (Jassim and Buday, 2006c). It comprises massive anhydrites and argillaceous limestones. These may correspond to the anomalous facies in the uppermost Mishrif Formation (see above) of Dunnington *et al.* (1959). Gaddo (1971) and Alkersan (1975) retained this interval within the Mishrif Formation. Gaddo (1971) noted that anhydrite intervals also occur within the Mishrif Formation in well *Rumaila-36* on the eastern flank of *Rumaila* field. He suggested that thick anhydrites may occur in the syncline between *Zubair* and *Rumaila.*

Al-Naqib (1967) noted that massive anhydrites of the Kifl Formation conformably overlie sub-basinal oligosteginal carbonates of the Rumaila Formation. Gaddo (1971) recorded shallow-water (lagoonal/fresh water) facies directly overlying oligosteginal limestones. The formation may

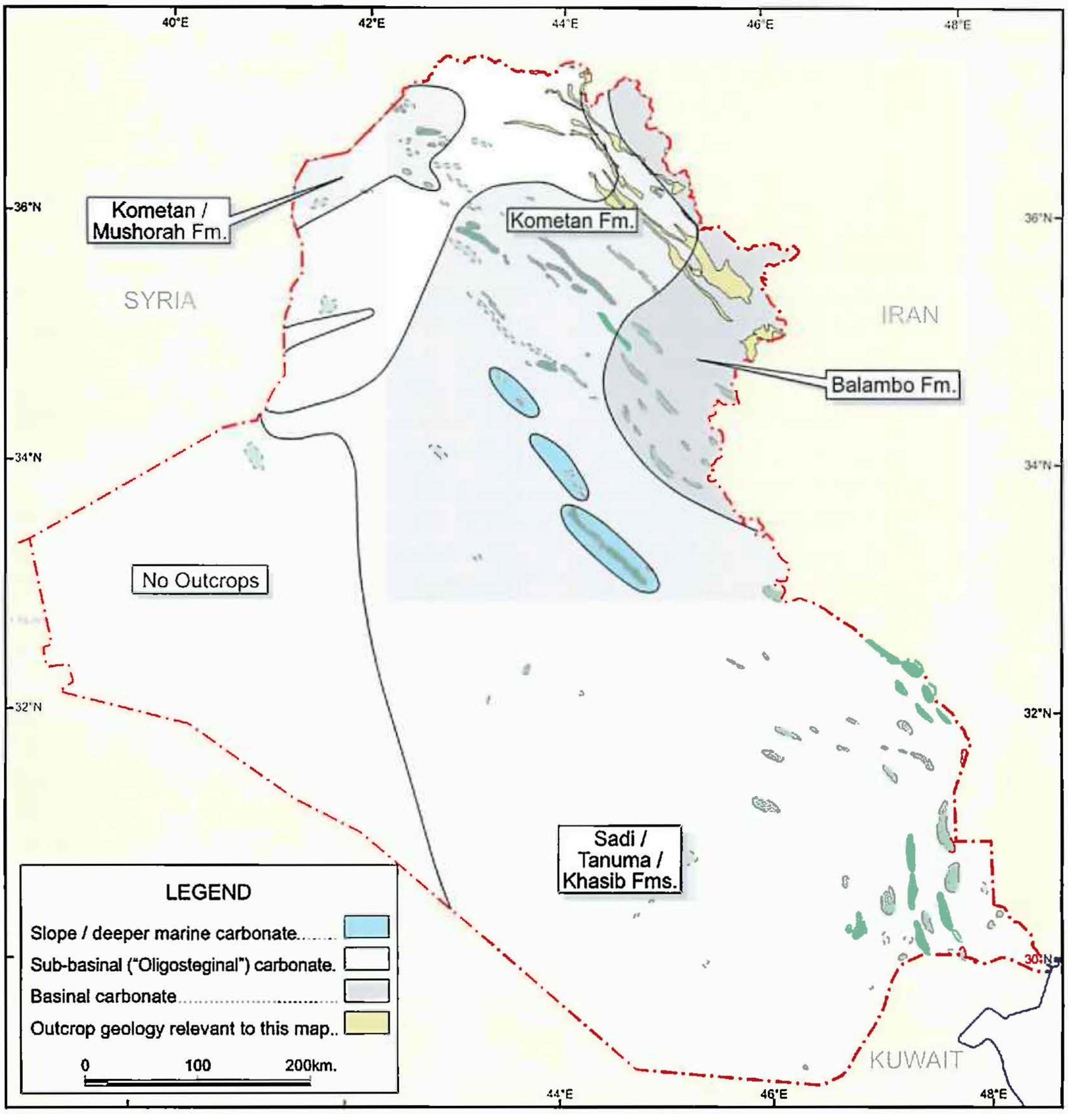


Fig. 7.42. Late Turonian – early Campanian palaeogeography of Iraq. Note the absence of outcrops in the Western Desert. Simplified Cambridge Carbonates Ltd map based on published data.

represent terminal evaporitic deposition in the Najaf Intrashelf Basin.

The **Gulneri Formation** is a thin, condensed, bituminous shale 1.1-1.2 m thick (Dunnington *et al.*, 1959). It contains a dwarf planktonic foraminiferal fauna with *Globotruncana (Helvetoglobotruncana) helvetica* of late early to early middle Turonian age. This restricted basinal unit indicates a pronounced break at the end of Supersequence IV deposition marked by low sea levels and reduced hemipelagic input.

Erosion of the Gir Bir and Qamchuqa Formations from footwall highs is associated with the formation of the thick conglomerates of the **Tel Hajar Formation** (Kaddouri, 1982a) (Fig. 7.46). Pebbles with *Pholas* borings indicate a high-energy shallow-water (beach) environment, possibly associated with a spit attached to an uplifted sediment source terrane (A. H., *pers. obs.*, 1988). Bored pebble facies similarly occur at the base of the coeval Ilam Formation in Iran (C. Dons, *Statoil, pers. comm.* to A. H., 2007) which disconformably overlies the Ahmadi Member of the Sarvak Formation (James and Wynd, 1965). In the Hamrin-Makhul-Mileh Tharthar area and on the Mosul High, later Turonian and younger formations often unconformably overlie Albian strata (Dunnington, 1958; Dunnington *et al.*, 1959).

Stratigraphic organisation and formations

The supersequence can be divided into three large-scale cycles or third-order sequences (Aqrawi, 1996). The first sequence corresponds to the Khasib Formation. The Tanuma Formation marks a major break (i.e. lowstand) at the base of the second sequence. The remainder of the second sequence and the third sequence are assigned to the Sa'di Formation (Fig. 7.43). Shaly and condensed intervals appear to form lowstands and TSTs to maximum flooding surfaces (Sharland *et al.*, 2001) (Fig. 7.44). These sequences can be subdivided into into medium-scale cycles or sub-sequences. Aqrawi (1996) suggested that there may be up to five such divisions, while Haddad and Ameen (2007) recorded

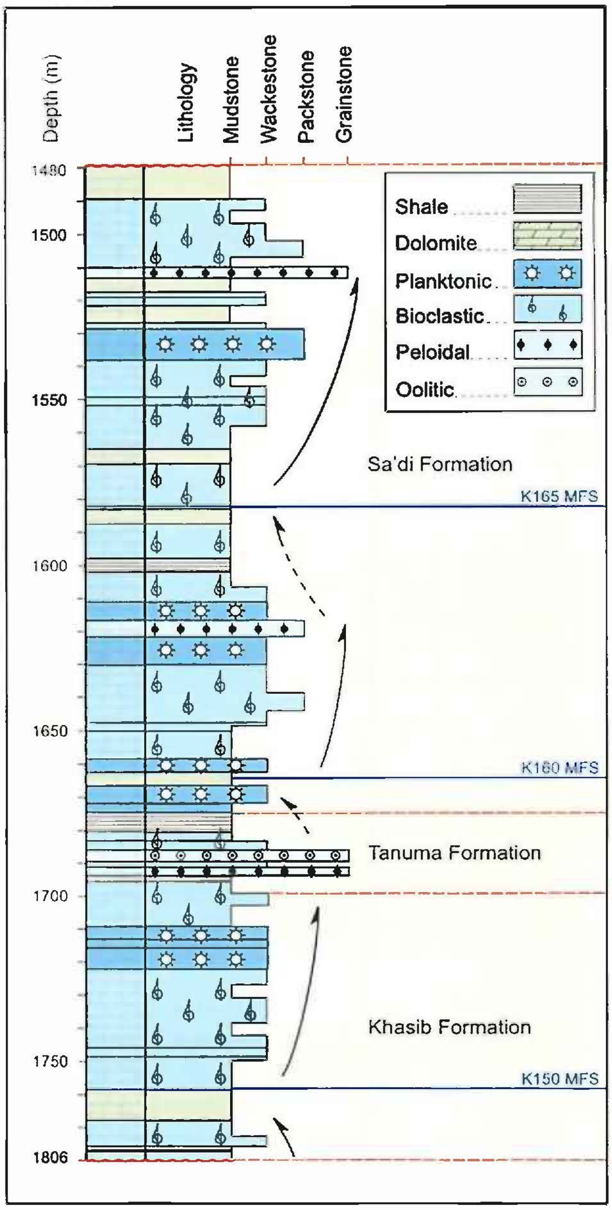


Fig. 7.43. Details of microfacies in the Sa'di, Tanuma and Khasib Formations in *Musaiyib-1*. After Aqrawi, 1996.

three second-order and eight third-order sequences.

Darmoian (1975), Kaddouri (1982b) and Haddad and Ameen (2007) dated the Khasib Formation as late Turonian to Coniacian based on the presence of *Globotruncana lapparenti* and the *G. renzi* zone. The Tanuma Formation is thought to be Coniacian since it also includes the *G. renzi* zone. The Sa'di Formation is Santonian to early Campanian based on the presence of the *G. concavata, G. fornicata* and *G. stewartiformis / G. stephensoni* zones (Darmoian, 1975). These stratigraphic intervals can be correlated with equivalent planktonic foraminiferal zones in Iran (Adams *et al.*, 1967).

The **Khasib Formation** (Fig. 7.47) reaches a thickness of 100 m in SE Iraq (Fig. 7.48). It has shallowest water characteristics at the *East Baghdad* field (Sadooni, 2004) (Fig. 7.47). The middle part of the formation consists of about 50 m of chalk with *Thalassinoides* (Plate 7.11); the lower and upper parts consist of marls and marly limestones.The formation contains abundant *Oligostegina* and a dwarf planktonic fossil assemblage (Plate 7.12) (Dunnington *et al.*, 1959; Jassim and Buday, 2006f). It was probably deposited in a sub-basinal restricted environment. The basal shale horizon (as shown in Fig. 7.43) is interpreted as a middle Turonian maximum flooding surface.

The lower part of the overlying **Tanuma Formation** consists of calcareous mudstones with interbedded oolitic grainstones (Dunnington *et al.*, 1959; Aqrawi, 1996) (Fig. 7.44; Plate 7.13). These represent a lowstand systems tract with water depths of only a few metres. The shale horizon at the top of the formation (as shown in Fig. 7.43) can be interpreted as the succeeding maximum flooding surface (MFS K160 of Sharland *et al.*, 2001). The Tanuma formation is thickest west of the Khasib Formation depocentre (Aqrawi, 1996) (Fig. 7.49).

The **Sa'di Formation** comprises deeper-water shelfal *Oligostegina*-bearing wackestones and packstones, and white, chalky, argillaceous globigerinid limestones. It is up to 300 m thick (Fig. 7.50). A 60 m thick marl (the Hamrina Marl Member) occurs at the top of the formation at the

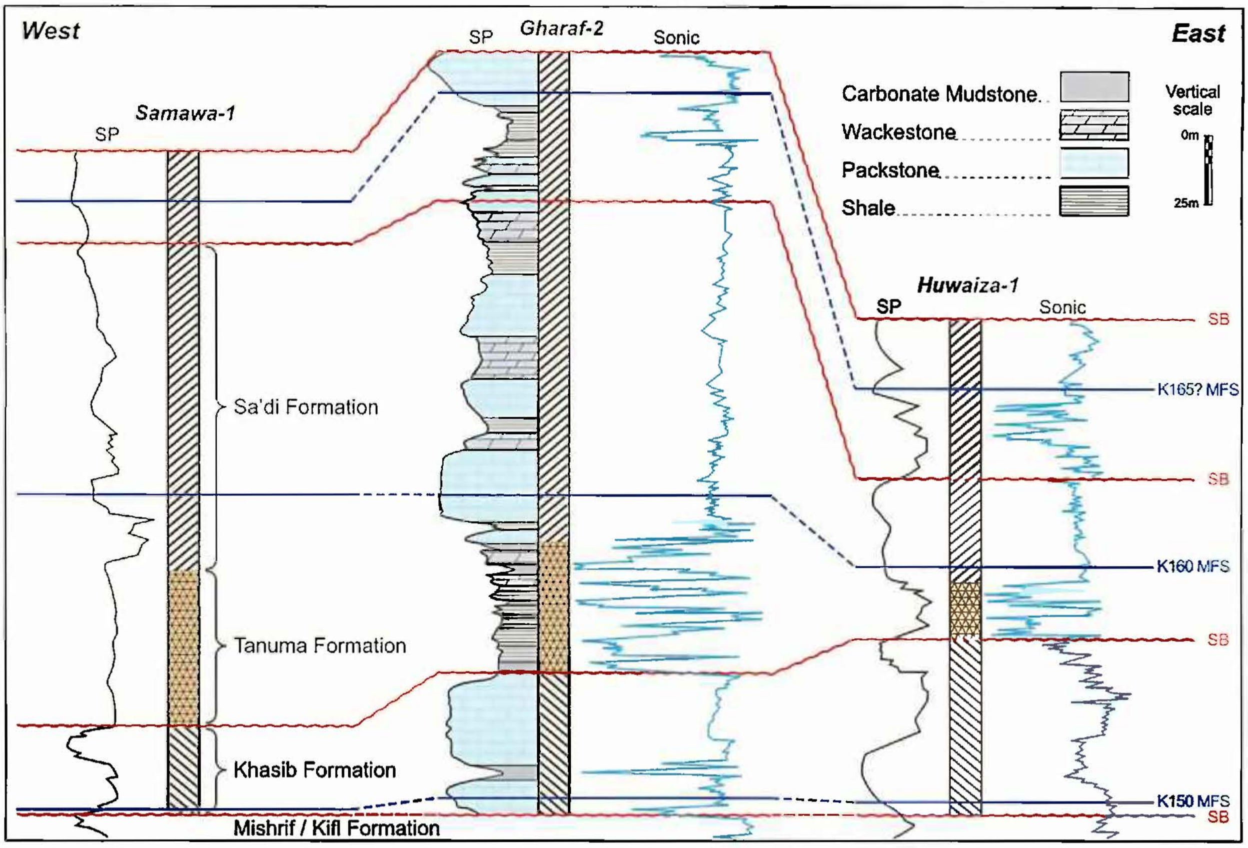


Fig. 7.44. Correlation of the Khasib, Tanuma and Sa'di Formations in southern Iraq. The chart shows eastwards thinning of the Tanuma and Sa'adi Formations from the depocentre in the Garaf area. Modified after Aqrawi, 1996.

type locality (*Zubair-3*: Dunnington *et al.*, 1959; Jassim and Buday, 2006f), and marks a suggested K165 MFS. Towards the east and NE, in *Nahr Umr*, *Siba* and *Dujaila*, the formation is dominated by argillaceous limestones (Jassim and Buday, 2006f). It is thickest to the SW of the Khasib and Tanuma depocentres along the boundary of the Salman Zone with the Balambo-Gurau Basin (Aqrawi, 1996).

A shallow-water organo-detrital limestone with benthic fossils occurs at the top of the Sa'di Formation and is known as the ***Pseudedomia* Limestone** (Dunnington *et al.*, 1959). It is only preserved in structurally low areas; Campanian erosion removed it from palaeohighs (Dunnington *et al.*, 1959).

Variations in the thickness of the Sa'di, Tanuma and Khasib Formations may have been controlled by subtle movements of basement blocks during deposition (Aqrawi, 1996), possibly inherited from movement during the preceding early Turonian lowstand. However, progressive onlap and incomplete infill of accommodation may have caused the axis of maximum hemipelagic deposition to shift progressively updip through time, as indicated by the isopachs of Aqrawi (1996) (Figs 7.48, 7.49, 7.50).

The Khasib, Tanuma and Sa'di Formations in Central Iraq can be correlated with the Mutriba and Gudair Formations in Kuwait (Owen and Nasr, 1958), and the Aruma Formation in Saudi Arabia (Powers *et al.*, 1966). In Iran, equivalent formations are the Surgah, Ilam and the lower part of the Gurpi Formations (James and Wynd, 1965; Adams *et al.*, 1967; Aqrawi, 1996).

In northern Iraq, the **Kometan Formation** is equivalent to the Khasib, Tanuma and Sa'di Formations (Dunnington *et al.*, 1959; Al-Naquib, 1960; Kaddouri, 1982b; Haddad and Ameen, 2007). It is interpreted to be an outer-shelf (or sub-basinal) deposit (Jassim and Buday, 2006f). The basal part of the formation in Iraqi Kurdistan, including the Sinjar area, contains *Globotruncana renzi* of Turonian age (Dunnington *et al.*, 1959; Kaddouri, 1982a) (Fig.7.46).

Elsewhere in NW Iraq (e.g. well *Sasan-1*: Fig. 7.26b) only a cherty *Oligostegina* limestone, equivalent to the uppermost part of the Sa'di Formation and known as the **Mushorah Formation**, is present (Dunnington *et al.*, 1959). At the *Ain Zalah* field, this comprises 85 m of crystalline limestones with bedded chert and flint, a basal dolomitised limestone and some thin beds of black bituminous limestones (El Zarka, 1993). At this location, it locally overlies a shelf carbonate known as the **Wajnah Formation**, which is composed of 15 m of dolomitic shaly limestone with ostracods, and abundant orbitoid foraminifera such as *Monolepidorbis* (*Praeorbitoides*) of early

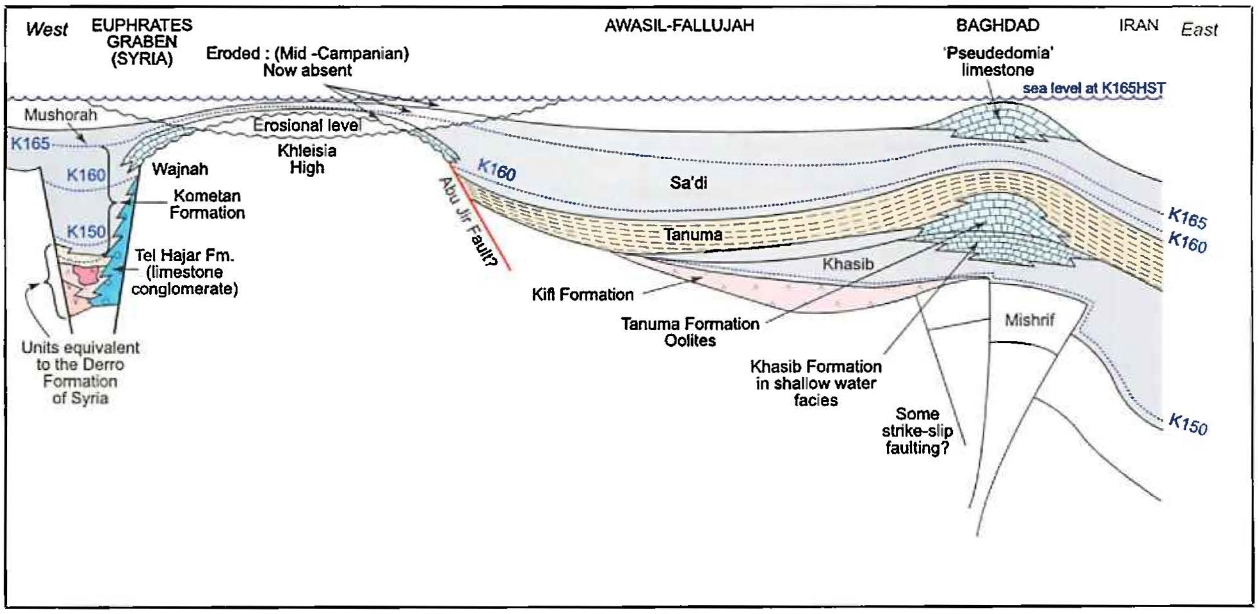


Fig. 7.45. Schematic west-east profile from the Euphrates Graben to Central Iraq illustrating the organisation and relative thicknesses of stratigraphic units in Supersequence V.

Plate 7.11. Porosity in bioturbated limestones of the Khasib Formation, typical of the *East Baghdad* field. Vugs are located along *Thalassanoides* burrows. From Sadooni, 2004.

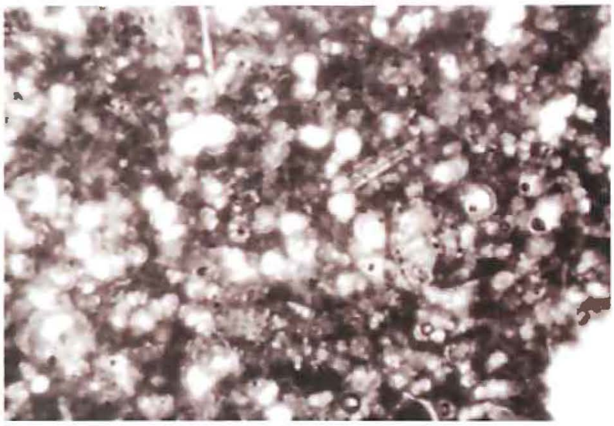


Plate 7.12. Photomicrograph (3 mm across) of planktonic packstone of the Khasib Formation with Textularia and *Oligostegina*. Well *Musaiyib-1*, ca. 5900 ft depth. Photo by A. Aqrawi.

Campanian age (Hart and Hay, 1974; El Zarka, 1993). At the *Butmah* field, the Mushorah Formation includes a basal conglomerate and unconformably overlies the "Nahr Umr" Formation shales (Albian) (Jassim and Buday, 2006f).

In the Makhul–Samarra area, the Mushorah Formation contains anhydrite (Jassim and Buday, 2006f) indicating hypersaline depositional conditions.

A long-lived (Cenomanian–Maastrichtian) and heterogeneous unit referred to as the "**Pilsener Limestone**" has been described from the *Qasab*, *Jawan*, *Najmah* and *Qaiyarah* fields (Dunnington *et al.*, 1959). Sadooni and Aqrawi (2000) proposed that this unit includes parts of the Kometan/Mushorah and Hartha/Shiranish Formations. Haddad and Ameen (2007) sub-divided the Pilsener Formation in the area to the SE of Mosul.

In the High Zagros and Kirkuk Embayment, the Kometan Formation passes eastwards into the uppermost **Balambo Formation** (Dunnington *et al.*, 1959; Al-Naquib, 1960). There is often a gap (perhaps due to stratigraphic condensation) between the uppermost Balambo Formation (Turonian) and the overlying upper Campanian Shiranish Formation (Dunnington *et al.*, 1959). Lower Campanian limestones at Gukab near Halabja in NE Iraqi Kurdistan resemble the Kometan Formation (Jassim and Buday, 2006f).

Nikolaevskiy (1972) noted that a shelf carbonate system of this age extends from NE Syria towards the Sufaiya and Abtakh areas of Iraq (Fig.7.51); it may also occur on the southern margin of the Sinjar Trough, and onlap the Khleisia High.

In SE Turkey, stratigraphically equivalent shelf carbonates consist of the Santonian Karababa

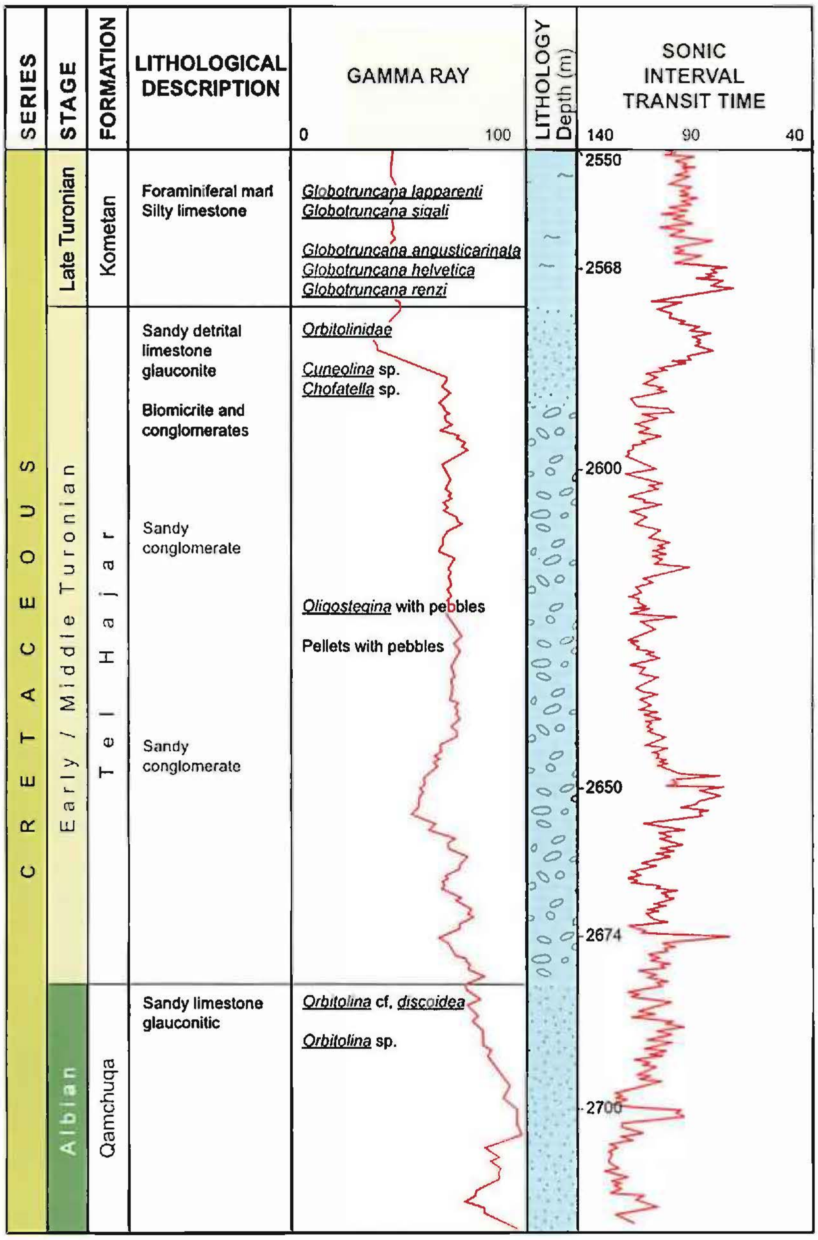


Fig. 7.46. Lithological log through the conglomerates of the Tel Hajar Formation (after Kaddouri, 1982a). The conglomerates rest unconformably on Albian rocks and contain clasts with *Oligostegina* which were probably derived from the Cenomanian succession.

Formation which unconformably overlies the lower Turonian Derdere Formation (Beer, 1966; Wagner and Pehlivan, 1987; Cater and Gillcrist, 1994).

In eastern Syria, the equivalent Soukhne Group comprises the Derro Red Beds, Erek Marl and Rmah Chert Members (Daniel, 1963; Ponikarov *et al.*, 1967). On the Rutbah – Mosul palaeohigh, localised deposition of the older (middle Turonian – Coniacian) portion of this supersequence occurred in the Syrian extension of the Anah Graben (the Euphrates Graben in the Deir ez Zor area). The syn-rift Derro Red Beds, described by Caron *et al.* (2000), are locally >200 m thick. They comprise continental clastics (shales, sandstones and conglomeratic sandstones), volcanics (basalts, tuffs and tuffaceous clastics) and evaporites (anhydrite and locally halite). Thick layers of volcanic ash contain laminae and veins of crystalline dolomite (Caron *et al.*, 2000).

The Red Beds are confined to graben systems cutting the Khleisia–Rutbah palaeohigh. NW of this high, where the Euphrates Graben joins the Palmyride Basin (the "Joura Ridge"), they pass into dolomites and argillaceous limestones of the "Kometan Formation" (Caron *et al.*, 2000). A similar facies change probably occurs along the eastern margin of the Khleisia High in Iraq. Evaporite units become more halite-dominated towards the Anah Graben of Iraq.

The Santonian – early Campanian R'mah Formation consists of 70–300 m of basal dolomites overlain by cherty limestones (Caron *et al.*, 2000).

The bounding unconformity at the top of Supersequence V is a significant intra- Campanian erosional suface. Upper Campanian sediments unconformably overlie older rocks over wide areas, for example in the *Khleisia* area, in the Rutbah–

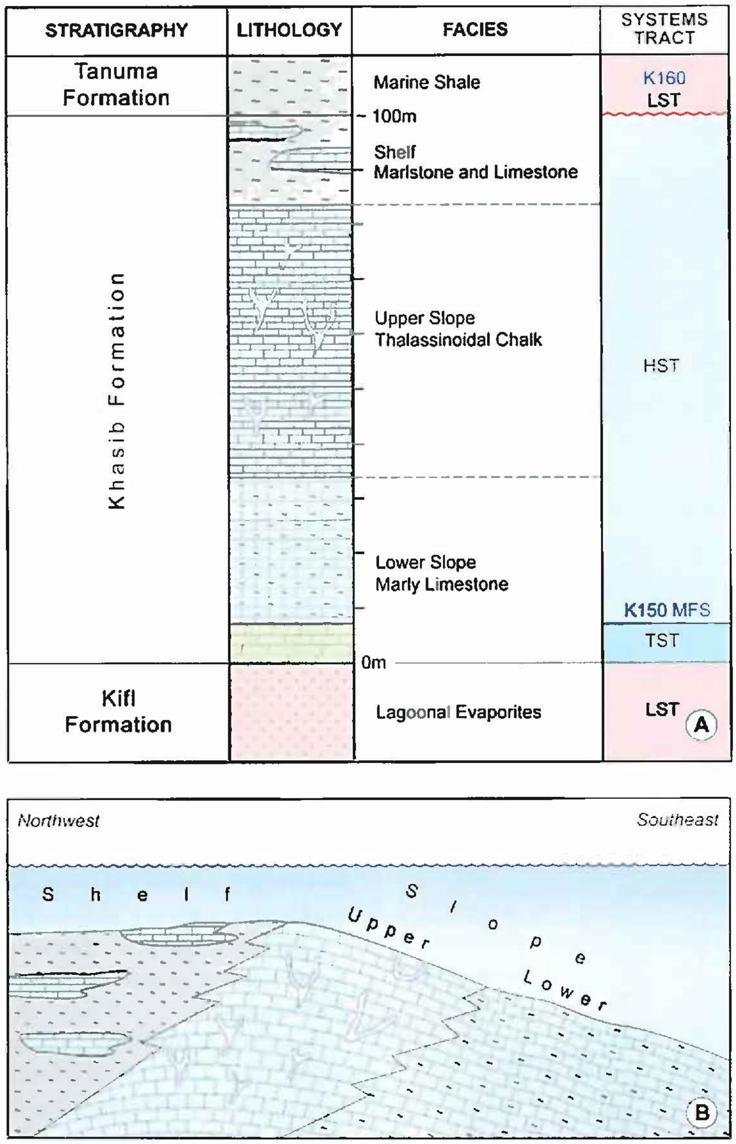


Fig. 7.47. Stratigraphy (A) and depositional model (B) for the Khasib Formation in the *East Baghdad* field. The formation is a shallower water deposit at this location than at its type section, probably as a result of uplift associated with a NW-SE trending flower structure. Reservoir quality and fracture development are enhanced, and the formation does not therefore provide a seal for underlying reservoirs in the Mishrif Formation. After Al-Qayim *et al.*, 1993.

Jezira Zone (Dunnington, 1958; Dunnington *et al.*, 1959; Kaddouri, 1982b; Jassim and Buday, 2006f), and over the constructional high in NE Iraq known as the "Qamchuqa ridge"(see page 165).

Petroleum System Components

Proven and Potential Reservoir Rocks

Supersequence V contains up to 14% of Iraq's Cretaceous oil reserves according to Al-Sakini (1992). These are located mainly in central Iraq in the *East Baghdad* and *Balad* fields with smaller reserves at *Ahdab* (Al-Sakini, 1992), *Samarra* and *Tikrit*. Oil shows occur in the *Nahr Umr* and *West Qurna* fields in southern Iraq (Al-Sakini, 1992). The Khasib Formation contains oil at *Ahdab*, *Dhefria* and *Dujaila* in central Iraq (Al-Sakini, 1992).

About 90% of the oil in this supersequence is present in the **Khasib Formation** in *East*

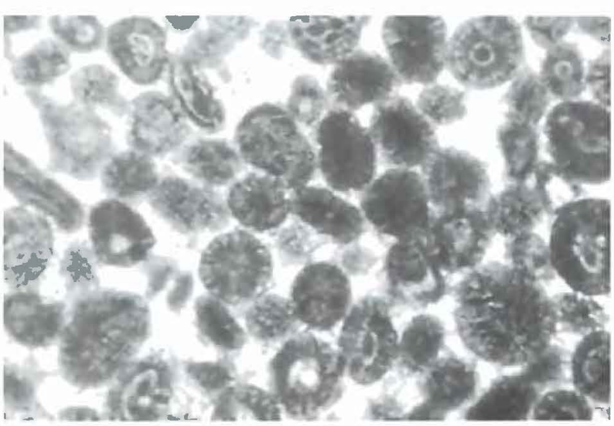


Plate 7.13. Thin section photomicrograph (3 mm across) of cemented oolitic grainstones of the Tanuma Formation. Well *Musaiyib-1*, depth 4971 ft. Photo by A. Aqrawi.

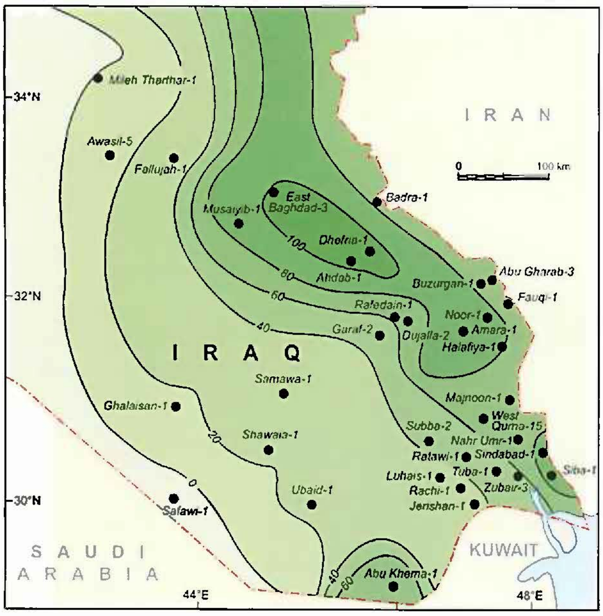


Fig. 7.48. Isopach (metres) of the Khasib Formation in SE Iraq. The depocentre is located close to the Iran-Iraq border, and the sediment package thins gradually to the west. Modified after Aqrawi, 1996 and Sadooni, 2004.

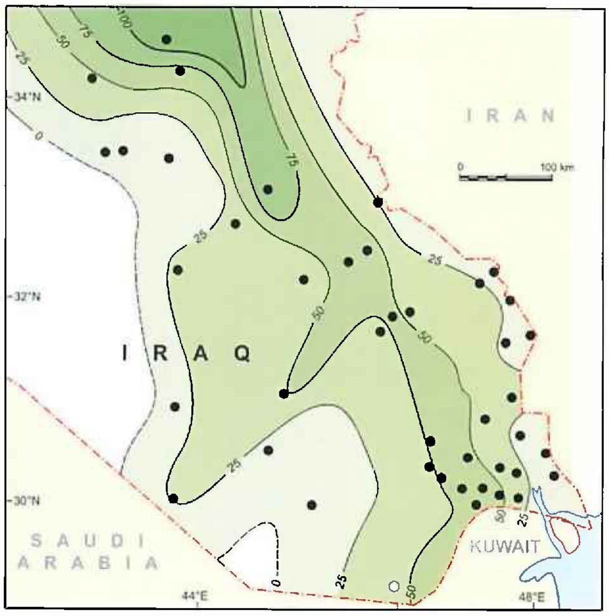


Fig. 7.49. Isopach (metres) of the Tanuma Formation in SE Iraq. Modified after Aqrawi, 1996.

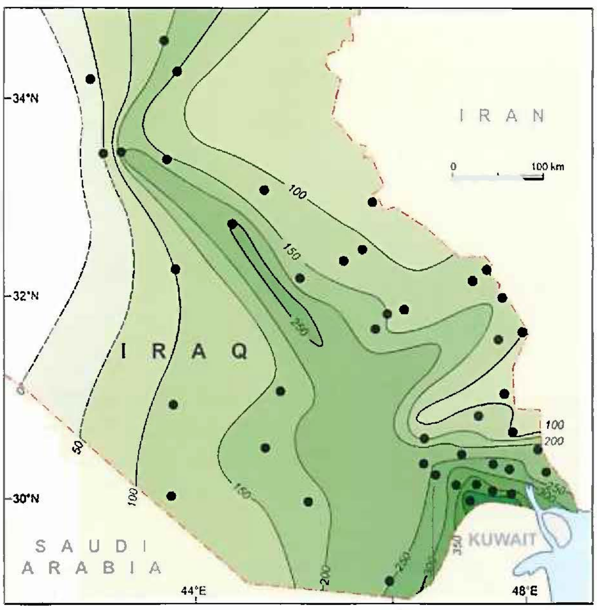


Fig. 7.50. Isopach (metres) of the Sa'di Formation; the depocentre is located to the SW of the Khasib and Tanuma Formation depocentres (Fig. 7.48, 9). Progressive thinning of sediments occurs to the east and west of the depocentre. Modified after Aqrawi (1996).

Baghdad. The formation was deposited in shallower waters here than elsewhere and consequently has relatively good reservoir characteristics (Sadooni, 2004). The main reservoir unit consists of bioturbated chalks in the middle of the formation, which have mean porosities of 23% (range 1.4-34.2%) and mean permeabilities of 4.98 mD in pay zones 12-15 m thick (Al-Sakini, 1992; Al-Qayim *et al.*, 1993; Sadooni, 2004). *Thalassinoides* burrows are often vuggy and oil stained (Plate 7.11). Secondary porosity is associated with vugs, stylolites and microfracture networks.

Porous oolitic grainstones and skeletal packstones occur in the **Sa'di** and **Tanuma Formations**, e.g. at *East Baghdad* and at *Dujaila-1* (Aqrawi, 1996). The Tanuma Formation contains significant volumes of oil at the *East Baghdad* field and in some southern oilfields (Sadooni and Aqrawi, 2000). The Tanuma carbonate reservoir has porosities of up to 30% (Al-Sakini, 1992). Oil shows occur in the Sa'di Formation in *Dujaila-1* (Sadooni, 2004), and the formation is oil-bearing at *Ahdab, Samarra* and *Tikrit* (Jassim and Al-Gailani, 2006).

In northern Iraq, minor production occurs at *Ain Zalah* where the Mushorah and Wajnah Formations form part of the Second Pay as defined by Hart and Hay (1974). Porosities are only about 1% in the oil-stained Mushorah Formation (El Zarka, 1993). Dunnington (1967a) noted that heavy oil (12-18° API) is reservoired in the "Pilsener Limestone" equivalent to this stratigraphic interval in the *Qasab, Jawan, Najmah* and *Qaiyarah* fields.

Upper Cretaceous shelfal carbonates in Iraq are analogous to the "Massive Limestone" and Mardin Limestone Group (Dunnington, 1967a; Nikolaevskiy, 1972) of Syria and Turkey, respectively. Significant production from these units occurs at the *Soueide, Rumelan* and *Karatchok* fields in NE Syria, and the *Selmo, Silivanka, Celikli, Magrip, Kurtalan, Garzan, West Raman* and *Raman* fields in SE Turkey. In NE Syria, lower Campanian breccias also form a porous reservoir (Nikolaevskiy, 1972).

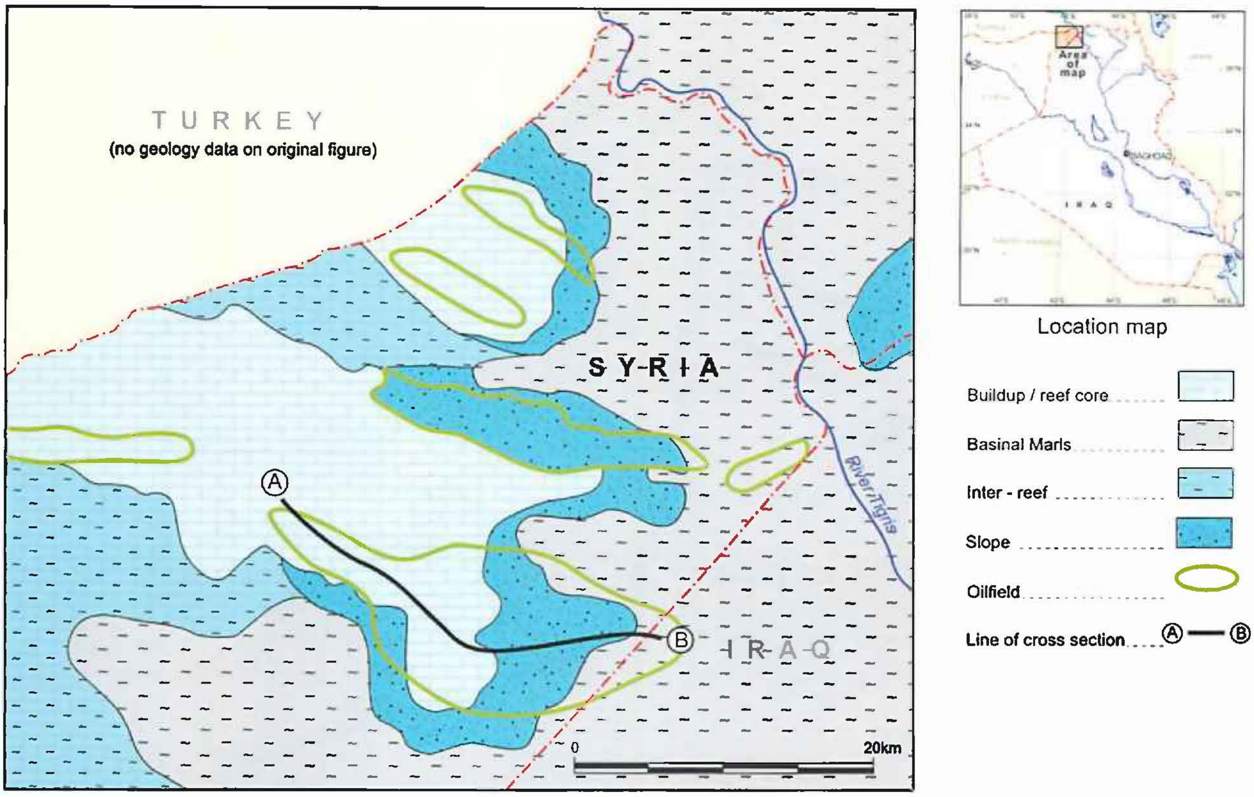


Fig. 7.51. Distribution of the Lower Campanian part of the Massive Limestone Formation shelf in NE Syria. The profile line shows the location of the cross-section in Fig. 7.40. After Nikolaevskiy (1972).

Age-equivalent reservoirs in SE Turkey include the uppermost Karababa Formation (Karababa"C"), comprising karstified bioclastic wackestones probably comparable to the *Pseudedomia* Limestone of the Sa'di Formation. The Karababa B and C units are secondary reservoirs with solution fissures and biomouldic porosity. Reserves are relatively small, with 8 MM brls oil in one field that has a 45 m pay, 8% porosity and 30-40% water saturation (Wagner and Pehlivan, 1987). In Iran, shelfal facies reservoirs of the Ilam Formation occur in the *Maleh Kuh*, *Sarkan* and *Veyzenhar* oilfields and the *Halush* gasfield (Bordenave and Huc, 1995).

At *Kirkuk*, the **Kometan Formation** produces oil at the Avanah and Baba Domes. The Upper Kometan Formation produces oil at *Bai Hassan* field and gas at *Jambur* (Dunnington, 1967a). Fractured Kometan Formation is reported to produce oil at high rates (35,000 b/d) at the *Taq Taq* field. In well *Taq Taq-10*, two intervals (67 and 49 m thick) were tested at rates of 19,380 and 14,800 b/d oil respectively*.These micritic oligosteginal carbonates have poor matrix porosities and permeability; production is probably controlled by fractures.

In the Euphrates Graben, Syria, the continental sandstones of the Coniacian Derro Formation have a net:gross ratio of 0.8 and average porosities up to 20% (de Ruiter *et al.*, 1995). Oil is also present in the overlying fractured limestones, cherts and thin sandstones of the Rmah Formation. Similar reservoirs may occur in the Cretaceous graben system in western Iraq.

Proven and Potential Source Rocks

No source rock potential has yet been identified in shale units in the Sa'di, Khasib, Tanuna or Kometan Formations in Iraq.

In Syria, the main source rock in the Euphrates Graben oilfields is the Santonian – lower Campanian Rmah Chert Formation (de Ruiter *et al.*, 1995; Caron *et al.*, 2000), which is mature for oil generation in the deepest parts of the graben system. Time-equivalent upper Turonian – lower Santonian sandy phosphorites in SE Jordan (Abed and Amireh, 1999) and Palymra (Chaimov *et al.*, 1993) indicate upwelling systems which may have developed along shelf margins in western parts of northern Arabia.

In NW Iraq, the cherty Mushorah Formation may be a source rock in the *Ain Zalah* field since it contains thin beds of black bituminous limestone, but no geochemical analyses have yet been performed (El Zarka, 1993). This formation is a facies- and age-equivalent of the Karababa A Formation in the *Adiyaman* area of SE Turkey, which is a prolific source rock with a TOC of 0.24-7.6% containing Types I and II kerogen (Wagner and Pehlivan, 1987, Soylu *et al.*, 2005). The formation is also the source of oils in the *Coskunsel* field (Soylu *et al.*, 2005).

* *www.gulfoilandgas.com*, 18.3.09

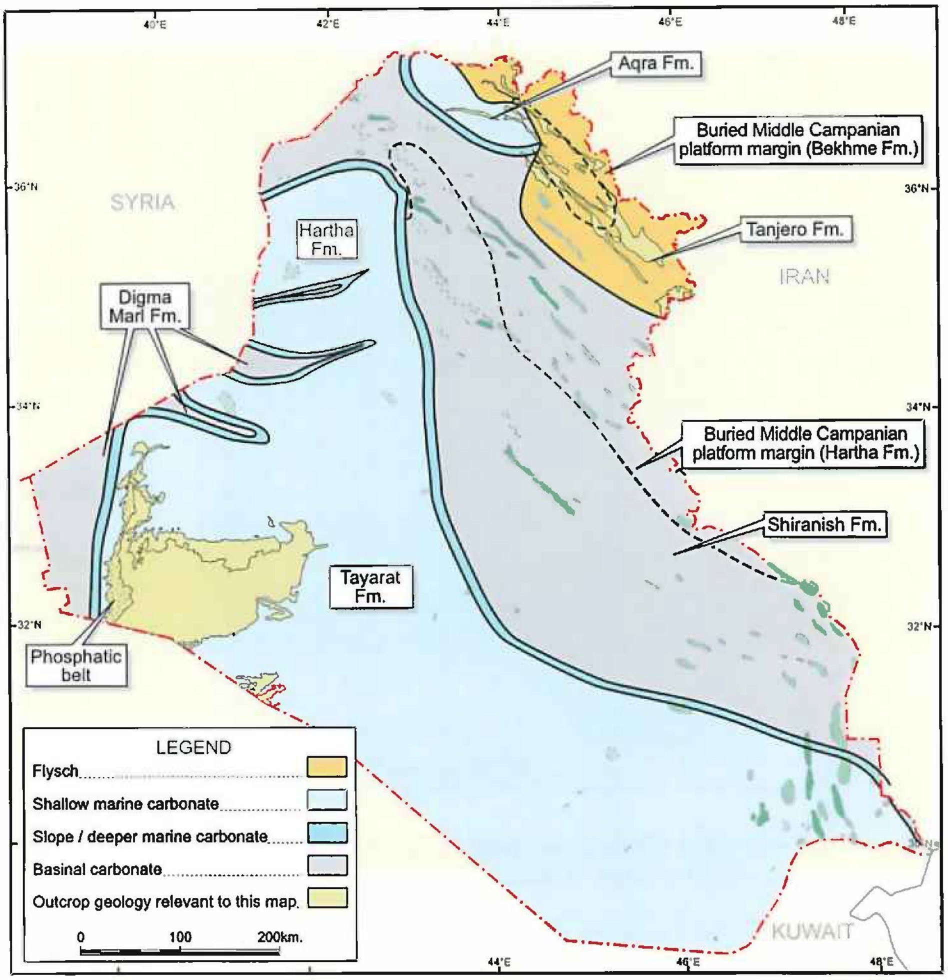


Fig. 7.52. Late Campanian – Maastrichtian palaeogeography of Iraq. Simplified Cambridge Carbonates Ltd map based on published data.

At Tang-e Garau, Iran, the Surgah Formation has a TOC of 0.5-0.7%; up to 75 m of bituminous marls occur in the basin centre (Bordenave and Huc, 1995). This source rock may be continuous with the deeper-water part of the Khasib Formation of NE Iraq. The overlying Santonian Ilam Formation (equivalent to the Sa'di Formation of Iraq) contains 100-200 m of bituminous argillaceous limestones with TOCs of about 1%; the 150 m thick section of the formation at Tang-e Garau has a TOC of 0.3-0.6% (Bordenave and Huc, 1995). *Rock-Eval* S2 is 3-8 kg/tonne (Bordenave and Burwood, 1990; Bordenave and Huc, 1995). It is here considered likely that oil source potential will be identified in the Sa'di and Khasib Formations in Iraq, and this may account for the large volumes of heavy oil present in the Khasib at the *East Baghdad* field.

Proven and Potential Cap Rocks

The Kifl evaporites are potential seals (Al-Naqib, 1967; Sadooni and Aqrawi, 2000), but usually overlie non-reservoir facies in relatively unstructured parts of the basin. Shale units in the Khasib, Tanuna and Sa'di Formations are local seals. A laterally extensive shale at the top of the Tanuma Formation may seal reservoirs in the Tanuma Formation and the underlying Khasib Formation. The basinal carbonates in the lower part of the Sa'di Formation may also provide a seal (Aqrawi, 1996). The Hamrina Marl member of the Sa'di Formation may seal reservoirs in the lower part of this formation (Sadooni and Aqrawi, 2000). Shales at the base of the Khasib Formation may seal Mishrif reservoirs (Sadooni and Aqrawi, 2000). Where the Khasib is carbonate-dominated and porous, oil has migrated up into it through the Mishrif Formation. Where the Khasib Formation is productive due to fractures, the Mishrif Formation is usually non-productive (e.g. in *East Baghdad* field).

In the *Ain Zalah* and *Kirkuk* fields, reservoir intervals in the Qamchuqa Formation are in communication with overlying Upper Cretaceous reservoirs, where intervening seals in the Mushorah Formation have been breached by fracturing (Dunnington, 1958; Hart and Hay, 1974; El Zarka, 1993).

In Syria, the Rmah Chert and Erek Marl act as regional seals above reservoirs in the Derro Red Bed, Rutbah and Mulussa Formations in the Euphrates Graben (de Ruiter *et al.*, 1995).

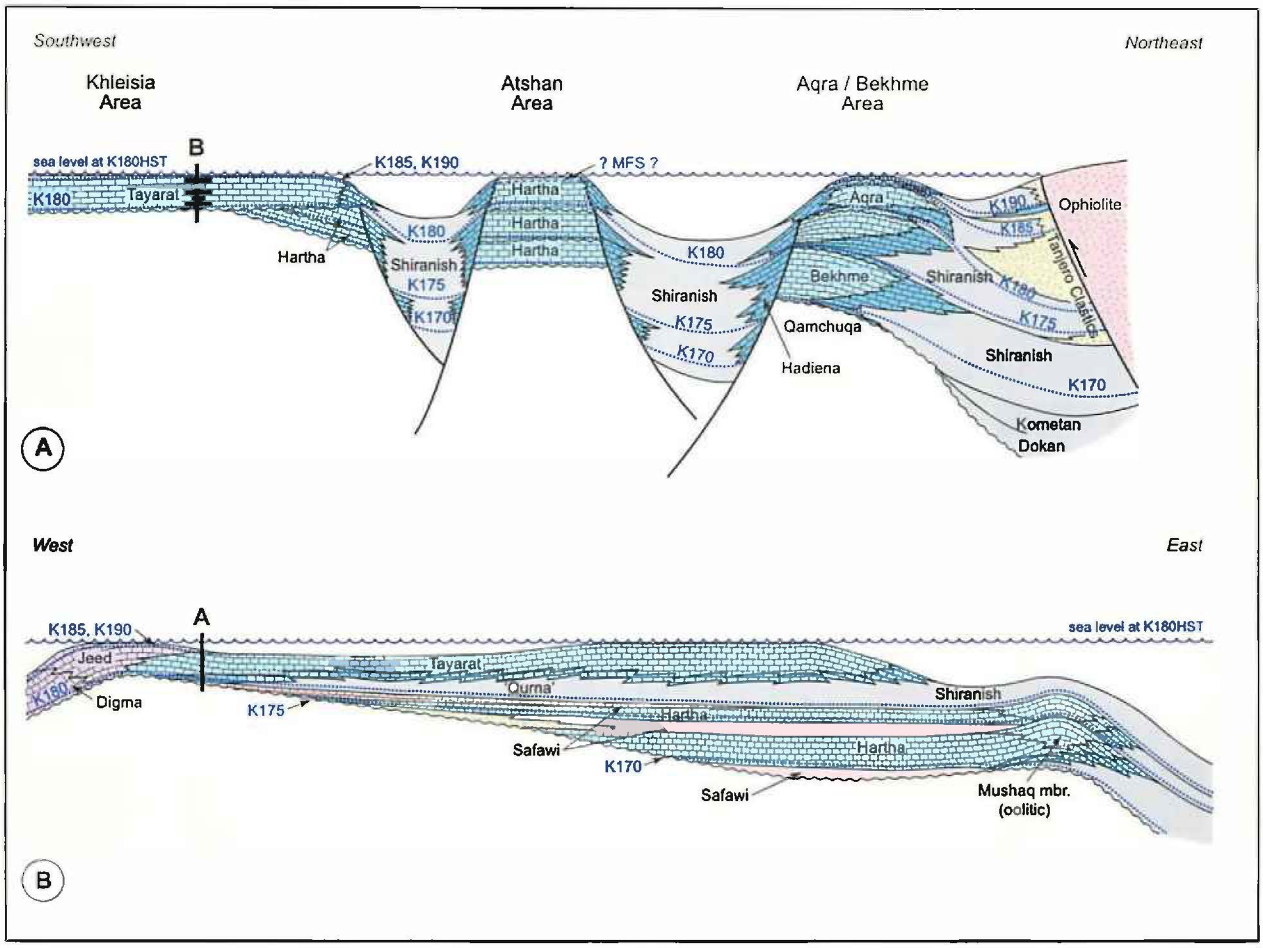


Fig. 7. 53. Schematic west-east profiles across (a) northern and (b) southern Iraq, illustrating the organisation and relative thicknesses of stratigraphic units in Supersequence VI.
Profile (a) shows highs in the west (Khleisia, Rutbah) bordered by deep graben (Sinjar, Ibrahim, Hamrin). Small-scale platforms developed on isolated fault blocks (e.g. Atshan-Alan) and pass via deeper-water areas in the Kirkuk-Ain Zalah axis into highs in front of the foreland basin on which the Aqra-Bekhme platforms developed. Ophiolite obduction on the NE Plate margin resulted in flysch transport into the basin. Profile B shows back-stepping of the carbonate platforms over western and SW Iraq. Progressive onlap occurred in western Iraq where Maastrichtian units overstep pre-Cretaceous stratigraphy. Evaporites (Safawi Formation) are present in intrashelf basins.

Supersequence VI: upper Campanian – Maastrichtian

Major onlap occurs in Supersequence VI; the whole of Iraq was submerged by the Maastrichtian (Fig. 7.52). The supersequence is characterised by strong westerly onlap onto a regional unconformity. Tectonically controlled facies changes occur in northern Iraq (Fig. 7.53).

The Hartha Formation is the main onlapping unit within the supersequence (Fig. 7.54). Over most of the Khleisia High and Stable Shelf, it is overlain by the Shiranish Formation (Dunnington *et al.*, 1959; Sadooni, 1996) which in turn is overlain towards the west and SW by the Tayarat and Digma Formations. These units pass towards the north and east, and locally within deep half-graben, into the Shiranish Formation. Towards the thrust front, the Shiranish Formation passes laterally into the Hadiena/Bekhme/Aqra Formations, which in turn pass NE into the Tanjero Clastic Formation. The Bekhme Formation may onlap units as old as Albian in this area (Plate 7.3).

Supersequence VI is bounded above by a regional unconformity; several hundred metres of strata have been eroded from inverted anticlines (i.e. formerly basinal areas) in northern Iraq (Dunnington, 1955). Uppermost Maastrichtian sediments are generally absent (Kassab, 1972, 1973; Kennedy and Lunn, 2000) (Fig. 7.55). However, recent redefinition (International Commission on Stratigraphy, 2004) of the Campanian–Mastrichtian boundary up into the *gansseri* Zone means that no Maastrichtian deposits (as currently defined) have been preserved in some areas.

Sediments of latest Cretaceous age with *Globotruncana falsocalcarata* (Kassab, 1972, 1975a) only occur in the top of the Tanjero Clastic Formation in Iraqi Kurdistan (in the Chalki and Sirwan Valleys). Danian sediments are absent in

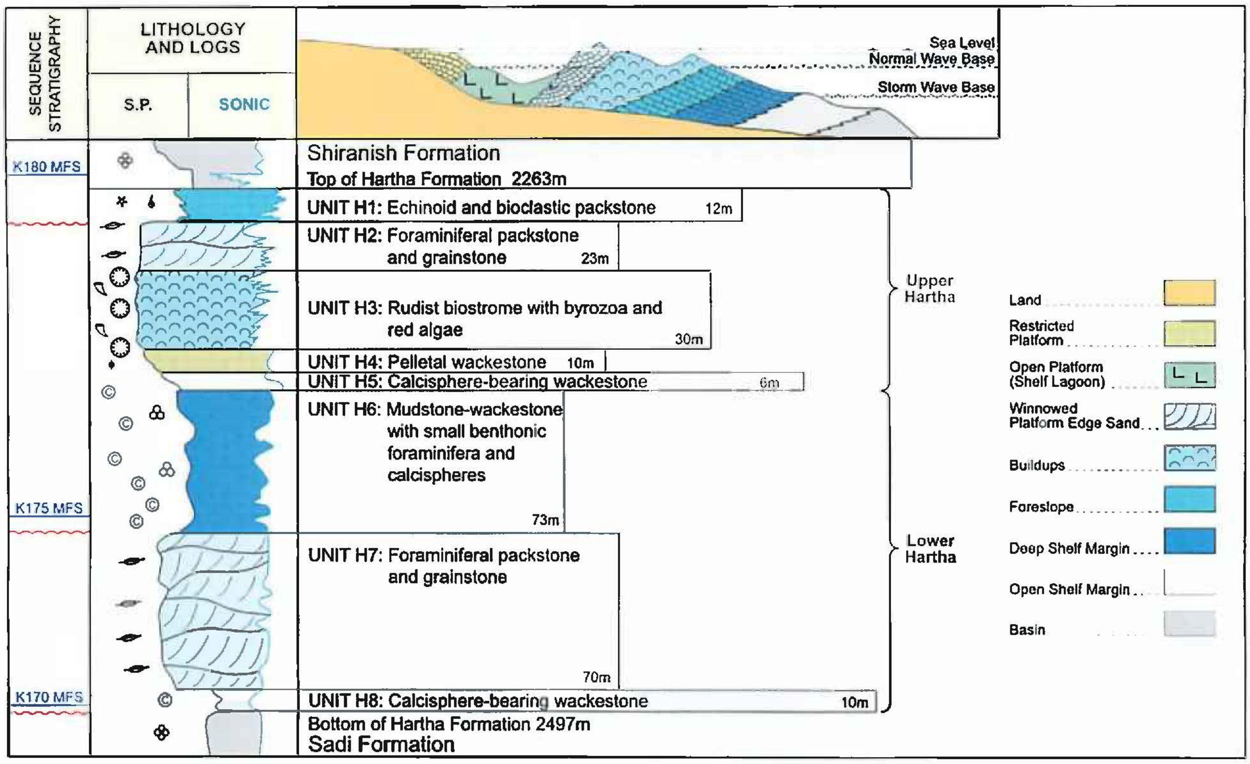


Fig. 7.54. Facies successions within the Hartha Formation at the *Adhab* field, showing two third-order sequences. The K170 and K175 MFSs are characterised by oligosteginal limestones, while highstand deposits consist of shallow-water facies. After Sadooni (1996).

Iraq except from Digma Formation shales in the Western Desert (Jassim and Buday, 2006g) and in the Dokan area of Iraqi Kurdistan (Abdel-Kireem, 1986a).

Deposition of up to 2 km of mostly basinal facies assigned to the Shiranish Formation occurred in narrow pull-apart basins: the Sinjar Trough and Anah Graben (e.g. Dunnington, 1958).

In NE Syria, seismic data indicate that Jebel Abd El Aziz is an inverted Campanian – Maastrichtian half-graben (Kent and Hickman, 1997). Uninverted basins of this age show a complex geometry (c.f. de Ruiter *et al.*, 1995; Caron *et al.*, 2000) (Fig. 3.13).

Formations

Basinal deposits consist of thinly-bedded shales, marls and argillaceous to marly limestones of the **Shiranish Formation** (Figs 7.56-7.59). The formation takes its name from a type section at Shiranish Islam in NW Iraqi Kurdistan. It was first described by Dunnington *et al.* (1959), and later by Al-Qayim *et al.* (1986) and Al-Qayim (1992) (Fig. 7.58). The formation occurs in the subsurface in both northern Iraq (Al-Naquib, 1960; Hart and Hay, 1974) and in the south (Owen and Nasr, 1958; Al-Naqib, 1967).

At its type locality, the formation consists of early Maastrichtian (now late Campanian) limestones overlain by middle-late Maastrichtian marls (argillaceous foraminiferal wackestone) (Al-Qayim *et al.*, 1986; Al-Qayim, 1992; Kassab, 1973) (Fig. 7.58). Dunnington *et al.* (1959) dated the base of the formation as latest Campanian, although a Maastrichtian age was given for the entire section by Al-Qayim *et al.* (1986) and Al-Qayim (1992); these ages probably require revision following the International Commission on Stratigraphy (2004). At the type locality, the formation passes conformably and gradationally down to the Bekhme Formation, and is overlain by the silty shales and thin sandstones of the Kolosh Formation (Al-Qayim *et al.*, 1986). Elsewhere in northern Iraq, the formation is overlain by the Paleogene Aaliji Formation, often with a marked hiatus (Dunnington, 1955; Hart and Hay, 1974).

To the SE at Dokan, the formation consists of marls with a diverse Campanian planktonic foraminiferal assemblage, overlain by early to middle Maastrichtian shales (Abawi *et al.*, 1982). The formation rests disconformably on the Turonian Kometan Formation (Abdel-Kireem, 1983, 1986a). The fauna is dominated by non-keeled (globigerinid) foraminifera (*Rugoglobigerina*, *Globigerinelloides* and *Heterohelix*: Abdel-Kireem, 1983) indicating deposition in an outer shelf environment in about 200 m water depth. Two intervals containing keeled planktonic foraminifera may be flooding surfaces (Abdel-Kireem, 1983), possibly the K175 and K180 MFSs of Sharland *et al.* (2001).

At the *Ain Zalah* field in NW Iraq, the Shiranish Formation comprises marly and shaly limestones

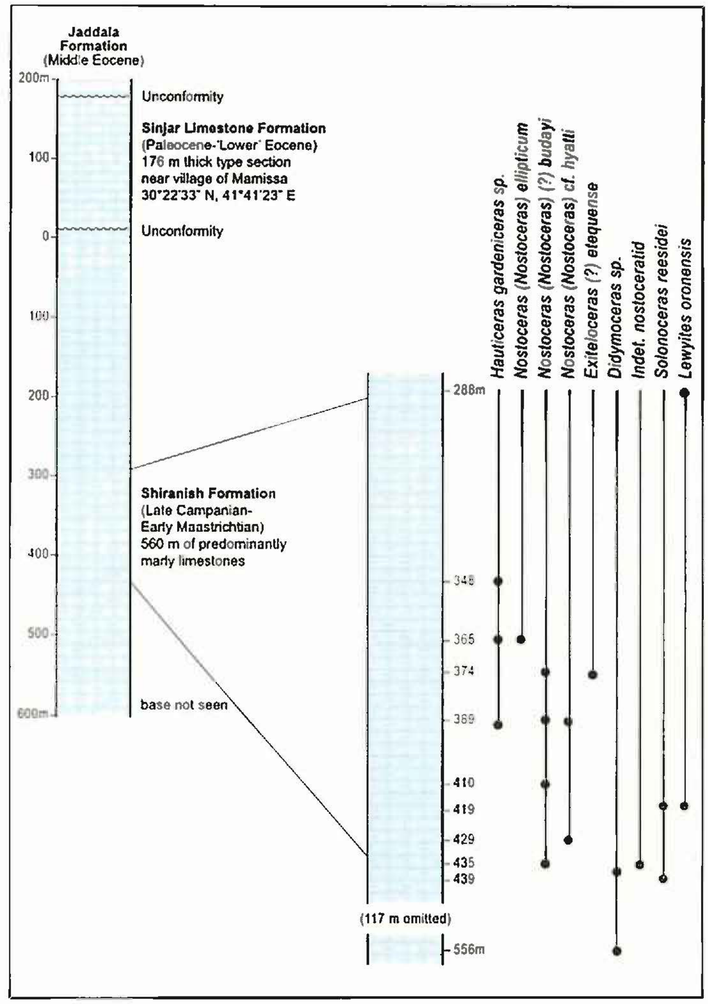


Fig. 7.55. Stratigraphy of the uppermost Cretaceous and basal Paleogene on Jebel Sinjar. The considerable hiatus (cited in the original publication as middle Maastrichtian — Danian, but probably including all the Maastrichtian and Danian) is also typical of many subsurface anticlines in NW Iraq. After Kennedy and Lunn, 2000.

The interval from 0 to -288 m is undated in terms of ammonite control (Kennedy and Lunn, 2000). However Dunnington *et al.* (1959) noted that "the larger part of the Maastrichtian is absent from the Sinjar area", but that the lower Maastrichtian is "thickly represented" and can be dated by ammonites.

(Hart and Hay, 1974; El Zarka, 1993). At Sulaimaniya, the formation includes a 200 m thick interval of marls and marly limestones dated as middle (now probably early) Maastrichtian based on a foraminiferal assemblage dominated by *Globotruncana*, *Bolivina*, *Heterohelix*, *Neoflabellina* and *Reussella* (Al-Shaibani, 1973).

At Shaqlawa (Wadi Hirjan), the Shiranish Formation rests unconformably on the Qamchuqa Formation (Yahya and Al-Shammary, 1993). In the subsurface, the formation overlies the Hartha Formation or Turonian - early Campanian units (Owen and Nasr, 1958; Dunnington *et al.*, 1959; Hart and Hay, 1974; Al-Jumaily and Domeci, 1976: Fig. 7.26; Al-Rawi *et al.*, 1980: Fig. 7.20; Sadooni, 1996: Fig. 7.54).

In NE Iraq near the thrust front, deposition of the Shiranish Formation was terminated by the diachronous entry of coarse clastics of the Tanjero Formation (Dunnington, 1955). Deposition of the Tanjero Formation began in the late (now probably middle) Campanian at Sirwan (Dunnington *et al.*, 1959; Abdel-Kireem, 1986b), and in the middle (now probably early) Maastrichtian at Dokan to the NW (Abdel-Kireem, 1983). Towards the basin centre, the middle (now early) Maastrichtian was marked by the appearance of resedimented carbonates within the Shiranish Formation (El-Anbaawy and Sadek, 1979; Al-Qayim *et al.*, 1986; Al-Qayim, 1992) (Figs 7.58, 7.59).

At outcrops in Iraqi Kurdistan, the Shiranish Formation is 100 to 400 m thick (Abdel-Kireem, 1986a; Al-Qayim *et al.*, 1986; Al-Qayim, 1992). It is 704 m thick at the *Ain Zalah* field (Hart and Hay, 1974; El Zarka, 1993), and more than 1500 m thick in the Sinjar Trough at well *Sasan-1* in NW Iraq (Al-Jumaily and Domaci, 1976; Fig. 7.26b) and in the Anah Graben (Dunnington *et al.*, 1959; Jassim and Buday, 2006f). Significant thickness variations may occur in western Iraq, and the formation thickens from 50 m on the western rim of the Ga'ara depression to 426 m in well *KH 7-12* (Jassim and Buday, 2006f).

Within the Shiranish Formation,several shallow-water intervals occur. For example at the type locality (Al-Qayim, 1992) (Fig. 7.58), the middle 20 m of the formation comprises alternating marly calcarenitic/sandy limestones (15-80 cm) and marls (50-250 cm). The limestones thicken-up and have sharp bases and gradational tops, and have a shallow-marine fauna including benthic foraminifera and a *Teichichnus* ichnofacies. This has been interpreted as a tempestite succession (Al-Qayim *et al.*, 1986; Al-Qayim, 1992). Bioclasts

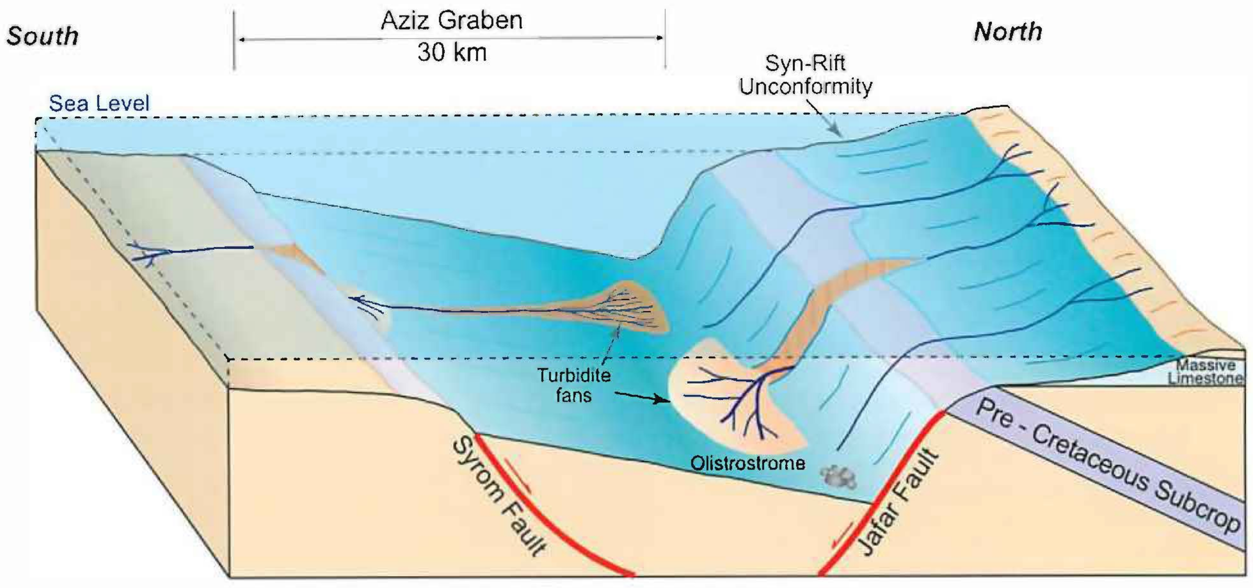


Fig. 7.56. Schematic model for the deposition of the Shiranish Formation and associated olistostromes in NE Syria. After Kent and Hickman, 1997.

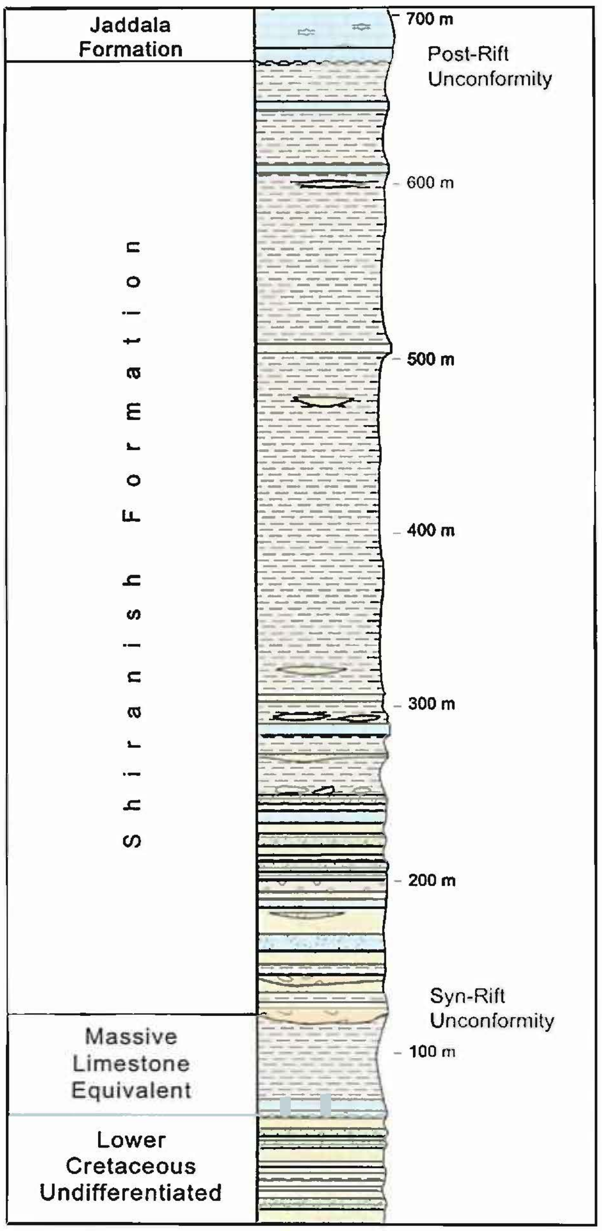


Fig. 7.57. Measured lithostratigaphic column through the Shiranish Formation at Jebel Abd El Aziz, Syria (Kent and Hickman, 1997). This is a basinal succession in which clastic sediment has been derived locally from the erosion of footwall highs. Higher in the stratigraphy, clastic input may be related to sea-level lowstands or further pulses of footwall uplift.

include rudist fragments of coarse to fine sand grade, together with algae, pelecypods and crinoids (Al-Qayim *et al.*, 1986). At Jebel Sinjar, Al-Rawi (1973) recorded a similar unit in the middle of the Shiranish Formation comprising alternating marls and sandy limestones with sole marks and graded bedding interpreted as a turbiditic unit. In the same location, El-Anbaawy and Sadek (1979) recorded relatively thin, shallow-marine intervals within a mainly pelagic succession (Fig. 7.59). Dunnington *et al.* (1959) recorded conglomerates in the same succession. Along strike to the west at Jebel Abd El Aziz in Syria, Fairbridge and Badoux (1960) and Kent and Hickman (1997) recorded the presence of olistoliths, indicating syndepositional faulting, comprising rocks as old as Tournaisian within the Shiranish Formation (Figs 7.56, 7.57).

In the Erek Graben, Syria, Supersequence VI comprises the late Campanian – early Maastrichtian Erek Formation (100 – 750 m of dark brown – black argillaceous limestones and beds of recrystallised sparry limestones); the early Maastrichtian Lower Shiranish Formation (400-1000 m of brown argillaceous lime mudstones and wackestones overlain by white limestones (Tayarat Formation); and the late Maastrichtian (Upper Shiranish Formation): 200–700 m of argillaceous lime mudstones and wackestones, marl, and thin glauconitic packstones (Caron *et al.*, 2000).

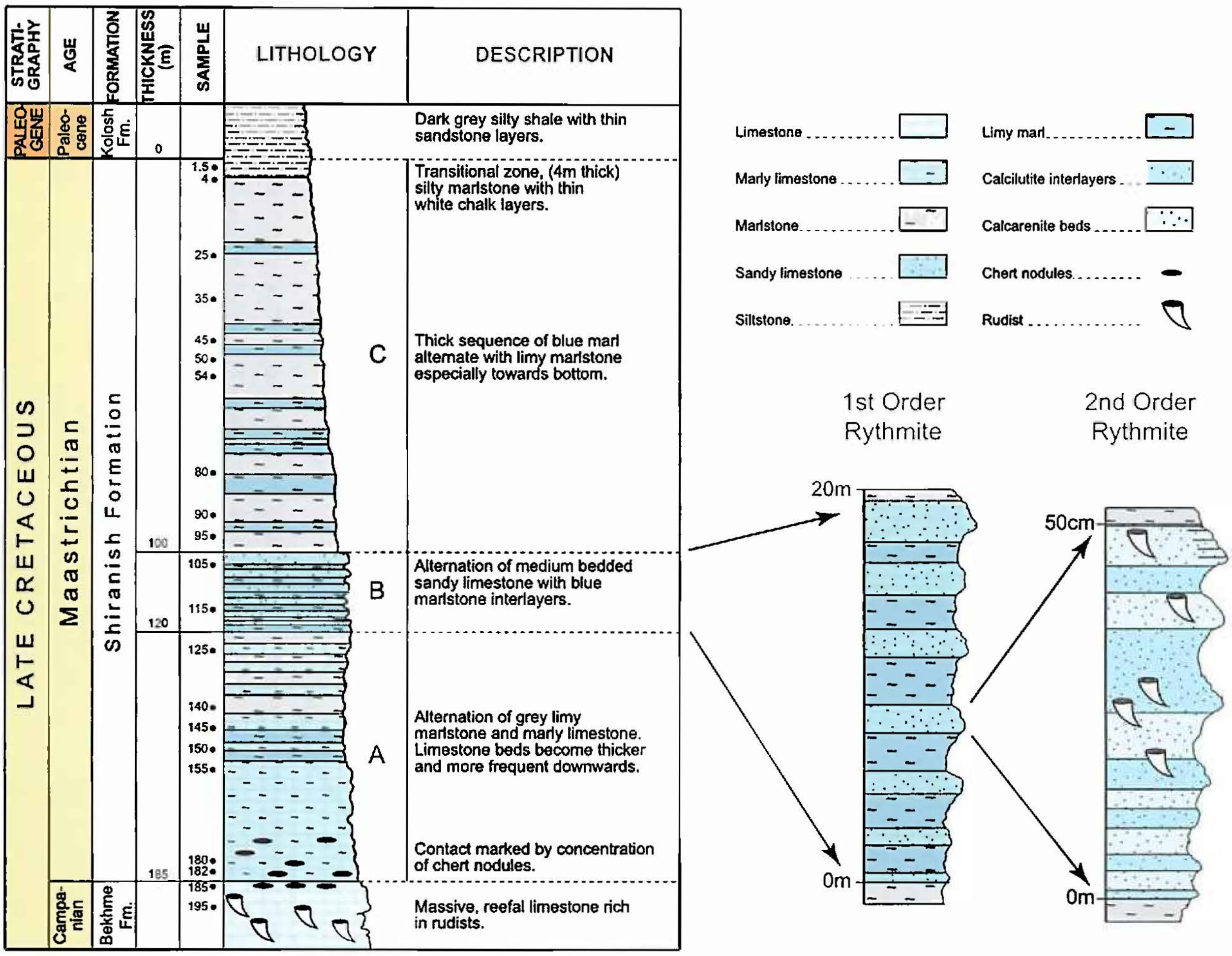


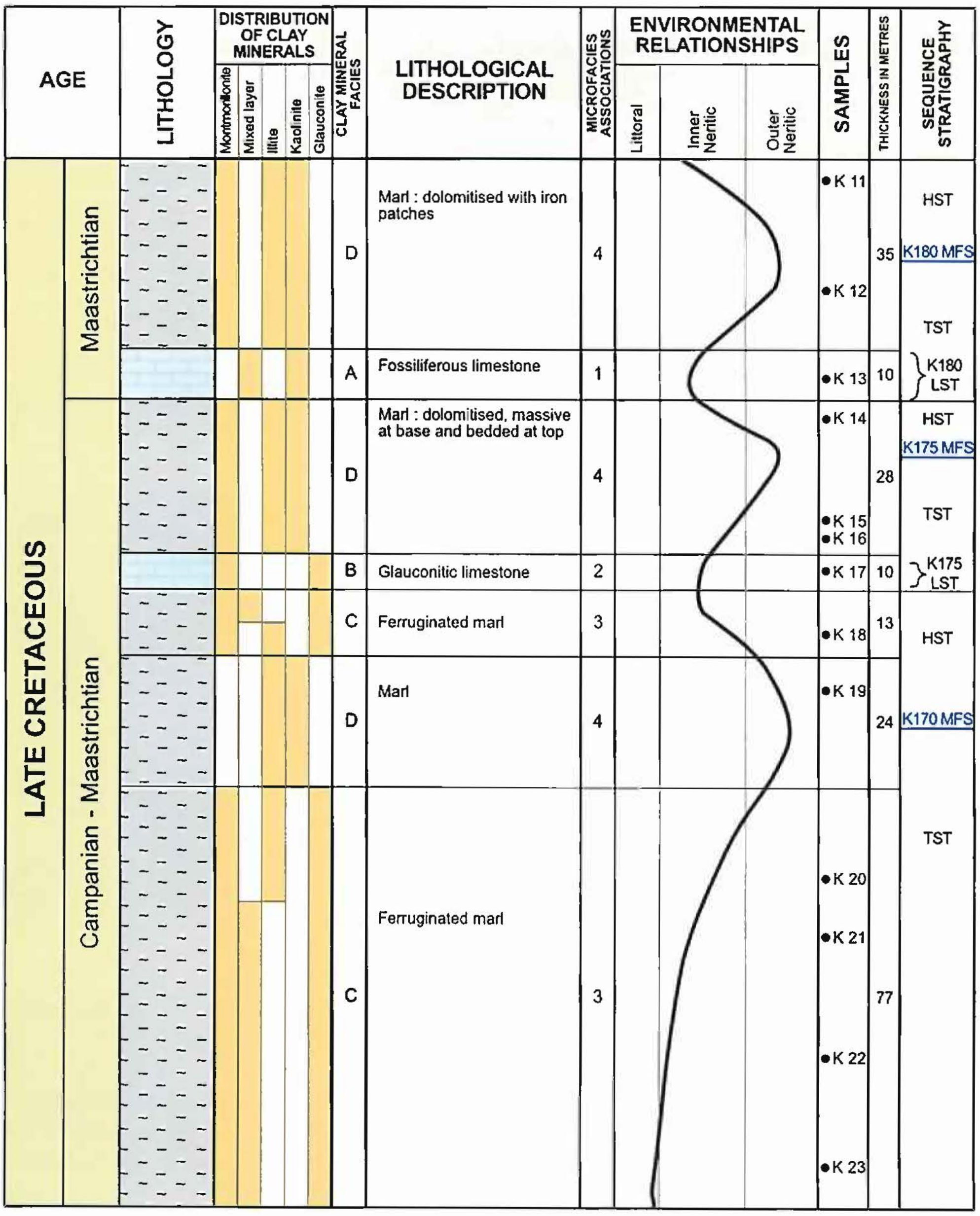
Fig.7.58. Stratigraphic column for the Shiranish Formation at its type section at Shiranish Islam, NW Iraqi Kurdistan. From Al-Qayim *et al.* (1986) and Al-Qayim (1992).

Rudist patch reefs in the **Hartha** and **Tayarat Formations** (Dunnington *et al.*, 1959) developed on stable regional highs and fault blocks in central Iraq (Sadooni and Aqrawi, 2000) (Fig. 7.53a). The rudist *Hippurites* is characteristic of the Hartha Formation. Oolitic/ sabkha facies occur in the Salman Zone (Jassim and Buday, 2006f). The Hartha Formation overlies the Rutbah Sandstone Formation of late Cenomanian age in the Western Desert (Jassim and Buday, 2006f).

In Central Iraq, the Hartha Formation is divided into Upper and Lower Members (Sadooni, 1996) (Fig. 7.54) which represent third-order sequences. Sadooni identified eight lithofacies based on petrographic and petrophysical characteristics (Plates 7.14–7.17). These include local rudist biostromal carbonates; echinoderm-rich packstones and grainstones with shallow-water larger foraminiferal shoal facies; and peloidal facies separated by deeper-water marly and fine-grained muddy carbonates. The formation is interpreted as an open platform deposit in central Iraq (Fig. 7.60). To the east, the formation passes into basinal facies of the Shiranish Formation; the transition is observed in the *Abu Ghirab* field (Jassim and Buday, 2006f).

In southern Iraq, the Hartha Formation is conformably overlain by a unit of the Shiranish Formation (referred to as the Qurna Formation by Owen and Nasr, 1958), which is assigned to the *gansseri* Zone of (now) latest Campanian age (Darmoian,1975). The Hartha Formation contains oolitic facies at *Luhais* and *Rachi* in southern Iraq, in the *Makhul* area (Mushaq Oolite Member of Dunnington *et al.*, 1959), and at the *Alan* structure (Dunnington *et al.*, 1959; Jassim and Buday, 2006f). Supratidal facies often occur to the west of the oolite belt (Jassim and Buday, 2006f). Around the Khleisia High, the Hartha Formation and its equivalents in eastern Syria are composed of reefal facies (Dubertret, 1966; Jassim and Buday, 2006f).

The Hartha Formation has been identified at outcrop in the Rutbah area of the Western Desert, where it is 30-160 m thick (Jassim *et al.*, 1984; Jassim and Buday, 2006f). The thickest section comprises 30 m of basal conglomerates, cross-bedded sandstones and highly fossiliferous limestones with *Hippurites;* these are overlain by 70 m of grey dolomites and pale grey argillaceous dolomites and argillaceous dolomites; and finally by 60 m of light grey fossiliferous dolomites with yellow fossiliferous marls and argillaceous



LEGEND

CLAY MINERAL FACIES

A. Kaolinite - mixed layer facies
B. Montmorillonite - glauconite facies
C. Montmorillonite - illite or mixed layer glauconite facies
D. Montmorillonite - illite - kaolinite facies

MICROFACIES

1. Orbitoid biosparite
2. Glauconitic biosparite
3. Glauconitic biomicrite
4. Planktonic biomicrite

Fig. 7.59. Stratigraphy of the Shiranish Formation at Jebel Sinjar showing input of clastic sediment and platform debris during lowstands. After El-Anbaawy and Sadek, 1979.

limestones (Jassim *et al.*, 1984). These carbonates thin and pass into marls towards the east. The formation is only 75 m thick about 35 km south of Rutbah. Within the thicker shelfal facies are 10-15 m thick cycles of sandstones passing up into shale, capped by limestones and dolomites. The sandstones wedge-out towards the SE (Jassim and Buday, 2006f). Fenestral fabrics dominate the carbonates within the Hartha Formation of the Western Desert. This suggests an overall supratidal depositional environment.

The unit now known as the **Safawi Formation** was originally described as the 50 m thick Dibs Anhydrite Member of the Pilsener Formation (Dunnington *et al.*, 1959). It was first formally named and described by Al-Naqib (1967) from well *Safawi-1*. The formation occurs in the Makhul-Najaf-Safawi area of the Stable Shelf (Jassim and Buday, 2006f). It probably represents lowstand deposition in a poorly-defined intrashelf basin, similar to the Najaf Intrashelf Basin in which the older (mid-Turonian) Kifl Formation was deposited.

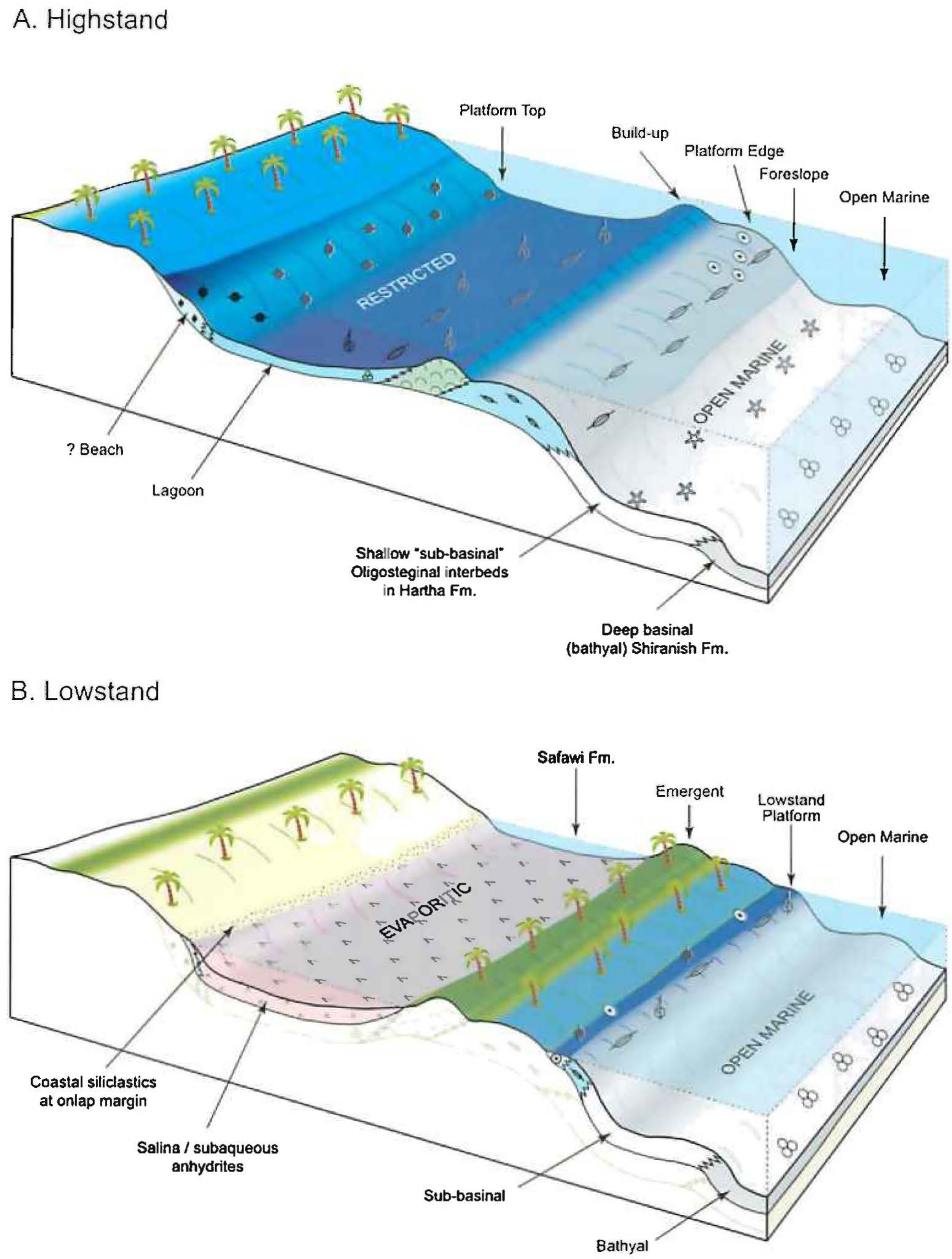


Fig. 7.60. Depositional model for the Hartha, Safawi and Qurna/Shiranish Formations in central Iraq. A: highstand facies; B: lowstand facies. After Sadooni, 1996.

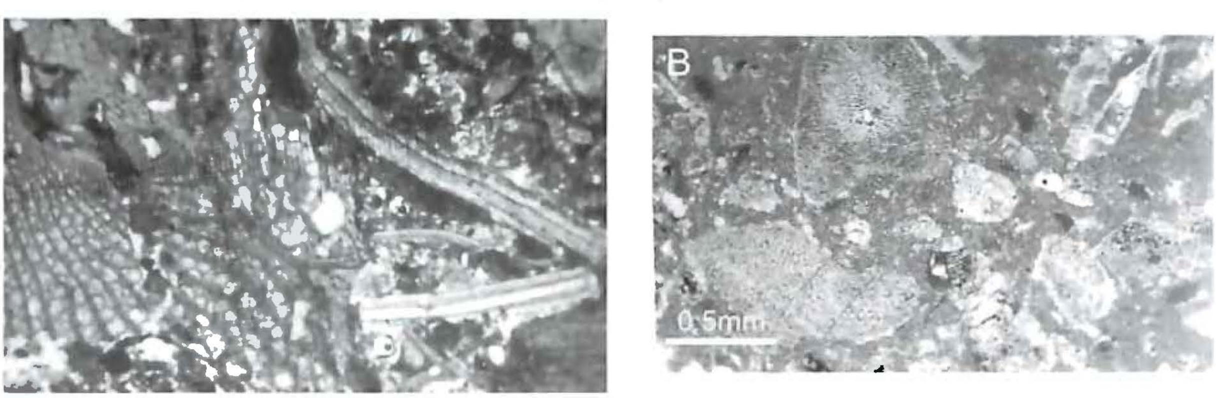
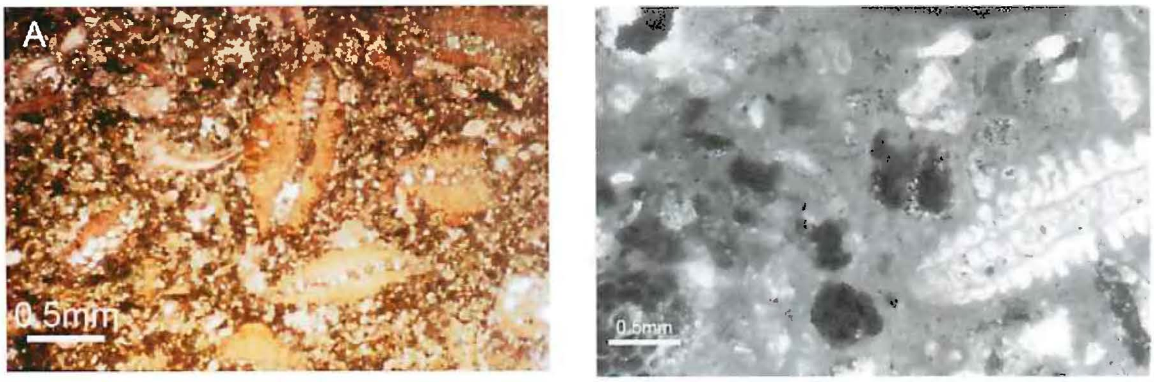


Plate 7.14. Microfacies of the Hartha Formation (photos by F. Sadooni).
(a) (left). Biostromal rudstone/grainstone (X nicols). Well *East Baghdad-2*, depth 2012 m.
(b) right). Packstone dominated by echinoderm debris. Well *East Baghdad-3*, depth 1698 m.



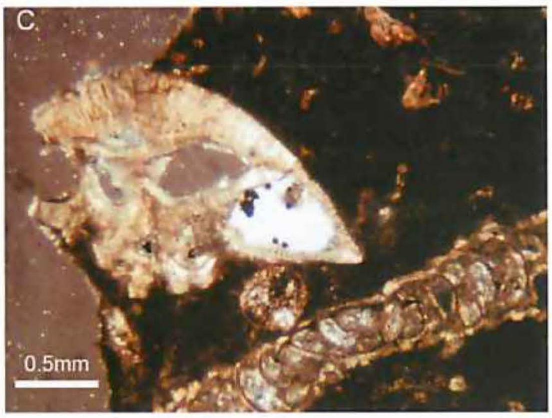


Plate 7.15. Photomicrographs of Hartha Formation foraminiferal grainstones (all X nicols). From Sadooni, 1996.

(a) *Monolepidorbis,* the most abundant large foraminiferal species in both the Lower and Upper Hartha. Well *East Baghdad-5,* 2267 m.
(b) *Sirritina* sp., the second-most abundant foraminifer in the Hartha Formation. Well *East Baghdad-6,* 2086 m.
(c) Thick-walled rotaliid and fragments of *Monolepidorbis.* Well *East Baghdad-5,* 2267 m.

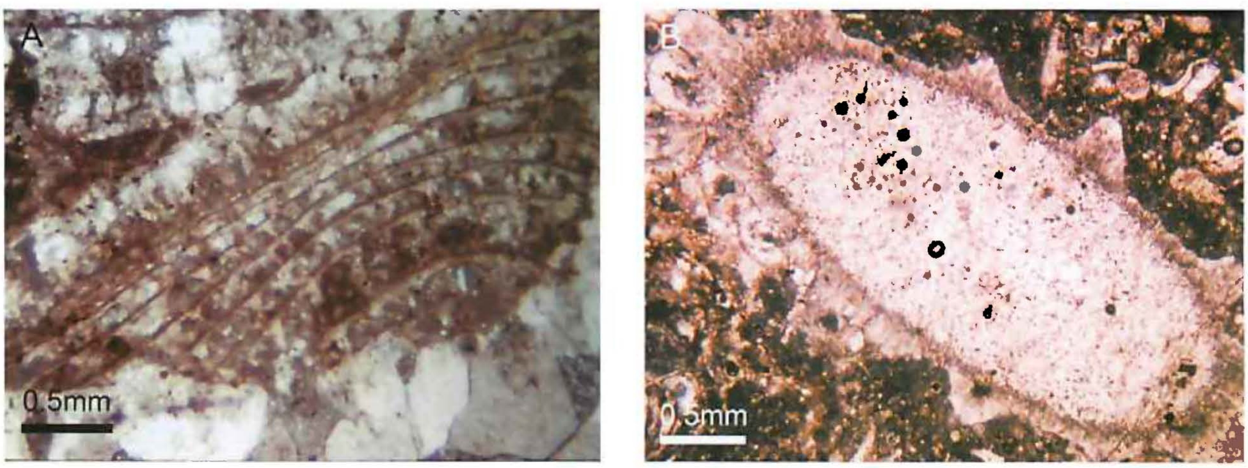


Plate 7.16. Diagenetic fabrics in the Hartha Formation (photos by F. Sadooni).
(a) (above left). Large rudist fragment surrounded by granular calcite cement. Well *East Baghdad-7,* depth 1766 m (from Sadooni, 1996).
(b) (above right) Echinoderm fragment. Well *East Baghdad-9,* depth 2267 m.

Plate 7.17. Cores recovered from the Hartha Formation in well *East Baghdad-4* showing the abrupt transition from the friable, greyish marls of unit H1 to white-grey foraminiferal limestones (unit H2) and rudist limestones (Unit H3). From Sadooni, 1996.

The **Tayarat Formation** is restricted to the Salman Zone and areas to the west. It is 48 m thick at its type locality in the Western Desert, and consists of basal conglomerates, siliciclastics and upper sandy carbonates with the foraminifera *Loftusia* (Dunnington *et al.*, 1959). Uppermost dolomitic conglomerates with geodes and chert concretions (Jassim and Buday, 2006f) may indicate a former evaporitic facies capping the formation. Towards the north, oyster limestones occur along the western rim of the Ga'ara depression, and charophyte-bearing limestones occur along the depression's northern rim (Jassim and Buday, 2006f).

The Tayarat Formation marks the final development of the Cretaceous shelf system. It unconformably overlies older units along the NW rim of the Ga'ara depression where the Hartha and Shiranish Formations have been cut out. Channelised conglomerates are present at this location at the base of the overlying Tayarat Formation (Jassim and Buday, 2006f).

In the Western Desert, the Tayarat Formation contains phosphate beds (Jassim and Buday, 2006f); the content of phosphate and chert increases in the semi-isolated Anah and Tinif Basins. The upper part of the Tayarat and Shiranish Formations passes into the **Digma (or Jid) Formation** which is 35 m thick in Wadi Jeed (Jassim and Buday, 2006f). The Digma consists of yellow marls with beds of *Lopha*-bearing limestone, especially near the top of the succession, for example on the Butte of Radhuma Safra in the Western Desert (pictured on the front cover of Jassim and Goff, 2006a). The formation contains a benthic fauna with some planktonic species (Amer, 1977). This phosphatic unit is interpreted to indicate an upwelling system.

During the late Campanian – Maastrichtian, a foreland basin developed in northern Iraq along the Zagros margin; its depocentre is dominated by the Tanjero Flysch Formation *(see below)*. An isolated carbonate platform comprising the **Aqra** and **Bekhme Formations** developed within the clastic-starved parts of the foreland basin to the SW. The Bekhme Limestone rests approximately along the isopach thick of the Qamchuqa Formation.

The **Aqra Limestone Formation** was first described by Dunnington *et al.* (1959) from NE Iraqi Kurdistan at exposures between Rowanduz (Greater Zab River) and the Hazilso River near the Iraq – Turkey-Syria border (Al-Ameri and Lawa, 1986). The formation has been studied in greatest detail at its type section at Aqra (Geli Sheikh Abdul Aziz). It is dated as Maastrichtian throughout (Dunnington *et al.*, 1959; Al-Rawi and Al-Hamadani, 1985; Al-Omari *et al.*, 1989). The formation usually overlies the Bekhme Limestone Formation although locally it rests on the Shiranish Formation (Dunnington *et al.*, 1959). At its type section, it is disconformably overlain by the Kolosh Formation which is dated as late Paleocene at its base (Al-Omari *et al.*, 1989). The Kolosh Formation is only 8 m thick, and represents a transgressive lag beneath the much thicker Khurmala Formation lagoonal carbonates (Al-Rawi and Al-Hamadani, 1985; Al-Omari *et al.*, 1989).

The Aqra Limestone Formation has been divided by different authors into between seven and nine rock units at its type locality with a total thickness of about 700 m (Fig.7.61; Plate 7.18). It contans several upwards-coarsening and/or upwards-shallowing cycles that pass from fore-reef, reef and reef flat to back-reef and lagoonal facies (Henson, 1950a). Al-Rawi and Al-Hamadani (1985) recorded an influx of planktonic foraminifera associated with fore-reef facies at the base of the uppermost sequence in the Geli Sheikh Abdul Aziz section. This may represent a new "K190" MFS, and may be equivalent to an uppermost Maastrichtian black shale which rests directly above the Tayarat Limestone in SW Iraq (Al-Naqib, 1967). The lowermost unit exposed at the type section includes deeper-water facies. This and the underlying Shiranish Formation may represent early HST deposits above the K180 MFS of Sharland *et al.* (2001). Identification of the deeper-water units assists correlation along-strike between outcrops at Aqra and Geli Zinta, 10 km to the SE (Al-Rawi and Al-Hamadani, 1985) (Fig. 7.62).

The Aqra Limestone fauna is dominated by rudists (Hanna *et al.*, 1993a,b: Plate 7.19) and the mega-foraminifera *Loftusia* (Kureshy, 1969; Al-Rawi and Al-Hamadani, 1985), together with calcareous algae (dascycladacean and some codiacean genera: Elliot, 1958; Al-Omari *et al.*, 1989). From the fauna present, Al-Ameri and Lawa (1986) constructed a depositional model which is similar to that of the present-day Bahamian platforms (Fig. 7.63). The model includes: fore-reef facies with rudist detritus, red algae and orbitoid foraminifera; reef crest deposits with large *in situ Durania* and *Hippurites* rudists together with smaller *Radiolites* and associated encrusting and boring biota; reef flat/patch reefs with smaller and broken *Eoradiolites* and *Bioradiolites* rudists, together with *Loftusia* and the gastropods *Acteonella* (a rudist predator) and *Trochus*; and lagoonal deposits with variable restriction indicated by a transition from a miliolid- into an algal-(dascycladacean) dominated microfacies.

A siliceous unit in the upper part of the succession (Al-Rawi and Al-Hamadani, 1985; Al-Omari *et al.*, 1989) indicates an input of clastic material, perhaps from the NE. The great thickness and relatively narrow age-range of the formation suggest high rates of subsidence (Al-Rawi and Al-Hamadani, 1985), with progressive infill of accommodation and platform aggradation as a result of the high productivity of the carbonate depositional system.

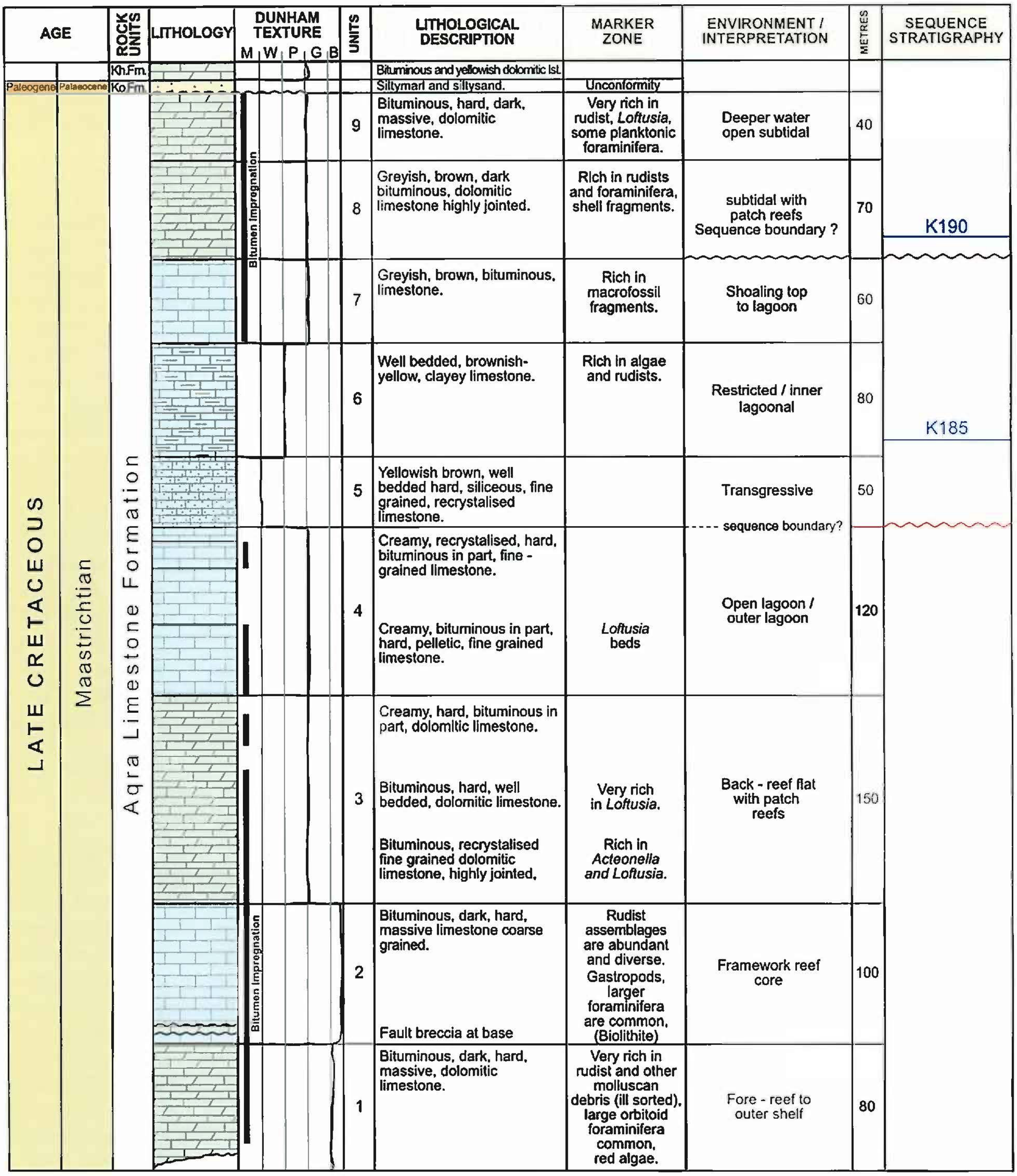


Fig. 7.61. Details of the Aqra Formation stratigraphy at Geli Sheikh Abdul-Aziz near Aqra, Iraqi Kurdistan. After Al-Rawi and Al-Hamadani, 1985; Al-Ameri and Lawa, 1986; Al-Omari *et al.*, 1989; and Hanna *et al.*, 1993a,b.

The diagenesis and porosity evolution of the Aqra Limestone have not been studied. The unit's upper contact is marked by a 2 m breccia that may indicate karstification. The formation is locally dolomitic and siliceous. Dolomitisation and recrystallisation are more intense to the SE towards Geli Zinta (Al-Rawi and Al-Hamadani, 1985). The upper ca. 180 m is bituminous (Dunnington *et al.*, 1959; Al-Rawi and Al-Hamadani, 1985), and bitumen also occurs lower in the formation (Al-Rawi and Al-Hamadani, 1985) (Fig. 7.62).

Mutwali *et al.* (2008) described conglomerates of the "**Bekhme Formation**" interbedded with deep-water Shiranish Formation facies in the Dohuk area. El-Anbaawy and Sadek (1979) recorded beds of orbitoid biosparites and/or glauconitic packstones within the thick Shiranish Formation at Jebel Sinjar (Fig. 7.59). These facies may be slope deposits or a lowstand fringing platform. They are comparable to the older (lower Campanian) "slope breccia"/ lowstand shelf facies described by Nikolaevskiy (1972) in NE Syria (Fig. 7.40).

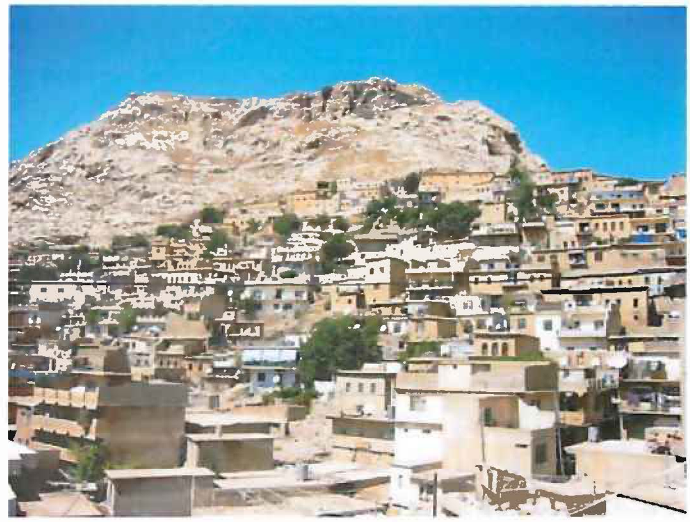


Plate 7.18. View of the town of Aqra in Iraqi Kurdistan, some 90 km north of Mosul. Above the town is a ridge of reefal Aqra Limestone. Photo by A. Aqrawi.

Plate 7.19. Close-up field photograph of weathered rudists in the Aqra Formation near Aqra, Iraqi Kurdistan. Pen for scale. Photo by A. Aqrawi.

To the north of the Aqra-Bekhme platform at the Ora anticline, the **Hadiena Formation** is 750 m thick. The formation comprises a basal dolomitic limestone (which is undated but may be as old as Cenomanian), overlain by silty marls and argillaceous sandy limestones containing phosphates, conglomerates and breccias. The upper portion consists of conglomerates and breccias with angular fragments of haematite (Dunnington *et al.*, 1959; Jassim and Buday, 2006f). The formation possibly unconformably overlies the Chia Gara, Barsarin and Naokelekan Formations. It is probably overlain by the Aqra Formation containing rudist build-ups (Hamza and Isaac, 1971, *in* Jassim and Buday, 2006f). Planktonic microfossils occur in the middle and upper part of the formation (Jassim and Buday, 2006f).

The unconformity at the base of this formation may have formed as a result of the emplacement of ophiolitic thrust sheets in NE Iraq (Jassim and Buday, 2006f). These allochthonous units are equivalent to the better-studied Koçali and Karadut thrust sheets along the Tauride margin of SE Turkey which were emplaced during deposition of the Campanian to early Maastrichtian Kastel Formation (Sungurlu, 1974). The thrust sheets in Turkey are overlain by platform carbonates of the mid-upper Maastrichtian Besni Formation (Özer, 1993).

At its type section at Sirwan near Halabja in NE Iraqi Kurdistan, the **Tanjero Formation** is divided into two members: a lower unit consisting of globigerinal marls with rare limestones and siltstones, 484 m thick; and an upper unit comprising silty marls, silstones, conglomerates and sandy or silty bioclastic to reefal limestones, up to 2010 m thick and dated as latest Campanian – latest Maastrichtian (Kassab, 1975a). In places, the lower member is similar to the upper Shiranish Formation into which it passes gradationally and diachronously (Abdel-Kireem, 1983).

The Tanjero Formation is exposed on the flanks of the Pir-i-Mugurun and Surdash anticlines, and elsewhere in the Foothills Belt in NE Iraq (Plate 7.20). At Dokan, the basal part of the formation is a sandy glauconitic marl to glauconitic sandstone (Abdel-Kireem, 1983). At Dokan the formation can be divided into three units (Abdel-Kireem, 1986a): (i) an upper unit (124 m) composed of sandy bioclastic limestones, silty shales and graded sandstones; (ii) a middle unit (209 m thick), with chalky marls with abundant planktonic

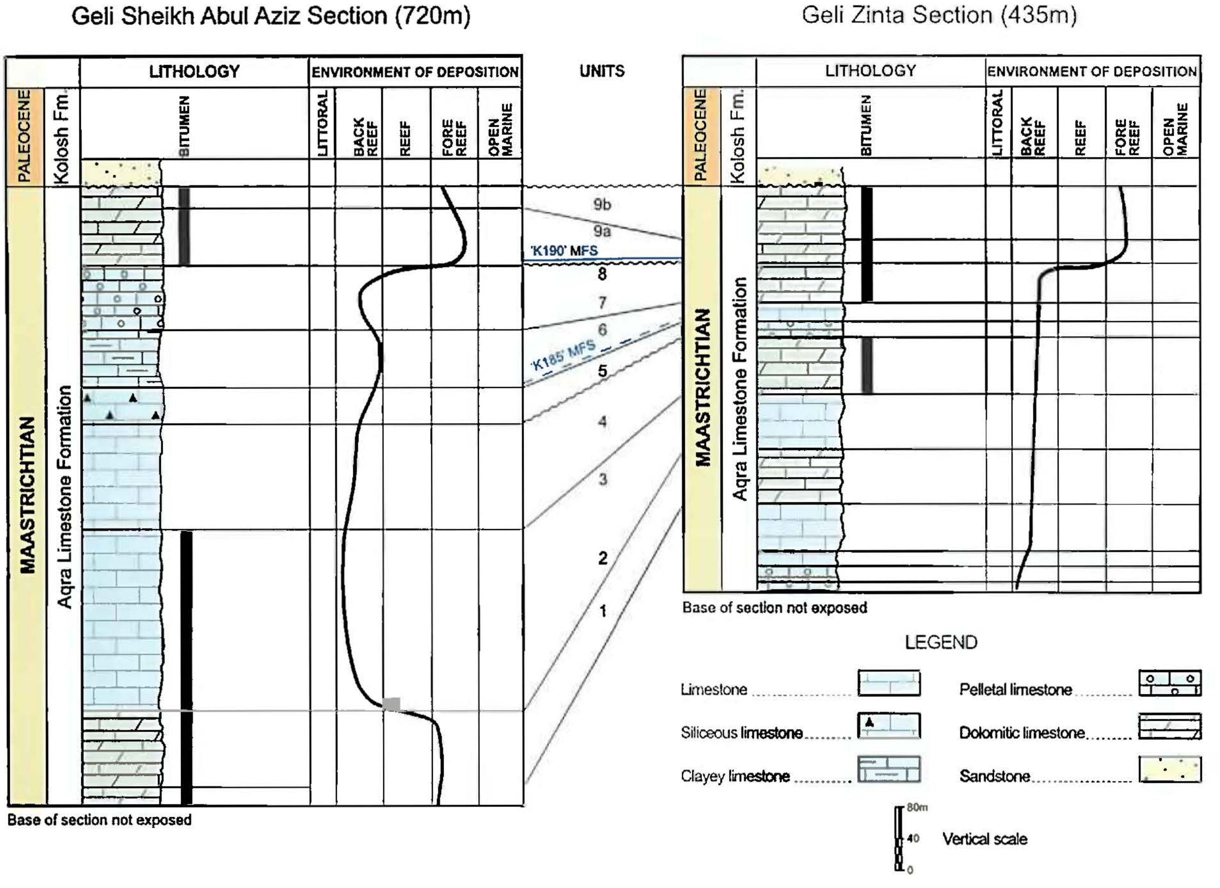


Fig. 7.62. Correlation of the two principal sections of the Aqra Limestone – at Geli Sheikh Abdul Aziz (a, left) and Geli Zinta (b, right), which are about 10 km apart. Note the regularity of the stratigraphy on the plaform top, and the presence of young (K185, K190) MFSs of late Maastrichtian age. After Al-Rawi and Al-Hamadani, 1985.

Plate 7.20. Greenish grey flysch sediments of the Tanjero Formation (at foot of slope) exposed at the town of Jundian, near Rawandoz, northern Iraqi Kurdistan. Photo by A. Aqrawi.

foraminifera; and (iii) a lower unit (460 m thick) composed of green marls and siltstones interbedded with fine-grained siliceous sandstones (beds 10 to 100 cm thick). The formation was dated here as late middle Maastrichtian or younger (now redefined as early Maastrichtian) (Abawi *et al.*, 1982).

The uppermost Tanjero Formation consists of sandy limestones with abundant gastropod shells and is overlain by glauconitic, bituminous siltstones of the Kolosh Formation, dated as early Paleocene at the base (Abdel-Kireem, 1986a). Although the *Globotruncana falsocalcarata* subzone is absent at this boundary, the stratigraphic gap appears to be small as the Tanjero Formation is of middle-late Maastrichtian age.

Kassab (1975a) recorded 78 foraminiferal species in the formation, spanning the *Globotruncana aegyptica* subzone (late Campanian) and the *Globotruncana falsocalcarata* subzone (late Maastrichtian). Although Kassab *(ibid.)* described mostly planktonic foraminiferal species, he recorded relatively few planktonics in the lower part of the formation which contained *Orbitoides* sp., *Omphalocyclus macroprous, Loftusia minor* and *Loftusia harisoni.* The upper part yielded a rich fauna of planktonic species with some benthonic foraminifera in silty marls and limestones indicating reef and fore-reef facies. These have been interpreted as lenses of the Aqra Formation (Dunnington *et al.*, 1959).

Petroleum System Components

Al-Sakini (1992) noted that Supersequence VI contains <2% of Cretaceous oil reserves in Iraq. This low figure is probably due to problems with reservoir quality and poor seal integrity.

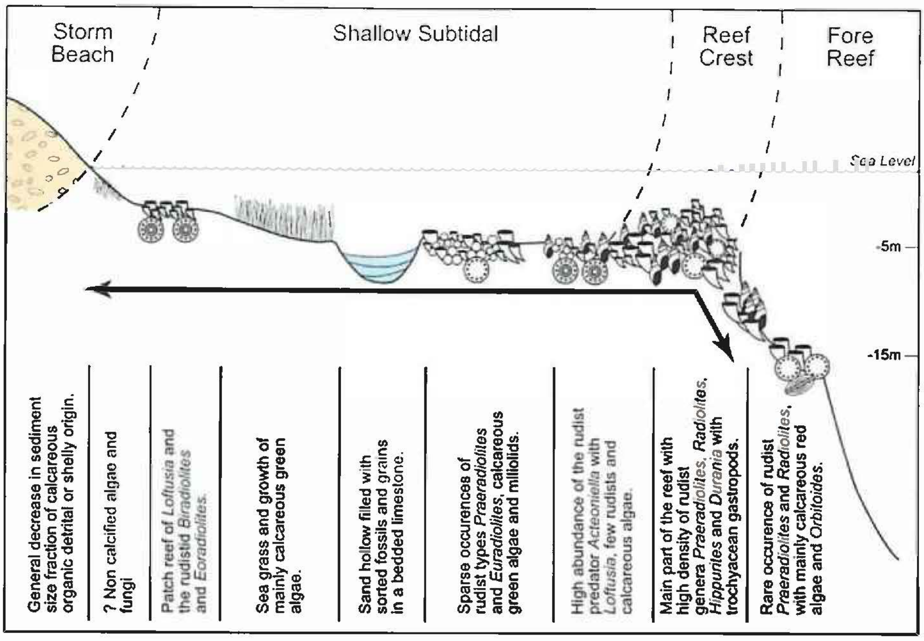


Fig. 7.63. Palaeoecology of the Aqra Limestone Formation and suggested facies belts in the upper Maastrichtian succession. After Al-Ameri and Lawa (1986).

Proven and Potential Reservoir Rocks

Carbonate reservoirs occur in the Shiranish, Hartha and Tayarat Formations in central and northern Iraq. Minor reserves occur in the Hartha Formation. This produced around 700 brl of oil on test from well *Merjan-1* in west-central Iraq. Oil shows have been recorded in the northern parts of the *East Baghdad* and *Ahdab* fields (Sadooni, 1996). Heavy oil occurs in this unit in the *Jawan, Najmah, Qasab* and *Qaiyarah* fields (Dunnington, 1967a).

The Hartha and Tayarat Formations have porosities of up to 21-24% (Jassim and Buday, 2006f). The Hartha and Aqra Limestone Formations have well developed primary and karstic (mouldic, vuggy) secondary porosity (Dunnington, 1967a; Sadooni, 1996). Henson (1950a) noted that fore-reef facies in Iraq are also often porous, particularly at Aqra (Plate 7.19). The Aqra and Bekhme Limestones at outcrop are bituminous. Cavernous porosity occurs where Mesozoic rocks are exposed in the frontal folds of the Zagros fold-and-thrust belt in Iraqi Kurdistan (Dunnington *et al.*, 1959). The Aqra anticline contains a breached Late Cretaceous oil accumulation with up to 1000 m of bitumen-impregnated stratigraphy (Fig. 7.62a).

Production occurs from this interval in adjacent parts of NE Syria and in karstified shelf carbonates in SE Turkey, for example at the *Selmo, Silivanka, Celikli, Magrip, Kurtalan, Garzan, West Raman* and *Raman* fields (Tasman and Egeran, 1952; Dunnington, 1967a; Wagner and Pehlivan, 1987), although accumulations tend to be small compared to those in the Cretaceous Balambo-Gurau Basin. In Iran, the lowstand shelf carbonates of the Lopha Limestone and Emam Hassan Limestone Members of the Gurpi Formation may constitute reservoirs in Lurestan (Bordenave and Burwood, 1990).

Plate 7.21. Outcrop photo of live heavy oil seeping from fractured limestones near Aqra City, Iraqi Kurdistan. Pen for scale. Photo: A. Aqrawi.

The Shiranish Formation forms a reservoir where recrystallised and fractured in anticlinal structures at the *Ain Zalah, Butmah* and in parts of the *Kirkuk* field in northern Iraq (Daniel, 1954; Dunnington, 1967a), and as can be seen in breached anticlines in Iraqi Kurdistan (Plate 7.21). Where it is marly, it tends not to be productive. At *Ain Zalah* field, the formation is fractured and has produced 30,000 b/d oil (Daniel, 1954; Dunnington, 1967a; Hart and Hay, 1974; El Zarka, 1993). Two intervals (136 and 85 m thick) in the fractured Shiranish Formation reportedly tested 17,700 and 13,780 b/d respectively*. Matrix porosities in the Shiranish Formation at *Ain Zalah* range up to 11% (with an average of 3.3% decreasing with depth: El Zarka, 1993). Permeability is low (<0.01 mD: Jassim and Al-Gailani, 2006). In the *Sufaiya* field, average

* *www.gulfoilandgas.com*, 18.3.09.

permeabilities of 13 mD have been calculated, although locally they may be much higher (Jassim and Al-Gailani, 2006). Correlative production is known from the *Karatchok, Rumelan* and *Soueide* fields in nearby parts of NE Syria (Dunnington, 1967a).

Oil has been produced from the fractured Shiranish Formation in the *Butmah* field, and from the Baba Dome of the *Kirkuk* field and the *Bai Hassan* field (Daniel, 1954; Dunnington, 1958, 1967a; Hart and Hay, 1974). These fractured argillaceous limestones and micritic marls form a significant secondary reservoir.

Proven and Potential Source Rocks

Source rocks have not so far been identified in the Shiranish Formation. It is locally bituminous (Dunnington, 1958; Ameen, 1992), but the bitumen may have migrated vertically from deeper source rocks or reservoirs (e.g. at *Butmah* and *Ain Zalah* fields). Further geochemical analyses may show that at least locally, the Shiranish Formation is an oil source rock.

In western Iraq, the Na'aja and Safra Members of the Jeed Formation (upper Campanian – lower Maastrichtian, and upper Maastrichtian, respectively) contain phosphatic units which are described as organic-rich (Al-Bassam and Al-Haba, 1990; Jassim and Al-Gailani, 2006). These were deposited on the flanks of Late Cretaceous fault-controlled basins such as the Damluk and Tinif troughs to the north and west of the Ga'ara High, where upwelling currents connected the deep basins with adjacent shelf areas (Al-Bassam *et al.*, 1983; Al-Bassam and Al-Haba, 1990). Phosphorites form part of a NE-SW trending belt extending for at least 400 km into Saudi Arabia (Turayf Phosphates), then into SE Jordan (Amman Formation: Abed and Amireh, 1999).

The Safra Member has TOC values of 0.3-0.6% and an HI of 263 to 466 mg/gTOC (Al-Bassam and Al-Haba, 1990). Organic material is of marine origin. Organic productivity is interpreted to reflect high nutrient input associated with upwelling and the development of an oxygen-minimum zone at the base of the water column (Al-Bassam and Al-Haba, *ibid.*; Abed and Amireh, 1999). Similar facies are present in well *Anah-1*, where the condensed Digma Formation contains phosphorite and chert (Dunnington *et al.*, 1959). In structures similar to the Anah Graben, these facies may be buried sufficiently deeply to expel hydrocarbons.

In Iran, the Campanian Gurpi Formation forms a local source rock along the central Khuzestan-Lurestan basin margin (Bordenave and Huc, 1995). Here, 40 to 120 m of slightly bituminous marls have TOCs of 1-1.5%, with maximum thicknesses being observed at *Marun* (Bordenave and Huc, 1995). Kerogen is Type II/III. *Rock-Eval* S2 is 2–10 kg/tonne (Bordenave and Burwood, 1990; Bordenave and Huc, 1995). At Qaleh Nar to the NW, the Gurpi marls are 160 m thick and have TOCs of 1.2-1.8%, with an HI of 150 to 200 g HC/kgC, and *Rock-Eval* S2 of 2-3 kg HC/kg rock. Although little information is available from northern Lurestan, it is reasonable to infer that this source rock system continues into SE Iraqi Kurdistan.

At Kuh-e Anaran in Iran, the lower Maastrichtian part of the Gurpi Formation includes 10 to 30 m of marls with mean TOCs of 2.2% (maximum: 4%; Bordenave and Huc, 1995). At *Dehluran* field, a total of 400 m of combined Surgah, Ilam and Gurpi Formations have TOCs ranging from 1.26 to 3% although at least some of this is due to measurement of migrated bitumen (Bordenave and Huc, 1995). The source rock character of the Gurpi marls is interpreted to reflect deposition in an arid climate with poor nutrient supply and probable low phytoplankton productivity. Sinking of heavy surface waters enriched in salt may have caused mixing and oxygenation in all but the deepest parts of the basin (Bordenave and Huc, 1995). This model could apply locally to the Shiranish Formation in Iraq.

In Syria, the upper Campanian – Maastrichtian Erek Marl Formation is a minor oil-prone source rock up to 750 m thick (de Ruiter *et al.*, 1995; Caron *et al.*, 2000). In NE Syria, the Shiranish Formation in well *Zarba-3* (1378-1396 m) had a *Rock-Eval* P1 + P2 yield of 7 kg/tonne (Abboud *et al.*, 2005).

In the Adiyaman area of SE Turkey, the middle Campanian Karabogaz Formation is a phosphatic organic-rich shelfal unit interpreted to have been deposited in upwelling, oxygen-poor and nutrient-rich waters. Source rocks with log-derived TOCs of 0.5-7.8% and Type I and II kerogen were recorded by Wagner and Pehlivan (1987), and TOCs of 0.5-5.86% by Soylu *et al.* (2005). The Karabogaz Formation has an HI of over 300 mg HC/g TOC and appears to be the main source rock for oils reservoired in the Adiyaman area. The overlying upper Campanian Sayindere Formation has an organic-rich base probably controlled by a combination of a global anoxic event and a sea-level rise (Wagner and Pehlivan, 1987).

Proven and Potential Cap Rocks

The clay content (and thus sealing capacity) of the Shiranish Formation marls increases towards the thrust front; vertical changes in clay content appear synchronously over wide areas (Dunnington *et al.*, 1959; Hart and Hay, 1974). The Shiranish Formation globigerinal mudstones seal the Cretaceous limestone reservoirs in the *Jawan, Najmah, Qaiyarah* and *Qasab* fields (Dunnington, 1967a). Thin Shiranish Formation and basal Tertiary shales seal Upper Cretaceous carbonate reservoirs in NE Syria (Nikolaevskiy, 1972) (Fig.7.40). Where fractured, the Shiranish

Formation seal has leaked, permitting vertical migration of Jurassic/Neocomian sourced oils into Tertiary reservoirs (Dunnington, 1958). Similarly in Iran, fracturing of the correlative Gurpi Formation has allowed vertical oil migration up into the highly productive Asmari Group reservoirs (Bordenave and Huc, 1995).

Proven and Potential Traps

Campanian platforms such as the Bekhme Limestone were drowned during the Maastrichtian sea-level rise (the K180 maximum flooding surface of Sharland *et al.*, 2001). This occurred in the *Najmah / Jawan / Qasab / Qaiyarah* areas of northern Iraq (Dunnington, 1967a). These reefs may form stratigraphic traps.

At Berat Dagh, Aqra and Bekhme in Iraqi Kurdistan, the Aqra Formation contains spectacular bitumen impregnations (Dunnington, 1958; A. A., *pers. obs.*) (Fig. 7.62). Henson (1950a) noted that the outcrops are "*saturated with bitumen wherever the rock has primary or secondary porosity*". Reworked Maastrichtian fossils such as *Omphalocyclus* at Aqra, Bekhme and Dar-e-Tesu in the overlying thin siliciclastics of the Kolosh and Khurmala Formations sometimes contain bitumen in their chambers; however, indigenous Paleocene fossils lack bitumen-filled chambers (Dunnington *et al.*, 1959). This may indicate that early migration of oil took place into pre-existing build-ups.

Palaeotraps may have been initiated during the end-Maastrichtian inversion documented by Dunnington (1955). Thus, the *Kirkuk* palaeostructure may have hosted a pre-Late Tertiary oil accumulation in Middle Cretaceous limestones (Dunnington 1958, 1967a). End-Cretaceous inversion may have given rise to early structures ino which oil may have been trapped. In addition, these palaeohighs could form nucleation sites for later Paleocene shelf margins, e.g. Jebel Sinjar in Iraq, and Jebels Bishri and Abd El Aziz in Syria (Dunnington *et al.*, 1959; Daniel, 1963; Kent and Hickman, 1997). Aqrawi and Horbury (2006) suggested that fringing lowstand platforms in shallow basins may offer excellent trap opportunities where basin inversion has taken place.

Concluding Remarks

The stratigraphic evolution of Iraq during the Cretaceous (Megasequences AP8 and AP9) in response to regional subsidence, sea level changes, and periods of (often subtle) structural deformation, controlled the development of plays and petroleum systems. In the late Tithonian, basinal topography remaining from the Jurassic Gotnia Basin was partially infilled, and the basin margins were onlapped during a regional transgression. Periodic anoxic conditions led to the deposition of important source rocks in the late Tithonian – earliest Cretaceous, and again in the Albian. The relatively open-marine Cretaceous basin in Iraq which succeeded the highly restricted Gotnia Basin is referred to as the Balambo-Garau Basin.

A remarkable feature of AP8 stratigraphy in Iraq is the stacking of multiple reservoir and seal horizons in four supersequences in a package of sediment up to 2000 m thick. In the Early Cretaceous, shelf carbonate and then clastic depositional systems became established; they prograded eastwards from the Arabian Shield into the Balambo-Garau Basin. Three of these shelfal systems (Yamama Formation oolitic grainstones, and the Zubair and Nahr Umr Formation sandstones) form major reservoir units in southern and central Iraq. Sedimentation kept pace with subsidence over large areas resulting in the growth of long-lived carbonate platforms, and the accumulation of sandy clastic wedges during regressions. During transgressions, widespread fine-grained clastic and carbonate lithologies were deposited and act as seals. Subtle tectonic movements and aggradation of carbonate platforms above inherited topography controlled the local formation of high quality carbonate reservoirs in the Yamama Formation.

Beginning in the Cenomanian, the shelf systems were drowned, and they then retreated back towards the Arabian Shield. A broad, relatively isolated carbonate platform developed in SE Iraq and adjacent parts of SW Iran in the Cenomanian. The stacking of shallow-water rudist carbonate reservoirs in the Mishrif Formation in this platform has created one of the largest oil plays in the Middle East, which includes the major *Rumaila, West Qurna* and *Majnoon* oilfields. Elsewhere, time-equivalent Cenomanian carbonate reservoirs are only locally developed (e.g in NW Iraq), and deeper-water carbonates, which represent regional top-seals, were deposited .

A major break in the Cretaceous stratigraphic succession is formed by the mid-Turonian regional unconformity, beneath which local karstification occurred. The pattern of subsidence and sedimentation changed above this break, with the deposition of two further supersequences in a second Cretaceous megasequence (AP9). From the late Turonian onwards, tectonism along the northern and eastern margin of the Arabian Plate led to regional deformation in Iraq which controlled the local formation of structural traps. Continuing subsidence in late Turonian – early Campanian time led to widespread deposition of fine-grained basinal sediments which form regional seals. Chalky carbonate reservoir rocks of the Khasib Formation were locally deposited and are important in oilfields in Central Iraq (e.g. *East Baghdad*).

In the late Campanian – Maastrichtian, rapid subsidence occurred in NE Iraq in a NW-SE trending foredeep basin. This basin developed in front of thrust sheets containing ophiolites derived from Neo-Tethys and deep-water sediments derived from the NE margin of the Arabian Plate. A series of east-west trending, deep, relatively narrow, fault-controlled extensional basins also formed, including the Sinjar and Anah troughs. NW-SE trending wrench zones (including the Samarra-East Baghdad flower structure) also developed in late Campanian-Maastrichtian time. Locally, thick, shallow-water carbonate platforms formed on structural highs. and include rudist carbonate reservoirs in the Hartha Formation (oil-bearing at *Qaiyarah* and adjacent fields) and the Aqra Formation. Large parts of these platforms were subsequently drowned by fine-grained basinal sediments. A phase of inversion occurred at the end of the Maastrichtian. Basinal carbonates of the Shiranish Formation locally form fractured reservoirs at *Ain Zalah* and *Butmah*, and in recent discoveries in Iraqi Kurdistan.

By the end of the Cretaceous, the whole of Iraq was covered with heterogeneous sediments containing major reservoir and seal units. Facies changes in the Cretaceous succession have created potential for stratigraphic traps due to updip pinch-out of carbonate reservoirs into finer-grained platform interior facies, or basinward pinch-out where regional easterly structural dips have been reversed.

The Cretaceous stratigraphy of Iraq is thus characterised by the development of abundant source, reservoir and seal facies. Regional subsidence and pulses of tectonic deformation led to the early formation and preservation of structural traps containing Cretaceous reservoirs that predated the generation of oil from upper Tithonian and Cretaceous source rocks. The Cretaceous petroleum system, the most important in Iraq, is further discussed in Chapter 9v (pp. 327-356).

8. CENOZOIC

The foreland basin which developed in Cenozoic time in Iraq is referred to here as the Mesopotamian Basin (Fig. 8.1). In Paleocene – Eocene time, a slightly progradational carbonate shelf developed on the passive SW margin of this basin, and a more aggradational shelf developed on the active NE margin. The deepwater area between these two shelf systems was starved of sediment.

During the Oligocene, lowstand deposition occurred and pre-existing accommodation was infilled by relatively narrow carbonate shelves. Minor clastic input from the SW resulted from thermal doming of the SW Arabian margin prior to opening of the Red Sea. In the latest Oligocene, the final foreland basin phase was initiated following closure of Neo-Tethys. Carbonate-evaporite deposition occurred in Early Miocene time. Basin-wide evaporites and marls were deposited in mid Miocene time and were followed in the Late Miocene – Pliocene by increasingly coarse clastics, mostly derived from the rising Zagros orogen to the NE but also from source areas in the Arabian Shield.

Stratigraphy

Cenozoic lithostratigraphic units can be dated using palaeontological data published by many authors e.g. van Bellen (1956, 1959); Al-Naquib (1960); Al-Naqib (1967); Kassab (1972; 1975a,b; 1976; 1978a,b); Prazak (1978); Hradecky *et al.* (1978); Buday (1980); Al-Hashimi and Amer (1985, 1986); Al-Ameri and Farouk, 1986; Abdel-Kireem (1986a); Abdel-Kireem *et al.* (1994); and Starkie (1994).

The Cenozoic stratigraphy of Iraq has not been defined consistently. The bio- and lithostratigraphy of the main productive formations at *Kirkuk* and nearby fields was detailed by Daniel (1954) and van Bellen (1956). However, formation definitions in the *Iraq Lexicon* are of variable quality. IPC geologists used benthic foraminiferal assemblages to subdivide the stratigraphy; planktonic foraminiferal zones were not well understood or used. van Bellen (1956, 1959) consequently acknowledged the difficulty of calibrating Oligocene benthic faunal zones in Iraq with those in Europe.

Some formations defined in the *Iraq Lexicon* had unsatisfactory type sections or inadequate biostratigraphic control. For example, the Lower Miocene Euphrates and Jeribe Formations were poorly described in the Euphrates Valley area, as noted by Prazak (1978). Thick, heterogeneous formations should probably have been given Group status in the *Lexicon*. Thus, the Paleocene – Eocene Kolosh Formation is so lithologically diverse that Abdel-Kireem (1986a) suggested that its upper portion should be re-assigned to the Sinjar Limestone or the Khurmala Formation. This comparatively general approach to the Cenozoic succession in the *Lexicon* contrasts with the detailed studies of the Cretaceous stratigraphy.

In the Paleogene succession in the *Kirkuk* area, the rapid alternation of formations indicates a more complex sequence stratigraphic pattern than was envisaged in the 1950s and 1960s. Planktonic foraminiferal biostratigraphy was first used in the *Kirkuk* area by Al-Naquib (1960), allowing correlation with regional-scale studies in Syria (Daniel, 1963; Ponikarov *et al.*, 1967) and Iran (James and Wynd, 1965). Early work on the Cenozoic stratigraphy of Iraq culminated in the study by Al-Hashimi and Amer (1986) which described and dated the fauna in each Cenozoic formation in greater detail than in the *Lexicon*.

Some studies of the Tertiary stratigraphy of Iraq in the late-1970s lacked logged sections and contained mis-identified lithostratigraphic units. Faunal lists included questionably-identified fossil species, and referred to internally-inconsistent and mis-dated fossil assemblages. Subsequent publications accepted this work, perpetrating the idea that the stratigraphy had been carefully re-calibrated. One example is the questionable identification of the microfossil *Orbulina ?universa* in the "Jeribe Formation" by Prazak (1978). The microfossil, and therefore the formation, was probably erroneously dated as middle Miocene (N9 zone, Langhian).

In other cases, "formations" were mis-identified although their biostratigraphy was carefully described. Thus limestones which closely matched

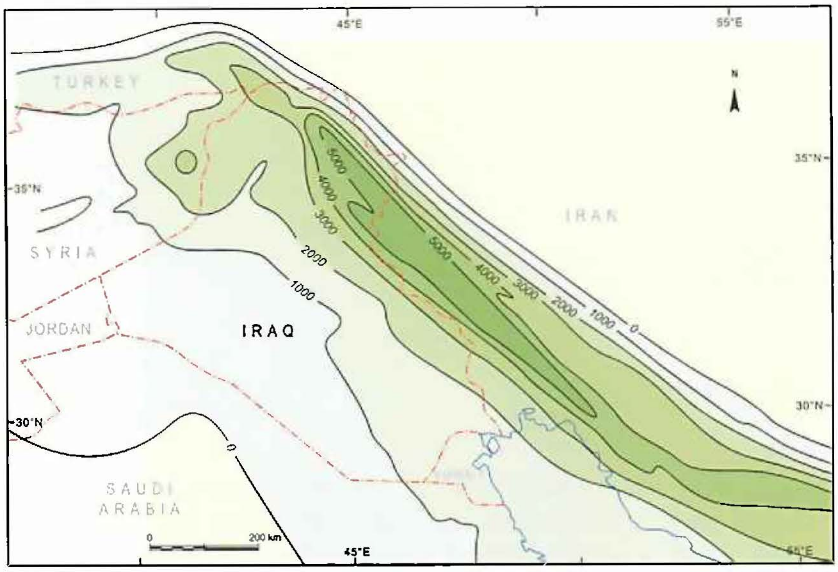


Fig. 8.1. Simplified restored Cenozoic isopach map (in metres) illustrating the NW-SE trending Mesopotamian Basin in Iraq and adjacent countries. After Goff *et al.*, 1995.

those originally described from the Jeribe Formation in the Western Desert were assigned to the Euphrates Formation by Ctyroky *et al.* (1975), and dated (correctly) as Burdigalian. This incorrect assignment of the Jeribe Formation and confusion with the Euphrates is common in subsurface sections (A.H., *pers. obs.*).

Further confusion has arisen when a formation has been correctly identified but mis-dated. Thus Abawi (1989) dated the Euphrates Formation as Burdigalian (N7/N8) on Jebel Sinjar, although the cited planktonic fauna contain both Aquitanian and Langhian index species (an Aquitanian age appearing to be preferable: G. Laursen, *pers. comm.* to A.H., 2009). Similarly, Al-Eisa (1992a,b) placed the Anah, Azkand and Ibrahim Formations in the Aquitanian, contrasting with the data presented by Al-Hashimi and Amer (1985, 1986).

Recent advances in chronostratigraphic calibration have relied on the results of Sr isotope studies of the upper Paleogene — lower Miocene stratigraphy in Iran (Ehrenberg *et al.*, 2007; van Buchem *et al.*, 2010). These studies demonstrate that the basin-centre evaporites (equivalent to the Basal Anhydrite, Dhiban and Lower Fars Formations of Iraq) define chronostratigraphic datums since they were deposited as chemical precipitates during periods of sea-level lowstand, as noted by van Bellen (1959) and reiterated by Sharland *et al.* (2001, 2004). Sr isotope analyses can be calibrated against techniques such as nannofossil analysis (Starkie, 1994). Further application of this technique may resolve many problems concerning the Cenozoic stratigraphy in Iraq.

The stratigraphic details of some Tertiary intervals in Iraq, such as the upper Miocene – Quaternary, have not yet been described. The Messinian lowstand, widely recognised throughout the Mediterranean area, should have some expression in northern Arabia. However, biostratigraphic resolution is poor in the Bakhtiari and Upper Fars Formations, and these units could not confidently be subdivided by Sharland *et al.* (2001, 2004) or interpreted within a sequence stratigraphic framework.

Based on the present authors' geological understanding and interpretation of the published data, a review of recent stratigraphic schemes for the Oligo-Miocene succession in Iraq is presented in Fig. 8.2. A chronostratigraphic interpretation of the Upper Cretaceous — Cenozoic succession is presented in Fig. 8.3.

The location of wells and fields referred to in this chapter is shown in Fig. 8.4.

Sequences and supersequences

Sharland *et al.* (2001, 2004), with recent amendments by Simmons *et al.* (2007), Ehrenberg *et al.* (2007), Al-Banna (2008) and Al-Juboury and McCann (2008), identified a total of ten third-order sequences (containing MFSs Pg10 to Pg50, and Ng10 to Ng40 inclusive) in the Tertiary. These sequences can be grouped into supersequences (I-IV: Fig. 8.3) reflecting four phases of basin development:

(i) a **Paleocene - Eocene supersequence** (equivalent to Megasequence AP10 of Sharland *et al.*, 2001) accompanying passive margin development (containing MFSs Pg10 and Pg20), during which carbonate shelves were developed on the Arabian margin and along the Zagros margin of the foreland basin;

(ii) an **Oligocene supersequence**, containing MFSs Pg30-50, during deposition of which the basin system showed lateral differentiation as narrow shelves were located downdip of older Paleogene margins. The basin was affected by compression along its Zagros margin and uplift along its Arabian margin due to the onset of Red Sea rifting;

(iii) a **lower Miocene supersequence** (with MFSs Ng10 to Ng20), characterised by the restriction of the basin and the initial deposition of evaporites. Widespread development of highstand carbonate shelf systems occurred, particularly in the SW of the basin. During this phase, accommodation which had been present (at least in some areas) since the Albian was finally filled;

(iv) a **middle Miocene to Quaternary supersequence** (with MFSs Ng30 to Ng40), which represents deposition of sediments during plate suturing. This supersequence, together with the Oligocene and lower Miocene supersequences, is equivalent to Megasequence AP11 of Sharland *et al.* (2001).

Tectonic setting and basin development

Paleocene - Eocene

Paleogene facies patterns in Iraq initially reflect the effects of regional end-Cretaceous inversion, as first described by Dunnington (1955).

Renewed compression occurred in the Paleogene. The NE part of the former Late Cretaceous foreland basin was strongly uplifted, and a new depocentre formed 50 km to the SW (Goff *et al.*, 1995). This is referred to here as the Paleogene Mesopotamian Basin. The clastic wedges of the Kolosh and Gerçus Formations were derived by erosion of the flanking thrust belt to the NE during uplift in Paleocene and mid-Eocene time, respectively.

Partial inversion of the western part of the Sinjar Trough occurred in the early Paleogene (Kennedy and Lunn, 2000). Inversion also propagated from north to south in Eastern Syria with inversion of the northern graben of the Euphrates system in the Paleocene and of the southern graben during the Eocene (Fig. 8.7) (Caron *et al.*, 2000). Late Cretaceous palaeohighs persisted into the Paleogene, although some (such as the Khleisia High: Fig. 8.5) were in a submarine setting. Grabens which were inverted at the end of the Cretaceous (e.g. Jebel Sinjar) formed other positive structures (Fig. 8.5).

Paleocene – Eocene sediments reach a thickness of 1200 m. Compacted sediment accumulation rates were about 10–40 m/Ma, except over the sediment-starved Khleisia High and adjacent areas where they are < 5 m/Ma. Paleocene – Eocene subsidence was probably driven mainly by sediment loading, with some contribution from thermal subsidence and flexural loading.

Aggradational platform margin stacking patterns in the lower Paleogene (Fig. 8.6) indicate rapid subsidence, and most Cretaceous platforms and palaeohighs were drowned. This was followed by continued but probably more gentle subsidence in the later Paleogene and early Neogene, punctuated by periods of compression and uplift on the NE margin of the Arabian Plate due to closure of Neo-Tethys.

Oligocene – early mid-Miocene

During the Oligocene and early Miocene, the Mesopotamian foreland basin in Iraq became asymmetrical (Fig. 8.6). Oligocene – lower Miocene platform margin successions show offlapping to aggradational geometries in front of Eocene basin-margin successions in the NE around *Kirkuk*, defining relatively narrow shelf systems (cf. Daniel, 1954; van Bellen, 1956). This probably indicates localised uplift along the Zagros margin as the Oligocene proceeded. More gentle offlap in the SW defines broader shelves (Fig. 8.6).

Oligocene sediments are absent from SW Iraq and much of NE Iraq. The main Oligocene basin in Iraq trended NW-SE and contains 50–200 m of sediments. Some 300 m of Oligocene globigerinid marls are present south of Jebel Sinjar (Dunnington, 1958). Carbonate shoals prograded into the basin from the SW and NE; the basin axis was sediment starved.

It is likely that very little tectonic subsidence occurred in Iraq during the Oligocene (34 to 24 Ma). Thermal subsidence following the localised Late Cretaceous extension had almost ceased, and no significant flexural subsidence occurred in the absence of plate convergence along the NE margin of the Arabian Plate. Oligocene sediments partly infill the inherited topography of the Eocene basin.

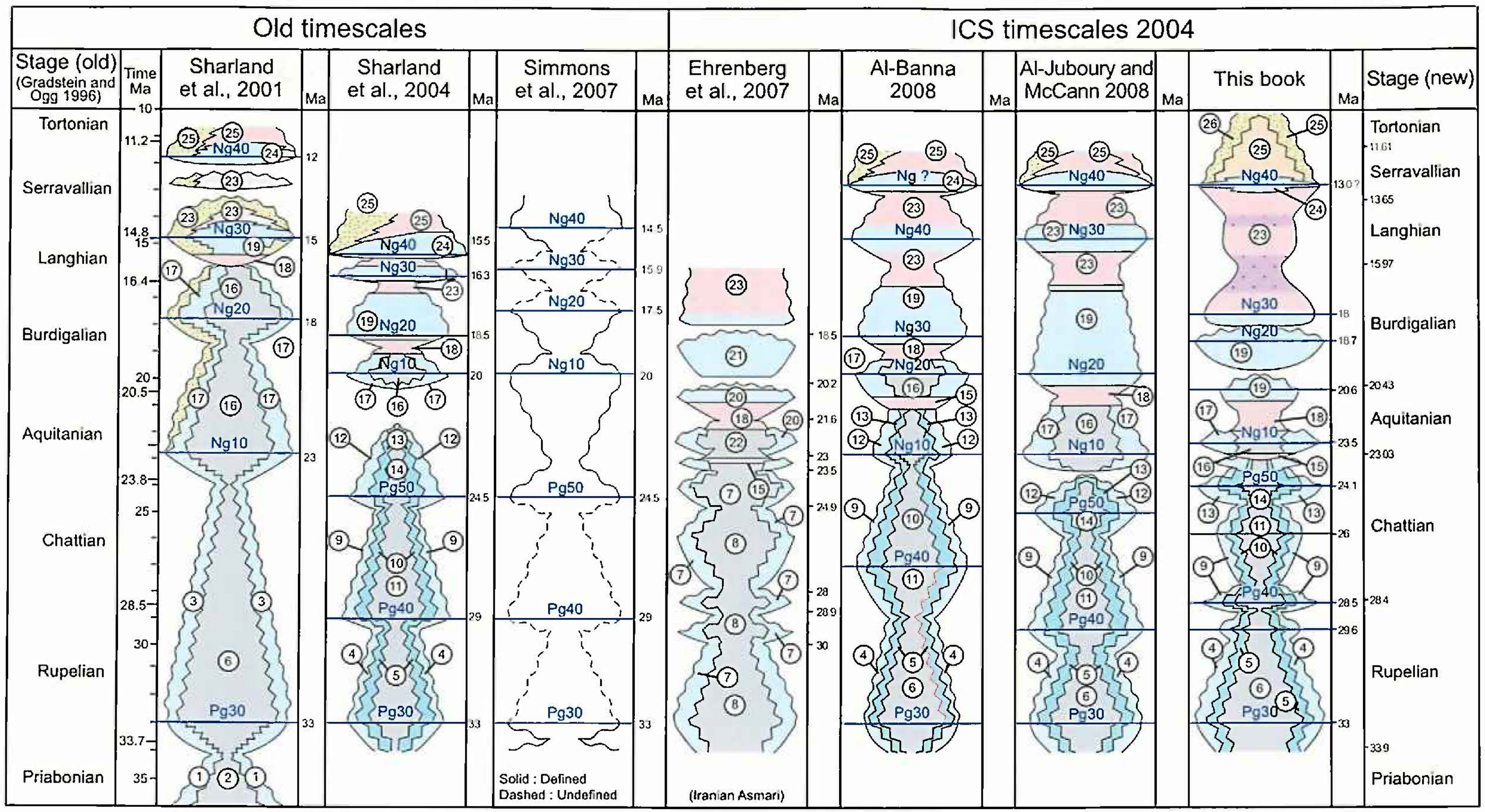
In the NW of the Euphrates Graben in Syria, by contrast, the Oligocene corresponds to a period of renewed extension on NW-SE trending normal faults (Caron *et al.*, 2000). Other regional-scale effects include thermal doming and the onset of rifting in the Gulf of Aden and Red Sea (Burke and Whiteman, 1973) which caused uplift of the SW margin of the Mesopotamian Basin, with shelf margins shifting hundreds of km to the NE (Goff *et al.*, 1995).

Early – early mid-Miocene depocentres in northern Iraq lie immediately south of the Oligocene depocentres. Up to 100–300 m of sediments were deposited in about 7 Ma. Subsidence probably occurred mainly by sediment loading of relict basin topography.

By the late early Miocene, laterally extensive shallow-water carbonate platforms had developed on the margins of the Mesopotamian Basin, and included the Asmari Limestone and Qum Limestone of Iran, and the Kirkuk Group of Iraq. At this time, a continuous marine connection existed around the northern edge of the Arabian Plate from the Eastern Mediterranean to the Hormuz Straits.

Late mid-Miocene – early late Miocene

There is evidence of intense uplift of the entire Zagros margin during the Burdigalian. A major



Avanah / Dammam / Pila Spi	1	Pabdeh	8	Basal Anhydrite	15	Brissopsis Beds	22
Jaddala	2	Bajawan	9	Serikagni	16	Lower Fars	23
Kirkuk Group (undivided)	3	Baba	10	Euphrates	17	Middle Fars / Guri Limestone	24
Shurau	4	Tarjil	11	Dhiban / Kalhur	18	Upper Fars	25
Sheikh Alas	5	Anah	12	Jeribe	19	Dibdibba	26
Palani	6	Azkand	13	Middle Asmari	20		
Lower Asmari	7	Ibrahim	14	Upper Asmari	21		

Fig. 8.2. Comparison of recently-published chronostratigraphic schemes for the Neogene succession in Iraq. The scheme adopted in this book, which is based on an evaluation of available data, is presented in the right-hand column. Some complexity has arisen because different authors have used different time-scales. The Sr-based data presented by van Buchem *et al.* (2010) is consistent with that given by Ehrenberg *et al.* (2007).

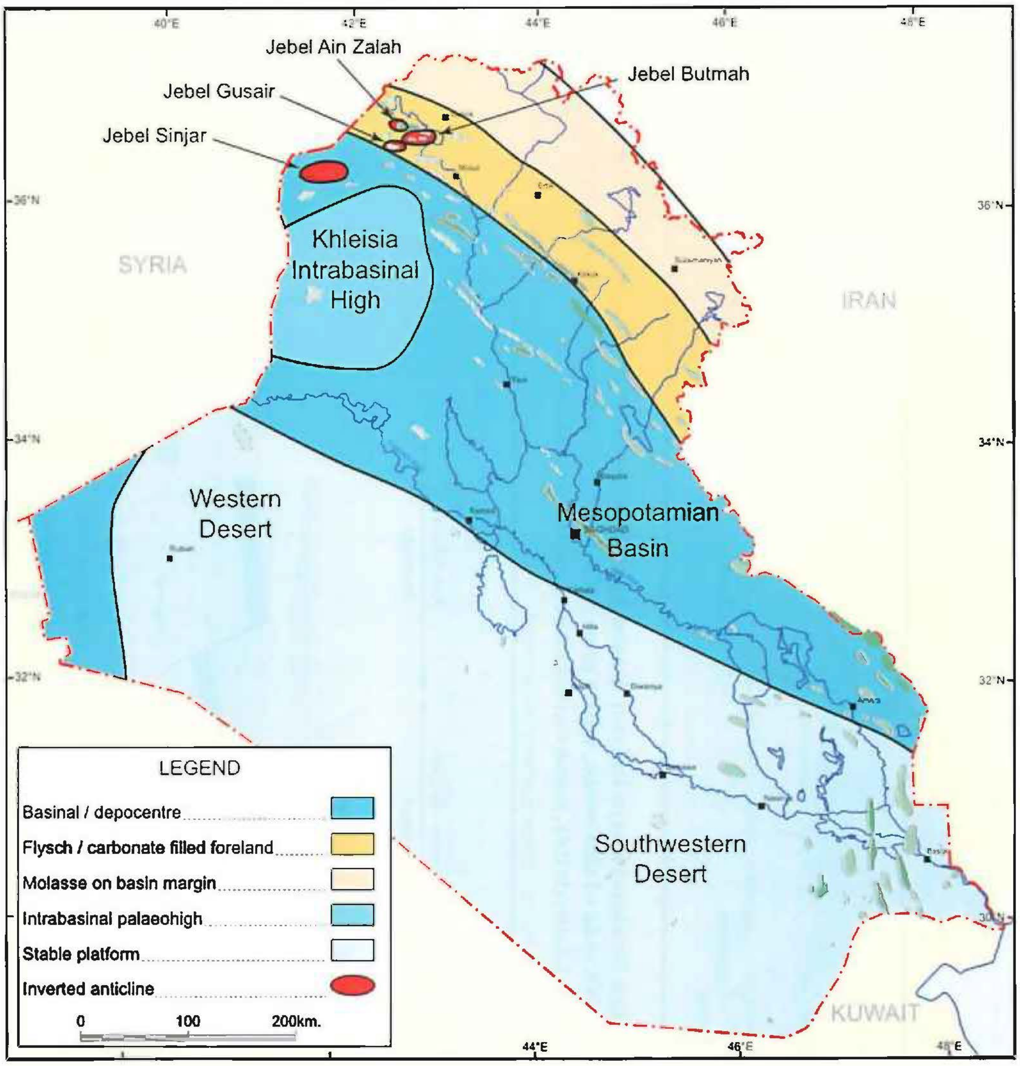


Fig. 8.5. Map of Iraq showing tectonic elements which were important in the Cenozoic including a shallow high in the SW Desert, an intrabasinal high in the Khleisia area, and various foreland-related features along the active NE plate margin.

angular unconformity is present in the Govanda Plateau of NE Iraqi Kurdistan. Burdigalian shelf carbonates of the Govanda Formation rest unconformably upon rocks as old as Albian (Qamchuqa Formation; van Bellen, 1959). A similar unconformity defines the base of the Upper Asmari in the Iranian High Zagros (James and Wynd, 1965). There is also evidence of minor growth of anticlines (e.g. Mansuriya) during deposition of the Dhiban Formation at about this time (van Bellen, 1959; Al-Juboury *et al.*, 2007)

Following infill of remaining Paleogene accommodation during the early-mid Miocene, a renewed phase of development of the Mesopotamian Basin began in late mid-Miocene time. From then to the early late Miocene (14-8 Ma), regional tectonic subsidence occurred in Iraq with the deposition of the Lower, Middle and Upper Fars Formations throughout NE Iraq. Up to 1600 m of marls and evaporites (Lower and Middle Fars) together with mudstones, siltstones and thin sandstones (Upper Fars) were deposited in a broad asymmetric sag basin whose axis trended east-west through the Sinjar area and NW-SE in southern NE Iraq. The Fars formations thin to the NE. SW Iraq was gently uplifted and no sediments of this age are preserved there (Goff *et al.*, 1995).

Tucker (1999) noted that Fischer plots of cycles in the Lower Fars Formation suggest a dominant tectonic control on deposition; this contrasts with the underlying shallow-water Jeribe Limestone which marks a flat, uniform depositional surface with little structural differentiation.

Compacted sediment accumulation rates in the Mesopotamian Basin reached 250 m/Ma during this time period due to intense tectonic subsidence and sediment loading. Rapid subsidence in Iraq was probably related to renewed tectonic compression along the NE active margin of the Arabian Plate. However, the depocentres of the Fars formations are located above the depocentres of the early to early-mid Miocene sequence (Goff *et al.*, 1995), indicating an underlying basement control on subsidence at this time.

There is little evidence of growth of individual anticlines in late mid-Miocene – early late Miocene

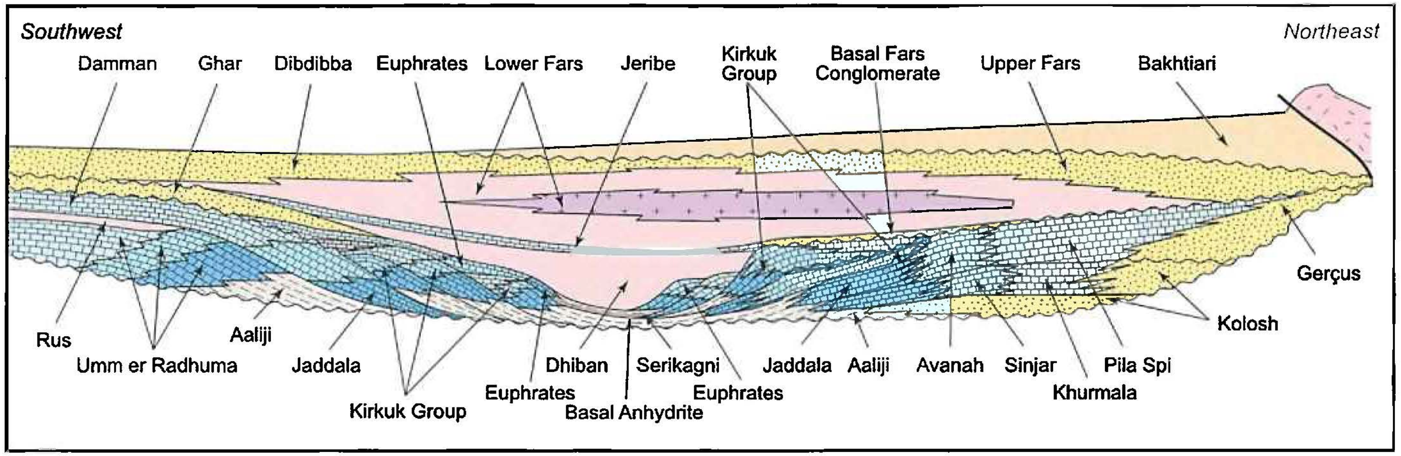


Fig. 8.6. Schematic SW-NE cross-section across the Cenozoic Mesopotamian foreland basin in Iraq. Based partly on Daniel (1954) and van Bellen (1956). Note progradation then aggradation of earlier Paleogene margins on the NE side of the basin, while progradation to offlap was dominant on the SW side. Infill of the basin centre began in the latest Oligocene with evaporites (Basal Anhydrite), some carbonates and siliciclastics.

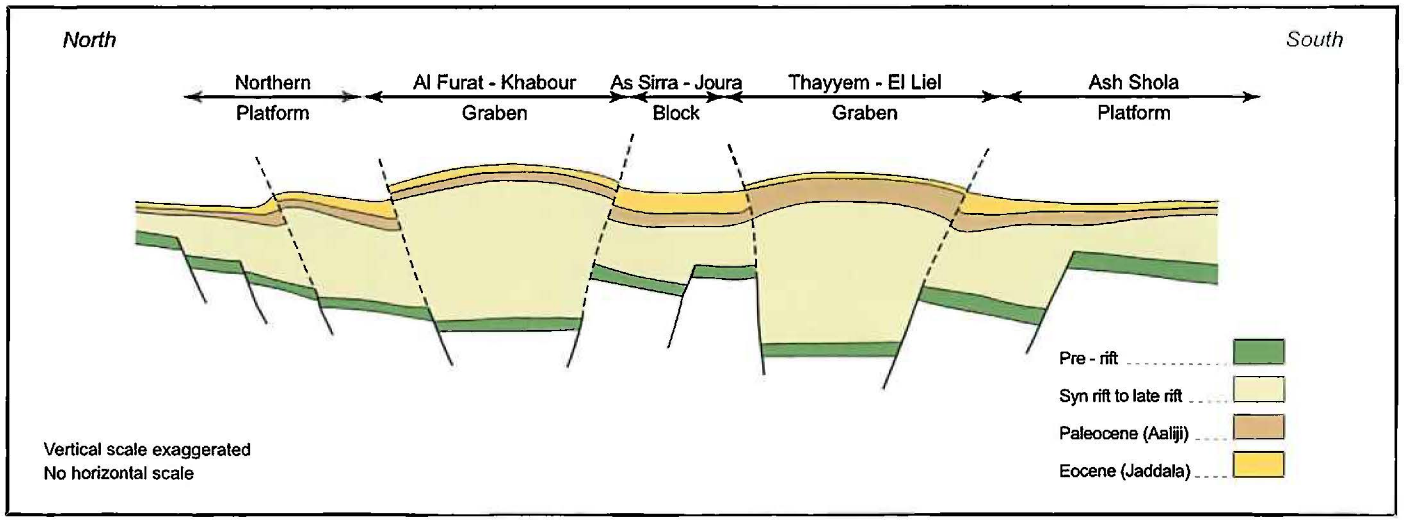


Fig. 8.7. Inversion of structures in the Euphrates Graben in Syria. After Caron *et al.*, 2000. The thick, syn- to late-rift Aaliji Formation thickens into the Thayyem graben, while the Jaddala Formation thins over inverted grabens.

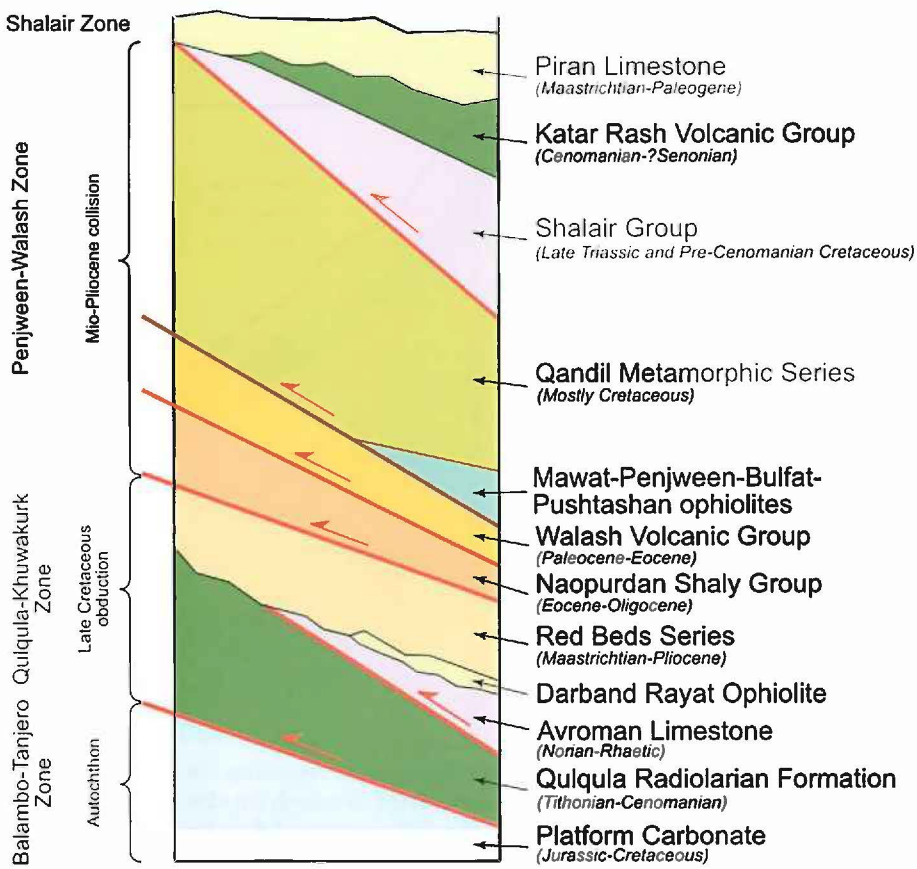


Fig. 8.8. Stratigraphy of thrust units in the High Zagros, showing the allochthonous units which were thrust onto the margin of the Arabian Plate. After Jassim *et al.*, 2006b.

time in Iraq. Seismic data from the area SE of the Kirkuk and Kor Mor anticlines confirms that deposition of the Fars formations predates the main phase of thrusting and anticlinal growth (cross-section 9, page 62). However, the broad flexural subsidence may have caused subtle tilting of older buried structures. Less subsidence occurred over the Khleisia–Mosul High which plunged gently to the north (see Fig. 14 of Dunnington, 1958).

Late late Miocene – Recent

In late Late Miocene time, intense compression propagated into the Middle Miocene foreland basin and resulted in the growth of large-scale Zagros anticlines, and the inversion of the Cretaceous half grabens in NW Iraq. A rapidly-subsiding foreland basin ("Neogene Mesopotamian Basin") formed in north and NE Iraq, flanked by a thrust belt. The basin was deepest to the SE, as illustrated by the Neogene isopach map (see Fig. 8.15).An intermontane basin also developed within the suture zone in which redbeds were deposited.

In the late Miocene (8–5 Ma) and Pliocene (5–2 Ma), up to 2000 m and 1000 m (respectively) of clastic sediments were deposited in the strongly subsiding Mesopotamian foredeep basin in Iraq. Sediment accumulation rates reached 700 m/ Ma in the late Miocene. Intense tectonic subsidence occurred in response to compressional deformation and overthrusting of allochthonous units along the NE margin of the Arabian Plate. These units comprise Paleogene forearc and volcanic arc units (Naopurdan and Walash Formations), ophiolites from the Neo-Tethys ocean floor (Penjween, Bulfat and Mawat Units), and metamorphic rocks of the Sandandaj/Sirjan Zone (Shalair and Katar Rash Units) (Jassim *et al.*, 2006b) (Fig. 8.8). Major growth of anticlines in the Folded Zone of Iraq occurred at this time.

By the Pliocene, structural development involved right-lateral transpression at the NE plate boundary as interpreted from studies in Syria (McBride *et al.*, 1990; Chaimov *et al.*, 1992; Best *et al.*, 1993). Convergence continued in Pliocene time and resulted in further growth of elongated NW-SE anticlines and parallel synclines which are characteristic of the Zagros fold-and-thrust belt. In the Pliocene, deposition of thick conglomerates and sandstones occurred with depocentres located between actively rising structures.

The Paleocene – Eocene Supersequence

The Paleocene – Eocene Supersequence shows significant lateral and vertical heterogeneity. An isopach map of this interval (Fig. 8.9) shows that great thicknesses of sediment were deposited in NE Iraq while the centre of the Paleogene Mesopotamian Basin was relatively sediment-starved, although sediment thicknesses increase again towards the

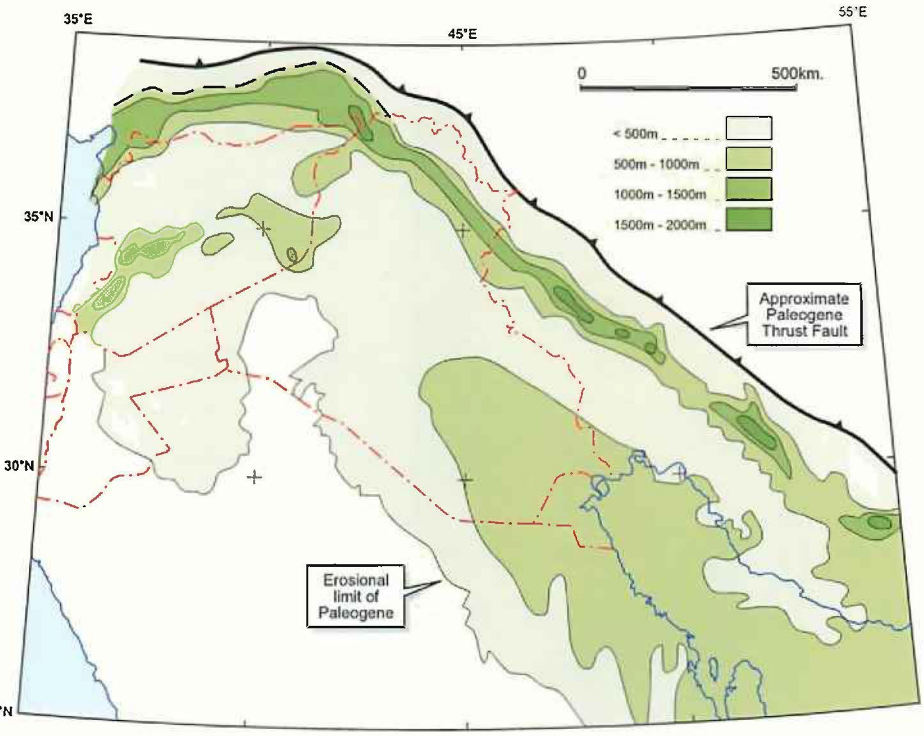


Fig. 8.9. Isopach map (in metres) of the Paleocene – Eocene succession in the Zagros foreland including the Mesopotamian Basin. Note the narrow, thick isopach on the NE basin margin, contrasting with the broader, thinner isopach on the SW margin. After Goff *et al.*, 1995.

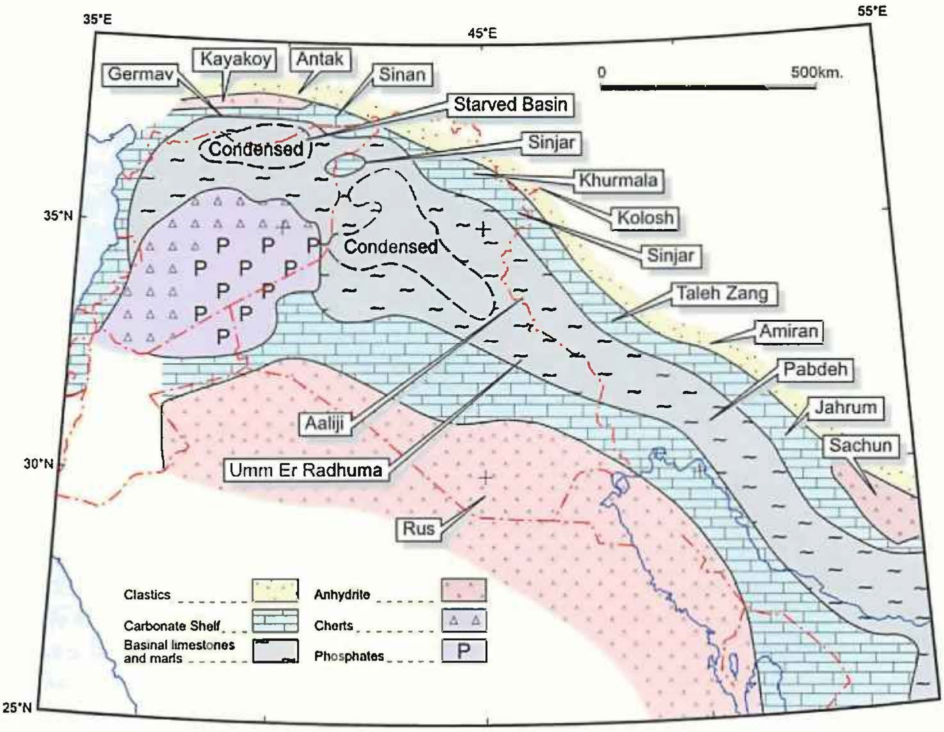


Fig. 8.10. Paleocene – early Eocene palaeogeography of Iraq, showing a central basin trending NW-SE bordered by carbonate shelves. To the NE are shoreline and redbed clastics that are related to uplift of the plate margin. Modified after Goff *et al.* 1995.

other side of the basin to the south and SE (Goff *et al.*, 1995). Some 250 – 900 m of Paleocene – lower Eocene sediments were deposited in a NW-SE trending depocentre (70 km wide) in NE Iraq. This narrow depocentre extends to the NW into Syria and Turkey, and SE into Iran. It was located above a relatively deep-water relict Late Cretaceous basin, immediately SW of the Aqra Formation carbonate platform and the Tanjero Formation flysch basin. Deposition of flysch in the depocentre in early-mid Paleocene time was followed by the formation of a SW-facing carbonate platform in the late Paleocene – early Eocene. The platform continued to subside in the mid-late Eocene with accumulation of a

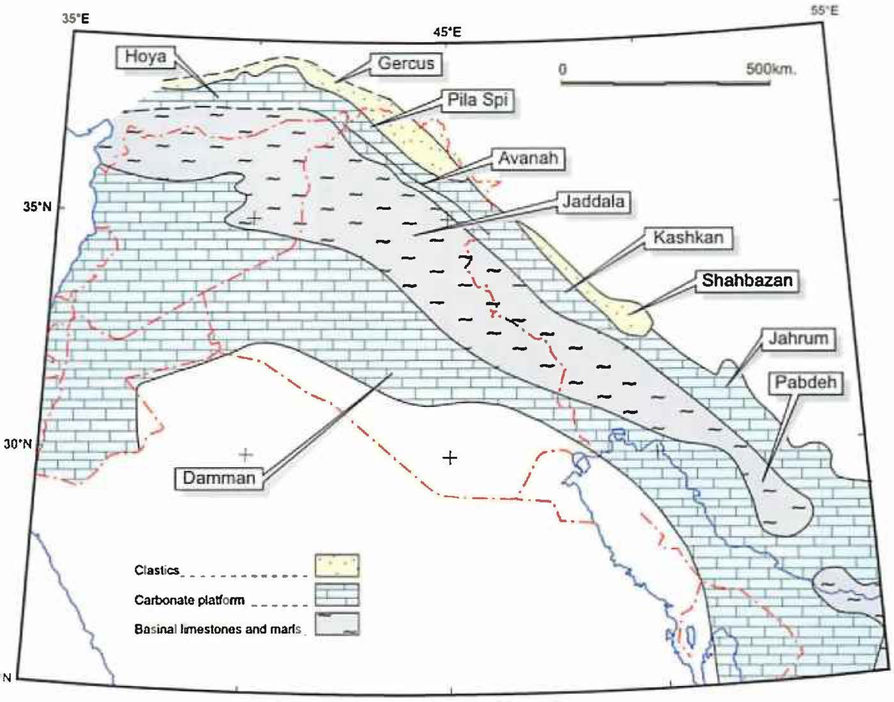


Fig. 8.11. Middle – late Eocene palaeogeography of Iraq showing a central basin trending NW-SE bordered by carbonate shelves. To the NE are shoreline and redbed clastics related to uplift of the plate margin. Modified after Goff *et al.*, 1995.

further 200–800 m of sediment. Carbonate deposition was interrupted in the mid-Eocene by deposition of molasse, and resumed in the mid–late Eocene. With the exception of the Sinjar Trough area, the area to the SW of the platform was relatively starved of sediment; Paleocene – early Eocene sediments are absent here, and mid- late Eocene sediments comprise basinal limestones typically < 100 m thick.

The Paleocene – Eocene succession overlies regionally extensive Upper Cretaceous formations (van Bellen, 1959). The contact is only locally conformable; the Danian and sometimes Selandian is often absent (Kassab, 1972, 1976). In northern Iraq, the Danian is only recorded in well *Tel Hajar-1* in NW Iraq (Kaddouri, 1982b).

Danian rocks also occur in the Western Desert where they are assigned to the **Akashat Formation** (Al-Bassam and Karim, 1982; Jassim and Buday, 2006g) (see Fig. 8.14). In Wadi Tarfawi 40 km WSW of Rutbah, this formation is 25 m thick and comprises a basal 7 m of buff to grey shales with chalk containing intraclasts of bone and phosphate. It contains load casts and a planktonic foraminiferal fauna including *Globigerina daubjergensis* which is typical of the earliest Paleocene (Jassim and Buday, 2006g). This is overlain by 7 m of yellow sandstones with phosphates, occasional beds of siliceous shales and limestones containing *Cibicides* sp. representing sand bars and bivalve shoals. These are overlain by 11 m of micritic limestones and cherts with recrystallised planktonic foraminiferal tests and *Lenticulina*. The section rests on Cretaceous limestones with *Lopha* (Jassim and Buday, 2006f). Further west on the Jordanian border, the basal shale member is 30 m thick and also contains *G. daubjergensis* (Jassim and Buday, 2006f).

A 20 m thick Danian section occurs in well *BH9* near the Akashat mine in the Western Desert (Jassim and Buday, 2006f). About 30 km to the NW of the mine, the Danian comprises 110 m of marl with benthonic and planktonic foraminifera (Jassim and Buday, 2006f). Basal-Danian fauna also occur in the *Traibeel* borehole close to the border with Jordan at a depth of 278 m (Jassim and Buday, 2006g). The Akashat Formation thins to the north. It is only 7 m thick at a location 28 km along the road to Akashat from the junction with the Rutbah-Amman highway, and 3 m thick on the NW margin of the Ga'ara depression (Jassim and Buday, 2006g).

The **Aaliji Formation** (Paleocene – early Eocene) and **Jaddala Formation** (mid-late Eocene) extend throughout the basin centre (Figs 8.6, 8.10, 8.11). They are interpreted as deep-water deposits (van Bellen, 1956, 1959; Al-Kufaishi and Al-Rubaie, 1986). A major hiatus frequently occurs at the base of the Aaliji Formation at which almost the entire Paleocene is missing, e.g. in well *Chemchemal-2* (Starkie, 1994). In the *Kirkuk* area, a several-metre thick glauconite-rich bed at the base of the Jaddala Formation (Al-Naquib, 1960) indicates condensed sedimentation during the lowstand separating sequences Pg10 and Pg20 and the subsequent Pg20 transgression. Al-Naquib *(ibid.)* also recorded other condensed basin-centre glauconitic beds marking the bases of overlying formations in the Oligocene.

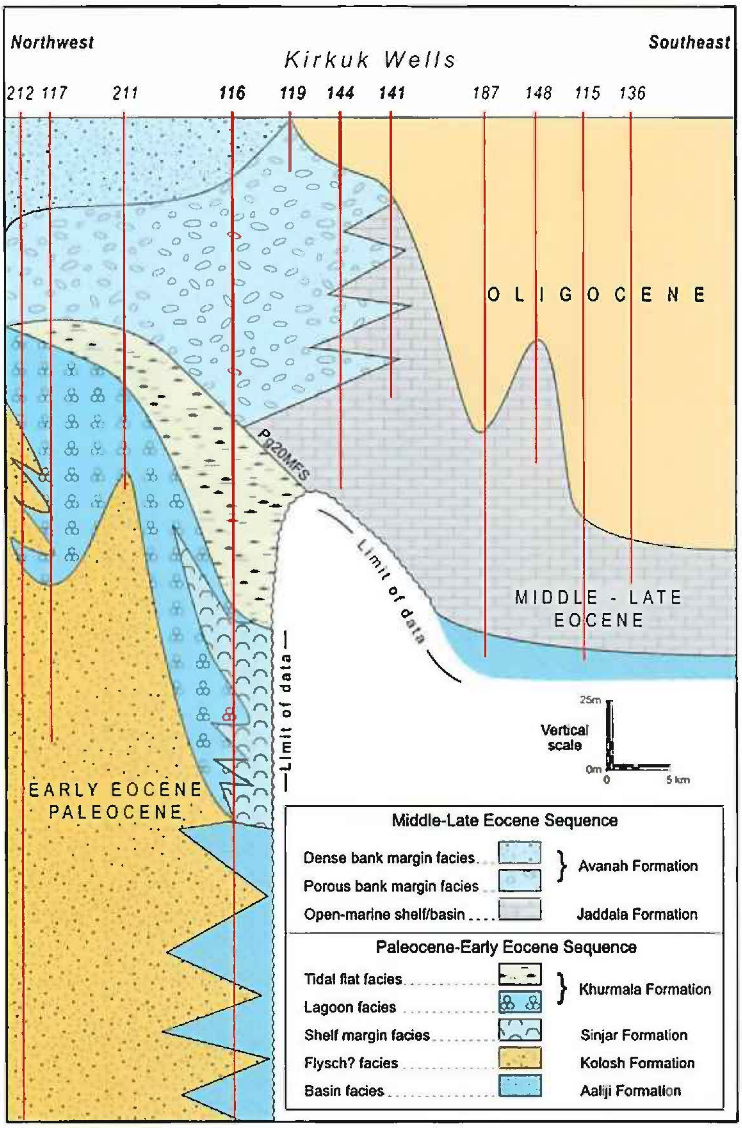


Fig. 8.12. Facies belts in the Paleocene to Eocene succession of the *Kirkuk* field. After Majid and Veizer, 1986. Note that the thickness of Aaliji Formation in the area of limited well penetration to the SE cannot be estimated accurately.

Away from the basin centre, these formations pass rapidly (within a few km) via mixed shelf/basinal facies into thick shelf carbonates, e.g. at the *Bai Hassan* and *Kirkuk* structures (Fig. 8.12) on the NE basin margin. The depositional system here began as a clastic-carbonate ramp which evolved into a rimmed shelf whose margin was located near well *Kirkuk-116* (Majid and Veizer, 1986) (Fig. 8.12). Lagoonal conditions (Khurmala Formation) were subsequently initiated behind the platform-margin barrier (Sinjar Formation: see below) (Fig. 8.10). A transgression in the middle Eocene (Pg20 MFS of Sharland *et al.*, 2001) led to the re-establishment of a second rimmed margin (Majid and Veizer, 1986) (Figs 8.11, 8.12).

The nummulitic shelf margin successions are assigned to the **Umm er Radhuma** and upper part of the **Dammam Formation** in the SW of the Mesopotamian Basin, and to the **Sinjar** and upper part of the **Avanah Formation** in the NE.

Upper Eocene shoal limestones of the Avanah Formation contain a fauna of *Nummulites* and *Orbitolites* (Al-Hashimi and Amer, 1985, their Plate 56). This facies is often completely recrystallised and locally partially dolomitised. This results in a honeycomb or even "loose sand" texture in which almost all fossil fragments have been lost, accompanied by partial dolomitisation (Daniel, 1954; Majid and Veizer, 1986). Dolomitisation is sporadic elsewhere.

Shelf to shelf-margin carbonates (e.g. the Sinjar Limestone Formation on Jebel Sinjar) were locally deposited on the elevated crests of end-Cretaceous inversion structures (van Bellen, 1959; Kennedy and Lunn, 2000) (Figs 7.55, 8.10). On other inverted highs such as Ain Zalah, deep-water Paleogene units thin over the most eroded and elevated portions of the Upper Cretaceous stratigraphy (Daniel, 1954). Shallow-water Paleogene facies development probably depends on the amount of inversion on the late Campanian – Maastrichtian normal faults. Most of the Maastrichtian and lower-middle Paleocene succession is missing in these locations (Kassab, 1972, 1976). An analogous structure (Jebel Abd El Aziz) in Syria was mapped by Kent and Hickman (1997) (Fig. 8.13). Considerable local palaeotopography was present here before Paleogene carbonate deposition began.

Plate 8.1. Dolomitic limestones of the Khurmala Formation with the upper part of the Kolosh Formation at Haibat Sultan ridge near Koya. Photo courtesy of B. Al-Qaiyim.

Plate 8.2. Thin limestones alternating with shales and clays in the Paleocene – Eocene Kolosh Formation. Between Salahaddin and Shaqlawa, 35 km NE of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

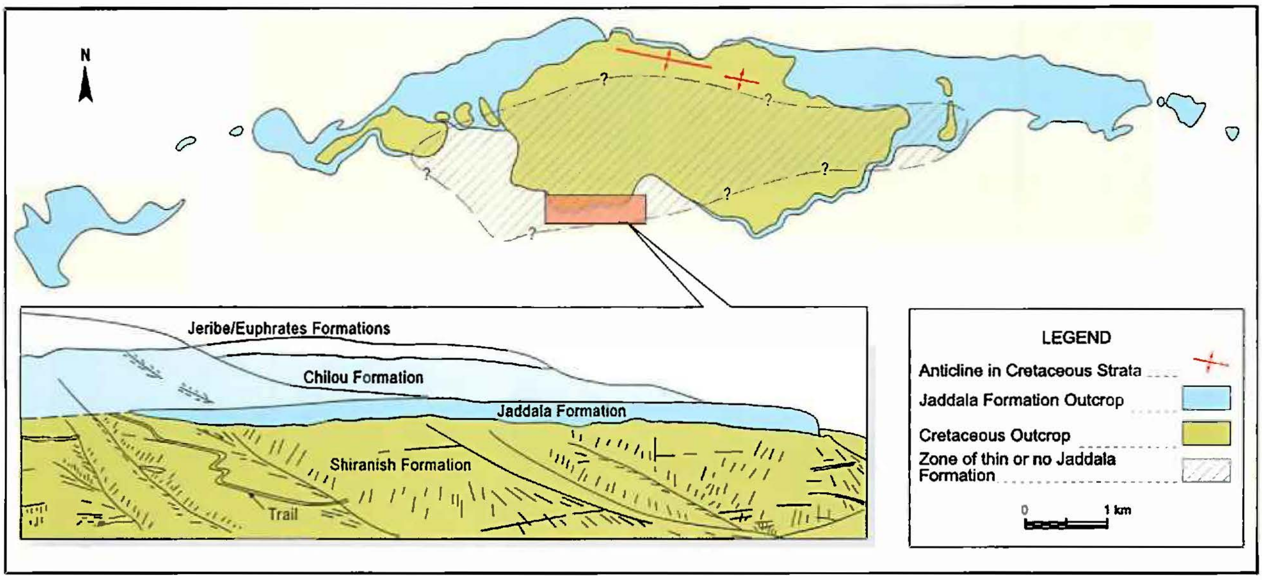


Fig. 8.13. Onlap of the Jaddala and Chilou Formations onto Cretaceous units, Jebel Abd El Aziz, NE Syria. From Kent and Hickman, 1997.

In places, carbonate deposition did not begin until Eocene or even early Miocene times with the deposition of the Jaddala and Chilou / Serikagni Formations (Daniel, 1963) (Fig. 8.13).

The only thick anhydrite unit in the Paleocene – Eocene succession in Iraq, the middle Eocene **Rus Formation**, occurs locally above the shelfal carbonates of the Umm Er Radhuma Formation in the SW (Fig. 8.10). This formation was probably deposited during minor fourth-order lowstands in a shallow intrashelf basin during third-order latest highstand to transgressive systems tract conditions, when sea levels generally were below the exposed platform margin.

Thick siliciclastic units were deposited on the Zagros (NE) margin of the Mesopotamian Basin (Figs 8.10, 8.11). These include the **Kolosh Formation** (Plates 8.1, 8.2) which is up to 1000 m thick near Derbendikhan (Jassim and Buday, 2006g). The formation was derived from Upper Cretaceous ophiolites and Cretaceoous and older sedimentary rocks exposed at the uplifted plate margin. It is equivalent to the upper parts of both the Germav Formation of Turkey (Ala and Moss, 1979) and the Amiran Formation of Iran (James and Wynd, 1965).

The depositional environment of the Kolosh Formation apears to vary from deep- to shallow-marine. The lower part of the formation contains sandstones; these are overlain by carbonate shelf deposits in the upper part. Detailed facies and palaeontological studies of the formation (Al-Qayim and Salman, 1986; Kassab, 1976; Abdel-Kireem *et al.*, 1994) suggest that there are two significant flooding surfaces beneath the Pg10 MFS of Sharland *et al.* (2001), and possibly another MFS in the overlying lower Eocene carbonates.

An overlying unit, the **Gerçus Formation** (Fig. 8.11; Plates 8.3, 8.4), is a redbed unit deposited during renewed uplift of the Zagros margin at the

Plate 8.3. Eocene Gerçus Formation exposed in a new road cutting near the town of Shaqlawa, 40 km north of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

Plate 8.4. Thin beds of limestone alternating with red clays in the Eocene Gerçus Formation. Near Shaqlawa, 40 km north of Erbil, Iraqi Kurdistan. Vertical scale: about 3 m. Photo by A. Aqrawi.

Plate 8.5. Thick bedded dolomitic limestones of the Khurmala Formation at Haibat Sultan Ridge, near Koya, midway between Erbil and Sulaimaniya, Iraqi Kurdistan. Photo by B. Al-Qaiyim.

end of the early Eocene. During this phase of uplift, rocks as old as Jurassic were elevated and eroded as indicated by the provenance of clasts within the basal part of the formation (van Bellen, 1959). In common with the Kolosh Formation, sediment was mainly derived from ophiolitic rocks and older sedimentary rocks.

Overlying these siliciclastic units and of greater economic significance are the lagoonal carbonates of the **Khurmala Formation** (Plates 8.1, 8.5) and **Pila Spi Formation** (Plates 8.6, 8.7, 8.8). In the Erbil area, Al-Ameri and Farouk (1986) established a reliable late middle to early late Eocene age for the Pila Spi Formation using palynomorphs. This confirmed the poorly calibrated ages suggested by van Bellen (1956, 1959) for the shelfal part of this succession. The thick Pila Spi limestones form a prominent topographic feature into which many gorges are cut. The unit is used as a surface marker during satellite mapping (M. Insley, *pers. comm.* to A.H., 2007). Lagoonal (Plate 8.8) to platform margin (shoal) carbonates are frequently present interbedded within clastic-dominated successions in the NE of the Mesopotamian Basin. The Pila Spi Formation is often overlain unconformably by the middle Miocene Lower Fars Formation (e.g. in the

Plate 8.6 (above left). Fractured limestones of the Eocene Pila Spi Formation exposed at Haibat Sultan Ridge, near Koya, midway betwen Erbil and Sulaimaniya (Iraqi Kurdistan). Geologist for scale is A. Aqrawi.

Plate 8.7 (above right). Eocene limestones of the Pila Spi Formation exposed in a recently excavated road cutting on the SW flank of the Pirmam Anticline near Salahaddin, 25 km north of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

Salahaddin and Taq Taq areas in NE Iraqi Kurdistan). The formation was subjected to prolonged karstification during the associated hiatus.

On the western margin of the Mesopotamian Basin in the present-day Western Desert of Iraq (Fig. 8.10), the phosphorite shelf deposition that commenced in the Late Cretaceous continued in Paleogene time with deposition of the **Akashat** and **Ratga Formations** (Jassim *et al.*, 1984), specifically the Eocene Swab and Damlouk Members (Al-Bassam and Karim, 1992) (Fig. 8.14).

The **Suwais Group** (Jassim *et al.*, 2006b) crops out in the Thrust Zone of NE Iraqi Kurdistan. It ranges in age from late Maastrichtian to ? Oligocene. The Suwais 1 Unit (50-10 m thick) comprises detrital and conglomeratic limestones, passing up into conglomerates and red shales. The formation contains abundant reworked late Maastrichtian fossils (rudists and foraminifera).

The Suwais 2 Unit (300 m thick) comprises red shales and blue-grey siltstones with lenticular conglomerates containing clearly reworked Cretaceous fossils and indigenous Paleocene – early Eocene fossils.

The Suwais 3 Unit comprises coarse conglomerates with chert boulders derived from the Qulqula Formation (Fig. 8.8), and sedimentary and basic igneous rocks. It averages 200 m in thickness with a maximum thickness of 400 m. The age of this unit is unknown (Jassim *et al.*, 2006b); both it and underlying Suwais units appear to be flysch or molasse deposits.

The Suwais 4 Unit comprises red marly mudstones and sandstones, with intervals of nummulitic limestones and some conglomerate beds. It is up to 800 m thick (Jassim *et al.*, 2006b) and probably represents alluvial to paralic/ shallow-marine deposition.

Plate 8.8. Thin section view of foraminiferal pack-grainstone of the Pila Spi Formation. The sample is from the NW plunge of the Sangaw Anticline near Sulaimaniya, Iraqi Kurdistan. Note the presence of *Praerhapydioina* sp. to the right of the image. Photo and bioclast identification by S. Packer; image courtesy of Sterling Energy Ltd. Field of view 5 mm.

Petroleum System Components

Proven and Potential Reservoir Rocks

In the central (Avanah) Dome and the NW-most (Khurmala) Dome of the *Kirkuk* structure, minor production occurs from Eocene (Avanah Formation) and Paleocene (Sinjar Formation) nummulitic carbonates. Al-Jawadi (1978, *in* Majid and Veizer, 1986) recorded a porosity of 5% and permeabilities of 0-10mD for Eocene rocks at *Kirkuk*. Limestone intervals in the Aaliji Formation at *Ain Zalah* (slope carbonates) have been described (Dunnington, 1958; Hart and Hay, 1974) as highly porous and sometimes oil saturated. Daniel (1954) noted that such facies in the *Kirkuk* field have generally poor reservoir characteristics and lack the excellent matrix porosities of the overlying Oligocene shoal/

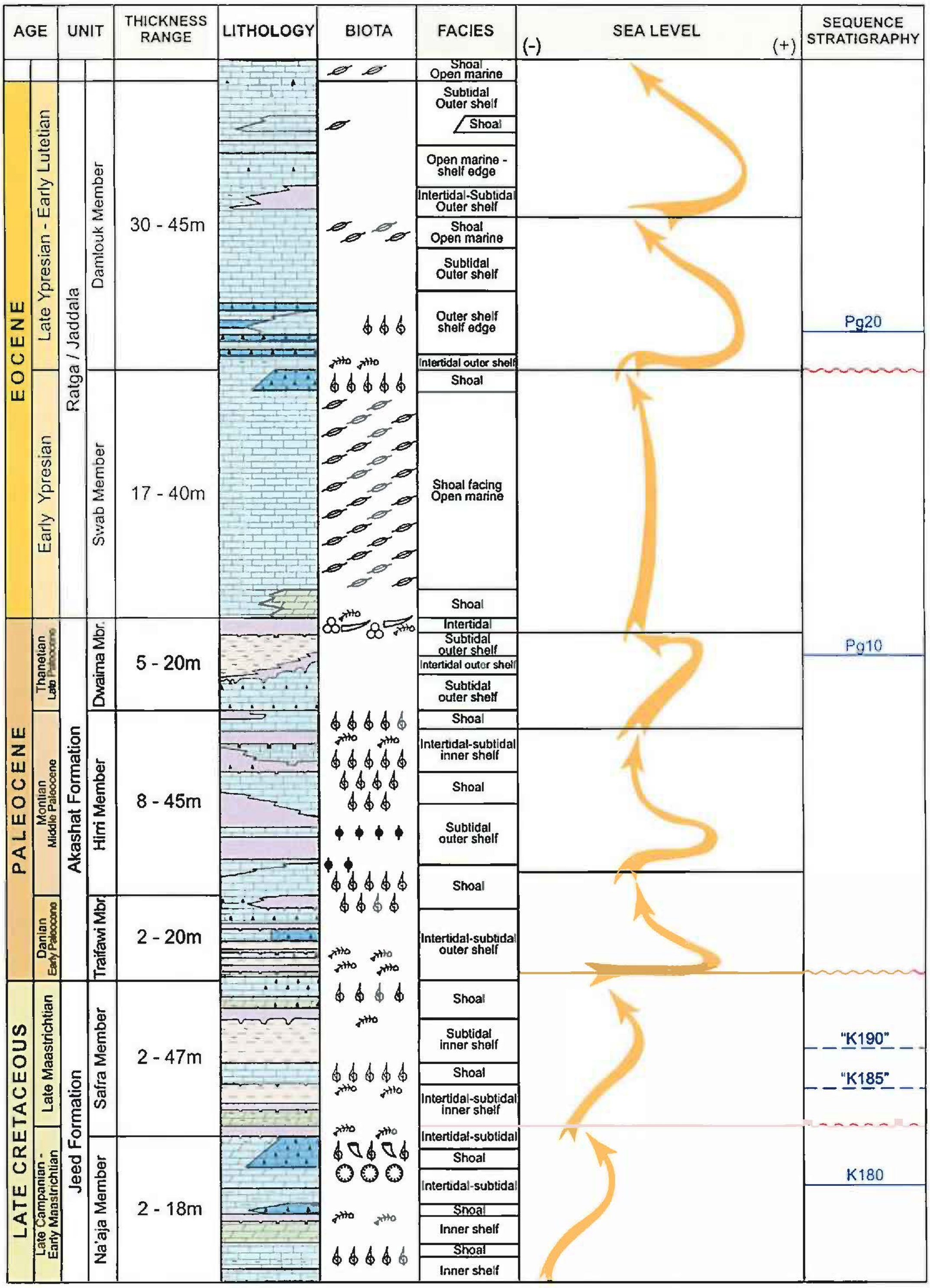


Fig. 8.14. Formations in the Western Desert. Stratigraphic column after Al-Bassam and Karim, 1992. Up to 15 beds of transgressive phosphorites are present and include mineralised hardgrounds together with porcellanites, coprolites and bone debris (Al-Bassam and Karim, 1992).

fore-reef facies, and also lack the fine fracturing often present in basinal facies.

The Pila Spi Formation forms a significant reservoir in NE Iraqi Kurdistan, particularly where overlying (Oligo-Miocene) shelfal carbonates are absent and it is overlain unconformably by the Lower Fars Formation. Reservoir potential occurs where the Pila Spi has been karstified for example at *Chemchemal-2* (IPC, 1956; Jassim and Buday, 2006g). The Pila Spi is believed to be one of the reservoirs at the recent *Tawke* discovery*. This suggests that a belt of Pila Spi Formation reservoirs may strike NW-SE to the NE of *Kirkuk*. Well *Chemchemal-2* reportedly flowed gas from the Pila Spi Formation (11 MM scf/d)**. The flow rate from the *Tawke-1* discovery is 5000 b/d* with 3840 b/d from *Tawke-2*. The siliciclastic-dominated Kolosh

**International Oil Letter/IHS News*, 19.6.06.
*** Sterling Energy, Financial Statement, 8/09.*

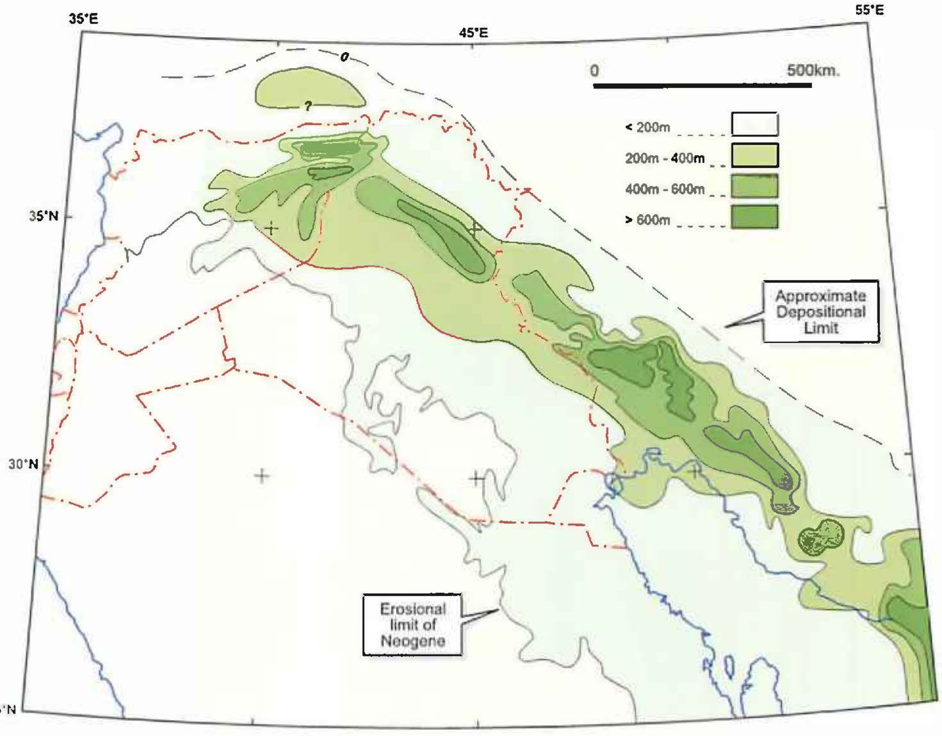


Fig. 8.15. Oligocene – lower Miocene isopach map (contours in metres) illustrating infill of the Mesopotamian Basin. The isopach defines a series of NW-SE trending sub-basins located within the centre of the Paleocene-Eocene basin illustrated in Fig. 8.9. After Goff *et al.*, 1995.

and Gerçus Formations, and siliciclastic intervals in the deepwater Aaliji and Jaddala Formations, may also have reservoir potential, particularly if fractured. However, the stratigraphic and sedimentological characteristics of these units are not sufficiently well understood for their reservoir potential to be properly evaluated.

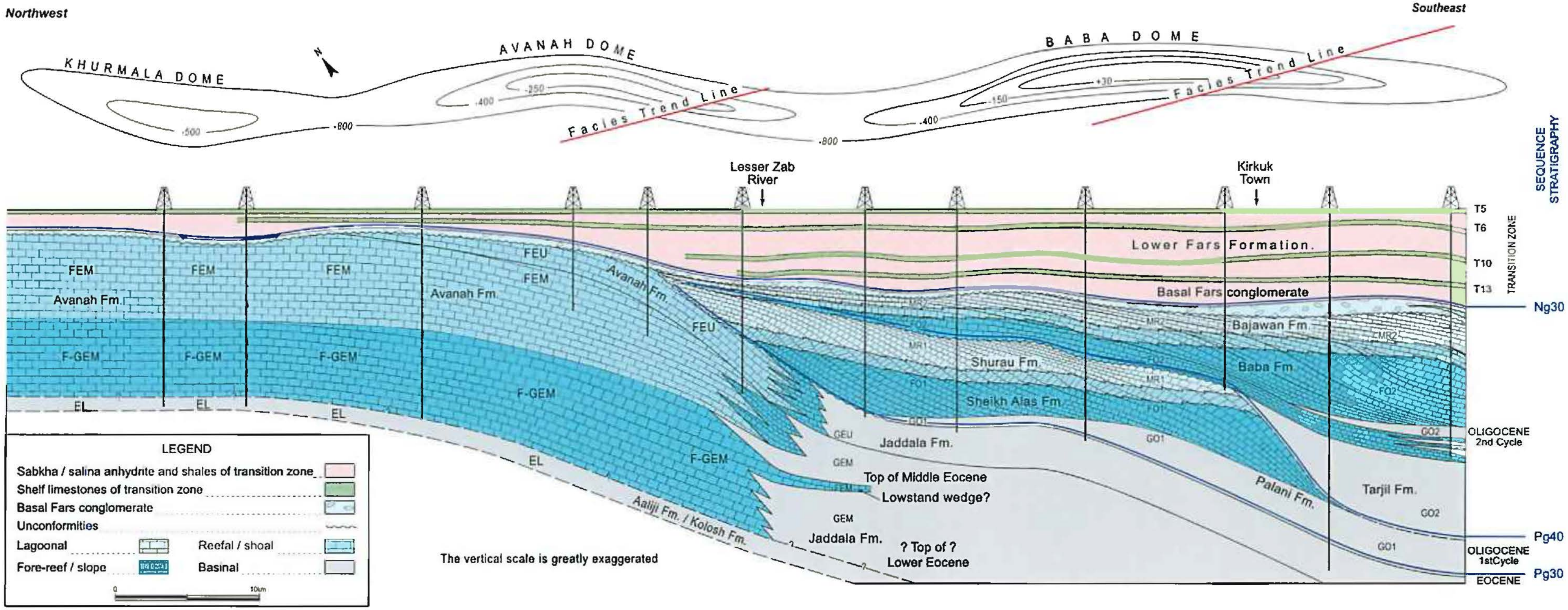
Proven and Potential Source Rocks

To date, no source rocks have been proven in this interval in Iraq, although Jassim and Al-Gailani (2006) suggested that the Aaliji Formation may have some source potential. In western Iraq, the Akashat and Ratga Formations, of Paleocene and Ypresian-Lutetian ages respectively, contain phosphatic units that are described as organic-rich. Although high organic contents may be associated with these formations, the facies belts may not extend sufficiently far eastwards to have source rock potential at depth. Samples from the Montian Hirri Member Phosphorite of the Akashat Formation at outcrop had a TOC of 2.14%, *Rock-Eval* S2 of 10.16 mg/g rock, HI of 474 mg HC/g TOC, and T_{max} of 415°C (Al-Bassam and Al-Haba, 1990). Samples of the Danian Traifawi Member shale and lime mudstone had a TOC of 1.68%, *Rock-Eval* S2 of 6.6 mg/g rock, HI of 382 mg HC/g TOC, and T_{max} of 412°C (Al-Bassam and Al-Haba, *ibid.*). Organic material is marine, related to high productivity reflecting high nutrient input associated with upwelling systems and the development of an oxygen-minimum zone at the base of the water column (Al-Bassam and Al-Haba, *ibid.*).Upper Eocene brown shales in the Pabdeh Formation, Iran, may also have some source potential (N. Pickard, *pers. comm.* to A.H., 2008).

Proven and Potential Cap Rocks

A major regional seal for the supersequence is provided by the unconformably-overlying Lower Fars Formation evaporites of Middle Miocene age. The Aaliji and Jaddala Formations, and shale units in the Kolosh Formation, may form seals in the basin centre above fractured Upper Cretaceous reservoirs in fields such as *Ain Zalah* (Hart and Hay, 1974; El Zarka, 1993), *Butmah*, parts of *Kirkuk* and the *Jawan-Qaiyarah-Najmah-Qasab* structure. A similar situation occurs in Iran, although the Pabdeh Formation is often fractured and does not form a significant barrier to upwards migration of Cretaceous-sourced oils into Asmari reservoirs (Bordenave and Huc, 1995). The sealing capacity of the Aaliji and Jaddala Formations will probably improve towards the SW away from areas of strong Zagros deformation, although the shale contents of these formations will be highest to the NE. Fracturing and failure of these Paleogene marl and shale seals may have occurred during Plio-Pleistocene compression, as proposed for Shiranish Formation seals (Dunnington, 1958).

The Rus Formation has the potential to seal Damman Formation reservoirs in SW Iraq, but is only known to function as a seal at the *Wafra* field, Kuwait (Beydoun, 1988b; Goff *et al.*, 1995).



MR2 Miliolid (lagoonal) and reef limestones of 2nd Oligocene cycle (Bajawan Fm.)
FO2 Fore reef (nummulitic and *Lepidocyclina*) limestones of 2nd Oligocene cycle (Baba Fm.)
GO2 Globigerinal (basinal) limestones of 2nd Oligocene cycle (Tarjil Fm.)
MR1 Miliolid (lagoonal) and reef limestones of 1st Oligocene cycle (Shurau Fm.)
FO1 Fore-reef (nummulitic and *Lepidocyclina*) limestones of 1st Oligocene cycle (Sheikh Alas Fm.)
GO1 Globigerinal (basinal) limestones of 1st Oligocene cycle (Palani Fm.)
FEU Shoal (nummulitic) limestones of Late Eocene age (Avanah Fm.)
GEU Globigerinal (basinal) limestones of Late Eocene age (Jaddala Fm.)
FEM Shoal (nummulitic) limestones of Middle Eocene age (Avanah Fm.)
GEM Globigerinal (basinal) limestones of Middle Eocene age (Jaddala Fm.)
F-GEM Globigerinal limestones with varying amounts of coarse-grade fossil detritus of Middle Eocene age (Avanah Fm.)
EL Thin bedded limestones and shales of ? Early Eocene age (Aaliji Fm. / Kolosh Fm.)

Fig. 8.16. Schematic NW-SE cross-section through the *Kirkuk* oilfield, showing the stratigraphic relationships of the producing Cenozoic reservoirs. Note the distinctive shingled (offlapping) geometries. Modified after Daniel (1954) and van Bellen (1956, 1959).

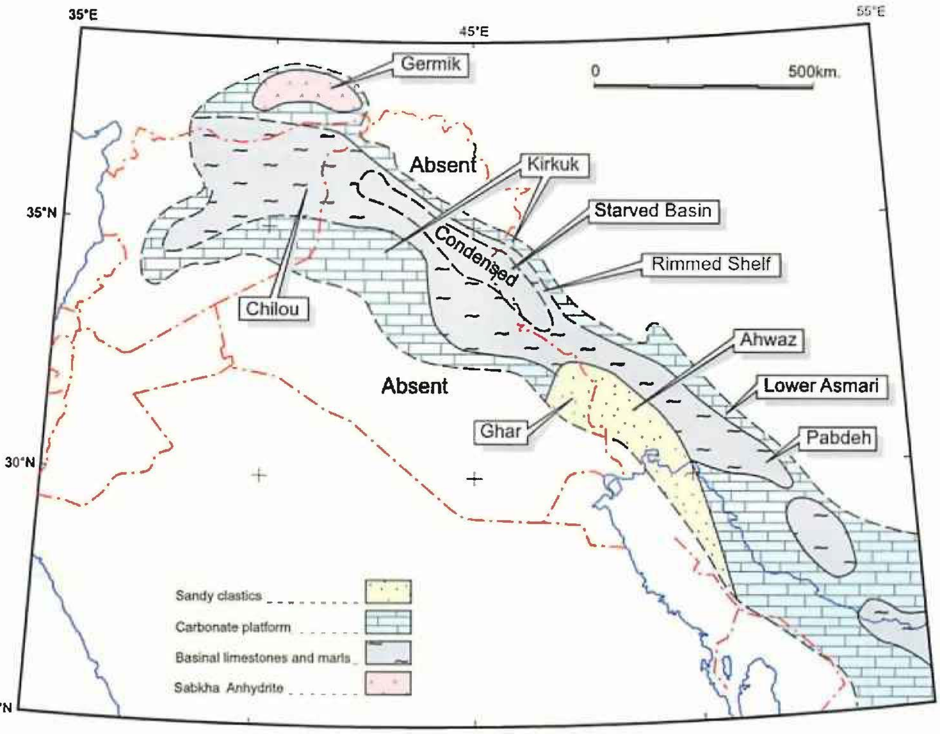


Fig. 8.17. Rupelian and early Chattian palaeogeography of Iraq, showing the infill of accommodation left after the end-Eocene regression; the starved basin centre is surrounded by narrow carbonate shelves. Modified after Goff *et al.*, 1995.

The Oligocene Supersequence

Isopach and facies maps of the Oligocene – lower Miocene show that deposition filled accommodation which was remaining after the Paleocene– Eocene (Fig. 8.15, 8.17). Up to 600 m of sediment is locally preserved (Goff *et al.*, 1995).

Oligocene units in Iraq are collectively known as the **"Kirkuk Group"** (Figs. 8.16, 8.17; Plates 8.9–8.13). The Group is composed of three sequences separated by the Pg30, Pg40 and Pg50 MFSs. These sequences can be differentiated biostratigraphically; *Lepidocyclina* is absent from the Pg30 sequence (Plate 8.12) and *Nummulites* only occurs in the lowest beds of the Pg50 sequence.

Each sequence is composed of three principal facies: reef/ back-reef (lagoonal); fore-reef; and basinal (Daniel, 1954; van Bellen, 1956, 1959). In an ideal composite succession from the top down, the Kirkuk Group therefore consists of the following formations:

Anah Formation: back-reef / reef;
Azkand Formation: fore-reef;
Ibrahim Formation: basinal, Pg50 MFS;
Bajawan Formation: back-reef / reef;
Baba Formation: fore-reef;
Tarjil Formation: basinal, Pg40 MFS;
Shurau Formation: back-reef / reef;
Sheikh Alas Formation: fore-reef; and
Palani Formation: basinal, Pg30 MFS.

However, only parts of the succession are present at any one location (Plate 8.9). The facies are characterized by distinct faunal assemblages (Henson, 1950a,b; van Bellen, 1956, 1959; Al-Qayim and Khaiwka, 1980; Al-Hashimi and Amer, 1985; Majid and Veizer, 1986; Al-Eisa, 1992b) (Fig. 8.18).

Back-reef (lagoonal) facies form part of the Anah, Bajawan and Shurau Formations (Plate 8.10) and comprise well-cemented bioclastic limestones with elements of reef debris and well-rounded bioclasts. *Miliolidae* and *Peneroplidae* are common together with corals and algae (Henson, 1950a,b; Al-Hashimi and Amer, 1985). Karstification has resulted in blue clay-plugged karstic pipes and caverns (Daniel, 1954), although porosity generation is minor.

Reef-zone facies occur in the Anah, Bajawan and Shurau Formations. They comprise heterolithic unbedded limestones with colonial corals and algae (Plate 8.11). *Rotaliidae* are characteristic foraminifera (Henson, 1950a,b). Lower and upper Oligocene reefal facies prograded only some 9 km and 13 km, respectively, in the *Kirkuk* area (Henson, 1950a,b; van Bellen, 1956). Here a shingled platform geometry developed (Fig. 8.16), controlled by the updip presence of former Eocene shelf margins which had strong palaeo-topographic relief (Majid and Veizer, 1986) (Fig. 8.19). Depending on sequence stacking patterns, Aquitanian lagoonal facies (Anah Formation) may locally occur, for example at Shiranish Islam in northern Iraq, and overlie Pila Spi Formation limestones (van Bellen, 1959). Oligocene shelf and shelf margin units appear to stack vertically in the Khanaquin area near the Iranian frontier (Hradecky *et al.*, 1978).

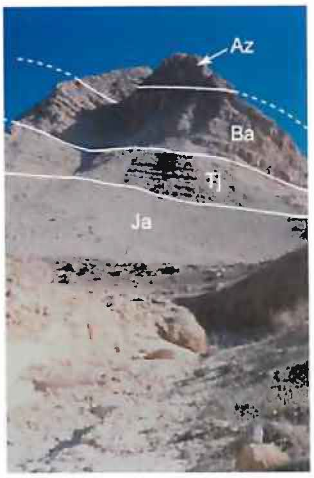


Plate 8.9. Eocene Jaddala Formation (Ja) overlain by the Tarjil (Tj), Baba (Ba) and Azkand (Az) Formations of the Kirkuk Group, indicating basin fill culminating with fore-reef carbonates. Location: Qarah Chauq anticline, south of *Kirkuk*. Photo by M. Tucker.

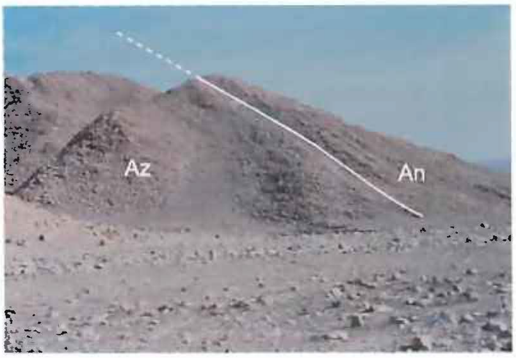


Plate 8.10. Bedded Anah Formation lagoonal grainstones (to right, An) and more massive Azkand Formation bioherms (Az). Location: Qarah Chauq anticline, south of *Kirkuk*. Photo by M. Tucker.

Plate 8.11. Coral bioherm in the Anah Formation. Location: Qarah Chauq anticline, south of *Kirkuk*. Photo by M. Tucker.

The *fore-reef to slope facies* of the Kirkuk Group are assigned to the Azkand, Baba and Sheikh Alas Formations (van Bellen, 1959). Fore-reef deposits comprise porous or calcite-cemented detrital limestones composed of angular calcareous debris from reefs and indigenous organisms, deposited below wave-base. Echinoids, *Nummulites* and orbitoid foraminifera are abundant (Plate 8.12). Algal patches may occur (Henson, 1950a,b). Lower energy facies comprise *Lepidocyclina* wackestones of the Baba Formation (Al-Hashimi and Amer,1985). A slope facies in *Kirkuk* consists of oil-stained limestones which have undergone selective recrystallisation (Daniel,1954). They are similar to the fore-reef facies except for their finer grain-size and relatively low permeability. The facies is typically massive and lacks the jointing recorded in the globigerinal limestones.

The *basinal (globigerinid limestone) facies* of the Kirkuk Group comprise planktonic foraminiferal wackestones of the Palani Formation (Al-Hashimi and Amer, 1985, their Plates 88-90), and foraminiferal wackestone of the Tarjil Formation (their Plates 102-104) and Ibrahim Formation. The Ibrahim Formation at its type section (well *Ibrahim-1*) was dated as Oligocene (van Bellen, 1959). This age was re-confirmed by Al-Hashimi and Amer (1986) whose data clearly showed that the upper part falls in the planktonic zone P22/N3 (Chattian, late Oligocene) based on the top occurrence of *G. selli* and *G. nana* (*re-evaluation by G. Laursen*), despite publications to the contrary (e.g. Al-Eisa,1992a). Some recrystallisation has occurred in the basinal facies but is insignificant compared to that in the fore-reef facies. Joints are common and the degree of jointing, rather than matrix porosity, controls the reservoir quality of this unit (Daniel, 1954).

Karstic fabrics resulting from late Oligocene - Miocene subaerial exposure include recrystallised nummulitic (fore-reef) limestones which are typically highly porous and permeable, together with reefal and back-reef limestones (Henson, 1950a,b, his Figures 1-7). These massive beds are "almost invariably" oil stained (Daniel, 1954). Limestones have been selectively recrystallised; some intervals with coarse-grained bioclasts (molluscs and nummulites) have been replaced by crystalline calcite, and have regular porosity and permeability. Where recrystallisation is more complete, large isolated vugs and cavities have formed due to the dissolution of fossils. Other intervals remain unrecrystallised and have a high primary porosity (Daniel, 1954).

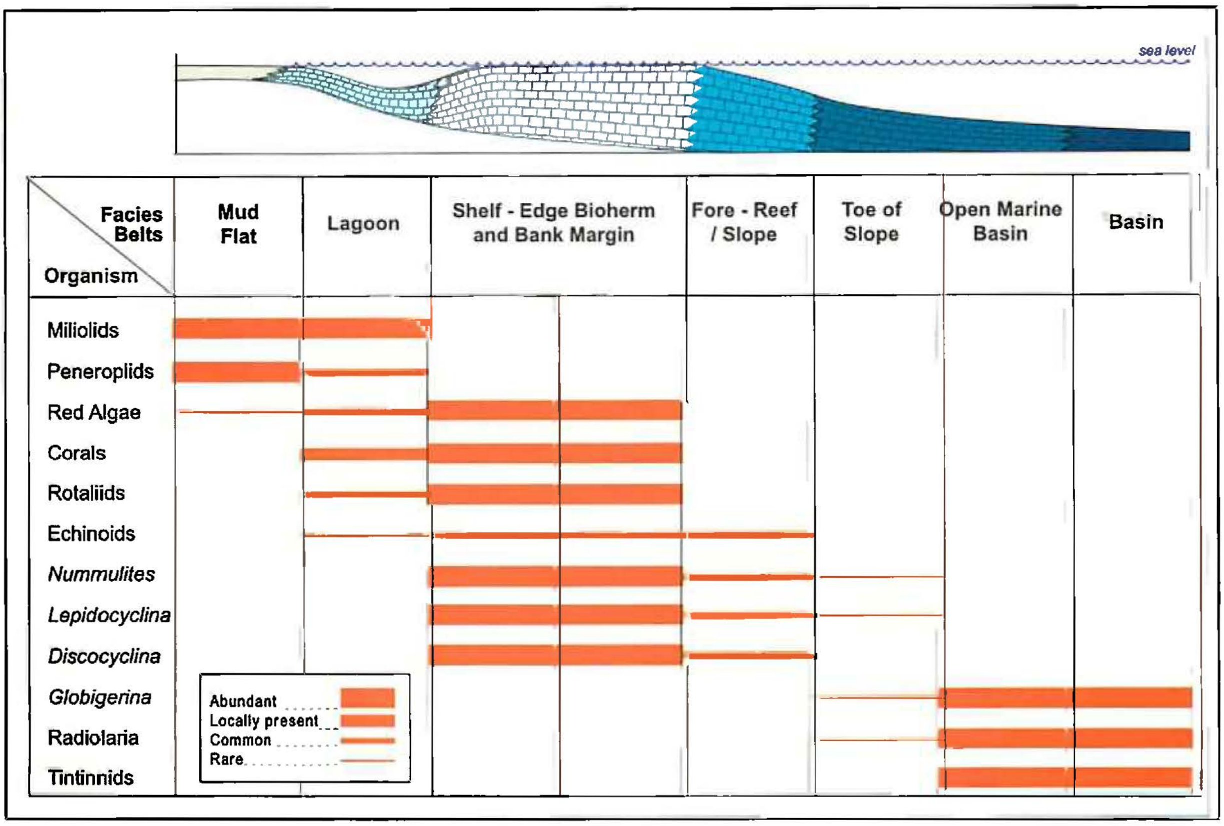


Fig. 8.18. Facies belts and biota in the Kirkuk Group (generalized for the whole of the Paleogene). After Majid and Veizer, 1986.

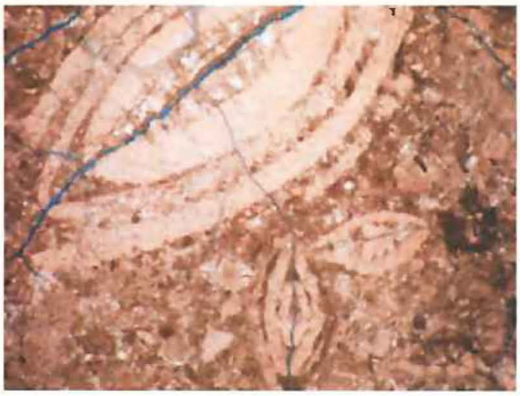


Plate 8.12. Photomicrograph of nummulitic packstone of the Sheikh Alas Formation; sample from Aj Dagh near Sulaimaniya, Iraqi Kurdistan. Note the presence of *Nummulites* (*N. vascus*?) but not *Lepidocyclina* which is indicative of the early Oligocene. Photo and bioclast identification by S. Packer; image courtesy of Sterling Energy Ltd. Field of view 5 mm.

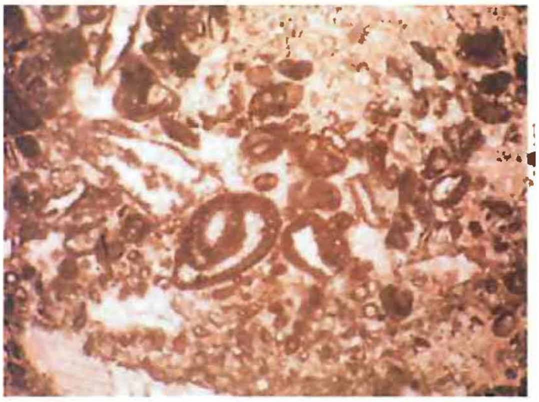


Plate 8.13. Photomicrograph of foraminiferal pack-grainstone of the Bajawan Formation; sample from the NW plunge of the Sangaw Anticline near Sulaimaniya, Iraqi Kurdistan. Note the presence of *Austrotrillina howchini* (centre of field) together with peloids and echinoderm fragments. Photo and bioclast identification by S. Packer; image courtesy of Sterling Energy Ltd. Field of view 5 mm.

Petroleum System Components

Proven and Potential Reservoir Rocks

It was originally suggested (e.g. Henson, 1950a,b; Freeman and Natanson, 1959) that production from the Kirkuk Group comes mainly from reefal carbonates. However the reefal facies are generally tight. Most production actually comes from fore-reef facies (mostly nummulitic limestones) which are variably recrystallized and partially dolomitised.

The highest porosities and permeabilities are associated with saccharoidal textures of recrystallised calcite and dolomite, enhanced by fissures, caverns and joints (Daniel, 1954). Coring at the *Kirkuk* oilfield rarely recovered more than 30% of the rock, and routine coring was at one stage abandoned because the recovered fragments were not considered representative of the most porous reservoir intervals (Daniel, 1954; IPC, 1956).

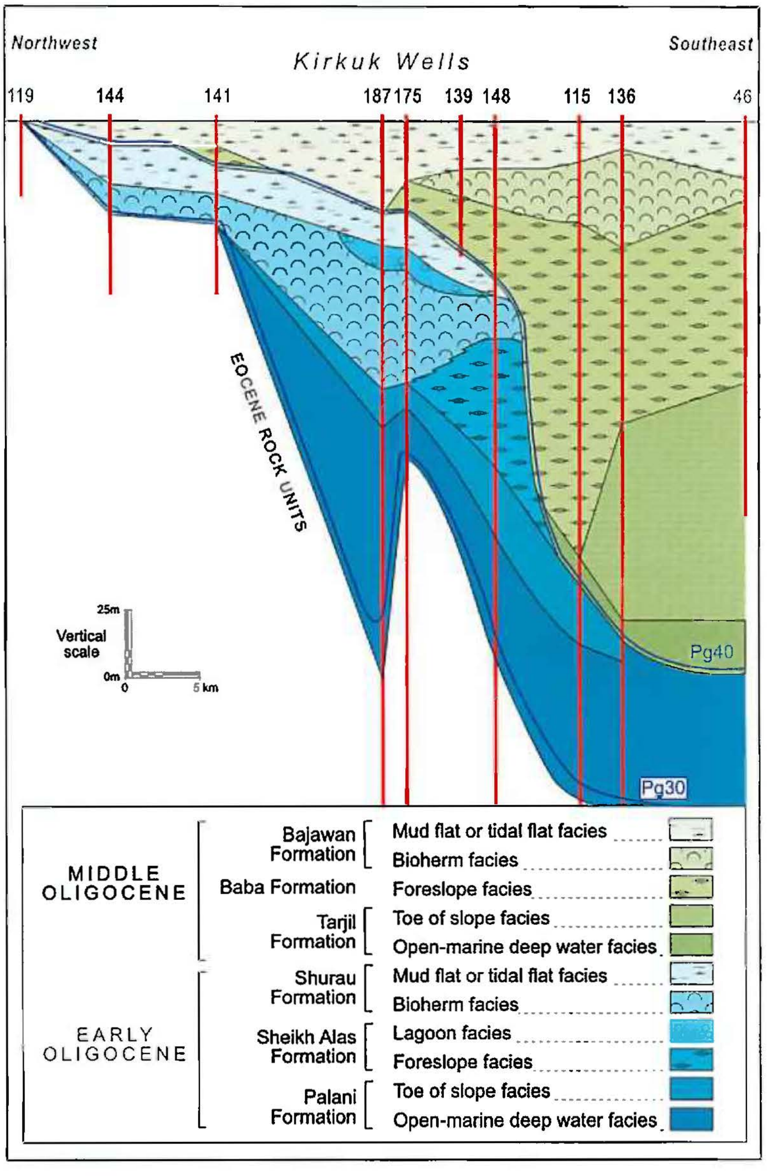


Fig. 8.19. Early and middle Oligocene facies in the *Kirkuk* field. After Majid and Veizer, 1986.

At *Kirkuk*, productive fore-reef deposits are assigned to the upper Oligocene Baba Formation and the lower Oligocene Sheikh Alas Formation. In the Baba Formation, the porosity averages 8% and permeability is 20 to 30 mD; in the Sheikh Alas Formation, porosity averages 8% and the permeability is 100 to 200 mD (Majid and Veiser, 1986). Daniel (1954) divided the reservoir on the basis of facies (see Fig. 8.16) and recorded their reservoir properties (Table 8.1). Production comes from similar reservoir units at the *Bai Hassan* field (Dunnington, 1967). Daniel (1954) noted that production at *Kirkuk* from basinal facies comes from dual-porosity systems in which matrix porosity of 4-20% is associated with fracturing. He also recorded the presence of cavernous zones which consumed large volumes of loss-control material. By contrast, the dense, well-cemented lagoonal to reefal facies (Shurau and Bajawan Formations, respectively) have little reservoir potential, with 0-4% porosity where unaltered and 4-10% porosity where recrystallised and/or dolomitised, with permeability of up to only 5 mD. The deeper-water slope and basinal facies developed towards the SE have 8-18% porosity but permeability of only up to 10 mD (Daniel, 1954). Pores in the basinal facies are on average smaller than those in other facies (Daniel, 1954).

The offlapping Oligocene stratigraphy, and the distribution of the principal facies (basinal, fore-reef, reef/lagoonal) within each sequence, controls the reservoir architecture in the *Kirkuk* field. The principal controls on development of reservoir quality are subaerial exposure and karstification which occurred during later Oligocene and early Miocene time, together with tectonic fracturing and jointing (Daniel, 1954; Majid and Veizer, 1986).

The Kirkuk Group has significantly higher reservoir qualities than the age-equivalent Asmari Formation in Iran (Saidi, 1987). Asmari reservoirs, for example at *Masjid-i Suleiman*, require both matrix porosity and fracture systems to be present in order to achieve sustained high production (Gibson, 1948); by contrast, the Kirkuk Group reservoir would still be exceptional if either matrix or fracture-related porosity was poor.

Table 8.1. Reservoir properties of facies in the *Kirkuk* field. After Daniel (1954) and Jassim and Al-Gailani (2006).

Facies *(from Daniel, 1954)*	ϕ (%) *(measured)*	*k* (mD) *(estimated)*
Transition Zone Limestones	0 - 30 (av. 15%)	about 100
Porcellanous reef / back-reef facies	0 - 4	0 - 5
Diagenetically altered reef / back-reef	4 - 10	not available
Partly recrystallised fore-reef facies	18 - 36	50 - 1000
Globigerinal micrites	8 - 18	0 - 10
Globigerinal micrites with turbidites	4 - 20	not available

Recent publications (e.g. Aqrawi *et al.*, 2006a; Wennberg *et al.*, 2006; Aqrawi and Wennberg, 2007) have emphasised the importance of dolomitisation and fracturing in the Asmari Formation as a factor enhancing the original reservoir quality. However, dolomitisation does not appear to be significant in the Kirkuk Group (c.f. van Bellen, 1959; Majid and Veizer, 1986) although it was discussed in conjuction with neomorphism/recrystallisation by Al-Qayim and Khaiwka (1980).

Proven and Potential Source Rocks

No source rocks are known from this interval in Iraq, although high API gamma intervals in basinal facies may indicate some source potential (N. Pickard, *pers. comm.* to A. H., 2008).

Proven and Potential Cap Rocks

There are no regional seals in this interval.

The lower Miocene Supersequence

Towards the end of the Oligocene, the basin system became restricted probably due to tectonic movements along the Zagros margin and progradational infill by Oligocene – Aquitanian shelf deposits. Restriction in the basin centre led to deposition of evaporites and conglomerates, initially the "Basal Anhydrite" and its correlative the Hamrin Formation (Al-Banna and Amin, 2000; Ahmad and Al-Eisa, 2003) and then the Aquitanian Dhiban Formation. Between these two units, the open-marine and organic-rich Serikagni Formation was deposited.

The **"Basal Anhydrite"** (Fig. 8.20) rests directly on the Ibrahim Formation. It is a key marker bed in Iraq. The Anhydrite represents the first total desiccation of the basin system. It is rarely more than 4-5 m thick in Iraq, although it may be 100 m or more thick where it passes into halite in Syria. It also occurs in Iran (A.H., *pers. obs*).

The overlying **Serikagni Formation** (Fig. 8.21) is 40 m thick in well *Hamrin-2* (Al-Juboury *et al.*, 2007). It includes a basal *Operculina-Globigerina* unit with planktonic foraminifera; and an upper unit containing an increased proportion of coralline red algae and other reef-constructing organisms (van Bellen, 1959; Al-Juboury *et al.*, 2007).

In the stratigraphically complete *Pulkhana-5* well, the basal part of the Serikagni Formation has been dated using nannofossils as Chattian (Starkie, 1994). The remainder of the formation contains early Aquitanian nannofossil assemblages (Starkie, 1994). Micropalaeontological data (Al-Hashimi and Amer, 1986) indicate the planktonic Zone N4 (Aquitanian) based on the first occurrence of *G. kugleri* and *G. primordius* (*re-evaluation courtesy of G. Laursen*). The Serikagni Formation is therefore correlative with the upper part of the Pabdeh Formation of Iran, in which the lowermost part of the "Brissopsis Beds" above the Basal Anhydrite yielded an Oligocene macrofauna in outcrops at Kuh-e Asmari (Thomas, 1950). Upper parts of the "Brissopsis Beds" beneath the Kalhur Anhydrite in Lurestan contain "lower Aquitanian" planktonic foraminifera. Thomas (1950) noted that *Miogypsina,* an index macrofossil for the early Miocene (although sometimes of late Oligocene age elsewhere: Drooger, 1963; Adams, 1973; Frost and Langheim, 1974) first occurs above the "Basal Anhydrite" at Kuh-e Asmari. *Miogypsina* also occurs in the Serikagni Formation in the *Kirkuk* area (Al-Naquib, 1960). These observations, together with supporting Sr isotope dates (Ehrenberg *et al.*, 2007; van Buchem *et al.*, 2010), suggest that the "Basal Anhydrite" and basal Serikagni Formation are of latest Oligocene age. This contrasts with recent re-interpretations of these units (e.g. Al-Eisa, 1992a) as later Miocene.

The shelf carbonate which is equivalent to the Serikagni Formation is the **Euphrates Limestone Formation** (Fig. 8.21). This formation reaches a maximum thickness of over 50 m at the Jambur structure where it is thickest at the expense of the underlying Serikagni Formation (Al-Juboury *et al.*, 2007). A similar stratigraphic succession indicating upward-shallowing has been recorded on Jebel Sinjar (Abawi, 1989). On the NE margin of the basin, a narrow belt of these shelf carbonates extend, apparently as a forced regressive wedge, further into the basin than the Oligocene shelf margins. In the SW of the basin, the Euphrates Limestone unconformably and

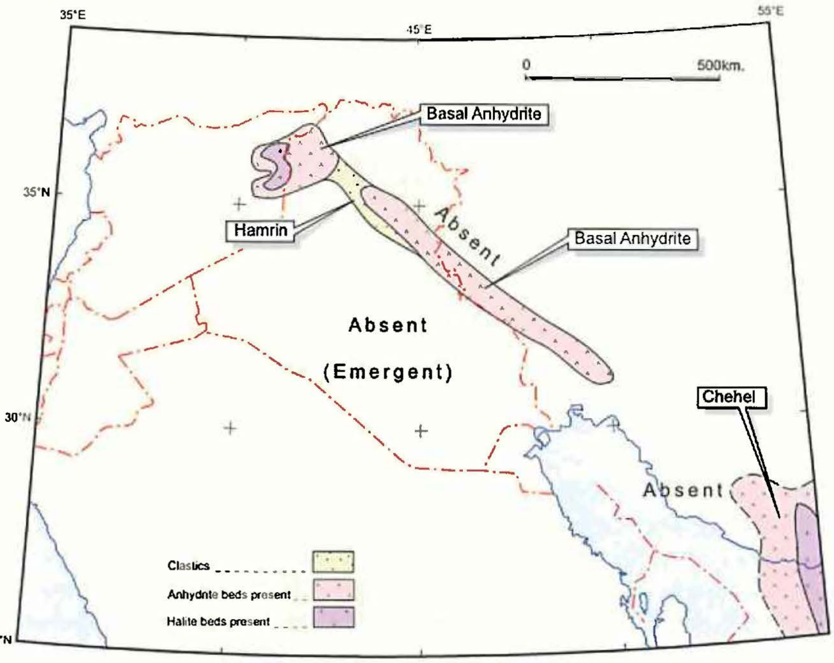


Fig. 8.20. Late Chattian palaeogeography of Iraq, showing the initial drawdown of the central basin which trends NW-SE through Iraq and Syria and its partial infill by anhydrites and locally by halite. Evaporitic depocentres were separated by emergent areas and conglomerates/ breccias. Modified after Goff *et al.*, 1995.

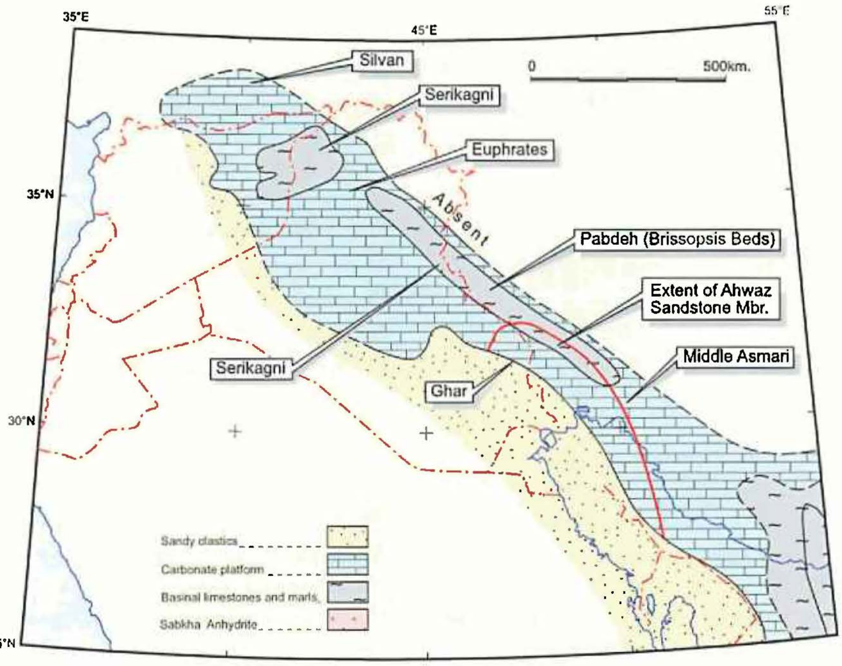


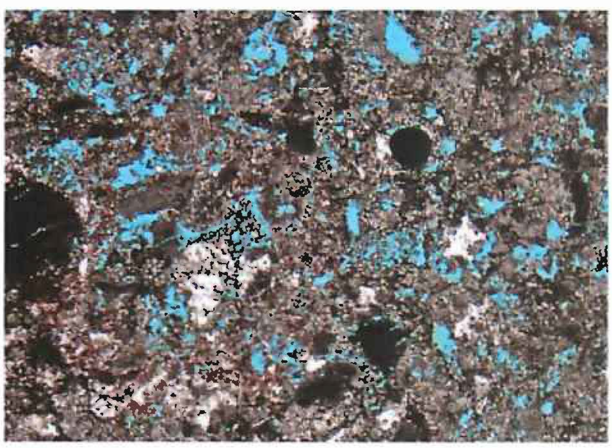
Fig. 8.21. Latest Chattian – early Aquitanian palaeogeography of Iraq, showing almost complete infill of the central basin which is bordered by carbonate shelves. To the SW are shoreline and redbed clastics which are derived from the uplift and opening of the Red Sea. Modified after Goff *et al.*, 1995.

extensively oversteps the Damman Formation (Al-Naqib, 1967) (Fig. 8.6). Facies identified by Al-Juboury *et al.* (2007) include fossiliferous packstones dominated by benthic foraminifera together with gastropods, algae and non-skeletal components such as oolites and pellets. The limestones are commonly early dolomitized and evaporitic (Banat and Al-Dyni, 1981) (Plate 8.14), particularly near the contact with the Dhiban Formation (Sun, 1992). Bioclasts include rhodoliths (Plates 8.15, 8.16) and sometimes planktonic foraminifera (Plate 8.17) which often indicate periods of platform drowning in Cenozoic carbonates (A.H., *pers. obs.*).

The Khleisia-Mosul uplifts may have formed an important bio-provincial boundary. Thus Jassim and Buday (2006g), after Ponikarov *et al.* (1967) and Powers *et al.* (1966), noted that *"the*

Plate 8.14 (above left). Core of the Euphrates Formation comprising vuggy dolomite with sulphur filled porosity. Well *Jawan-10*. Photo by A. Horbury.

Plate 8.15 (above right). Core of the Euphrates Formation from well *Qaiyarah-55* composed of rhodolith limestones. Photo by A. Horbury.



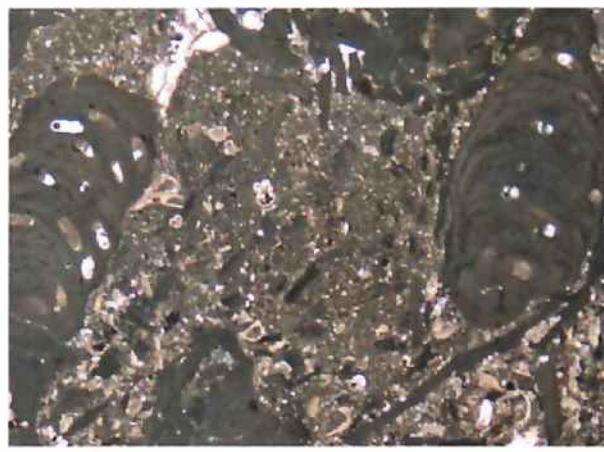


Plate 8.16 (above left). Photomicrograph of dolomitised Euphrates Limestone in Plate 8.14 from well *Jawan-10*. Note intercrystalline porosity (blue) and scattered coralline red algal thalli (darker areas). Photo by F. Witkowski.

Plate 8.17 (above right). Photomicrograph of the Euphrates Limestone in Plate 8.15 showing coralline red algae and globigerinid foraminifera, suggesting a deeper-water shelf environment. Photo by F. Witkowski.

NW basin clearly belonged to the Mediterranean faunal province ... whereas the SE basin belonged to the eastern Indopacific bioprovince". Prazak (1978) similarly discussed the appearance of Miogypsinid faunas from the Indo-Pacific realm during the deposition of the Euphrates Limestone and Lower Fars Formations, while oyster faunas in the Euphrates Formation have Mediterranean affinities.

The **Dhiban Formation** has a similar distribution to the "Basal Anhydrite" and fills inherited accommodation in the basin centre (Fig. 8.22). It reaches a thickness of 173 m in well *Qumar-1* (Al-Juboury *et al.*, 2007), contrasting with the Basal Anhydrite which is typically only a few metres thick. Facies in the Dhiban Formation comprise laminated to massive anhydrites, and halite occurs locally in the basal part of the unit (Al-Juboury *et al.*, 2007). The formation is only known at outcrop from its type section at Jebel Sinjar in NW Iraq (van Bellen, 1959), although marly beds occurring between the Euphrates and Jeribe Formations in the Euphrates Valley were assigned to this unit by Prazak (1978). The Dhiban Formation represents a final stage of infill of basin centre accommodation which in SE Iraqi Kurdistan had originated in the Aalenian with the deposition of the earliest portion of the Sargelu Formation.

The final Burdigalian unit below the Lower Fars Formation is the **Jeribe Limestone Formation** (Figs 8.23, 8.24; Plate 8.18). It was deposited relatively uniformly throughout the basin. A maximum thickness of 63 m was recorded at well *Injana-5* by Al-Juboury *et al.* (2007). In the basin centre, cycles 1 to 10 m thick occur in which porous open-marine carbonates are interbedded with relatively tight, restricted marine carbonates and evaporites (e.g. in the *East Baghdad* field; Al-Murani, 1986 *in* Sun and Esteban, 1994) (Fig. 8.23). Microfacies are dominated by generally low-energy mudstones to wackestones with some packstones in Iraq (van Bellen, 1956, 1959; Sun and Esteban, 1994; Al-Juboury *et al.*, 2007), and in the *Jebissa* field in Syria (Philip *et al.*, 1972). Al-Juboury *et al.* (2007) recorded a succession in NE Iraq passing upwards from an "echinoderm unit" to a "miliolid unit"with a local "echinoderm-gastropod unit" at the top. Fossils (van Bellen, 1956, 1959; Al-Naquib,1960) include coralline red algae (*Lithophyllum* and *Lithocodium*), foraminifera

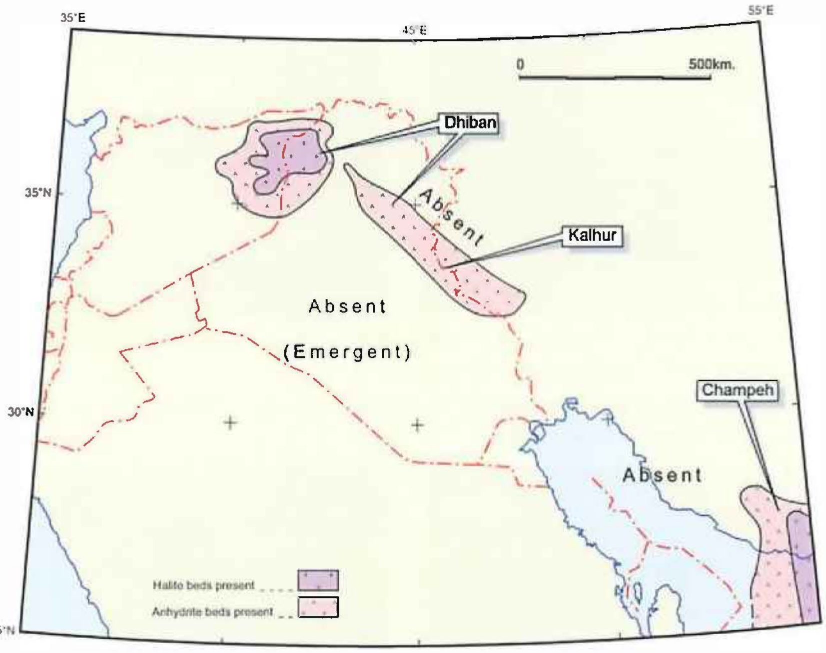


Fig. 8.22. Middle Aquitanian palaeogeography of Iraq, showing deposition of anhydrite and halite in the central basin which trends NW-SE through Iraq and Syria. Evaporitic depocentres were separated by emergent areas. Modified after Goff *et al.*, 1995.

Plate 8.18. Secondary porosity (evaporite collapse breccia) in the Jeribe Formation. Jebel Sinjar, northern Iraq. Photo by M. Tucker.

(*Dendritina* sp., *Spirolina* sp., *Miogypsina* sp., *Asmaria* sp., *Textularia* sp., *Amphistegina* sp., *Elphidium* sp., *Nonion* sp., *Miliolidae*, *Neoalveolinidae* including the first appearance of *Borelis melo* var. *curdica*, also *Rotalidae* including *R.beccarii*), chilostomelids, dendritinids, ostracods, fragments (moulds) of gastropods and lamellibranchs (see plates in Sun, 1992; Sun and Esteban, 1994), echinoids, *Microcodium* and "difficult to identify" brachiopods (possibly mis-identified oysters: A.H.) with fenestral fabrics in some facies. Grainstones are absent from the succession at *Jebissa* field (Philip *et al.*, 1972).

The Jeribe Formation probably represents an upward-shallowing carbonate ramp sequence. Cycle stacking (Fig. 8.23) suggests that another sequence is present locally at its top. The formation may be equivalent to the upper part of the Middle Asmari and the Upper Asmari of Iran, as defined by James and Wynd (1965) and Motiei (1993).

A unit known as the **Govanda Formation** occurs along the Zagros basin margin (Fig. 8.24). It comprises a 6 m thick basal conglomerate passing up into red pebbly sandstones and mudstones, overlain by 20 m of sandy limestones with abundant reworked Cretaceous fossils, overlain in turn by 80-90 m of shallow-water limestones. The unit probably represents shelf to reefal carbonate deposition. It onlaps units as old as Albian (Qamchuqa Formation), as indicated by field relationships and ages of the clasts in the basal conglomerate (van Bellen, 1959).

In southern Iraq, siliciclastics of the **Ghar Formation** (Fig. 8.21) are the updip equivalent of the Ahwaz Sandstone Member of the Asmari Formation (Al-Juboury *et al.*, 2010). They probably represent transgressive and highstand systems tract deposition related to the Ng10 and Ng20 maximum flooding events of Sharland *et al.* (2001, 2004). The Ghar Formation overlies the Euphrates Limestone (Karim and Al-Atia, 1992). Although older "Ghar" sandstones may have been deposited, they were largely reworked, or bypassed the Kirkuk Group carbonate shelf, and were deposited / redeposited during lowstands in the deeper parts of the Asmari Basin in Iran (c.f. Motiei, 1993). The Ghar Formation was deposited within a major fluvial system originating in the uplifted west and SW margin of the Arabian Plate (Al-Juboury *et al.*, 2010). It consists of stacked fining-upward cycles comprisng pebbly alluvial-fan sandstones and calcareous shallow-marine sandstones and dolomites. Karim and Al-Atia (1992) interpreted the presence of marsh deposits in the formation. The Arabian Shield had been uplifted rapidly as a consequence of thermal doming at ca. 25 Ma, prior to and immediately following the opening of the Red Sea rift (Gass, 1970).

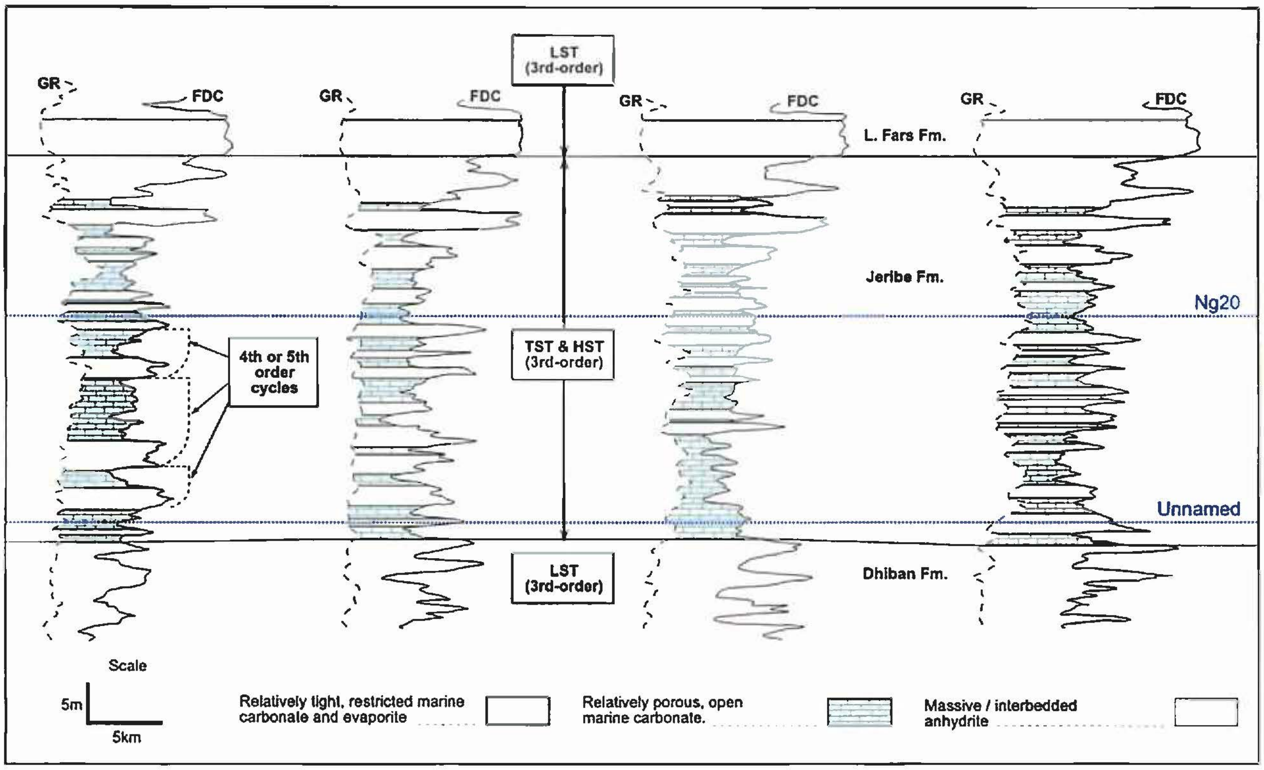


Fig. 8.23. Cyclicity in the Jeribe Formation in the basin centre (probably at *East Baghdad* field), showing the strongly layered nature of the reservoir (Sun and Esteban, 1994; after Al-Murani, 1986).

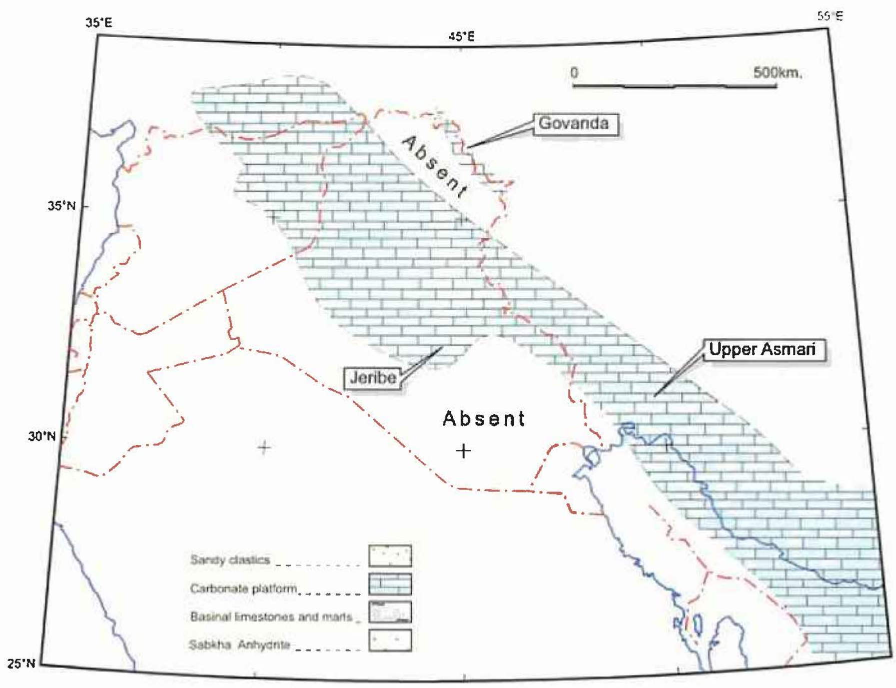


Fig. 8.24. Late Aquitanian – early Burdigalian palaeogeography of Iraq, showing the re-establishment of a carbonate shelf across the former basin centre, together with carbonate deposition in the developing foreland basin to the NE. Modified after Goff *et al.*, 1995.

At the top of the sequence, the contact between the Jeribe and overlying Lower Fars Formations appears conformable in the basin centre. A similar relationship between the Upper Asmari and Gachsaran Formations occurs to the SE in Iran (Thomas, 1950). However, a locally significant unconformity occurs along the Zagros basin margin where progressively younger units of the Lower Fars Formation onlap Oligocene and then Eocene units, for example in the NW of the Kirkuk structure (Daniel, 1954) (Fig. 8.16). This may indicate uplift of the NW part of the Kirkuk structure during the Oligocene – early Miocene.

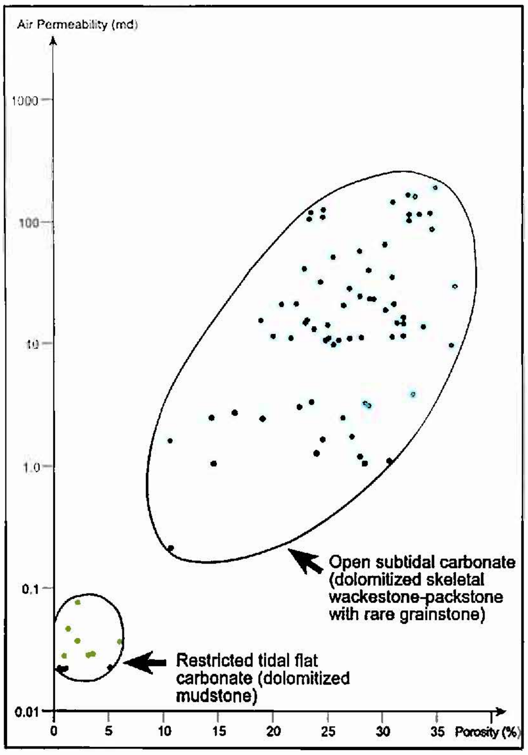


Fig. 8.25. Reservoir quality of the Jeribe Formation in central Iraq. From Sun and Esteban, 1994.

Petroleum System Components

Proven and Potential Reservoir Rocks

Jassim and Al-Gailani (2006) reported that the Euphrates Formation has a porosity of 15 to 30% (mean: 20%) with permeabilities of 8 to 500 mD (mean: 10 mD). Pore systems are related to both remnant primary and secondary porosity due to dolomitisation (see Plates 8.14 and 8.16).

The reservoir quality of the Euphrates and Jeribe Formations was discussed by Sun and Esteban (1994). In Central Iraq, these carbonates have porosities of 10-35% and permeability ranging from 1 to several hundred mD in open-marine facies; tidal flat facies are very tight (Fig. 8.25). Optimum reservoir quality occurs in mud-lean skeletal packstones with leached mouldic and vuggy porosity, or oolitic pack-grainstones with primary intergranular porosity, and in coarsely crystalline dolomites. Sun (1992) suggested that dolomitisation occurred when the Euphrates and Jeribe Formations were exposed to saline brines following transgressions across the carbonate platforms. The descriptions of Banat and Al-Dyni (1981) indicate that the Euphrates Formation is more strongly dolomitised than the Jeribe Formation.

Jassim and Al-Gailani (2006) noted that the Jeribe Formation has a porosity of 14 to 21% (mean: 17%) with permeabilities of 1 to 1146 mD (mean: 200 mD). In facies which were originally packstones, dolomitisation has created porosities of up to 38% (mean: 23%) and permeabilities of up to 200 mD (mean: 10 mD). Dolomitised mudstones have poorer reservoir qualities (Al-Murani, 1986; Sun and Esteban, 1994) (Fig. 8.25).

The Jeribe Limestone Formation is up to 60 m thick and forms a poor-quality reservoir in NE Syria at the *Jebissa* field (Metwalli *et al.*, 1972). Secondary (mouldic) porosity, typically ranging from 17 to 28% (at depths of 500-600 m) was recorded from bioclastic packstone and dolomitised facies in the Jeribe Limestone by Philip *et al.* (1972). Dolomitic facies commonly have lower porosities (10-15%) due to anhydrite cementation. Micritic lithologies (mudstones and wackestones) have porosities below 10% (Philip *et al.*, 1972). In the Euphrates Graben of Syria, the Jeribe Formation contains minor pools of oil; for example in well *Thayyem-1X*, a 14 m column tested oil at modest rates (de Ruiter *et al.*, 1995).

Minor production may occur from fractured Serikagni Formation limestones. In the *Jebissa* area of Syria, Metwalli *et al.* (1972) reported that the equivalent Chilou Formation contains bitumen in fractures and joints. The upper part of the Dhiban Formation is an effective reservoir at well *Jebissa-7* (Metwalli *et al.*, 1972).

The deltaic sandstones of the Ghar Formation form a shallow reservoir in SE Iraq. Similar sandstones occur in the Ghar Formation in Kuwait, and in the Ahwaz Sandstone Member of the Asmari Formation in Iran described by Shanor *et al.* (1993). Diagenesis of the Ghar was described by Al-Juboury *et al.*(2010) who noted that dolomite cementation was the main cause of porosity occlusion.

Proven and Potential Source Rocks

To date, no source rocks have been proven from this supersequence in Iraq. However, organic-rich, high-API GR shales occur in parts of the Cenozoic succession, and include the Serikagni Formation which is sandwiched between the "Basal Anhydrite" and the Dhiban Formation anhydrite. At well *Tel Hajar-1*, the Serikagni consists of "paper" shales and thin interbedded limestones which show prolific oil staining. The oil appears to have been generated *in situ* (A.H., *pers. obs.*, 1988).

Source potential has been recorded from argillaceous limestones in the long-ranging and diachronous Pabdeh Formation in Iran. These limestones were described as "excellent" source rocks although they are probably only mature in the NE part of the Dezful Embayment and a few deeper areas to the SW (Bordenave and Huc, 1995). The Pabdeh source rock may be a chronostratigraphic and facies equivalent of the Serikagni Formation in Iraq. TOCs in the Pabdeh ranged from 1.0 to 12.0% over a thickness of 230 m with Type IIs kerogen. *Rock-Eval* S2 ranged from 7 to 40 kg/tonne (Bordenave and Burwood, 1990; Bordenave and Huc, 1995). These source rocks have probably contributed marginally to Central Dezful Embayment fields as indicated by the presence of

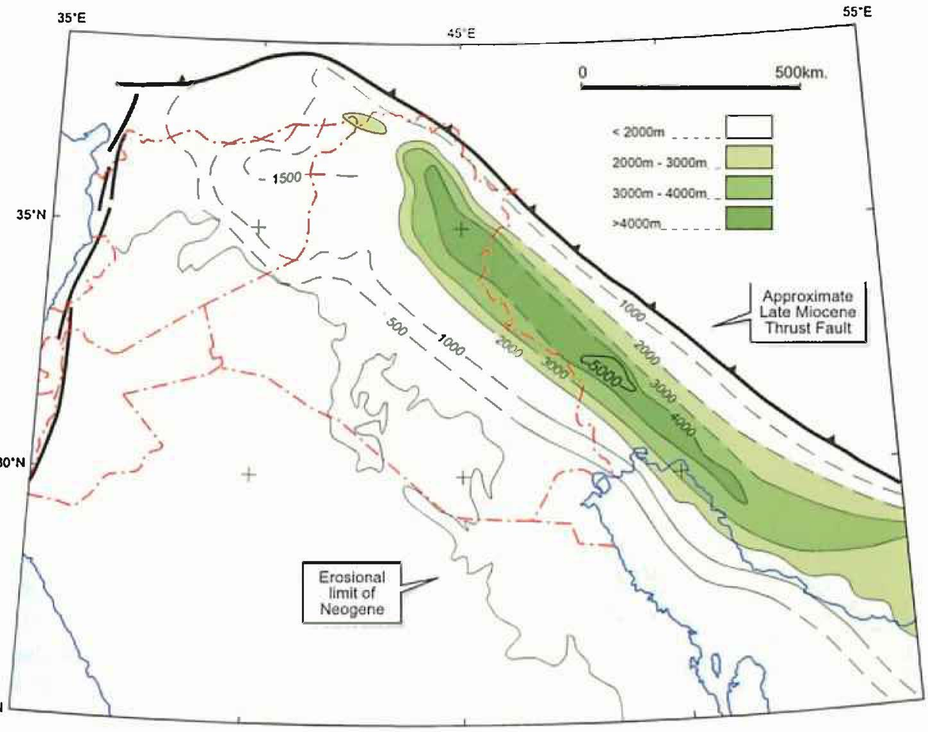


Fig. 8.26. Very generalized Middle Miocene – Pliocene isopach (in metres) illustrating the final morphology of the Mesopotamian foreland basin. After Goff *et al.*, 1995.

the biomarker oleanane in oils from fields including *Agha Jari* (Bordenave and Huc, 1995).

Proven and Potential Cap Rocks

There are no regional seals in this supersequence. The Dhiban Formation may form a local seal, but as it generally overlies basinal carbonates and marls of the Serikagni Formation, it is not significant. The Basal Anhydrite can locally seal oil columns in the Hamrin Formation and the upper part of the Ibrahim Formation (N. Pickard, *pers. comm.* to A.H., 2008). Similarly in Syria, the Chilou Formation (= Serikagni Formation) has heavy oil shows "*mostly in the upper part of this formation, directly under anhydrite beds of the Dhiban Formation*" (Metwalli *et al.*, 1972).

Anhydritic and dense carbonate intervals may occur locally within some reservoir units, for example the Jeribe Limestone Formation in the *East Baghdad* field (Al-Murani, 1986, *in* Sun and Esteban, 1994). This is most likely to affect Neogene (Jeribe and Euphrates Formation) carbonate reservoirs which are present within central parts of the Mesopotamian Basin. The presence of such anhydrite intervals will result in a marked layering of the reservoir system.

The middle Miocene – Quaternary Supersequence

This supersequence was deposited during the Zagros orogeny. Evaporites and fine-grained siliciclastics were deposited in large depocentres which formed during the early stages of regional compression, while great thicknesses of overlying molasse-like clastics were deposited during the convergence and suturing of the Arabian and Asian Plates. Alluvial fans and terrace gravels onlapping anticlines indicate post-orogenic isostatic uplift.

Deposition of the thick middle Miocene – Pliocene succession (Fig. 8.26) resulted in burial and thermal maturation of underlying Mesozoic source rocks. The evaporites of the Lower Fars Formation at the base of this succession provide an important regional seal for oil and gas trapped in underlying reservoirs. Structural growth of major anticlines resulting in trap development occurred from the mid-Miocene onwards.

The isopach map shows that the Mesopotamian Basin was generally symmetrical, with the greatest thicknesses of sediment in SE Iraqi Kurdistan (Fig. 8.26). A schematic cross-section through the Neogene stratigraphy, showing thicknesses and boundary relationships, is shown in Fig.8.37 (page 279). At the base of the supersequence is the Fars Group (Lower, Middle and Upper Fars Formations). These pass to the NE into the thick molasse deposits of the Bakhtiari Formation; and to the SW into the fine-grained siliciclastics of the Dibdibba Formation. The Fars Group is estimated to be 1250 m thick in the Sinjar Trough and 1500 m thick in the Mesopotomian Basin. Thicknesses may be distorted by thrust repetition and salt movement.

The earliest description of the Fars and Bakhtiari Groups was by Pilgrim (1908). The Lower Bakhtiari Formation was described in Iran by Busk and Mayo (1918). Equivalent sediments in Iraq were described as the "Kurd Series" by Pascoe (1922).

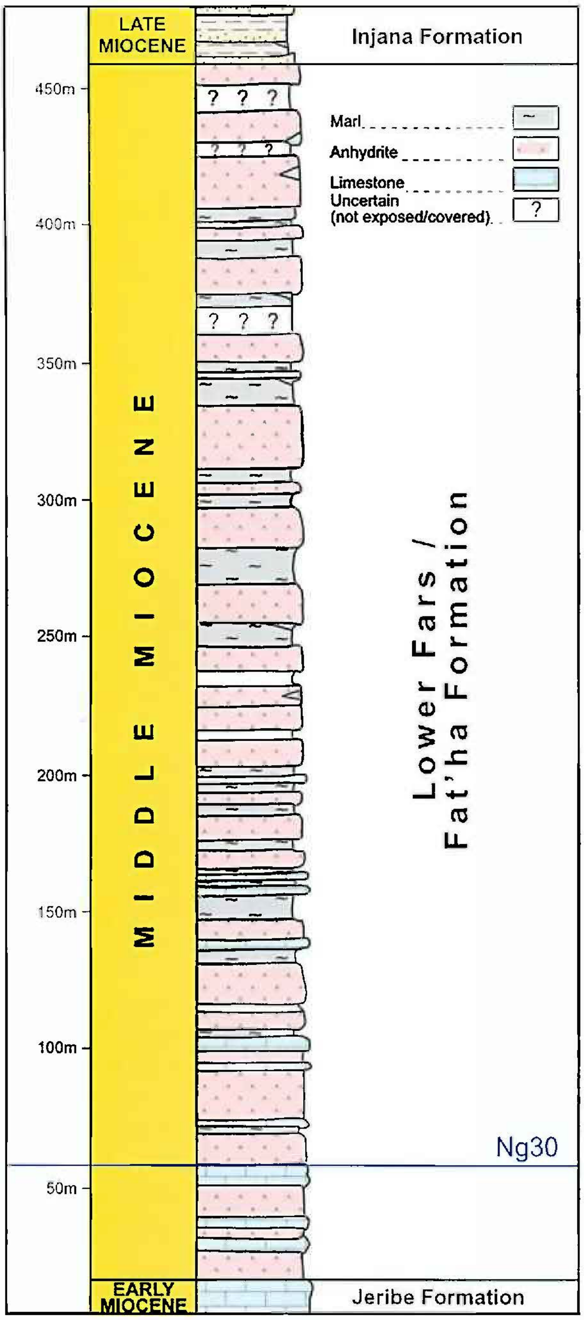


Fig. 8.27. Stratigraphic column through the Lower Fars (Fat'ha) Formation at its type locality (Jebel Makhul). After Al-Rawi *et al.*, 1992.

Lower Fars Formation

This formation forms the regional topseal for almost all the Cenozoic reservoirs in Arabia (Goff *et al.*, 1995). As originally described in Iraq (van Bellen, 1959), no type section was defined. The formation was renamed the Fat'ha Formation by Al-Rawi *et al.* (1992). They defined a type section (Fig. 8.27) on the SW flank of Jebel Makhul, 23 km from the Al-Fatha Ferry (location on Fig. 8.4). This type locality is not in the basin centre and does not include the halite facies which occurs in subsurface sections to the NE. More complete examples of the formation's stratigraphy were reported by Al-Juboury and McCann (2008) (Fig. 8.28).

Thickness

The formation thickens towards the centre and SE of the Mesopotamian Basin (Aqrawi, 1993a). At the type locality at Jebel Makhul, the formation is 445 m thick (Al-Rawi *et al.*, 1992). It is 305 m thick on the NW (Khurmala) Dome of the *Kirkuk* structure, 610 m thick on the SE (Baba) Dome, 762 m thick in Chia Surkh and up to 900 m thick near Amarah (van Bellen, 1959; Aqrawi *et al.*, 1989; Aqrawi, 1993a). Tectonically induced thickening of halite-rich units often occurs (Dunnington, 1968). The "Saliferous Beds" are often absent due to non-deposition on the basin margins, e.g. at Fat'ha (Jassim and Buday, 2006h). Facies in NE Iraq are 100-300 m thick (Youkana and Sissakian, 1986).

Stratigraphy

Dunnington (1968) presented a schematic stratigraphic column through the Lower Fars Formation in northern Iraq showing the subdivisions adopted by IPC geologists (Fig. 8.29). These comprise in ascending order the Basal Fars Conglomerate, the Transition Beds, the halite-bearing Saliferous Beds, the Seepage Beds and the Upper Red Beds. The Transition Beds form the upper part of the undeformed "Competent Group"; the Saliferous Beds form the "Mobile Group" in which most of the internal deformation is localised. The topmost intervals of the Lower Fars together with overlying formations comprise the "Passive Group" which has undergone little internal deformation. Thirty-three depositional cycles are shown on Dunnington's column (allowing for three cycles in the Basal Conglomerate division).

The lower 54 m of the formation at the Jebel Makhul type section consists of alternating limestone and anhydrite beds in six depositional cycles. The overlying 100 m consists of green-grey marls, limestones and anhydrite in seven cycles. The upper 291 m consists of brown red marls, limestones and anhydrite in 20 cycles.

In southern Iraq, the divisions are less well-defined (Buday, 1980) although Aqrawi *et al.* (1989) and Aqrawi (1993a) noted that a three- to four-fold system can be identified, with a carbonate-dominated base, an evaporitic middle, and a clastic top (Fig. 8.30).

Depositional cycles and facies

Depositional cycles, as first defined by Dunnington (1968), ideally begin with a mudstone layer, 1–20 m thick, followed by a thin limestone up to 5 m thick abruptly overlain by an anhydrite unit 5–10 m thick, sometimes followed by halite. However this pattern may vary considerably; for example, carbonates commonly directly overlie anhydrite towards the basin margin.

Detailed facies analyses of marginal (i.e. non-halitic) areas in NW and northern Iraq, specifically in the Mosul area were undertaken by Shawkat

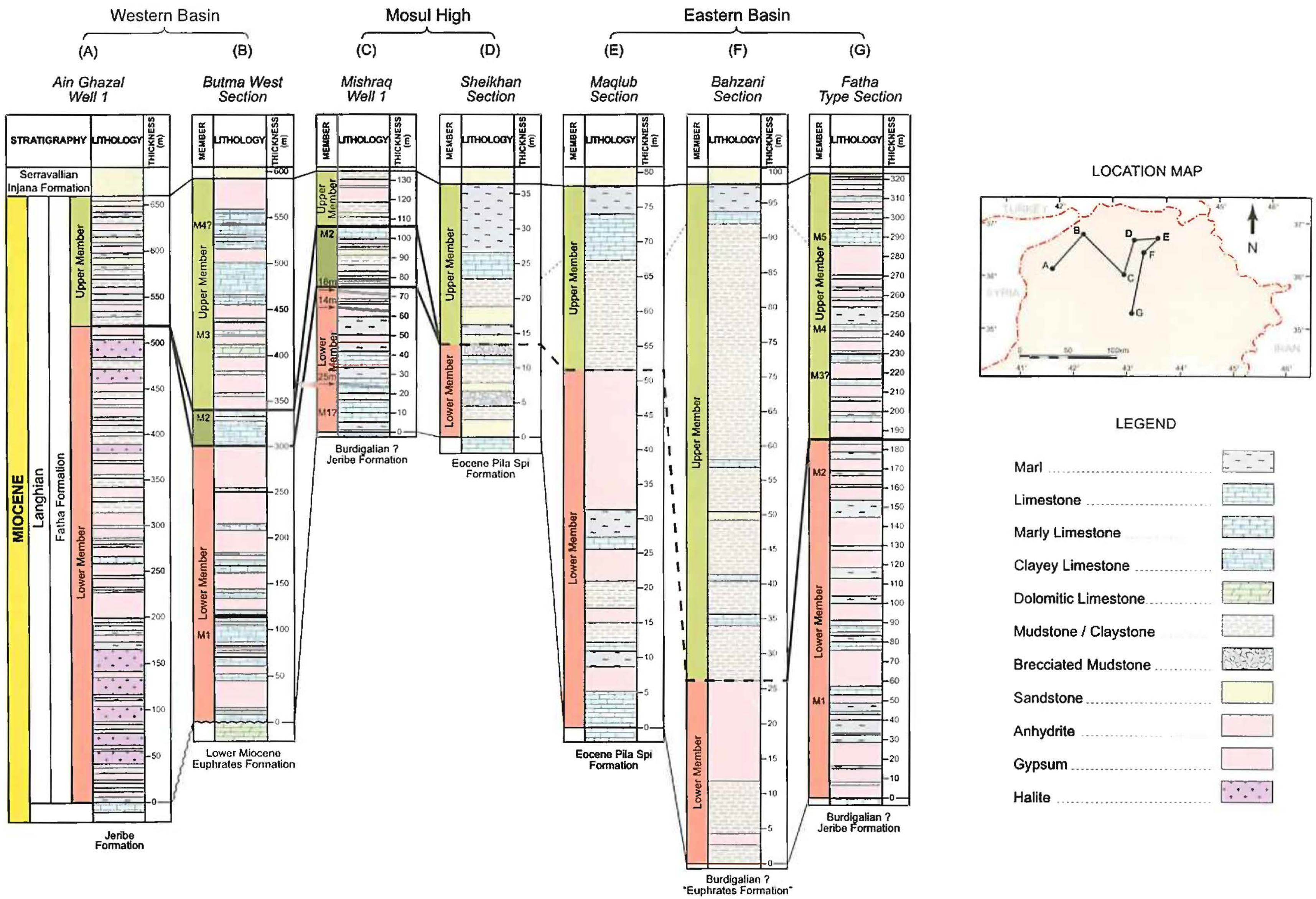


Fig. 8.28. Lithological and stratigraphic columns through the Lower Fars Formation at various locations in northern Iraq (see inset map), showing local variations in the formation's thickness and stratigraphy in individual sub-basins. Modified from Al-Juboury and McCann, 2008; their sub-divisions are based on a two-member scheme proposed by Ma'ala *et al.* (1988) (cited in Al-Juboury and McCann, 2008).

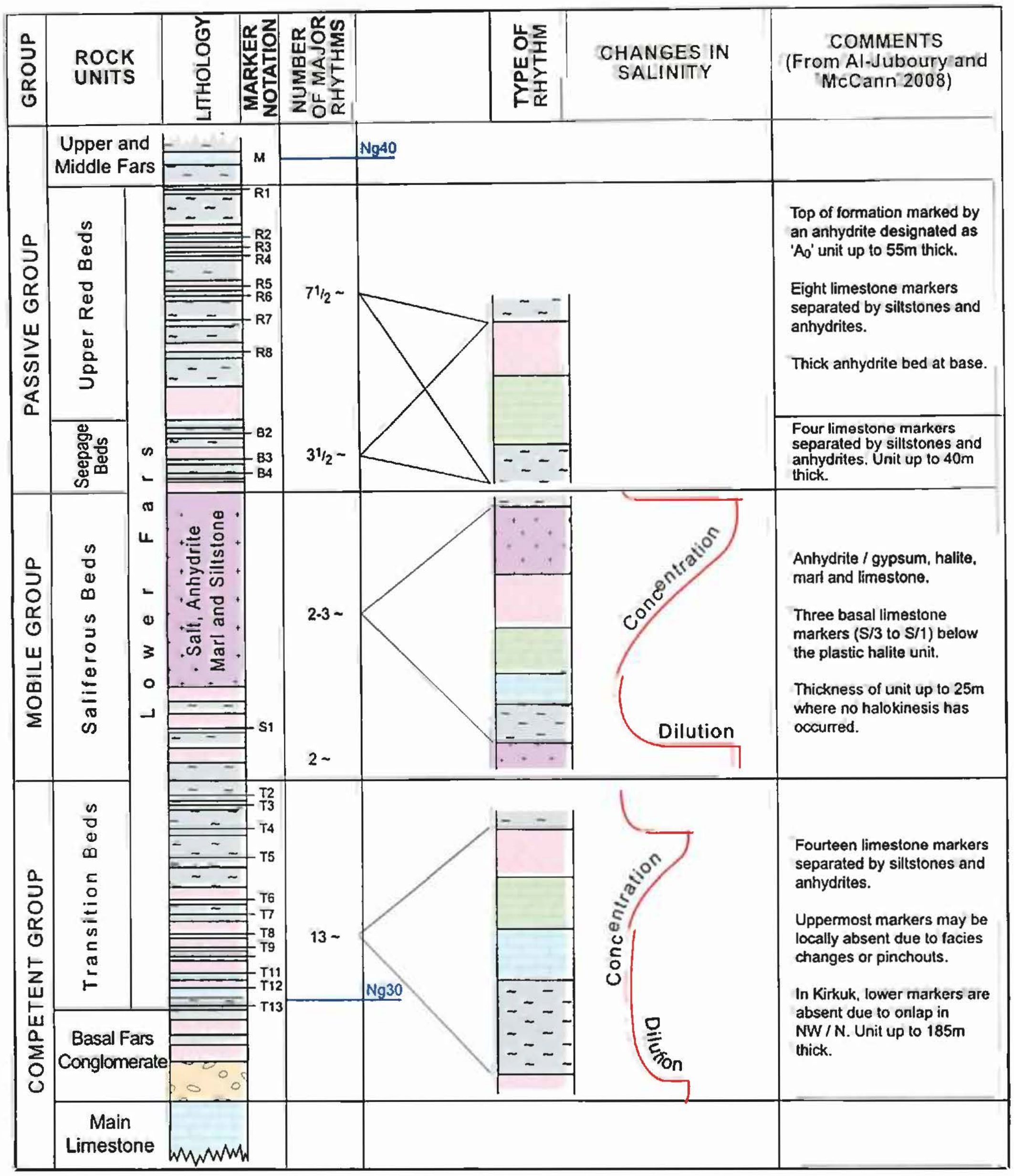


Fig. 8.29. Stratigraphic column through the Lower Fars Formation showing details of its internal cyclicity. After Dunnington (1968) and Al-Jubowry and McCann (2008) after original studies including Sugden, 1951 (*in* Al-Juboury and McCann, 2008) and Daniel (1954, *in* van Bellen, 1959).

and Tucker (1978), Tucker and Shawkat (1980), Haji and Al-Rawi (1992), and Tucker (1999) (Fig. 8.31). In these areas, a carbonate-dominated lower stratigraphic succession is overlain by a clastic-dominated succession, with the proportions of evaporites (sulphates) remaining relatively constant (Tucker, 1999).

Limestones comprise cyclic bioclastic, chemical and peritidal units; thin stromatolitic (Plate 8.19) and locally oolitic grainstone beds (Plate 8.20) also occur (Shawkat and Tucker, 1978). Subtidal (lower energy) facies may be bioturbated or bored (Plate 8.21).

Dolomitised beds are common in the lower part of the stratigraphic succession (Al-Juboury and McCann, 2008) and frequently have a very finely crystalline, dark-coloured microtexture with vugs after bioclasts and/ or evaporites.

Sulphates (Plate 8.22, 8.23) include massive, laminated and nodular gypsum (Al-Juboury and McCann, 2008). Nodular gypsum occurs on cycle tops.

Petrographic studies have shown that carbonate microfacies vary from bioclastic wacke-packstones and packstones (Plates 8.24, 8.25) to oolitic and skeletal grainstones (Plates 8.20, 8.26) with local dolomites. Carbonate beds in the lower part of the Lower Fars are predominantly composed of dolomites and skeletal-peloidal wackestones higher up (Al-Juboury and McCann, 2008) (Plate 8.27), with skeletal-peloidal packstones (Plate 8.25) in the upper part of the formation. Skeletal fragments are dominated by molluscs; a cellular structure within oyster debris is particularly common (Plate 8.24).

Each cycle represents the progressive evaporation of sea-water after an initial marine

Plate 8.19. Stromatolitic algal lamination, Lower Fars Formation. Location: Jebel Sheikh Ibrahim, about 50 km west of Mosul. Photo by M. Tucker.

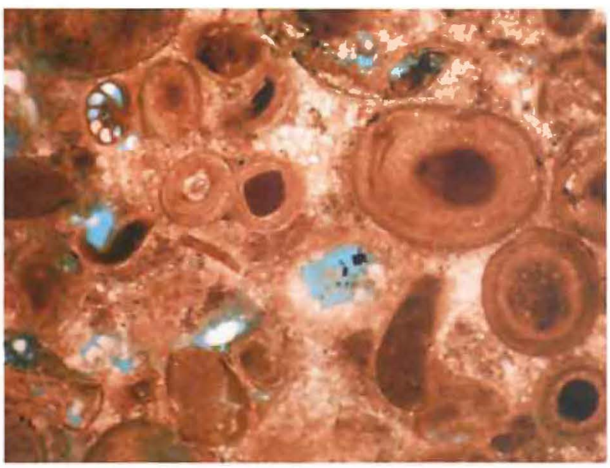


Plate 8.20. Thin-section view of oolitic pack-grainstone in the Lower Fars Formation; sample from the basin margin at the NW plunge of the Sangaw Anticline near Sulaimaniya, Iraqi Kurdistan. Note the presence of a benthic foram (?*Dendritina*); this together with peloids/ micritic intraclasts forms ooid nuclei. An inclusion-rich meniscus fabric between grains may represent vadose cements. Photo and bioclast identification by S. Packer; image courtesy of Sterling Energy Ltd. Field of view 5 mm.

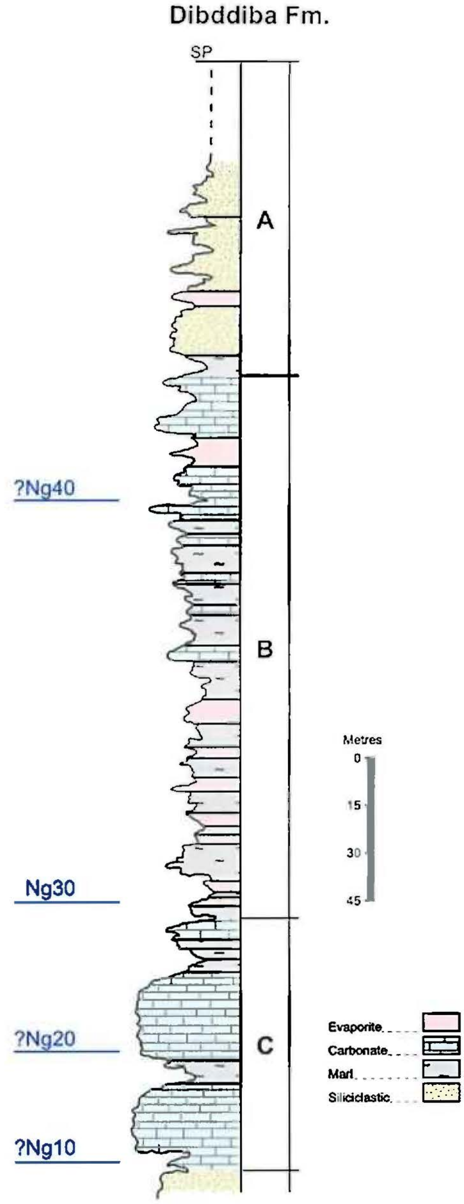


Fig. 8.30. Stratigraphic column through the Lower Fars Formation in southern Iraq; note the carbonate-dominated base (C), the mixed evaporitic and carbonate dominated middle portion (B), and the siliciclastic dominated top part (A). After Aqrawi, 1993a.

Plate 8.21. Burrows in limestones of the Lower Fars Formation. Jebel Bashiqa, about 30 km north of Mosul. Photo by M. Tucker.

Plate 8.22. Gypsum nodules in limestones of the Lower Fars Formation in a column at Hatra, ca. 100 km south of Mosul. Photo by M. Tucker.

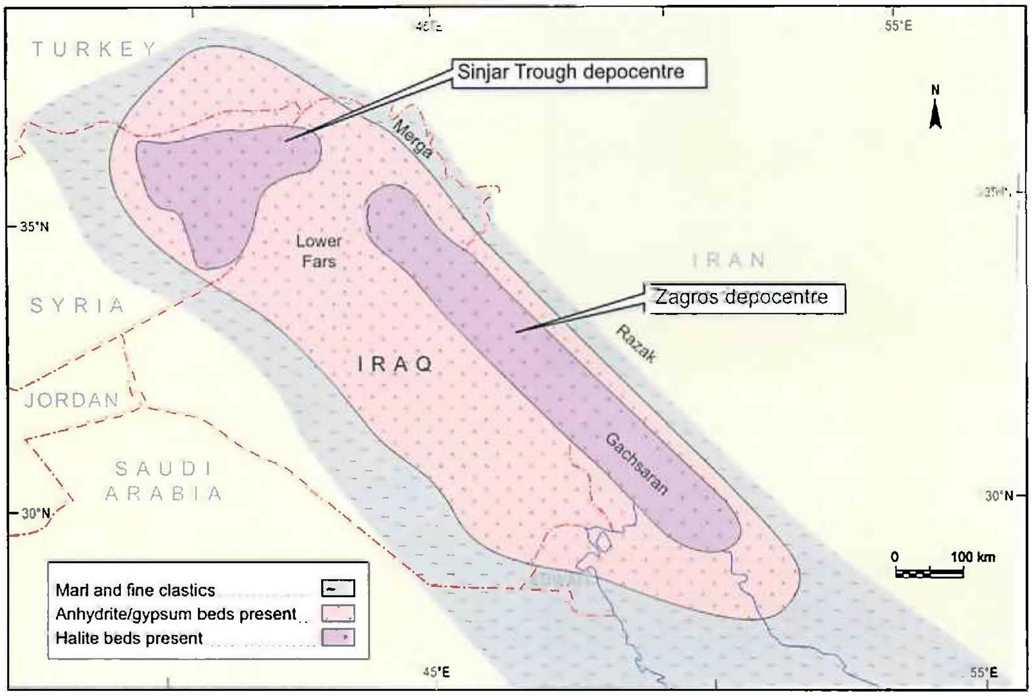


Fig. 8.31. Map showing the generalized original facies distribution of the Lower Fars / Gachsaran Formations; note that this unit is now largely absent from Lurestan (Iran) due to uplift and erosion. Halite occurs in the Mesopotamian basin and in a second depocentre which extends into Syria; the Iraqi part of this depocentre is known as the Sinjar Trough. After Goff *et al.*, 1995.

transgression or flooding event during a period of high run-off from the Zagros hinterland to the NE. The thicknesses of the evaporites suggest that there was continued reflux of water into the basins, with rates of water input and evaporation varying in a cyclic fashion. Cycles increase in number and thickness towards the basin centre and are thought to reflect glacio-eustatic control together with some tectonic influences as well as autocyclic controls such as sabkha-tidal flat progradation (Tucker, 1999), although Al-Juboury and McCann (2008) proposed a eustatic control on cycle development.

Plate 8.23. Laminar gypsum, Lower Fars Formation. Location: Jebel Bashiqa, about 30 km north of Mosul. Photo by M. Tucker.

Lateral variations

The relative proportions of marls, carbonates, anhydrite and halite vary, and the isopach map can be used to indicate the relative structural position of localities within the basin (cf. Tucker, 1999). Lateral variations in the thickness and lithofacies of the Lower Fars Formation in northern Iraq are shown in Fig.8.28. An isopach map (Fig. 8.32) illustrates the influence of the Rutbah / Mosul Arch on the thickness of the formation. Distinct halite-filled depocentres are recognised in the Sinjar Trough (NW Iraq) (Fig. 8.33) and NE Iraq (Mustafa, 1980). Laminated anhydrites are similarly found in deeper basinal areas (Plate 8.23).

To the NE of the Kirkuk structure, the formation unconformably overlies the Eocene Pila Spi Formation (Al-Naquib, 1960; Jassim *et al.*, 1987); a 4 m thick conglomerate rests on the unconformity surface. The formation in these areas comprises more than 50% red-brown mudstone in beds < 1–3 m thick (Al-Juboury and McCann, 2008) (Fig. 8.28). Red-brown siltstones and shales (Plate 8.28) become more abundant in the upper part of the formation in beds up to 1 m thick. Five cm to 1 m thick sandstone beds occur in the uppermost part of the formation. Beds of limestone (0.1–1.5 m thick), locally up to 20 m thick, and gypsum beds up to 10 m thick, also occur. Limestones can be fossiliferous, dolomitic and bituminous, and many contain chert nodules.

On the basin margin to the NE (for example at Govanda: van Bellen, 1959), the formation thins rapidly with a reduction of anhydrite/gypsum beds and an increasing proportion of silty or sandy

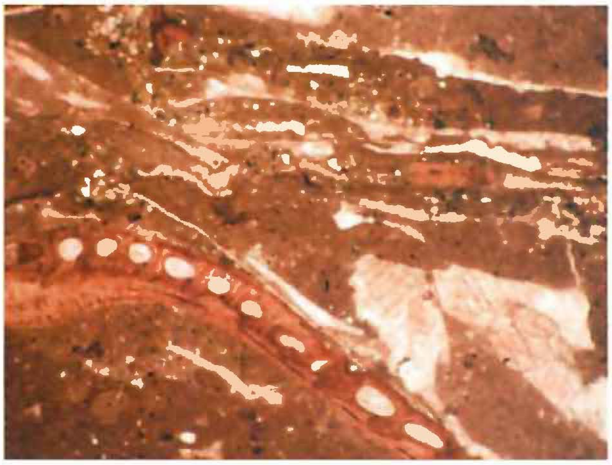
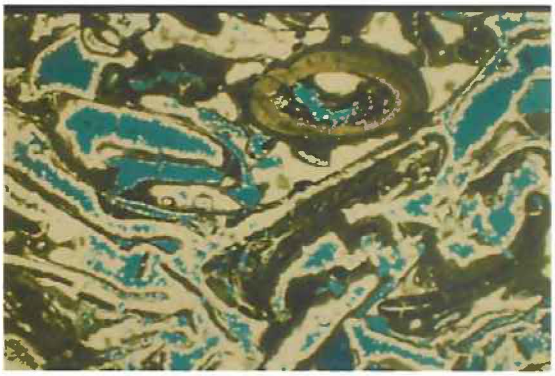
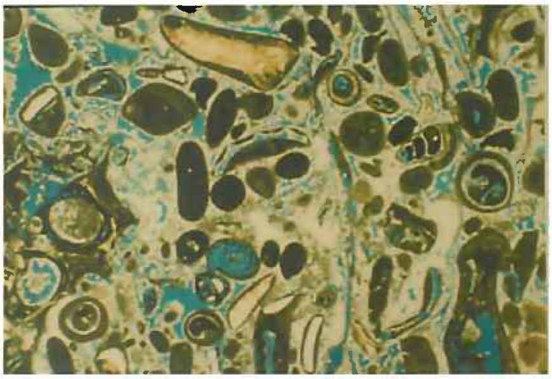


Plate 8.24. Thin-section view of oyster packstones in the Lower Fars Formation; sample from the Sangaw Anticline near Sulaimaniya, Iraqi Kurdistan. Note the distinctive cellular structure of the oyster fragment; oysters are common in the lower units of the Lower Fars Formation as mapped in the field and from satellite data. Field of view 5 mm. Photo and bioclast identification by S. Packer; image courtesy of Sterling Energy Ltd. Field of view 5 mm.





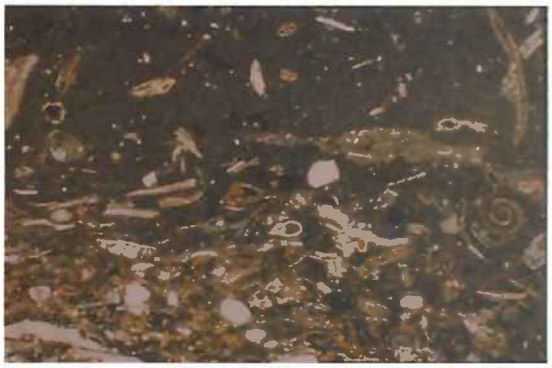


Plate 8.25 (above left). Lower Fars Formation: skeletal grainstone with gastropods and mouldic and intergranular porosity. Photo by M. Tucker.

Plate 8.26 (above). Lower Fars Formation: shallow-water, skeletal packstones with mouldic and intergranular porosity. Photo by M. Tucker.

Plate 8.27 (left). Deepwater skeletal packstones in the Lower Fars Formation. Photo by M. Tucker.

material (Plate 8.29). Al-Juboury and McCann (2008) noted that these facies are red and variegated marls, silts and fine sandstones of aeolian to lagoonal/fluvial-deltaic origin. It has been described as the "Undifferentiated Fars" or part of the "Tertiary Red Beds" (Jassim *et al.*, 1987; Jassim and Buday, 2006c). Siliciclastics are also present within the Lower Fars Formation on the SW margin of the basin, and are thought to be derived as a result of aeolian processes from the Rutba-Hail arch (Aqrawi *et al.*, 1989; Aqrawi, 1993a).

Age

Thomas (1950) stated that *Neoalveolina (Borelis) melo curdica* "definitely occurs" in the Lower Fars, an observation supported by Prazak (1978). Mahdi (1983) dated the Lower Fars Formation as "late early Miocene" (Burdigalian) in northern Iraq, thereby confirming the correlation with that of James and Wynd (1965) for the equivalent basal part of the Gachsaran Formation in Iran.

Basal contact

The basal interval of the Lower Fars/Gachsaran Formation is known locally as the Cap Rock / Transition Beds. *Neoalveolina (Borelis) melo* var. *curdica* occurs in both Iraq (van Bellen, 1959) and Iran (Thomas, 1950; James and Wynd, 1965) in the underlying limestones. These are assigned to the Jeribe Formation and Upper Member of the Asmari Formation, respectively. It also occurs in lowermost limestones of the overlying Lower Fars/ Gachsaran Formation (Thomas, 1950; Slinger and Crichton, 1959; James and Wynd, 1965). This fossil indicates a Burdigalian or younger age.

The basal interval has a distinctive stratigraphy as defined in Iran by analysis of mineral inclusions (magnesite, quartz) in anhydrite and fauna in key interbeds, for example in the *Agha Jari* field (Ion *et al.*, 1951). The contact of the Lower Fars and Jeribe Formations is interpreted to be conformable in the basin centre (Thomas, 1950). Thomas noted (*ibid.*, p. 40) that: *"There is every reason to believe that*

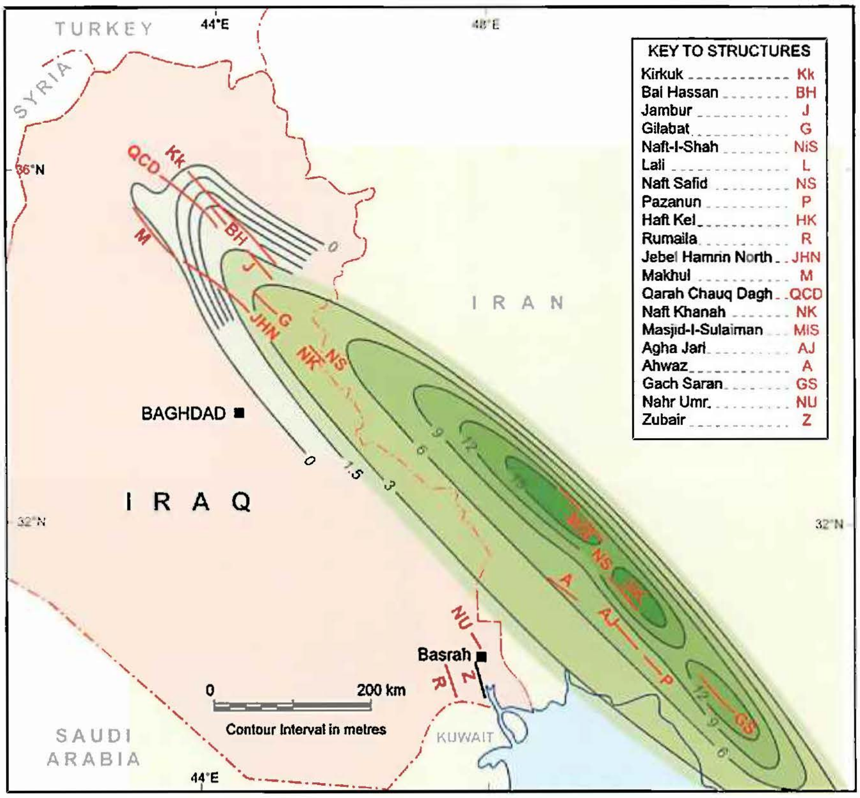


Fig. 8.32. Isopach map showing the approximate original (i.e. restored) thickness of the Mobile Group of the Lower Fars Formation in the Mesopotamian Basin and Zagros foredeep (after Dunnington, 1968). The Mobile Group is the halite-bearing unit of the Lower Fars Formation (see Fig. 8.29). Thicknesses in metres.

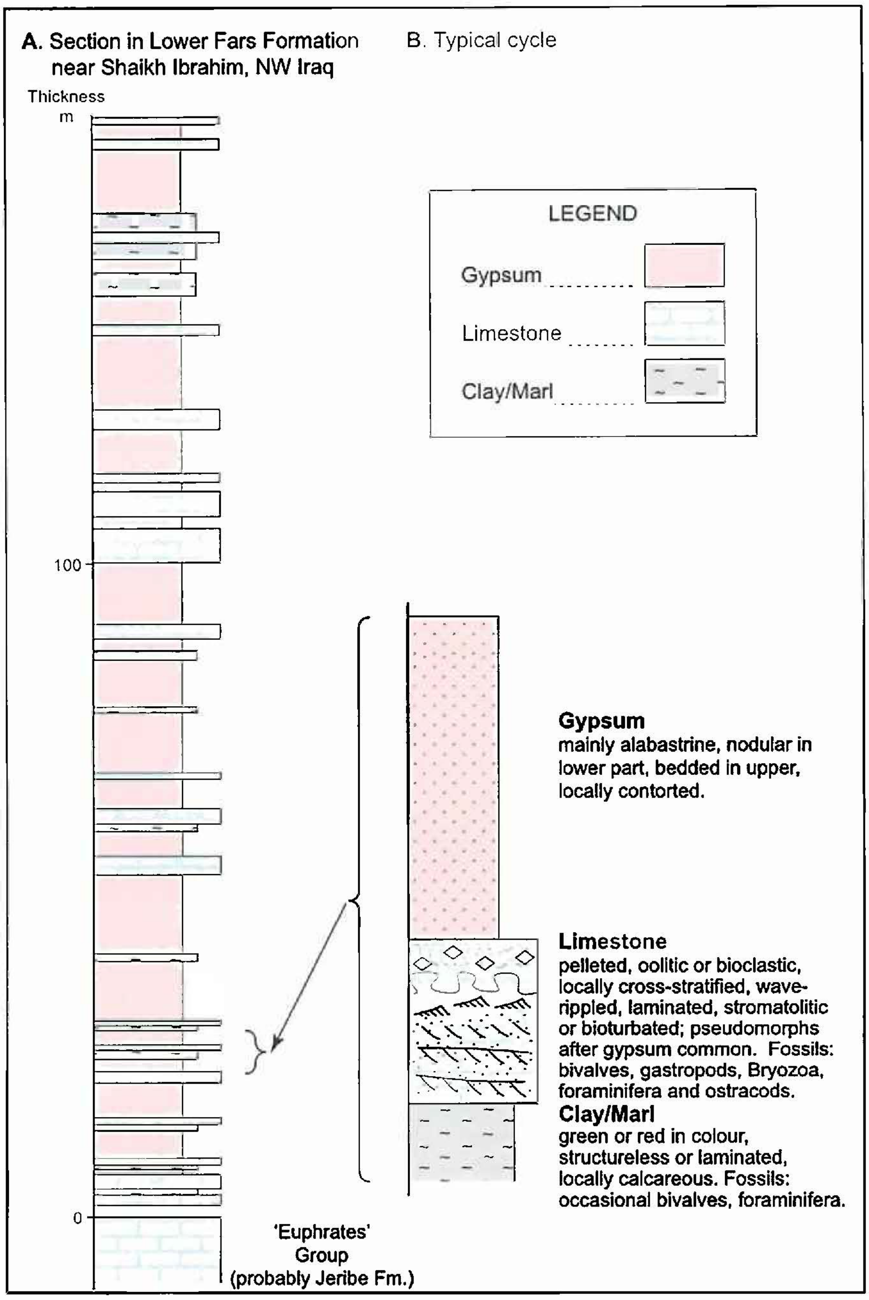
Plate 8.28. Lower Fars Formation exposed on the Pirman anticline, 25 km north of Erbil, Iraqi Kurdistan. Fallen blocks include evaporites and gypsiferous limestone. Photo by A. Aqrawi.

Plate 8.29. Nodular gypsum and sandstones in the Lower Fars Formation exposed in the SW limb of the Pirmam anticline, 25 km north of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

where it is developed the junction with the Asmari Limestone is at almost exactly the same time plane. This is based on the fact that a similar lithological and faunal sequence is found in many places in the Lower Fars Formation immediately overlying the "Cap Rock" whilst beds with Neoalveolina melo curdica Reichel *invariably occur below it".*

Recent studies have used Sr dating to investigate sequence boundaries in the Asmari Formation of Iran (Ehrenburg *et al.*, 2007; van Buchem *et al.*, 2010). These studies have confirmed a mid-Burdigalian age for the base of the Gachsaran Formation. They have also established that the uppermost Asmari Formation carbonates prior to evaporite deposition were deposited at 18.5 Ma (mid-Burdigalian on the 2004 ICS timescale). In Iraq, where local onlap of the formation occurs with a basal conglomerate often with dolocrete fabrics (Al-Delemi, 2006, *in* Al-Juboury and McCann, 2008), the basal contact is clearly unconformable. This suggests that precursor palaeohighs were present.

Fig. 8.33. Stratigraphy of the Lower Fars cycles at outcrop in the Mosul region, northern Iraq. After Shawkat and Tucker, 1978.



Middle Fars Formation

Al-Naquib (1960) defined this formation in Iraq as the interval occuring between the uppermost anhydrite and the uppermost fossiliferous limestone in the Fars Group. It comprises alternating red shales, siltstones and sandstones, limestones and rare gypsum lenses (Al-Naquib, 1960) interpreted here to indicate a littoral to paralic depositional environment. Marine limestones near the base mark the Ng40 MFS of Sharland *et al.* (2001). Fossils include fish vertebrae, crab remains, bivalves and gastropods; oolites and frequent ripple marks may occur. The formation is generally about 100 m thick (Al-Naquib, 1960), but reaches 122 m at *Naft Khanah* (van Bellen, 1959). It has been described as far north as *Jambur* (Al-Naquib, 1960) and Jebel Hamrin where an oolitic unit known as the Mubaddad Limestone Member occurs at its base (Sahib and Lateef, 1976). Towards the basin margins, the formation cannot be identified (e.g. at *Kirkuk*) due to the loss of its marine character, and it grades into the basal Upper Fars Formation (van Bellen, 1959). Al-Rawi *et al.* (1992) included it within the basal part of the Injana Formation. Al-Juboury and McCann (2008) noted that the Injana Formation comprises approximately 20m of "transitional" fluvio-deltaic facies with significant channel forms which probably characterise the margins of a carbonate-centred, clastic-rimmed lagoon. Similarly in southern Iraq , the "Middle Fars" grades into the Dibdibba Formation (van Bellen, 1959).

In Iran, the equivalent Guri Limestone Member of the Mishan Formation, which occurs above the Gachsaran Formation (= Lower Fars Formation of Iraq) contains the first appearance of the diagnostic (N9) microfossil *Orbulina universa* (James and Wynd, 1965; Sanpo, 1969). This was questionably

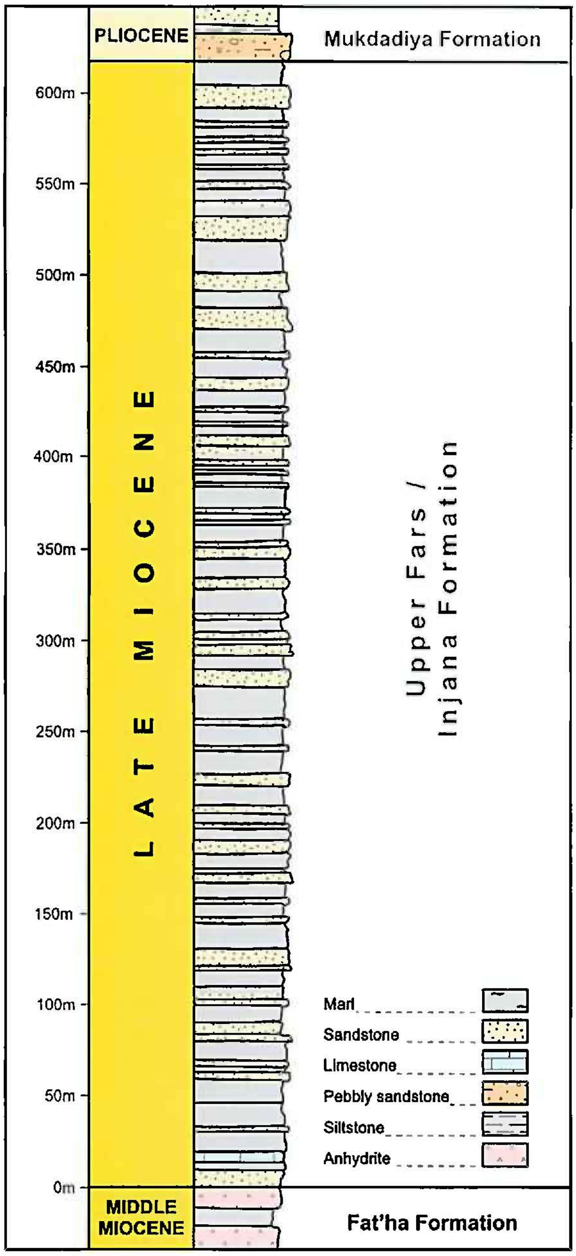


Fig. 8.34. Stratigraphic column for the Upper Fars (Injana) Formation at its type locality at Jebel Hamrin. After Al-Rawi *et al.*, 1992.

reported from the Jeribe Limestone underlying the Lower Fars by Prazak (1978).

Upper Fars Formation

This formation comprises varicoloured marls and siltstones with beds of sandstones and grits. Occasional beds of freshwater limestones (with ostracods and charophytes), lacustrine clays and bentonites also occur (Plate 8.30). The formation is typically 600 to 800 m thick (Fig. 8.34) and forms "badlands" topography (Plate 8.31). Buday (1980) and Al-Rawi *et al* (1992) reported that the formation reaches 2000 m in thickness but this may be an overestimate because of probable inclusion of the overlying Lower Bakhtiari Formation where this is composed mostly of mudstones.

Plate 8.30. Middle-Upper Fars Formation. Lacustrine clays, limestones and bentonite. Injana, Jebel Hamrin South. Photo by M. Tucker.

Plate 8.31. Upper Fars Formation "badlands" topography, Injana, Jebel Hamrin South. View from a gypsum ridge at the top of the Lower Fars. Photo by M. Tucker.

Plate 8.32. Conglomerates and sandstones of the Lower Bakhtiari Formation cropping out in the Khanzad hills, about 15 km north of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

Al-Rawi *et al.* (1992) renamed the Upper Fars Formation the Injana Formation, and defined a type locality at Injana along the main Baghdad–Kirkuk road on the NE limb of Jebel Hamrin South (Plate 8.31). A supplementary type section occurs in well *Gilabat-1* (Al-Rawi *et al.*, 1992). The formation is 620 m thick at Injana and consists of alternating red, brown and grey marls, siltstones, and sandstones with seams of gypsum; fossils include gastropods and bivalves. In the Jambur and

Makhul-Khanuqah areas, rare freshwater limestones containing ostracods and charophytes occur. An oyster limestone was recorded 60 m above the base of the formation at Jebel Pulkhana (Al-Naquib, 1960).

The formation is assumed to be of early late Miocene age based on its stratigraphic position below the uppermost Miocene Lower Bakhtiari Formation. It is interpreted here to have been deposited in an estuarine to lacustrine environment.

Lower Bakhtiari Formation

This formation (Plate 8.32) was deposited synchronously with the growth of major anticlines and thus varies in thickness and facies. It was originally included in the "Kurd Series" by Pascoe (1922) but was later reassigned to the Lower Bakhtiari Formation in the Tertiary part of the *Iraq Lexicon* (van Bellen, 1959). Al-Rawi *et al.* (1992) renamed the Lower Bakhtiari Formation the Mukdadiya Formation, whose type section (Fig. 8.35) is on the NE flank of Jebel Hamrin. Here, the formation is 1411 m thick here and comprises sandstones, pebbly sandstones, grey mudstones and siltstones with stacked "fining up cycles".

Thickness

Dunnington (1958) published an isopach map of northern Iraq (Fig.8.36) for the combined Upper Fars and Bakhtiari Formations using estimated thicknesses for synclinal areas. He noted that the major anticlines grew during deposition of the Bakhtiari and considered that *"a true isopach should reveal closures of attenuation over every rising structure but that unfortunately the information which would be required for such a map is not accessible"*. He noted that it is difficult to estimate the thickness of the Bakhtiari Formation because thickness measurements can be made only on the flanks of anticlines *"where depositional and some erosional attenuation is known to have occurred"*.

His final isopach map (Dunnington, 1968) was created after "arbitrary elimination of crestal attenuation". He emphasised the shallowing of the basin to the NW so that *"the synclinal thicknesses in the vicinity of the NW plunge of Kirkuk were only of the order of 5000 ft (1525m)"*. He noted that the original thickness of the "Passive Group" comprising all units above the middle part of the Lower Fars was between 6000 and 13,000 ft (1830-3960 m) prior to rapid late Pliocene – early Pleistocene uplift and erosion. The maximum recorded thickness of the Lower Bakhtiari Formation in Iraq is 2050 m (van Bellen *et al.*,1959) although the location of this section was not given.

On the NE flank of the Kirkuk anticline, Pascoe (1922) noted that the thickness of the Lower Stage Kurd Series (equivalent to the Upper Fars and Lower Bakhtiari) exceeds 7000 ft (2000 m), and that the thickness of the combined Lower and Upper Bakhtiari Series "must exceed 12,000 ft (3500 m)".

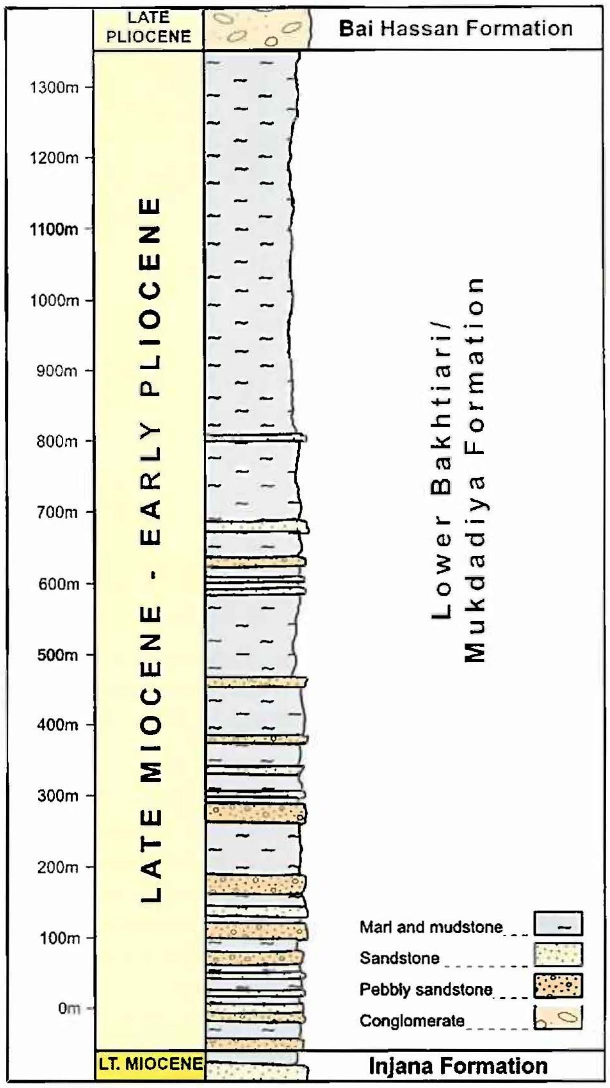


Fig. 8.35. Stratigraphic column for the Lower Bakhtiari (Mukdadiya) Formation at its type locality at Jebel Hamrin. After Al-Rawi *et al.*, 1992.

Stratigraphy

Pascoe (1922) informally recognised five units in the "Kurd Series" in the Kifri area. The lower unit (Lower Stage Unit: a) can be correlated with the Upper Fars Formation. The succeeding units (b) and (c) in the Lower Stage correspond to the Lower Bakhtiari Formation.

In unit (b), Pascoe (1922) recorded the presence of thick, massive sandstone beds which were relatively soft, friable and frequently current bedded, and sometimes full of "root-like concretions". He noted that the sandstone intervals increase in thickness upwards in the middle of the unit, and that the sandstones become pebbly in the same direction and contain thin conglomerates. He observed that the unit *"produces topography consisting of ridge after ridge rapidly alternating with deep, narrow, straight, simple valleys"*.

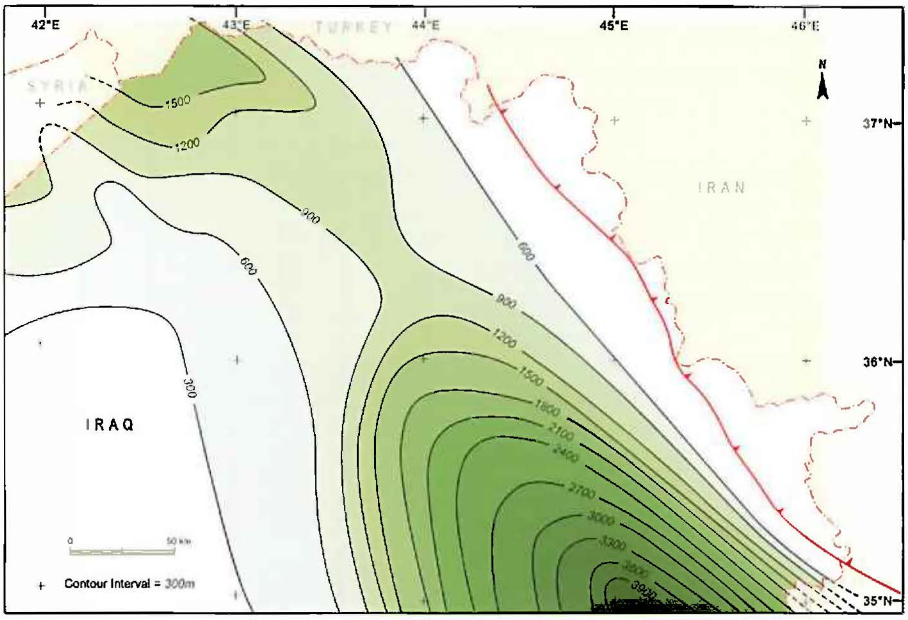


Fig. 8.36. Isopach map of the Bakhtiari and Upper Fars Formations showing the influence of the long-lived Khleisia-Mosul High, separating the foreland into two basins. After Dunnington, 1958; original thicknesses converted to metres.

Unit (c) consists of light brown claystone with few sandstone bands whose frequency increases towards the contact with unit (b). The sandstones contain lenses of pebbles, and thin discontinuous conglomerates occur. Pascoe (1922) noted that the colour of the clays was very characteristic and contrasted with the red colour of unit (a) clays. He recorded that in the Hamrin area, erosion has created outcrops *"of the most broken kind of ground which is as bewildering to the eye as it is wearisome to the feet"*.

Contacts

The base of the Lower Bakhtiari Formation has usually been taken at the base of the first gravel-bearing sandstone (Al-Rawi *et al.*, 1992). Pilgrim (1908) considered that there was a major unconformity between the Fars and Bakhtiari. Pascoe (1922) also noted that the precise correlation of the "Kurd Series" with the Upper Fars and Bakhtiari Series in Iran required further work. He considered that *"localities will be found where an unconformity will be visible or demonstrable"*. van Bellen (1959) considered this boundary to be diachronous; however, the boundary does not appear to have been studied in detail. van Bellen (1959) noted that unconformities occur within the Lower Bakhtiari Formation with *"folding of many of the present anticlines proceeding, with temporary uplifts of crests above the erosional base level, during the deposition of the unit"*.

In the Mamatain area of the Iranian Zagros, the basal beds of the lower Bakhtiari Formation contain pebbles of gypsum derived from the Gachsaran (Lower Fars) Formation, and an unconformity locally occurs at the base of the lower Bakhtiari (Fig. 8.37).

Onlap of formations onto uplifting structures can be demonstrated. Dunnington (1968) showed that the Lower Bakhtiari is absent on the NE flank of Jebel Hamrin North and that the Upper Bakhtiari conglomerates rest unconformably on eroded Upper Fars Formation.

Facies and depositional models

Kukal and Al-Jassim (1971) studied the sedimentology of the molasse deposits in the Lower Bakhtiari Formation. They recorded planar cross-bedded coarse-grained sandstones, trough cross-bedded medium-grained sandstones, fine-grained sandstones with ripple drift bedding, silty mudstones with some fine sand and variable carbonate content, and marls. Sandstones contain planar- and trough cross-bedding in roughly equal proportions. The thickness distribution of planar cross-beds is bimodal with maxima at 40–80 and 120–160 cm, while trough cross-beds are typically 20–60 cm thick. Foreset inclination in planar cross-bedded units is 20–32° (average 24°) and 16–24° in trough cross-bedded units. Troughs in the trough cross-bedded units are elongate with their long axes predominantly striking NE-SW.Foresets predominantly dip to the SW. Sedimentary structures include mud balls, flute casts and rare ripple marks. Flute casts are 10 – 15 cm in length and have an azimuth of 260°. The sandstones are usually medium- to coarse-grained (2% conglomerate, 43 % coarse-grained sandstone, 48% medium-grained sandstone, and 7% fine-grained sandstone). Some 98% of the sandstones analysed were greywackes (i.e. they were argillaceous and lithic) and only 2% were arkoses. Silty mudstones (the dominant fine-grained facies in the formation) typically contain 30–60% calcium carbonate,

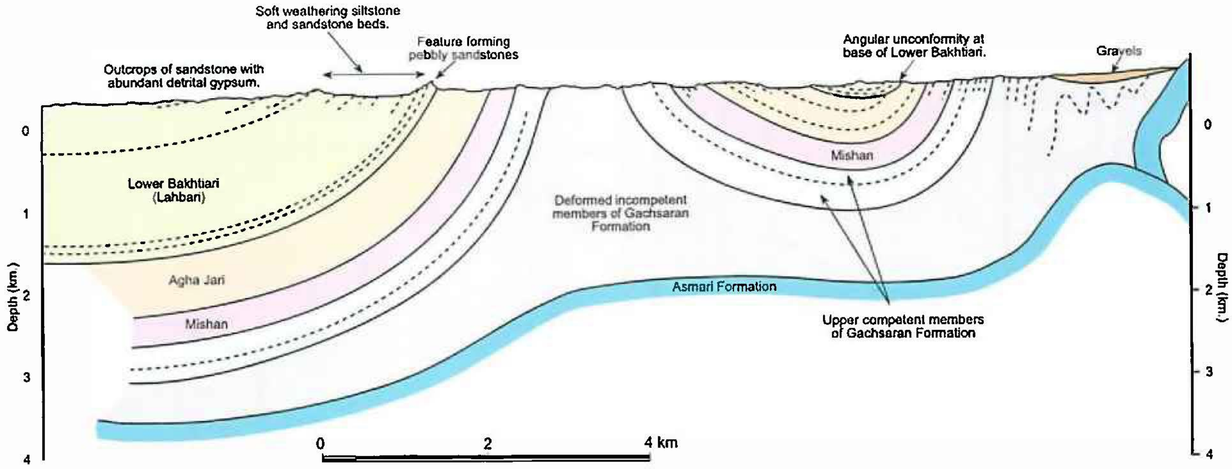


Fig. 8.37. Late Miocene to Pliocene deformation and growth of anticlines. After a 1930s archive Anglo-Iranian Oil Company cross-section through the Mamatain area of the Iranian Zagros.

similar to the recent alluvium of Iraqi rivers which contain over 50% $CaCO_3$.

The frequent fining-up cycles observed in the Lower Bakhtiari are typical of fluviatile deposits. Sandstone facies indicate deposition by powerful rivers. The rare marl beds appear to indicate temporary lacustrine environments.

Al-Naquib (1960) recorded that pebbles in the formation are "*very varied in type, size and colour, the most prolific being red, brown and grey chert, basic igneous rocks and vein quartz*", especially in lenses in the lower part of the formation. Ali and Khoshaba (1981) measured sections 1120 – 1300 m thick in the Lower Bakhtiari Formation at three locations (Injana, Kifri and Zakho) (Fig. 8.38). The formation comprised 20-30% sandstone and 70-80 % calcareous mudstone and siltstone. Sandstone units are typically 5-10 m thick but locally reach thicknesses of up to 35 m, and were frequently pebbly and cross-bedded.The sandstones have very similar petrographic and heavy mineral compositions (Figs. 8.39, 8.40) at the three locations comprising 12-13% quartz, 8-10% feldspar (predominantly plagioclase), 65% lithic fragments, 10% heavy minerals and 10% cement (mostly calcite); the sandstones can thus be classified as litharenites. Rock fragments consist of 50% carbonates (limestone and dolomite), 21% chert, 15% metamorphic rocks, and 14% igneous rocks.

Ali and Khoshaba (1981) also analysed over 3000 gravel samples. Heavy minerals were dominated by pyroxene, epidote and opaques, and there were significant amphiboles (including glaucophane), chlorite, muscovite and biotite (Fig. 8.40). At Zakho, igneous rock pebbles made up 40% of the gravel clasts present and include basalt, andesite, dacite, granodiorite, monzonite, rhyolite, trachyte and volcanic glass (Fig. 8.41). Carbonates form 25-29 % of the clasts, and quartz 8-18%. Multicoloured chert gravels were abundant in the Kifri and Injana sections (40%). Pebbles of sandstone (1-5%) and metamorphic rocks (4%) account for the remainder of the clasts. The metamorphic rock pebbles included quartzite, marble and schist. The composition of the gravels indicates that they were derived from deep erosion of thrust sheets containing igneous and metamorphic rocks and cherts. The glaucophane was probably derived from exhumed Cretaceous blueschists.

Al-Naquib (1960) recorded the presence in higher horizons of clasts of Cretaceous and Eocene limestone. He also recorded the presence of lenses of *manjak* (bitumen) pebbles some 330 m above the base of the formation at Ain Lailah.

Fauna and age

Polygenic sandy conglomerates near the base of the Lower Bakhtiari Formation at Injana (Thomas *et al.*, 1981) contain a rich vertebrate fauna (21 species) including large carnivores, mastodons, horses, rhinoceros, giraffe, antelope, ostrich and brachypotheres (hippopotamus-like mammals) characteristic of savannas and steppes with rivers. Animals characteristic of a forest environment are absent. The authors considered that the fossil assemblage is probably equivalent to the "Vallesian Land Mammal Stage" of the late Miocene (8–10 Ma). Similarly, the Lower Bakhtiari in Iran contain upper Miocene to lowermost Pliocene vertebrates (Harrison, 1932, *in* James and Wynd, 1965).

Upper Bakhtiari Formation

Al-Rawi *et al.* (1992) defined a type section for this formation, which they referred to as the Bai Hassan Formation, on the west bank of the Zab River about 5 km NW of Bai Hassan village on the NE limb of Jebel Bai Hassan. The formation here is 638 m thick (Fig. 8.42). No fossils have been recorded. A late Pliocene age has been assumed, based in part on the known vertebrate fauna of the underlying unit and on magnetostratigraphic dates of between <2.5 and 1.8 Ma (Lateef, 1992). The formation locally

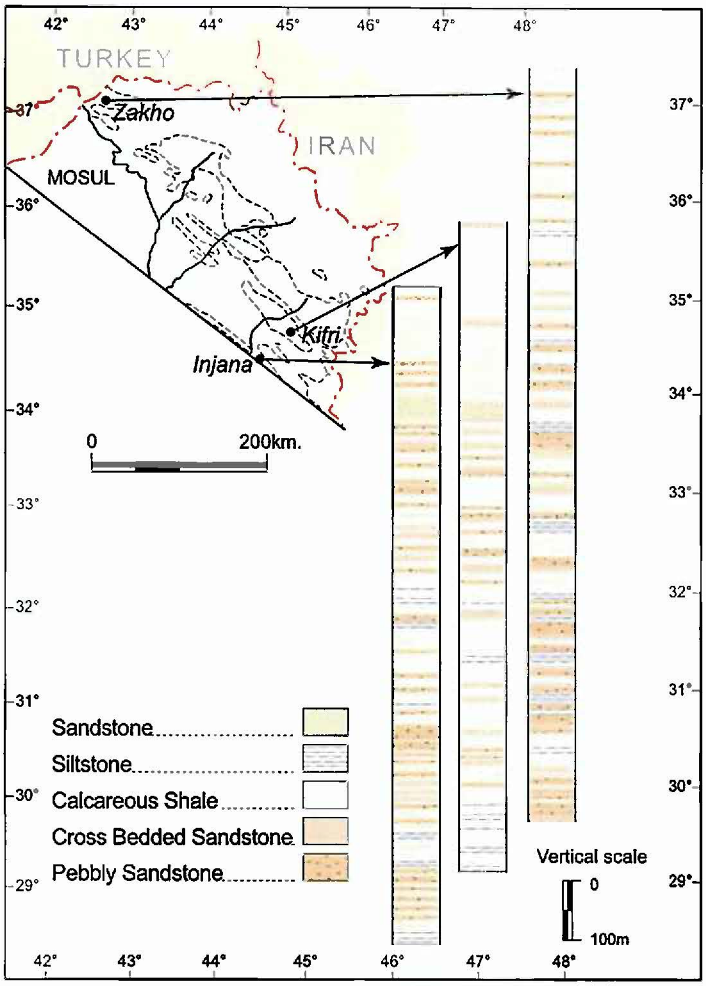


Fig. 8.38. Lithostratigraphy of the Bakhtiari Formation at the Injana, Kifri and Zakho locations in northern Iraq. Outcrop areas are dashed. After Ali and Khoshaba, 1981.

rests unconformably on the Lower Bakhtiari, for example on the NE flank of Jebel Pulkhana (Al-Naquib, 1960). It forms a series of topographic ridges in the Low Folded Zone.

Youkana and Sissakian (1986) described the Upper Bakhtiari Formation from outcrops over a large area of NE Iraqi Kurdistan north of Kirkuk. Here, the formation comprises mudstones and conglomerates with some sandstones and siltstones. Rapid lateral variations in lithofacies occur, as first recorded by Al-Naquib (1960) at Jebel Pulkhana and Jebel Jambur. Mudstones are dominant in the lower part of the formation. Individual mudstone units are 1-30 m thick with a maximum thickness of 100 m.They are multicoloured (red, pale brown and green) and contain small lenses of conglomerates less than 3 m thick which are interpreted as channel fills. In the middle part of the formation, mudstones and conglomerates occur in equal proportions. Conglomerates are dominant in the upper part of the formation in beds 20-30 m thick. Clasts are predominantly limestone (generally 3–8 cm in length). The long axis of most of the clasts trends NE which is interpreted as the palaeocurrent direction. Lenses of sandstones occur in the conglomerate beds. The authors noted that it was difficult to determine the thickness of the formation, but that it might reach 2500 m in the Taq-Taq and Raidar areas. Conglomerate beds in the formation increase in frequency and thickness towards the NE, towards the eroded source area from which they were derived. Apart from these details, the upper part of the formation has not been studied as extensively as the lower part. Al-Naquib (1960) noted that it may be dificult to distinguish the Lower and Upper Bakhtiari where they are conformable.

Merga Group

The Merga Group only crops out in the Thrust Zone of NE Iraqi Kurdistan (Fig. 3.7). (Buday, 1980). The Lower Merga Group consists of red calcareous, silty mudstones with beds of coarse-grained sandstone, pebbly sandstones and locally conglomerates; it is up to 250 m thick. The Upper Merga Group comprises massive conglomerates with boulders and pebbles of metamorphic and igneous rocks; it is 200–250 m thick. The age of the Merga Group is not known for certain but it overlies the early Miocene Govanda Limestone.The Merga Group is overthrust by allochthonous rocks or is overlain by Quaternary terrace or boulder deposits. The Lower and Upper Merga Group rocks may be the lateral equivalents of the Fars and Lower Bakhtiari Formations, respectively.

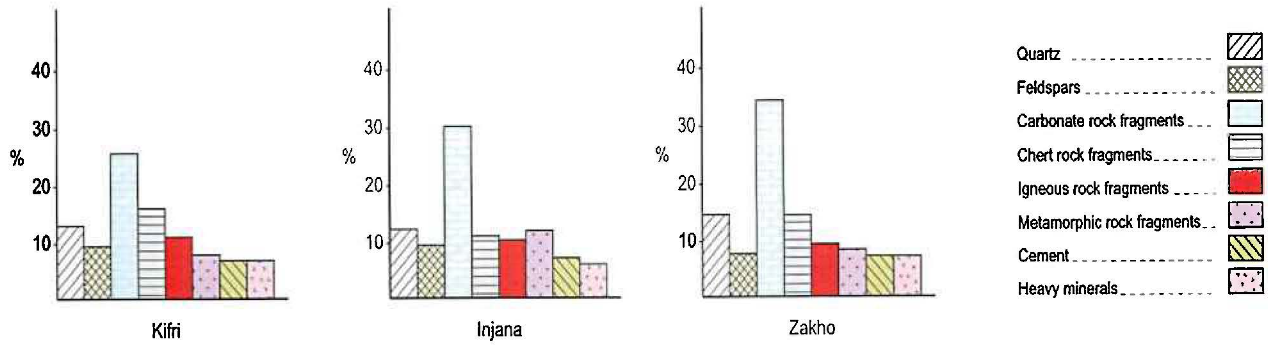


Fig. 8.39. Average percentages of mineral components in the Lower Bakhtiari Formation sandstones at Injana, Kifri and Zakho. After Ali and Khoshaba, 1981.

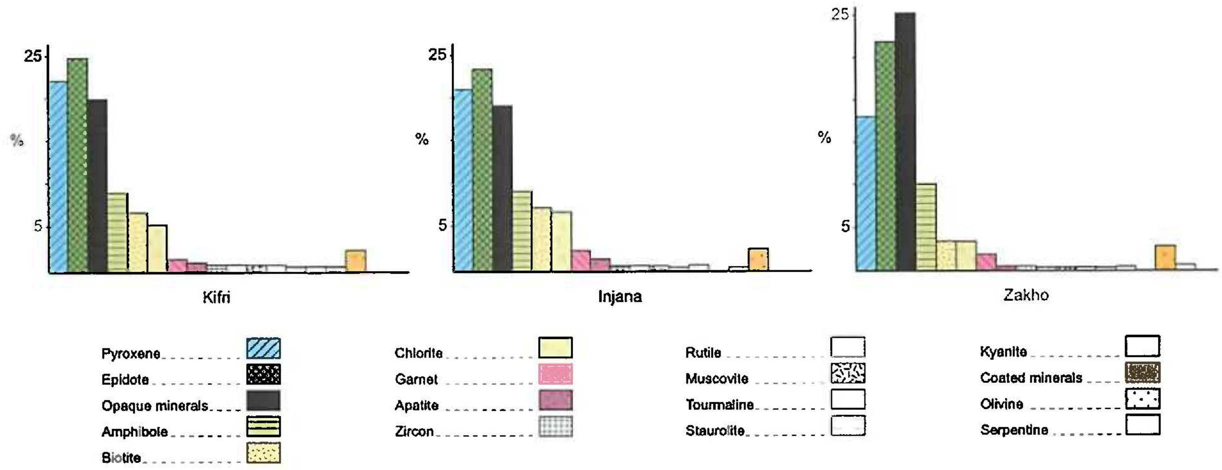


Fig. 8.40. Heavy mineral content in the Lower Bakhtiari sandstones at Kifri, Injana and Zakho. After Ali and Khoshaba, 1981.

Dibdibba Formation

In southern Iraq , the Lower Bakhtiari Formation passes laterally and gradationally into part of the Dibdibba Formation (van Bellen, 1959). This formation is of late Miocene to early Pleistocene age (Al-Rawi and Sadik, 1981). The Dibdibba Formation thickens from 153 m in the *Rumaila* field and 213 m in the south of the *Zubair* field, to 354 m in the northern part of the *Zubair* field (van Bellen, 1959). It thins to the west (Al-Rawi and Sadik, 1981). It consists of sands and gravels composed mainly of acid to intermediate igneous lithologies including pink granites and finely crystalline intrusive rocks, together with white quartz pebbles, sandstones, metamorphic rocks, limestones and chert (van Bellen, 1959; Al-Rawi and Sadik, 1981). Sedimentary structures include planar and cross-stratification, massive beds, channels, scour-and-fill structures, and clay balls (Al-Rawi and Sadik, 1981). The formation overlies the Lower Fars Formation and is thought to be correlative with the Upper Fars and Bakhtiari (van Bellen, 1959), with sediment probably derived from the SW as part of a major NE-flowing fluvial-alluvial fan system developed in a relatively wet climate (Al-Rawi and Sadik, 1981). It underlies Quaternary terrace gravels (van Bellen, 1959).

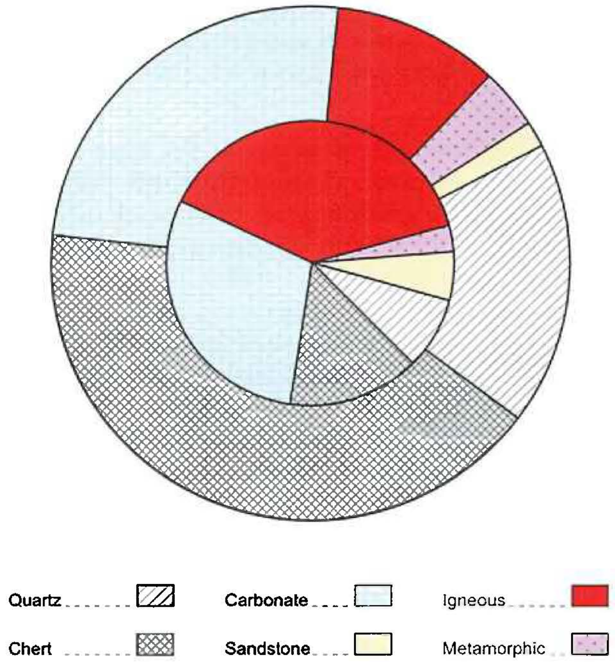


Fig. 8.41. Pie chart illustrating the composition of the Lower Bakhtiari Formation clasts in gravels at Injana and Kifri (large circle) and Zakho (smaller circle). After Ali and Khoshaba, 1981.

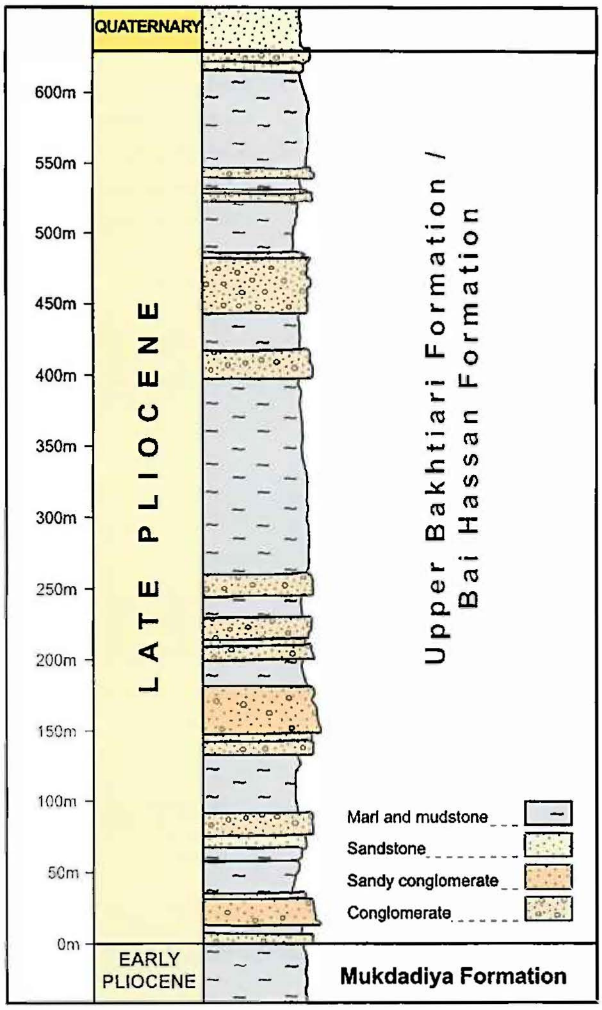


Fig. 8.42. Stratigraphic column through the Upper Bakhtiari (Bai Hassan) Formation at its type locality. After Al-Rawi *et al.*, 1992.

Quaternary

A major unconformity occurs at the base of the Quaternary. Regional isostatic uplift followed Pliocene deformation and anticlinal folding (Hradecky *et al.*, 1978). Quaternary sediments locally exceed 250 m in thickness on the Mesopotamian Plain (Aqrawi *et al.*, 2006c). Fluvial gravels and outwash fans shed from late Tertiary anticlines pass into fluvial-lacustrine and locally marine sediments (Jassim, 1981a; Jassim and Buday, 2006f).The Hammar Formation records a Quaternary marine transgression in SE Iraq (van Bellen, 1959; Aqrawi 1993,b,c; Aqrawi *et al.*, 2006c) although this was not noted by Sharland *et al.* (2001, 2004).

Sediments continue to be transported down the Tigris and Euphrates Rivers into the NW Gulf at the present day. The head of the Gulf is dominated by oolitic sediments at the present day (Aqrawi and Sadooni, 1987; Aqrawi and Darmoian, 1988; Aqrawi, 1994), and very low rates of sedimentation occur in the marshlands to the north. This suggests that for the past 3000 years, most of the sediment carried by these rivers was transported down the Karun River rather than the Shatt Al-Arab. Alternatively, sediment has remained trapped within marshes and lakes (Ahwar) in higher reaches of the Mesopotamian Basin (Aqrawi, 1993b, 1995b, 1996b, 1997; Aqrawi and Evans, 1994).

In western Iraq, the Ga'ara and Khleisia blocks were tilted down to the NE and east during the Quaternary, and are at present sites of net erosion. Wadi floors contain poorly sorted fluvial sedimentary rocks; remnant fluvial terraces are present.

In parts of NE Iraq such as Jebel Hemrin South and on the SW flank of the Jambur structure, residual and terrace gravels of Pleistocene – Recent age rest with high-angle unconformity on the deeply eroded and steeply dipping (up to 65°) Upper Bakhtiari and older formations (Al-Naquib, 1960; Hradecky *et al.*, 1978).

River terraces (comprising thin gravel beds) typically occur every 5–10 m at elevations between 5 and 55 m above river level along the Euphrates and Tigris Rivers. The lowest terrace is interpreted to be Recent and the higher terraces to be of Pleistocene age (Aqrawi *et al.*, 2006c).

In the Foothills Zone, fluvial sedimentary rocks (comprising poorly-sorted gravels and intervals of cemented conglomerates) fill broad depressions between narrow anticlines. Terraces of these sedimentary rocks occur up to 30 m above the present level of the rivers. In the Thrust Zone, fluvial terraces are present at heights up to 50 m and sometimes up to 250 m above valley floors (Aqrawi *et al.*, 2006c). The terrace gravels are locally up to 30 m thick. Lacustrine sedimentary rocks (lower or upper Pleistocene) fill some intramontane depressions. In broad depressions in the High Folded Zone, post-tectonic gravels cover large areas and include large outwash fans; locally in SE Iraqi Kurdistan, these have been assigned to the Maidan Unit (Hradecky *et al.*, 1978).

Petroleum System Components

Proven and Potential Reservoir Rocks

Porosities in carbonates of the Lower Fars Formation (the basal Transition Zone limestones) are 15-20% with permeabilities of about 100 mD (Jassim and Al-Gailani, 2006). Porosity is commonly vuggy after dissolution of anhydrite nodules, a process which the authors have also observed in the Euphrates and Jeribe Formations and which is due to bacterial reduction of sulphates (c.f. Gutteridge *et al.*'s (2000) study of the Eocene reservoir at the *Wafra* field, Kuwait). These carbonates are in fracture/fault contact with the Main Limestone at *Kirkuk.* Oil drains down into the Main Limestone from this unit as gas rises into it in the Baba Dome (Daniel, 1954). Where porosity is present, it is commonly filled with heavy oil or bitumen.

The Basal Fars Conglomerate marks the base of an onlap surface which is clearly diachronous; it overlies Oligocene carbonates in the Baba and SE

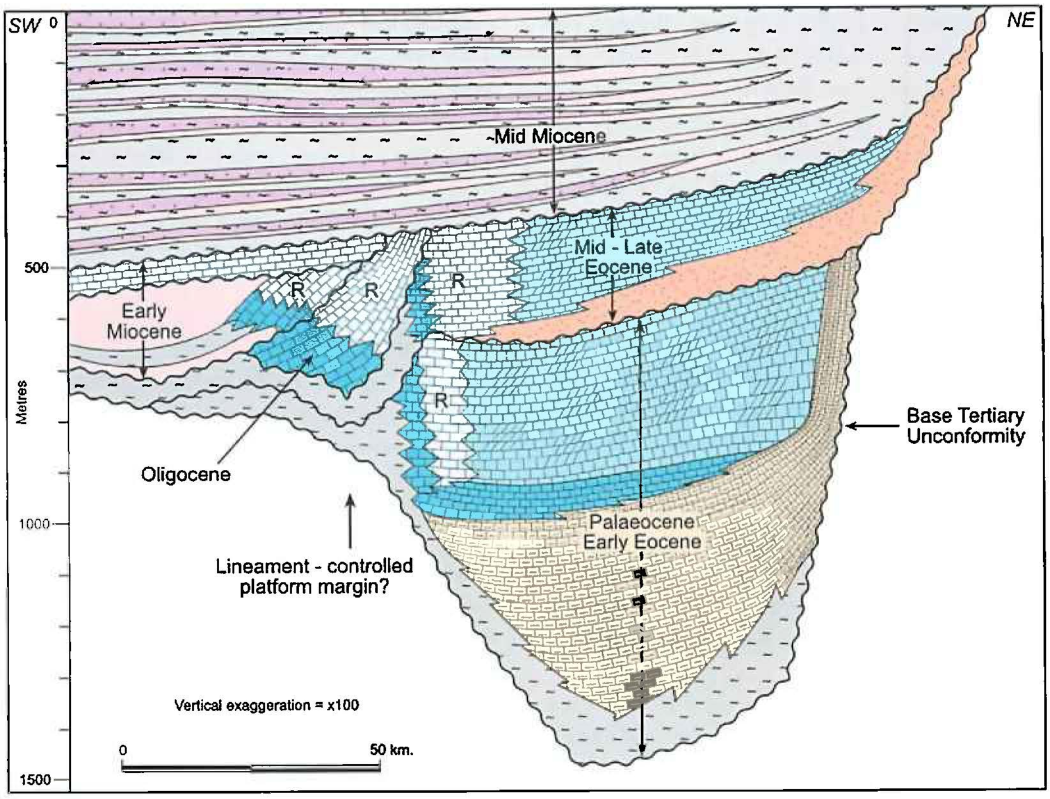


Fig. 8.43. Schematic SW-NE cross-section passing through the *Kirkuk* field in NE Iraq showing Cenozoic basinal successions. Note datum at top of the Lower Fars Formation. R: platform margin carbonate reservoir. After Goff *et al.*, 2004c.

Avanah Domes, and Eocene carbonates in the NW Avanah and Khurmala Domes of the *Kirkuk* field. Slinger and Crichton (1959) stated that the underlying limestones were uplifted and eroded prior to deposition of the Lower Fars. The Basal Fars Conglomerate is dense and impermeable, with a matrix of argillaceous/calcareous cement, and "scarcely anywhere shows any oil content" (Daniel, 1954).

In the Basra area (IPC, 1956; Al-Naqib, 1967), oil-bearing limestones in the basal Lower Fars occur above the oil-bearing sandstones of the Ghar Formation. However, given the more economic underlying reservoirs nearby, the oil in this unit has not been developed except for local use in lighting or heating. Fars Group oils were however used in historical times; oils from the seep at Hit in central Iraq were used in buildings at Babylon.

Proven and Potential Source Rocks

To date, no source rocks are known to occur in this interval in Iraq.

Proven and Potential Cap Rocks

The Lower Fars Formation forms a major regional seal for underlying Cenozoic reservoirs (and possibly Mesozoic reservoirs) throughout the Mesopotamian Basin (Fig. 9.6.1, 9.6.3) (Aqrawi, 1993a; Goff *et al.*,1995). In general, sealing is optimal in the halite-dominated parts of the basin, and seal capacity decreases towards less evaporitic-dominated areas, e.g. the *Demir Dagh-1* well. Seals may also occur locally as shales and marls higher in the succession.

Concluding Remarks

In Paleogene – Early Miocene time, carbonate platforms aggraded along the margins of, and prograded into, the Mesopotamian Basin. Successive periods of subsidence led to the deposition of three supersequences of Paleocene – Eocene, Oligocene and Early Miocene ages. Carbonate reservoirs were best developed on the margins of the platforms which faced into the basin. Relatively slow but steady subsidence resulted in the deposition of Oligocene and Early Miocene carbonates of excellent reservoir quality. In late Aquitanian – early Burdigalian time, the basin had shallowed sufficiently to allow widespread deposition of shallow-water carbonates. Formation of a regional unconformity of mid-Miocene age led to subaerial exposure of the Palaeogene - Early Miocene carbonate platforms, and the formation of secondary porosity systems.

The prospectivity of NE Iraq has been increased by the stacking (i.e. superimposition) of Paleogene and earliest Neogene shelf margins orientated approximately parallel to the axis of later Neogene deformation, particularly in the *Kirkuk* structure (Fig. 8.43). This resulted in the development of thick reservoir sequences that have good communication and strong pressure/aquifer support. Where the stratigraphy is more divided (e.g. in the centre and SW of the Mesopotamian Basin), reservoirs are thinner and reservoir units are more isolated. The stacking patterns of platform margins probably have an underlying structural control. The *Kirkuk* area for example was structurally elevated compared to the NW and SE areas of Iraqi Kurdistan. *Kirkuk* field dominates the Tertiary play system of Iraq.

The onset of rapid regional subsidence in late Burdigalian time was accompanied by supply of fine-grained clastic sediments, from the rising NE (active) margin of the Arabian Plate. Initially, clastic sedimentation was frequently outpaced by subsidence, resulting in the deposition of widespread units of halite and anhydrite which act as regional seals for underlying Tertiary carbonate reservoirs. All major Tertiary hydrocarbon accumulations in Iraq and adjacent areas of the Zagros of Iran rely on this evaporite top-seal.

Tectonic deformation in Iraq became progressively more intense from late Late Miocene time onwards. This deformation exerted a strong control on sediment thickness and facies of the Bakhtiari Formation, and formed the major structural traps of the Zagros. A regional unconformity at the base of the Quaternary is associated with the cessation of major tectonic subsidence in the Mesopotamian Basin. This may prove to be a megasequence boundary associated with a change in deformation style along the northern and NE margin of the Arabian Plate. A veneer of Pleistocene – Recent sediments was deposited on this unconformity surface.

The tectonic development of the Mesopotamian Basin has exerted a major control on hydrocarbon prospectivity. The Cenozoic margin of the NE Arabian Plate formed a hinterland where carbonate and ophiolitic rocks were uplifted in Paleocene and Eocene time. They provided relatively minor quantities of coarse-grained clastics to the developing foreland basin (Kolosh and Gercus Formations). The limited clastic supply from the NE allowed the development of carbonate platforms on the NE margin of the Mesopotamian Basin. Lateral facies changes in Paleocene to early Eocene, mid to late Eocene, Oligocene and early Miocene time are summarised on Fig. 8.43. Important platform margin carbonate reservoirs were deposited in and along strike from the Kirkuk structure. The SW margin of the basin evolved in a different way to the Zagros margin. On this margin, the carbonate platforms prograded further into the basin forming gently dipping ramps, with very limited clastic sediment input. Rapid subsidence in mid– early Late Miocene time was accompanied by an influx of fine-grained muddy and silty sediment of the Fars formations. By the time coarse clastic sediments of the Baktiari Formation entered the Mesopotamian Basin, underlying Cenozoic reservoirs were deeply buried and regionally sealed.

It is instructive to compare the Cenozoic evolution of the Arabian Plate with that of the neighbouring Indian Plate, where a broadly similar Permian-Cretaceous Tethyan stratigraphy was more radically shortened. In the Himalayas, major thick-skinned thrusts brought basement rocks to the surface, resulting in an almost entirely coarse clastic-dominated Tertiary foreland basin fill. The contrast in the hydrocarbon prospectivity of the Cenozoic succession on these two compressional margins is immediately apparent.

The Tertiary succession in Iraq does not contain significant mature source rocks, and thus underlying Mesozoic source rocks are required to charge Tertiary reservoirs. Hydrocarbon plays in Tertiary carbonate reservoirs in Iraq are discussed in Chapter 9vi (pp. 357-380). The rapid late subsidence in Iraq, and the accompanying deposition of thick clastic sediments in the Mesopotamian Basin in mid-Miocene – Pliocene time, has controlled the major phase of maturation of underlying Mesozoic source rocks, and the final phase of maturation of Lower Palaeozoic source rocks in Iraq.

9. PETROLEUM SYSTEMS

i. Introduction

This chapter reviews the petroleum systems and hydrocarbon habitats so far identified in Iraq and summarises the geological elements which control them.There has been little hydrocarbon exploration in Iraq over the last 25 years, and understanding of the petroleum systems is therefore limited.

The unique nature of the Arabian Plate's petroleum systems was first discussed by Henson (1951a,b). Dunnington's (1958) seminal paper on the petroleum systems of northern Iraq was recently (2006) reprinted in *GeoArabia* as a mark of its continuing relevance. Murris (1980) and Beydoun (1991) noted that, while no single component of Arabian Plate petroleum systems is exceptional, the sheer scale of the Arabian basin is perhaps the most important factor controlling its resource base. The repeated occurrence of source, reservoir and caprocks, together with the favourable timing of hydrocarbon generation and trap formation, are factors which further enhance the basin's prospectivity.

A petroleum system as defined here (after Magoon and Dow, 1994) is the rock volume within which oil, generated from a source rock, migrates to and accumulates in a trap. In Iraq, four petroleum systems can be recognised on this basis: Palaeozoic, Triassic, Jurassic and Cretaceous. These systems are discussed in Parts ii, iii, iv and v of this Chapter. Cenozoic play systems and reservoirs, which mostly contain migrated (or remigrated) hydrocarbons generated by Jurassic and Cretaceous source rocks, are discussed in Part vi.(Brief Concluding comments are on pp.381-382). The petroleum systems are confined to different parts of Iraq but frequently overlap.Verma *et al.* (2004) by contrast recognised only three Total Petroleum Systems (TPSs) in Iraq: Palaeozoic (TPS 202301), Jurassic (TPS 202302), and Cretaceous-Tertiary (TPS 203001) (Fig. 9.1.1).

Lower Silurian source rocks have been identified in western Iraq, and may charge Palaeozoic reservoirs ranging in age from Ordovician to Permian. However, few exploration wells have penetrated Palaeozoic rocks. Only one Palaeozoic hydrocarbon discovery has been made (*Akkas*), where oil occurs in Silurian sandstones and gas in Upper Ordovician sandstones. The extent of the Palaeozoic petroleum system and the possible contribution of pre-Silurian source rocks remain to be established.

Exploration for Triassic reservoirs has been largely confined to NW Iraq, where Triassic source rocks have charged Triassic carbonate reservoirs. However, the extent of the Triassic petroleum system outside this area of limited well control is unknown. The Jurassic petroleum system is also poorly understood despite the presence of regionally extensive Jurassic source rocks. No fields yet produce from Jurassic reservoirs. The Cretaceous and Tertiary petroleum systems account for > 99% of the discovered oil reserves in Iraq and are better understood, but detailed studies typing oils to source rocks are lacking.

Petroleum system components

The principal ***source rocks*** in Iraq (Fig. 9.1.2) comprise Lower Silurian shales which have charged Palaeozoic reservoirs; and Upper Jurassic and Lower Cretaceous shales, marly limestones and marls which are the main sources of hydrocarbons trapped in Cretaceous and Tertiary reservoirs. Extensive ***reservoir rocks*** were deposited in basin-margin or shelfal settings. Regional-scale ***caprocks*** include evaporites of Late Jurassic and middle Miocene ages together with siliciclastics; carbonate seals may provide effective seals at a field scale.

Structural traps are the principal exploration target in Iraq. Stratigraphic traps may occur in the Palaeozoic siliciclastic succession (Al-Hadidy, 2007) and in Mesozoic rudist-bearing carbonates (e.g. Aqrawi *et al*,. 1998, Sadooni and Aqrawi, 2000). Traps with Mesozoic (mainly Cretaceous) and Cenozoic reservoirs have been investigated relatively thoroughly, particularly in the Mesopotamian Basin and Low Folded Zone. Traps containing Palaeozoic reservoirs remain largely unexplored.

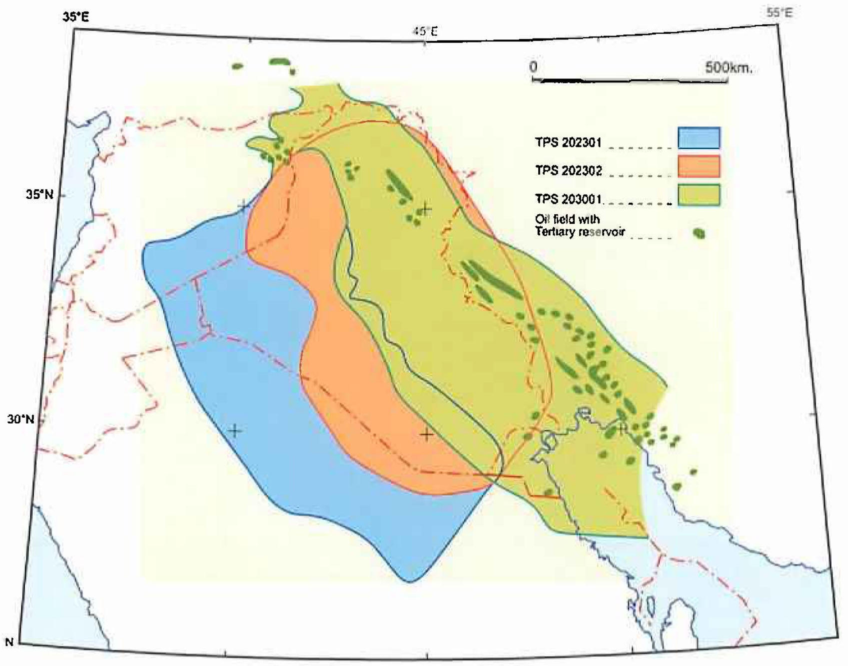


Fig. 9.1.1. Map showing the extent of Total Petroleum Systems (TPSs) in Iraq according to Verma *et al.* (2004). The systems are TPS 202301 (Palaeozoic); TPS 202302 (Jurassic); and TPS202303 (Cretaceous-Tertiary).

Stratigraphic distribution of reserves

Reservoir rocks in Iraq cover a wide stratigraphic interval from Palaeozoic to Tertiary (Fig. 9.1.2), and are dominated by carbonates. Verma *et al* (2004) stated that Cenozoic reservoirs contain 24% of Iraq's reserves, Cretaceous reservoirs 76%, and older reservoirs only about 0.1%. A similar division of reserves was noted by Al-Khirsan and Al-Siddiki (1989), who recorded 24 B brl of oil in the Cenozoic and 76 B brl in the Cretaceous, with some 100 MM brl in the Jurassic and Triassic. Al-Sakini (1992: Table 9.1.1) suggested that the Cenozoic contribution is somewhat less. There is thus uncertainty over a precise reserves distribution.

Most fields in Iraq are dominated by oil although a few "free gas" fields produce from Cenozoic reservoirs in the Zagros foldbelt (Pitman *et al.*, 2004) and one (*Akkas*) produces from a Palaeozoic reservoir in Western Iraq (Al-Haba *et al.*, 1994).

Table 9.1.1. Reserves percentages per reservoir age (based on Al-Sakini, 1992).

Rervoir age	Percentage of reserves
Tertiary	16.3%
Late Cretaceous	13.8%
Middle Cretaceous	39.5%
Early Cretaceous	29.7%
Older reservoirs	0.70%

Traps

Verma *et al.* (2004) noted that 526 "structures" (i.e. traps) are known in Iraq, of which 370 remain undrilled. Six principal trap types occur in the Arabian Plate (Beydoun, 1991) and this classification may also be applied to Iraq:

i. Anticlinal traps in NE and northern Iraq (e.g. *Kirkuk*) formed during Late Tertiary Zagros compression (page 57). Relatively short, asymmetric anticlines in NW Iraq result from inversion of pre-existing graben or half-graben e.g. at *Ain Zalah* field (Hart and Hay, 1974).

ii. North-south trending anticlines formed by uplift of basement highs or by inversion. These include the *Rumaila-Zubair* group of structures in SE Iraq.

iii. Stratigraphic traps: Beydoun (1991) noted that stratigraphic traps throughout the Arabian Plate are uncommon due to the "layer-cake" nature of the sedimentary cover and the absence of favourable updip lateral facies changes. However, carbonate build-ups in the Mishrif Formation may locally form stratigraphic traps (Aqrawi *et al.*, 1998).

iv. Transpressional/transtensional structures occur in a NW-SE trending zone in central Iraq (Fig. 3.7) and form traps at *Sadid, East Baghdad* and *Al-Ahdab*. Sadooni (1996) proposed that these traps are associated with low-relief positive flower structures.

v. Tilted fault-block traps occur locally, particularly in association with Late Cretaceous half-graben around the Khleisia High. Tilted fault blocks are likely to occur in NW Iraq where Ameen (1992) documented an extensional, WNW-ENE

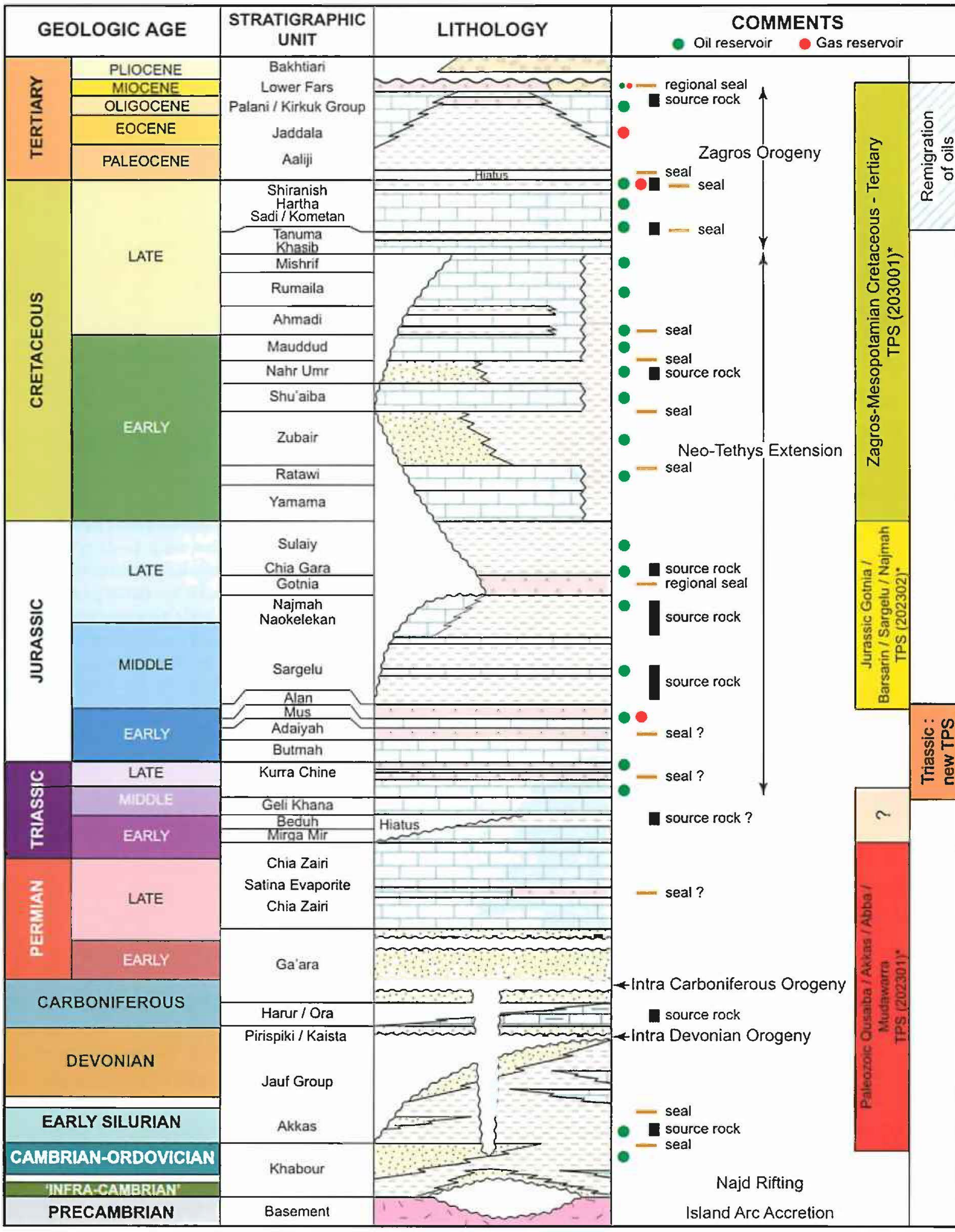


Fig. 9.1.2. The stratigraphic distribution of source rocks, resevoirs and seals in Iraq. TPSs 202301, 202302 and 202303 after Verma *et al.*, 2004, with suggested additions.

oriented graben system similar to the NW-SE oriented Euphrates Graben system in Syria (Litak *et al.*, 1998; Caron *et al.*, 2000).

vi. Salt-cored traps: Jebel Sanam is the only salt diapir known in Iraq (page 69). This trap type is therefore likely to be less significant than in the southern Gulf.

Thermal conductivity, heat flow and factors influencing source rock maturity

Thermal parameters in Iraq control source rock maturation and timing of hydrocarbon generation and expulsion. They are briefly reviewed in the following paragraphs.

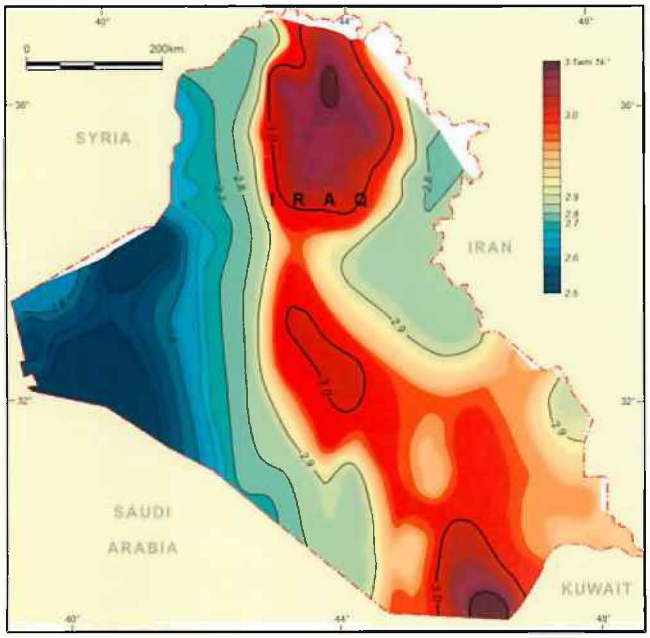


Fig. 9.1.3. Map of Iraq showing the thermal conductivity of the sedimentary cover above basement rocks. Adapted from Jassim and Al-Gailani, 2006.

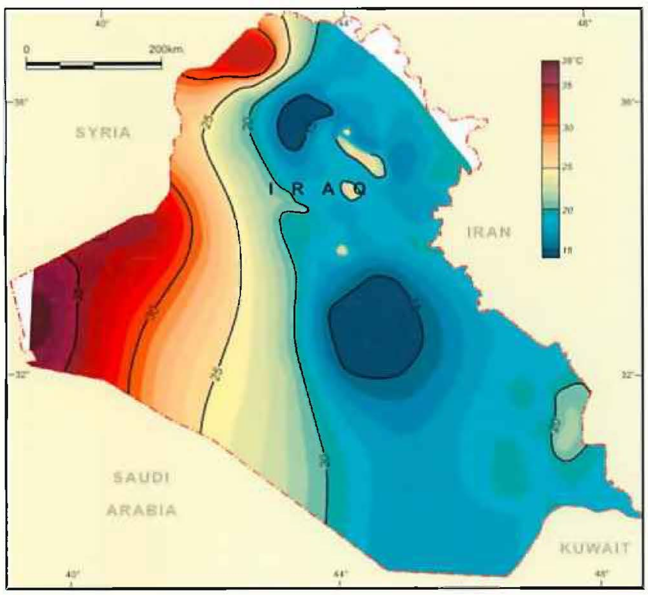


Fig. 9.1.4. Map of geothermal gradients in Iraq (°C/km). The map is derived from uncorrected bottom-hole temperatures and should therefore be interpreted with care; true bottom-hole temperatures will be higher because of cooling of the borehole walls by drilling mud. Adapted from Jassim and Al-Gailani, 2006.

Thermal conductivity

Precise measurements of thermal conductivities of sedimentary rock in Iraq are not available. Jassim and Al-Gailani (2006) estimated the mean thermal conductivity of the sedimentary cover (Fig. 9.1.3).The lowest mean thermal conductivities occur in the west of Iraq and are due to the presence of thick Lower Palaeozoic mudstones. High thermal conductivites in central Iraq are due to a thick succession of Permian to lower Miocene carbonates.

Heat flow

Detailed studies of heat flow in Iraq have not yet been performed or are not available. In southern Jordan, Forster *et al.* (2007) calculated heat flows based on measurements of temperature and thermal conductivity in five shallow boreholes (<1000 m deep) drilled through Silurian and Ordovician rocks. The average heat flow was 60 +/- 3 mW/m^2.

In Iraq, calculated present-day heat flow values range from 45 mW/m^2 in the southern Mesopotamian Basin to 48 mW/m^2 in the Zagros foldbelt (Pitman *et al.*, 2004), assuming a mean surface temperature of 27°C. These relatively low heat flows may be due to high sedimentation rates in the late Miocene – Pliocene. PGA (2000 *in* Pitman *et al.*, 2004) suggested that palaeo heat flows in six widely-spaced wells were around 60 mW/m^2 in the Middle and Late Jurassic, and subsequently decayed linearly to present-day values.

Geothermal gradient

The geothermal gradient map of Iraq published by Jassim and Al-Gailani (2006) (Fig. 9.1.4) is based on uncorrected bottom-hole temperatures and should therefore be interpreted with care. The map indicates that the uncorrected geothermal gradient in western Iraq (outside the Mesopotamian Basin) (> 28°C/km) is substantially greater than that to the east. The highest uncorrected gradients, up to 37°C/km, occur in the Western Desert and in NW Iraq in the Sufaiyah-Mushorah area.

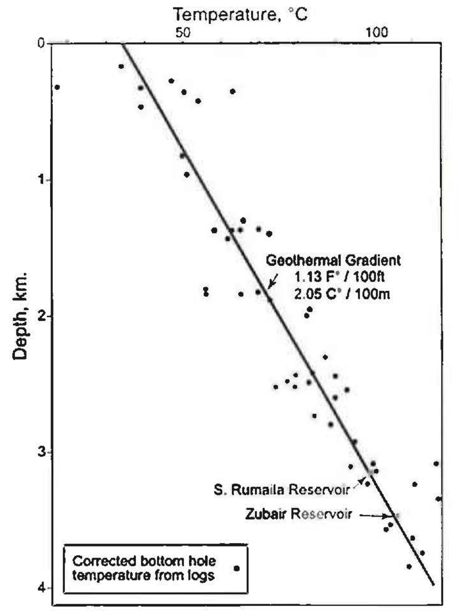


Fig. 9.1.5. Geothermal gradient in southern Iraq. After Ibrahim, 1983. Note that at depths below 3000 m, corrected bottom-hole temperatures are about 20°C higher than uncorrected temperatures.

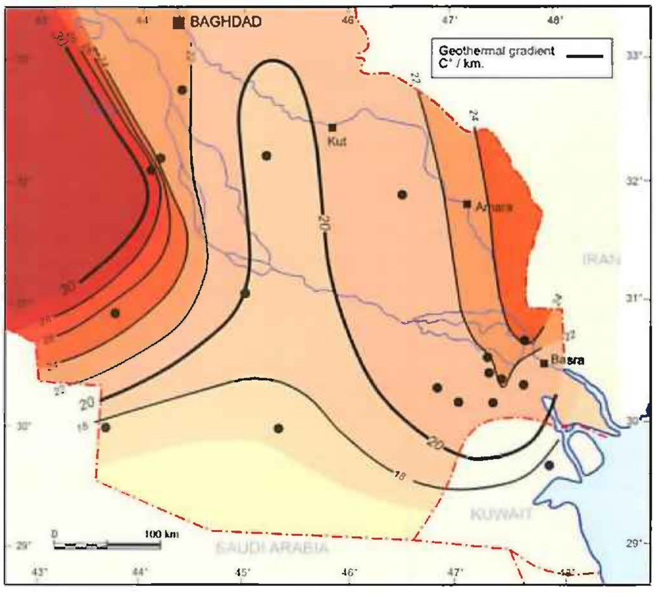


Fig. 9.1.6 Corrected geothermal gradient map for southern Iraq. After Ibrahim, 1984.

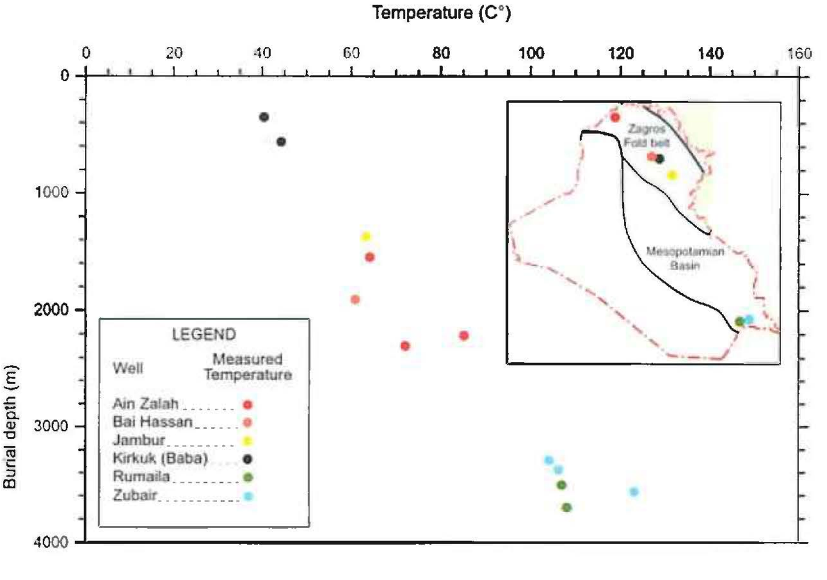


Fig. 9.1.7. Temperature versus depth for wells across Iraq. After Pitman *et al.*, 2004.

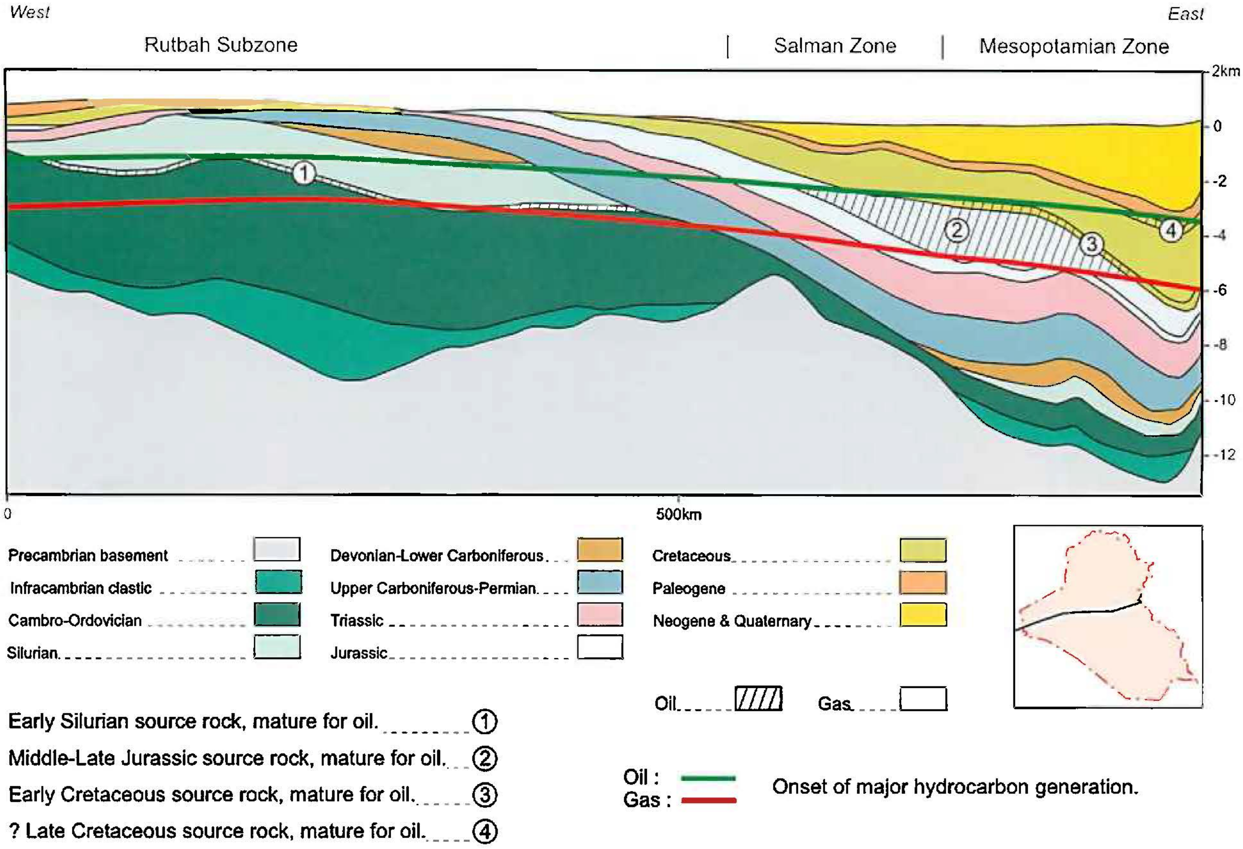


Fig. 9.1.8. Approximately west-east cross-section across central Iraq (modified after Jassim and Buday, 2006b) showing distribution of mature source rocks.

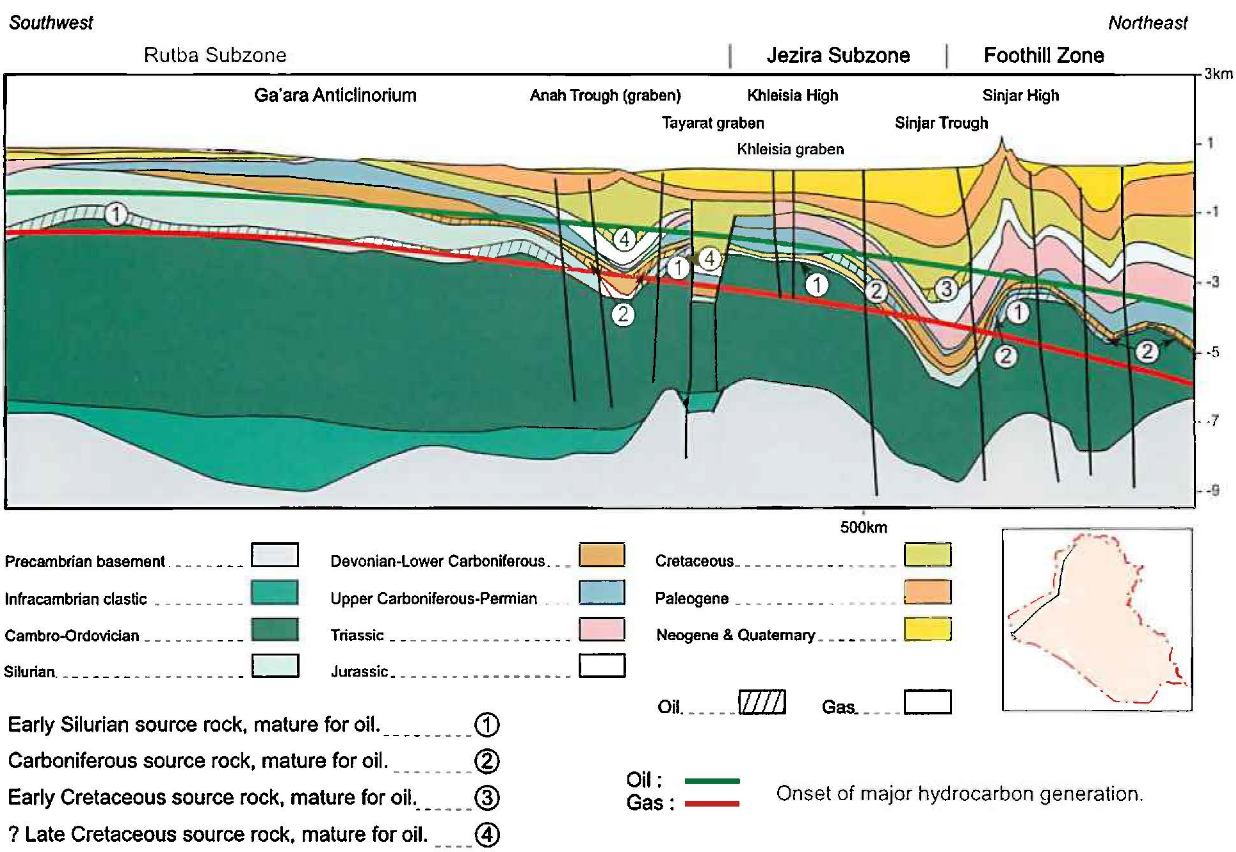


Fig. 9.1.9. SW-NE cross-section across western Iraq (modified after Jassim and Buday, 2006b) showing distribution of mature source rocks.

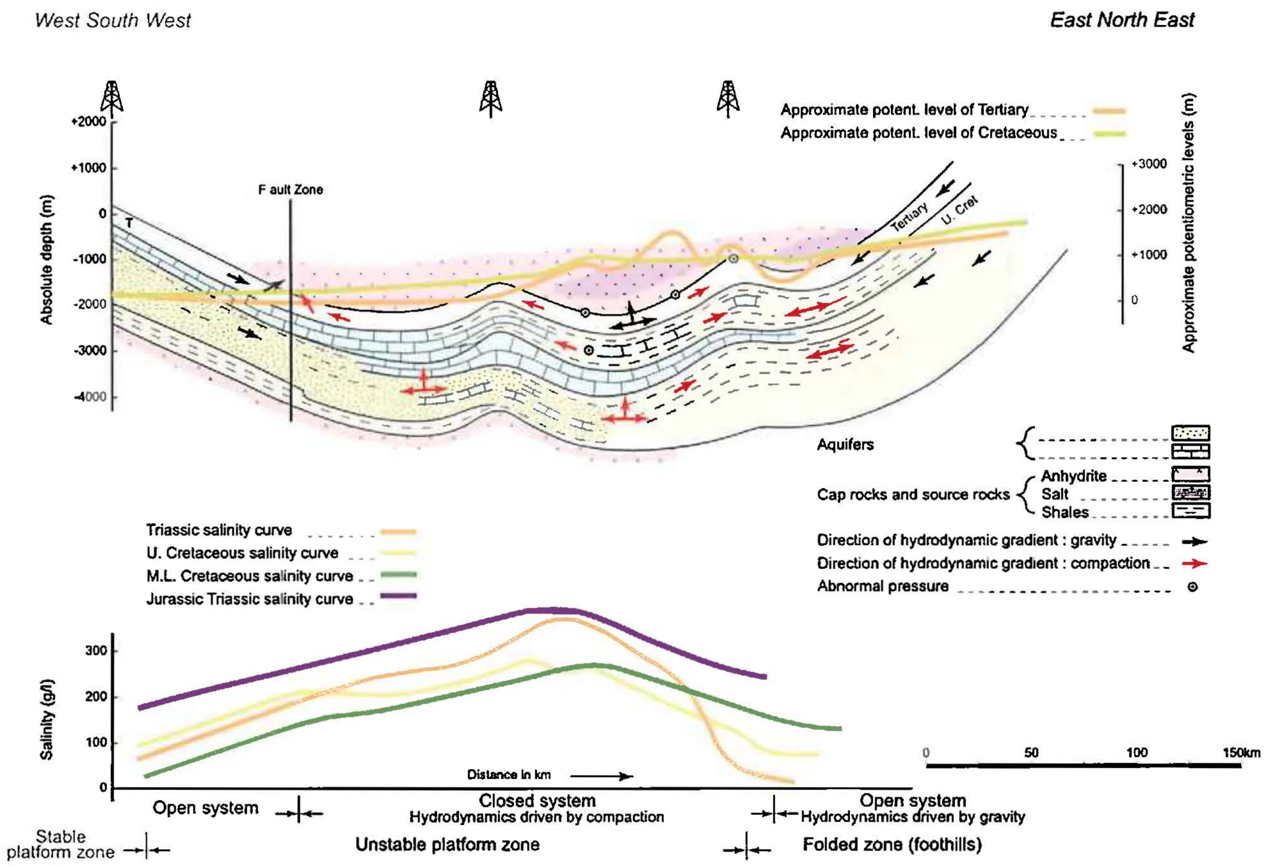


Fig. 9.1.10. Schematic hydrological cross-section across the Mesopotamian Basin (see text for discussion). Figure adapted after Al-Mashadani (1986).

Ibrahim (1983) studied subsurface termperature data in SE Iraq corrected for the cooling effects of drilling mud (Fig. 9.1.5). Corrected temperatures are about 20°C higher at a depth of 3000 m than uncorrected temperatures. A contour map of the corrected geothermal gradient in SE Iraq is shown in Fig. 9.1.6.

Al-Shdidi *et al.* (1995) determined a geothermal gradient of 25°C/km in the Kirkuk area based on temperature data from nearby wells. El Zarka (1993) noted that the geothermal gradient at the *Ain Zalah* field is 28°C/km. Geothermal gradients are in general relatively low in the Zagros fold-and-thrust belt (Fig. 9.1.7) (18-23°C/km; Pitman *et al.*, 2004), where very thick Cenozoic sedimentary rocks occur.

The geothermal gradient at the *Risha* field in East Jordan is 40°C/km (Beydoun *et al.*, 1994). Jassim and Al-Gailani (2006) suggested that the heat flow in the adjacent Rutbah subzone of Iraq is also high because of higher heat production in the continental crust, or because of heating associated with the eruption of Neogene basalts in adjacent parts of NE Jordan and SE Syria.

In SE Iraq, the present-day geothermal gradient is about 24°C/km as determined by subsurface temperatures of about 107°C recorded at 3400 m depth with an average surface temperature of 25°C. A measured temperature of about 122°C at 3600 m at *Zubair* (Fig. 9.1.7) indicates the geothermal gradient is 27°C/km.

Lateral variations in maturity

The approximate depths to the top of oil and gas generation in Iraq are shown in two regional cross-sections (Figs 9.1.8 and 9.1.9). Depths to the top of the oil and gas windows are least in the west due to the lower average thermal conductivities, higher heat flow, and uplift. Depths to the oil and gas windows are greater in the east due to lower heat flows.

Regional maturation maps for the Silurian and Jurassic source rocks on the Arabian Plate (including Iraq) based on basin modelling have been published by Pietraszek-Mattner *et al.* (2008).

Hydrogeological Systems

Hydrogeological systems determine the extent of freshwater invasion into subsurface units and thus the resultant biodegredation of reservoired oils.

Al-Mashadani (1986) reviewed 350 well tests and 450 water analyses from Iraq and defined four hydrogeological units by integrating stratigraphic, hydrochemical and hydrodynamic data: Tertiary; Upper Cretaceous; Lower-Middle Cretaceous; and Jurassic-Triassic.

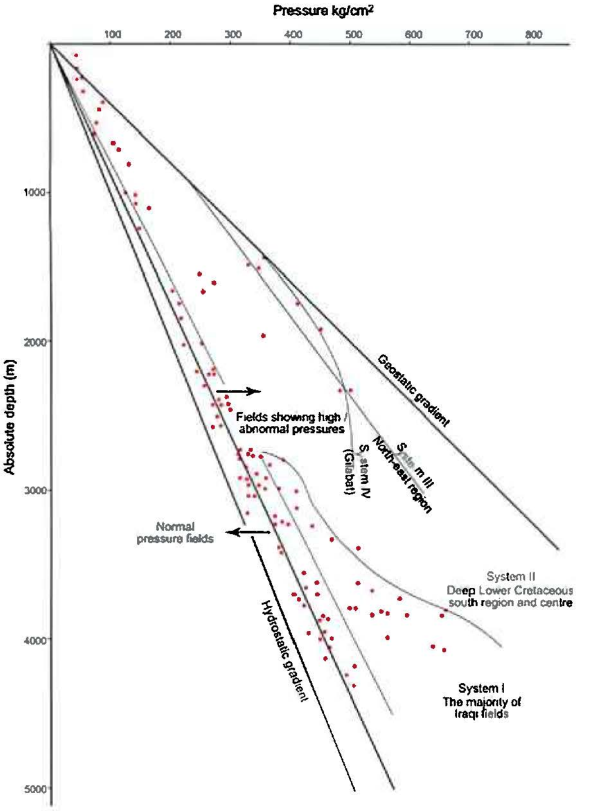


Fig. 9.1.11. Pressure versus depth relationships for different types of wells in Iraq, showing the development of four types of aquifer system (see text for discussion). Figure adapted after Al-Mashadani (1986).

Ibrahim (1983) presented fluid pressure data derived from mudweights and DSTs. Reservoir pressures usually hydrostatic down to 3000 m. Below 3700 m, they increase rapidly to 50-60 MPa in the lower part of the Lower Cretaceous section in SE Iraq. The Jurassic section in SE Iraq is probably highly overpressured by analogy with the equivalent section in Kuwait (Goff, 2005). High pore pressurs also occur within the evaporite-bearing Lower Fars Formation of northern Iraq.

Gravity is responsible for the recharge of aquifers in the Zagros and Arabian Shield areas (Fig. 9.1.10). These systems ultimately drain via fracture systems and springs into the Euphrates and Tigris valleys.

Gravity recharge of formation waters occurs via aquifers in the west (in the Western and Southwestern Deserts) and from the Zagros Mountains in the east (black arrows in Fig. 9.1.10). Within the basin, compaction forces fluids to move in the direction of least potential energy according to potentiometric gradients (red arrows). Because of the regional Lower Fars seal (anhydrites in pink and salt in purple at the top of the upper figure), the resulting flow patterns cause large-scale escape of fluids along the Abu Jir fault zone (Fig. 9.1.10). The Zagros aquifer system dominates the area of anticlines and productive fields to the east of this fault zone. The basin centre is a closed system in which salinities are generally high, while the areas of active recharge on the basin margins are less saline. Internal permeability barriers within the main part of the basin account for local pressure and flow anomalies.

There are several types of aquifer system in Iraq (Al-Mashadani, 1986) (Fig. 9.1.11):

(i) System I, comprising the majority of Iraqi reservoirs, show pressures close to hydrostatic down to nearly 3000 m.

(ii) System II reservoirs have normal gradients at shallow levels and higher gradients at depth, particularly in wells that penetrate the Lower Cretaceous where well-developed pressure seals are present.

(iii) Systems III and IV reservoirs associated with the Lower Fars Formation in the Zagros fold-and-thrust belt are generally highly overpressured, with pressures close to geostatic.

9. PETROLEUM SYSTEMS

ii. Palaeozoic

Little is known of the Palaeozoic petroleum system in Iraq because of the limited amount of pre-Mesozoic exploration. A schematic cross-section through the Palaeozoic petroleum system is shown in Fig. 9.2.1. At least 15 exploration wells have been drilled to the Triassic in Iraq but only eight have reached the Palaeozoic (*Khleisia-1, Jebel Kand-1, Mityaha-1, Atshan-1, Akkas-1, West Kifl-1, Diwan-1* and *Qaim-1:* locations in Fig. 4.2).

The oldest Palaeozoic rocks encountered are thick Middle Ordovician mudstones of the K7 Member of the Khabour Formation in wells *Akkas-1* and *Khleisia-1*.

The Arabian Plate Palaeozoic petroleum system comprises source rocks of Early Silurian and Ordovician ages together with Ordovician- Permian sandstone reservoirs and Upper Permian carbonate reservoirs (Mahmoud *et al.*, 1992; McGillivray and Husseini, 1992; Cole *et al.*, 1994a,b; Bishop, 1995; Jones and Stump, 1999). Palaeozoic oils are commonly >40°API with low sulphur contents (Aqrawi, 1998; Wender *et al.*, 1998; Fox and Ahlbrandt, 2002). Ahlbrandt *et al.* (2000) estimated that undiscovered Palaeozoic reserves in Iraq, taken as the 5th and 95th percentiles of the probability distribution, range from 0.5 to 3.1 billion brls oil (mean: 1.6 billion brls), with 12.6 to 68.8 TCF gas (mean: 38.7 TCF).

The discovery of gas in Permian carbonates in Qatar, Iran, UAE and Saudi Arabia encouraged exploration of the Palaeozoic succession in Iraq. Interest was further stimulated by the identification of an organic-rich Silurian source rock in the IPC well *Khleisia-1* in the late 1980s, by the discovery of gas in Ordovician sandstones at *Risha* in 1987, and by the discovery in 1989-1990 of oil and gas in Palaeozoic sandstones in central Saudi Arabia (McGillivray and Husseini, 1992). Oil and gas was subsequently discovered in 1992 at *Akkas* (Aqrawi, 1998), the only Palaeozoic discovery so far made in Iraq.

The Palaeozoic petroleum system contains siliciclastic reservoir rocks which comprise highstand shelf sandstones and lowstand turbidites. Source rocks are associated with major flooding events. Traps in areas where Palaeozoic source rocks are mature include regional structural highs which may have a stratigraphic trapping component. In areas of later extensional faulting (e.g. in the Euphrates Graben and around *Akkas*), tilted fault blocks are the most important trap type (Aqrawi, 1998). Oil is generated by Lower Silurian or older Ordovician source rocks.

Source rocks

The most important Palaeozoic source rocks on the northern Arabian Plate are of Early Silurian (early Llandovery) age (Fig. 9.2.2). In Iraq, source rock intervals may also occur in the Infracambrian, Middle-Upper Ordovician, Upper Silurian and lowermost Carboniferous. Upper Carboniferous – Lower Permian coals and Devonian shales may have source potential in the SW Desert.

i. Potential Infracambrian source rocks

Source rocks may occur in the Upper Precambrian – Cambrian succession in southern Iraq in the Nukhaib Basin in the SW Desert (Fig. 4.4) (Jassim, 2006c). A potential Infracambrian play may occur in Iraq by analogy with the salt-bearing basins of Oman, where hydrocarbons are generated by Infracambrian and Cambrian silicilytes (organic-rich cherts) (Gorin *et al.*, 1982; Grantham *et al.*, 1988; Terken and Frewen, 2000) and sapropelic limestones (Amthor *et al.*, 2005).

ii. Ordovician source rocks

Lower Ordovician deposition ended with a major marine transgression (the Llanvirn O30 MFS of Sharland *et al.*, 2001) across the entire Arabian Plate including Iraq. This event is represented by the shales assigned to Member 7 of the Khabour Formation (Al-Hadidy, 2007). However these shales contain <1% TOC at the *Akkas* field (Fig. 9.2.3) and at the *Khleisia-1* well (Fig. 9.2.4).

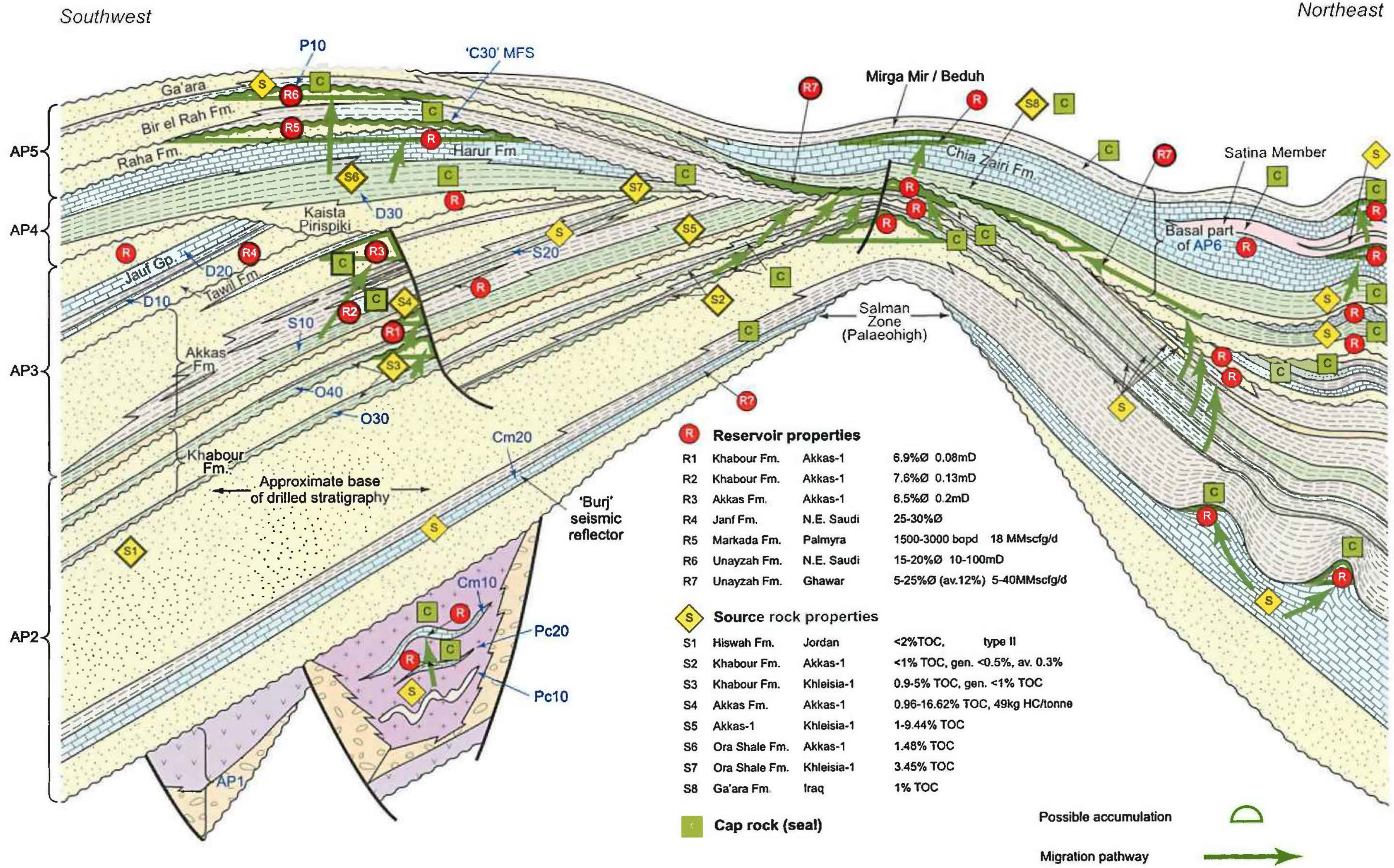


Fig. 9.2.1. Schematic cross-section through the Palaeozoic (and potential Infracambrian) petroleum systems in Iraq.

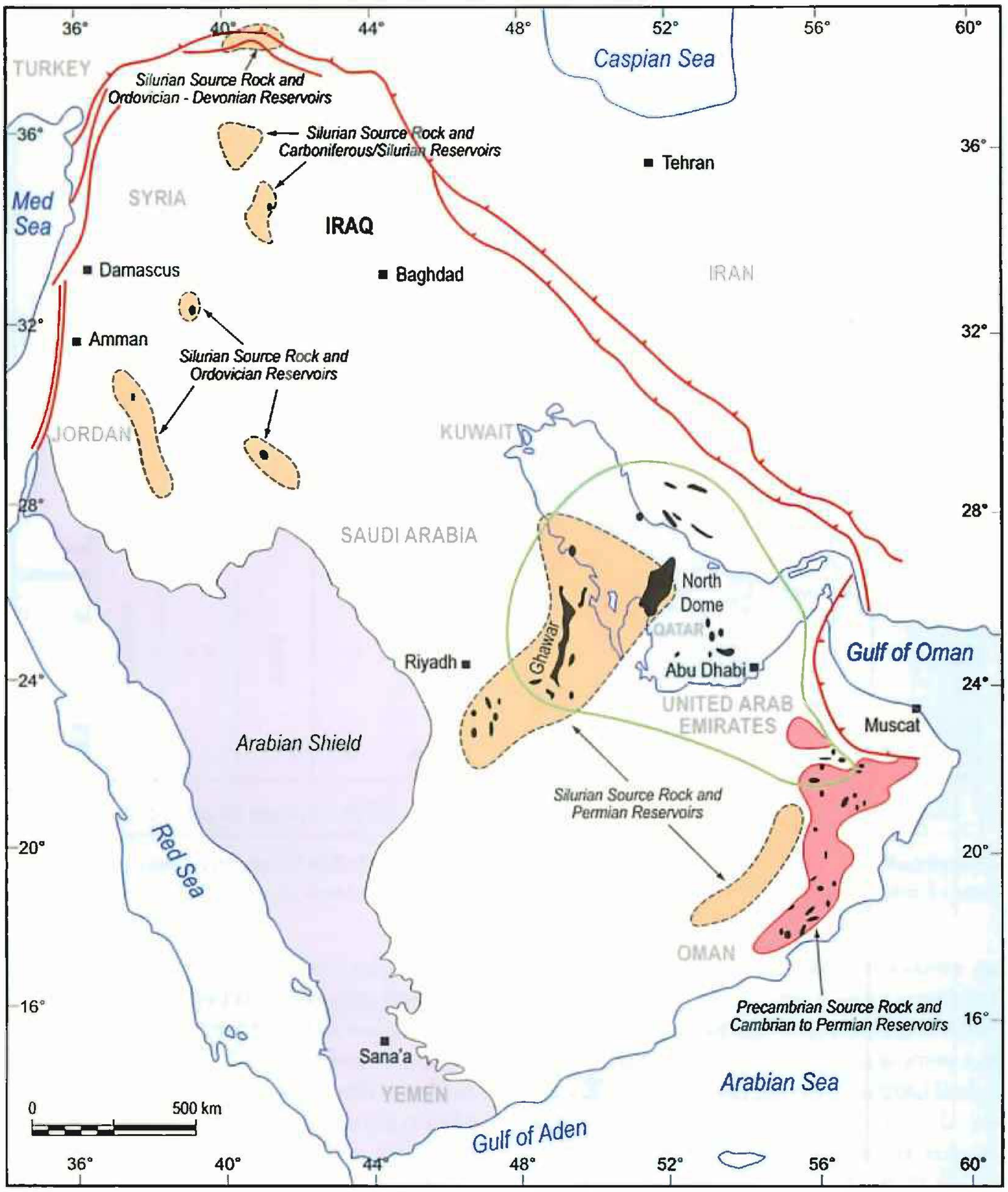


Fig. 9.2.2. Map of the Arabian Peninsula showing the areas where Silurian source rocks are known to have generated hydrocarbons. These source rocks are of major significance in the Gulf region, and have been identified in NW Arabia in the Azraq, Risha, Akkas, Euphrates Graben and Hazro areas. After Konert *et al.*, 2001.

The lower part of the Khabour Formation can be correlated with the shales in the Hanadir Member of the Qasim Formation in the NE Nafud Basin, Northern Saudi Arabia (Aoudeh and Al-Hajri, 1995; Al-Hajri and Owens, 2000). It can also be correlated with shales in the Hiswah Formation at the *Risha* gasfield, Jordan, and at outcrop in Jordan (Powell, 1989; Andrews *et al.*, 1991; Aqrawi *et al.*, 2006b). The Hiswah Formation has a TOC of up to 2% and contains Type II kerogen in NE Jordan (Beydoun *et al.*, 1994).

Shales of Sandbian (formerly Caradoc) age, encompassing the K2 to K4 members of the Khabour Formation (Al-Hadidy, 2007), can be correlated with the O40 MFS of Sharland *et al.* (2001), and are equivalent to the Ra'an Member of the Qasim Formation (Al-Hajri and Owens, 2000), and the Dubaydib Formation of Jordan (Powell, 1989; Andrews *et al.*, 1991).

In Saudi Arabia, the Hanadir Member of the Qasim Formation has a maximum recorded TOC content of 1.13% (Schlumberger, 1991). The stratigraphy of the Hanadir Member was described by Senalp and Al-Duaiji (2001) in a 60 m cored interval from well *Kahfah-1*. The lower part of the formation was observed to comprise dark grey to black, pyritic, micaceous shales. The upper part was composed of similar lithologies with interbedded laminated shales. Minor siltstones and very fine grained sandstones formed less than 10% of the cored interval. The black shales in the basal part of the formation have a "hot" gamma response.

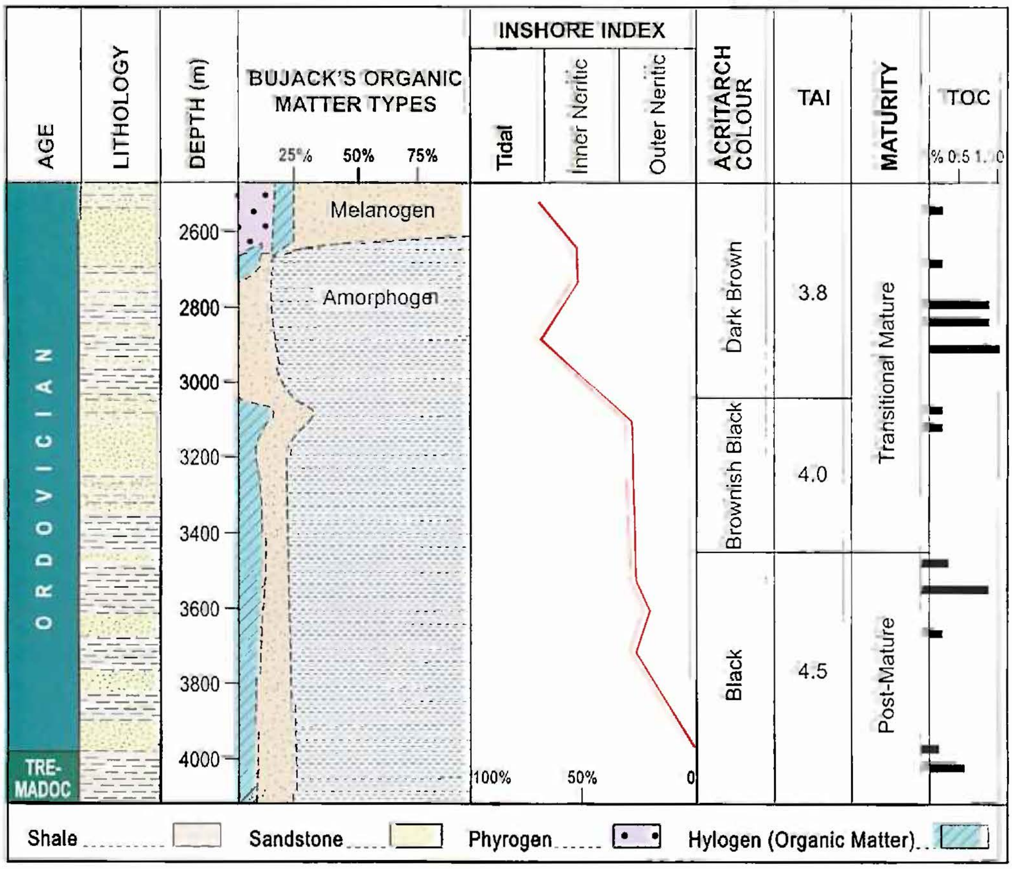


Fig. 9.2.3. Summary of source rock and maturity data for the Ordovician succession at well *Akkas-1*. After Al-Ameri and Baban, 2002; organic matter types after Bujack *et al.*, 1977.

iii. Silurian source rocks

Distribution of source rocks in Iraq

Regional data suggests that the lower Llandovery source rocks were deposited on a passive margin in restricted shelf basins covering most of Iraq (Konert *et al.*, 2001; Jassim, 2006c). Organic-rich shales were deposited in widespread anoxic conditions during a global post-glacial transgression. In western Iraq, mature Silurian source rocks may occur over an area of about 300,000 sq. km. Similar high-TOC Lower Silurian "hot shales" are known to occur throughout Arabia and North Africa (e.g. Mahmoud *et al.*, 1992; Beydoun, 1993; Cole *et al.*, 1994; Macgregor, 1996; Lüning *et al.*, 2005).

Lower Llandovery source rocks were first identified in well *Khleisia-1* in 1988 by a joint BP / Idemitsu / OEC team using a "source hound" (portable pyrolysis instrument) to analyse hand-picked cuttings samples from a badly caved "radioactive" interval which had previously been assigned a Carboniferous age by IPC. The presence of Lower Silurian "hot shales" at wells *Akkas-1* (Fig. 9.2.5, 9.2.6) and *Khleisia-1* was described by Al-Haba *et al.* (1994). The shales have an average thickness of about 65 m and an average TOC of 6% (Aqrawi, 1998). In well *Khleisia-1*, only one source rock unit is present as indicated by the GR log (Fig. 4.14); two units are present at *Akkas-1* (Al-Ameri and Baban, 2002; Al-Hadidy, 2007) (Fig. 9.2.6).

The distribution of Silurian source rocks in Iraq is poorly constrained because there are at present only three subsurface penetrations (*Khleisia-1*, *Akkas-1* and *Qaim-1*; Al-Hadidy, 2007). *Keyhole* wells in the Western Desert all reach TD before penetrating the Ordovician (Kaddouri, 1992), neither proving nor disproving the presence of the Llandovery source rock. However, the similarity of log responses of Silurian rocks in the *Akkas* and *Khleisia* boreholes with those recorded in the adjacent *Risha* area of NE Jordan (Fig.4.15; Andrews *et al.*, 1991) indicate that the shales may extend throughout the Western and SW Deserts (Aqrawi, 1998; Lüning *et al.*, 2005). The distribution of Silurian source rocks in eastern Iraq is unknown, although Jassim (2006c) suggested that the Silurian may be present in the centre and south (Fig. 9.2.7).

The extent of Silurian source rocks in Iraq was modified by erosion at the Late Devonian and Late Carboniferous unconformities. The Silurian is absent from outcrops in northern Iraqi Kurdistan (Dunnington *et al.*, 1959) due to erosion at the Late Devonian unconformity. This suggests gradual cut-out of the underlying Devonian, Silurian and Upper Ordovician stratigraphy north of well *Khleisia-1*. At this well, Upper Devonian rocks of the Pirispiki Formation rest unconformably on the Lower Silurian Akkas Formation (Al-Haba *et al.*, 1994; Jassim, 2006c; Al-Hadidy, 2007) (Fig. 4.22).

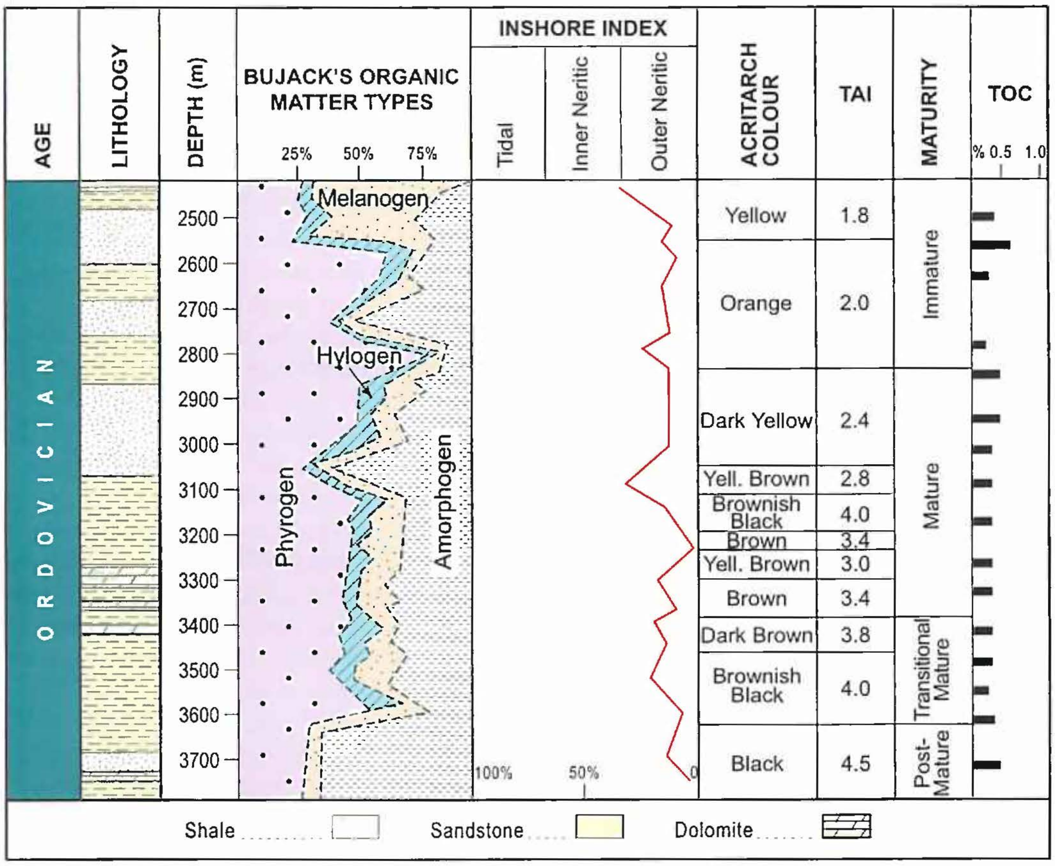


Fig. 9.2.4. Summary of source rock and maturity data for the Ordovician succession at well *Khleisia-1*. After Al-Ameri and Baban, 2002; organic matter types after Bujack *et al.*, 1977.

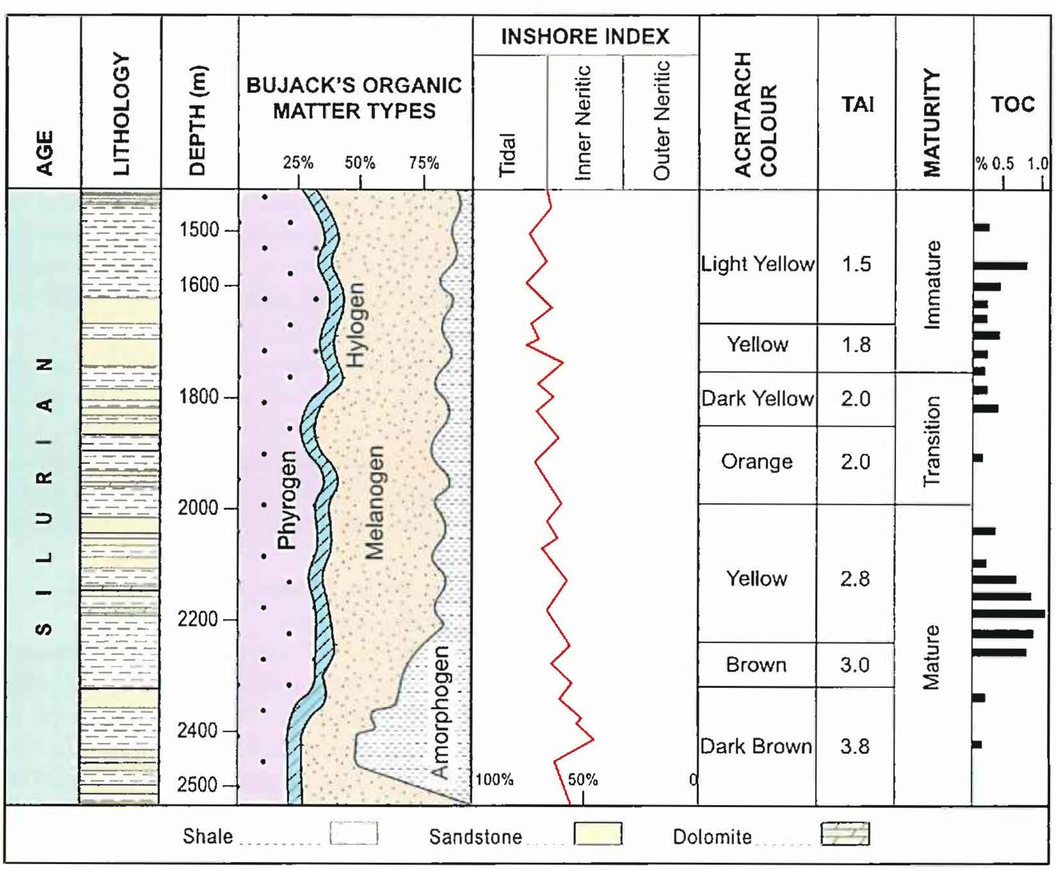


Fig. 9.2.5. Summary of source rocks and maturity data from the Silurian of the *Akkas-1* well. After Al-Ameri and Baban, 2002.

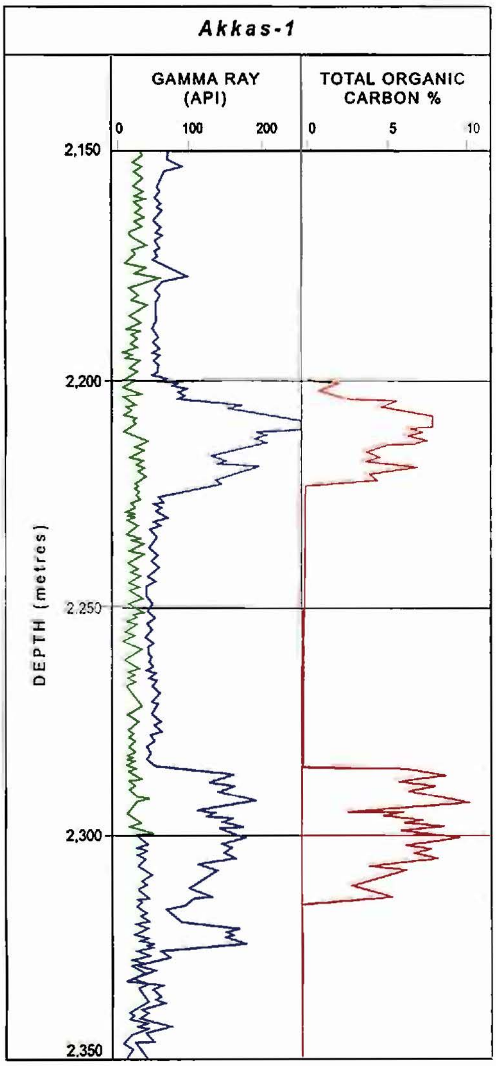


Fig. 9.2.6. Well log at *Akkas-1* through the Lower Silurian (lower Llandovery) source rock interval, showing log responses and TOC (based on Al-Haba, 1994). Blue trace: spectral gamma-ray (total radiation); green trace: computed gamma-ray (Th and K only).

The Silurian source rock interval was removed from the crests of structures which were uplifted during Late Carboniferous deformation in Saudi Arabia and Kuwait (Khan, 1989; Al-Husseini, 2000; Jassim, 2006c; Ruban *et al.*, 2007) (Fig. 4.29). These uplifted structures have been interpreted as re-activated Rayn anticlines (Al-Husseini, 2000). Mohammed (2006) suggested (from seismic data) that less erosion has occurred at the Late Carboniferous unconformity in the Salman Zone than was suggested by Jasim (2006c). Silurian source rocks may thus locally be preserved there.

Progressive westerly erosion of the Silurian at the Late Carboniferous unconformity is also recorded in eastern Jordan and NW Saudi Arabia (Andrews *et al.*, 1991; Konert *et al.*, 2000). This may have affected Western Iraq adjacent to the *Risha* structure, where the uppermost part of the Silurian section has been removed (Al-Ameri and Baban, 2002).

Regional distribution

In NW Saudi Arabia, the Qusaiba Shale Member of the Lower Silurian Qalibah Formation is predicted to be 600-1500 m thick in the Nafud Basin near the border with Iraq (Jones and Stump, 1999). "Hot shales" are 10-30 m thick, and their maximum drilled thickness is 53 m (Aoudeh and Al-Hajri 1994); they are often thickest in areas where the Qalibah is thinnest (Jones and Stump, 1999). In Central Saudi Arabia, the Qusaiba "hot shale" exceeds 30 m in thickness over an area of 100,000 sq. km. An immature sample of Silurian shale had a *Rock-Eval* T_{max} of 419°C and a Hydrogen Index of 469 mg/g TOC (Mahmoud *et al.*, 1992). Extracts of Silurian "hot shales" (e.g. Cole *et al.*, 1994b) have similar organic geochemical characteristics to hydrocarbons produced from Palaeozoic reservoirs in Saudi Arabia (McGillivray and Husseini, 1992)

In eastern Jordan (*Risha* area), the Silurian section is up to 2000 – 2500 m thick. It contains two relatively thin high-API gamma source rock units (Andrews *et al.*, 1991; Lüning *et al.*, 2005). The lower of these, the basal Llandovery "hot shale", thins to the east onto a "palaeohigh" covered with Ordovican glacial siliciclastics up to 150 m thick (Andrews *et al.*, 1991; Lüning *et al.*, 2005). The upper "hot shale" (late Llandovery / Wenlock) has source rock potential at *Risha-3* (Andrews *et al.*, 1991) (Fig. 4.19). These shales may extend into Western Iraq, but are cut-out by the Late Devonian unconformity further to the east and north.

In Jordan, light oils attributed to the Silurian source rocks occur in the Wadi Sirhan area (Andrews *et al.*, 1991; Beydoun *et al.* 1994). Silurian-sourced oils from the basal organic-rich part of the Abba Formation have also been identified based on their distinctive geochemical signatures in several accumulations in the Euphrates Graben, Syria (de Ruiter *et al.*, 1995). Bordenave and Burwood (1990) and Bordenave (2008) recorded Silurian black shales in the High Zagros, Iran.

In the Hazro area, SE Turkey, slightly younger Silurian (Ludlow) shales of the basal Dadas Formation are present (Fontaine *et al.*, 1980). These shales are organic rich (Fontaine, 1981) and may have generated the oil in the overlying Lower Devonian sandstones (Tasman and Egeran, 1952).

iv. Potential Lower Carboniferous source rocks

The Ora Shale Formation consists mostly of dark calcareous shales both at outcrop (Dunnington *et al.*, 1959) and in the subsurface at well *Khleisia-1* in northern Iraq (Al-Hadidy, 2007). In the Western Desert, an organic-rich interval with a TOC content up to 7.6% is recorded at well *KH 5/1* (Al-Haba *et al.*, 1994) containing gas-prone Type III kerogen, for example to the east of the Ga'ara-Akkas-Khleisia region. Modelling indicates that the Ora Shale Formation is mature for gas generation in Central

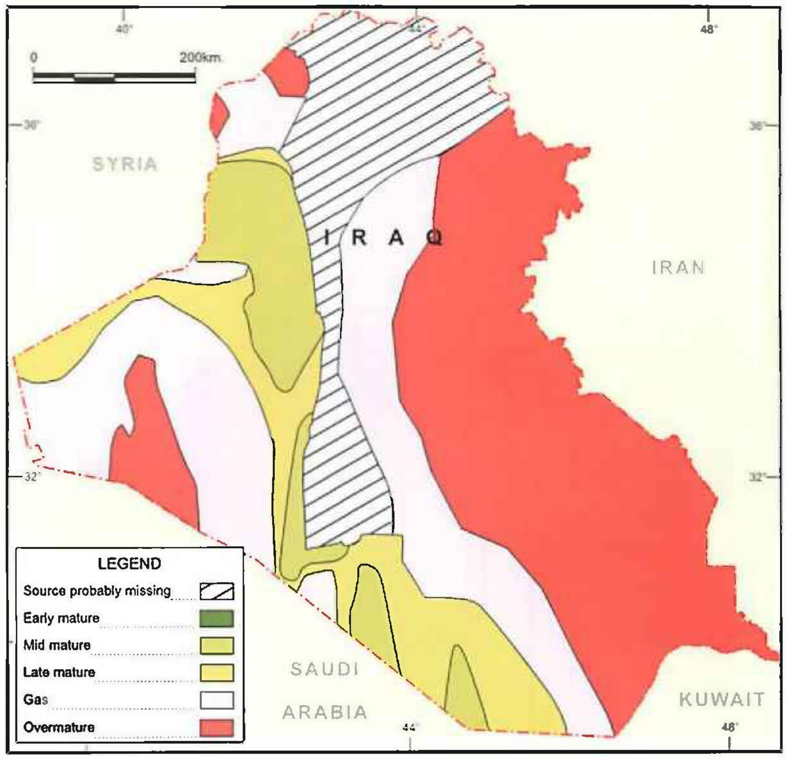


Fig. 9.2.7. Maturity map of the basal Silurian source rock in Iraq. Modified from Jassim and Al-Gailani, 2006. The source rock is mature for gas generation adjacent to the *Risha* gasfield in Jordan, and for light oil and gas near the *Akkas* field. Note the presence of the source rock east of the Risha, Akkas and Khleisia areas is not proven (not yet drilled). The hatched area indicates where the Silurian source rock is interpreted to be absent due to Devonian - Carboniferous erosion.

and Eastern Iraq (Fig. 9.2.8). Facies equivalents of the Ora Shale occur in SE Turkey (Koprülü Black Shales: Janvier *et al.*, 1984) and Syria (Markada Formation: Ravn *et al.*, 1994).

In the Western Desert, the overlying Upper Carboniferous – Permian succession is dominated by coarse-grained siliciclastics (Kaddouri, 1992; Al-Hadidy, 2007) with little source rock potential. In Saudi Arabia, the equivalent Berwath/Al Khlata Formations are composed of similar lithologies (Al-Laboun, 1986; Al-Hajri and Owens, 2000).

The Ora Shale source rock facies may therefore be limited to the northern Western Desert and northern Iraq. Its original areal extent has been modified by erosion during Late Carboniferous uplift (Jassim, 2006c; Ruban *et al.*, 2007).

v. Potential Upper Carboniferous – Permian source rocks

Source rock potential is probably associated with coals which have been reported from the Ga'ara Formation in *Keyhole* wells in the Western Desert (Kaddouri, 1992) (Fig. 4.27). Fine-grained lacustrine deposits of the Bir El Rah Formation in the Western Desert (Jassim, 2006c) may also have source potential.

Upper Permian carbonates (Chia Zairi Formation) have been penetrated by only five wells in Iraq (*Mityaha-1, Jebel Kand 1, Atshan 1, West Kifl-1* and *Diwan-1*: Aqrawi, 1998; Al-Hadidy, 2007) and are known at outcrop in the north of the country. Shales in the basal 20 m of the formation (sometimes assigned to the Ga'ara Formation) have a TOC of about 1% (Al-Haba *et al.* 1994). These are associated with the P20 MFS (i.e. in the basal part of Megasequence AP6) of Sharland *et al.* (2001) in wells *Jebel Kand-1, Atshan-1, West Kifl-1* and *Diwan-1* (Al-Hadidy, 2007) (Figs. 5.8, 5.9).

At the *Burgan* structure (Kuwait), Khan (1989) noted that "hot shales" are associated with evaporite units interbedded within Permian carbonates. These may extend northwards into southern Iraq and may have source rock potential.

Maturity

The thermal maturity of the Silurian source rocks in Iraq (Figs. 9.2.7, 9.2.9) is poorly constrained due to uncertainities in burial and thermal history. Silurian source rocks are immature at well *Khleisia-1* and mature for oil generation in western Iraq at *Akkas-1* (Al-Ameri and Baban, 2000, 2002; Jassim and Al-Gailani, 2006) (Fig. 9.2.10).

Little data is available concerning thermal gradients and heat flows in western Iraq. The present-day maturity of the Silurian source rocks in western Iraq and their thermal history is therefore uncertain. The average geothermal gradient may reach 40°C/km or more in western Iraq adjacent to the *Risha* area of Jordan. At *Akkas-1*, the bottom-hole temperature at 4100 m is 171°C (Al-Haba *et al.* 1994; Al-Sammarai *et al.*, 1994), which for a surface temperature of 20°C corresponds to a geothermal gradient of 37°C/km. The temperature at 2500 m (some 200 m below the Silurian source rock) was 116°C, corresponding to a geothermal gradient of 38 °C/km. Silurian source rocks will be mature for oil and wet gas generation at depths of between 3400 and 5000 m over large parts of western Iraq (Fig. 9.2.7).

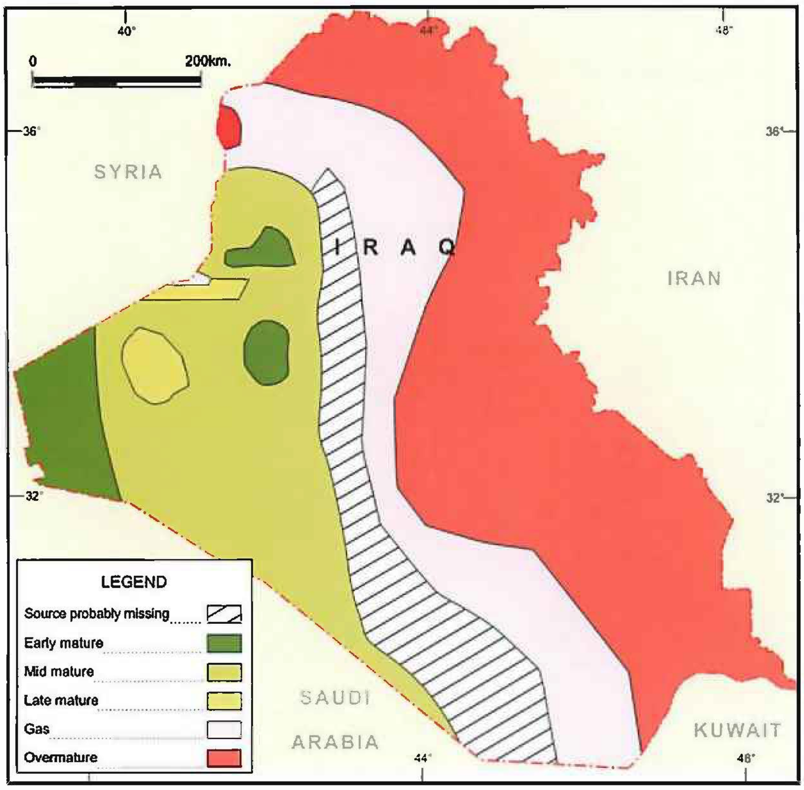


Fig. 9.2.8. Maturity map of potential Lower Carboniferous source rocks in Iraq. Modified from Jassim and Al-Gailani, 2006. The Lower Carboniferous section is interpreted to have been removed by Late Carboniferous erosion over the Salman Zone.

At *Risha* in NE Jordan, the upper of the two basal Llandovery "hot shale" intervals has a vitrinite reflectance of 0.8-0.95 %R_0 (Beydoun *et al.*, 1994). The shales are late- to post-mature in this area at a present-day burial depth of 2500 m (Lüning *et al.*, 2005). There was probably significant Late Carboniferous erosion in the *Risha* area. Given this thermal gradient, the basal Silurian source rock is mature for oil generation (110-150°C) over a shallower depth range (2125-3125 m),with temperatures of 160 and 200°C reached at 3375 m and 4375 m, respectively (Beydoun *et al.*, 1994).

Maturity studies of Ordovician samples suggests that wet gas and condensate in addition to dry gas could have been generated within the Khabour Formation, particularly in the *Akkas* area (Figs. 9.2.6, 9.2.10) (Al-Ameri and Baban, 2002). Similar maturities may extend to Jordan and the SW Desert of Iraq except in Late Cretaceous graben (e.g. the Euphrates, Anah and Sinjar grabens).

By contrast,Ordovician source rocks are presently only early mature for oil generation in the *Khleisia-1* well (Al-Ameri and Baban, 2002) (Fig. 9.2.4). In NE Jordan, the Hiswah Formation (Ordovician) has a maturity of about 1.3-1.5 % R_0. Here, the average geothermal gradient increases from 30°C/km in *Risha-2* where the Silurian section has been eroded, to up to 50 °C/km in well *Risha-3* (Beydoun *et al.*, 1994).

Timing of oil and gas generation

The timing of hydrocarbon generation by Silurian source rocks relative to the timing of major structural deformation and trap formation is important. Early generation of oil and gas may have occurred in areas of deep burial and high heat flow prior to Late Carboniferous uplift and erosion. Further hydrocarbon generation may have occurred during renewed burial in Permian–Jurassic, Cretaceous and Tertiary times, and slowed or ceased during periods of uplift and erosion.

In western Iraq, initial oil and gas generation probably occurred when basal Silurian source rocks were buried to depths of up to 3000 m prior to Late Carboniferous uplift. Generation ceased during Late Carboniferous – Triassic and later Cretaceous uplift, and would not have begun again until maximum burial depths were reached during the Late Tertiary. A cross-section through western Iraq showing the depth to the oil window and of major gas generation is shown in Fig. 9.2.9.

In eastern Iraq, less subsidence took place during the Palaeozoic than in areas to the west, and oil and gas generation from Lower Silurian source rocks may not have occurred until Cretaceous time (Jassim, 2006c).

Cole *et al.* (1994a) modelled the maturation history of the basal Qusaiba Shale source rock in NW Saudi Arabia. They calculated that at 360 Ma, immediately prior to Late Carboniferous uplift, the source rock was buried to depths of over 4600 m and reached maturities of 1.3–2.0 % R_0. They concluded that heat flows decreased from 70–75 mW/m^2 during the Silurian-Devonian, to 60–65 mW/m^2 in the Mesozoic, and 50–57.5 mW/m^2 at present. Cole *et al.* *(ibid.)* also suggested that as much as 2250 m of Devonian – Lower Carboniferous strata were removed during Late Carboniferous uplift and erosion in the Ar'ar area of northern Saudi

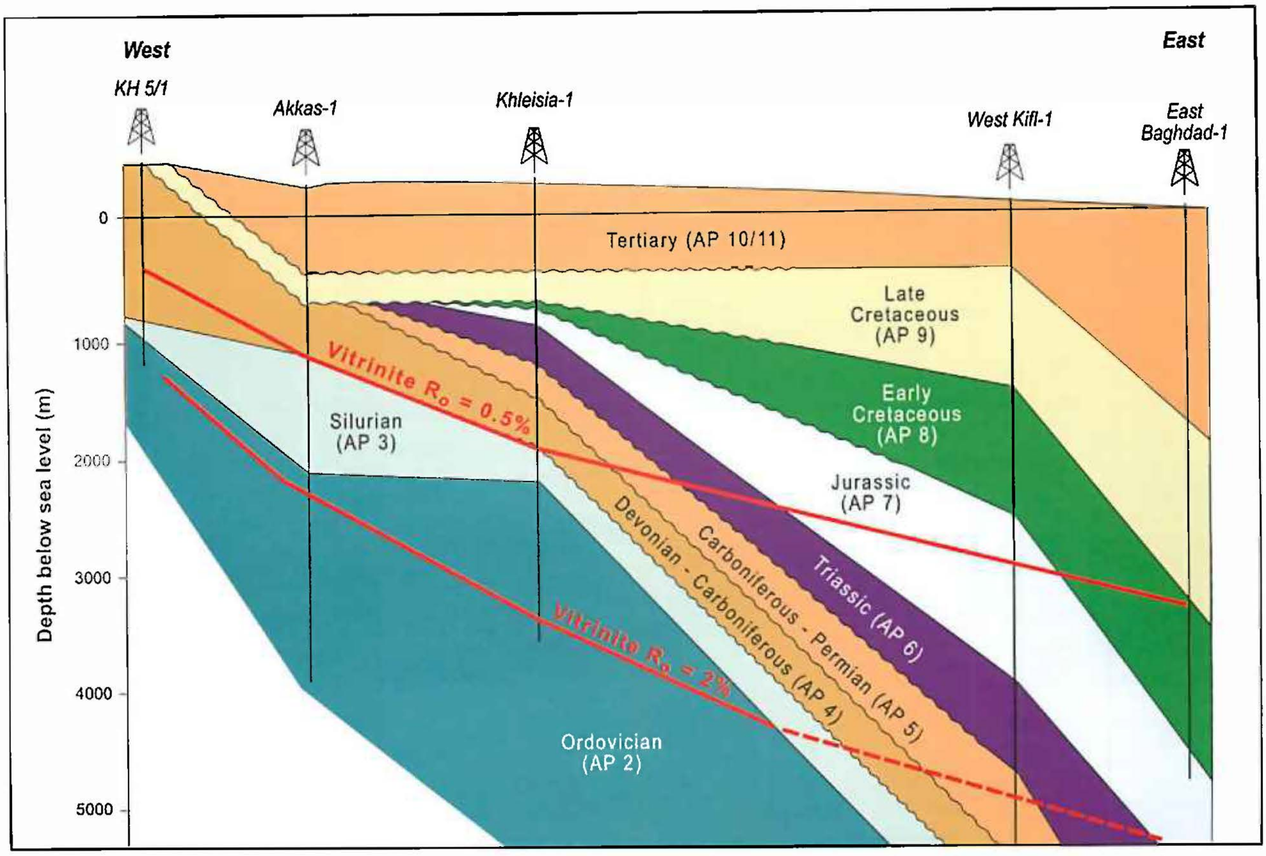


Fig. 9.2.9. Cross-section through western-central Iraq showing vitrinite reflectance versus depth and stratigraphy. Modified from Aqrawi, 1998, based on Al-Haba, 1994.

Arabia, immediately adjacent to the probable Palaeozoic depocentre in Iraq. The present-day burial depth of the base of the Qusaiba ranges from 3000–4500 m in the area near the Iraq – Saudi Arabia frontier to 1500–3000 m to the NW.

Bishop (1995) modelled the maturation history of the Qusaiba Shale source rock throughout the Middle East. He concluded that this source rock generated most hydrocarbons during Mesozoic burial with a further phase of generation in the Late Tertiary. He suggested that over much of western Iraq, early trapped oil would have been displaced by gas, and that traps formed after oil expulsion from source rocks (e.g. at *North Dome* field in Qatar) will probably only contain gas.

Basin modelling (Al-Haba *et al.*, 1994) has shown that at well *Akkas-1*, expulsion and migration of hydrocarbons took place at about 250 Ma (Middle Triassic) (Fig. 9.2.11), with migration directed towards the west. However it appears that Al-Haba *et al.* (1994) did not take into account the degree of erosion on the Late Carboniferous unconformity. Similar Middle – Late Triassic expulsion and migration occurred in northern Saudi Arabia where the Qusaiba Shale entered the oil window at 230 Ma (Wender *et al.*, 1998). Abu-Ali *et al.* (1999) indicated that in the *Ghawar* area, Silurian source rocks became mature at 140 Ma (Late Jurassic) and began to expel oil at about 120 Ma (Aptian). This situation may form a valid analogue for the Palaeozoic petroleum system beneath the Salman Zone in Iraq.

Reservoir rocks

Ordovician – Silurian reservoir rocks have been proven in the *Akkas* field in the Western Desert of Iraq, in the *Risha* field and the Wadi Sirhan area of SE Jordan (Aqrawi, 1998; Aqrawi *et al.*, 2006a), and also in several fields in Central Saudi Arabia (Abu Ali *et al.*, 1999). Reservoir rocks of similar age and facies occur elsewhere in the Western Desert. Other potential reservoir rocks include the Permo-Carboniferous Ga'ara Sandstone and the Upper Permian Chia Zairi Formation together with Carboniferous Harur reefal limestones in northern Iraq.

Reservoir quality is a critical factor for Palaeozoic plays in Iraq. Early entrapment of hydrocarbons may have preserved porosity by preventing or slowing cementation in Lower Palaeozoic sandstones. This was documented by Aqrawi *et al.* (2006a) and may occur in Ordovician reservoir units in the Wadi Sirhan area of Jordan (A. H., *pers. obs.*, 1989).

i. Infracambrian and Lower Cambrian

In Iraq, Infracambrian and Lower Cambrian sediments are probably confined to local basins, as in Oman and Jordan. A number of Infracambrian

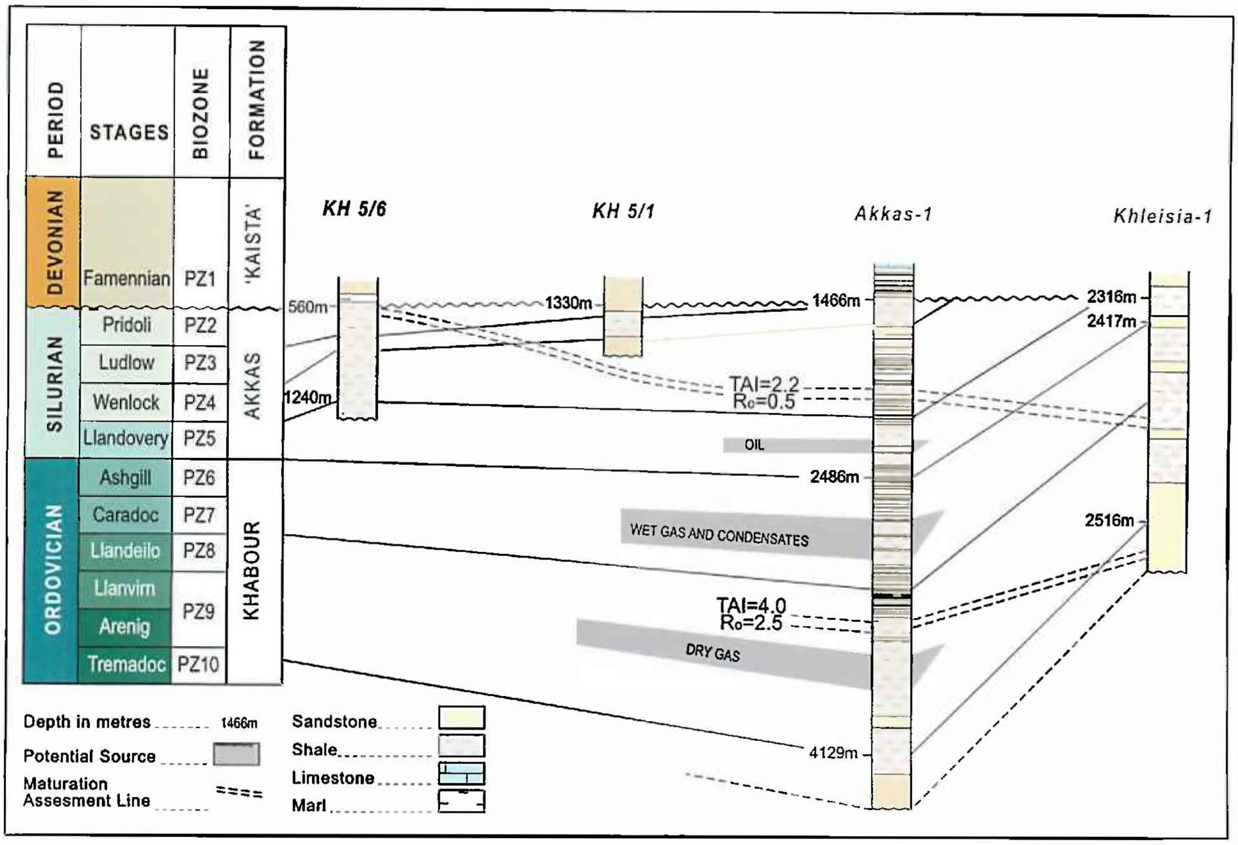


Fig. 9.2.10. Stratigraphy of deep wells in the west of Iraq, showing location of source rocks and maximum maturities. After Al-Ameri and Baban, 2002. Note that the oldest Ordovician rocks in *Akkas-1* are interpreted by Al-Hadidy (2007) to be of Llanvirn-Llandeilo ages (based on dating of sidewall cores at 4020 and 4132 m).

– Cambrian basins were tentatively identified by Jassim (2006c) (Fig. 4.4). Black algal dolomites have been recorded from the Jebel Sanam salt dome in SE Iraq. Outside the grabens, the Early Cambrian was a period of little net deposition in Iraq. Pebbly arkosic siliciclastics similar to those in the Salib Formation of Jordan may have been deposited in the Western and SW Deserts (page 72).

Middle Cambrian deposition took place on epeiric shelves dominated by carbonates (such as the Burj Limestone of Jordan), with mixed siliciclastics and carbonates occurring at the margins (Fig. 4.12). The Burj has been interpreted on deep seismic sections in western Iraq (Al-Haba *et al.*, 1994).

ii. Cambrian and Ordovician

Thick Upper Cambrian and Lower Ordovician quartzites occur in northern Arabia. They are generally more highly cemented by quartz overgrowths in the subsurface than in surface exposures. At Petra (Jordan), Cambrian-Ordovician sandstones are assigned to the Disi, Umm Sahm, Umm Ishrin and Dubaidib Formations (page 78). The friable Disi Formation is weakly cemented and easily worked by local craftsmen.

The Ordovician Khabour Formation sandstones at *Akkas* were estimated to contain 2.5 TCF gas (Verma *et al.*, 2004). At *Akkas*, the Khabour Formation has similar reservoir properties to the age-equivalent Upper Dubaydib / Trebeel Formation at the *Risha* field, Jordan (Fig. 9.2.3). Primary intergranular porosity is almost negligible in these sandstones, and they are only likely to have reservoir potential where they are highly fractured. However, Aqrawi *et al.* (2006a) reported the preservation of high porosities in sandstones in the subsurface of Jordan at depths >3000 m due to the presence of chlorite clay coatings which prevented the development of quartz overgrowths. Tamar-Agha (2009) discussed the diagenetic history and reservoir quality of the Upper Ordovician Risha Sandstones in eastern Jordan.

In Syria, equivalent sandstones in the Afendi Formation have low porosities (6%) due to compaction and quartz cementation; these may be tight gas reservoir targets (Konert *et al.*, 2001; Frijhoff, 2006*). Reservoir quality is reduced due to low net:gross. Local late partial dissolution of fracture-filling carbonate cements has enhanced reservoir quality (Konert *et al.*, 2001).

iii. Silurian and Lower Devonian

At the *Akkas* field, a Silurian sandstone reservoir containing light (42-49° API) oils was recorded by Al-Haba *et al.* (1994) and Aqrawi (1998). Well log data (Al-Hadidy, 2007) indicate that the reservoir

* *oral presentation,* Geo2006 Conference, Bahrain.

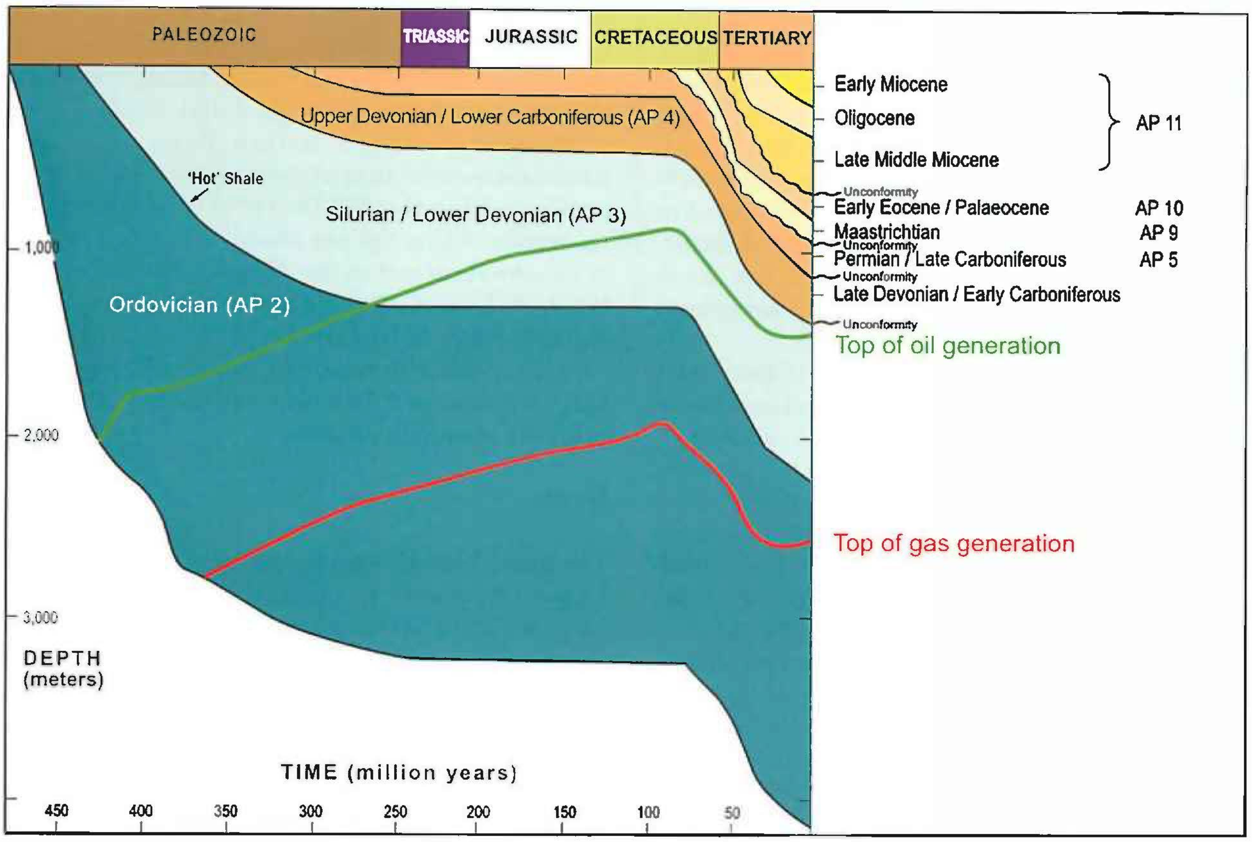


Fig. 9.2.11. Burial history and thermal maturation plot for the *Akkas-1* well. After Aqrawi, 1998, based on Al-Haba *et al.*, 1994. According to this interpretation, the main phase of oil generation from the basal Silurian source rock occurred during Late Cretaceous to Tertiary burial. Gas generation from Ordovician source rocks is interpeted to have begun in the Late Devonian.

sandstones are very thin. The Silurian may have some reservoir potential in other parts of the Western and SW Deserts (Aqrawi, 1998).

Lower-Middle Devonian rocks have not yet been reported either at outcrop in Iraq (Buday, 1980) or in the subsurface (Kaddouri, 1992). Devonian sandstones occur in northern Saudi Arabia (Helal, 1964a, 1965; 1968; Al-Laboun, 1986), and probably exend into southern and SW Iraq.

iv. Upper Devonian – Lower Carboniferous

No proven reservoir rocks of this age are known in Iraq. Red-beds (Pirispiki Formation) associated with volcanics and tuffs (Dunnington *et al.*, 1959) were derived from local reworking of older sedimentary rocks (Al-Hadidy, 2007; Al-Jubowry and Al-Hadidy, 2008a). The reservoir quality of these sandstones is likely to be fair. Marine sandstones of the uppermost Famennian Kaista Formation are probably calcite cemented due to a high content of bioclastic material (brachiopod and coral debris) (c.f. Dunnington *et al.*, 1959).Tournaisian reefal limestones (Harur Limestone) may have local reservoir potential, particularly where enclosed in deeper-water facies.

Much of the Lower Carboniferous and Devonian successions may have been eroded during Late Carboniferous uplift (cf. Fig. 9.2.8), particularly over high areas such as the Salman Zone. Overlying Viséan and Namurian reservoirs occur in the Euphrates Graben, Syria. They comprise sandstones of low net:gross ratio, and leached carbonates from which there is minor production (de Ruiter *et al.*, 1995; Litak *et al.*, 1998). Similar facies occur in the Western Desert of Iraq (Kaddouri, 1992) and in Saudi Arabia (Al-Laboun, 1986) and may extend into the intervening SW Desert of Iraq (Aqrawi, 1998).

v. Upper Palaeozoic sandstones above the Late Carboniferous Unconformity

Westphalian – Sakmarian sandstones are proven gas reservoirs in the Widyan Basin of Saudi Arabia (i.e. Unayzah Formation; Al-Laboun, 1986) and in the Palmyra area of Syria (Lucic *et al.*, 2003; Maric-Durekovic *et al.*, 2004). They may extend into the SW Desert of Iraq (Aqrawi, 1998).

Fluvial and marginal-marine Upper Carboniferous – Middle Permian sandstones of the Ga'ara Formation and sandstones at the base of the transgressive Upper Permian sequence are potential reservoirs in Western Iraq. The distribution and thickness of these sandstones and of overlying mudstone seals is poorly understood. Tanoli *et al.* (2008) described fluvial and coastal plain clastics of the Unayzah Formation and Basal Khuff clastics from a deep well in North Kuwait.

vi. Permian carbonates

Upper Permian carbonates are one of the most important reservoir rocks in the Gulf. The Khuff Formation (Permo-Triassic) is a proven gas reservoir in the southern Gulf. The *Awali* field, Bahrain, was the first hydrocarbon discovery (1949) made in this region. Khuff discoveries followed in Saudi Arabia, Abu Dhabi, Iran, Oman and Qatar. The largest gas reservoir in the World, the *North Dome/South Pars* field of Qatar/Iran, discovered in 1971, produces from this reservoir.

Khuff-equivalent carbonates (Chia Zairi Formation) have no reservoir potential at outcrop in Northern Iraq or at wells *Mityaha-1, Atshan-1, Jebel Kand-1, West Kifl-1* and *Diwan-1* at present-day burial depths of 2700–5800 m (Hudson, 1958; Dunnington *et al.*, 1959; Al-Hadidy, 2007). Neutron porosity logs from wells *Mityaha-1* and *Jebel Kand-1* indicate that the formation comprises tight limestones and dolomites (Al-Hadidy, 2007).

No information has otherwise been published on the lithofacies or reservoir quality of Permian carbonates penetrated in deep wells in Iraq. Reservoir quality will be controlled by the stratigraphic architecture and diagenetic history of the Permian carbonate platform. Close to the Folded Zone, Permian carbonates may be too deeply buried to have reservoir potential. Dolomitic carbonates where present are generally highly compacted and cemented. Reservoir quality may however locally be enhanced by secondary porosity due to leaching, dolomitisation and fracturing.

Comparison of the Chia Zairi Formation with the Khuff facies described in detail by Insalaco *et al.* (2006) is hampered by a lack of sedimentological data from Iraq. However, the descriptions by Hudson (1958) indicate that the Chia Zairi carbonates are more open-marine and less anhydritic than typical "Khuff" facies.

Al-Jallal (1995) interpreted that the Khuff Formation in southern Iraq was deposited on a restricted evaporitic-carbonate shelf and has poor reservoir quality. He suggested that higher energy carbonate facies may lie to the east of the Iraq/Iran border. Within shelfal sucessions, muddy carbonate facies are dominant and coarser-grained facies (grainstones) have anhydrite cement.

Khuff gas reservoirs may consist of up to four separate pay-zones each comprising thick, late aggradational/retrogradational carbonates. Carbonate facies include limestones with mouldic porosity (main reservoir); aggradational shallow-water oolitic grainstones (minor reservoir); dolomitised shoal, lagoonal and tidal flat facies with high porosity and permeability; and transgressive mouldic bioclastic and oolitic sandwave facies (Al-Jallal, 1995; Insalaco *et al.*, 2006). Reservoir quality is heterogeneous (both laterally and vertically) due to dolomitisation, anhydrite cementation, leaching and fracturing. Oomouldic porosity is recorded in some fields in Saudi Arabia (e.g. Kamal, 2000). In northern Saudi Arabia, where interbedded anhydrites are more than 60 m thick, porosities may decrease to near zero (Al-Jallal, 1995).

Reservoir targets within Permian mixed siliciclastic-carbonate-evaporite deposits may be present within the SW Desert of Iraq. Carbonate reservoirs of this age are absent due to onlap and/or erosional cut-out in the *Akkas-1, Khleisia-1* and Western Desert *Keyhole* wells (Kaddouri, 1992; Aqrawi, 1998; Al Hadidy, 2007).

Gas souring in the deep, hot Khuff reservoirs (Ali and Sildawi, 1989) is associated with the presence of anhydrite beds.

Seals

The basal-Llandovery organic-rich shales seal the Upper Ordovician gas reservoir at *Akkas* in Iraq (Aqrawi, 1998). At the *Risha* field in Iraq, the basal "hot shale" is absent and seal capacity is provided by the overlying Silurian shales (Lüning *et al.*, 2005). Lower Silurian shales also act as seals in the Wadi Sirhan area of Jordan (Aqrawi *et al.*, 2006a). The seal may have been removed by erosion from structures uplifted during the Late Devonian or Late Carboniferous. Overlying reservoir units in the Akkas Formation are sealed by intraformational shales (Al-Hadidy, 2007).

Regionally extensive shales occur within the Devonian succession in Saudi Arabia. Equivalent units in Iraq may seal Devonian sandstone reservoirs.

The Ora Shale Formation may form a regional seal in northern Iraq and Iraqi Kurdistan. It conformably overlies potential Upper Devonian sandstone and limestone reservoirs, and rests unconformably on older units on the margins of the Late Palaeozoic basin. Shales of the Markada Formation, however, are generally not sufficiently thick to seal age-equivalent Carboniferous sandstone reservoirs in Syria (de Ruiter *et al.*, 1995).

Upper Palaeozoic seals may occur in the Ga'ara Sandstone Formation. In particular, shales associated with the P20 MFS and the associated TST (i.e. the basal part of Megasequence AP6 of Sharland *et al.*, 2001) could form a significant seal above AP5 and older reservoir units. Intraformational shale seals may occur within the Ga'ara Formation, as recorded in the *Keyhole* wells in the Western Desert (Kaddouri, 1992). Fine-grained lacustrine sediments of the Bir El Rah Formation in the Western Desert, as defined by Jassim (2006c), possibly seal underlying stratigraphic units. Intra-Unayzah Formation siltstones may act as intraformational seals in the *Ghawar* structure, Saudi Arabia (Wender *et al.*, 1998) (Fig. 9.2.12).

Aqrawi (1998) suggested that the intraformational "Satina Evaporite Member" of the

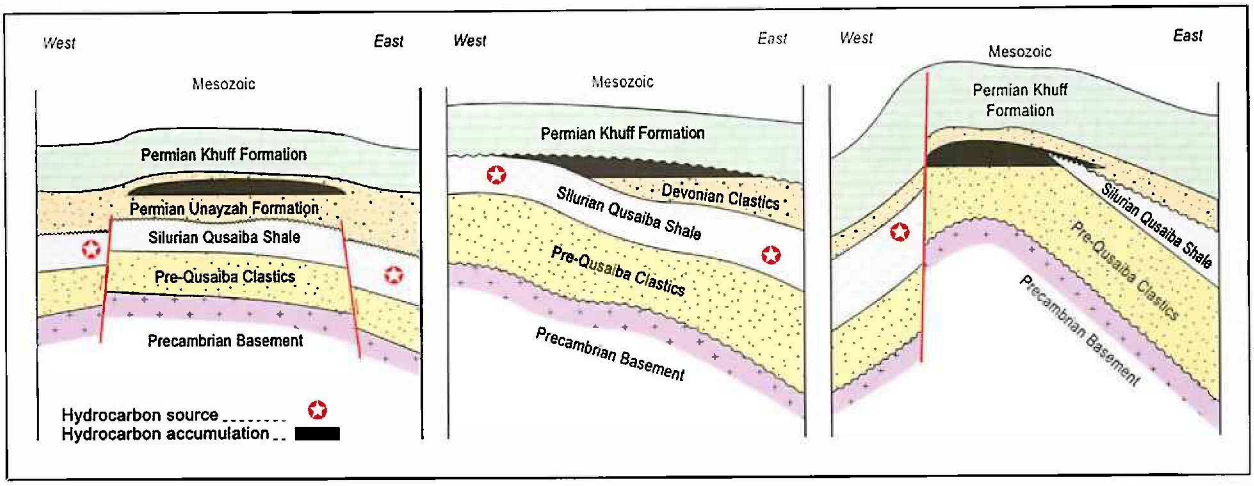


Fig. 9.2.12. Trap configurations for pre-Khuff reservoirs in central Saudi Arabia, which may form analogues for exploration targets in the Salman Zone of Iraq. Palaeozoic traps in Central Saudi Arabia are moderate relief, fault-generated structures with closures of 30 to 100 m which mainly formed in Triassic – Early Jurassic time. After McGillivray and Husseini, 1992.

Permian Chia Zairi Formation may act as a regional seal. However, this unit is often represented by breccias (Hudson, 1958; Dunnington *et al.*, 1959), and evaporites do not appear in any of the logs published by Al-Hadidy (2007). Evaporites are present in the Khuff Formation in Kuwait (Khan, 1989). Al-Jallal (1995) suggested that the total thickness of anhydrite beds in the Khuff Formation decreases to the north from 60 m to <15 m, representing only about 2% of the formation's thickness.

To the south of Iraq, the Khuff Formation is sealed regionally by the Lower Triassic Sudair Shale Formation (Alsharhan and Nairn, 1997). In Iraq, the equivalent sealing unit would be the Beduh Shale, although argillaceous beds in the Mirga Mir Formation may also have some sealing capacity. The Beduh Shale and Mirga Mir Formation are absent over major palaeohighs, such as those penetrated by the *Akkas-1* and *Khleisia-1* wells.

Migration and entrapment of oil and gas

The migration of oil and gas out of the Lower Silurian source rocks and the enclosing non-source mudstones will depend on the distribution of carrier beds within the immediately underlying and overlying sections (Fig. 9.2.1). Where the basal Silurian "hot shales" directly overlie Upper Ordovician sandstones, oil and gas may be expelled downwards into these underlying reservoir rocks, as occurs in the upper part of the *Akkas* reservoir (Al-Hadidy, 2007) and in the nearby *Risha* gasfield (Beydoun *et al.*, 1994). Hydrocarbons may be trapped structurally in uppermost Ordovician sandstones in tilted fault blocks and palaeohighs, and stratigraphically in channel sandbodies (Fig. 9.2.1). Secondary migration may then occur towards structural highs, stratigraphic pinch-outs or unconformities (Late Devonian, Late Carboniferous) (Fig. 9.2.12).

Interbedding of mature source rocks and reservoir rocks increases the possibility of hydrocarbon entrapment in Ordovician and Lower Silurian sandstone reservoirs. Traps in the Euphrates Graben, where there are some Palaeozoic discoveries, are all structural (de Ruiter *et al.*, 1995). By contrast, the stratigraphic complexity of the Risha area, Jordan (Andrews *et al.*, 1991; Beydoun *et al.*, 1994) may contribute to gas entrapment at the *Risha* field.

Where downward expulsion into Upper Ordovician sandstones does not occur but sandstones are present in the overlying Silurian section, oil and gas will migrate vertically upwards into sealed sandstone units and then updip through Silurian and younger Palaeozoic sediments. Thus oil occurs in thin Silurian sandstones in *Akkas* and also in many Palaeozoic fields in central Saudi Arabia (Husseini, 1992).

Where sealed sandstones do not occur in the Silurian succession, oil and gas will migrate vertically upwards through Devonian or Lower Carboniferous strata until seals are encountered (Fig. 9.2.12). If no seals are present, migration will continue as far as reservoir intervals overlying the Late Carboniferous unconformity. Silurian source rocks may thus charge Upper Carboniferous or Permian sandstones, Permian platform carbonates or even Triassic sandstones, and oil may migrate updip towards structural closures or stratigraphic pinch-outs (Fig. 9.2.12). Mature Silurian source rocks may locally occur directly below the Late Devonian or Late Carboniferous unconformities, enhancing possible oil and gas migration into overlying reservoir units (Fig. 9.2.12).

The stratigraphic distribution of regional seals in the section beneath the Upper Carboniferous unconformity, and in the Palaeozoic succession onlapping the unconformity, will determine where petroleum generated from Silurian source rocks will be trapped. Large volumes of petroleum generated in Iraq may have migrated updip (i.e. southwards) into northern Saudi Arabia (Fig. 9.2.7).

9. PETROLEUM SYSTEMS

iii. Triassic

The Triassic petroleum system has only been recognised in NW Iraq but may be more extensive. It was first identified at *Ain Zalah* field in NW Iraq, where Lower Jurassic anhydrites contain live oil (Dunnington, 1958). At *Butmah* field, Triassic oils were found to have a different composition to Cretaceous oils (Dunnington, 1967a). In Syria, a Triassic gas play was discovered in the Palmyra area in well *Soukhne-1* in 1967 (Hips and Árgyelán, 2007); further Triassic discoveries were subsequently made in NE Syria (Wetzel, 1974).

The Triassic succession on the northern Arabian platform contains reservoir, source and seal lithologies. It is a target for future oil exploration, particularly in NW, west and SW Iraq and central and eastern Syria (i.e. on and around the Khleisia-Mosul highs). Here, the Triassic succession is locally > 2500 m thick (Sadooni, 1995; Jassim *et al.*, 2006a) as a result of rift-related subsidence. In Iraq, Syria, Jordan and Iran, the succession is mainly composed of dolomites and anhydrites with interbedded oolites, limestone breccia, conglomerates and thin black shales. It was deposited in intrashelf basin systems in which evaporites were deposited during lowstands.

Current knowledge of the Triassic petroleum system is summarised in Fig. 9.3.1. By 1994, i.e. at about the end of systematic exploration by INOC/OEC, less than twenty wells had reached the Triassic (Sadooni, 1995), mostly in northern Iraq. To the south, *Diwan-1* and *West Kifl-1* drilled through the Triassic and two deep wells, *East Baghdad-1* and *Rumaila-172,* terminate within the Triassic, the latter at a TD of 5381 m (OEC, 1989).

Source rocks

The Triassic succession in Northern Iraq contains thin beds of carbonaceous mudstones and bituminous limestones. Al-Ameri *et al.* (2009) analysed the source potential of the Upper Triassic Kurra Chine Formation from seven wells in the Mosul area of NW Iraq (*Alan-1, Ain Zalah-1, Butmah-15, Jebel Kand-1, Mileh Tharthar-1, Qalian-1* and *Sufaiyah-1:* locations in Fig. 5.4). TOC contents ranged from 0.3 to 5% (Fig.9.3.2). The samples ranged from immature to mature with Production Indices ($P_1/P_1 + P_2$) of 0.25-0.55 recorded at *Butmah-15* . A plot of T_{max} versus HI (Fig.9.3.3) showed that the samples contained Types II and III kerogen which was mature for oil generation.

In Syria, Abboud *et al.* (2005) showed that Triassic source rocks with relatively low TOC contents generated some of the oils in Mesozoic reservoir rocks. These oils have pristane/phytane ratios of <1.0, high sulphur contents (1.4-3.2%) and high poryphrin contents (vanadyl porphyrins up to 521 ppm) (Abboud, 1995, 1996). They identified two oil types (A and B) which they related to different source rocks.

The compositions of Group A oils in four samples from the NE of the Palmyra Trough indicated derivation from marine non-carbonate source rocks. Geochemical markers indicated that the Group A oils were sourced by the Lower Triassic Amanus Shale Formation. The Amanus Shale is interpreted to have been deposited on a restricted shallow-marine shelf and is up to 300 m thick; the net source rock thickness is not known. A sample from the *Shamal Alhosin-19* well (2420-2430 m) had a *Rock-Eval* S1 of 4 kg/tonne, S2 of 6 kg/tonne, and a PI of 0.4 (Abboud *et al.*, 2005). Howell and Dagherty (1980, *in* Abboud *et al.* 2005) suggested that the Amanus Shale is the source rock for the oil at *Habary* field in the Bilas Block, Palmyra. The Amanus Shale is similar to the equivalent Mirga Mir Formation in Iraq, which likewise includes beds of laminated dark shales.

The composition of Group B oils indicated that they were derived from marine carbonate-evaporite source rocks, which can be correlated with the Kurrachine Dolomite Formation of NE Syria (equivalent to the Geli Khana Formation of Iraq; Fig. 9.3.1). This comprises up to 600 m of dense, finely-crystalline dolomite with thin interbedded shales passing up into evaporites. The formation represents an inner marine shelf (intertidal) depositional environment according to Abboud *et*

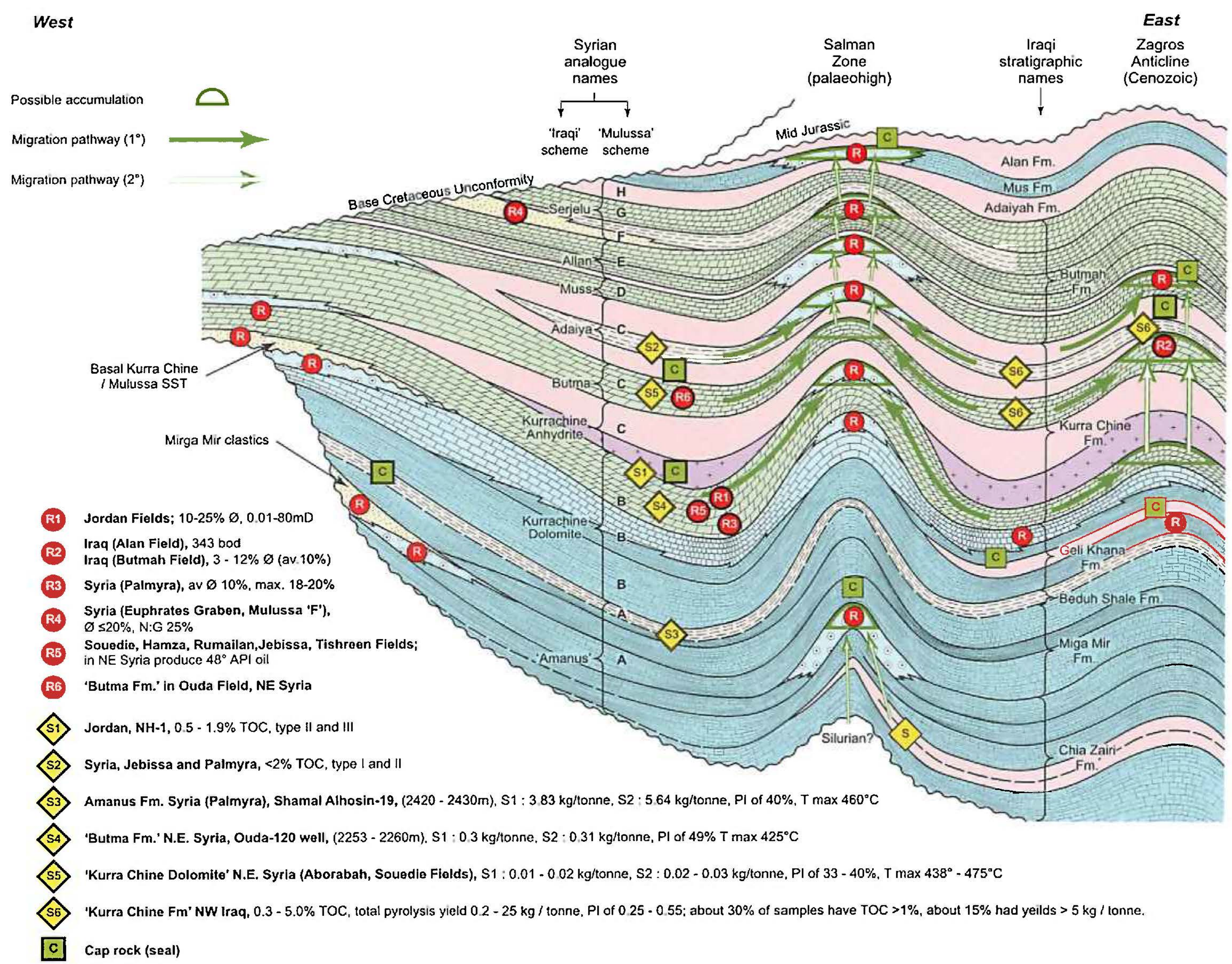


Fig. 9.3.1. Schematic cross-section through the Triassic petroleum system in Iraq summarising the spatial distribution of the different play elements. This diagram includes proven and potential play concepts. At present there is little evidence for leakage of Triassic oil into the overlying succession.

al. (2005). However, geochemical analyses (quoted in Abboud *et al.*, 2005) suggest very limited source rock potential. Nevertheless, the geochemical signature of this interval could be identified in sixteen of the reservoir oils in the study.

Hips and Árgyelán (2007) noted that the lower part of the "Kurrachine Dolomite" in the Palmyra Basin contains thin beds of dark grey subtidal mudstones with "fair to good" source rock quality. These have TOC contents of 2% and contain Types I and II kerogen. To the NE, the Triassic succession at 3341-3600 m in well *Jebissa-5* contains calcareous laminated shales with possible source potential (Metwalli *et al.*, 1972).

In Jordan, shales and argillaceous carbonates within the Abu Ruweis Formation (partly equivalent to the Kurra Chine Formation of Iraq) may have source potential (Sadooni and Dalqamouni, 1998). The Abu Ruweis Formation consists of laminated dolomitic marls, limestones, clays, thick units of laminated gypsum and locally halite. The presence of the alga *Tasmanites* is interpreted to indicate that organic matter is of terrestrial / coastal marine origin (Sadooni and Dalqamouni, 1998). Geochemical analyses of grey claystones from well *Risha-1* (850-1380 m depths) indicate that the OM consists mainly of amorphous material with minor miospores, structured wood and pollen which may generate only minor volumes of oil at high maturities (Ahmad and Nabulsi, 1987, *in* Sadooni and Dalqamouni, 1998). In well *Northern Highlands-1*, shales and carbonates in unit AR4 have TOC values of 0.5-1.9% and may include oil-prone source rocks (Dungworth *et al.*, 1987, *in* Sadooni and Dalqamouni, 1998). Beydoun *et al.* (1994) suggested that similar Triassic argillaceous sediments with mixed Type II-III kerogen, but with low-to-moderate TOC contents, may also have source potential.

Hasan (1989) identified two units of Triassic source rocks in the Gulailah Formation in the *Nasr* field in Abu Dhabi. These units have gross thicknesses of 58 and 85 m, with TOC in the range 0.5 – 5.1% and pyrolysis yields of 0.8 – 4.3 kg/tonne at a high maturity level of > 1.22% R_o.

Husain *et al.* (2009) reported a unit of argillaceous carbonate source rock from west Kuwait in the Mutriba and Kra Al-Maru areas. It lies between the Sudair and Jilh Formations and is thus probably of Mid-Triassic age. The original TOC was estimated to be 3–4% and the original Hydrogen Index to be 300 – 500 mg/gTOC. The source rock reached a maturity for wet gas generation in Late Cretaceous time. A Triassic petroleum system has also recently been described in Saudi Arabia (Hakami *et al.*, 2007).

The association of thick Triassic source rocks and lowstand evaporites (see Chapter 5) suggests that the source rocks may have been deposited in intrashelf basins.

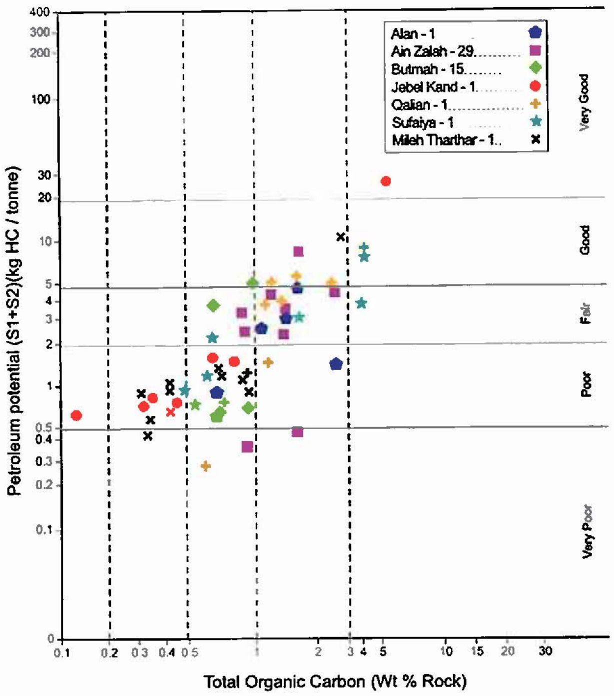


Fig. 9.3.2. Plot of TOC versus *Rock Eval* S1 + S2 for the Kurra Chine Formation in seven wells in NW Iraq. After Al-Ameri *et al.*, 2009.

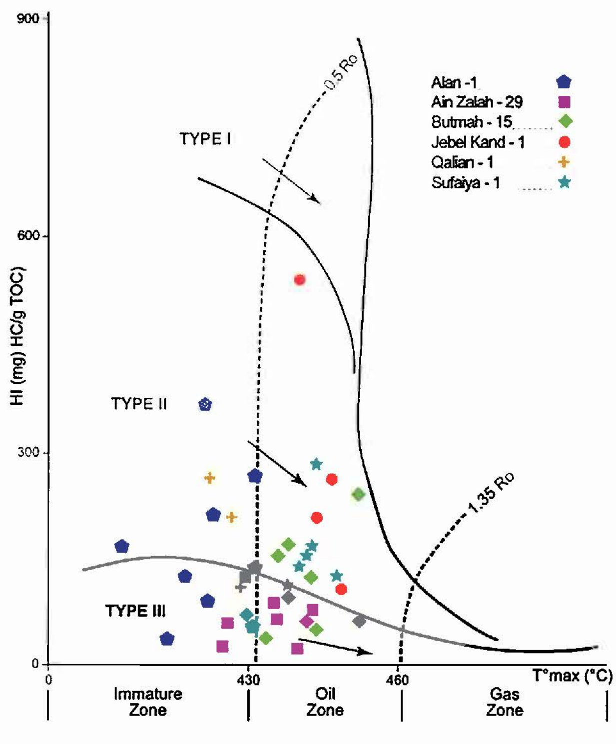


Fig. 9.3.3. Plot of *Rock Eval* T_{max} versus Hydrogen Index for Kurra Chine Formation samples from six wells in NW Iraq. After Al-Ameri *et al.*, 2009.

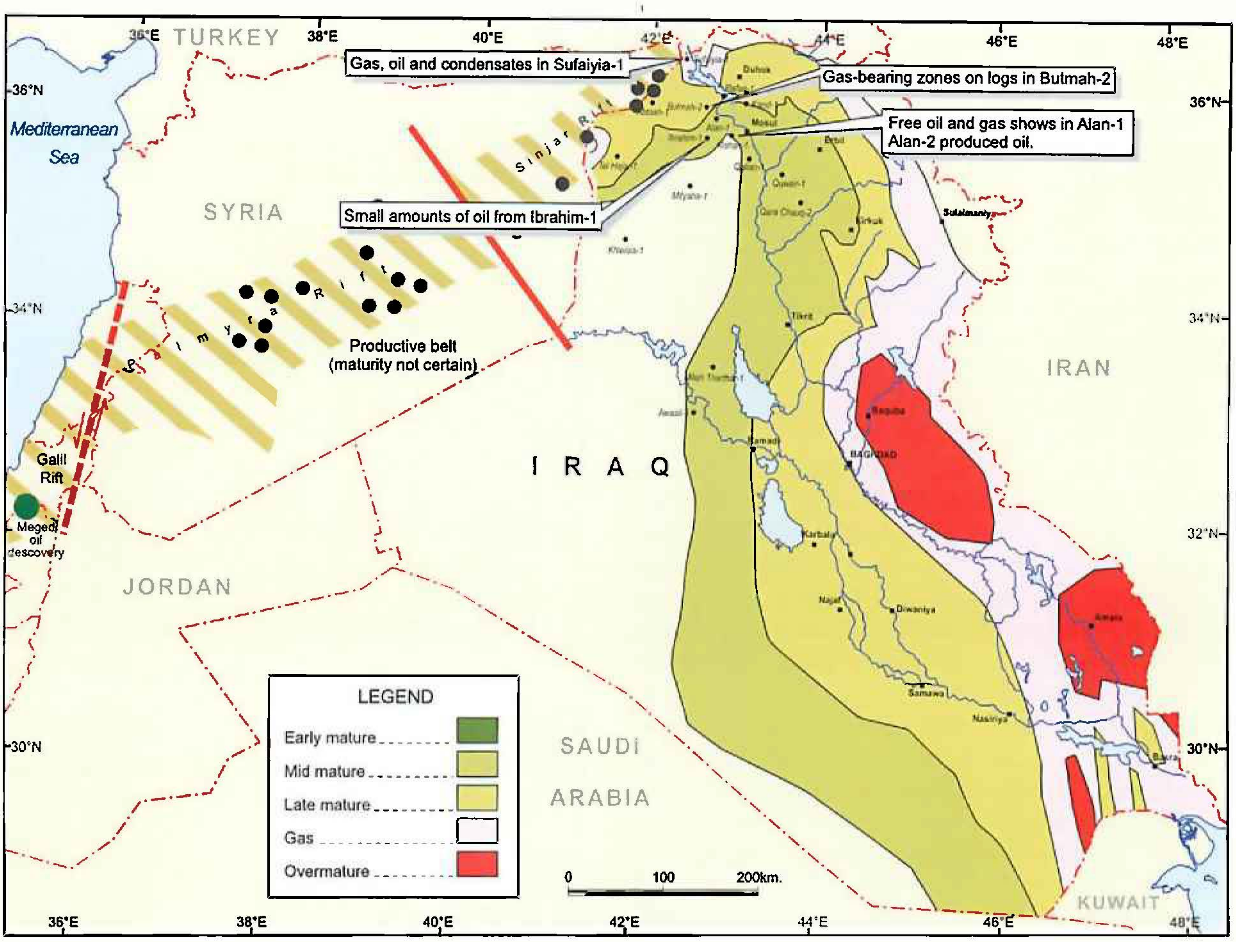


Fig. 9.3.4. Maturity of Triassic sedimentary rocks in Iraq, with location of known oil and gas shows. After Sadooni (1995) and Jassim and Al-Gailani (2006).

Maturity

Maturation of source rocks in the Triassic petroleum system of Iraq occurred during maximum burial which took place as a result of Neogene subsidence.

The Triassic section is mature for oil generation beneath the Mesopotamian Basin, and in NW Iraq beneath the Sinjar Trough (Fig. 9.3.4) It is immature in western Iraq over the Khleisia and Ga'ara Highs. Well *Jebel Kand-1*, north of Mosul, reached a depth of 5848 m and penetrated the Harur Formation (Al-Hadidy, 2007). Al-Haba (1988 unpublished, *in* Al-Sakini, 1992) determined that oil expulsion had occurred below 3000 m in this well and that the entire Traissic was within the oil generation window.

In Syria, the "Kurrachine Formation" may be at the onset of the oil window in the Aleppo Plateau area, and mature or overmature in basinal areas in *Jebissa, Soukhne* and *Souedie* in eastern Syria (Al-Sakini, 1992).

Timing of oil and gas generation

In western and SW Iraq (Fig. 9.3.4), Triassic rocks have not yet entered the oil generation window but will be mature for oil generation on the flanks of the Salman Zone and Khleisia High. In deeper parts of the basin system, gas generation from Triassic source rocks probably began in the Cretaceous and ended during the Cenozoic as source rocks became overmature. The Triassic is probably 8 to 9 km deep in eastern Iraq close to the Iranian border (Jassim and Al-Gailani, 2006, their Fig. 5-3).

In NE Syria, Hips and Árgyelán (2007) determined that the "Kurrachine Dolomite" source rocks entered the oil window during the Cretaceous – Paleogene, and reached the base of the gas window by the time that traps formed in the late Miocene – Pliocene.

Reservoir rocks

Triassic reservoir rocks in Iraq contain < 1% of the country's proven oil reserves (Al-Sakini, 1992). Oil and gas has been discovered in NW Iraq, in thin porous carbonate beds sealed by intraformational evaporites and tight carbonates (Sadooni, 1995). Several fields in Iraq and NE Syria have produced significant volumes of oil and gas from Triassic reservoirs during production tests. The most important reservoir rocks occur in the 500 m thick Upper Triassic (Carnian-Norian) Kurra Chine Formation, for example in the *Butmah, Sufaiyah* and *Alan* oilfields in northern Iraq, and in the Kurrachine (*sic.)* and Butma Formation in the *Souedie, Rumelan, Jebissa* and *Tishreen* fields in Syria (May, 1991; Sadooni, 1995; Sadooni and Alsharhan, 2004). The main producing interval in Iraq lies in the carbonates of the upper part of the Kurra Chine Formation, which occur between two thick anhydrite intervals and were probably intensively fractured during folding.

Triassic reservoir units in Iraq were described by Sadooni (1995). At the *Alan* field, located north of Mosul, reservoirs in the Kurra Chine Formation are composed of limestones and anhydrites apparently with little porosity; production is probably controlled by fractures. Free oil was encountered at depths of 2569-2570 m in *Alan-1* and gas shows at 2564 m. In well *Alan-2*, productive intervals in the Kurra Chine Formation consist of fractured anhydritic, dolomitic limestones with intergranular porosity. The interval 2408-2466 m produced an average of 343 b/d of oil. Gas and condensate came from 2762-2799 m.

At well *Ibrahim-1*, porous dolomites in the lower part of the Kurra Chine Formation occurred at 2756-2778 m. Fractures were recorded in a cored dolomite interval at 3078-3165 m. Reservoir evaluation suggested a pay which was approximately 82 m thick (Sadooni, 1995).

In *Sufaiyah* field, well *Sf-1* tested gas and condensate at 2884-2906 m, and oil and water from 2927 m to 3045 m (Sadooni, 1995; Sadooni and Alsharhan, 2004).

The Lower Triassic succession includes several potential reservoir intervals. The basal part of the Mirga Mir Formation is oolitic and sandy at outcrop (Dunnington *et al.*, 1959; Gayara, 1992). The proportion of sandstone in the formation probably increases close to onlap margins. Sandstones occur around the Permo-Triassic boundary in the uppermost Chia Zairi and Mirga Mir Formations at the *Mityaha-1* well (Nader *et al.*, 1993b; Al-Hadidy, 2007). The Beduh Formation at outcrop contains only very thin beds of sandstone. Reservoir intervals may occur within the overlying Geli Khana Formation which consists of two sequences (Sharland *et al.*, 2001) composed of carbonates, sometimes capped by evaporite collapse breccias and/or karstic fabrics as recorded both at outcrop and in the subsurface (Dunnington *et al.*, 1959).

The uppermost Triassic to lowermost Jurassic Baluti and Butmah Formations locally contain clean carbonates and sandstones with reservoir potential. Coeval fluvial and nearshore sandstones in the Mulussa "F" Formation of the Euphrates Graben (Syria) have a net:gross of 25% with porosities of up to 20% (de Ruiter *et al.*, 1995). Similar sandstones may occur where the graben systems extend into western Iraq, where siliciclastic reservoir units interfinger with the Kurra Chine Formation. Dunnington *et al.* (1959) and Sadooni (1995) reported that the lower part of this unit becomes clastic dominated in central and western Iraq.

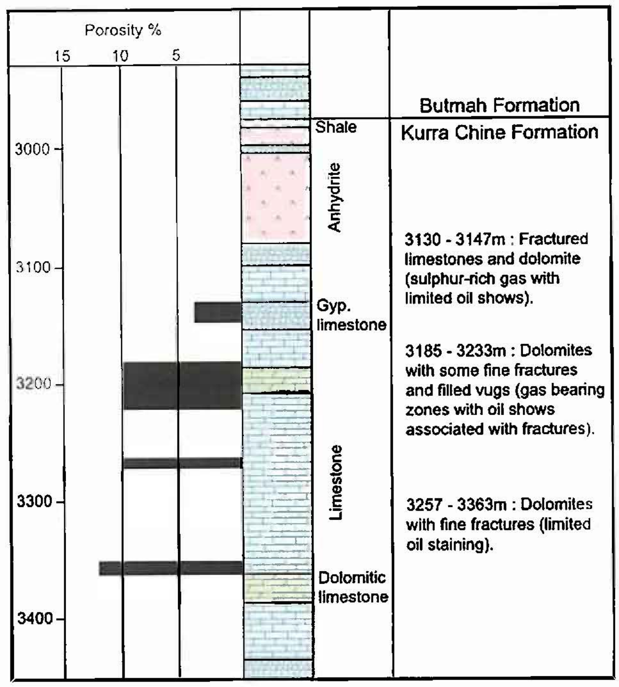


Fig. 9.3.5. Lithological log of the Kurra Chine reservoir at the *Butmah* field in northern Iraq. After Jassim and Al-Gailani, 2006.

Sadooni (1995) studied the diagenesis of the Kurra Chine reservoir in three wells in NW Iraq (*Ibrahim-1, Butmah-15* and *Alan-1*). Porosity is predominantly secondary comprising intercrystalline, dissolution and fracture types. Primary porosity was almost completely destroyed by extensive anhydrite and calcite cementation. Secondary porosity formed by dissolution of skeletal bioclasts, dolomite rhombs and evaporite crystals. Intercrystalline porosity often contains residual bitumen. Minor residual intergranular porosity enhanced by dissolution occurs in oolitic-peloidal limestones. Open and filled fractures occur in cores from wells *Ibrahim-1* and *Butmah-15*. In well *Butmah-2*, the average porosity of Upper Triassic rocks is about 10% (Sadooni, 1995; Sadooni and Alsharhan, 2004). In well *Butmah-15*, the porosity of the Triassic is 3-12% (Sadooni and Alsharhan, 2004; Jassim and Al-Gailani, 2006) (Fig. 9.3.5).

The reservoir quality of the Triassic carbonates may be enhanced by secondary porosity development at sequence boundaries. Carbonate reservoir quality may also locally be improved in areas which were positive tectonic features during Triassic deposition — for example subtle swells controlled by horsts and tilted fault blocks.

Husain *et al.* (2009) reported gas-bearing low permeability Triassic carbonates in Kuwait. The reservoir comprises naturally fractured dolomites with a mudstone texture and anhydrite cement. They are interbedded with dolomitic shale and anhydrite. The matrix permeability is generally

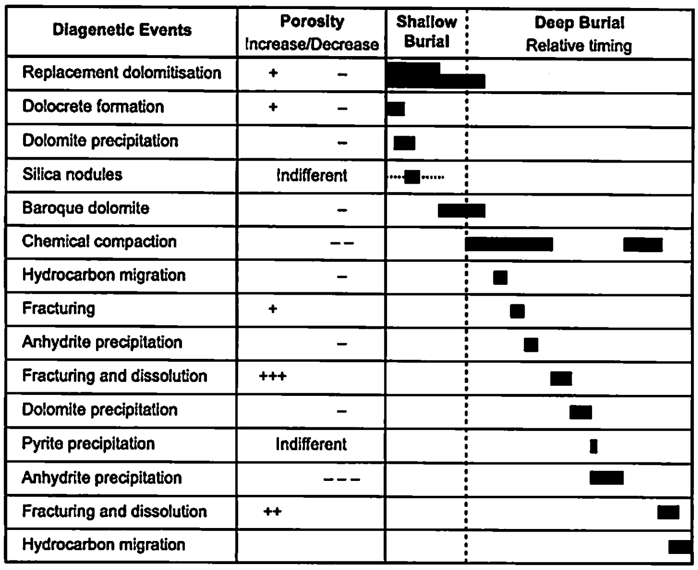


Fig. 9.3.6. Paragenesis of the Kurrachine Formation reservoir in the Palmyra area of Syria (equivalent to the Geli Khana Formation in Iraq). After Hips and Árgyelán, 2007.

less than 0.01mD; fracture related permeabilities are up to 3 mD. A halite unit in the Jilh Formation acts as a regional seal.

Equivalent reservoir rocks in Syria and Jordan

At the *Kurbet* field, Syria, oil is present in Triassic reservoirs at 3100 m; at the *Rumelan* field, the "Kurrachina" produces 48°API oil (Dunnington *et al.*, 1967a; Metwalli *et al.*, 1974). Dunnington (1967a) recorded production from the "Lower Jurassic" at *Souedie* (although this is probably a Triassic reservoir). In *Jebissa-5*, dark brown-stained dolomites of the "Kurrachine" Formation flowed oil and condensate from 3118-3210 m (Metwalli *et al.*, 1974).

The lower "Mulussa" carbonates of the Euphrates Graben area, equivalent to the Kurra Chine of Iraq, include low net:gross reservoir intervals with low porosities and permeabilities (de Ruiter *et al.*, 1995).

In the Palmyra area, an equivalent unit in the middle of the Kurrachine Dolomite comprises 5-15 m of shales overlain by 8-20 m of dolomites which forms the Main Productive Zone (Hips and Árgyelán, 2007). The diagenetic history of this reservoir is summarised in Fig. 9.3.6. The upper part of the "Kurrachine Dolomite" (probably equivalent to the basal Kurra Chine Formation in Iraq) comprises tight dolomites, calcareous dolomites and argillaceous limestones, with beds of anhydrite towards the top. The unit contains a laterally extensive, porous dolomite 7.5–19 m thick.

Porosity was enhanced by partial dissolution of anhydrite cement during deep burial, and late stage leaching which followed late fracturing. Secondary porosity is present as fractures, and solution-enlarged intercrystalline pores and vugs. Very late fractures, post-dating all other diagenetic features, have apertures of 50–100 microns. Porosities in the Palmyra reservoirs are up to 20% and average 10% (Hips and Árgyelán, 2007).

In Jordan, the Carnian Abu Ruweis Formation includes fractured porous dolomites and dolomitic limestones with intercrystalline porosity (Sadooni and Dalqamouni 1998). In well *Northern Highlands-2,* it contains a 15 m thick cored interval of heterogeneous carbonates with permeabilities of 0.01-100 mD including thin intervals with 10–25% porosity and 10–80 mD permeability. The main reservoir is in unit AR-4 at the base of the formation, which contains oolitic/peloidal limestones interbedded with coarse crystalline porous dolomites and anhydritic dolomites. Porous dolomites and fractured limestones in the top of unit AR-1 also have reservoir potential.

Seals

In Iraq, thick intervals of anhydrites, local halite units and tight carbonates containing anhydrite cement within the Triassic succession are likely to act as effective regional seals preventing vertical migration of oil and gas from the underlying Palaeozoic petroleum system, except around the less anhydritic margins of the Triassic intrashelf basins. The uppermost anhydrite unit of the Kurra Chine Formation and the overlying Baluti Shale probably serve as regional seals for the Triassic petroleum system. Migration of oil into overlying Mesozoic and Tertiary reservoirs is only likely to have occurred in structures affected by intense Late Tertiary fracturing.

Shales, marls and argillaceous limestones within the Mirga Mir Formation and mudstones in the Beduh Formation probably act as regional seals at the base of the Triassic petroleum system.

Shales associated with the intra-Geli Khana Formation flooding surface (Tr50 of Sharland *et al.*, 2001) may also serve as a seal.

In Syria, de Ruiter *et al.* (1995) considered that reservoirs in the Middle Triassic Mulussa Formation in the Euphrates Graben were sealed intraformationally. Druckman (1977), Jamal *et al.* (2000) and Hips and Árgyelán (2007) proposed that evaporite units representing the principal seals thin from the basin centre towards the margins.

Mudstones and anhydrite of the "Kurrachine Anhydrite" provide a regional seal in the Palmyra area (Hips and Árgyelán, 2007). This comprises metre-scale cycles of anhydrites and shales, with interbedded claystones, marlstones, dolomitic mudstones, dolomite and halite. The thickness and frequency of halite beds decreases from west to east towards the margins of the Palmyra Basin.

Entrapment of oil and gas

Extensional structures (tilted blocks) may have formed during the Middle and Late Triassic as suggested by isopach variations. Extension was probably related to Ladinian–Norian rifting along the margins of Neo-Tethys to the NE. This extension may have led to the formation of early tilted fault blocks, for example in NW Iraq and NE Syria (Sadooni and Alsharhan, 2004). The Triassic succession was divided into fault blocks during Cretaceous extension, and further deformed by inversion and folding in the Late Tertiary.

The *Jebissa* structure in NE Syria, which contains productive Triassic reservoir rocks, is an exmple of an inversion anticline which developed during late Miocene – Recent shortening. Extensional faults of Cretaceous age have been identified here on 2D seismic sections (Metwalli *et al.*, 1972). The structure is located in the Sinjar Trough, about 20 km west of Jebel Sinjar.

In terms of traps, the lowest-risk area for Triassic exploration appears to be the Kand Basin in northern Iraq (located in Fig. 5.1), where the greatest number of discoveries (in anticlinal traps) have been made (Sadooni, 1995). Elsewhere, the Triassic is a target where it is not buried too deeply, particularly over palaeohighs such as the Salman Zone. However, the Triassic has not yet been tested rigorously in these areas.

Migration of oil and gas

Al-Ameri *et al.* (2009) concluded that migration paths for oils in the Triassic petroleum system in Iraq were short. Similarly, in the Palymra area of Syria, Hips and Árgyelán (2007) proposed that source rock intervals in the Kurrachine Dolomite produced oils which either migrated for only short distances within the Dolomite itself, or migrated down into the underlying Permian Amanus Sandstone. They described two phases of migration into reservoirs: an early, post-compaction event (Fig. 9.3.6), and late stage migration post-dating fracturing

Oils in fields

Oil and gas have been tested from Upper Triassic Kurra Chine Formation carbonates in the *Alan, Butmah, Ibrahim* and *Sufaiyah* structures in NW Iraq. At the *Alan* field, the interval 2408-2466 m produced 29.6°API oil; gas and condensate was recovered at 2762-2799 m (Sadooni and Alsharhan, 2004). Hydrocarbon-bearing zones occur in fractured dolomites and dolomitic intervals and in relatively thin porous dolomite beds.

The Kurra Chine Formation reservoir at *Butmah* contains 35°API oil (Dunnington, 1967). Gas-bearing zones were encountered in *Butmah-2* at 3198-3233 m and 3253-3255 m, and an oil zone at 3276-3278 m.

Ibrahim-1 produced small volumes of 26° API oil and gas from the lower part of the Kurra Chine Formation, and tar and dead oil at 2756-2778 m. During coring, oil and gas were observed in the fractured dolomite interval at 3078-3165 m (Sadooni and Alsharhan, 2004).

In the *Sufaiyah* field, well *Sf-1* produced gas and condensate from the Kurra Chine Formation at 2884-2906 m, and oil and water from 2927-3045 m (Sadooni, 1995; Sadooni and Alsharhan, 2004).

Oil and gas shows were reported by Sadooni (1985) from wells *Atshan-1, Jebel Kand-1* and *Kifl-3;* oil shows were reported from wells *Qalian-1* and *Tel Hajar-1*, and heavy oil shows were reported from well *Mileh Tharthar-1.*

Gulf Keystone (2009) reported* an oil discovery in the upper part of the Triassic in well *Shaikan-1,* about 50 km north of Mosul. Multiple drilling breaks occurred in a 81 m gross interval at 2402 to 2483 m. These probably correspond to thin porous beds in the Kurra Chine Formation. They flowed 2000 b/d of 40° API oil with a GOR of approximately 1000 SCF/brl.

In the Euphrates Graben, oil was tested from both leached dolomites and sandstones in the lower Mulussa Formation (Al-Sakini, 1992; de Ruiter *et al.*, 1995; Litak *et al.*, 1998). Metwalli *et al.* (1972, 1974) noted that Triassic oils from the *Jebissa* field have different geochemical signatures to the Cretaceous and Tertiary oils from the same structure. The Triassic oils are lighter (40.6°API) with low sulphur and asphaltene contents (0.62% and 0.1% respectively) than the oils in shallower petroleum systems.

In the Palmyra area of Syria, oil gravity ranges from 11 to 38° API and sulphur contents from 0.5 to 3% (Hips and Árgyelán, 2007). Abboud *et al.*

* *Gulf Keystone press release,* 6.10. 09.

(2005) carried out detailed organic geochemical and biomarker analyses of oils and extracts from Triassic source rocks and reservoirs, and tied several Triassic reservoir oils to Triassic source rocks. Geochemical signatures of oils in the *Souedie* and *Hamza* fields in NE Syria indicate sources in both the "Amanus Shale" and the "Kurrachine Dolomite". However, in 16 samples from nearby wells, only the "Kurrachine Dolomite" signature could be found. At the *Rumelan* field, 48°API oil is present in the "Kurrachine Dolomite" (Dunnington, 1967).

9. PETROLEUM SYSTEMS

iv. Jurassic

The Jurassic petroleum system of Arabia contains *Ghawar*, the world's largest oilfield (Ayres *et al.*, 1982). According to the USGS definition, the Jurassic petroleum system in Iraq includes source rocks of the Sargelu, Naokelekan and Gotnia Formations and reservoirs of the same age (Verma *et al.*, 2004). Goff (2005) summarised current knowledge of the Jurassic petroleum system in Iraq.

The Middle – Upper Jurassic Megasequence AP7 in Iraq contains all the elements required for a successful petroleum system (Fig. 9.4.1). Basal units include highly organic-rich source rock intervals; reservoir facies are present in the middle of the succession around the margins of the Gotnia Basin, and locally thick overlying evaporites constitute an effective seal. High-energy carbonates with enhanced reservoir characteristics may occur in the crestal locations of traps.

In Iraq, the stratigraphic architecture is more complex than in Saudi Arabia, and the lateral infill geometry of the Gotnia Basin together with locally intense post-Jurassic erosion reduces the potential for the development of large-scale accumulations. Nevertheless, a variety of play types are present in the Jurassic and include: an Arab-type play similar to that at *Ghawar*; a basin-margin dolomite play; a fractured carbonate source rock play; subcrop plays related to the base-Cretaceous unconformity; a basin-centre isolated carbonate build-up play; a play relying on shelf or basin-margin facies sealed by updip evaporites; plays associated with downward migration into the Mus (Marrat) Formation; and plays in porous lowstand shelfal carbonates or collapse breccias isolated within basinal shales and low-energy carbonates.

In northern Iraq, it is difficult to separate the Jurassic (Megasequence AP7) petroleum system from that in Cretaceous Megasequence AP8. Source rock intervals in AP8 occur over a similar geographical area to those in AP7, and the oils generated by the two systems are very similar in composition (Goff, 2005). They are probably mixed in areas where the Gotnia Formation anhydrite seal is absent or breached by faulting.

This chapter focusses on the petroleum system which is associated with Middle – Upper Jurassic source rocks. Cretaceous (or mixed Jurassic – Cretaceous) source rocks are discussed in Chapter 9v.

Maturation Modelling and Oil Migration

Pitman *et al.* (2004) modelled the maturation of the Jurassic source rocks in Iraq, the timing of hydrocarbon generation, and the migration pathways of expelled oil (Figs 9.4.2 – 9.4.6). They considered that the Sargelu and Naokelekan Formations are the most important Jurassic source rocks in Iraq, and that Cretaceous source rocks had contributed only small amounts of oil to the Cretaceous-Tertiary Petroleum System (TPS 202303). An average initial Total Organic Carbon content of 5% wt was used, with an initial Hydrogen Index of 600 mgHC/g TOC. Pitman *et al. (ibid.)* considered that anhydrites of the Upper Jurassic Gotnia Formation are a regional seal, but that it may locally be ineffective due to facies changes or fracturing. They studied present-day thermal gradients at six well locations (*Ain Zalah, Bai Hassan, Jambur, Kirkuk, Rumaila* and *Zubair*), and determined thermal gradients in the range 17–23 °C/km corresponding to present-day heat flows of 45 and 48 mW/m^2 in the southern Mesopotamian Basin and Zagros Fold Belt, respectively.

Pitman *et al.* (2004) calculated maturity values corresponding to vitrinite reflectance values of 0.4–0.6% at a present-day depth of 2000 m, 0.5–0.7% at 3000 m, 0.6–0.9% at 4000 m, and 0.8-1.3% at 5000 m. For comparison, measured vitrinite reflectances (Al-Haba and Abdullah, 1989) are 0.6–1.0% in the depth range 3000 – 3400 m in well *Kirkuk-109*, 0.55% at 2700 m in *Qarah Chauq-1*, and 0.4 – 0.7% over depths of 2300–3100 m in well *Pulkana-5*.

Pitman *et al.* (2004) attributed the low present-day heat flows to the relatively rapid deposition rate

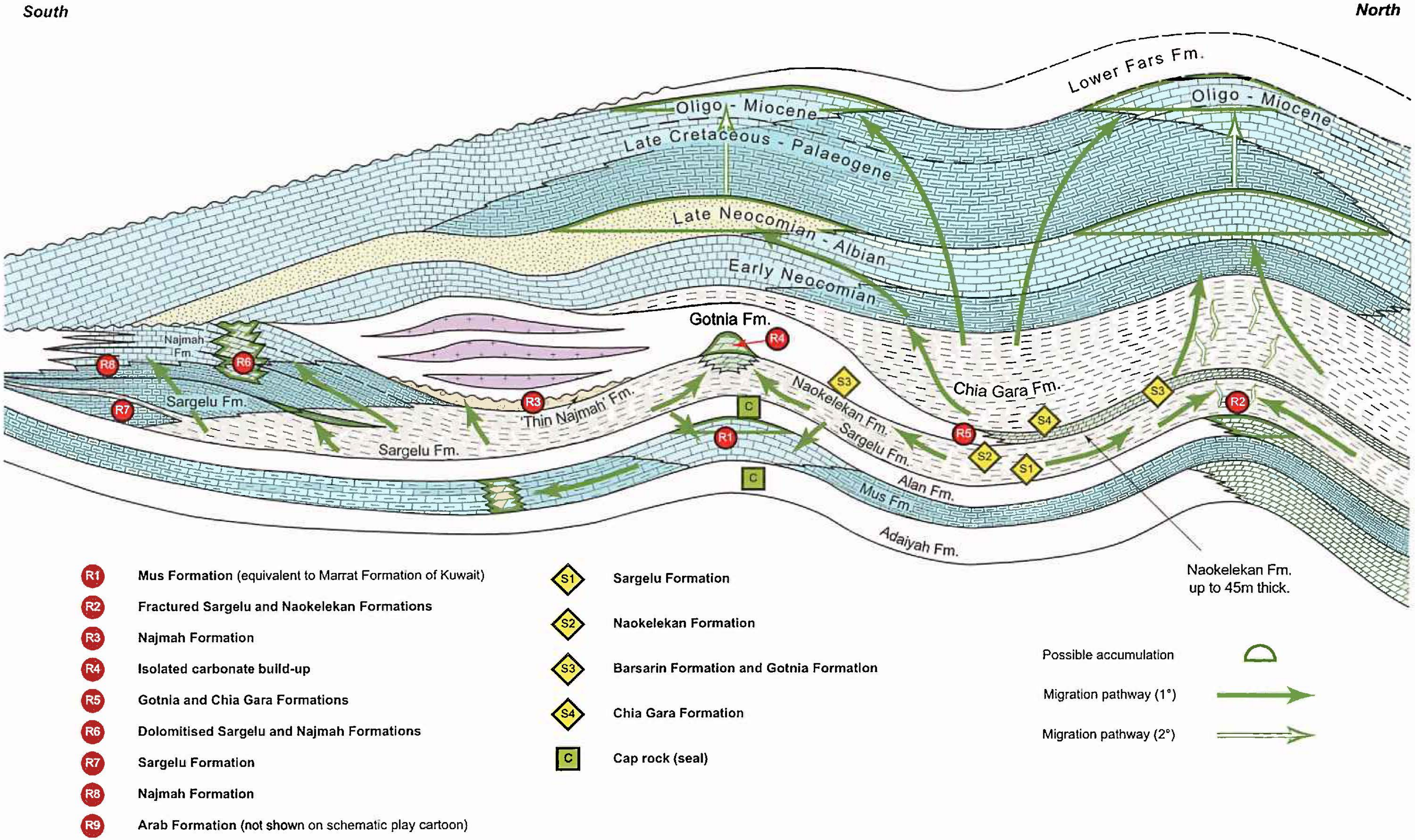


Fig. 9.4.1. Schematic cross-section through the Jurassic petroleum system in Iraq.

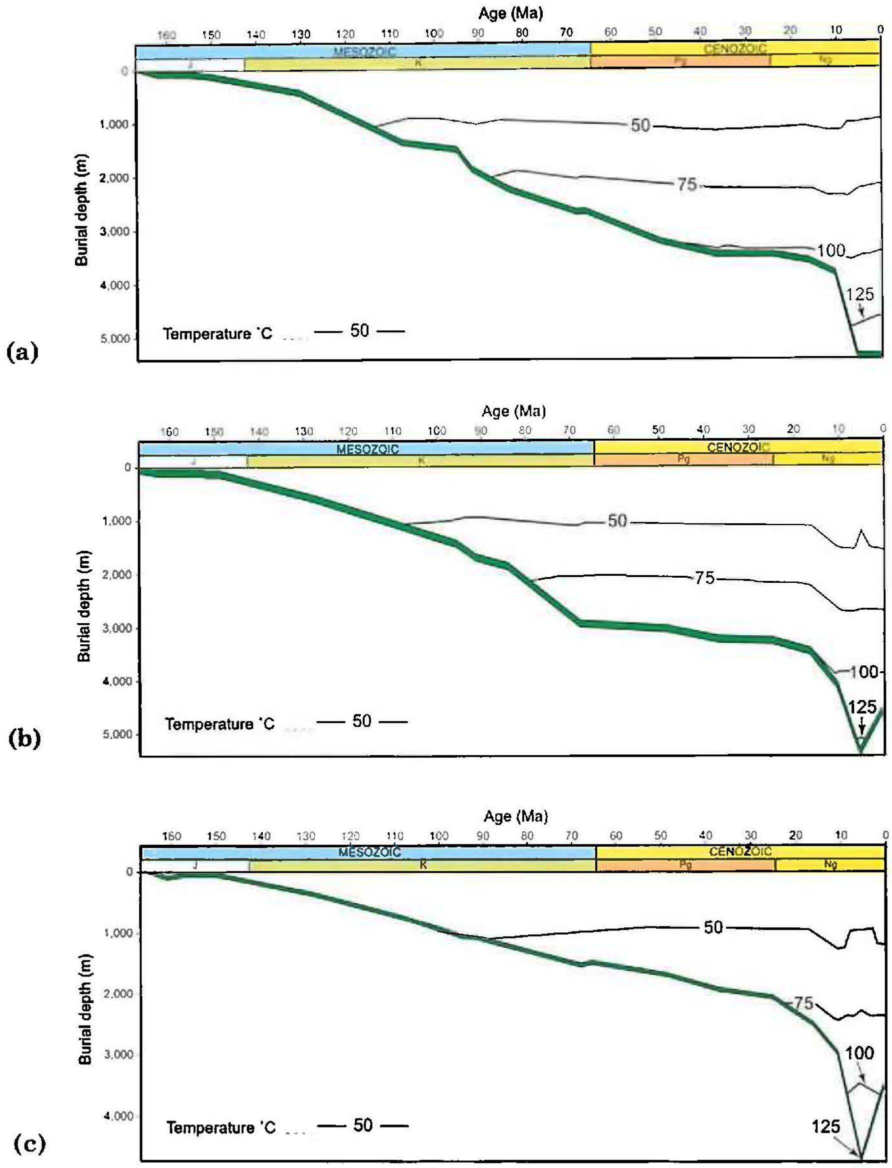


Fig. 9.4.2. Burial and thermal history curves for Jurassic source rocks at (a) *Zubair* field; (b) *Khashim Ahmar* field; and (c) *Kirkuk* (Baba Dome). After Pitman *et al.*, 2004, with permission of *GeoArabia*.

of Late Miocene – Pliocene sediments. Based on the relatively high sulphur contents of Iraqi oils, they considered that the source rocks contained a sulphur-rich kerogen similar to that in the Permian Phosphoria Formation of the USA. Therefore, they used kinetic parameters determined for the latter unit to model the formation of oil from Jurassic source rocks in Iraq. The kerogen's oil and gas yields were determined to be 522 and 78 mgHC/gTOC, respectively, based on isothermal pyrolysis data (87% of the potential petroleum yield from the kerogen is thus oil and 13% gas). Gas:oil ratios were < 1000 SCF/brl during oil generation. Oil-to-gas cracking was modelled using appropriate kinetic parameters; this occurred at deep burial at temperatures greater than 150 °C.

Modelling yielded low temperatures (ca. 100 °C) for the completion of oil generation (kerogen transformation ratio of > 0.95) from Jurassic source rocks at *Zubair* (Pitman *et al.*, 2004). These low temperatures are associated with the breakdown of the kerogen into an early oil product, rich in sulphur-bearing compounds. More mature oils with a lower sulphur content will be produced at higher temperatures in the oil window (100–150 °C).

Maximum temperatures in the range 130–150 °C were determined at maximum burial depths of 4650–5350 m at three modelled locations (*Zubair* in SE Iraq, *Kirkuk* in the north and *Khashim Ahmar* in central Iraq, north of Baghdad) (Fig. 9.4.2). Regional palaeoburial maps for the Jurassic source rocks at 25 Ma (late Oligocene), 10 Ma (middle Miocene), 8 Ma (late Miocene) and the present day were used to model the maturation of the Jurassic source rocks through Late Tertiary – Recent time by Pitman *et al.* (2004).

Results of the modelling indicated that onset of oil generation occurred in Late Cretaceous – Paleogene time in SE Iraq and in the Zagros foldbelt (Fig. 9.4.3). By late Oligocene – mid-Miocene time,

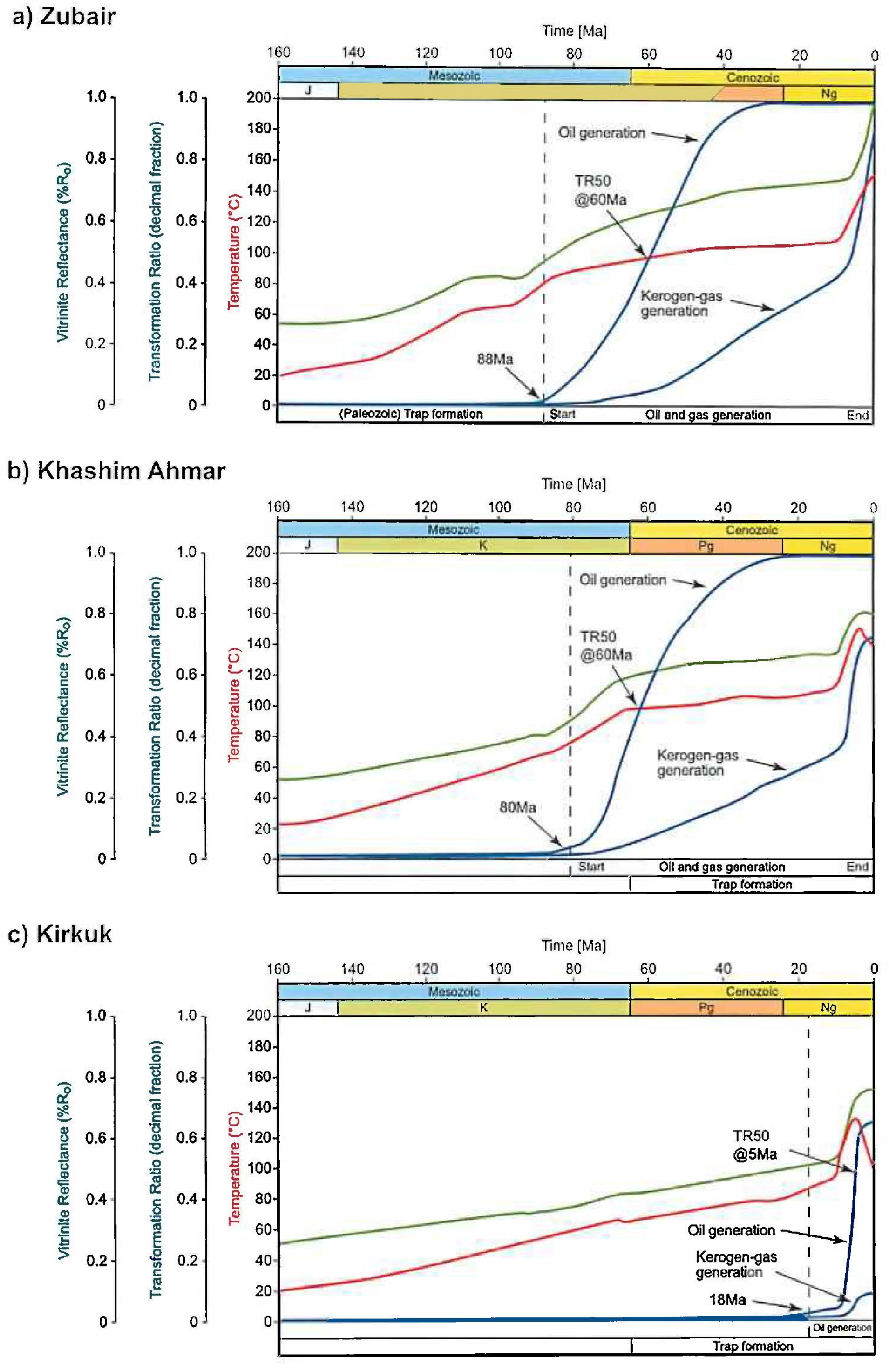


Fig. 9.4.3. Generation profiles for the three wells modelled in Fig. 9.4.2. After Pitman *et al.*, 2004, with permission of *GeoArabia*. TR: transformation ratio.

oil generation was completed in these areas. During late Miocene burial, the area of mature source rock expanded with oil generation occurring throughout the Mesopotamian Basin and central Zagros Fold Belt (Fig. 9.4.4). A present-day maturity map of Jurassic source rocks in Iraq prepared by Pitman *et al.* (2004) is shown in Fig. 9.4.5; Fig. 9.4.6 is a map of present day transformation ratios for these source rocks.The structurally complex area in NE Iraq containing thick foredeep sediments of Late Cretaceous age was not modelled by Pitman *et al.* Here it is likely that relatively early oil generation also occurred.

Carrigan *et al.* (1995) studied the geochemical properties of the Callovian-Oxfordian source rocks of the Tuwaiq Mountain and Hanifa Formations of Saudi Arabia. These rocks were deposited in a separate intrashelf basin to the Naokelekan Formation, but at the same time. Immature samples of the Callovian Tuwaiq Mountain Formation (with T_{max} values of < 425 °C equivalent to a vitrinite reflectance < 0.5%) had Hydrogen

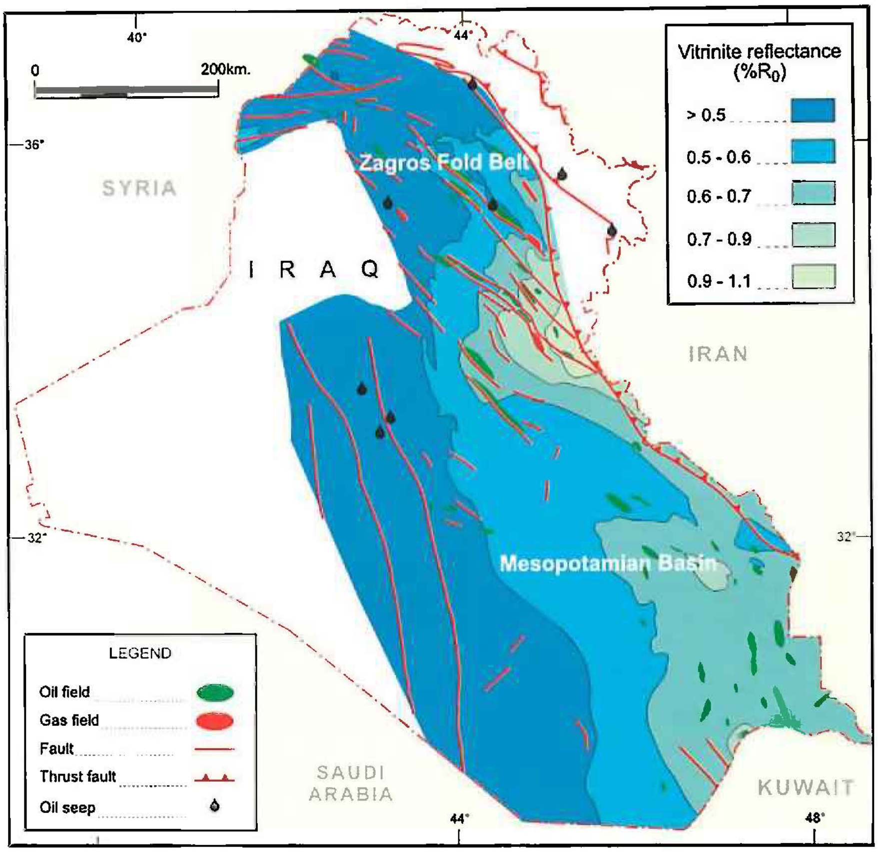


Fig. 9.4.4. Maturity of Middle-Upper Jurassic source rocks in Late Miocene time. After Pitman *et al.*, 2004, with permission of *GeoArabia*.

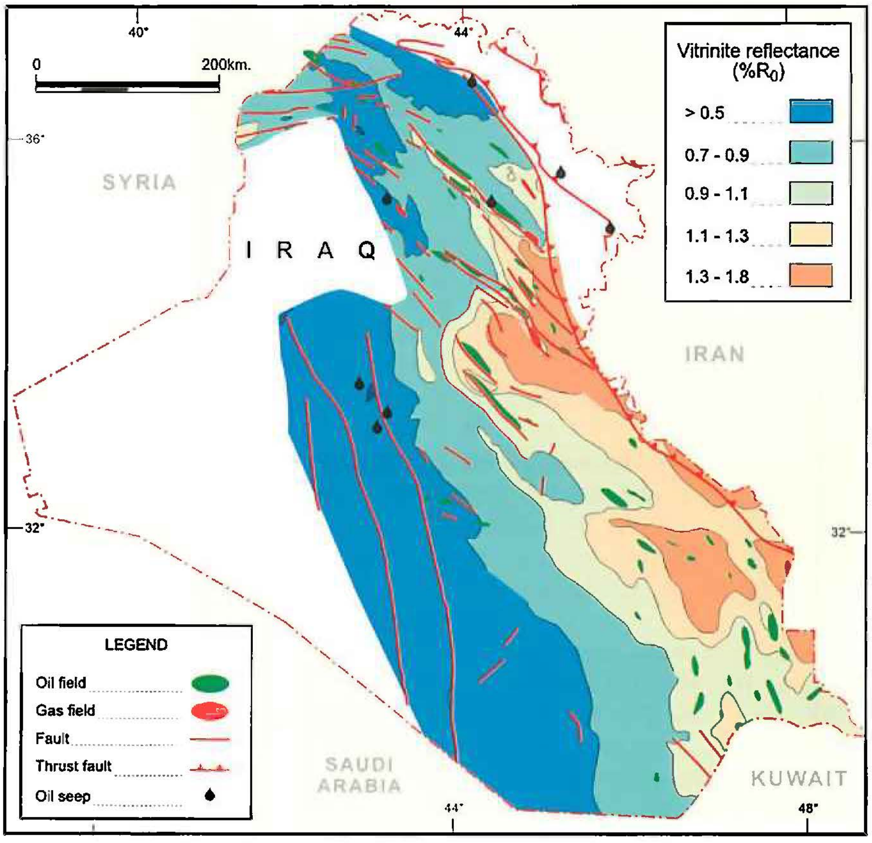


Fig. 9.4.5. Present-day maturity map for Middle-Upper Jurassic source rocks. After Pitman *et al.*, 2004, with permission of *GeoArabia*.

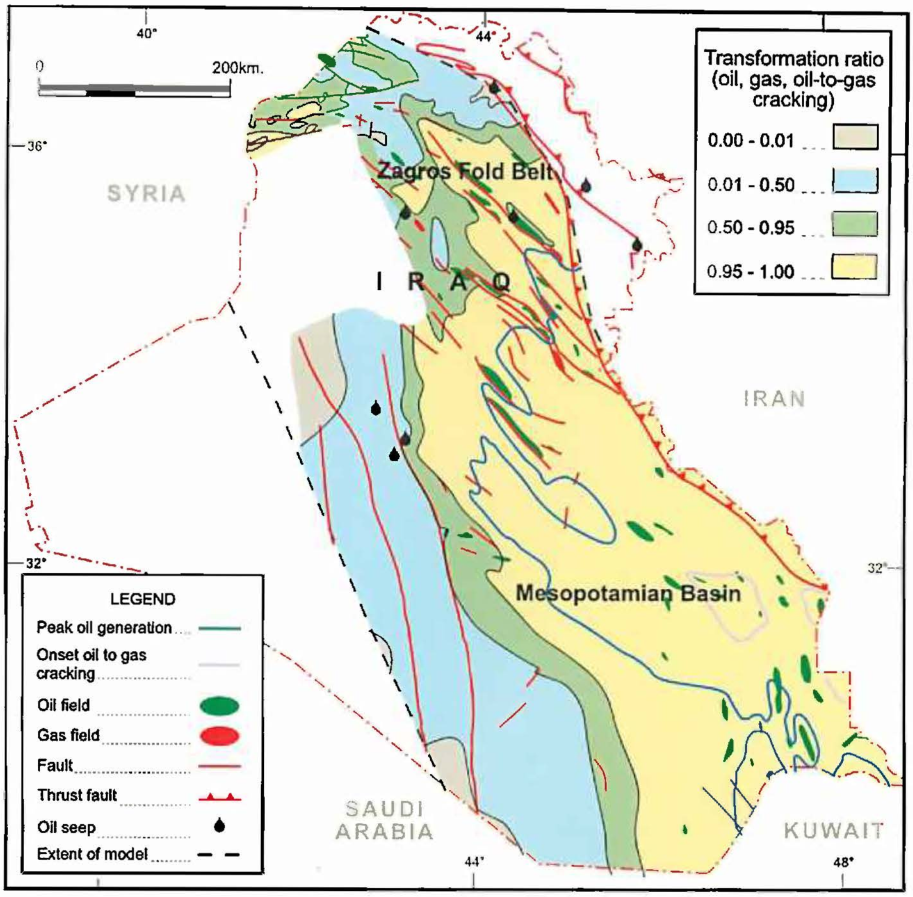


Fig. 9.4.6. Present-day transformation ratios for Middle-Upper Jurassic source rocks. After Pitman *et al.*, 2004, with permission from *GeoArabia*.

Indices of 600 – 800 mgHC/gTOC, with TOC contents of up to 7%. The net thickness of source rocks with > 1% TOC is up to 150 m (Ayres *et al.*, 1982).

Source rocks

In northern Iraq, bituminous shales ("coal horizons") of the Naokelekan Formation constitute a local fuel source (Dunnington *et al.*, 1959). Dunnington (1958) recognised the source rock potential of similar Jurassic shales throughout the Arabian Basin. Later authors (e.g. Murris, 1980; Ayres *et al.*, 1982; Lehner, 1984; Wilson, 1984) interpreted these laminated black shales and peloidal limestones as the deposits of euxinic intrashelf basins which developed during the Jurassic, particularly during the Callovian and Oxfordian.

In Iraq, source rock intervals occur in the Sargelu, Naokelekan, Barsarin and Gotnia Formations (see Chapter 6 and Fig. 9.4.1). The Naokelekan Formation includes the most organic-rich source rock intervals. The TOC averages about 4% at *Kirkuk-109* and *Qarah Chauq-1*. The Sargelu Formation may include intervals with higher TOC contents. These source rocks generally contain Type II kerogen. Pitman *et al.* (2004) proposed a mean TOC of 5% for the Sargelu and Naokelekan Formations. Based on the thickness values of the Jurassic formations, the volumetrically most important source rock is probably the Sargelu, followed by the Naokelekan and the Barsarin/Gotnia.

Maturity

Jassim and Al-Gailani (2006) published a maturity map for Middle–Upper Jurassic source rocks in Iraq (Fig. 9.4.7). This map probably underestimates the maturity of Jurassic source rocks in the NE where they are deeply buried in areas flanking the major anticlines in the foredeep basin, and in areas which have undergone major late Tertiary uplift and erosion. Bitumen seeps, which occur along the Tigris River in northern Iraq and to the west of the Euphrates between Ramadi and Karbala, may be derived from marginally-mature source rocks along the edge of the source kitchen.

(i) Northern Iraq

Original Hydrogen Indices for the Sargelu and Naokelekan Formations in northern Iraq were probably 600 mgHC/gTOC (Pitman *et al.*, 2004). Present-day values range from <100 to 600 mgHC/gTOC (Al-Haba and Abdullah, 1989). In well *Taq Taq-1*, the HI is 22 mg/g at 3236 m (Sadooni and Alsharhan, 2003); in well *Kirkuk-109*, the HI was

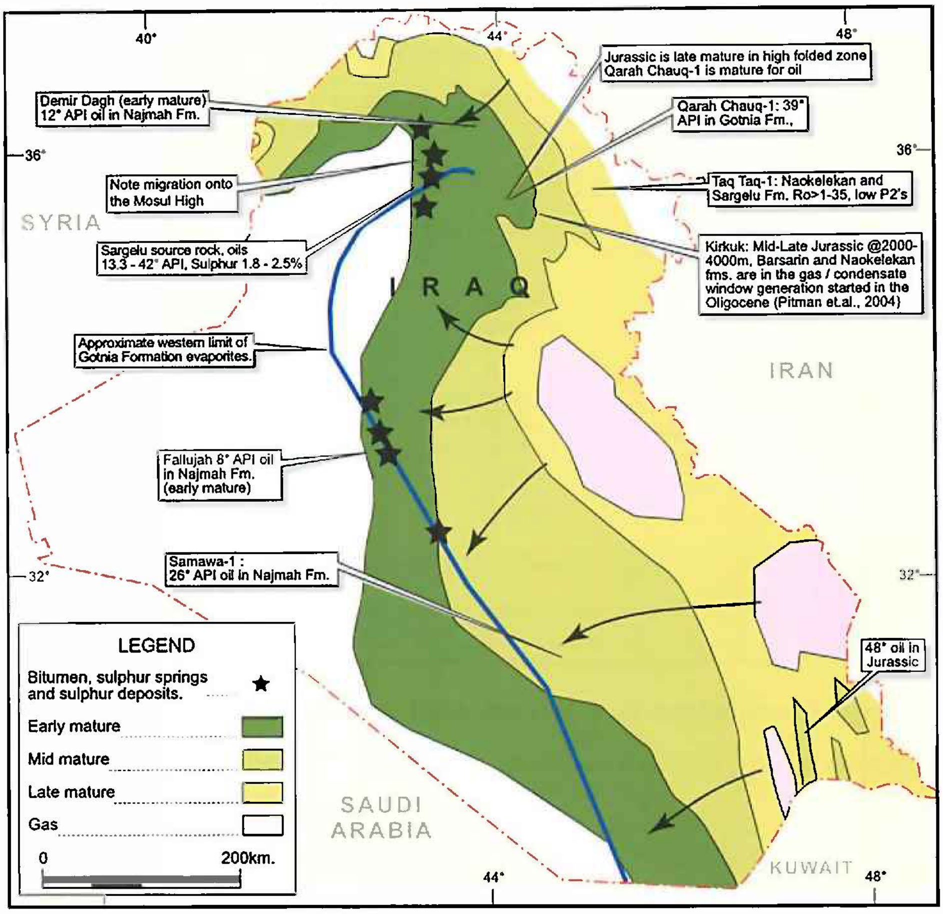


Fig. 9.4.7. Maximun maturity map for the Middle to Upper Jurassic of Iraq. After Jassim and Al-Gailani (2006) with additional data from various sources.

69 mg/g and T_{max} was 450°C at 3396 m (PGA, 2000). Al-Haba and Abdullah (1989) showed that at well *Kirkuk-109*, the Middle – Upper Jurassic interval is buried to depths of 2200-4000 m. The Barsarin and Naokelekan Formations below 3000 m have entered the gas and condensate generation windows. At well *Taq Taq-1* closer to the mountain front, the Naokelekan and Sargelu Formations are more mature (R_o>1.35) indicating that they have already generated liquid hydrocarbons (Odisho and Othman, 1992). Samples from well *Qarah Chauq-1*, also in northern Iraq, are mature for oil generation (Al-Haba and Abdullah, *ibid.).* Al-Haba and Abdullah (1989) reported that Middle-Upper Jurassic source rocks were immature in well *Jebel Kand-1* due to insufficient burial. Odisho and Othman (1992) found that the Sargelu Formation at this well has an HI of 426 and a T_{max} of 441°C.

At the Baba Dome (*Kirkuk* field), vitrinite reflectance data show that Jurassic source rocks were buried to depths of 4650 m and reached maximum temperatures of 130°C although at the present-day these rocks are at 3300 m (and temperatures of 90°C: Pitman *et al.*, 2004). In structurally low areas between anticlines, Jurassic source rocks are estimated to have reached temperatures of 170° in the late Miocene but may have cooled to 135°C as a result of Pliocene – Quaternary uplift (Pitman *et al.*, 2004).

(ii) Southern Iraq

In the Mesopotamian Basin, Jurassic source rocks are currently at or close to their maximum burial depths. For a present-day geothermal gradient of 27°C/km and a mean surface temperature of 25°C, the top of the oil window occurs at a depth of about 3000 m. Peak oil generation takes place between 3500 and 4000 m, and light oil and condensate generation between 4000 and 5000 m. Gas is probably being expelled at the present day in the parts of the basin closest to Iran (Fig. 9.4.5).

(iii) Central Iraq

Between the Zagros foldbelt and SE Iraq, burial history modelling (Pitman *et al.*, 2004) indicates an intermediate maturation history. At *Khashim Al-Ahmar* field, Jurassic source rocks reached peak temperatures in the late Miocene (temperatures of 150°C at 5300 m), decreasing following uplift to present-day values of 140° at 4400 m.

In summary, most Jurassic source rocks in Iraq have already reached or exceeded peak oil generation and have started to generate significant quantities of gas. However, areas of oil generation have expanded westwards through time (Fig. 9.4.6). Heavy oil generation may have occurred in areas to the west of the Salman Zone. Uplift beginning in the late Miocene locally terminated hydrocarbon

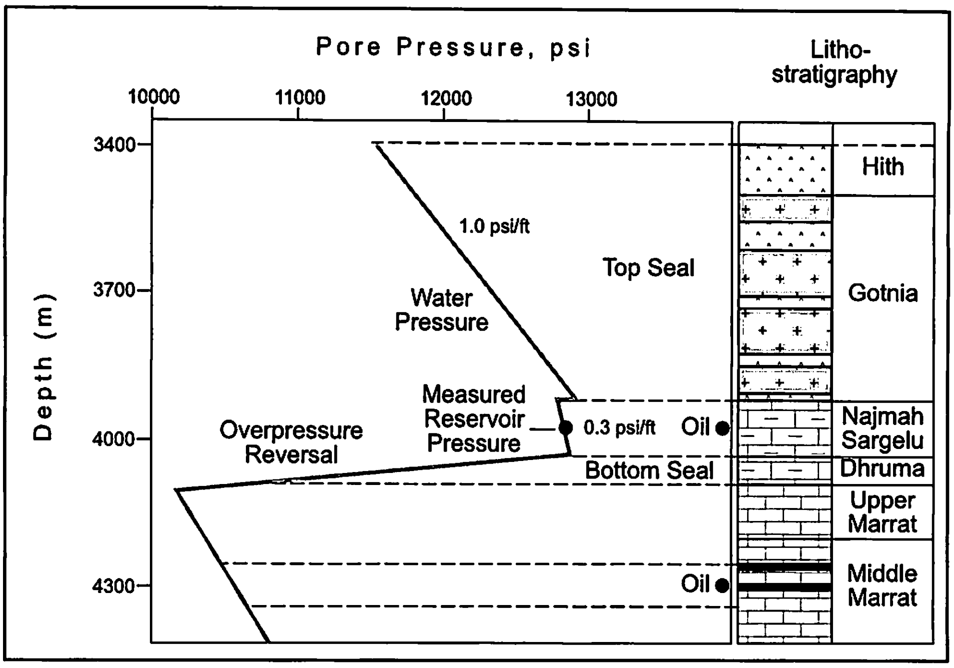


Fig. 9.4.8. Pore pressure profile from West Kuwait. After Goff, 2005.

generation by Jurassic source rocks in northern Iraq.

Overpressuring

The deeply-buried Mid-Upper Jurassic succession in the Gotnia Basin is strongly overpressured. An overpressure profile through the Jurassic succession in Western Kuwait (Fig. 9.4.8) may be representative of the pore-pressure regime in SE Iraq where thick halite beds are present (Goff, 2005). The pore pressure gradient increases rapidly downwards through the 100 m thick Hith Formation anhydrites (equivalent to the uppermost part of the Gotnia Formation in Iraq). It exceeds 17.0 ppg (0.88 psi/ft) at the base of the Hith and about 19.25 ppg (1.00 psi/ft) at 3810 m in the lower part of the Gotnia Formation halites and anhydrites (Al-Saeedi *et al.*, 2003). A decrease in overpressure typically occurs at the boundary between the evaporites and the underlying fractured carbonate source rocks (Fig. 9.4.9). In Kuwait, the pore pressure gradient in the source rocks is generally in the range 16.0–18.8 ppg (0.83–0.98 psi/ft) (Al-Saeedi *et al.*, 2003). Pore pressures at the crest of the *Minagish* structure are very high (12,750 psi at 3386 m), equivalent to a pore pressure gradient of 1.00 psi/ft, increasing to 13,000 psi at 4145 m with an oil pressure gradient of 0.3 psi/ft (Al-Saeedi *et al.*, 2001). Pore and fracture pressures converge to similar values at the crest of the structure at 3810 m; the difference between them then increases with depth to 500 psi at 4084 m (Al-Saeedi *et al.*, 2001). A further decrease in overpressure occurs between the calcareous shales of the Dhruma Formation and the underlying Marrat Formation carbonates. The pore pressure gradient is typically 1–3 ppg lower in the Marrat Formation than in the Najmah/Sargelu; pore pressure gradients in the Marrat normally range from 14.0 to 16.0 ppg (0.73–0.83 psi/ft) (Goff, 2005). Overpressured Middle-Upper Jurassic source rocks charge underlying Marrat Formation reservoirs (Fig. 9.4.10).

Reservoir rocks

The Najmah Formation, equivalent to the Arab Formation of the southern Gulf region, includes proven reservoir rock intervals. Jassim and Al-Gailani (2006) proposed that 19 structures in Iraq contain hydrocarbons in this formation, although none are productive at present. Reservoir facies include oolitic-peloidal grainstones and packstones with intergranular porosity, enhanced in some cases by ooid dissolution, and dolomitic limestones with intercrystalline porosity (Sadooni, 1997) (Fig. 6.8). Jassim and Al-Gailani (2006) suggested that maximum porosities in this formation were 20-30%, with permeabilities varying according to the degree of dolomitisation. The petrophysical characteristics of the Najmah Formation have not been described in detail, and the small amount of published data may be biased due to poor sampling procedures or poor location of wells. However, the available data suggests that the Najmah Formation may constitute a reservoir target, particularly in central and southern Iraq where potential coarse-grained facies are 50 to 150 m thick (Sadooni, 1997).

Conventional porous reservoir rock intervals have not yet been identified within Jurassic limestone successions in Iraq; reservoir quality may be restricted to dolomitised units and fractured low porosity carbonates (Goff, 2005). The origin of these dolomite reservoirs is discussed in Chapter 6 (pp. 147-148).

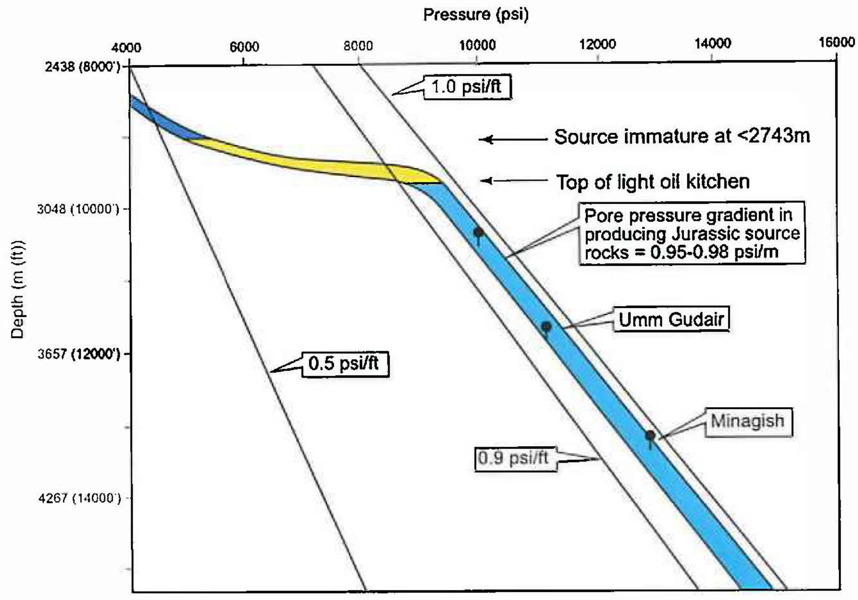


Fig. 9.4.9. Jurassic pore pressure versus depth in West Kuwait. (After Goff, 2005).

In order to compensate for the risk of possible seal failure where the overlying seal (Gotnia Formation) is thin, INOC explored for Najmah reservoirs at locations where the Gotnia was predicted to be thick. Well *Diwan-1* in south-central Iraq (see Fig. 6.1) was drilled in 1988 to the SE of *Samawa-1* to test for enhanced oolite development in the Najmah and a better seal in the Gotnia. However, the thick oolitic limestone succession was highly cemented (Sadooni, 1997).

Al-Gailani (1998a) noted that the Mus Formation may be an effective reservoir in southern Iraq, where it comprises oolitic to "pseudo-oolitic" (?peloidal and coated grain) carbonate facies. These facies may correspond to the productive reservoirs in wells *North Rumaila-172* and *West Qurna-15* (Sadooni, 1997). The equivalent Marrat Formation "C" Member forms a significant reservoir in the *Humma Marat* and *Minagish* fields in Kuwait (Meddaugh *et al.*, 2006), where it may be up to 200 m thick, with the highest porosities occurring at the top of the unit (Yousif and Nouman, 1997).

The extent to which shoal units (shallow water carbonates) occur in the Najmah and Mus Formations in the subsurface of Iraq has probably been underestimated.

Seals

Thick Gotnia Formation anhydrites represent a potential regional seal for the Jurassic petroleum system in SE Iraq. In SW Iraq, the Gotnia Formation is thinner but may seal the underlying Najmah Formation shelfal facies (Al-Naqib, 1967). To the north of *Makhul* and *East Baghdad*, the Gotnia Formation is replaced by the collapse breccias of the Barsarin Formation which probably do not constitute an effective seal. The Gotnia Formation is present at wells *Qarah Chauq-1* and *Jebel Kand-1* (OEC, 1989; Odisho and Othman, 1992); and the Barsarin Formation is thick and similar to the Gotnia at well *Kirkuk-109* although it thins towards the *Taq Taq* location (Dunnington *et al.*, 1959; Kaddouri, 1986). Massive evaporites in the upper part of Megasequence AP7 in northern Iraq are less common and more difficult to predict than in the south (Fig. 9.4.1).

At its type section in well *Awasil-5*, the Gotnia Formation comprises "*bedded anhydrite with subordinate intercalations of brown calcareous shales and thin black bituminous shales, and of recrystallised, fluffy-textured and rare pseudo-oolitic limestones*" (Dunnington *et al.*, 1959). However, the sealing capacity of the formation may be affected by fracturing.

Pitman *et al.* (2004) modelled the efficiency of the Upper Jurassic Gotnia Formation caprock in the *Majnoon* area. They assumed that it comprised a mixture of anhydrite, calcite and dolomite based on descriptions of the lithology of the Gotnia Formation in wells drilled further west provided by Ibrahim (1983). They concluded that if the Gotnia Formation contains a high proportion of carbonates, its sealing efficiency may be reduced to a level which would allow oil generated from the underlying Jurassic source rocks to migrate through it into Cretaceous reservoirs at *Majnoon*. However the Gotnia Formation in northern Kuwait and beneath the Cretaceous oil reservoirs of *Rumaila* contains thick beds of halite which may extend over a large part of SE Iraq including the area of *Majnoon* field. Unless there are significant faults cutting the Gotnia Formation, upward vertical oil migration from Jurassic source rocks underlying the salt layers is unlikely. Late Tithonian (latest Jurassic) source rocks immediately *overlying* the Gotnia Formation together with Cretaceous source rocks may thus have provided most of the oil charge into the Cretaceous reservoirs in SE Iraq.

Cap-rock failure due to dolomitisation occurred synchronously with oil migration into the

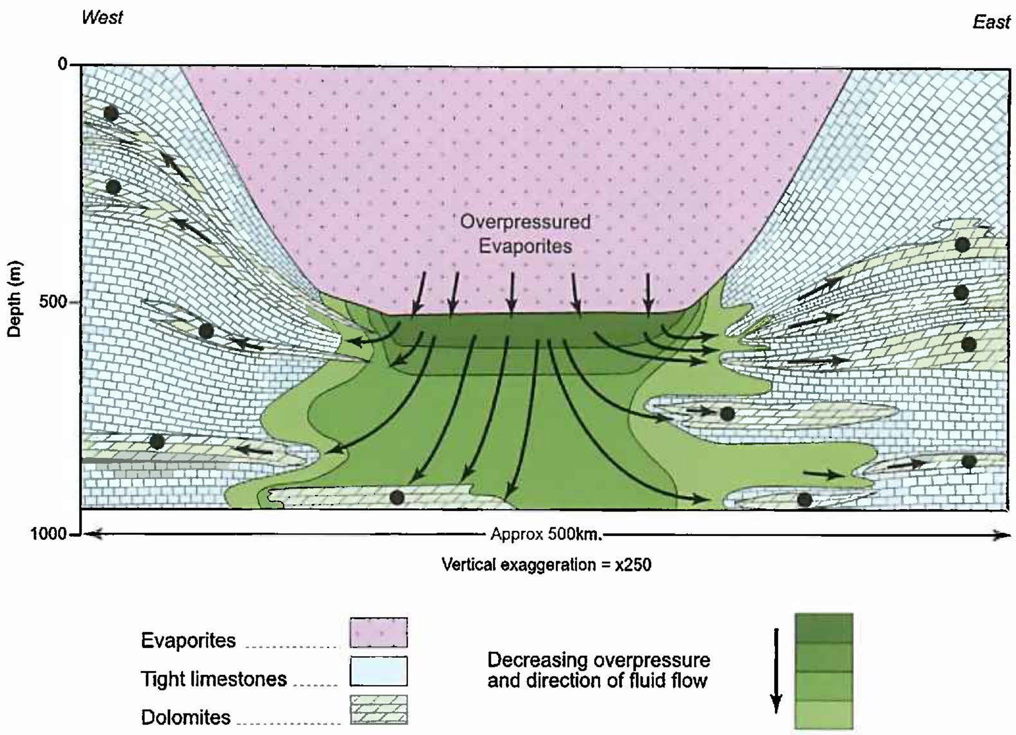


Fig. 9.4.10. Jurassic fluid flow beneath overpressured evaporites of the Gotnia Formation. After Goff, 2005. The stratigraphy is illustrated in more detail in Fig. 6.5.

Cretaceous succession in northern Saudi Arabia (Broomhall and Allan, 1987). A similar process may have occurred in Northern Iraq during folding and fracturing in the late Miocene, continuing through Pliocene and later uplift and erosion. In the Zagros, bitumen seeps through fractures to the surface, for example at Kuh-e Mungasht in Iran (Plate 6.8). Bitumen also seeps from porous dolomites at outcrop in the summer months. These dolomites represent an exhumed oil reservoir (Goff, 2005).

In NW Iraq, the Sargelu and Najmah Formations are unconformably overlain by heterogeneous Cretaceous formations of variable sealing potential. These units onlap the Jurassic on the flanks of structural highs, but there is a high probability of seal failure and spillage in any given structure due to the presence of carrier beds.

Al-Gailani (1998a) noted that the underlying evaporitic Alan and Adaiyah Formations pass northwards into tight "pseudo-oolitic" limestones. Although this facies change may occur in the Zagros fold-thrust belt and in the *Taq Taq* area, as well as in southern Iraq on palaeohighs such as *Kifl-1* (see logs in Al-Naqib, 1967 and Al-Mashadani, 1986), these Lower Jurassic units contain evaporites> They may therefore represent a sub-regional basal seal to the Jurassic petroleum system.

Migration of oil and gas

Where the Gotnia Formation acts as an efficient regional seal, significant lateral migration of petroleum and other subsurface fluids may occur in underlying permeable carbonate units. "Plumes" of high-temperature, high-salinity dolomite containing hydrocarbon inclusions and pore-fills extend up to 150 km from the basin margins (Fig. 6.10) (c.f. Broomhall and Allan, 1987; Goff, 2005). These fluids would have migrated laterally along carrier beds that connect to vertical migration conduits such as the Najmah Formation platform margin carbonates. However, in other cases both lateral and vertical migration was hindered by low formation permeabilities, leading to development of significant overpressures and the migration of oil only locally into fractures of both tectonic and hydraulic origin within the Mid-Upper Jurassic source rock itself (Goff, 2005).

Entrapment of oil and gas

The following plays are of potential relevance to the Jurassic petroleum system of Iraq (9.4.11) and are discussed in turn below:

1. an Arab-type play similar to that at *Ghawar* and in the southern Gulf.
2. basin-margin dolomites;
3. fractured carbonate source rocks;
4. plays related to the base-Cretaceous unconformity;
5. isolated basin-centre carbonate build-ups;
6. shelf or basin-margin facies sealed by updip evaporites;
7. plays associate with downward migration into the Mus (Marrat) Formation;
8. porous shelfal carbonates or collapse breccias isolated within basinal shales and low-energy carbonates.

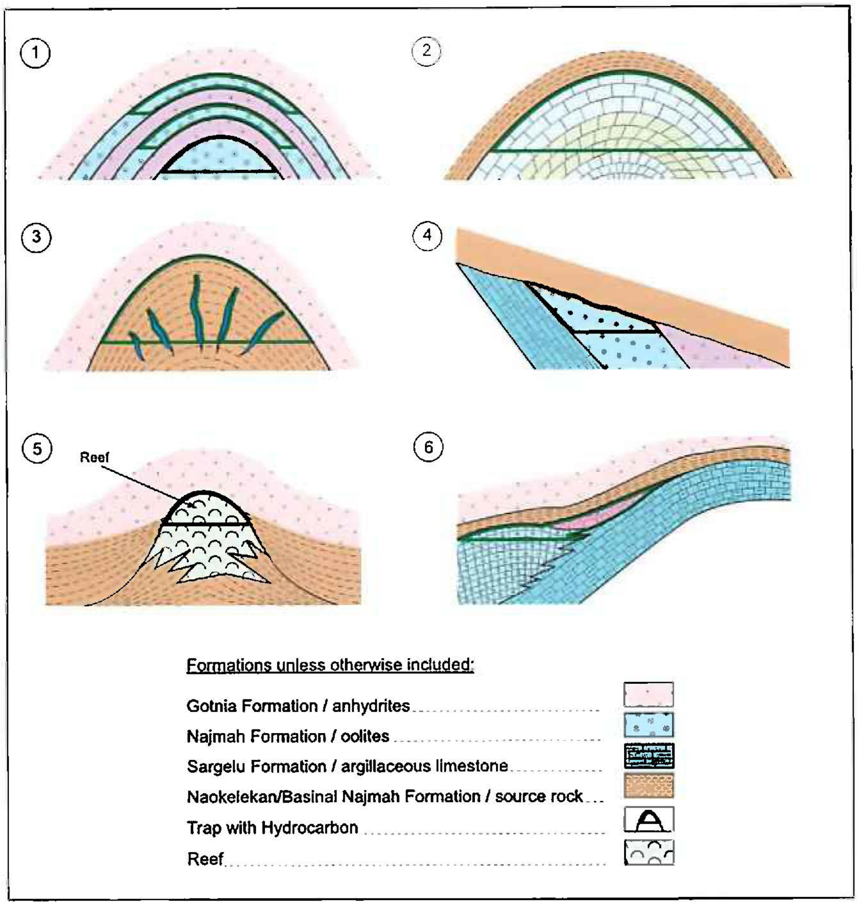


Fig. 9.4.11. Possible trap types for the Jurassic in Iraq:
1. Arab-type reservoir in an anticline (multiple stacked pays);
2. Dolomitised shelf carbonates in an anticline (single large pay);
3. Fractured source rocks;
4. Unconformity trap: karstified shallow-water Jurassic facies are sealed by Cretaceous shales;
5. Carbonate build-up with shale / evaporite seal;
6. Updip wedge-out for shelf and slope / talus / lowstand deposits.

Structural traps will be dominated by Zagros anticlines.

1. **Arab-type plays** may occur in the Salman Zone in southern Iraq to the west of the Gotnia Basin. Here, porous limestones and dolomites may occur within the platform succession sealed by overlying anhydrites (equivalent to the Hith Formation). Analogous giant fields in southern Arabia comprise broad drape folds over Infracambrian / "Hercynian" palaeohighs (e.g. *Ghawar*) with higher-energy reservoir facies located over structural crests.

However, access to a mature oil charge will require long distance migration from the source kitchen to the east depending on the location of the structures.

2. **Basin-margin dolomite plays** comprise potential reservoir units within otherwise tight carbonate (and even evaporite) successions, but will probably require four-way dip closures and a regional seal in order to be productive. However the dolomite bodies themselves may not form valid traps within tight limestones because of the risk on lateral seal. Broomhall and Allan (1987) noted that these reservoir systems are frequently disappointing in terms of production. This may be because the dolomitising fluid systems are aggressive and have breached the seal.

The occurrence of oil in Jurassic platform-margin dolomites on both sides of the Gotnia Basin indicates that lateral migration of petroleum beneath regional Jurassic evaporites and carbonate seals has occurred. Carrier beds probably comprise thin, partly dolomitized intervals (with connected secondary porosity), which have locally allowed large-scale migration of both dolomitising fluids and oil into the adjacent platform carbonates on the flanks of the basin (Goff, 2005). These partially-dolomitized intervals have been recorded in the subsurface (in cores), at outcrop, and downdip from the platform margins. Dolomite crystals from these beds contain abundant oil inclusions, indicating that synchronous migration of oil and dolomitising fluids has occurred (Goff, 2005).

3. **Fractured source rocks:** Fractured carbonate source rock units (such as the Sargelu Formation in southern Iraq and the Naokelekan

in northern Iraq) may constitute a valid play. The origin of the fractures in the Upper Jurassic succession in Kuwait (Goff, 2005) was discussed on pp. 156-157. Jassim and Al-Gailani (2006) noted the presence of fractures filled with heavy and bituminous oil in the Sargelu Formation in both northern Iraq and in the Salman Zone.

4. **Unconformity traps:** Traps in basin-marginal locations in northern Iraq may include matrix porosity systems in the Najmah Formation as it pinches-out updip beneath the base-Cretaceous unconformity, and karstified intervals in the Sargelu Formation. This play type requires a regional seal within the basal part of the onlapping Cretaceous section. However, potential thin reservoir units within the Cretaceous succession may act as "thief" units (e.g. grain-rich carbonates in the Garagu / Yamama Formations).

5. **Isolated carbonate build-ups:** Age-equivalent stratigraphic traps in isolated reefal build-ups include the highly productive Cotton Valley play of the Gulf of Mexico (c.f. Crevello and Harris, 1984; Montgomery, 1996; Spaw *et al.*, 2000), but this play type is speculative in Iraq.

Sponge-stromatoporoid reefal build-ups were recorded in the Najmah Formation by Sadooni (1997) (Fig. 6.8), and may have developed as isolated structures in central parts of the Gotnia Basin from the Bajocian-Bathonian onwards. Their development ceased as a result of restriction and lowstands in the later Oxfordian and Kimmeridgian. The build-ups may then have been isolated within anhydrites and halites of the Gotnia Formation. Analogous build-ups onlapped and sealed by evaporites are known from the Silurian of the Great Lakes area of North America (e.g. Bay, 1983; Cercone and Lohmann, 1985).

6. **Stratigraphic traps** may exist in the transitional area where potential thick "Arab Formation" carbonates may pass into the massive Gotnia Formation anhydrites providing a top and lateral seal. However, because evaporites in the Gotnia Formation relate to basin-centre drawdown systems, rather than to sabkha-related systems behind (i.e. updip from) the platform margin, successful plays will need to close against the regional structural dip.

7. Oil typing in West Kuwait has shown that **reversed pore pressure gradients** have resulted in the downward migration of oil from the Najmah-Sargelu Formations for about 300 m into the Dhruma and Upper Marrat Formations (Barwise *et al.*,1999). Reservoir facies in the Marrat Member "C" appear to be present above Rayn Anticline palaeohighs in Kuwait, and an analogous play may occur in Iraq in the Salman Zone.

8. Within the Gotnia Basin, **lowstand wedges** consisting of porous shelf carbonates or collapse breccias may occur locally. Data in Kaddouri (1986) from the Benavi area of northern Iraq (Fig. 5.20), and Jassim *et al.* (2006a) from the Halabja area, suggest that shallower-water facies may be present within the upper part of the Sargelu Formation in what was originally considered to be a basinal area (Dunnington, 1958; Dunnington *et al.*, 1959).

Oils in fields

As a consequence of the sealing efficiency of the Gotnia Formation, large-scale migration from sub-evaporitic Jurassic (Megasequence AP7) source rocks into overlying strata is unlikely to have occurred. Megasequence AP7 source rocks are however important in northern Iraq, where the Barsarin Formation generally does not constitute a barrier to migration. Here, AP7 and overlying (basal AP8) source rocks contribute to the petroleum charge (Goff, 2005). These mixed-source oils are discussed in Chapter 9v.

Al-Gailani (1998a) noted that the oils in the Jurassic petroleum system of SE Iraq are typically light (API 48°) with low sulphur contents and sour dissolved gas, e.g. in the *North Rumaila* and *West Qurna* fields. At the basin margins, the oils are heavy due to early source rock maturation and biodegradation. Some 330 b/d of heavy oil was produced from the Najmah Formation at well *Samawa-1*. Oil shows were reported in the Mus and Najmah Formations in well *Kifl-1* (Sadooni, 1997), and in the Najmah and Gotnia Formations in *Abu Khema-1* (Roychoudhury and Handoo, 1980). Oil gravities in Saudi Arabia increases with reservoir age. Thus 36-42°API oils occur in the Dhruma Formation, 31-37°API oils in the Hanifa and Tuwaiq Mountain Formations, and 28-36° API oils in the Arab Formation. Fluid inclusion data from the Surmeh Formation dolomites at Kuh-e Mungasht in Iran indicates that basin-margin structures contain migrated 20-40°API oil (Goff, 2005).

Jassim and Al-Gailani (2006) noted that the oil in the Sargelu Formation of northern Iraq and in the Salman Zone is 13.3-42°API with sulphur contents of 1.8 to 2.5%. Najmah reservoirs contain oils of 8 to 46°API. Low-API oils are found in *Fallujah* (8°API) and *Demir Dagh* (12°API) (Jassim and Al-Gailani, 2006) and have sulphur contents of up to 5.9%. In the Adaiyah-Mus-Alan reservoir-seal triplet of the *Ain Zalah* field at the base of the petroleum system, oils range from 28 to 34°API, with 1.9% sulphur.

9. PETROLEUM SYSTEMS

v. Cretaceous

The Cretaceous petroleum system is the most important in Iraq (Fig. 9.5.1) and is contained in Megasequences AP8 and AP9 of Sharland *et al.* (2001). Tithonian (uppermost Jurassic) to Lower Cretaceous source rocks charged Cretaceous reservoirs in anticlinal structures throughout central and southern Iraq, and Cretaceous and Cenozoic reservoirs in northern and NE Iraq. Underlying Jurassic source rocks may also have charged Cretaceous reservoirs where the Upper Jurassic evaporite seal is ineffective (Pitman *et al.*, 2004; Goff, 2005).

Source rocks

The importance of uppermost Jurassic — Lower Cretaceous source rocks in charging Cretaceous and Cenozoic reservoirs in northern Iraq was discussed by Dunnington (1958). Cretaceous source rocks have been identified in Northern Iraq by Al-Haba and Abdullah (1989) and Odisho and Othman (1992).

The highest-quality source rocks occur in the basal part of Megasequence AP8 and are of late Tithonian – earliest Cretaceous age (see page 178). Fig. 7.15 shows a similar pattern of TOC variation through the Garau Formation in Iran, suggesting similarities between the Iraqi and Iranian (Lurestan) source rock systems.

In northern Iraq, the most important source rocks are the shale-dominated Chia Gara Formation (Tithonian – Berriasian) and the basal parts of the overlying Balambo Formation. TOC in the Chia Gara Formation averages 2.2% (maximum: >6%) (Al-Haba and Abdullah, 1989). The basal Balambo Formation in well *Pulkhana-5* in the Kirkuk Embayment, northern Iraq, has a TOC of 1.2-8.8% (Al-Haba and Abdullah, 1989). Although the Balambo Formation has an average TOC of only 0.9%, which is lower than that of underlying Jurassic source rocks, its thickness (100-700 m) is considerably greater and it is therefore considered to be "a major source of oil in the Kirkuk Embayment" (Jassim and Al-Gailani, 2006).

The areal extent of Tithonian – Lower Cretaceous source rocks is poorly understood. Their western limit is probably controlled by the location of inherited topography on the east-facing Upper Jurassic platform margin.

The Sulaiy Formation is up to 300 m thick, decreasing to less than 50 m in central Iraq (Jassim and Buday, 2006e). Al-Sakini (1992) considered that the formation is an important source of oil in Cretaceous reservoirs. In Kuwait, source intervals in the Sulaiy Formation have probably contributed to the oil charge supplied to overlying Cretaceous reservoirs (Abdullah and Kinghorn, 1996).

Al-Ameri *et al.* (1999) described the source rock potential of the Sulaiy Formation of late Tithonian – Berriasian age, analysing samples from wells *Dibdibba-1, Jerishan-1, Luhais-2, Noor-1, Rachi-2, Ratawi-6* and *Rumaila-167.* TOC was 0.5-1.0% but the organic matter was oil-prone with a pyrolysis yield of 200 – 500 mgHC/gTOC, equivalent to a yield of 1-5 kg/tonne. They recognised three palynofacies with varying proportions of amorphous organic matter, palynomorphs and phytoclasts. Palynofacies 1 and 2 had no significant source potential. Palynofacies 3 contained 90-100% amorphous organic matter with up to 10% of bacterially degraded palynomorphs and phytoclasts. It occurred in argillaceous or pyritic limestones which were 180 – 200 m thick in the wells studied. The amount of hydrocarbons generated from these lean source rocks would be equivalent to a more organic-rich but thinner source rock with a yield of 10 – 50 kg/tonne and a thickness of 18–20 m. Oil-to-source correlation studies are required to determine if the Sulaiy Formation is the source of the oils trapped in the Yamama and Zubair Formation reservoirs.

Rich source rocks have recently been identified in the basal Sulaiy Formation in *Rumaila* field. Core and cuttings samples from a 28 m thick interval in well *Rumaila-167* at 4482 – 4510 m had a TOC content of 3.26 – 7.33 wt% (mean 4.43%) and a pyrolysis yield of 2.01–4.61 kg/tonne (Al-Ameri

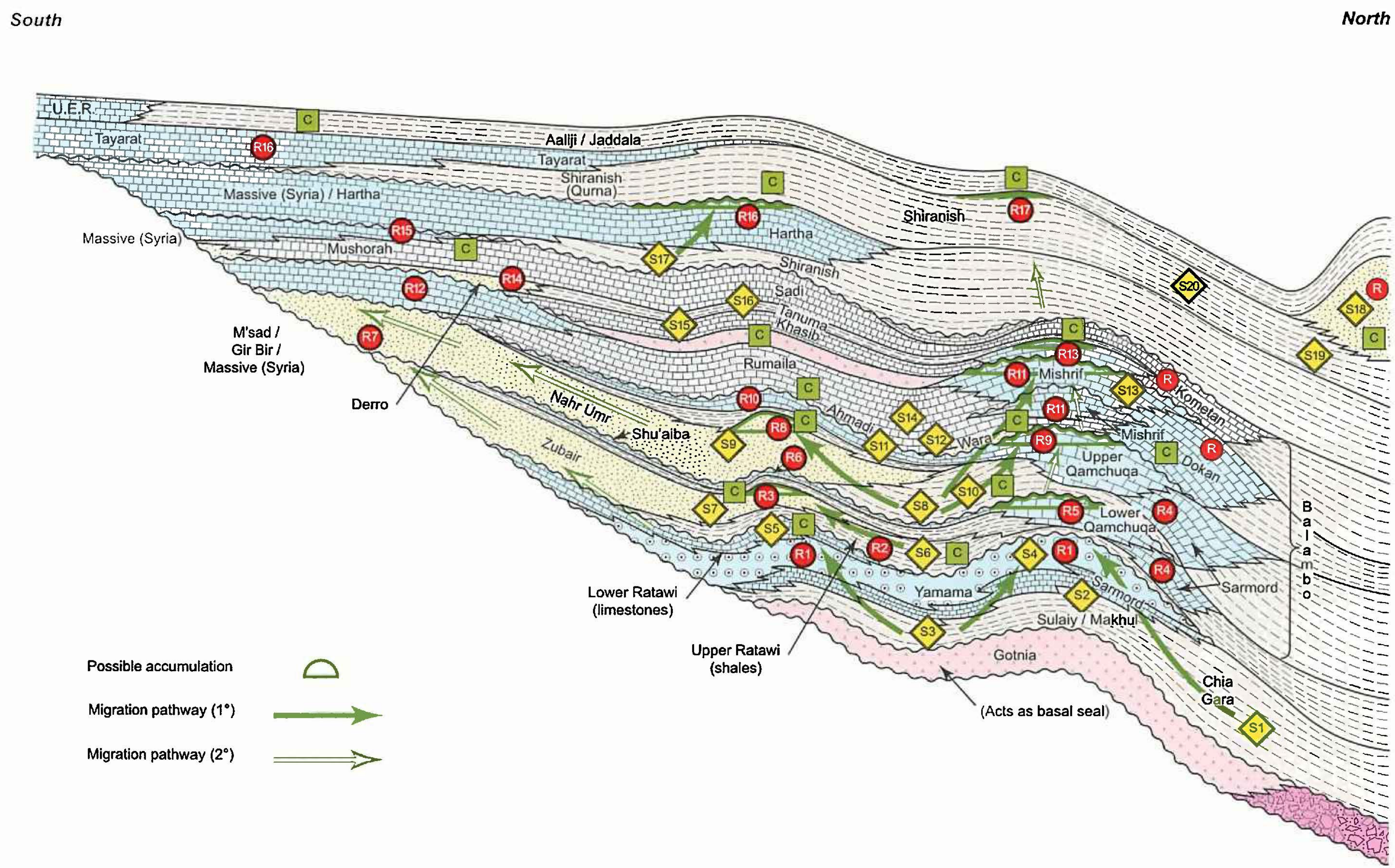


Fig. 9.5.1a. Schematic cross-section through the Cretaceous petroleum system in Iraq showing the spatial distribution of source, reservoir and seal units. The most important source rocks are probably in Supersequences I (S1 and S2) and II (S10). Very limited data has been published on Cretaceous source rocks in Iraq.

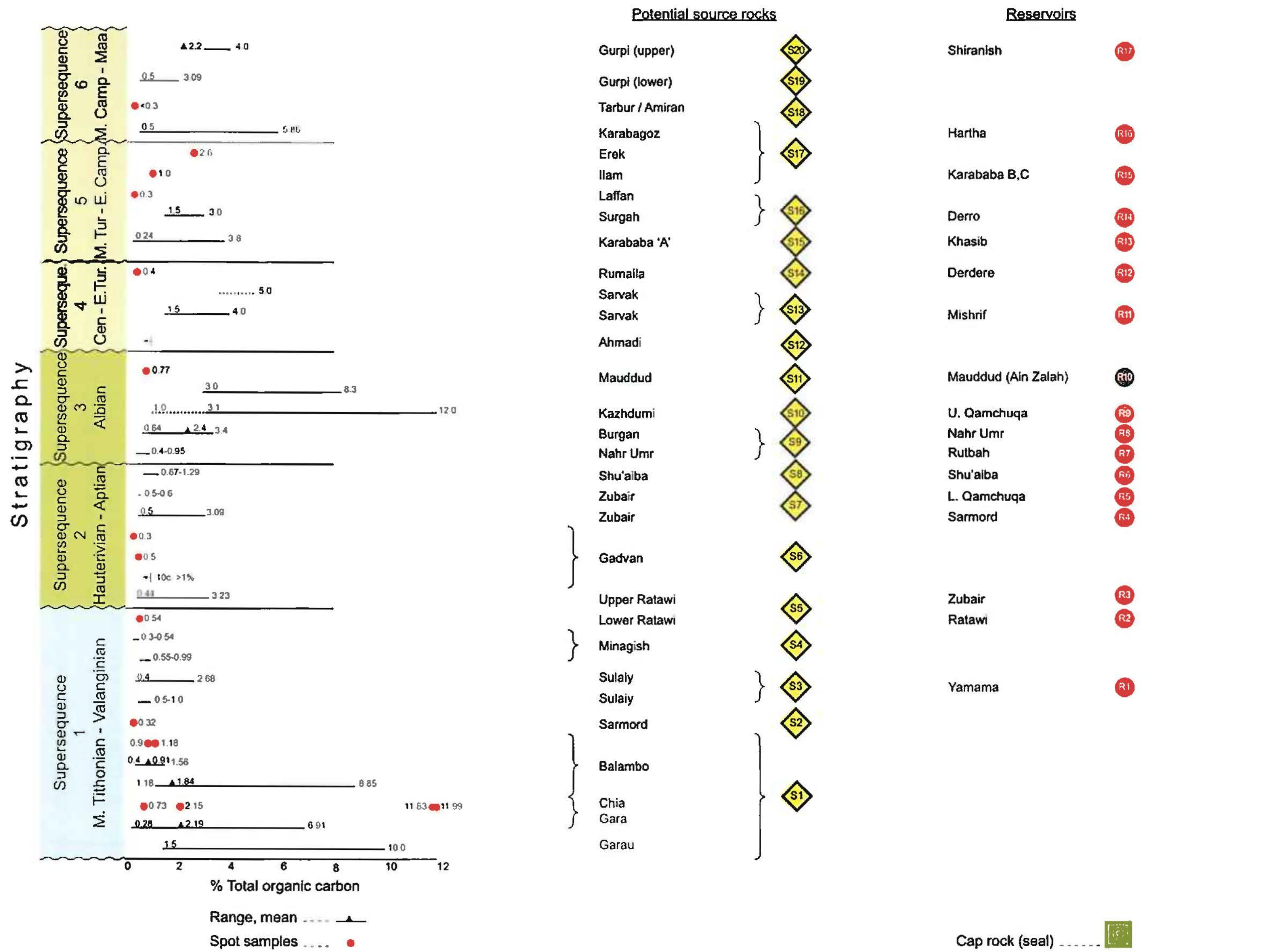


Fig. 9.5.1.b. Legend to symbols used in Fig. 9.5.1a and compilation of available numerical data for potential source rocks in the Cretaceous petroleum system from Iraq and adjacent countries (SE Turkey, Syria, Kuwait and Iran). Many of these potential source rocks have not yet been proved to occur in Iraq. Reservoir rock properties are discussed in the text.

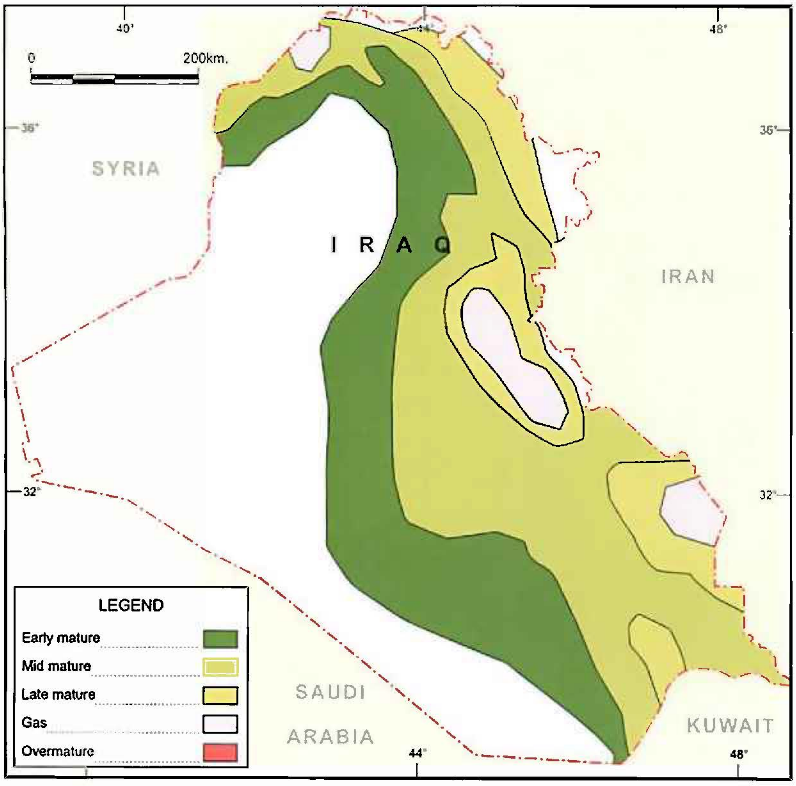


Fig. 9.5.2. Present-day maturity of Early Cretaceous source rocks in Iraq. After Jassim and Al-Gailani, 2006.

et al., 2009b). The Hydrogen Indices (41 – 130 mg/gTOC) and T_{max} temperatures (467–475 °C) indicate that the source rocks are now overmature for oil generation. High TOC values were also recorded from samples at 4375 and 4456 m (2.05 – 5.95%). The original petroleum yield of the Tithonian part of the Sulaiy Formation was probably about 30 kg/tonne. Samples from the upper part of the Sulaiy Formation (of probable earliest Cretaceous age) (4220 – 4322 m) had very low TOC contents (0.1 – 0.16%), indicating that they are not an effective source rock.

Bordenave and Burwood (1990) and Bordenave and Huc (1995) identified three source rock systems in Iran: the Garau, Kazhdumi and Gurpi Formations, which are equivalent to the Balambo/ Chia Gara, Nahr Umr and Shiranish Formations in Iraq, respectively. The basal intervals of the Garau Formation have the highest TOCs (up to 10%); overlying (Neocomian) intervals have TOCs of <1% (Fig. 7.15). This data suggests that a Garau-equivalent source-rock system may extend across central and SE Iraq.

Potential source rocks in the successions overlying Cretaceous Supersequence I in Iraq are less frequent and are of poorer quality. The Nahr Umr Formation, which is equivalent to the Kazhdumi Formation of Iran, may have good source rock potential in SE and east Iraq, near the Dezful Embayment of SW Iran. At *East Baghdad*, shales in the Zubair Formation (Supersequence II) have a TOC of 0.5-6.0% (Al-Ameri and Batten, 1997). The Nahr Umr Formation (Supersequence III) has a TOC of 0.4-0.95% at this location and contains marine algal kerogen (Al-Ameri *et al.*, 2001).

In Kuwait, organic matter in the Ratawi, Zubair and Burgan Formations is dominated by Type III kerogen due to an input of terrestrial material. The organic-rich part of the age-equivalent Kazhdumi Formation in Iran may extend into SE Iraq (Bordenave and Huc, 1995, their Fig.13). The development of a Kazhdumi-type source facies in the Batiwah/ Jawan Formation of northern Iraq bounded to the SW by deltaic sandstones and to the NE by platform-margin carbonates is also possible.

Marly limestones of the Rumaila, Mishrif and Mauddud Formations have little proven source potential. The Ahmadi Formation may have good source rock potential in basinal settings. No source rock data for the overlying Sa'di, Tanuma, Khasib and Kometan Formations in Iraq has been published. However, in the *Ain Zalah* field, lower Senonian — lower Campanian sediments comprise shales, cherts and limestones with a restriced fauna, and "*may be regarded as a possible source for the Second Pay oil*" (Dunnington, 1958).

Cretaceous source rocks occur elsewhere in the Arabian Plate including the Shilaif Basin in the southern Gulf (Alsharhan and Nairn, 1988). In the Euphrates Graben of eastern Syria, the Santonian — lower Campanian Rmah Chert and Erek Marl Formations include prolific source rock intervals (de Ruiter *et al.*, 1995) with average TOCs of 2.6% (Serryea, 1990). Similar source rocks may occur in the Sinjar Trough of northern Iraq in the Mushorah Formation (a facies equivalent of the Rmah Chert) but no relevant geochemical data has been published. El Zarka (1993) suggested that the Mushorah Formation, and shales in the Qamchuqa Formation, have charged the Cretaceous reservoir

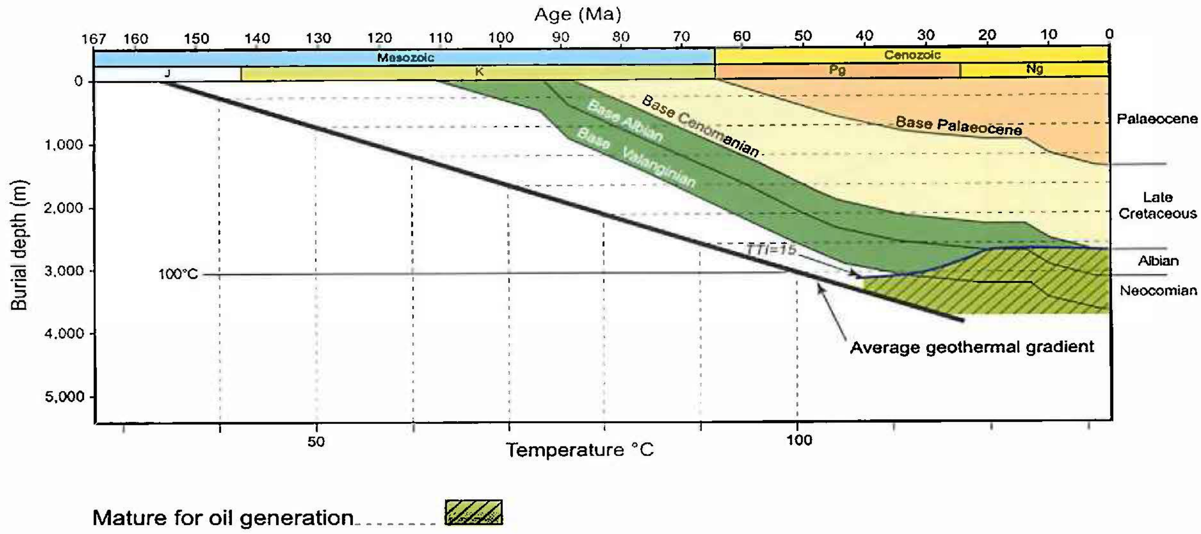


Fig. 9.5.3. Burial history and geothermal gradient for well *Tuba-1*, near Basra. **After Ibrahim, 1983.**

rocks at *Ain Zalah*. In addition, source rock intervals in the Karababa-A and Karabagoz Formations in SE Turkey (Soylu *et al.*, 2005) may extend along strike into NW Iraq. Dunnington (1958) discussed the possibility that the Shiranish Formation is a source rock in the *Ain Zalah* field, as previously proposed by Daniel (1954).

Maturity

Al-Haba and Abdullah (1989) analysed uppermost Jurassic to Neocomian source rocks (from Cretaceous Supersequence 1) in NE Iraq. They found that in well *Kirkuk-109*, the Chia Gara Formation is within the oil window at depths of 2700 to 3000 m (Fig. 9.5.2) with a mean PI of 0.26. Al-Shdidi *et al.* (1995) recorded that potential source rocks in the Chia Gara, Lower Sarmord, Garagu and Middle Sarmord Formations are currently in the oil window in the *Kirkuk* area. At well *Pulkhana-5*, the Balambo Formation is within the oil window from 2550-3650 m (Al-Haba and Abdullah, 1989; Sadooni, 2004). The formation is also mature in well *Jambur-18* (Sadooni, 2004). Further south, the Chia Gara and Sulaiy Formations are interpreted to have generated the oil at *East Baghdad* (Al-Ameri *et al.*, 2001). The Neocomian Chia Gara, Balambo and Sulaiy Formations are mature close to the border with Iran (Ibrahim, 1983), e.g. in well *Tuba-1* (Fig. 9.5.3). By contrast, modelling of wells *Dujaila-1* (Fig. 9.5.4), *Safawi-1* (Fig. 9.5.5) and *Ghalaisan-1* in SW Iraq showed that the Sulaiy Formation is immature (Ibrahim, 1983). Near Basra, source rocks are mature for the generation of medium gravity oil (Fig. 9.5.2). Equivalent Garau Formation source rocks are mature in Lurestan (Bordenave and Huc, 1995).

In the Salman Zone, the base of the Ratawi Formation has just entered the oil window. It is in the oil window in the Zubair and Euphrates sub-blocks, and in the wet gas zone in the Tigris sub-block of southern Mesopotamia (Jassim and Al-Gailani, 2006) (Fig. 9.5.2). Vitrinite reflectance (R_o) of 0.6 has been recorded in the upper member of the Ratawi Formation in the nearby *Raudhatain* and *Ash Shahan* fields (Kuwait) (Abdullah and Kinghorn, 1996). Overlying source rock units are therefore immature (Abdullah and Kinghorn, 1996). The equivalent Gadvan Formation in Iran also has limited source potential due to its low initial organic richness, limited extent and unfavourable burial history (Bordenave and Huc, 1995).

Ibrahim (1983) studied the maturation of Lower Cretaceous source rocks in SE Iraq. Throughout southern Iraq, Albian source rocks (Fig. 9.5.6a) are less mature than the deeper Neocomian (Fig. 9.5.6b) and Tithonian units. The Mauddud, Ahmadi, Mishrif, Khasib and Sa'di Formations can be considered as a single petroleum sub-system, although the Mishrif Formation is the dominant reservoir. Oils in these reservoirs are of medium gravity (20–26° API). They are interpreted to have been expelled from carbonate source rocks that have reached only a moderate maturation level probably corresponding to maximum palaeo temperatures of 100–130°C which were reached during the Miocene. The most likely source rocks are in the argillaceous limestones of the Albian Nahr Umr Formation, a lateral equivalent of the Kazhdumi Formation. The Kazhdumi is similarly mature for oil generation in the Dezful Embayment of Iran, and has expelled very large volumes of oil into the overlying Bangestan Group carbonate reservoirs (Bordenave and Burwood, 1990).

Source rocks at the base of the Nahr Umr Formation, modelled by Ibrahim (1983) in SE Iraq, reached a maximum palaeo temperature of 130°C. Albian source rocks are immature in the *Kifl-1* area, where oils in the Nahr Umr Formation are probably derived from deeper sources or from lateral

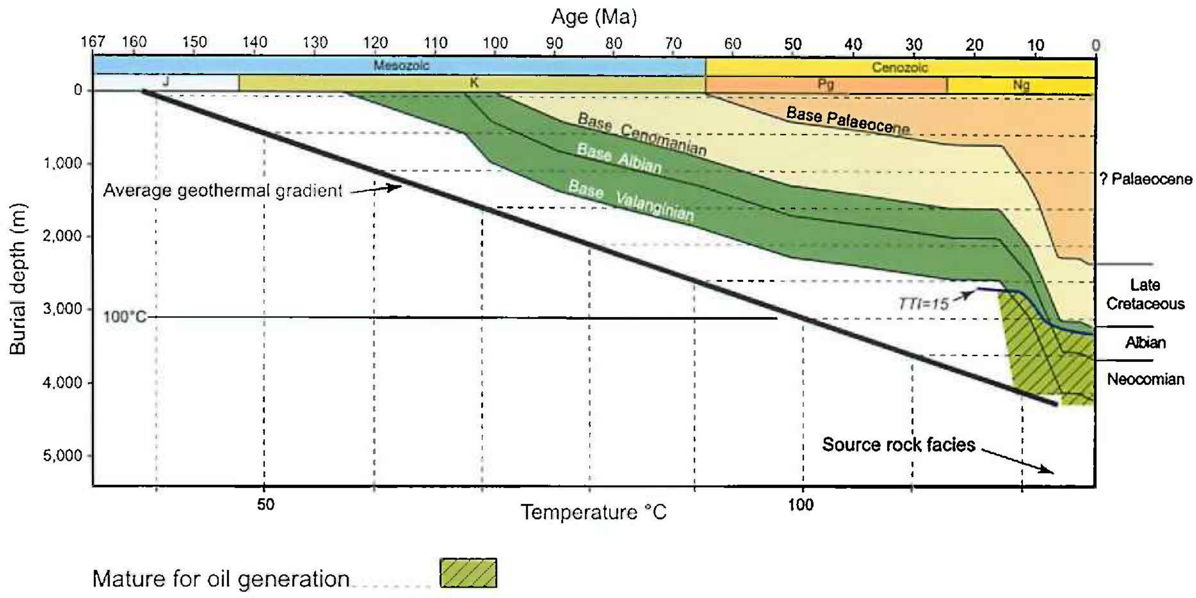


Fig. 9.5.4. Burial history and geothermal gradient for well *Dujaila-1,* SE Iraq, where Cretaceous source rocks have only relatively recently become mature. After Ibrahim, 1983.

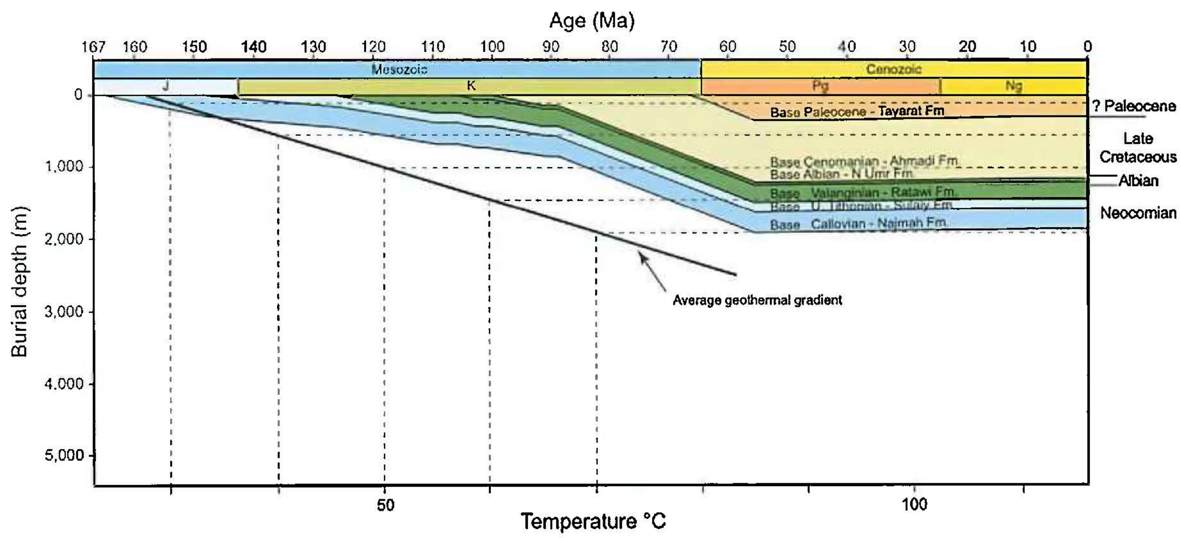


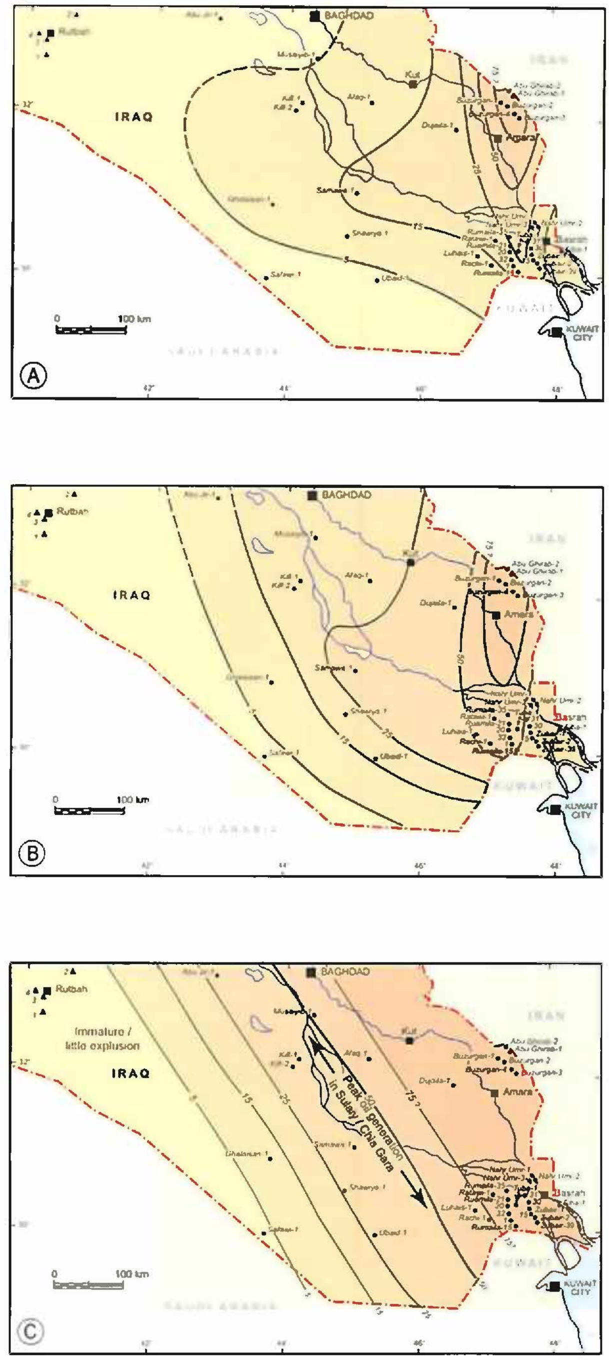
Fig. 9.5.5. Burial history and geothermal gradient for well *Safawi-1* in the SW Desert where the Cretaceous succession remains thermally immature. After Ibrahim, 1983.

migration. Ibrahim (1983) suggested that further east in well *Dujaila-1,* the heavy oils in the Nahr Umr Formation are early mature products.

Within the Upper Cretaceous succession (Cretaceous Supersequences III to VI), intervals overlying the Ahmadi Formation are immature throughout Kuwait (Abdullah and Kinghorn, 1996) and probably in most of Iraq. Both Al-Haba (1983) and Al-Sakini (1992) reported that the Upper Cretaceous succession in the *East Baghdad* area is immature. However Al-Haba (*pers. com.* to J.C.G., 1988) noted that very heavy oils in *East Baghdad* have unaltered *n*-alkane distributions and could thus be an early expulsion product from a low maturity Cretaceous source rock. Maturities of Cretaceous source rocks will be highest in deep Upper Cretaceous grabens and beneath the axis of the Tertiary Mesopotamian Basin (Fig. 9.5.7). (Sadooni and Aqrawi, 2000; Jassim and Buday, 2006f).

In eastern Syria, Albian strata are locally buried to 5 km (Caron *et al.*, 2000). Source rock intervals in the Rmah Formation have a vitrinite reflectance (R_o) of 0.6-1.0% in the deepest parts of the Euphrates Graben (de Ruiter *et al.*, 1995). Jassim and Gailani (2006f) mapped the maturity of age-equivalent Upper Cretaceous units in Iraq, including the Shiranish Formation, together with potential source rocks in the Jib'ab Marl and Digma Phosphate Members. They showed that these units would be early-mature for oil generation in the Anah and Tayarat Grabens and mature in the Sinjar Graben (Fig. 9.5.7). Underlying Cretaceous and Jurassic source rocks may be absent from these grabens due

Fig. 9.5.6. Iso-TTI contour maps of southern Iraq for (a) the base of the Nahr Umr Formation; (b) the base of the Ratawi Formation; (c) the base of the Sulaiy-Chia Gara Formation. After Ibrahim, 1983.



to non-deposition or erosion. However, at the *Ghouna-1* and *Tel Hajar-1* wells in the Iraq-Syria border area near Jebel Sinjar, the Middle Jurassic Sargelu Formation has been recorded in erosional remnants (Dunnington *et al.*, 1959; Kaddouri and Al-Shaibani, 1993), and may have provided some additional source rock potential.

Timing of oil generation and expulsion

The onset of oil generation from uppermost Jurassic — Lower Cretaceous source rocks probably occurred in the latest Cretaceous in the Mesopotamian Basin, and in the Paleocene — Eocene in the Zagros fold-thrust belt, i.e. slightly later than in the Middle and Upper Jurassic source rocks modelled by Pitman *et al.* (2004). Oil generation from Upper Cretaceous source rocks in the Anah and Sinjar Grabens probably took place more recently, given the more recent burial (Jassim and Al-Gailani, 2006) (Fig. 9.5.7).

Al-Ameri *et al.* (2009b) modelled the timing of oil generation from the Sulaiy Formation at the *Zubair-47* well location and concluded that oil generation began in latest Cretaceous time, with peak oil generation occurring in the Tertiary. The advanced maturity of the Sulaiy Formation source rocks in the *Rumaila/Zubair* area is consistent with them charging the Yamama and Zubair Formations in SE Iraq which contain mature light oils. Ibrahim (1983) modelled source rock maturation in well

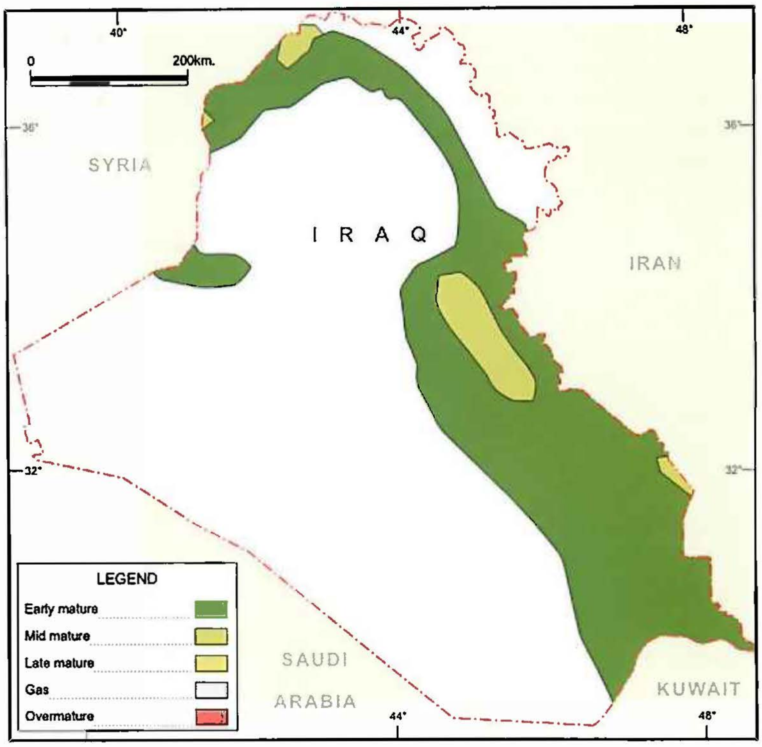


Fig. 9.5.7. Present-day maturity of Late Cretaceous source rocks in Iraq. Note presence of a small possible "kitchen" in the Anah area. After Jassim and Al-Gailani, 2006.

Tuba-1: Neocomian source rocks may have begun to generate oil in the late Paleocene — early Eocene; while Albian source rocks entered the oil window in the Oligocene (Fig. 9.5.3). He suggested that oil migration in the NE part of the Mesopotamian Basin began in the Miocene. At Aqra in northern Iraqi Kurdistan, the basal Kolosh Formation contains bitumen-filled, reworked Maastrichtian-Campanian foraminifera; indigenous Paleogene microfossils contain no bitumen (Dunnington *et al.*, 1959), suggesting that oil migration occurred as early as the Late Cretaceous in this area. Middle Jurassic — lower Cretaceous source rocks would have been buried to depths of approximately 2.5 km by the end of Aqra Limestone deposition, and may therefore be possible sources of this oil. Al-Haba and Abdullah (1989) suggested that the lower part of the Balambo Formation entered the oil window at 15 Ma in the Kirkuk Embayment and that it is currently at peak maturity for generation.

In SE Turkey and NE Syria (and possibly NW Iraq), generation and migration from upper Cretaceous source rocks probably occurred in the middle to late Tertiary (Beydoun, 1991). Soylu *et al.* (2005) found that source rocks in the lower Senonian Karababa Formation A Member in SE Turkey generate oil at relatively low maturities. This is due to the high sulphur content of component organic matter, causing oil generation to occur at relatively low temperatures.

Reservoir rocks

Lower Cretaceous reservoir rocks contain about 30% of Iraq's hydrocarbon reserves, mostly in the Zubair Formation. In the Upper Cretaceous succession, the Mishrif Formation alone contains a further 25-30% (Al-Sakini, 1992). About 10% of reserves occur in the Upper Cretaceous Khasib, Tanuma and Sa'di Formations, with a further 6% in the Shiranish, Hartha and Tayarat Formations (Al-Sakini, 1992).

The four most significant reservoir units are the Yamama, Zubair, Mishrif and Khasib Formations and these are briefly described in the following paragraphs.

Carbonates in the Neocomian **Yamama Formation** are reported to contain hydrocarbons at 26 structures in southern Iraq including the *West Qurna, North Rumaila* and *Majnoon* fields (Jassim and Al-Gailani, 2006) (page 170). Sadooni (1993b) identified three reservoir intervals in the Yamama Formation (YR-A, -B and -C: Fig. 7.9), equivalent to the three divisions in the Minagish Formation of Kuwait (Abdullah and Kinghorn, 1996; Al-Fares *et al.*, 1998; Sharland *et al.*, 2001). Porosity is dominated by intergranular macroporosity and some intragranular to chalky matrix microporosity, with local secondary (dissolution) porosity. Such microporosity systems often have high water saturations if water-wet, or are bitumen-plugged if oil-wet. At the *Rumaila – West Qurna* structure, the reservoir potential of the Yamama Formation increases from south to north, probably due to progradational thickening and stacking of shoal facies in this direction. Flow rates are very variable; a maximum test flow rate of 19,000 b/d was recorded in well *Ratawi-3*. Only weak flow was recorded in well *Jerishan-1* (Sadooni, 1993b).

The most important sandstone reservoir in southern Iraq is the **Zubair Formation** (page 181), recorded as oil-bearing in 30 structures including

Rumaila North and *South* and *Zubair* (the so-called 3rd and 4th Pays) (Al-Naqib, 1967; Jassim and Al-Gailani, 2006), as well as *East Baghdad* in Central Iraq. The Zubair forms a secondary reservoir at *Ratawi, Tuba* and *Luhais*, and contains smaller reserves at *Majnoon, Halfaiya* and *Huwaiza* (Jassim and Al-Gailani, 2006).

The NE limit of the Zubair fairway is defined by a facies change from delta-front or chenier sandstones to shelfal mudstones. The *East Baghdad* and *Balad* fields and the *Mileh Tharthar-1* well lie just within the limit of the sandstone facies (Ali and Aziz, 1993; Al-Ameri and Batten, 1997). Net-to-gross in the Zubair Formation is around zero near the Iranian border; a thickness of over 200 m of sandstone is present in the *Zubair* field and the Karbala area of central Iraq. Porosities likewise increase from an average of 15% near the border with Iran to around 30% in wells in the Salman Zone such as *Kifl-1* (Al-Naqib, 1967; Jassim and Goff, 2006a).

The **Mishrif Formation** (page 200) is the most important carbonate reservoir in SE Iraq (Aqrawi *et al.*, 1998) and contains oil at 32 structures (Jassim and Al-Gailani, 2006). The largest accumulations are in the *Rumaila North, Rumaila South, West Qurna, Zubair, Majnoon* and *Halfaiya* fields, located on large-scale north-south trending anticlines. At least 15 other commercial oil accumulations in the Mishrif Formation have been discovered in SE Iraq: *Abu Ghirab, Ahdab, Amara, Buzurgan, Dujaila, Jebel Fauqi, Gharaf, Huwaiza, Kumait, Nahr Umr, Noor, Rafadian, Rafadian E, Ratawi* and *Tuba* (for details, see Appendix 2 of Jassim and Al-Gailani, 2006).

Gaddo (1971) reported mean porosities of 9% at *Zubair* and 16% at *Rumaila*. Porosities of up to 36% and permeabilities of up to 1560 mD occur in rudist-rich carbonates. Reservoir thicknesses of several hundred metres and a high net:gross (often >90%) are also recorded. Sadooni (2005) noted that the most productive Mishrif facies are peri-reefal bioclastic carbonates; rudist-rich rudstones are frequently well-cemented as at *Buzurgan*. The pore system is dominated by vuggy macro- to mesoporosity which is often biomouldic and associated with recrystallisation and dolomitistation. Fuloria (1976, *in* Sadooni, 2005) noted that reservoir quality tends to decrease in downflank wells; this may be due to structural control on reservoir facies or diagenetic factors.

The Mishrif Formation play occupies a relatively narrow belt running NW-SE across central and SE Iraq. Reservoir quality decreases towards the Najaf Intrashelf Basin to the SW (Gaddo, 1971). The reservoir is massive in the centre of the Mishrif isopach maximum in SE Iraq along the border with Iran (Aqrawi *et al.*, 1998). Towards the flanks, internal vertical permeability barriers (probably correlative with the K140 MFS of Sharland *et al.*, 2001 and other minor MFSs) become significant and the reservoir can be divided into separate pay zones. Gaddo (1971) identified two such pay zones ("Mi-A" and "-C") separated by the tight "Mi-B" zone.

The Mishrif Formation is less prospective in the strike-slip fault zone between *Samarra, East Baghdad* and *Badra*. Here, the overlying Khasib Formation is porous with reservoir potential (Sadooni, 2004) and does not act as a seal. In fields near the fault zone, the Mishrif may partly be charged by oil from Jurassic (sub-Gotnia Formation) source rocks. Stratigraphic traps may occur within the Mishrif Formation, particularly along the shelf margin (Sadooni, 2005; Aqrawi and Horbury, 2008).

About 90% of oil in the middle Turonian — lower Campanian Supersequence V is located in the **Khasib Formation** (page 215) mostly in the *East Baghdad* and *Balad* fields (Aqrawi, 1996) which are reported to contain 9 B brls of oil (Al-Sakini, 1992). The Khasib Formation also contains significant volumes of oil at the *Nahr Umr* and *West Qurna* fields in southern Iraq, in the *Ahdab, Dhafriia* and *Dujaila* fields in central Iraq (Al-Sakini, 1992), and at *Samarra* and *Tikrit* (Aljawadi, 1990). Reservoir quality data is summarized in page 219).

At *East Baghdad*, the formation comprises chalky carbonates deposited in relatively shallow water. The carbonates are thicker here (100 m versus 50 m) than at the type section (*Zubair-3*, near Basra) (Owen and Nasr, 1958).

The Khasib reservoir has both fracture- and microporosity. Porosities and matrix permeabilities at *East Baghdad* are up to 23% and 5 mD. Thin, relatively porous intervals are separated by thicker tight zones and net:gross is 15% (Al-Sakini, 1992; Sadooni, 2004). Sadooni (2004) noted that it is not clear whether reservoir quality at *East Baghad* is enhanced compared to the type section due to facies differences or structural factors such as fractures and faults.

Secondary reservoirs

"Secondary" reservoirs with significant production include the Qamchuqa, Shiranish, Hartha and Kometan Formations in northern Iraq, and the Sulaiy, Ratawi, Shu'aiba, Mauddud, Rumaila, Sa'di-Tanuma, Hartha and Tayarat Formations in southern Iraq (Jassim and Al-Gailani, 2006).

The heterolithic **Ratawi Formation** locally has reservoir potential where it is composed of shallow-water carbonates on the crests of structures in SE Iraq such as *Rumaila* and *Zubair* (Sadooni, 1993b). Porosity is intergranular and mouldic.

The **Shu'aiba Formation** is a reservoir unit at *Ahdab, Jerishan, Majnoon, Samawa, Zubair* and *North Rumaila* fields in southern Iraq. The equivalent Lower Qamchuqa Formation in northern Iraq is a reservoir at *Kirkuk* (Baba and Khurmala Domes), *Bai Hassan, Khabbaz, Makhul, Qarah Chauq* and *Jambur* (Al-Rawi *et al.*, 1980;

Dunnington, 1967a). Porosity is intergranular and mouldic. The best reservoir properties occur where the formation has been recrystallised and dolomitised (Al-Rawi *et al.*, 1980; Al-Shdidi *et al.*, 1995). Al-Naqib (1967) noted that the Shu'aiba Formation is associated with significant lost circulation during drilling, suggesting high permeabilities. In southern and SE Iraq, the unit may locally be sealed by shales at the base of the Nahr Umr reservoir. Where it is erosively overlain by channel sands of the Nahr Umr Formation, no seal is present between the two formations.

The **Nahr Umr Formation** is a reservoir in 37 structures (Jassim and Al-Gailani, 2006). Two reservoir zones are present (Sadooni and Aqrawi, 2000); reservoir quality is lower than that in the underlying Zubair Formation (Al-Naqib, 1967). The equivalent Burgan Formation in northern Kuwait is composed of well-sorted sandstones with excellent reservoir properties (Al-Eiden *et al.*, 2001): at the *Raudhatain* and *Sabriyah* fields in Kuwait, the Upper Burgan has a net:gross of 0.2-0.9. Sandbodies are up to 24 m thick but are in general less than 1000 m wide and are probably sinuous. Porosities range up to 24.5% and permeability is up to >1500 mD. Kv/Kh varies from 0.7 in massive sandstones to 0.1 in more thinly-bedded facies. Productivity is highest in crestal wells, declining in flank wells due to poorer reservoir quality. The lower part of the Burgan Formation in Kuwait is generally well layered, while channel sands with better vertical connectivity increase up into the Upper Burgan. Porosities in the Nahr Umr/Burgan Formation in the *Soroosh* and *Nowrooz* fields, offshore Iran, are 23-29% with permeabilities of 2-11 Darcy. Net pay is 40-73 m (Denby *et al.*, 2001).

The **Maududd / Upper Qamchuqa Formation** carbonates form a reservoir in 19 structures (Jassim and Al-Gailani, 2006). The carbonates contain heavy oil at *Ratawi* (Sadooni and Alsharhan, 2003) and oil has been tested in several other fields in NE Iraq (e.g. *Kirkuk, Bai Hassan* and *Jambur*) (Jassim and Al-Gailani, 2006). Porosity is intergranular and mouldic; and reservoir qualities are highest where dolomitization has occurred as at *Jambur* (Al-Rawi *et al.*, 1980) and *Kabbaz* (Sadooni and Alsharhan, 2003). Porosity is <15% and permeability is generally <10 mD (Jassim and Al-Gailani, 2006). Sadooni and Alsharhan (2003) recorded that at *Khabbaz*, permeabilities in planar-e dolomites increase above a porosity cut-off of 15%, and that non planar-e dolomites show highest permeabilities at the mid-range of porosities. This may be due to fracturing of mid-range porosity samples and development of isolated vuggy pores in high-porosity samples. At *Ain Zalah*, Elzarka (1993) recorded low matrix porosities (1.3%; but up to 20% in thin intervals) and matrix permeabilities of 1 mD; however, production rates of up to 8000 b/d were achieved because of fracturing.

The **Gir Bir Formation** in northern Iraq is locally preserved in Late Cretaceous half-grabens; it was largely eroded from palaeohighs during the Turonian – Campanian (Dunnington *et al.*, 1959). These grabens were inverted during end-Cretaceous shortening, and the Gir Bir Formation forms a secondary reservoir in the resulting anticlines (e.g. *Ain Zalah:* Hart and Hay, 1974). Reservoir quality is enhanced due to karstification and recrystallisation (Gaddo; 1971; A.H. and F.S., *pers. obs.* at *Sufaiya* field, 1988).

The **Ahmadi Formation** contains oil in the *Majnoon* field (Jassim and Al-Gailani, 2006).

The **Tanuma Formation** is reported to be an oil reservoir at *East Baghdad* (Aqrawi, 1996), *Balad* and *Ahdab* (Al-Sakini, 1992), and *Samarra* and *Tikrit* (Aljawadi, 1990). The formation contains oil shows in the *Nahr Umr* and *West Qurna* fields in southern Iraq (Al-Sakini, 1992). Reservoirs have high matrix porosities but generally low permeabilities because of their chalky composition; permeabilities are locally enhanced by fracturing. Higher matrix porosities may occur within oolites in the middle of the formation (Owen and Nasr, 1958; Dunnington *et al.*, 1959).

Reservoirs in the **Sa'adi Formation** have high matrix porosities but low permeabilities due to their chalky composition. High matrix porosities may occur in bioclastic limestones ("*Pseudedomia*" Limestone) near the top of the formation, which is only recorded from palaeo-lows having been eroded from anticlinal crests in southern Iraq (Dunnington *et al.*, 1959).

In northern Iraq, oil occurs in the **"Pilsener Limestone"** at *Qasab, Jawan, Najmah* and *Qaiyarah* (Dunnington, 1958). The term "Pilsener Limestone" covers a heterogeneous and extensive (Cenomanian-Maastrichtian) suite of rocks which in southern Iraq has been divided into the Tayarat, Hartha, Sa'adi, Tanuma and Khasib Formations (and perhaps parts of the Mishrif and Shiranish Formations). In adjacent parts of Turkey and Syria, there is production from analogous Upper Cretaceous platform carbonates (the Mardin and Massive Limestones) at *Karatchok, Rumelan, Soueide, Selmo, Celikli, Magrip, Kurtalan, Garzan, West Raman* and *Raman* (Dunnington, 1967b).

The **Hartha Formation** is a reservoir at 30 structures (Jassim and Al-Gailani, 2006) including *Qasab, Qaiyarah, Jawan* and *Najmah* in NW Iraq (Sadooni, 1995). The formation contains oil at *Ahdab* and in the northern part of *East Baghdad* where it has been dolomitised (Sadooni, 1996). Net pay is 30 m in *East Baghdad* and *Ahdab* (Sadooni, 1996) and up to 45 m elsewhere (Jassim and Al-Gailani, 2006). Sadooni (1996) noted that the uppermost units of the Hartha Formation (members H2 – H5) have been karstified and contain meteoric cement. Porosity types include intergranular pores in foraminiferal pack-grainstones, dissolution (mouldic) porosity after rudists and foraminifera, chalky microporosity in finer-grained facies, and fracture porosity associated with the development of flower structures along the *East Baghdad* trend (Sadooni, 1996).

The **Shiranish Formation** forms a reservoir where it is fractured, for example in anticlinal structures at *Ain Zalah, Butmah, Bai Hassan* and parts of *Kirkuk* (Daniel, 1954; Dunnington, 1967; Hart and Hay, 1974; El Zarka, 1993) and *Sufaiyah* (Jassim an Al-Gailani, 2006). The Shiranish reservoir at *Ain Zalah* has produced oil at rates of 30,000 b/d (Daniel, 1954; Hart and Hay, 1974). The Shiranish is most productive in parts of the structure affected by erosion and recrystallisation during end-Maastrichtian uplift. The matrix is water-saturated and production is restricted to fracture networks (Daniel, 1954; El Zarka, 1993).

Minor reservoirs

The **Garagu Formation**, a lateral and facies-equivalent of the Yamama Formation, is reported to contain oil in the *Bai Hassan* and *Jambur* fields, northern Iraq (Dunnington, 1967a; Al-Rawi *et al.*, 1980).

The **Rutbah Sandstone Formation**, an important reservoir in the Euphrates Graben of Syria (de Ruiter *et al.*, 1995), may extend into western Iraq.

Conglomerates in the **Tel Hajar Formation** are bituminous at *Tel Hajar-1* (Kaddouri, 1982a), where oil-stained pores are present in bored pebbles and in the sandy matrix (A. H. *pers. obs.*, 1988).

In the *Kirkuk* field, the fractured **Kometan Formation** is reported to produce oil in the Avanah and Baba Domes (Dunnington, 1967a).

In the Euphrates Graben, syn-rift continental sandstones (**Derro Formation**) of Senonian age are a secondary reservoir in some fields (de Ruiter *et al.*, 1995; Caron *et al.*, 2000), charged by the Erek Marl Formation. Equivalent sandstones may occur in grabens in western Iraq. In the Euphrates Graben, oil occurs in fractured limestones and cherts of the **Rmah Chert Formation** (de Ruiter *et al.*, 1995). An equivalent cherty unit in Iraq is the Mushorah Formation, present for example as part of the Second Pay at *Ain Zalah* field (Hart and Hay, 1974).

The shelfal **Wajnah Formation** forms part of the Second Pay at *Ain Zalah* (Hart and Hay, 1974) and also at *Butmah* field (Dunnington, 1967a).

Seals

Cretaceous petroleum systems in Iraq rely on a balance between the proportion of reservoir facies and sealing facies present. Large areas in stratigraphically updip and downdip locations have limited prospectivity because seals or reservoirs, respectively, are absent. Seal efficiency is thus of critical importance. Thick evaporites in the Gotnia Formation form an effective seal between the Jurassic and Cretaceous petroleum systems in SE Iraq. North of Makhul, the Gotnia–equivalent collapse breccias of the Barsarin Formation are less likely to form a regional seal. Also, the upper contact of the Najmah and Sargelu Formations in northern and NW Iraq is an erosional unconformity allowing migration of Jurassic-sourced oils into the Cretaceous section. Where thick Najmah overlies Sargelu Formation along the Salman Zone, the Gotnia is thin and may not form an effective seal.

The **Yamama Formation** reservoir is sealed by mudstones and marls of the Ratawi Formation which is up to 350 m thick in SE Iraq (Sadooni, 1993b). Mudstones in the upper part of the Ratawi Formation separate normally-pressured sandstone reservoirs of the Zubair and Nahr Umr Formations from the underlying overpressured Yamama Formation carbonates (Al-Mashadani, 1986). Argillaceous limestones in the Yamama Formation (zones YB-1 and YB-2 of Sadooni, 1993b) also form barriers and possibly local seals, although they may have microporosities of about 10% in *West Qurna* field (Sadooni, 1993b).

The three **Zubair Formation** sandstone reservoirs are sealed by intraformational shales (Al-Sakini, 1992) including a shale interval underlying the Shu'aiba Formation (Al-Naqib, 1967). Ibrahim (1983) proposed that the absence of producible oil in the Nahr Umr Formation at the *Zubair* and *Siba* fields was due to the absence of an effective seal in the uppermost Zubair shale. At a regional scale, where the Zubair Formation reservoir is sealed and oil charged, the Nahr Umr reservoir is not and *vice-versa* (Dunnington, 1967).

Nahr Umr Formation sandstone reservoirs in SE Iraq are locally sealed by shales beneath the Mauddud Formation (Al-Naqib, 1967; Ibrahim, 1983). A shale unit (locally containing the Dair Limestone Member: Dunnington *et al.*, 1959) may act as an intraformational seal within the Nahr Umr Formation. Distal equivalents of the Nahr Umr Formation (the Upper Sarmord and Batiwah Formations) may form internal seals for Qamchuqa Formation reservoirs at the *Kirkuk, Bai Hassan, Khabbaz* and *Jambur* fields in NE Iraq (Al-Rawi *et al.*, 1980; Al-Shdidi *et al.*, 1995). Where the **Mauddud Formation** is not properly sealed due to truncation or wedge-out of the overlying Ahmadi Formation, as at *Ratawi*, reservoired oils tend to be heavy (Sadooni and Alsharhan, 2003).

Tight muddy and micritic layers and paralic shales within the **Mishrif Formation** provide local barriers for intra-Mishrif reservoir units (Aqrawi *et al.*, 1998). Kifl evaporites (Al-Naqib, 1967) may locally seal reservoirs in the Najaf Intrashelf Basin to the west.

The **Khasib Formation** forms a regional seal for the Mishrif play (Aqrawi *et al.*, 1998). The

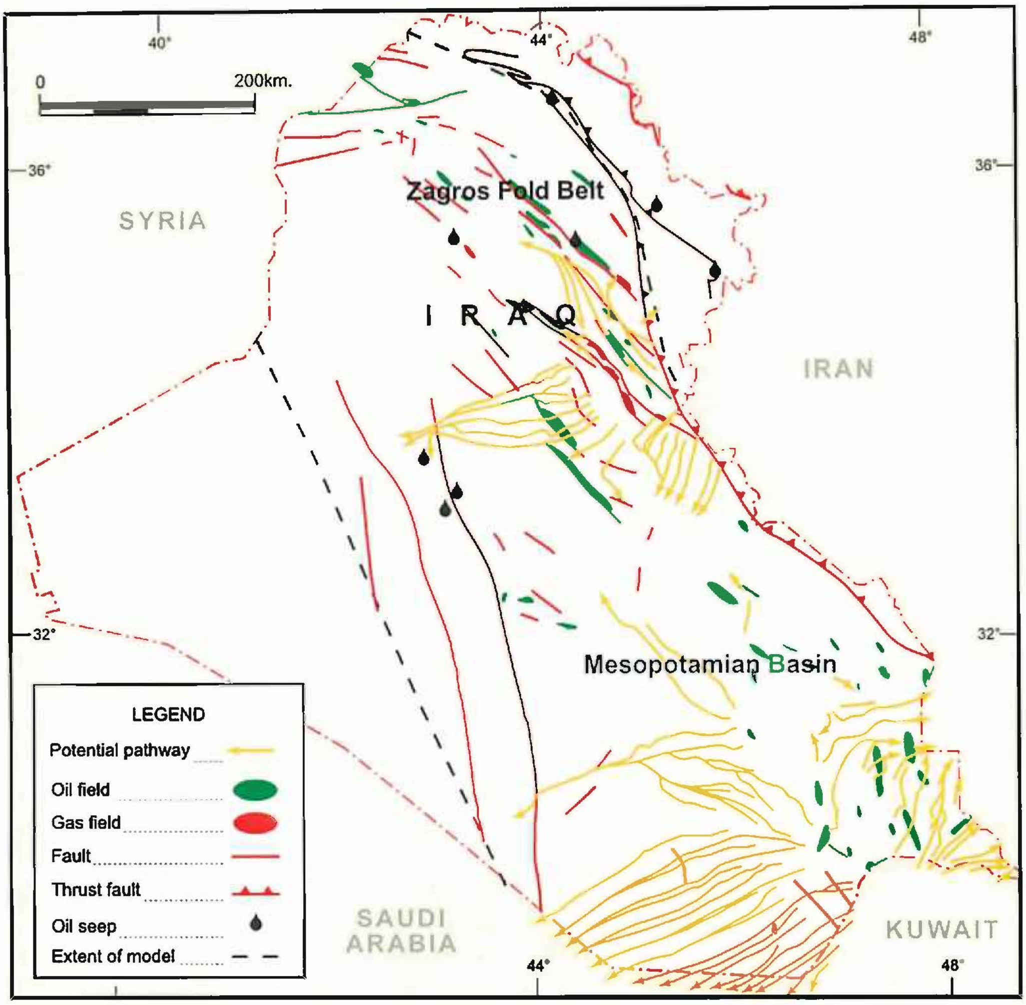


Fig. 9.5.8. Early migration routes (late Oligocene burial) from Mesozoic source kitchens in Iraq. After Pitman *et al.*, 2004, courtesy of *GeoArabia*.

combined Sa'di/Tanuma/Khasib Formations form a major regional seal between the Lower and Upper Cretaceous aquifer systems (Al-Mashadani, 1986). The Khasib and overlying Sa'di Formations are locally oil-bearing in SE Iraq in the *Ahdab*, *Amara*, *Halfaiya*, *Huwaiza*, *Majnoon*, *Nahr Umr* and *West Qurna* fields (Jassim and Al-Gailani, 2006). These formations contain oil with very similar properties to that in the underlying Mishrif Formation, suggesting that oil has locally leaked through the caprock at the base of the Khasib Formation. The Khasib Formation comprises shallow-water facies in a belt between well *Samarra-1* and Iran to the SE of Baghdad, and is here unlikely to act as a seal for the Mishrif Formation.

The **Tanuma Formation** provides a regional seal for reservoir units in the underlying Khasib Formation. The deep-water and locally marly limestones of the lower part of the Sa'di Formation act locally seal both Tanuma and Khasib reservoirs (Aqrawi, 1996; Sadooni and Aqrawi, 2000).

At *Ain Zalah*, the Mushorah and basal Shiranish Formations imperfectly seal the underlying shelf carbonates of the Gir Bir and Qamchuqa Formations (El Zarka, 1993).

Oligosteginal micritic limestones in the **Hartha Formation** form partial intraformational seals in Central Iraq (Sadooni, 1996). Laterally extensive anhydrites of the Safawi Formation in central and SW Iraq (Sadooni, 1996) potentially seal underlying shelfal carbonates.

The **Shiranish Formation**, consisting of mudstones, marls and occasional limestones, seals the Hartha and Tayarat Formations in southern Iraq (Jassim and Al-Gailani, 2006). Its efficiency as a top seal for Albian to lower Turonian reservoir units in northern Iraq (i.e. the Mauddud/Upper Qamchuqa and Gir Bir Formations) is locally reduced by fracturing. Bordenave and Huc (1995) showed that fracturing of the equivalent Gurpi and Pabdeh Formations in Iran has permitted large-scale leakage of oil from the Sarvak reservoirs (correlative with the Qamchuqa-Mishrif) into the overlying Oligo-Miocene Asmari Formation.

The entire Cretaceous Petroleum System is sealed in the basin centre by regionally-extensive marls of the Paleogene Aaliji and Jaddala Formations, which seal the fractured Shiranish Formation reservoir, for example at *Ain Zalah* (El Zarka, 1993).

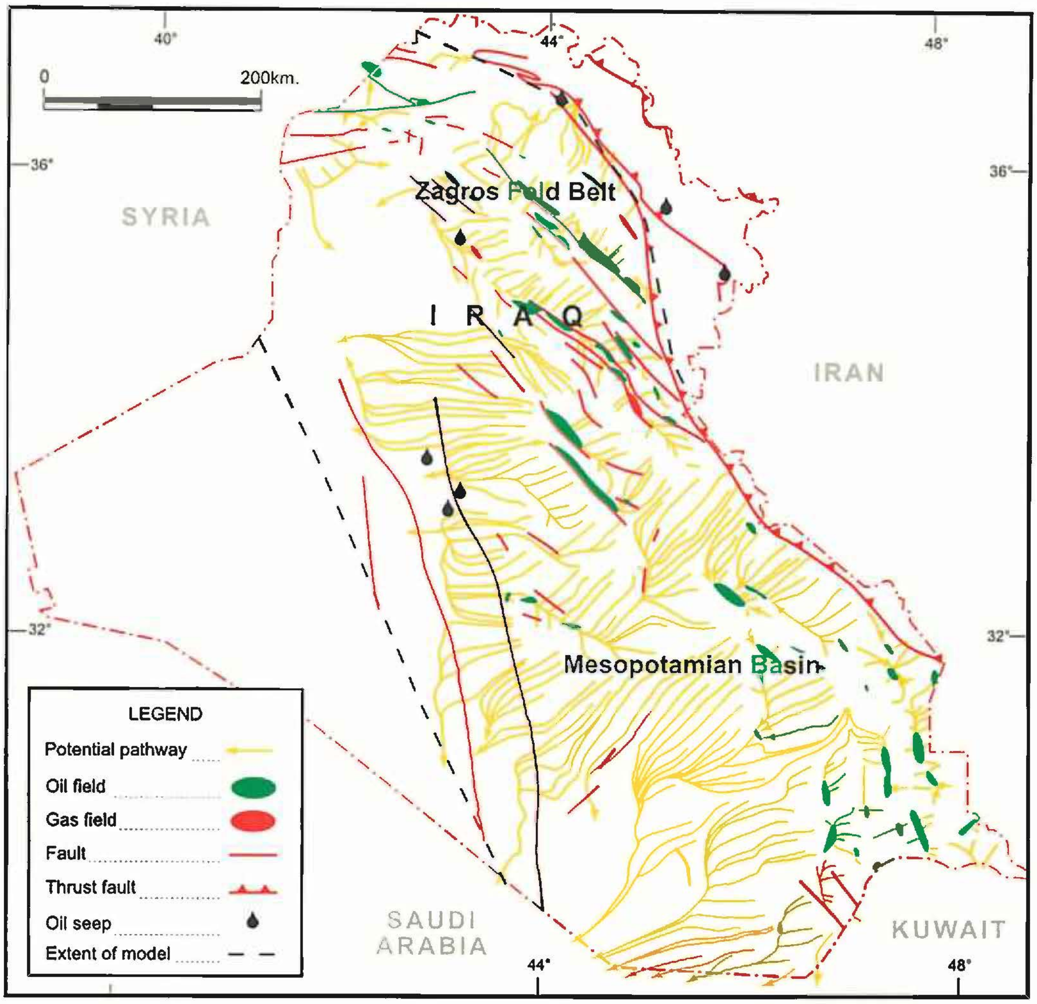


Fig. 9.5.9. Present-day migration routes out of Mesozoic source kitchen in Iraq. After Pitman *et al.*, 2004, courtesy of *GeoArabia*.

Migration of oil and gas

Pitman *et al.* (2004) noted that almost all the Cretaceous and Tertiary oil and gas accumulations in the Mesopotamian Basin and Zagros foldbelt overlie mature Jurassic and Lower Cretaceous source rocks, emphasising the importance of vertical migration. Accumulations are situated on or close to modelled migration pathways, and early-filled traps are located closest to the intrashelf basins in which source rocks matured earliest; they typically began to receive their oil charge in the Late Cretaceous to middle Miocene. Pre-late Miocene migration was from local kitchens (Fig. 9.5.8).

In Late Miocene - Pliocene time, the area of mature source rocks expanded to the west due to rapid burial and heating, and large-scale updip migration of oil occurred (Fig. 9.5.9).

The importance of lateral oil migration within the mid-Cretaceous carrier bed succession was first proposed by Dunnington (1958) who noted that *"oil may have entered (the Middle Cretaceous) .... to reach the Ain Zalah trap after more or less extensive lateral migration in the main reservoir-carrier formation"*. Dunnington (1958) suggested that the oil at *Ain Zalah* was sourced by Lower Cretaceous euxinic shales and limestones to the NE of the field.

Significant volumes of oil were lost to the surface, as indicated by the surface seeps along the Tigris and Euphrates rivers and in the Zagros foldbelt (Fig. 9.5.9).

If Middle-Upper Jurassic and Lower Cretaceous seals were breached due to faulting or fracturing, or were erosively removed at the basin margin, Jurassic-sourced hydrocarbons may migrate up into Cretaceous reservoirs. The Abu Jir fault zone, which passes close to well *Kifl-2* (Ibrahim, 1983; Al-Mashadani, 1986), may represent such a vertical migration pathway.

Charging of Cretaceous reservoirs within the Cretaceous petroleum system can be summarised as follows (Fig. 9.5.1). Source rocks in the Chia Gara/Makhul/Sulaiy Formations charge reservoirs in the Ratawi, Nahr Umr, Mauddud, Mishrif and Sa'di-Tanuma-Khasib Formations in SE Iraq. In NE Iraq, they charge the Qamchuqa Formation. Al-Ameri *et al.* (2004) suggested that oil in the Khasib Formation at *East Baghdad* was sourced from the Chia Gara Formation and the lower part of the Ratawi Formation and probably also from

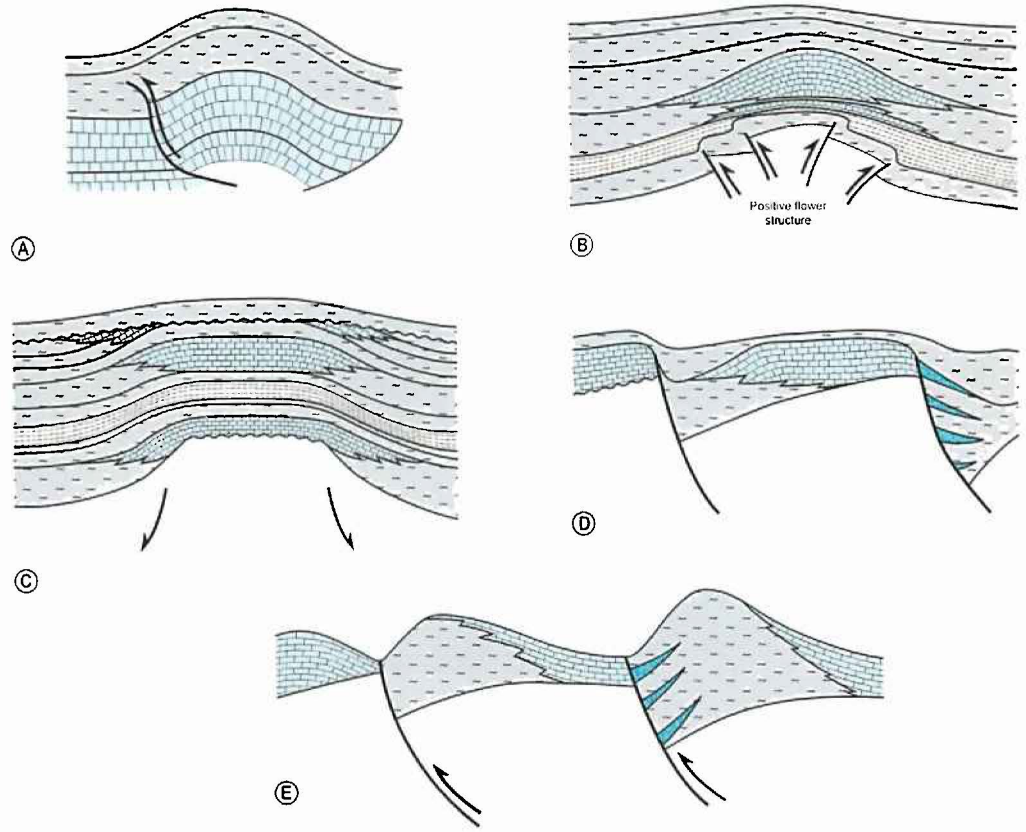


Fig. 9.5.10. Proven and likely trap types in the Cretaceous of Iraq:
a. typical Zagros compressional anticline.
b. anticline in Central Iraq with flower structure; note control on facies;
c. north-south oriented anticline in southern Iraq (e.g. *Rumaila*); note control on facies;
d. half graben typical of northern Iraq; note control on facies;
e. inverted half graben as in northern Iraq; note that the poorest reservoir quality facies are in the core of the anticline.

the Nahr Umr and Ahmadi Formations.

Reservoir units may locally have received an oil charge from pro-delta source rocks in the Zubair/Ratawi Formations (Al-Ameri and Batten, 1997). An oil charge from Middle-Upper Jurassic source rocks is highly probable in north and NE Iraq.

Long-distance lateral migration from Kazhdumi-type source rocks may charge Qamchuqa/Mauddud, Nahr Umr and Mishrif Formation reservoirs in SE Iraq. Ibrahim (1983) suggested that Lower Cretaceous source rocks were responsible for most of the oil in Albian reservoirs in SE Iraq. Overlying Cretaceous source rocks may charge Upper Cretaceous reservoirs in west and NW Iraq and locally in the Balambo-Garau Basin in NE Iraq (Fig. 9.5.1), by analogy with Syria and SE Turkey. Maturation may have occurred locally in deep basins, generating oil which may have charged reservoirs in the Shiranish/Bekhme Formations at *Ain Zalah, Butmah* and other fields. Jurassic and Triassic source rocks were probably also significant in NW Iraq (c.f. Thode and Monster, 1970).

In the Euphrates Basin, initial oil migration was generally vertical and subsequent migration may have been obstructed by fault zones at the basin margins. In Syria, the same source rocks charge reservoirs in the pre-rift Rutbah Sandstone and Mulussa Member 'F' sandstone, as well as less significant Palaeozoic reservoirs (de Ruiter *et al.*, 1995). A similar model may be applicable to the Khleisia High and the Mosul area in Iraq.

Entrapment of oil and gas

Three types of structural trap are associated with the Cretaceous petroleum system in Iraq (Fig. 9.5.10): NW-SE oriented late Neogene "Zagros" anticlines in NE Iraq and inversion structures in northern Iraq; NW-SE oriented flower structures e.g. *East Baghdad*; and north-south oriented anticlines e.g. *Rumaila* and *Zubair* in SE Iraq. Potential stratigraphic traps include reefal carbonates (e.g. Mishrif Formation: Aqrawi and Horbury, 2008) developed on palaeohighs, as in SE Turkey (Wagner and Pehlivan, 1987).

Zagros anticlines and inversion structures

NW-SE to east-west oriented anticlinal folds are the main trap type in northern and NE Iraq (Fig. 9.5.10a); they are tens to hundreds of km in length and may have closures of more than 1000 m (Ameen,1992; Hessami *et al.*, 2001). Some anticlines formed by reverse movement on pre-existing extensional faults.

Major NW-SE anticlines formed during late Miocene – Pliocene compression. They include *Chemchemal, Pulkhana, Jambur, Bai Hassan, Qarah Chauq* and *Khabbaz*. However, recent studies (Haddad and Ameen, 2007) have suggested that the *Qarah Chauq* and *Chemchemal* anticlines may be inverted Senonian half-graben. Reservoir quality in Zagros anticlines may be poorer than that in anticlines with more complex structural histories due to the lack of an early oil charge and the absence of karstification.

In Syria, recent studies have indicated that uplift and erosion was caused by reverse movement on former normal faults; evidence comes from seismic data from the Euphrates Graben (Caron *et al.*, 2000) and from Jebel Abd El Aziz (Kent and Hickman, 1997) (Fig. 3.11). Subaerial exposure is inferred from the local occurrence of shallow-water nummulitic carbonates of Paleogene age above eroded Cretaceous anticlines in both NW Iraq (Jebel Sinjar: van Bellen, 1959; Kennedy and Lunn, 2000; Fig. 7.55) and Syria e.g. Jebel Abd El Aziz (Kent and Hickman, 1997) and Jebel Bishri (Daniel, 1963). At other anticlines (e.g. *Ain Zalah*), basinal Paleocene sediments thin over truncated basinal Upper Cretaceous deposits (Hart and Hay, 1974), and there is less evidence for subaerial exposure.

Inverted Upper Cretaceous half-grabens typically have width:length ratios of less than 5:1. Inversion has placed Cretaceous basinal facies of generally poor reservoir quality in structurally elevated positions, while shelf carbonates with higher reservoir potential tend to be located in synclinal areas representing former footwalls (Aqrawi and Horbury, 2006). Deeply buried units that were eroded from footwall highs, such as the Gir Bir and Wajnah Formations, may however only be present within these inverted basins. Another feature of these anticlines is that whereras the structural closure of the shallow stratigraphy may be relatively simple (e.g. the top of the 1st Pay, the Shiranish Formation at *Ain Zalah*: Fig. 9.5.27), the underlying section may be structurally more complex (e.g. the top of the 2nd Pay, the Mushorah Formation at *Ain Zalah*: Fig. 9.5.28). This is because inversion may have restored the graben to its pre-Late Cretaceous structural configuration.

Traps in Central Iraq with a strike-slip element

The Khasib Formation play in Central Iraq occurs in a structural zone characterized by strike-slip faulting. Traps are associated with positive flower structures (Fig. 9.5.10b), e.g. *Makhul, East Baghdad, Balad, Samarra* and *Tikrit*. At *East Baghdad,* the structure is block faulted. Some fault blocks contain producible oil; others are non-productive or water-saturated (Sadooni, 2004).

Strike-slip faults were active in the Late Cretaceous. Structures began to develop in the early Cenomanian (Khaiwka, 1989 *in* Sadooni, 1996) when they controlled the location of the Mishrif shelf margin. Fault reactivation in the mid-Late Cretaceous may have been due to the onset of compression along the NE margin of Arabia. Structural closure at *East Baghdad* may have developed as early as the late Maastrichtian.

The area of strike-slip deformation was characteristsed by shallow-water carbonate deposition (Khasib, Tanuma and Sa'di Formations). The presence of shallow-water facies enhances the prospectivity of structural traps. The shallow-water facies pass to the NE and SW into the basinal carbonates of the Kometan and Balambo Formations which are less prospective.

Upper Cretaceous reservoir facies can be expected to occur within the strike-slip associated structures rather than on their flanks, in contrast to the inversion anticlines in northern Iraq (Aqrawi and Horbury, 2006).

North-south oriented traps in Southern Iraq

North-south oriented anticlines in southern Iraq, including the *Burgan* and *Ghawar* structural trend, are the northern continuation of the Precambrian Ar Rayn structural terrane of Al-Husseini (2000). The anticlines are tens of km long and have closures of hundreds of metres. They result from folding in the Late Carboniferous, and subsequent shortening beginning in the Cenomanian-Turonian and continuing into the Cenozoic (Ibrahim, 1983; Khan, 1989; Beydoun *et al.*, 1992; Bordenave, 2008). Uplift of the palaeohighs resulted in crestal erosion. Later normal faulting occurred on the flanks (Fig. 9.5.10c).

The super-giant *Rumaila* field, divided into *Rumaila North* and *South* is the largest field in Iraq. The structure at *Rumaila* is an asymmetric NNW-SSE oriented anticline, some 70 km long (IPC, 1956), which is divided into separate domes now referred to as *(South) Rumaila* (covering an area of about 34 x 7 km) and *North Rumaila (*32 x 8 km), the latter being structurally lower than the former (Jamil, 1978).

The anticlines are often asymmetrical. The steepest dips at the *Raudhatain* and *Sabriyah* structures, Kuwait, are on the western and eastern flanks, respectively (Al-Eidan *et al.*, 2001). They are internally faulted, particularly in crestal areas, with fault planes dipping at 45-60°; throws are up to 50 m. Fault patterns may influence reservoir compartmentalization and permeability.

Although the structural aspects of traps in Southern Iraq are poorly described, facies variations are better documented (Figs 9.5.10c). The Yamama Formation contains carbonate build-ups in crestal areas (Sadooni, 1993b) as does the Ratawi Formation (Sadooni and Aqrawi, 2000). In the Mishrif Formation, higher-energy facies are developed best in anticlinal crests (Gaddo, 1971; Aqrawi *et al.*, 1998). Palaeolows such as the *Tuba-*

1 well locality between the *Rumaila* and *Zubair* anticlines have lower energy facies. These structures were re-activated during the mid-Turonian, during compression of the Arabian Plate margin, and a related unconformity locally cuts down into the earliest Cenomanian stratigraphy. Carbonate units in crestal locations may have enhanced reservoir characteristics as a result of karstification and leaching.

Stratigraphic traps

Stratigraphic traps may occur on the flanks of anticlines or on palaeohighs (Fig. 9.5.10d,e). Heavy and dead oil shows in the Cretaceous successions of wells *Atshan-1* and *Demir Dagh-1* (Jassim and Al-Gailani, 2006a, Appendix 2) may represent oil originally trapped in isolated platform carbonates (Aqra, Bekhme and Hartha Formations) on fault-block highs which were breached during late Tertiary deformation. Alternatively, the oil may originally have been reservoired within carbonate debris flow and lowstand platform deposits enclosed within basinal sediments, which subsequently leaked into overlying units (Aqrawi and Horbury, 2006). Possible analogues include the Aqra and Bekhme Limestone Formations that crop out at Berat Dagh (Dunnington, 1958), and which are known to contain great thicknesses of bitumen-saturated carbonates.

Other stratigraphic trap types can be identified from outcrop data. Bitumen saturation of the Qamchuqa platform margin occurs in the Pir-i Mugrun anticline (Henson, 1950a; Dunnington, 1958). This may be evidence of a stratigraphic trap, because although the oil occurs in a four-way closure, it is clear that facies patterns control hydrocarbon distribution in the anticline.

Rudist-bearing carbonates of the Mishrif and Hartha Formations may form stratigraphic traps in shelf-margin locations (Aqrawi and Horbury, 2008). Analoguous build-ups in the Garzan Formation are productive in SE Turkey at the *West Raman*, *Silivanka*, *Germik*, *Garzan* and *Magrip* fields (Dunnington, 1967a).

Oils in fields

Data in this section has been compiled mainly from Dunnington (1967) and Appendix 2 of Jassim and Al-Gailani (2006a).

In southern Iraq, oil gravities increase towards the basin margin and vertically upwards, probably due to charge from source rocks of progressively lower maturity and biodegradation of oil in shallow reservoirs. In northern Iraq, gravities generally decrease upwards, as light fractions migrate up from underlying heavier oils through fracture systems developed during Zagros deformation. Oil gravity in Cretaceous reservoirs decreases with decreasing reservoir age (Table 9.5.1).

In the west of Iraq, oil and bitumen shows in the Zubair and Nahr Umr Formation sandstones in well *Ghalaisan-1* indicate long distance lateral oil migration from the source kitchen in the Mesopotamian Basin has occured. A line of oil seepages along the Abu Jir fault zone (Pitman *et al.*, 2004) marks the western limit of migration pathways out of the Mesopotamian Basin.

In northern Iraq, geochemically-similar Jurassic- and Cretaceous-sourced oils are likely to have mixed where the Gotnia-equivalent Barsarin Formation does not provide an effective regional seal (Goff, 2005). Ayres *et al.* (1982) suggested that offshore eastern Saudi Arabia, oil from Jurassic reservoirs has re-migrated vertically up to 1500 m into Cretaceous reservoirs. Jurassic sourced oils in the Arab Formation may have the same geochemical characteristics (pristane/phytane ratios, even-odd carbon number preferences in the *n*-paraffins, naphthenic-aromatic ratios, specific gravities, and gas chromatogram signatures of saturate and aromatic C_{15+} fractions) as Cretaceous-sourced oils (Chaube and Al-Samahiji, 1995).

Within individual fields, stacked Cretaceous reservoirs are characterised by vertical variations in API through reservoir zones. Zubair Formation oils tend to be lighter in the deeper parts of structures. The 3rd Pay at *Zubair* field contains 36°API oil, and the underlying 4th Pay contains 42°API oil (Al-Naqib, 1967). Oil gravities increase with depth within individual reservoirs, however; this is probably due the presence of early mature oil, probably sourced by the Nahr Umr and Ahmadi Formations, and also to biodegradation. Similarly, low-GOR oils in fields offshore Iran show gravity segregation. The Burgan B reservoir at *Soroosh* has 20° API oil (with 23 cP viscosity) at the crest of the structure, passing into 15°API oil (with a viscosity of 70 cP) and then heavy oil and a tar mat at the OWC (Denby *et al.*, 2001). This kind of vertical segregation generally indicates a high degree of reservoir connectivity.

Variation of oil properties with stratigraphy

The variation of oil specific gravities with stratigraphy is illustrated in Figs. 9.5.11 to 9.5.16.

In **Supersequence I** (Fig. 9.5.11), light oils (30-40°API) are found in SE Iraq, while progressively heavier oils occur westwards towards the Salman Zone. *Samawa-1* is reported to contain bitumen or heavy oil (Sadooni, 1993b).

In the Yamama Formation, oil gravity ranges from 16 to 43°API (Jassim and Al-Gailani, 2006) but is typically 33-43° (Sadooni, 1993b), with 0.9-4.5% sulphur.

In **Supersequence II** (Fig. 9.5.12), oil gravities appear to be controlled by the burial depth of source rocks in the adjacent kitchen. Light oils (30-40°API)

Table 9.5.1. Mean porosity and permeability for reservoirs in Iraq, by supersequence. Original data taken from Appendix 2 of Jassim and Al-Gailani (2006a). Note that the data is not always independently verifiable and caution should therefore be applied to its precise interpretation.

Super-sequence	mean porosity (%)	n	mean permeability (mD)	n
I	11.6	20	37.7	9
II	18.5	21	695	12
III	27.2	28	374	14
IV	17.2	23	195	16
V	18.6	17	22	5
VI	15.1	10	78	3

Table 9.5.2. Variation of oil gravities and sulphur contents through the Cretaceous stratigraphy of Iraq. Data from Appendix 2 of Jassim and Al-Gailani (2006a).

Super-sequence	API Gravity	n	Sulphur content (%)	n
VI	14.7	33	2.82	18
V	23.8	29	3.49	8
IV	24.5	48	3.91	13
III	26.8	42	2.3	12
II	30.1	29	2.06	10
I	33.4	30	1.47	8

occur in SE Iraq and progressively heavier oils occur towards the Salman Zone. Zubair Formation oils range from 16 to 39°API (Jassim and Al-Gailani, 2006); 34-36° oils occur at *Zubair* and *South Rumaila* (Dunnington, 1967), with sulphur contents of 1.5-2.2% (mean 1.8%).

Oil gravities vary from 16-27° in the west of Iraq to 34° in the east (Jassim and Al-Gailani, 2006). A well in the *Luhais* field flowed 32.5°API oil from the upper part of the Zubair Formation at 9081–9211 ft brt (2768-2808 m) and is the westernmost test of high quality oil in SE Iraq (Verma *et al.*, 2004). In the Ratawi Formation at well *Abu Khema-1*, heavier oils have much higher sulphur contents (up to 8.8%) (Roychoudhury and Handoo, 1980). Oils typically range from 20–40 °API in the Lower Qamchuqa Formation of northern Iraq (Dunnington, 1967a; Jassim and Al-Gailani, 2006) with sulphur contents of 0.92 to 3.7%. Oils in fields around Basra are therefore similar to those in Kuwait, where APIs of 31 to 35° are widespread (Dunnington, 1967a).

In **Supersequence III** (Fig. 9.5.13), the distribution of oils is variable and low- and high-API oils may be found in nearby structures. Thus 41°API oil occurs in the *Nahr Umr* structure and 15°API oil in the *Ratawi* structure. Also, 42°API oil is present in the *Sasan* structure in NW Iraq, and 13°API oil in the *Gusair* structure.

Oils in Nahr Umr reservoirs are of two types. Medium gravity oils (with APIs of 20-28°) are very similar to those in the overlying Mishrif Formation and occur in the *Ahdab*, *Huwaiza*, *Noor*, *Rafedain*, *Ratawi*, *Rumaila South*, *Tuba* and *Subba* fields. Lighter oils (30-32.5°API) occur in the *Amara*, *Halfaiya*, *Jerishan*, *Luhais*, *Majnoon*, *Nasiriya*, *Rumaila North*, *West Luhais* and *Zubair* fields. At *Nahr Umr*, the formation contains oil with API gravities of 20-25°API (mean 28°) and sulphur contents of 0.92-3.7% (mean 2%) (Jassim and Al-Gailani, 2006).

Mauddud Formation oils vary from 12 to 38° (mean 25°: Jassim and Al-Gailani,2006). Anomalously light oils in the *Sasan* structure suggest the presence of a locally deeply buried Jurassic or Lower Cretaceous source rock. Sulphur contents range from 1.2 to 3%.

In the Burgan Formation, oils range in gravity from 16° API at *Cyrus* but 36° at *Raudhatain* (Dunnington, 1967a). The coeval Rutbah Formation (Neocomian-Albian) in Syria tested 37°API, low-GOR low-sulphur oil in the Euphrates Basin (de Ruiter *et al.*, 1995), generated from Upper Cretaceous source rocks.

In **Supersequence IV** (Fig. 9.5.14), oil gravities are generally between 20° and 30° API. This is probably due to the restricted nature of the reservoir facies (Mishrif Formation) which is confined to a band parallel to the axis of the Mesopotamian Basin. Along this trend, structures are charged with generally similar fluids.

Mishrif Formation reservoirs are characterised by 19–37° API oils (Jassim and Al-Gailani, 2006), with 26° API oil recorded in both *South Rumaila* and *Zubair* (Al-Naqib, 1967). These oils have a high sulphur content (3–6 %) (Jassim and Al-Gailani, 2006) probably due to local charge from the Kazhdumi Formation to the east. Al-Ameri *et al.* (2009b) concluded that the oils in the Mishrif Formation were sourced from Upper Jurassic – Lower Cretaceous carbonates based on their average C_{28}/C_{29} sterane ratio (see their Figure 7). The relatively low maturity of the Mishrif Formation oil (24 API and > 4% sulphur) is consistent with it being derived from Albian source rocks (110 – 100 Ma) equivalent to the Kadhzumi Formation of SW Iran. This has charged the Bangestan Group carbonate reservoirs (the lateral equivalent of the Mishrif Formation in Iran).

In **Supersequence** V (Fig. 9.5.15), the variation in oil gravities reflects the general burial trends of source rocks and the diversity of reservoirs compared to Supersequence IV. In areas where moderate-API oils occur in Supersequence IV, oils are of similar type (APIs of 20-30) in Supersequence V. Deeper parts of the basin have high-API oils, and gas is present at *Chemchemal.* To the south, reservoirs in the Sa'di/Tanuma/Khasib Formations contain oils ranging from 16 to 28°API (mean: 22°), and sulphur ranging from 2.9 to 4.4% (mean: 3.5%) (Jassim and Al-Gailani, 2006).

Anomalous low-API oils are probably biodegraded. The lower part of the Pilsener Limestone in north-central Iraq contains oils with APIs of 12 to 18° (Dunnington, 1967a) which may be an early expulsion product that has migrated to the basin margin. The equivalent Senonian part of the Massive Limestone of Syria contains 20 to 23° API oil, while oil in the Mardin Limestone (Karababa Formation Member "C") in SE Turkey has a gravity of 12-35° API in the west (Soylu *et al.*, 2005) and 31-39°API in the east (Dunnington, 1967a). The uppermost part of the Senonian Sarvak Formation contains 19-36° API oils (Dunnington, 1967a) in Iran.

Supersequence VI (Fig. 9.5.16) also contains heterogenous oils due to variations in source rock maturity. Heavy oils occur on the western basin margin, particularly in the Mosul and Fallujah areas where early migration products and/or biodegredation are important. Light (41°API) oils in the *Sasan* structure were probably charged by relatively deeply-buried Jurassic or Cretaceous source rocks in the Sinjar Trough. The Hartha Formation contains heavy oils at the *Qasab, Qaiyarah, Jawan* and *Najmah* fields (12-18°API; Dunnington, 1967a), and in the *Merjan-1* well in central Iraq (Sadooni, 1995). Oil gravities range from 15 to 30°API with sulphur contents of 1.45 to 5.9% (mean 4%). In fractured Shiranish Formation reservoirs, APIs vary from 14 to 63° (mean 25°) and are highest in the *Chemchemal* field (63°API; Jassim and Al-Gailani, 2006). Produced oils show a narrower range; in the *Ain Zalah* field, the oil is 31.5°API (Dunnington, 1967a) with between 2.5 and 2.6% sulphur (El Zarka, 1993); in the *Butmah* field, the oil is 29°API (Dunnington, 1967a); at the Baba Dome of the *Kirkuk* field, the oil is 33°API; and at *Bai Hassan,* the oil is 28°API (Dunnington, 1967a), with 28° oil in the *Sufaiya* field (Jassim and Goff, 2006a).

Aquifers

Aquifers influence biodegredation of reservoired oils in Late Cretaceous shelf carbonates in northern Iraq. Al-Mashadani (1986) identified two Cretaceous aquifers in Iraq. The **Upper Cretaceous aquifer** (Figs. 9.5.17; 9.5.18) of the Tayarat, Shiranish-Hartha, Sa'adi and Khasib Formations is overlain by argillaceous and locally evaporitic Eocene-Paleocene sediments. This aquifer system is in communication with the Tertiary aquifer at the basin margins where caprocks are absent. Gravity flow occurs in the aquifer from the Foothills Zone and elevated parts of the platform into the centre of the basin (Fig. 9.5.17).

The Tayarat Formation in the Western Desert may constitute an important regional surface aquifer (Al-Naqib, 1967) where it overlies sealing rocks (e.g. the Shiranish / Qurna Formations, and further east, the Sa'adi / Tanuma / Khasib Formations). In northern Iraq, SE Turkey and NE Syria, equivalent Cretaceous shelf carbonates form major aquifers in which freshwater flushing has formed heavy and sulphur-rich oils (Beydoun, 1991). A high pressure zone occurs in the Basra area beneath a regional Lower Cretaceous seal.

Three salinity cells can be identified in these aquifers: the Sinjar-Sufaiyah basin; the Khleisia-Tel Hajar basin; and the Mesopotamanian basin from Kirkuk to Amara. Salinities are similar to those in Tertiary reservoirs and increase basinwards from 50g/1 to 100g/1. Salinities are very low (3500-5000 ppm) on the Mosul High (Fig. 9.5.18) where fresh water has penetrated the Hartha Formation, degrading the oils in the Qaiyarah area so that they have low APIs (Fig. 9.5.16). Salinities are also low (8000 ppm) adjacent to the Cretaceous outcrops in NE Iraq (Fig. 9.5.18). Salinities increase from <50,000 ppm along the flanks of the Mesopotamian Basin to 250,000 ppm (locally up to 300,000 ppm) NE of Amara (Fig. 9.5.18). Salinities exceed 50,000 ppm in the Sinjar-Sufayah and Khlesia-Tel Hajar basins (Fig. 9.5.18). Waters are generally $CaCl_2$-rich but on the basin margins contain $NaSO_4$ suggesting a meteoric origin (Al-Mashadani, 1986). Late Cretaceous aquifers are separated from Tertiary aquifers by Paleocene-Eocene and Upper Campanian-Maastrichtian marls and mudstones.

The **Lower and Middle Cretaceous aquifer** (Figs . 9.5.19; 20; 21) comprises the Mishrif, Fahad, Mauddud, Nahr Umr, Zubair and Yamama

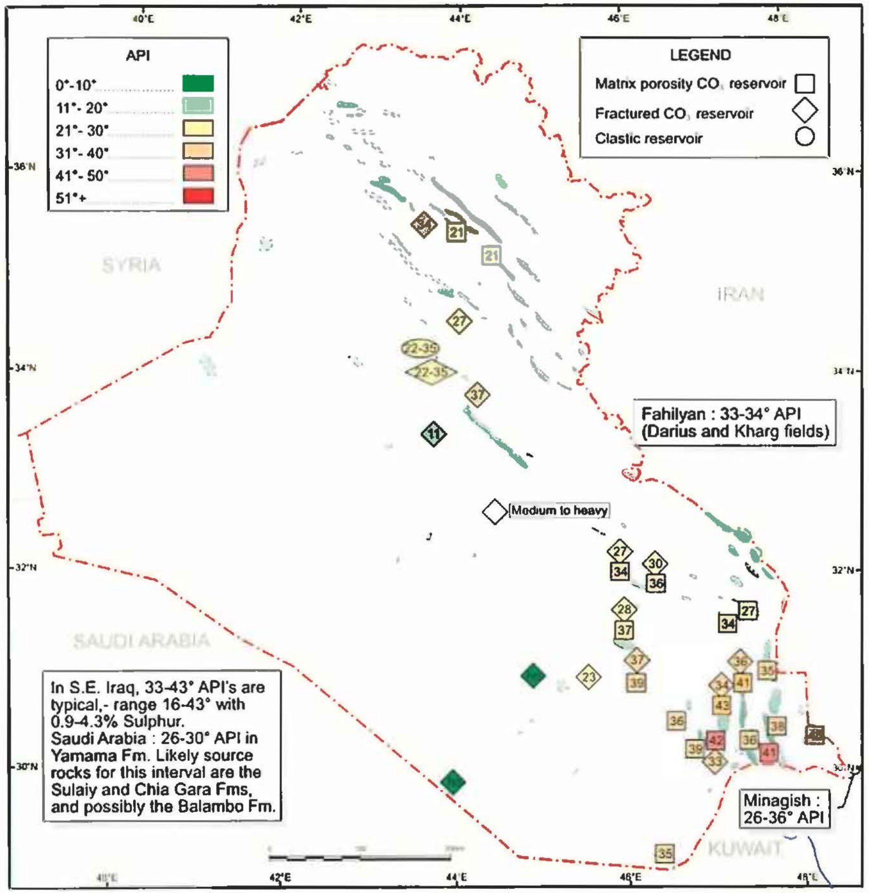


Fig. 9.5.11. Distribution of oils in Supersequence I reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani (2006a, Appendix 2).

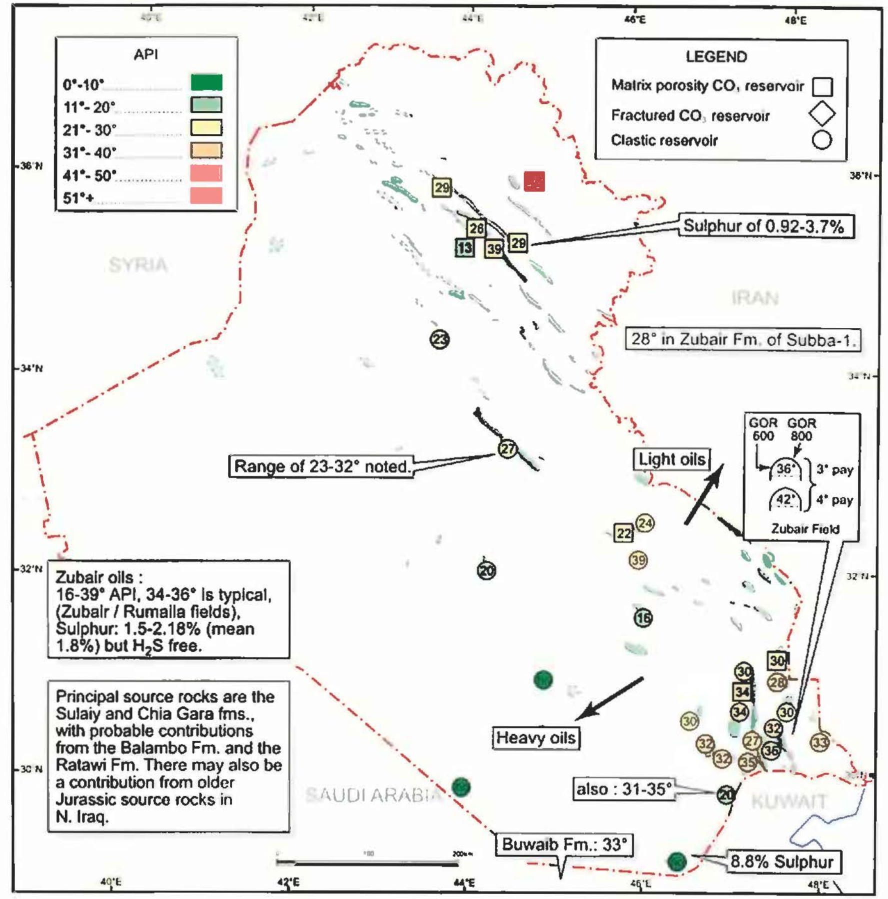


Fig. 9.5.12. Distribution of oils in Supersequence II reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani (2006a, Appendix 2).

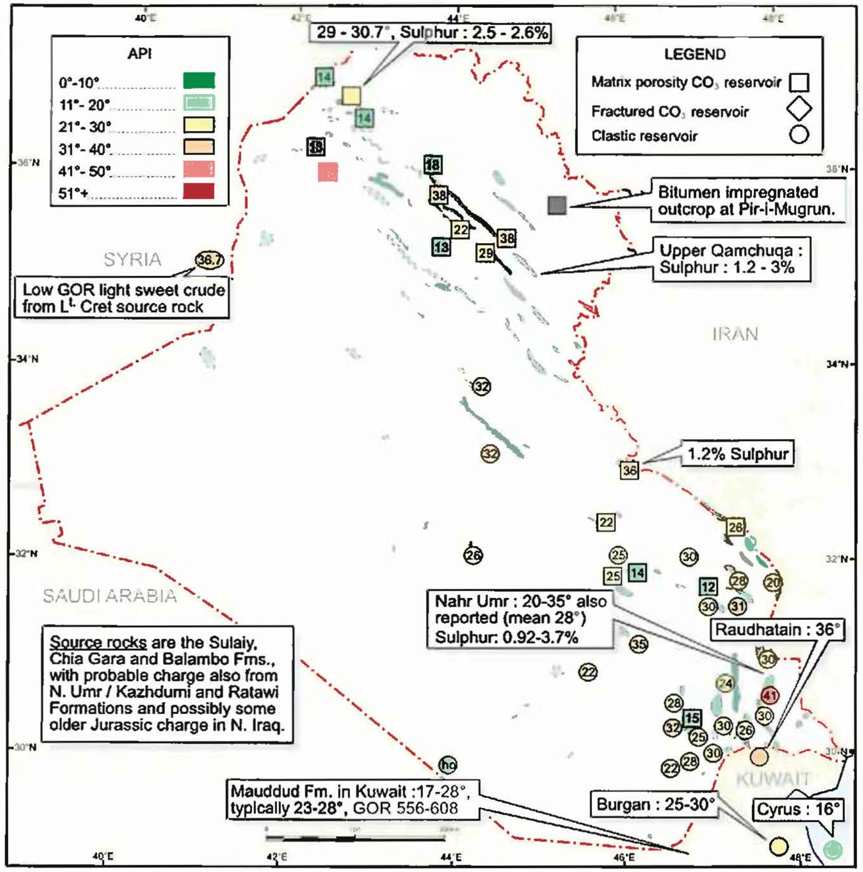


Fig. 9.5.13. Distribution of oils in Supersequence III reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani (2006a, Appendix 2).

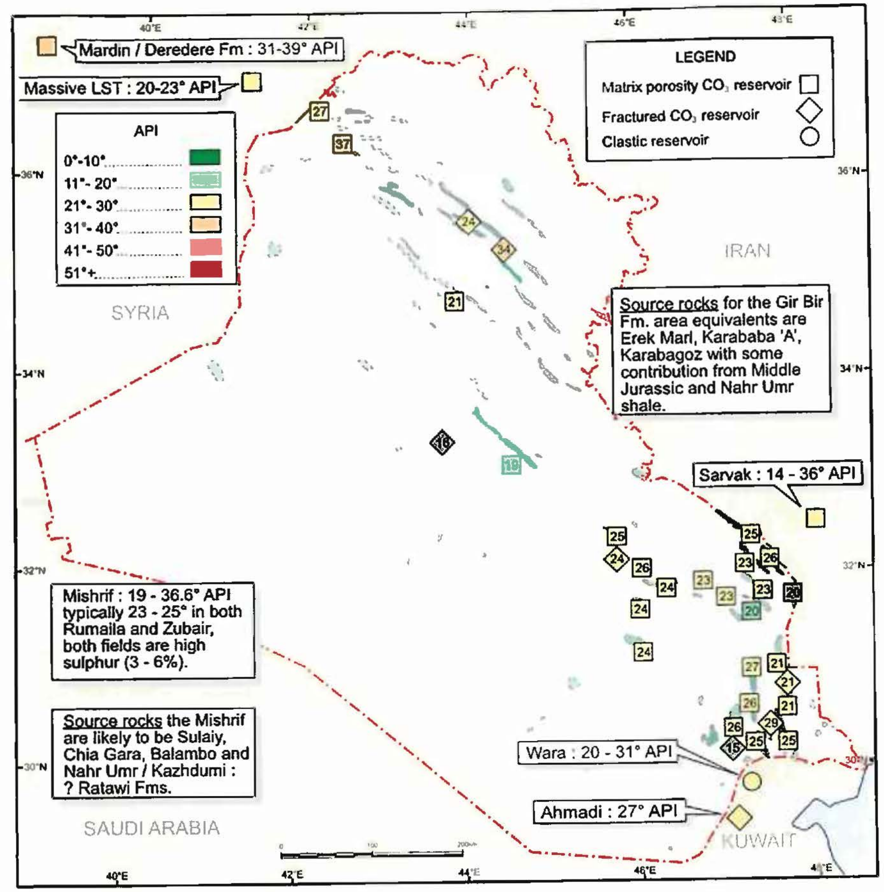


Fig. 9.5.14. Distribution of oils in Supersequence IV reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani (2006a, Appendix 2).

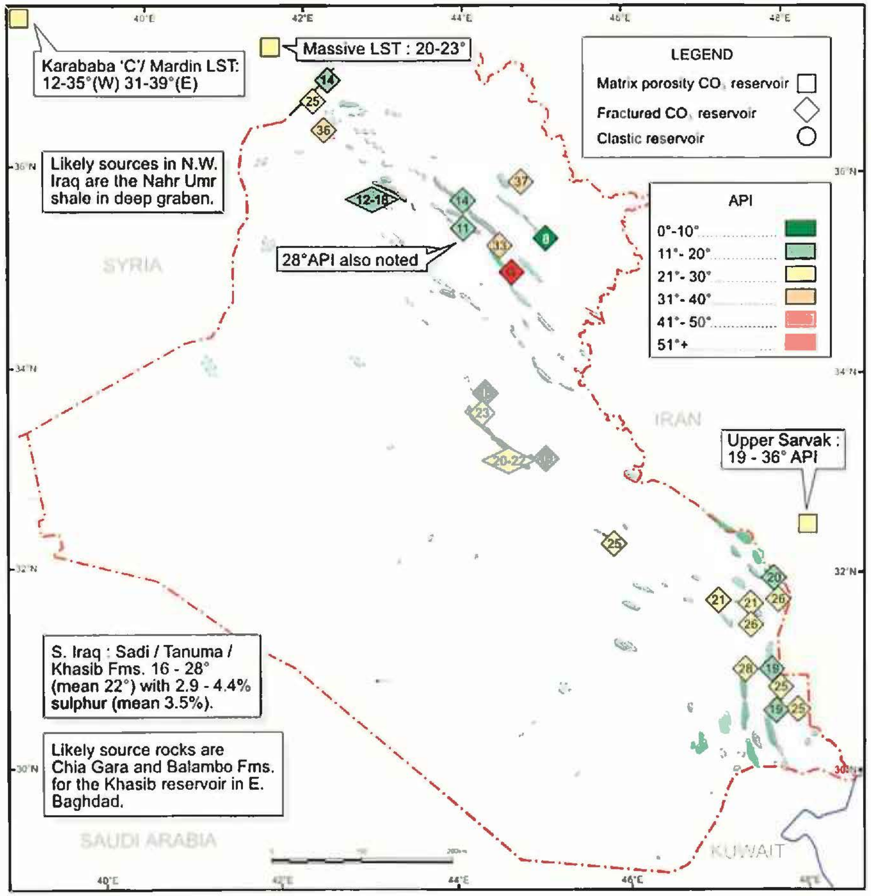


Fig. 9.5.15. Distribution of oils in Supersequence V reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani (2006a, Appendix 2).

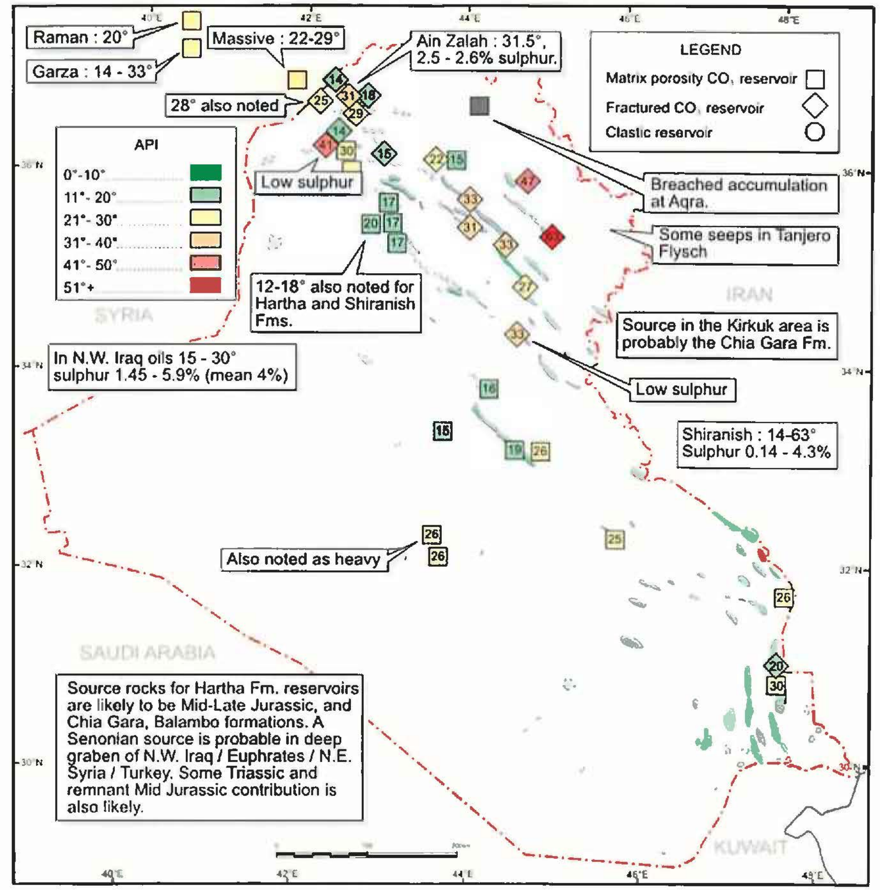


Fig. 9.5.16. Distribution of oils in Supersequence VI reservoirs. Data after various sources including Dunnington (1967a) and Jassim and Al-Gailani, (2006a, Appendix 2).

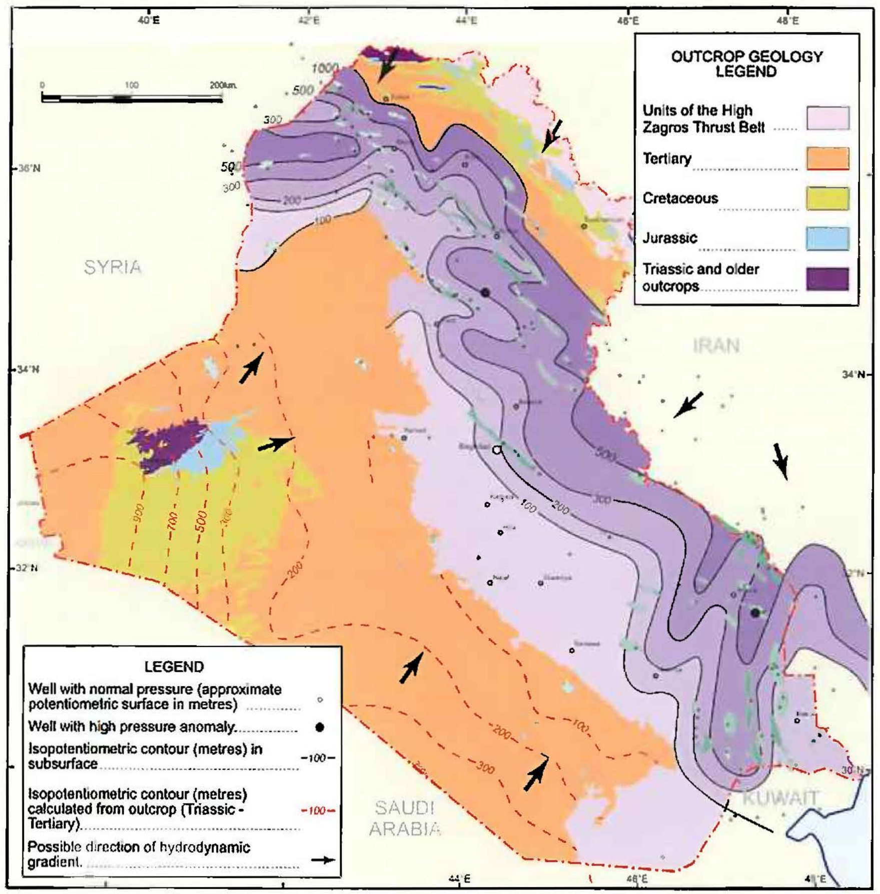


Fig. 9.5.17. Approximate potentiometric surface map for the Upper Cretaceous aquifer. Contour intervals shaded purple. Modified from Al-Mashadani, 1986.

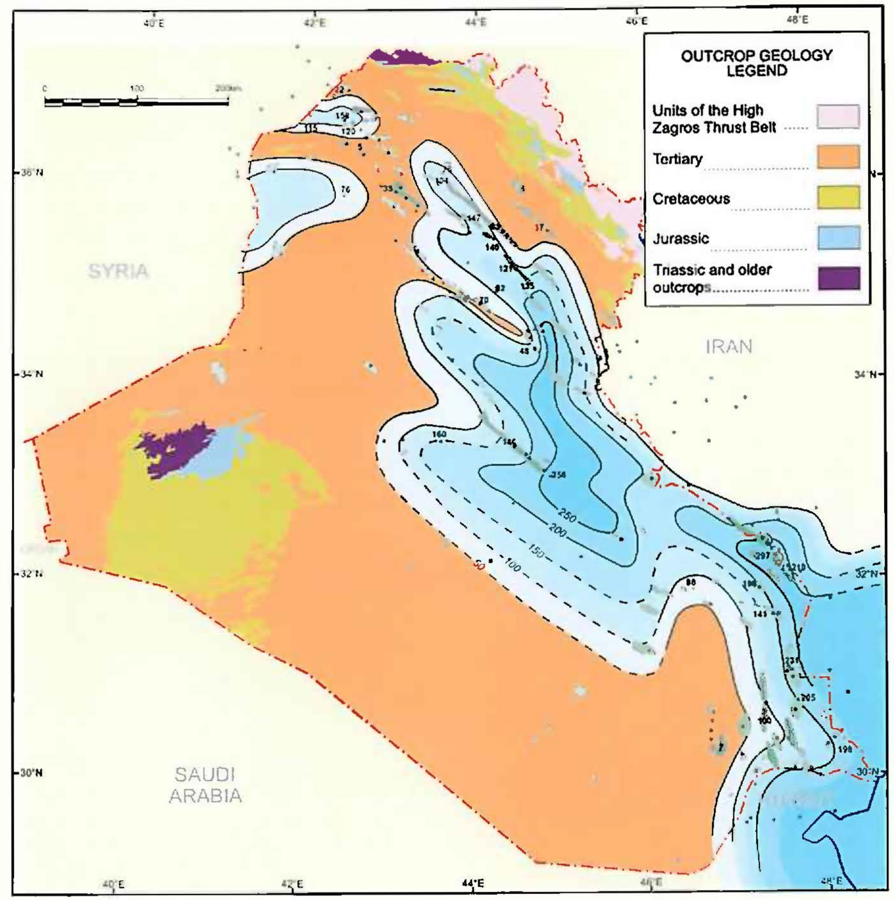


Fig. 9.5.18. Isosalinity map (contours in increments of 50g/l between 50 and 250 g/l) for the Upper Cretaceous aquifer. Contour intervals shaded blue. Modified from Al-Mashadani, 1986.

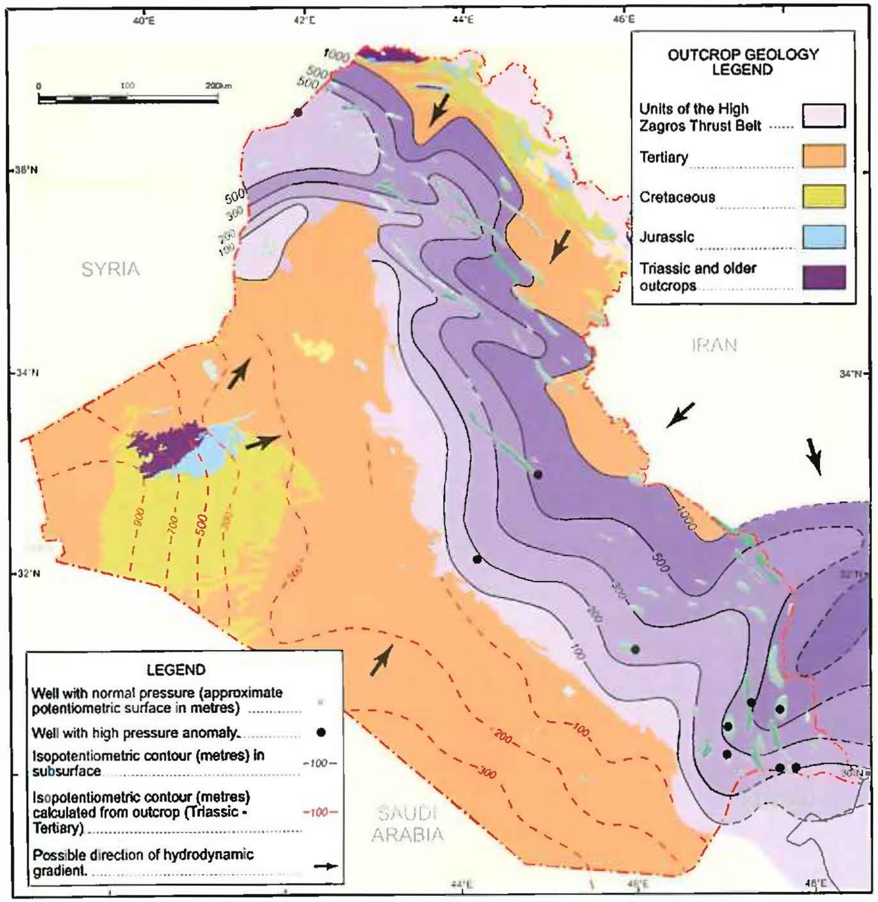


Fig. 9.5.19. Approximate potentiometric surface map for the Lower Middle Cretaceous aquifer. Contour intervals shaded purple. Modified from Al-Mashadani, 1986.

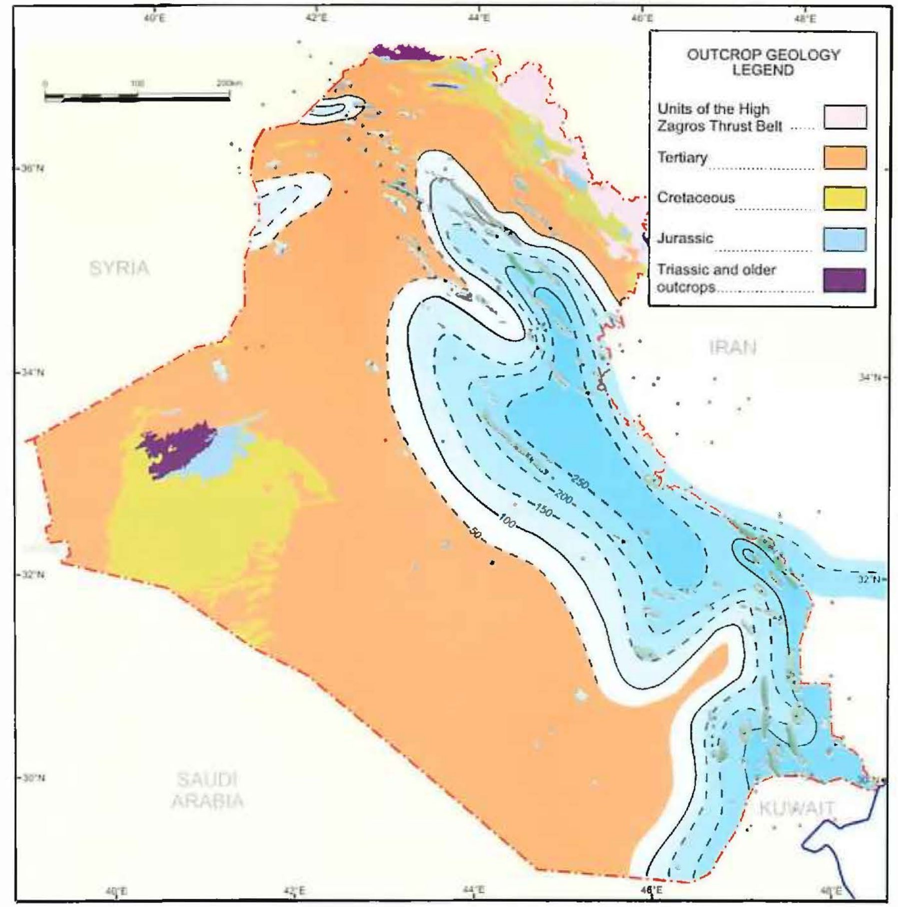


Fig. 9.5.20. Isosalinity map (contours in increments of 50g/l between 50 and 250 g/l) for the Lower Middle Cretaceous aquifer. Contour intervals shaded blue. Modified from Al-Mashadani, 1986.

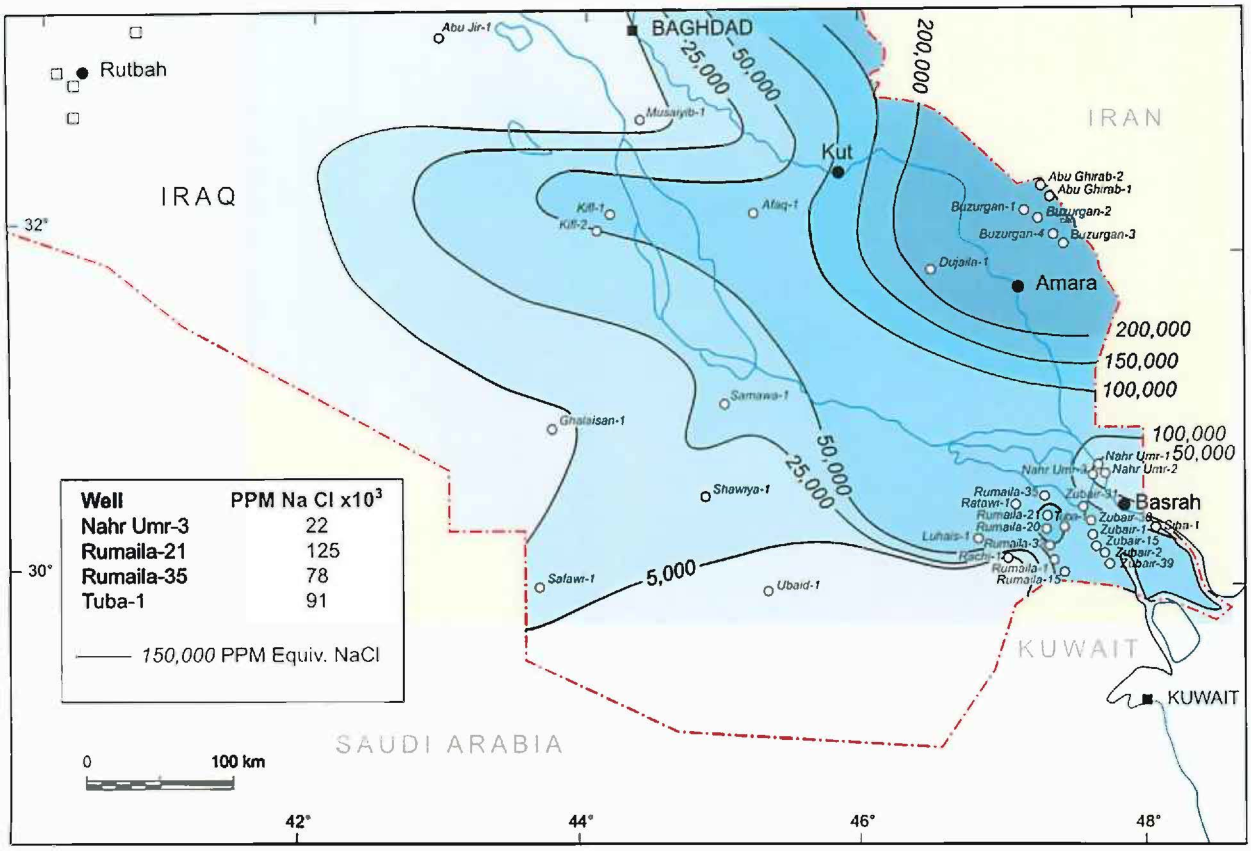


Fig. 9.5.21. Isosalinity map for the Nahr Umr Formation in SE Iraq. Modified from Ibrahim, 1983.

Formations (Al-Mashadani, 1986). The Rutbah Formation (Cenomanian) is a regional shallow aquifer in the Western Desert (Al-Naqib, 1967; Ibrahim, 1978). Upper Cretaceous argillaceous and anhydritic rocks provide a seal. Turonian – lower Campanian marls, shales, and low permeability limestones of the Sa'di, Tanuma and Khasib Formations are the main sealing units.The Ratawi Formation provides a local barrier in SE Iraq where it is thick, while the Gotnia Formation provides a regional bottom seal (Al-Mashadani, 1986). Gravity flow in the aquifer takes place from the Foothills Zone, with limited recharge from the Arabian Platform, into the central Mesopotamian basin. In SW Iraq, aquifers are recharged from the Zagros mountains (Fig. 9.5.19) (Ibrahim, 1983).

The salinity distribution in Lower Cretaceous reservoirs is similar to that in the Upper Cretaceous, although salinities are in general higher close to the border with Iran (Fig.9.5.20). At a regional scale, Lower-Middle Cretaceous aquifers can be divided into two groups: those in the Basra area with relatively high salinities, and those in the SW Desert with relatively fresh waters (Ibrahim, 1983) (Fig. 9.5.21).

The separation of the Foothills and the platform acts as a zone of vertical bypass (Al-Mashadani, 1986). Where updip migration of formation brines and hydrocarbons converges with the downdip movement of aquifer water in the vicinity of the Abu Jir lineament, the brines and hydrocarbons flow to the surface along faults and fractures. This explains the presence of surface seeps around Abu Jir and Hit. Salinities increase abruptly with depth in the Mesopotamian basin and less so in the Arabian Platform. Increased salinities and a net reduction of SO_4/Cl ratios and CaCl charged water suggest that the aquifer is confined (Al-Mashadani, 1986).

Formation waters at *Rumaila* and *Zubair* have similar compositions (Al-Mashadani and Coustau, 1985) (Figs. 9.5.22 and 9.5.23). Both fields are dominated by connate waters with little compositional variety at Lower Cretaceous level, and salinities are 80,000 to 260,000 ppm.

Jamil (1978) studied the aquifer waters of both the *Rumaila* closures and the *Zubair* field and noted that formation waters tended to flow towards the SW within *South Rumaila* (and the southern dome of *Zubair*), and to the NW in the northern dome of *Zubair*. Formation waters were of marine origin and were of calcium-sodium chloride type

Salinities at *Rumaila* vary from 189,000 to 230,000 ppm (contrasting with 170,000 to 198,800 ppm at *Zubair*) (Jamil, 1978). In the *Rumaila* field, salinity contours show that salinity increases primarily with depth.

In *South Rumaila* and the south of *North Rumaila*, rNa/rCl ratios range from 0.753 to 0.700 and decrease towards the SW. rCa/rMg ranges from

3.84 to 2.01, decreasing in a SW direction; rCl/rMg ratio varies from 20.1 to 10.5, also decreasing towards the SW, i.e in the opposite direction to the decrease in salinity, suggesting cation exchange as Mg and Ca from the rock replace Na in the waters (Jamil, 1978, after Dabrowski, 1972). Jamil (1978) concluded that *South Rumaila* and the south of *North Rumaila* are zones where there is little hydrodynamic flow.

Case study

Ain Zalah field

Ain Zalah oilfield, located some 60 km NW of Mosul (Fig.1.3), was discovered in 1939 and came on stream in 1952. The surface topography of the oilfield area is dominated by Jebel Ain Zalah, a prominent feature formed by limestones and gypsum of the Lower Fars Formation (Daniel, 1954). The Euphrates Limestone Formation is exposed in the centre of the *jebel* (Dunnington, 1958) (Fig. 9.5.24). By end-1998, *Ain Zalah* had produced 194 MM brl of 31.5 API oil, around 65% of total (estimated) recoverable reserves of 295 MM brl oil and 0.09 TCF gas (Verma *et al.*, 2004).

The structure at *Ain Zalah* is a relatively simple anticline (Hart and Hay, 1974) (Figs. 9.5.24, 25). Drilling has shown that the field is 12 miles long by 3 miles (20 by 5km) wide (Dunnington, 1958). The oil-water contact is tilted, suggesting an active hydrodynamic regime along the eastern flank of the structure (Elzarka and Ahmed, 1983).

Reservoir rocks at *Ain Zalah* comprise fractured Late Cetaceous micritic limestones of the Shiranish Formation ("First Pay") (Fig. 9.5.26); and fractured Middle Cretaceous limestones and dolomites ("Second Pay") assigned to the Qamchuqa Group (Wajnah Formations). Estimated initial reserves were 37 MM brl and 158 MM brl, respectively (El Zarka, 1993). Oils in the First and Second Pays have similar gravities, sulphur contents (2.7-3.1%) and GORs (250 cu ft/brl: El Zarka, 1993; or 278 cu ft/brl: Verma *et al.*, 2004). Reservoir temperature in the First Pay is 64.4°C indicating a geothermal gradient of 28°C/km (El Zarka, 1993). Matrix porosity is thought to be completely water saturated (Daniel, 1954) while fractures appear to have produced oil without significant water cut until 1969 (El Zarka, 1993) suggesting very low *Sw* (at least in the fracture system).

Trap geometry

Hart and Hay (1974) noted that "member F" limestones in the Lower Fars Formation, which crop out continuously at *Ain Zalah*, can be used as a structural datum. The limestones outline a folded anticline typical of the Foothills area in front of the Zagros Mountains (Hart and Hay, 1974), whose limbs dip 25 to 30° (Daniel, 1954; Dunnington, 1958) (Fig. 9.5.24). The top of the First Pay is structurally conformable with this surface anticline (Hart and Hay, 1974). Faults include an east-west trending "scissors fault" which cuts across the *Ain Zalah* structure at the top of the Second Pay, with some 200 m of normal offset in the western portion, and some 150 m of reverse displacement in the east (Elzarka and Ahmed, 1983). The age of this fault is not certain. Isopach maps (Hart and Hay, 1974) indicate two phases of syndepositional normal faulting dated as late Campanian and Maastrichtian (Fig. 9.5.27). A phase of compression at the end of the Maastrichtian with associated

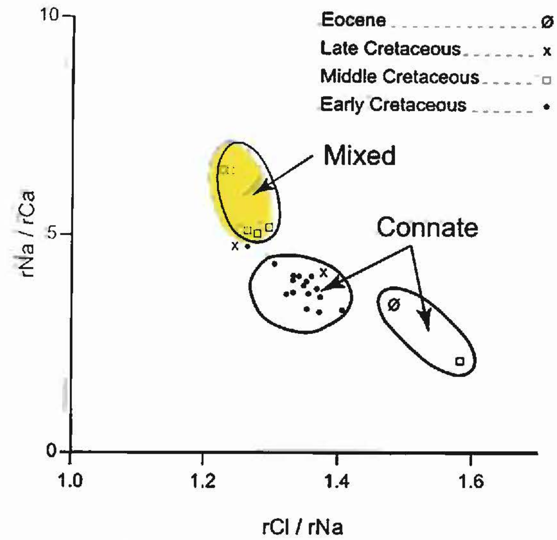


Fig. 9.5.22. Oilfield water cross-plot for the *Rumaila* field. Note how the main Lower Cretaceous connate waters all cluster together and are separate from the Middle (and Upper) Cretaceous waters which have more mixed characteristics. After Al-Mashadani and Coustau, 1985.

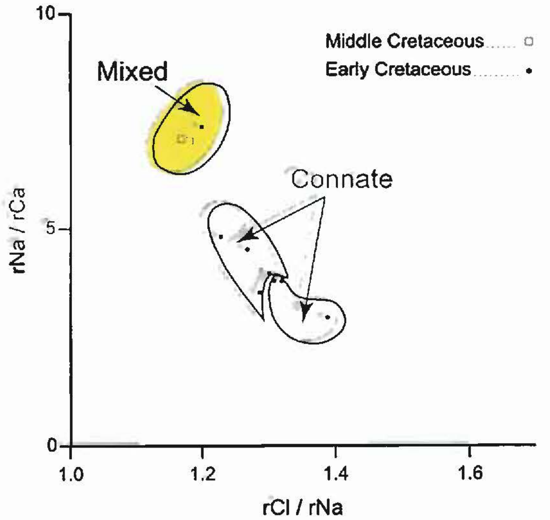


Fig. 9.5.23. Oilfield water cross-plot for the *Zubair* field. The Zubair Formation waters are similar to those in *Rumaila* field. After Al-Mashadani and Coustau, 1985.

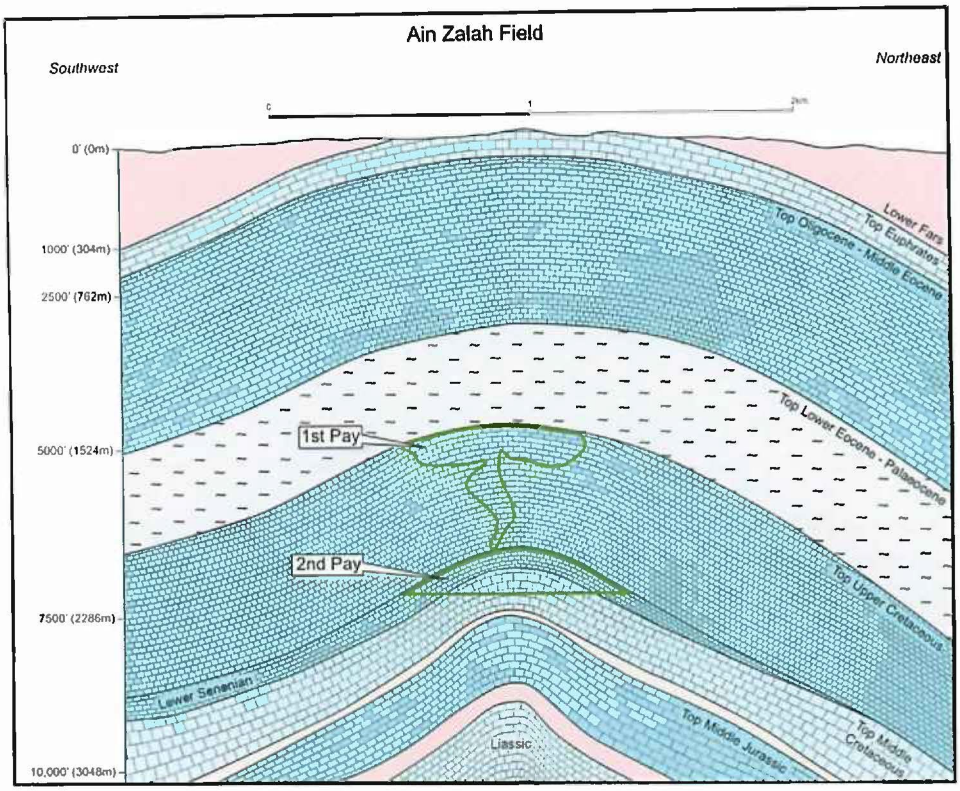


Fig. 9.5.24. SW-NE cross-section through the *Ain Zalah* field. After various sources including Daniel (1954), IPC (1956) and Dunnington (1958).

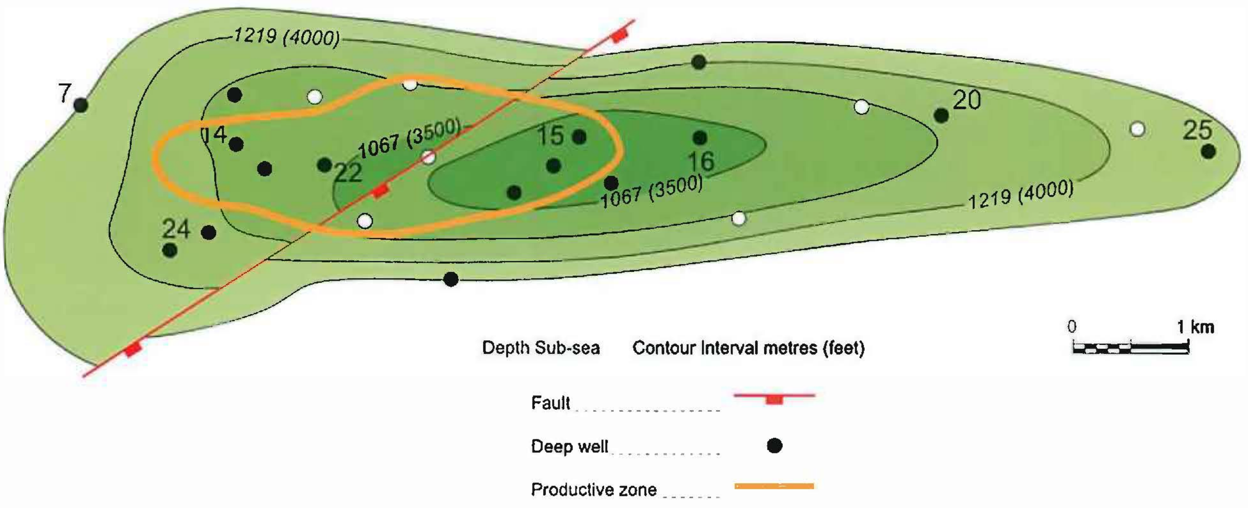


Fig. 9.5.25. Structural envelope for the Shiranish Formation (Campanian – Maastrichtian) First Pay in *Ain Zalah*. The anticline is cut by a single fault. After Hart and Hay (1974) and El Zarka (1993).

uplift led to the loss of some 100-200 ft (30 to 61 m) of uppermost Shiranish Formation. In the late Miocene-Pliocene, steeply dipping Late Cretaceous faults were folded which resulted in the present-day *jebel* structure (Hart and Hay, 1974). Deformation was severe as the flanks of the First Pay steepened from 4° to 25-30° (Daniel, 1954).

Production History

A gravity survey at *Ain Zalah* field in 1938 confirmed that the surface anticline had a subsurface expression (El Zarka, 1993). A discovery well was drilled by BOD in 1939 but drilling was shut down in 1941 due to wartime constraints and did not resume until 1947; 13 wells were drilled in the next three years (El Zarka, 1993). No water leg was found in the early drilling phase; the base of the reservoir was thought to be limited only by the lower limit of fracturing (IPC, 1956). Initial production policy therefore focused on acquiring data on reservoir performance and behaviour (Daniel, 1954). The field came on production in September, 1952 with a flow rate of 27,000 b/d, mostly from the First Pay (Daniel, 1954). By the mid-1970s, there were only ten wells still in production at the field (El Zarka, 1993).

There was a steep decline in initial production at *Ain Zalah*. Before water injection, the decline rate was initially 5% but rose to 70%; following injection, decline rates stabilised at 10% (El Zarka, 1993). Some wells had very high initial production, but this could not be maintained except with a steep pressure decline which was detrimental to ultimate recovery (Daniel, 1954). Fairly large flow rates were obtained for moderate bottom-hole differential pressures (BHDPs), with rapid recovery of BHDP to normal when a major producer was cut back or closed in (Daniel, 1954), suggesting considerable volumes of oil with comparatively free connection. Initial reservoir pressure in both First and Second Pays was 16.7 MPa; by the mid-1970s following water injection, it was 13.26 MPa (El Zarka, 1993).

Production at *Ain Zalah* was stimulated by acidisation soon after output began, and eight out of 11 wells had been acidised one or more times by 1954 (Daniel, 1954). Acidisation removed mudcake and fine cuttings from the walls of open fractures, but had little or no effect on the limestone matrix, or on widening existing pores or fine fractures.

Migration / Remigration

Oil in the First and Second Pays at *Ain Zalah* is thought to have been sourced from underlying source rocks in the Middle Cretaceous or Jurassic successions. Horst blocks of the Qamchuqa Group probably formed initial trap structures, which were subsequently breached allowing the oil to re-migrate up into the Shiranish Formation.

The First Pay

Reservoir rocks in the First Pay comprise fine-grained limestones assigned to the Maastrichtian to Campanian Shiranish Formation, sealed above by Paleocene-Eocene shales and marls of the Aaliji Formation. The reservoir limestones have little porosity or matrix permeability and oil production relies on the presence of extensive fracture systems.

The Shiranish Formation is 2315 ft (705 m) thick at the crest of the *Ain Zalah* structure (Daniel, 1954) and consists of six units identified on well logs. The uppermost of these units has been used to assess post-depositional erosion (Hart and Hay, 1974). Log correlation shows that the unit is absent from part of the western crestal area of the field (Daniel, 1954; Hart and Hay, 1974). This erosion is recognized at a core scale by pitting in the uppermost-Cretaceous surface, and "solution potholes" are filled with Paleocene sediments. A 5 cm thick "indurated surface crust" is present (Daniel, 1954); this is probably either a submarine hardground or a palaeosol.

Reservoir facies comprise massive, dense, extremely tight, globigerinal micritic limestones. The limestones consist of wack-packestones with some mudstones, with 30 to 40% bioclasts (mainly planktonic foraminifera: Ahmed *et al.*, 1986). The presence of abundant *Globotruncana gr. stuarti* and *G. calcarata* between depths of 1800 and 2000 ft (548-762 m) give a Maastrichtian - late Campanian age (Hart and Hay, 1974).

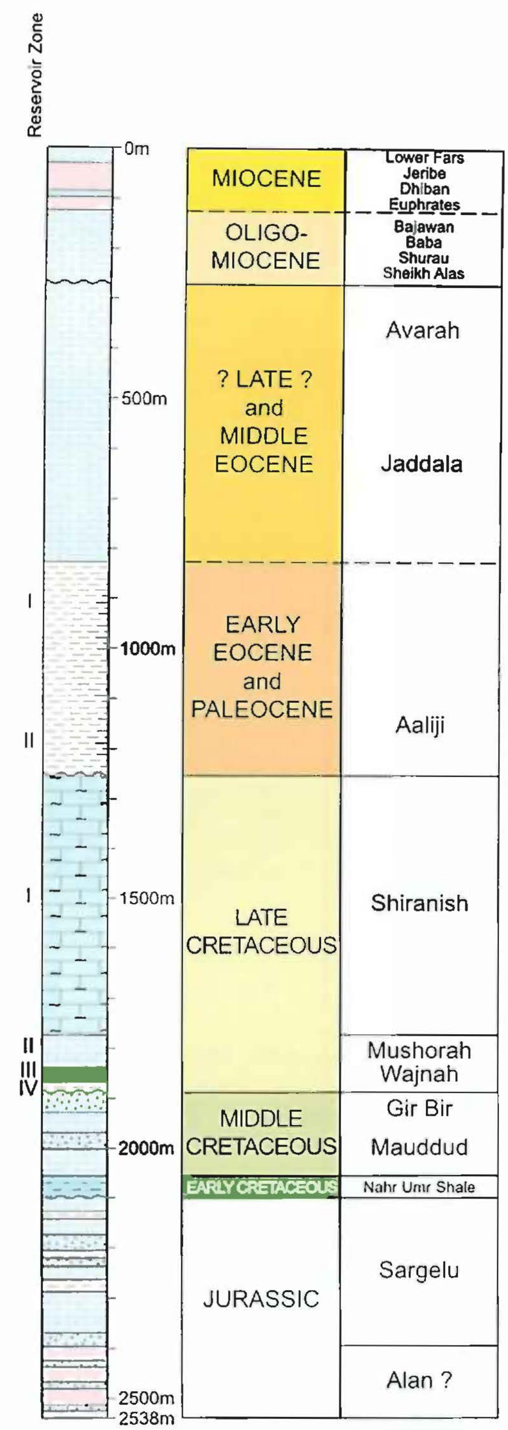


Fig. 9.5.26. Simplified stratigraphy at the *Ain Zalah* field (after Daniel, 1954); formations after Hart and Hay, 1974.

There is significant variation in the clay content of the Shiranish Formation. The clay material represents clastic input from the flysch deposits of the Tanjero Formation which was being deposited at the same time as the Shiranish some distance to

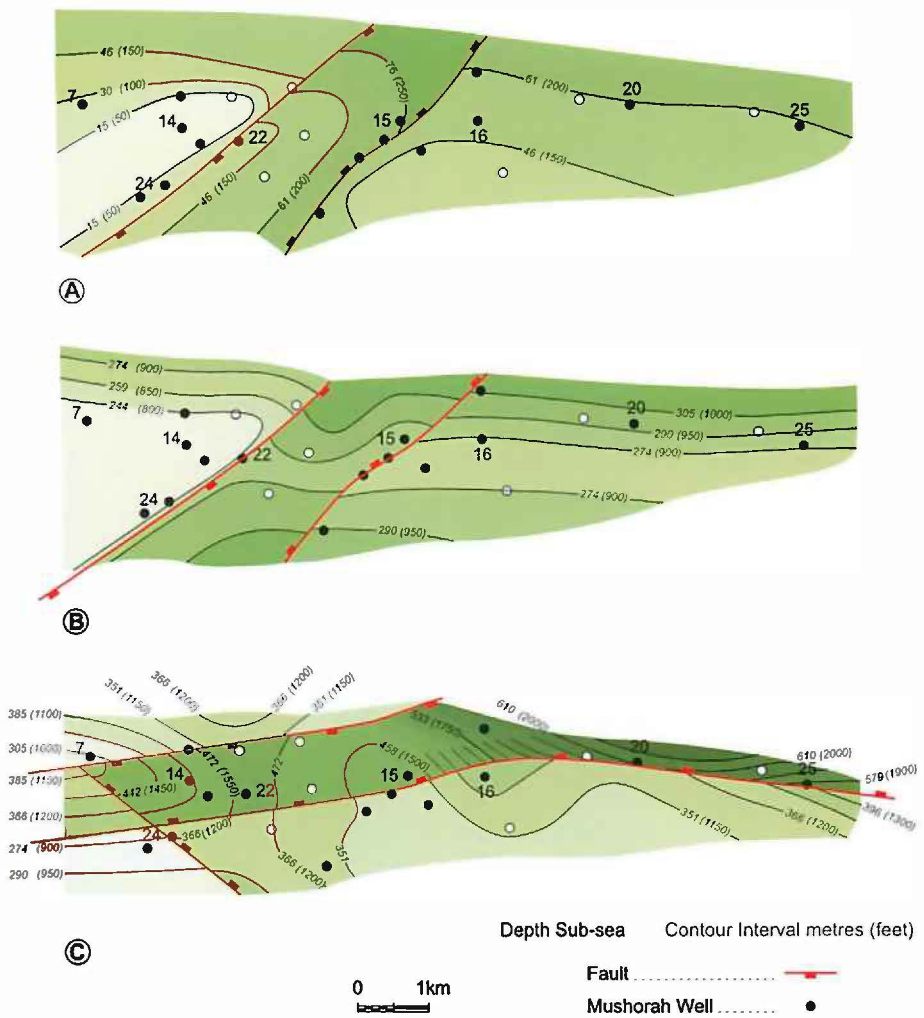


Fig. 9.5.27. Isopachs of the Shiranish Formation (First Pay: Campanian-Masstrichtian) at *Ain Zalah*. (a) Upper unit (?middle - upper Maastrichtian), showing SW-NE oriented graben and highs to the west and SE; (b) middle unit (?lower Maastrichtian) showing SW-NE oriented graben and highs to the west and east. (c) Lower unit (?upper Campanian) showing a WSW-ENE oriented graben traversing the centre of the field. After Hart and Hay, 1974.

the NE, along the present-day Iraq-Iran-Turkey border (Dunnington, 1955; Hart and Hay, 1974).

Ahmed *et al.* (1986) recorded intensive neomorphism towards the top of the Shiranish Formation. Stylolitic suturing is fairly common and probably post-dates calcite cementation of the fractures, since mineralised fractures rarely displace a stylolite seam (Dunnington, 1954).

Second Pay

The Second Pay at *Ain Zalah* comprises the lowest part of the Upper Cretaceous succession and the whole of the middle Cretaceous, a total drilled thickness of 1320 ft (402 m). The Second Pay has an irregular top that does not correspond to the surface anticline (Hart and Hay, 1974) (Fig. 9.5.28). Structure below the Cretaceous is unknown (El Zarka, 1993). In common with the First Pay, this is a fractured reservoir, and fractures are considerably more abundant in this interval than in the First Pay (Daniel, 1954). However, it differs in terms of lithological heterogeneity as it includes some intervals of porous dolomitic limestone.

The pay was discovered in 1949/1950 following the first deep test (Daniel, 1954). An apparently non-productive zone some 2000 ft (610 m) thick separates the two pay zones and forms an imperfect top seal for the lower reservoir. By 1954, two wells had reached the Second Pay (Daniel, 1954). Ahmed *et al.* (1986) recorded that six of the 28 wells drilled at *Ain Zalah* had reached the pay by the late 1980s.

Reservoir rocks are assigned to the Qamchuqa, originally defined as a formation but re-defined as a Group by Hart and Hay (1974), which is made up of the Mauddud, Gir Bir and Wajnah Formations. These formations are composed of recrystallised neritic limestones.The overlying Mushorah Formation is a pelagic oligosteginal wack-packestone with planktonic foraminifera including *Globigerina* and *Globotruncana* (Hart and Hay, 1974; Ahmed *et al.*, 1986).

Two unconformities within the reservoir section are present and are associated with dolomitisation of the underlying beds, but do not seem to have

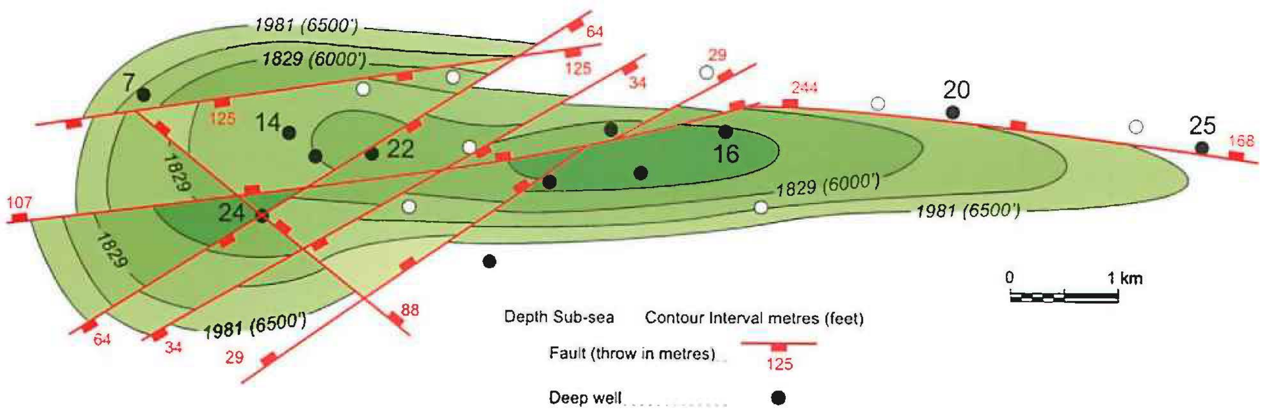


Fig. 9.5.28. Structural envelope at the top of the Second Pay in the *Ain Zalah* field. Note the complex, fault-compartmentalised structure. After Hart and Hay, 1974.

resulted in any effective secondary porosity. A major hiatus is present between the Lower Cretaceous and the Middle Jurassic but there is no evidence of extensive erosion.

Initial reserves in the Second Pay were estimated at 158 MM brl oil from material balance calculations (El Zarka, 1993). Estimated cumulative production as of 1974 was 146 MM brl oil.

Fracturing

Fracture systems at *Ain Zalah* have been extensively studied because of their critical importance to oil production. Fracture distribution has been inferred from mud loss data. Typical mud losses are relatively low and range from 370 to 1000 barrels/well (Daniel, 1954). Low mud losses were also however interpreted by IPC to indicate an abundance of fine fractures, which were sufficiently wide to allow mud to pass into them but which became blocked before large volumes of fluid were lost. The two most intensely fractured reservoir zones are associated with the elliptical area of maximum Cretaceous-Paleocene uplift (see Figs 9.5.25, 28).

Open fractures in cores were categorised as follows by Daniel (1954):

1. Bedding-parallel, calcite filled fractures;
2. Fractures at 30-35° to the long axis of the core;
3. Vertical to near-vertical fractures;
4. A poorly-developed fracture set dipping 65 to 70° relative to the long axis of the core.

Fracture widths vary from hairline up to about 18 mm. Little enlargement due to later dissolution is recorded (Daniel, 1954). Fracture fills, where developed, are a mixture of calcite and dolomite.

Daniel (1954) recognized that fractures were not necessarily genetically related to the growth of the *Ain Zalah* anticline during Miocene-Pliocene folding, and an earlier phase of fracturing was also recorded. He suggested that the calcite-filled fractures may contribute to oil production. Daniel (1954) noted that when the field came on production, pressure commuication was observed between the First and Second Pays. This suggests that the fracture systems in the two pay zones are interconnected with a fracture network apparently traversing some 2000 ft (610m) of intervening strata.

9. PETROLEUM SYSTEMS

vi. Tertiary: Migration and Leakage

About 16% of Iraq's oil reserves occur within the Cenozoic succession (Al-Sakini, 1992). The reservoirs at the first oil find in Iraq (*Naft Khanah*) and at the first major discovery (*Kirkuk*) are of Cenozoic age. However, successful development of Cenozoic resources in Iraq has been restricted to a narrow play fairway which is now largely developed. The ages of Cenozoic reservoirs varies almost without exception according to which formation lies beneath the middle Miocene Lower Fars Formation caprock at a given locality. Thus Paleogene reservoirs with light oil and gas are dominant NE of *Kirkuk*, while reservoirs to the west and south are of Neogene age.

Hydrocarbons in Cenozoic reservoirs in Iraq are now thought mainly to have migrated directly from mature Cretaceous and Jurassic source rocks into Eocene – lower Miocene carbonates which are sealed by middle Miocene evaporites (Fig. 9.6.1). Henson (1950a), Daniel (1954) and Dunnington (1955, 1958), writing before the thermal origin of oil had generally been accepted, suggested that oil in Tertiary reservoirs had first accumulated in Cretaceous and Jurassic stratigraphic traps, and had then leaked due to caprock failure during late Tertiary folding.

Source Rocks

Cenozoic source rocks (see Chapter 8 and Fig. 9.6.1) include the Paleocene – Eocene Akashat and Ratga Formations of the Western Desert of Iraq (Al-Bassam and Al-Haba, 1990; Al-Bassam and Karim, 1992); and the Pabdeh Formation of Iran (Bordenave and Burwood, 1990; Bordenave, 2002). In Iraq, the Paleogene Aaliji Formation may have source potential (Jassim and Al-Gailani, 2006), as may high API GR-log shales in the Serikagni Formation which are associated with Neogene evaporitic units (A. H. *pers. obs.*, 1988).

Maturity

The Upper Fars and Bakhtiari Formations of Late Neogene age are up to 4 km thick in SE Iraqi Kurdistan (Dunnington, 1958; Goff *et al.*, 1995) (Fig. 8.26, detail in Fig. 8.35). Rapid deposition of these formations in the Mesopotamian Basin resulted in thermal maturation of underlying source units (Pitman *et al.*, 2004). In Iran, the Pabdeh Formation is only mature locally in the NE of the Dezful Embayment (Bordenave and Huc, 1995). The formation is immature for oil generation on anticlinal crests, and is probably more mature in intervening synclines.

Reservoir rocks

The **Sinjar Formation** (early Eocene) is the oldest unit in the Cenozoic First Pay (the principal reservoir unit: see page 375) at *Kirkuk* , and has produced oil in the Khurmala and Avanah Domes (Daniel, 1954; IPC, 1956; Dunnington, 1967). The equivalent Sinan Formation produces oil at *Selmo* and *Silivanka* in Turkey (Dunnington, 1967). The Eocene **Avanah Formation**, also part of the First Pay at *Kirkuk,* produces oil at the Khurmala, Avanah and Baba Domes and at *Bai Hassan* (Daniel, 1954; IPC, 1956; Dunnington, 1967a). At *Kirkuk,* porosity and permeability are generally poor in these intervals (Majid and Veizer, 1986).

The middle-late Eocene **Pila Spi Formation** produces oil at the *Taq Taq* field to the NE of *Kirkuk* and forms the upper productive interval, with an oil column 180 m thick, at the *Tawke* field near Zahko in Iraqi Kurdistan*.

The Oligocene **Kirkuk Group** forms the main productive interval in the First Pay at *Kirkuk* (Avanah and Baba Domes) and at *Bai Hassan* (Daniel, 1954; IPC, 1956; Dunnington, 1958, 1967 (Fig. 9.6.2c). The Kirkuk Group reservoirs are discussed in Chapter 8.

The Miocene **Euphrates Formation** is the youngest unit in the First Pay at *Kirkuk* (Dunnington, 1967). It produces oil at *Bai Hassan,*

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* *International Oil Letters / IHS News,* 19.06.06; *Oil Voice,* 27.12.07.

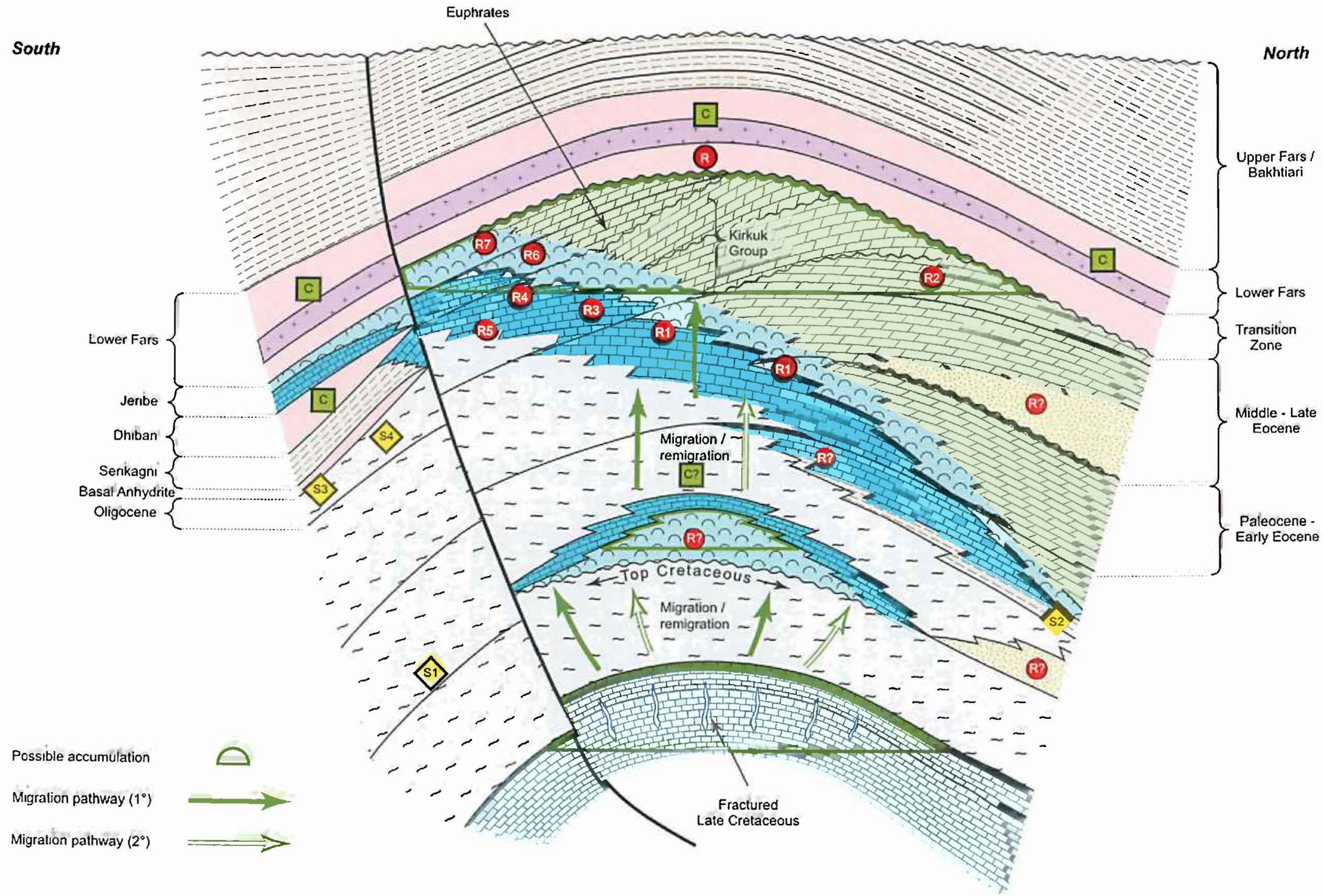


Fig. 9.6.1a. Schematic cross-section showing the main reservoirs and seals in Cenozoic plays in Iraq. Most production comes from late Neogene anticlines with a top seal provided by the Lower Fars Formation. The most productive reservoir intervals have well-developed matrix porosity and are highly fractured.

Reservoir rocks

		Ø	K	
R1	Eocene (Avanah Fm.)	5%		Kirkuk Field
R2	Pila Spi Fm.			5,000 b/d (Tawke-1) 11 MMscfg/d (Chem Chemal-2)
R3	Sheikh Alas (/ Shurau)	18%	108-200mD	up to 30,000 b/d / well
R4	Baba (/ Bajawan)	8%	20-30mD	
R5	Oligocene (general)	4 - 20% (Typical) 0 - 4% 4 - 10% 18 - 36% 8 - 18%	0 - 5mD 50 - 1000mD 0 - 10mD	Backreef Altered Backreef Recrystallised Fore-reef Turbiditic Basinal
R6	Euphrates	15 - 30% (mean 20%)	8 - 500mD (mean 10mD)	
R7	Jeribe	8 - 38% (mean 23%) 17 - 28% max 14 - 21% (mean 17%)	0.1 - 200 (mean 10)mD 1 - 1146 (mean 200)mD	East Baghdad Jebissa (Syria), 60m thick Un-named Iraq
R8	Transition Zone	0 - 30% (Typical 15 - 20%)	100mD	

Source rocks

S1	Aaliji ?	Suggested, not proven		
S2	W. Desert, Akashat, Ratga	TOC 1.68 - 2.14, HI 382 - 474, PI 0.01	S1 0.03 - 0.04, PP 6.64 - 10.19,	S2 6.6 - 10.16 T_{max} 412 - 415
S3	Pabdeh, Iran	TOC 1.0 - 12.0,	Type IIs, 7 - 40kg / tonne	
S4	Serikagni	Oil bleed in core		

Cap rocks (seal)

C

Fig. 9.6.1b. Legend to Fig. 9.6.1a and compilation of available numerical data relating to the Tertiary petroleum system.

Jambur and *Naft Khanah* (Daniel, 1954; IPC, 1956; Dunnington, 1967a; Jassim and Al-Gailani, 2006); it contains heavy oil at *Qasab, Jawan, Najmah* and *Qaiyarah* (Dunnington, 1967a). Reservoir quality improves towards the top of the formation (Fig. 9.6.2b). The formation may form a reservoir in more basin-centre locations than the Kirkuk Group, and may be important in Central Iraq, e.g. at *East Baghdad, Balad, Samarra* and *Tikrit.*

The Miocene **Jeribe Formation** produces oil at *Jambur* and *Naft Khanah* (Dunnington, 1967a), and contains heavy oil at *Qasab, Jawan, Najmah* and *Qaiyarah* (Dunnington, 1967a), and minor oil in the Euphrates Graben (de Ruiter *et al.*, 1995) and in the *Jebissa* field of NE Syria (Metwalli *et al.*, 1972). Both primary and secondary (dolomitization-related) porosity is present (Jassim and Al-Gailani, 2006). At *East Baghdad*, extensive sheet-like intervals of anhydrite are interbedded within the reservoir carbonates (Al-Murani, 1986; Sun and Esteban, 1994) (Fig. 8.23). In common with the Jeribe Formation, the Euphrates Formation has reservoir potential in basin-centre locations such as *Tikrit, Balad* and *Samarra.*

The "Main Limestone" produces oil at the *Judaida, Khabbaz, Ajeel* and *Hamrin* fields in north-central Iraq, and at *Jebel Fauqi, Halfaiya* and *Buzurgan* in SE Iraq (Jassim and Al-Gailani, 2006). Most of the production in these fields may come from the Miocene Euphrates and Jeribe Formations.

Other formations

Goff *et al.* (1995) noted that in the Zagros foreland outside the area sealed by the Lower Fars Formation, only a single oilfield produces from a Cenozoic reservoir, namely *Wafra* in Kuwait (Fig. 9.6.3). The reservoir here is the Eocene Wafra

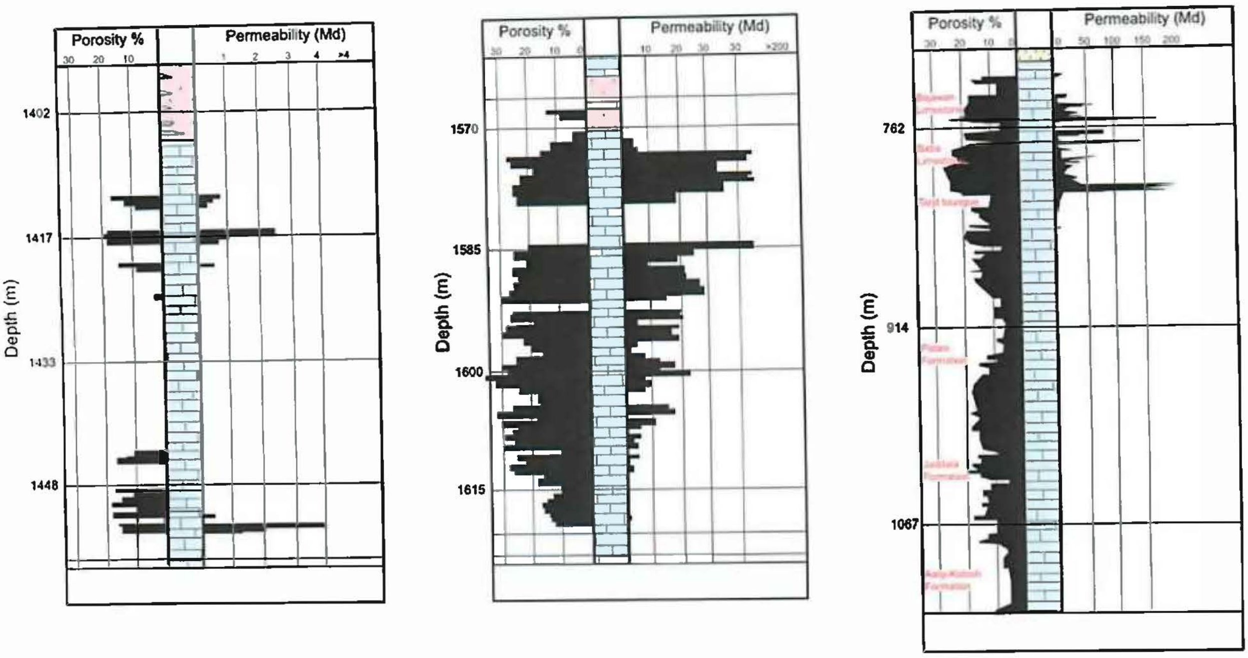


Fig. 9.6.2. Profiles of porosity/ permeability of (a) the Jeribe Formation at *Jambur* field; (b) the Euphrates Formation at *Jambur*; and (c) the "Main Limestone" at *Kirkuk*. After Jassim and Al-Gailani, 2006.

Limestone (in fact an anhydritic dolomite), sealed by the Rus Formation (Gutteridge *et al.*, 2000).

In NE Iraq, the Paleogene siliciclastics and carbonates of the Kolosh and Gerçus Formations may locally have reservoir potential. Jassim and Al-Gailani (2006) noted that oil is present in the Gerçus Formation in well *Demir Dagh-1*. The detailed stratigraphy of these formations is not known and their reservoir (and seal) potential is therefore a matter of speculation.

The Transition Unit at the base of the Lower Fars Formation contains thin beds of limestone which are often overpressured, and which may contain significant volumes of hydrocarbons. Minor production from the Lower Fars takes place in the Mosul area (Jassim and Al-Gailani, 2006). The formation contains gas at *Chia Surkh*, and oil and gas at *Gilabat, Khashim Ahmar* and *Mansuriya* in northern Iraq. Oil is produced at *Ajeel* in central Iraq, and at *Zubair, Rumaila, Suhain, Majnoon, Nahr Umr* and *Kifl* in the south (Jassim and Al-Gailani, 2006).

In SE Iraq, Paleogene shelf margin carbonates of the Damman and the overlying Neogene Ghar Formations form potential reservoirs at the *Nahr Umr* and *Zubair* fields (Dunnington, 1967a). At *Wafra* in Kuwait, there are two reservoir zones in the Dammam Formation and two in the Umm Er Radhuma (Dunnington, 1967a). The Dammam Formation also forms a reservoir at *Fuwaris* (Dunnington *et al.*, 1967). The Umm Er Radhuma, Damman and Ghar Formations may have reservoir potential on the SW margin of the Mesopotamian Basin where they occur as lowstand platform deposits in front of the main platform margin.

Seals

The thick, evaporitic Lower Fars Formation provides a top seal for the major Cenozoic discoveries in the Mesopotamian Basin (Goff *et al.*, 1995) and Dezful Embayment (Aqrawi *et al.*, 2006a) (Fig. 9.6.3). Oil columns of several hundreds of metres can be supported; at *Gachsaran* in Iran, the oil column was 2180 m high (Slinger and Crichton, 1959).

Potential secondary seals include the Dhiban Formation and the Rus Formation (lower Eocene) which forms the seal at *Wafra* (Beydoun, 1988b; Goff *et al.*, 1995).

Basinal carbonates, terrigenous shales or lagoonal/tidal flat carbonates may form baffles to fluid migration. Thus in the Kirkuk Group at *Kirkuk* field, production comes from two fore-reef intervals separated by non-pay (Daniel, 1954). Barriers may be present in the Gerçus and Kolosh Formations, but little data is currently available on the importance of these units within producing fields.

Migration of oil and gas

Migration to Cenozoic reservoirs has taken place along vertical pathways from underlying Mesozoic source rocks. Indirect evidence for this is that Cenozoic oil and gas accumulations are generally located directly above modelled areas of mature source rock (Pitman *et al.*, 2004).

There is considerable evidence for vertical remigration of oil from palaeotraps to Cenozoic reservoirs. This evidence includes both geological

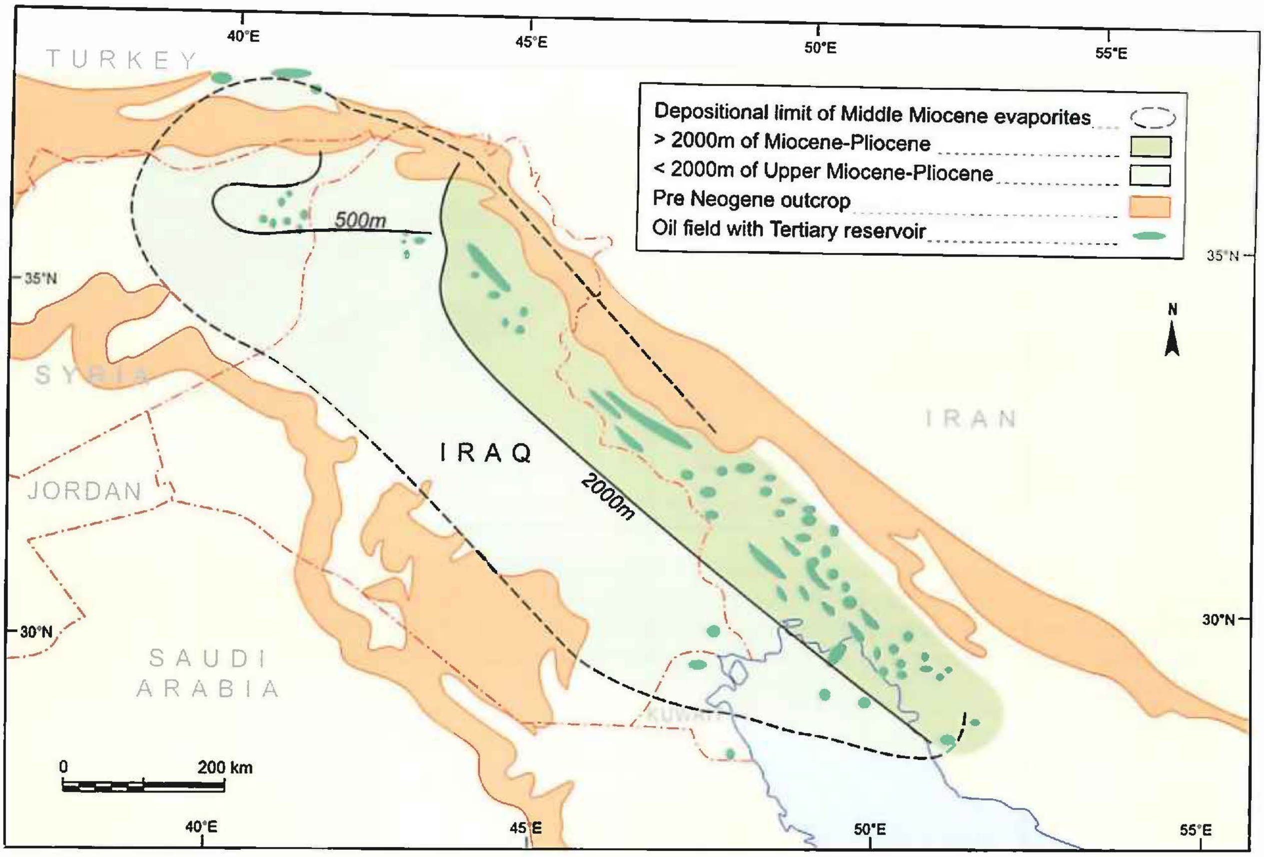


Fig. 9.6.3. Summary map of Iraq and nearby areas showing the distribution of Cenozoic fields which are dependant on the regional seal provided by the Lower Fars/ Gachsaran evaporites. After Goff *et al.*, 1995.

observations (Henson, 1950a; Daniel, 1954; Dunnington, 1958; Al-Mashadani, 1986; Beydoun *et al.*, 1992), and oil gravity and compositions (Lees, 1950; Dunnington, 1958; Thode and Monster, 1970; Al-Shahristani and Al-Atyia, 1972; Al-Shahristani and Hanna, 1974). Dunnington (1958, 1967a, 1975) suggested that palaeotraps formed at or near the *Ain Zalah, Butmah, Jawan, Najmah, Qasab* and *Qaiyarah, Bai Hassan* and *Kirkuk* fields (Figs. 9.6.4, 9.6.5a,b and 9.6.6).

Seals above palaeotraps may have been breached due to tectonic fracturing during Zagros deformation (Dunnington, 1958; Beydoun *et al.*, 1992; Al-Shdidi *et al.*, 1995), allowing upwards migration of Jurassic- and Cretaceous-sourced oils (Fig. 9.5.1). The similar geochemical characteristics of Tertiary and Jurassic-Cretaceous oils suggest a similar origin, probably in source rocks in the Sargelu Formation (and Naokelekan, Barsarin / Gotnia Formations) and the Chia Gara Formation.

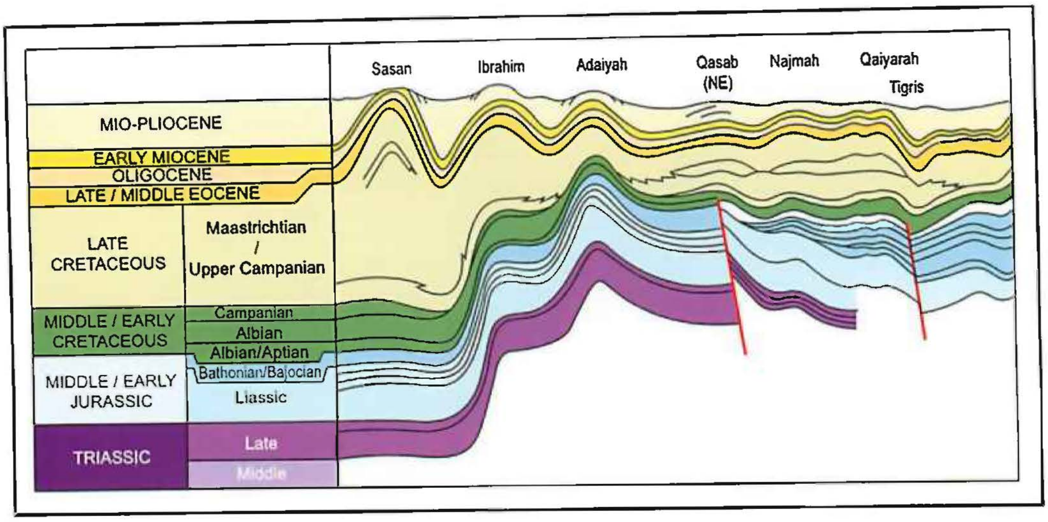
Entrapment of oil and gas

About 500 m of late Neogene uplift and erosion is estimated to have occurred in the Mesopotamian Basin, increasing to up to 1500 m in the Zagros area (Pitman *et al.*, 2004), and 2000 m near the Thrust Belt. Insley (2007, *pers. comm.* to A. H.) noted that satellite imagery indicates that structures in the High Folded Zone may be uplifted by some 1600 m compared to adjacent structures in the Low Folded Zone. The structures are commonly eroded to the top of the Eocene Pila Spi Formation. This uplift may have resulted in the degassing of oils and the leakage of petroleum from traps. Seal failure will cause a gas cap to bleed-off from the crestal part of an anticline, resulting in surface seeps such as those at *Baba Gurgur (Kirkuk)* (see Plate 9.6.3).

Traps containing proven Cenozoic oil accumulations are structural. They can be divided into Zagros anticlines; traps in central Iraq associated with strike-slip faults; and north-south oriented structures in southern Iraq.

1. Zagros Anticlines

Major NW-SE to west-east anticlines form the main trap types in northern and NE Iraq, and result from late Neogene compression during Zagros deformation. A few anticlines are interpreted as inversion structures. The onlap of Paleogene carbonates onto eroded Cretaceous anticlines in NW Iraq such as Jebel Sinjar (van Bellen, 1959; Kennedy and Lunn, 2000) and *Ain Zalah* (Hart and Hay, 1974) indicates repeated uplift and erosion of pre-existing palaeostructures. Fold geometries and geophysical surveys also indicate that structures such as Jebel Pulkhana and Jebel Jaria Pika are probably inverted anticlines (Hradecky *et al.*, 1978). Folds formed as a result of reverse movement on pre-existing extensional faults (Ameen, 1992;



Figs. 9.6.4a. Generalized cross-section along the NE margin of the Khleisia High, NW Iraq (after Dunnington, 1975) illustrating the geometry of structures now interpreted as inversion anticlines. Higher relief structures correspond to greater thicknesses of section in pre-inversion (Late Cretaceous) basins. Lower relief structures (Qasab to Qaiyarah) correspond to pre-inversion palaeohighs.

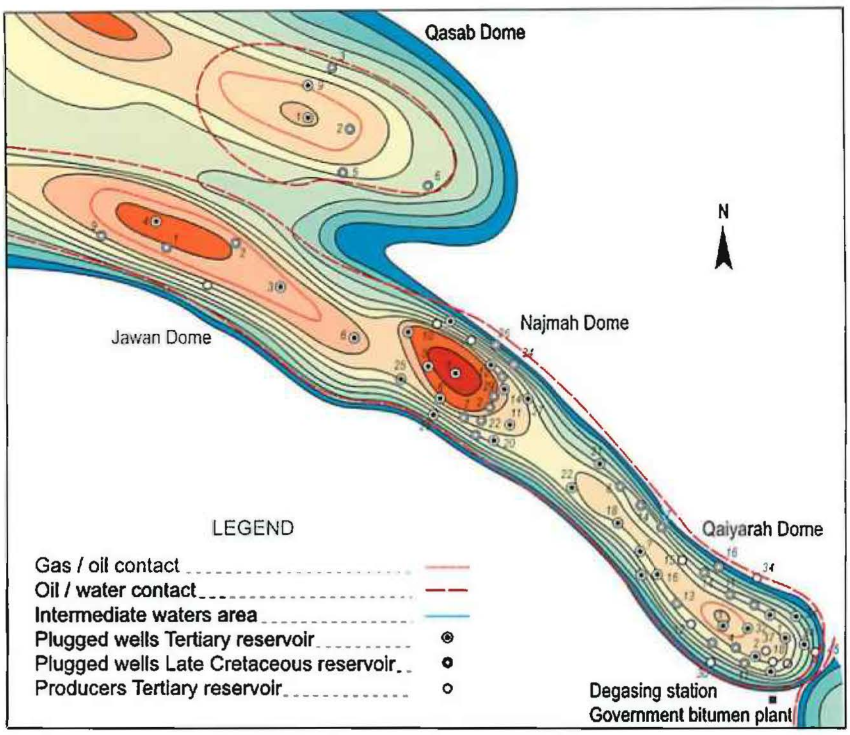


Fig. 9.6.4b. Map of the *Jawan-Najmah-Qaiyarah* field complex north of Mosul. Structure contours show the presence of separate culminations within a larger-scale anticlinorium. After Dunnington, 1975.

Hessami *et al.*, 2001). They probably originated during latest Cretaceous inversion (Dunnington, 1955), and may have been overprinted in the late Paleogene and again in the late Neogene during Zagros deformation (Pitman *et al.*, 2004. Recent studies (Haddad and Ameen, 2007) have shown that the *Chemchemal, Pulkhana, Jambur, Bai Hassan, Qarah Chauq,* and *Khabbaz* anticlines may be associated with inversion of Senonian half-graben (Fig. 9.5.10).

2. Traps in Central Iraq associated with strike-slip faults

The structures at the *East Baghdad, Balad, Samarra* and *Tikrit* fields are related to a strike-slip fault zone in Central Iraq (Aljawady, 1993; Sadooni, 2004).

3. North-south oriented traps in southern Iraq

Basement controlled and salt-influenced anticlines in the Basra area probably underwent further

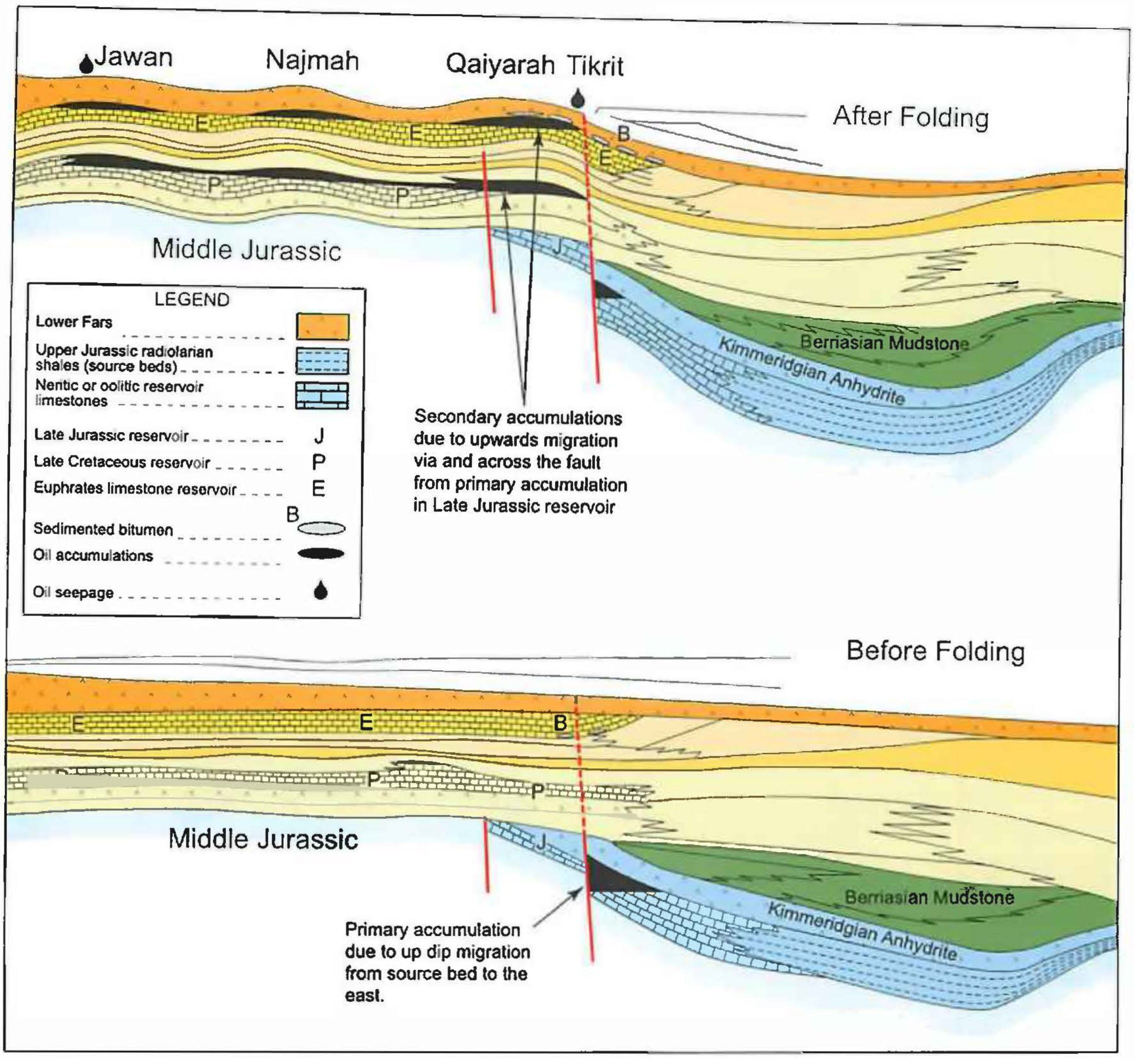


Fig. 9.6.4c. Summary cross-sections showing a model of oil remigration and the evolution of traps at the *Jawan-Najmah-Qaiyarah* field complex. After Dunnington, 1958. The model assumes that oil was initially reservoired in the Najmah Formation downdip of the Qaiyarah area; the oil then remigrated to the NW across the Tikrit fault following late Neogene structural deformation.

structural growth in late Miocene time synchronous with the Zagros folding. The main phase of structural growth of these anticlines, however, had occurred earlier, in Late Cretaceous time.

4. Stratigraphic traps

No purely stratigraphic traps with Cenozoic reservoir rocks have so far been proven in Iraq. However, such traps may occur where early Paleogene platform carbonates were deposited on the crests of inverted Late Cretaceous graben such as Jebel Sinjar in Iraq, and Jebels Abd El Aziz and Bishri in Syria. If Paleogene carbonates are overlain by deep-water deposits, as at Jebel Sinjar, they may form stratigraphic traps. Unfortunately, examples of these relationships to-date have come from breached surface anticlines and not from intact subsurface traps.

Potential stratigraphic traps may also occur in the NE basin margin in the Kolosh and Gerçus Formations, where downdip sandbodies or reefal carbonates may be enclosed by deepwater shales.

Oils in fields and seepages

Cenozoic reservoirs contain petroleum with a range of API gravities. Heavy oil occurs in Neogene reservoirs in the central and western parts of the Mesopotamian Basin, including the *Abu Ghirab, Abu Jir, Halfaiya, Ajeel, Nahr Umr, Majnoon, Rumaila, Sadid, Sindabad, West Qurna* and *Zubair* fields (Jassim and Al-Gailani, 2006). Jassim and Al-Gailani (2006) noted that oils in Cenozoic reservoirs comprise both high-API oils (and gas) in NE Iraq, particularly in the Foothills Belt, and low-API (18-20°API) sulphur-rich oils around the Mosul High and in southern Iraq. These variations are due to differences in source rock maturity and to the effects of biodegradation.

The characteristics of the oils in subsurface accumulations and surface seepages are summarised in Figs. 9.6.7 to 9.6.13. Oils in Paleogene reservoirs (Figs. 9.6.7, 8, 9) at the *Kirkuk* and *Bai Hassan* fields generally range from 34-36° API (Daniel, 1954; IPC, 1956; Dunnington, 1967a).

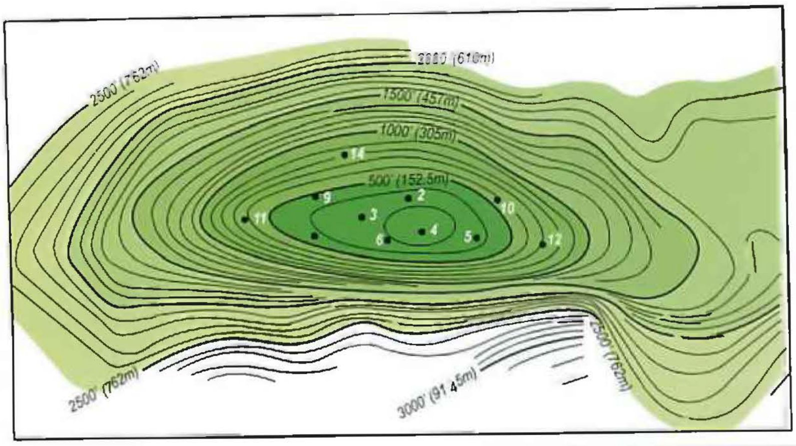


Fig. 9.6.5a. Structure contour map of the top-Cretaceous at the *Butmah* field. After Dunnington, 1975.

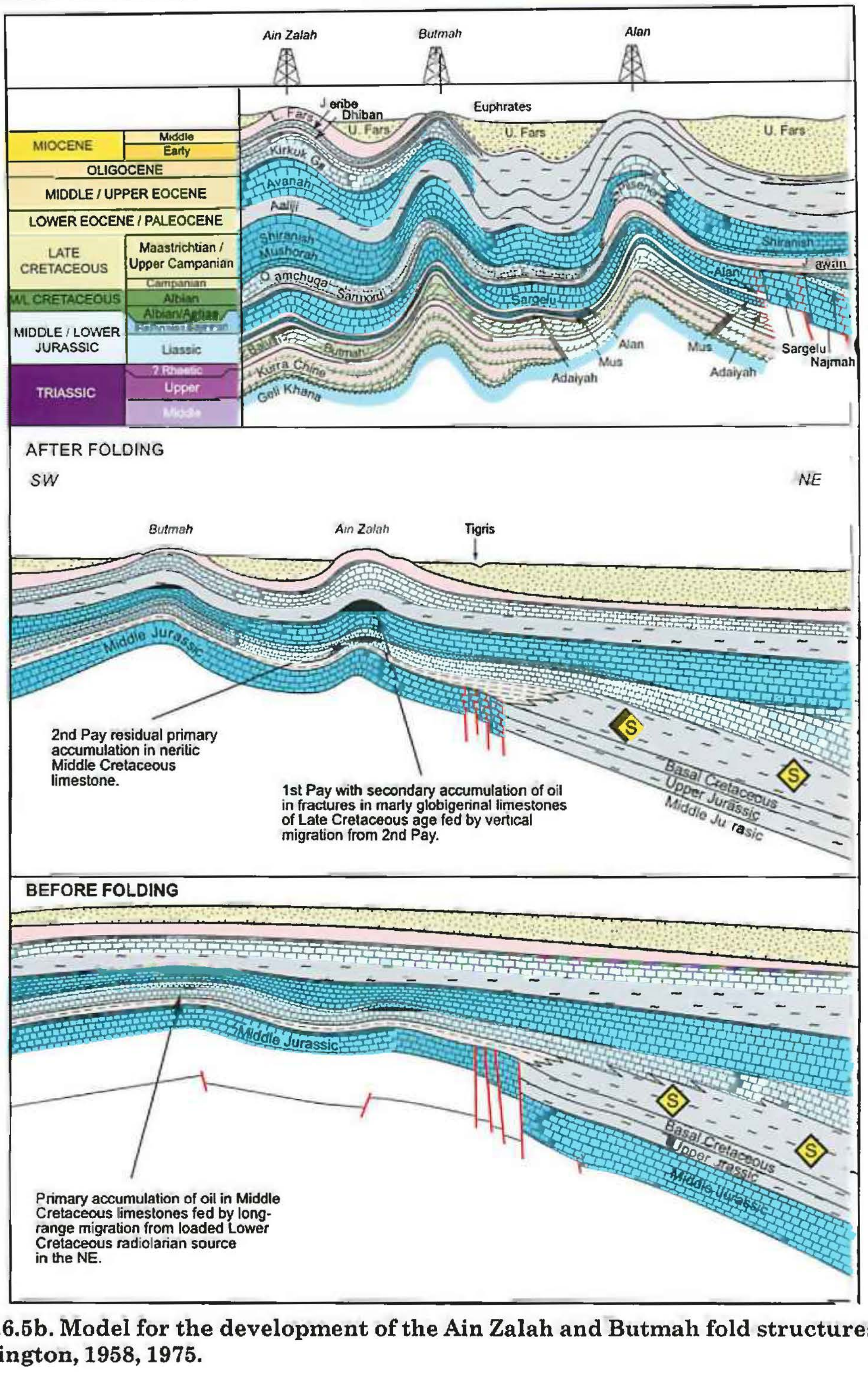


Fig. 9.6.5b. Model for the development of the Ain Zalah and Butmah fold structures in NW Iraq. After Dunnington, 1958, 1975.

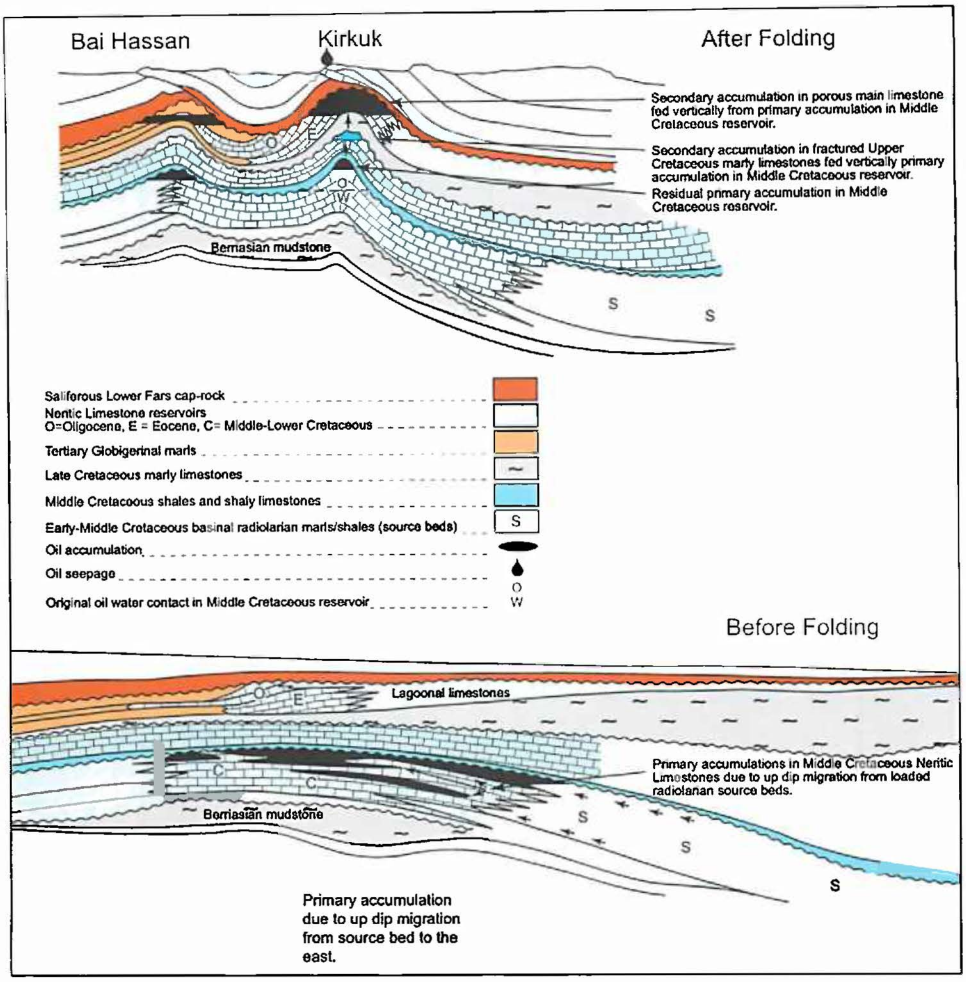


Fig. 9.6.6. Model of oil remigration, and the evolution of anticlines, in the *Kirkuk* area (after Dunnington, 1958). The model envisaged that Cenozoic (Kirkuk Group) structures contain oil which has remigrated from older Cretaceous fractured carbonate reservoirs (Qamchuqa Formation).

At *Kirkuk,* oils are variable, reflecting along-strike differences in the position of the OWC and the height of the structures. Heavy crudes are trapped in calcite-sealed vugs (Henson, 1950a; Daniel, 1954; IPC, 1956). Original GORs in this reservoir were 200-220 cu. ft/brl (IPC, 1956). By contrast, oils in the Tertiary reservoir at the *Tawke* field have an API of 25° and have low GORs*.

On the Mosul High, Neogene reservoirs in the Euphrates and Jeribe Formations (Figs. 9.6.10 and 11) contain heavy oils resulting from biodegradation and water-washing due to seal breaching and flushing of reservoirs by freshwaters (Jassim and Al-Gailani, 2006). Oil gravities are 11°-19° API at *Qasab,* 17° at *Jawan,* 11-18° at *Najmah,* and 15° at *Qaiyarah* (Dunnington, 1967a). The Euphrates Formation oil has a sulphur content of 1.5 to 3.97% (mean: 2%) while that in the Jeribe has a sulphur content of 0.4-7.1% (Jassim and Al-Gailani, 2006). Neogene reservoirs are intimately associated with numerous active seeps and sulphur deposits (Jassim *et al.,* 1999; Jassim and Al-Gailani, 2006).

Oils produced from Neogene reservoirs to the NE are light (Figs. 9.6.10 and 11). In the Baba Dome of the *Kirkuk* field, and the *Bai Hassan* field, oils have the same gravities (34-36°API) as those in underlying Paleogene reservoirs, since there is no intervening seal. To the SE, where the source rocks are more mature, oil gravities are lighter and 40-41°API oil occurs at *Jambur.* At *Naft Khanah,* reservoirs of the same age contain 42° API oil (Daniel, 1954; IPC, 1956; Dunnington, 1967a).

In southern Iraq, Neogene oils have gravities of about 20°API and are probably generated by mid-mature Cretaceous source rocks (Jassim and Al-Gailani, 2006). At *Nahr Umr,* oils are 15-20° API in the Ghar Formation (Fig. 9.6.10), the overlying Lower Fars (Fig. 9.6.12) and the underlying Dammam Formation (Fig. 9.6.8). At *Zubair,* oils are 10-15° API (Dunnington, 1967a). In the overlying Transition Beds of the Lower Fars, oils are similarly heavy (<22°API) due to biodegradation (Jassim and Al-Gailani, 2006) (Fig. 9.6.12).

Oils in surrounding countries resemble those in nearby parts of Iraq. In the *Wafra* field of Kuwait, the Dammam Formation (Fig. 9.6.8) and the Umm Er Radhuma (Fig. 9.6.7) contain 16-18° API oils (Dunnington, 1967a). At *Fuwaris,* 17-19°API oils are present in the Damman Formation (Dunnington, 1967a).

* *OilVoice,* 27.12.07.

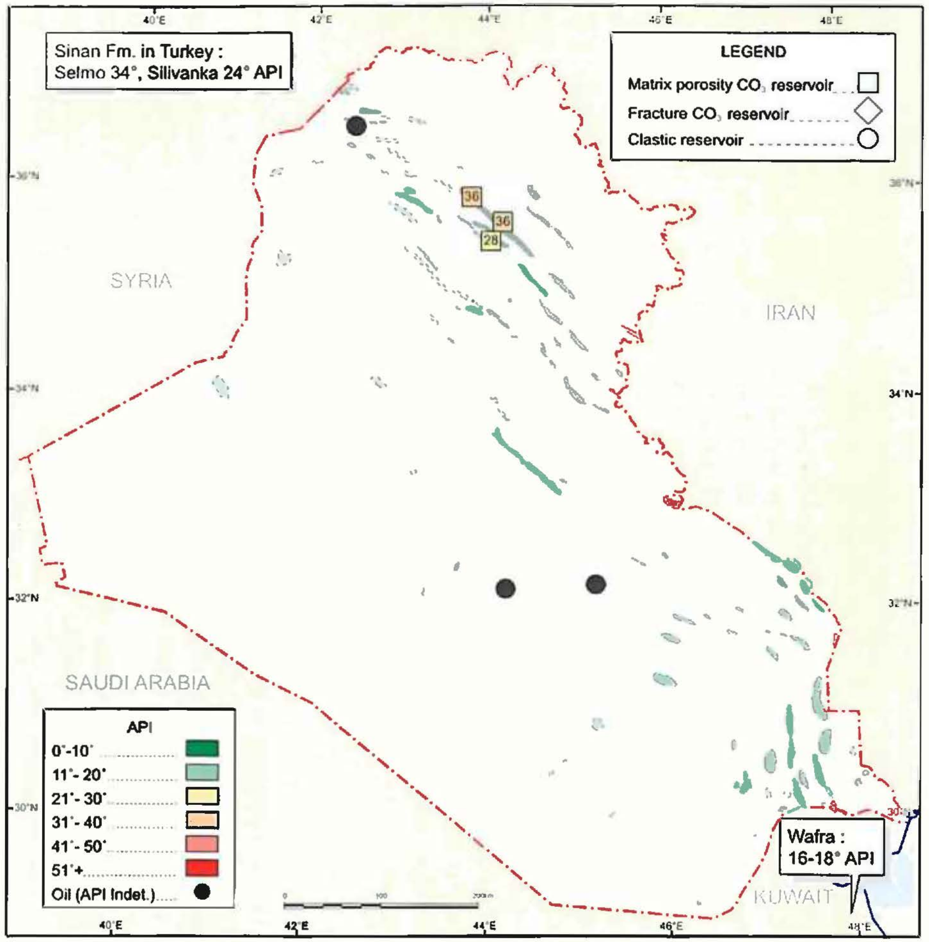


Fig. 9.6.7. Map showing the occurrence of oil in Paleocene – middle Eocene reservoirs in Iraq. Note the high concentration of occurrences in the *Kirkuk - Bai Hassan* area.

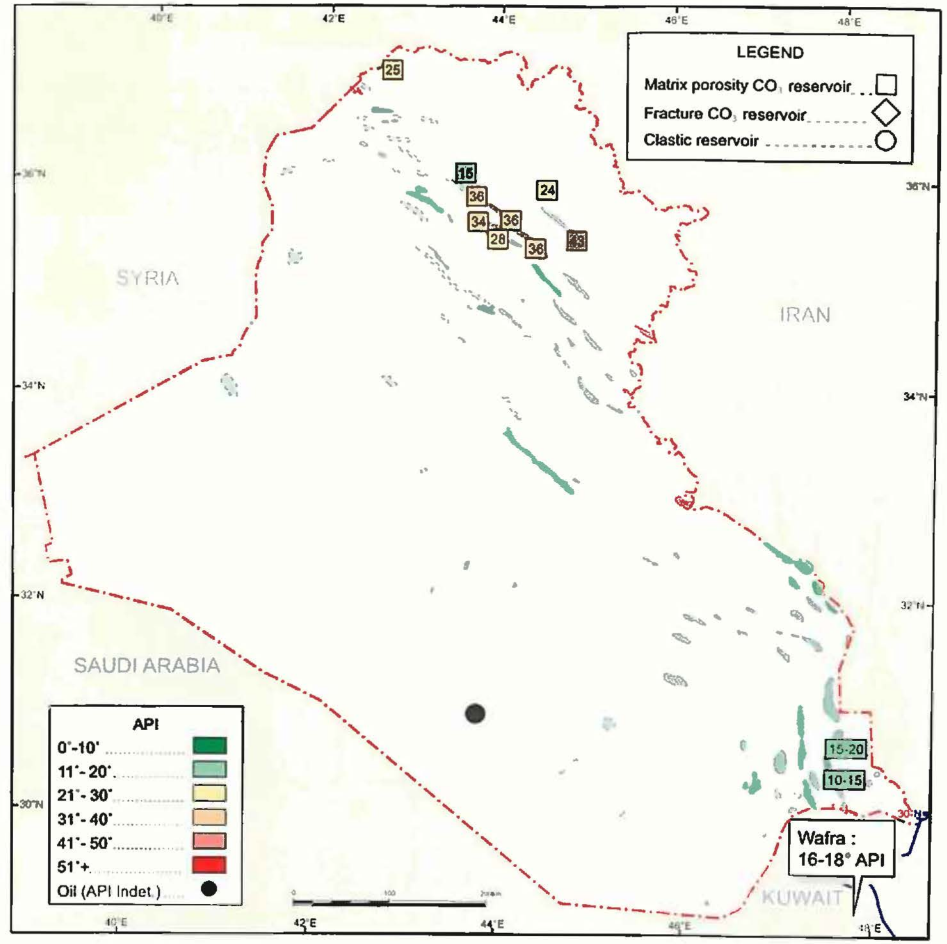


Fig. 9.6.8. Map showing the occurrence of oil in middle – late Eocene reservoirs in Iraq. Petroleum in reservoirs of this age is more widespread than that in Paleocene- middle Eocene reservoirs (Fig. 9.6.7). Middle- late Eocene reservoirs in NE Iraqi Kurdistan have a Lower Fars topseal (e.g. the Tawke, Taq Taq and Chemchemal structures).

In Iran, Cenozoic Pabdeh-sourced oils have been identified in the *Agha Jari* field by the use of biomarkers (Bordenave and Huc, 1995). The presence of 18αβ(H) oleanane in oils from this field, indicates the presence of terrigenous higher plant material in the precursor source rocks. No similar biomarker studies of oils in Cenozoic reservoirs in Iraq have yet been undertaken.

Seepages

Oil seeps in Iraq are located in Fig. 9.6.13. Hydrocarbon seepages and seepage-related features occur in three main areas: the Salman Zone in Central Iraq, the Mosul area, and the Zagros fold-and-thrust belt in the NE.

(i) The Salman Zone

Seepages in the Salman Zone are located along the western boundary of the Mesopotamian Basin. The seepages are situated on the north-south trending Abu Jir fault zone. Here, bitumen lakes around 2 km in diameter are located at Abu Jir, Ain Jabha, Ain Hit and Ata'it. Nearby, bitumen-rich intervals are interbedded within the marls and carbonates of the Lower Fars Formation. Seepage activity began in the middle Miocene and a substantial volume of oil has since been lost to the surface (Jassim and Al-Gailani, 2006). In the Hit area, the Lower Fars Formation has been eroded down to the top of the underlying Euphrates Limestone. The area was mapped by Noble and Evans in 1919-1920 (Noble, 1954). They found that two "bands" of bitumen (0.3-0.5 m thick) mixed with gypsum occur about 6 and 12 m, respectively, above the base of the Lower Fars Formation on the east bank of the Euphrates river. The lower band can be traced over a distance of 6 km and is estimated to have a minimum area of 50 sq. km. The seepages originate in bitumen-saturated limestone beds in the Euphrates Limestone Formation. Pits in the limestone contain springs of sulphur-bearing water in which lumps of solid bitumen occur. Eight km NW of Hit is a bitumen lake about 200 m across in which gas and solid lumps of bitumen rise to the surface. Bitumen-impregnated beds occur in the Lower Fars Formation nearby in the Awasil area, indicating that generation and migration had begun here by the middle Miocene (Dunnington, 1958).

At locations in the SW Desert, karstic features (dolines) are lined with sulphur, and sulphur deposits have been mined for many centuries (Al-Naqib, 1967). The largest of these is at Ain Kibritia (Fig. 9.6.13) (Al-Naqib, 1967; Jassim and Al-Gailani, 2006). The dolines are thought to have originated by hydrocarbons migrating upwards and causing sulphate reduction of the evaporites in the Rus Formation where it is buried at shallow depths and has been affected by surface (meteoric) waters. Both acidic groundwaters that enhance karstic activity and native sulphur are products of sulphate reduction (Jassim and Al-Gailani, 2006).

(ii) The Mosul area

The occurrence of bitumen and sulphur in the Lower Fars Formation in the Mosul area was first reported by Pascoe (1922) who recorded the occurrence of sulphur in the tops of cliffs in a branch of the River Tigris above its confluence with the Greater Zab River (Fig. 9.6.14). A lake here contained yellow, sulphur-rich waters smelling strongly of H_2S; the Arabic name (*Nafoorat Jahannam*) for the locality is translated as "the Fountain of Hell". A seep of tarry oil occurs in a valley about 2 km to the west, and another seep is located in the same valley near the junction with the Tigris. At least four centres of native sulphur deposits are located nearby (Al-Sawaf, 1977; Jassim *et al.*, 1999). These are related to oil seepages from the Lower Fars Formation.

"Gach-e turush" is a Kurdish phrase describing sulphur-rich soils (the English translation is "sour soil" or "bitter soil"). Sulphates are reduced during near-surface bacterial oxidation of hydrocarbons (mainly gas), with the formation of H_2S which undergoes further bacterial oxidation to form free sulphur (Jassim and Al-Naqib, 1989; Bordenave, 2008). It has been estimated that the approximately 1 B tons of sulphur deposits present in northern Iraq required a supply of some 5-10 B brls of oil for their formation (Jassim and Al-Gailani, 2006).

The sulphur deposits of the Mishraq anticline (Fig. 9.6.15) have been described by Sokolov (1965), Lein *et al.* (1975), Al-Sawaf (1977), Barker *et al.* (1979), and Jassim *et al.* (1999). Sulphur occurs here in the "Productive Series" or "Productive Member" (60–140 m thick) of the Lower Fars Formation. The Productive Member comprises bituminous dolomites, limestones and marls, with three sulphur-bearing limestone intervals which pass laterally into gypsum/anhydrite. The upper part of the unit crops out on the west bank of the Tigris River. The NW part of the Mishraq anticline contains a 5 m thick, low pressure (2–3 atm) sour gas reservoir in limestones of the same member. The gas composition is 63% methane and ethane, 24% H_2S and 13% CO_2 (Barker *et al.*, 1979). Sulphur-bearing limestones in the Productive Member contain up to 10% bitumen (average content is 2%) (Barker *et al.*, 1979). The limestones are karstified and groundwater flow occurs through secondary porosity, caves and joints.

Pascoe (1922) described hot, sulphur-rich springs at **Hammam Al-Alil** (Fig. 9.6.14). The temperature of these waters is 48°C (Al-Sawaf, 1977). Traces of tarry oil and ropey strands of bitumen rise to the surface in several of the springs. The bitumen is collected and used locally for medicinal purposes. Pascoe (*ibid.*) also mapped four areas of seepage in the **Qaiyarah** area (Fig. 9.6.13),

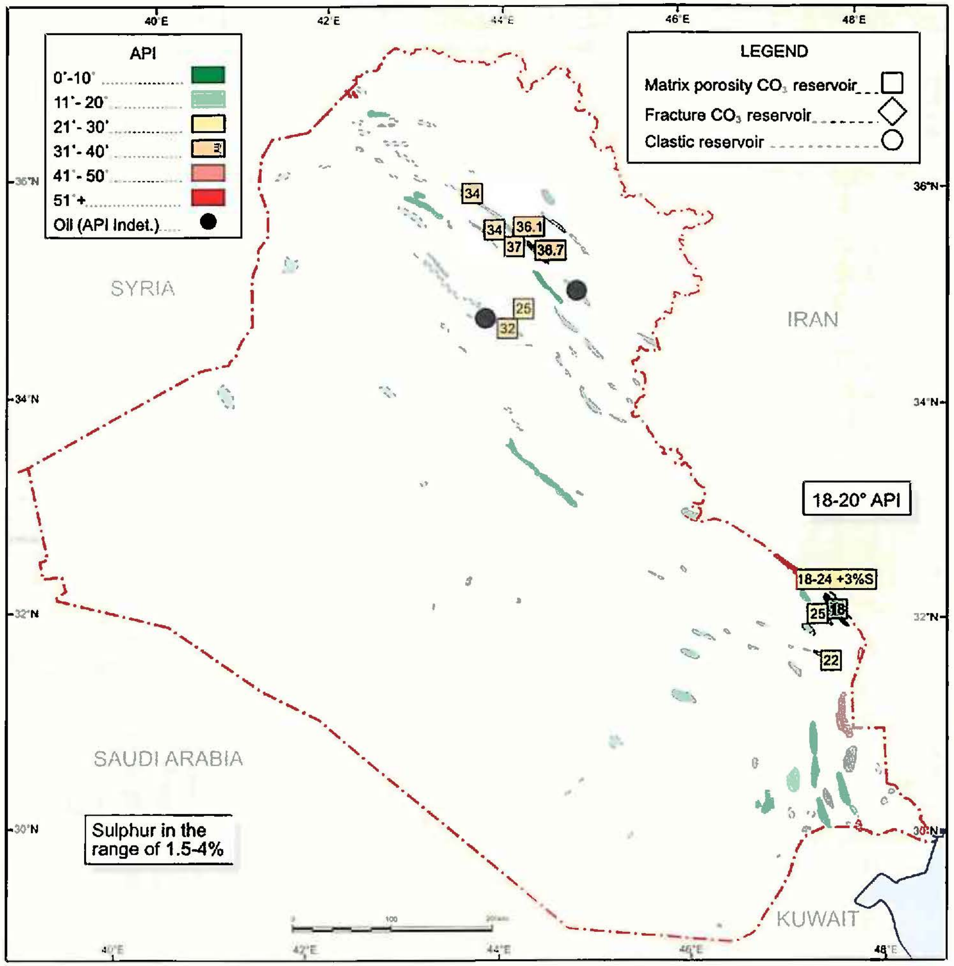


Fig. 9.6.9. Map showing the occurrence of oil in Oligocene (Kirkuk Group) reservoirs in Iraq. Note the presence of relatively light oil in fields in northern Iraq, and heavy oils in the SE of the country (north of Basra).

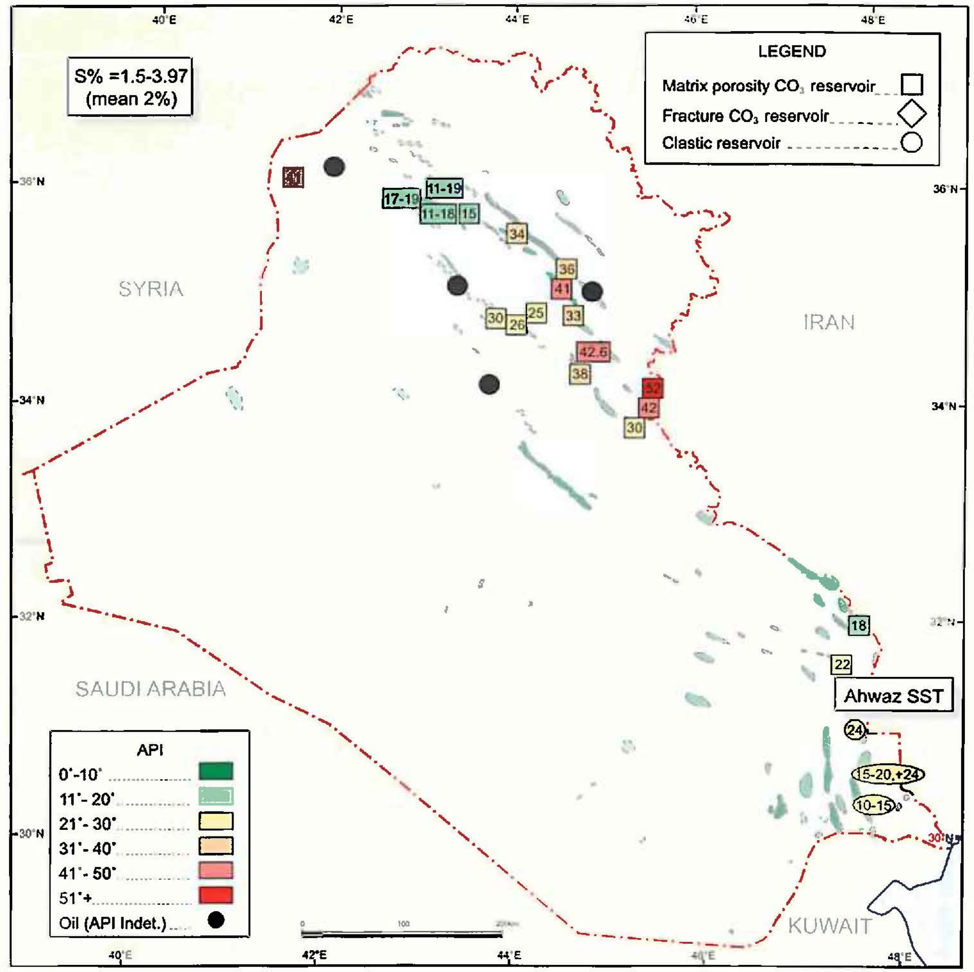


Fig. 9.6.10. Map showing the occurrence of oil in early Miocene (Euphrates and Ghar Formation) reservoirs in Iraq. Note the presence of heavy oils in the Mosul area; medium-API oils in the Hamrin area and in southern Iraq; and light oils, condensates and gases around Naft Khanah (and towards the Syrian frontier).

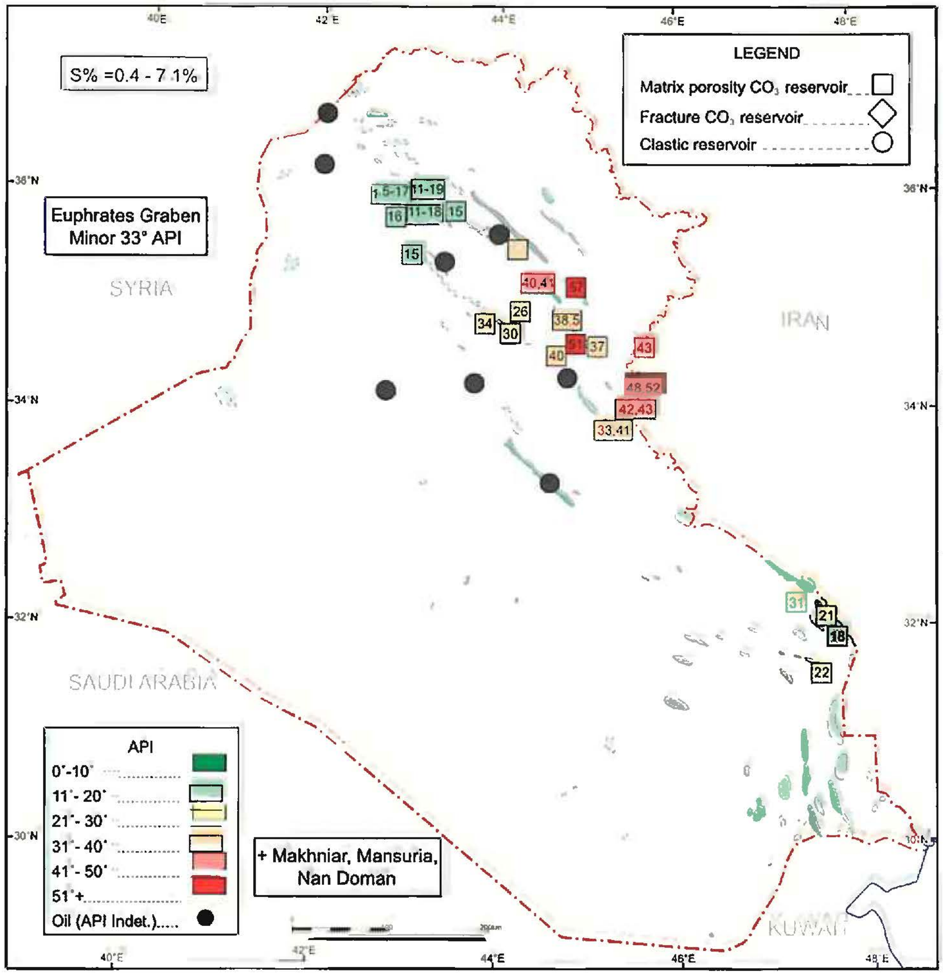


Fig. 9.6.11. Map showing the occurrence of oil in early Miocene (Jeribe Formation) reservoirs in Iraq. The distribution of oils of different API gravities is similar to that in the Euphrates Formation (Fig. 9.6.10), suggesting that the intervening Dhiban Formation is not an effective regional seal.

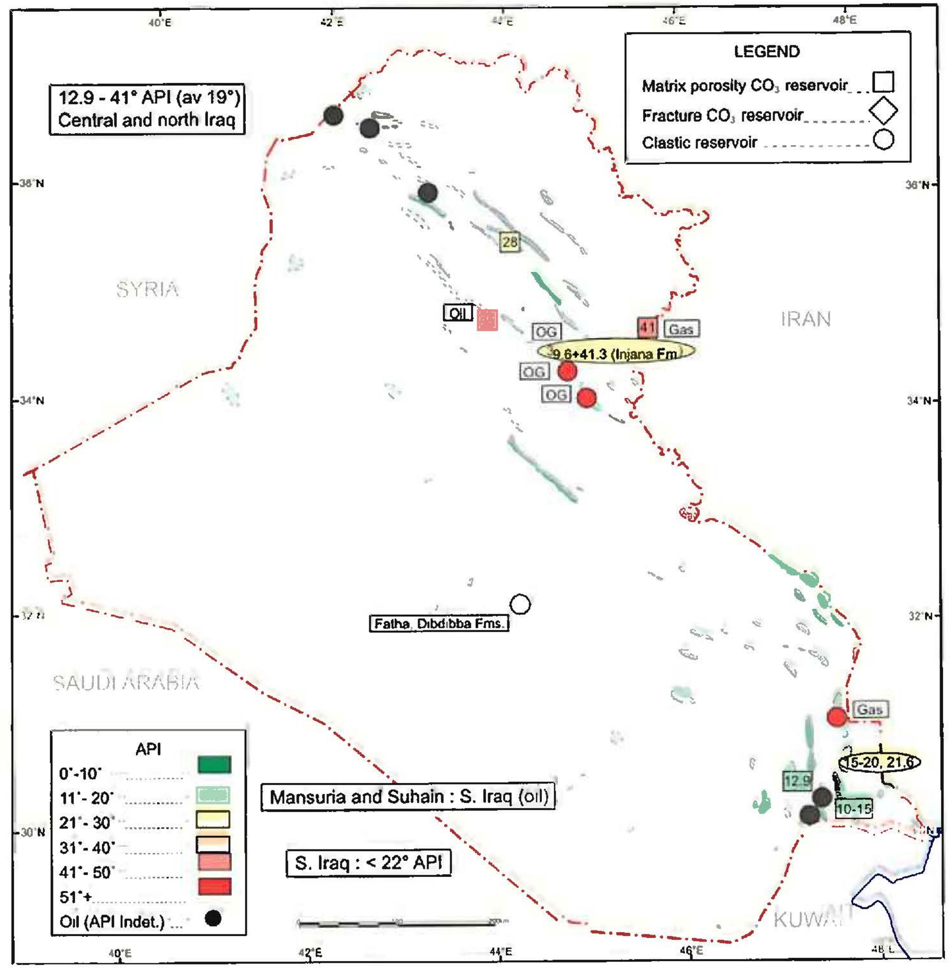


Fig. 9.6.12. Map showing the occurrence of oil in late Neogene reservoirs in Iraq. OG = oil and gas (indet.).

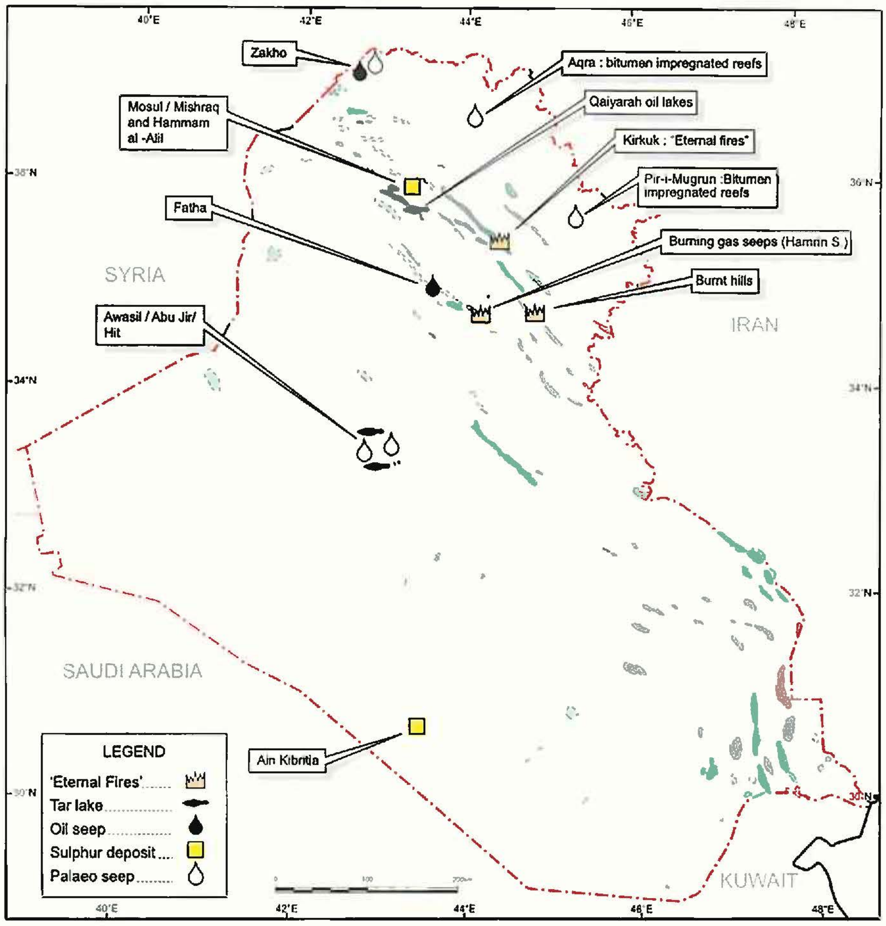


Fig.9.6.13. **Map showing surface oil shows, seeps and associated phenomena in Iraq.**

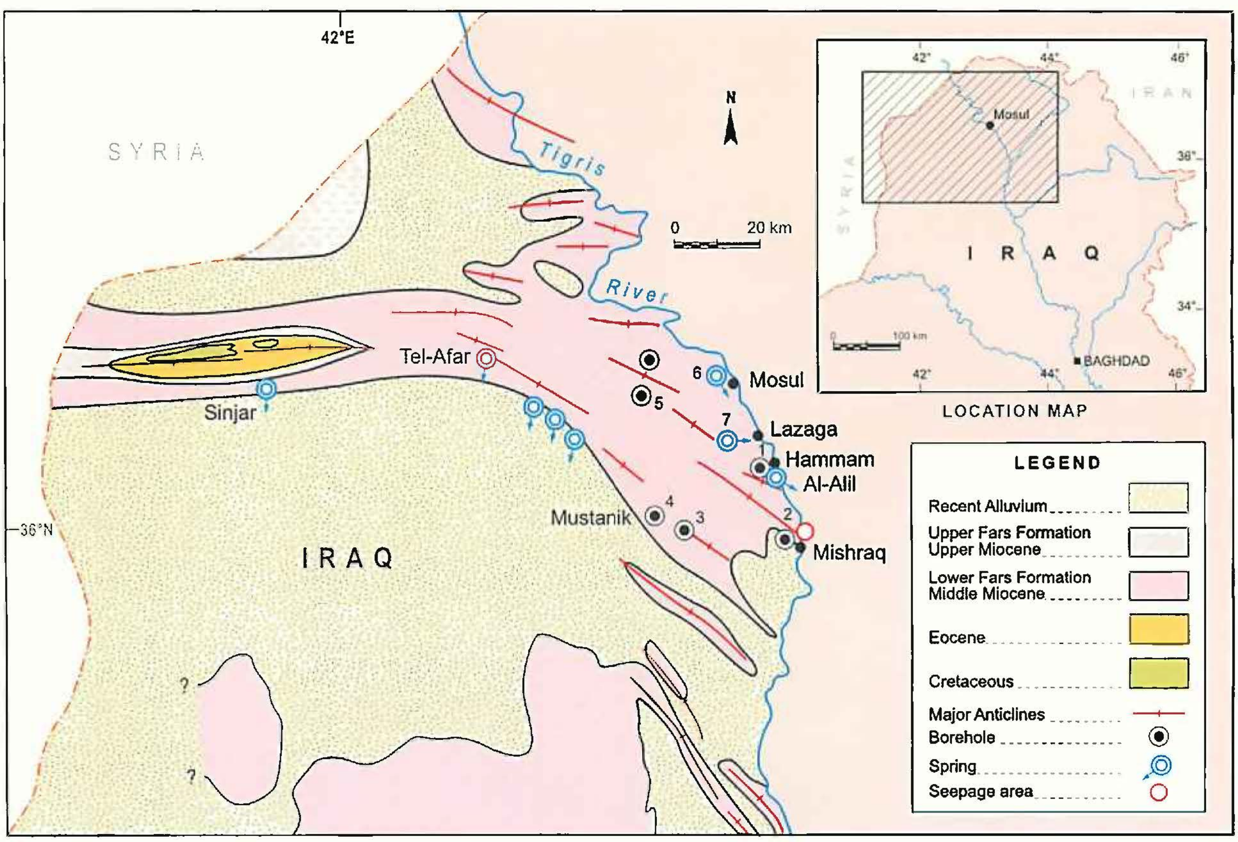


Fig. 9.6.14. **Map of NW Iraq showing the distribution of oil seeps and sulphur springs (Al-Sawaf, 1977).**

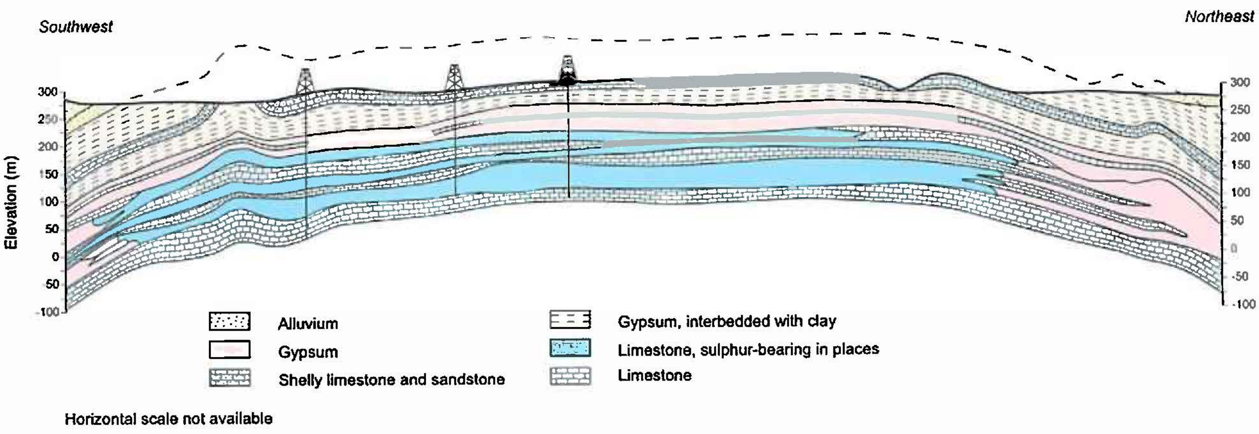


Fig. 9.6.15. Cross-section through the Mishraq sulphur deposit (modified after Sokolov, 1965). See Fig. 9.6.14 for location.

where three bitumen lakes cover areas of 10,000 sq m, 40,000 sq m and about 50,000 sq m, respectively. Two of the lakes are connected by a stream of bitumen. He described numerous small vents from which inflammable gas (mainly H_2S) issued, together with a thick tarry oil which he assumed was in the process of being transformed into bitumen. **Quwair** is located nearby on the left bank of the Greater Zab River. Seepages of black tarry oil occur along the river bank here. Pascoe (*ibid.*) considered that the oil is derived from a limestone bed whose outcrop is covered by gravelly alluvium.

Al-Fathah (Fig. 9.6.13) is located where the Tigris River cuts through the Jebel Hamrin – Jebel Makhul anticline. Lumps of weed- and algal-impregnated bitumen float down the river here, some associated with light films of oil, and in some places the river banks are impregnated with bitumen. On the east side of the Tigris, a sulphur-rich soil is clearly exposed on the crest of the Jebel Hamrin structure in a road cutting. Dikes and veins of bitumen occur here and contain large (1-2 cm) crystals of gypsum (Pascoe, 1922).

(iii) Seepages in the Zagros fold-and-thrust belt

Seepages in the Foothill Zone include *Baba Gurgur* or "Eternal Fires" at *Kirkuk*, and numerous bitumen and burning gas seepages at Hamrin South (Basi and Jassim, 1974). Pascoe (1922) described the oil seepages NE of Sulaiman Beg on the Pulkhana anticline. Oil pits occur in a line close to the axial plane of an isoclinal fold on the NE flank of the structure. "Coal" mines (solidified bitumen) are located about five km ESE of Kifri in the Upper Fars Formation, about 300 m above the top of the Lower Fars Formation.

Basi and Jassim (1974) described six "Burnt Hills" on Jebel Pulkhana, capped by dark vesicular rocks (resembling volcanic rocks) underlain by both baked and unaltered sedimentary rocks (Figs. 9.6.16, 9.6.17). The baked rocks are thought to have recrystallised at the surface at temperatures of 1100–1370 °C. Field and petrographic evidence indicates that the rocks formed as a result of spontaneous combustion of hydrocarbons in small pits located along a thrust fault. The rocks are resistant to erosion and thus cap local hills. They are composed predominantly of pyroxene and plagioclase, with minor detrital quartz and polycrystalline silica and silica glass. Jassim (1976) studied two craters adjacent to one of the burnt hills. The craters occur within the Upper Fars Formation which is made up of brown sandstones interbedded with brown marls. SW of the craters were pyroclastic-like rocks composed of angular fragments of sandstone and marl with up to 10% bitumen fragments. Sediments in the crater lake were composed of fine-grained material with coarse bitumen fragments. Jassim (1976) considered that these craters and "pyroclastic" rocks formed by explosive, violent eruption of hydrocarbons. The burnt hills are estimated to be about 25,000 years old and the craters about 1200 years old.

A visit to the "Eternal Fires" on the crest of the Kirkuk anticline in 1988 by A. Horbury and J. Goff recorded that there were two areas of gas seepage some 200 m apart. The Fires form a crater 20 m across and about 2 m deep (page 376). Burning gas emerges from the floor and sides of the crater, producing orange flames up to 1 m high. Sulphur lines cracks and cavities, and forms crusts down the sides of the crater (a hand specimen is shown in Plate 9.6.1 and a thin-section in Plate 9.6.2). A nearby crater was dormant but was reported to be have been alight in 1976.

Evans (1919-1920) described the oil seepages seven miles east of **Zakho** in NW Iraqi Kurdistan. These occur on a low ridge of hills composed of the sandstones and marls of the Upper Fars Formation. Two unworked seepages are present. Evans noted that one of these seepages occurred where asphalt flowed into two valleys adjacent to the ridge. A nearby structure has recently been drilled and is the site of the *Tawke* discovery*.

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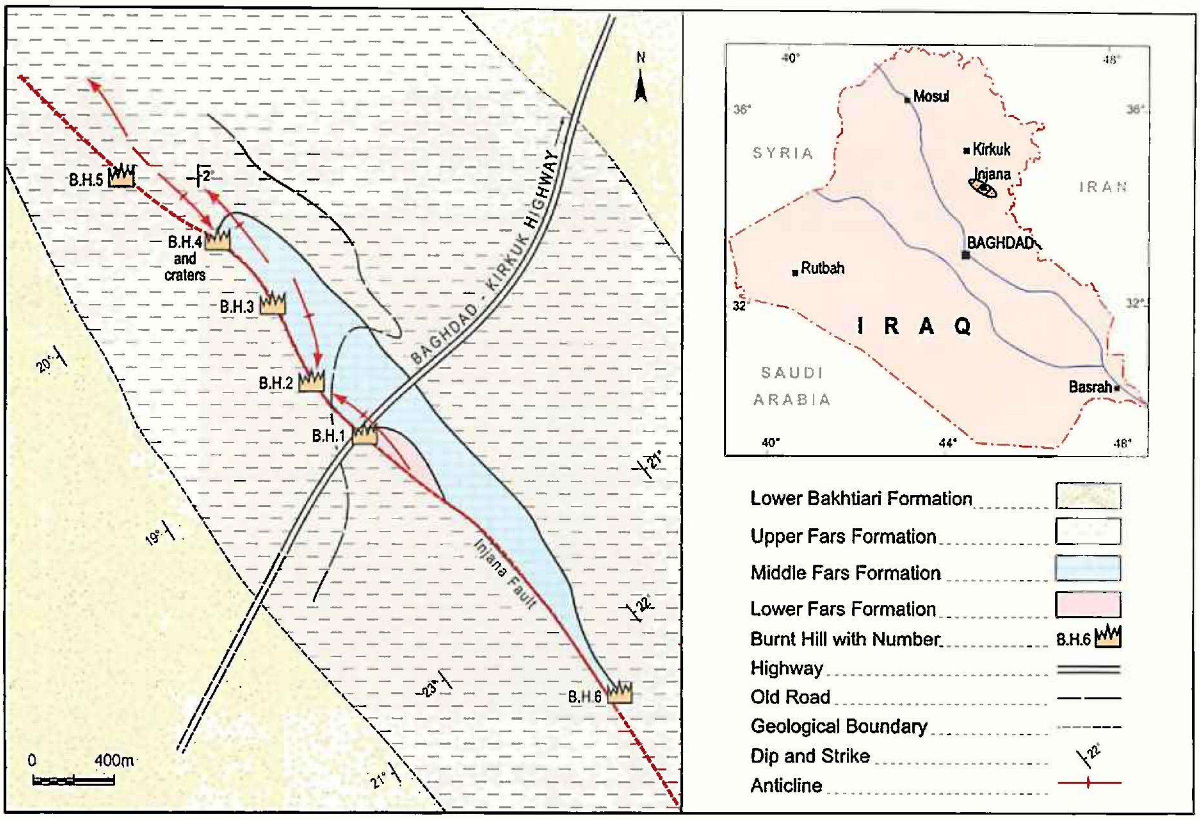

Fig. 9.6.16. Map showing the location of "burnt hills" at Jebel Hamrin South (Injana); the *BH1* structure was studied in particular detail (see Fig. 9.6.17). After Basi and Jassim, 1974.

In summary, seepages appear to be controlled by major north-south faults, by faults that cut to the surface in major anticlines, and also apparently by the western limit of the Upper Jurassic Gotnia Formation caprock as suggested by Pitman *et al.* (2004) and Jassim and Al-Gailani (2006).

Aquifers

In Iraq, the Tertiary hydrogeological unit is characterised by fresh water influx into outcropping aquifer rocks in the west and SW where groundwaters flow to the NE (Fig. 9.6.18). Fresh waters also enter outcropping Tertiary aquifers along the length of the Zagros fold-and-thrust belt in NE Iraq, and isolated outcrops near Mosul and at Sinjar (Al-Mashadani, 1986).

Tertiary aquifers in Iraq can be divided into gravity-flow and high pressure systems (Al-Mashadani, 1986). Gravity-flow aquifers are recharged from topographically high areas including the Foothills Belt in the east and NE, and from areas of outcrop in west and SW Iraq (Figs 9.6.18). Aquifers occur in the Ghar, Jeribe, Euphrates, Anah, Tarjil and Palani Formations and in porous parts of the Paleocene-Eocene succession (Al-Mashadani, 1986). Recharge originates as far away as SW Iran and the Gulf region. Tilted oil-water contacts along the NE of the Mesopotamian Basin / Zagros fold-and-thrust belt indicate strong aquifer recharge (Saidi, 1987),

Plate 9.6.1. Crust of sulphur flow from the crater of the Eternal Fires, Kirkuk. Photo by A. Horbury.

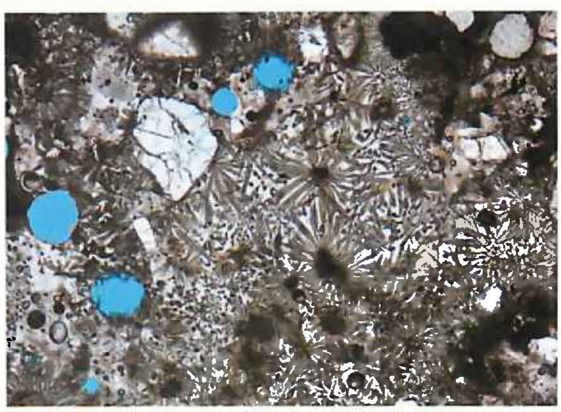

Plate 9.6.2. Whole thin-section scan image of sulphur crust from the Eternal Fires, Kirkuk (image by F. Witkowski).

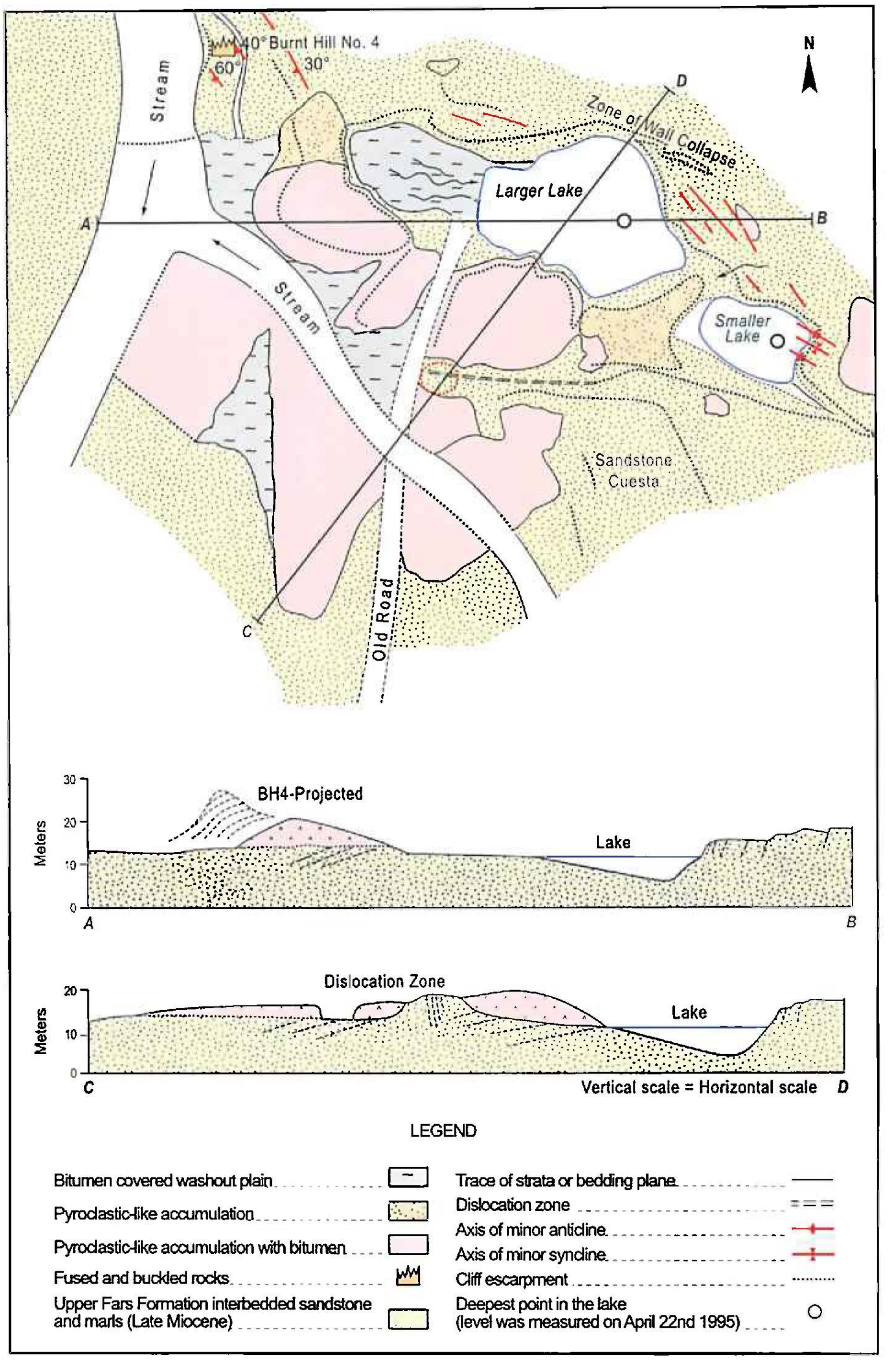

Fig. 9.6.17. Location, structure and other characteristics of *Burnt Hill (BH) 1* near Jebel Hamrin South (see Fig. 9.6.16 for regional location). After Basi and Jassim, 1974.

for example at the *Gachsaran* field in Iran (Slinger and Crichton, 1959). In Iraq, the *Bai Hassan* field has a tilted OWC (IPC, 1956).

Protected aquifers dominated by CaCl occur in Central and Southern Iraq. A high pressure aquifer system occurs within the Foothills Zone (Fig. 9.6.18). The Jeribe Formation is overlain here by evaporites of the Lower Fars Formation and underlain by those of the Dhiban Formation. Abnormal potentiometric values in this area are located by black dots on Fig. 9.6.18. Abnormal values also occur in the Lower Fars Formation due to the presence of uncompacted shale beds (Al-Mashadani, 1986). Consequently, the formation is often overpressured and represents a drilling hazard in many areas (Fig. 9.6.18).

The Tigris and Euphrates Rivers mark an area of minimum *iso*potential (Al-Mashadani, 1986). Flow is generally upwards resulting in asphalt seeps and salt springs (pp. 367-368).

Carbonate beds in the Lower Fars Formation are overpressured where multiple evaporite caprocks are present and pore pressure reach 500 kg/cm^2 at 2400 m (Al-Mashadani, 1986). Marls in the Lower Fars are significantly undercompacted and overpressured in the axis of the Mesopotamian

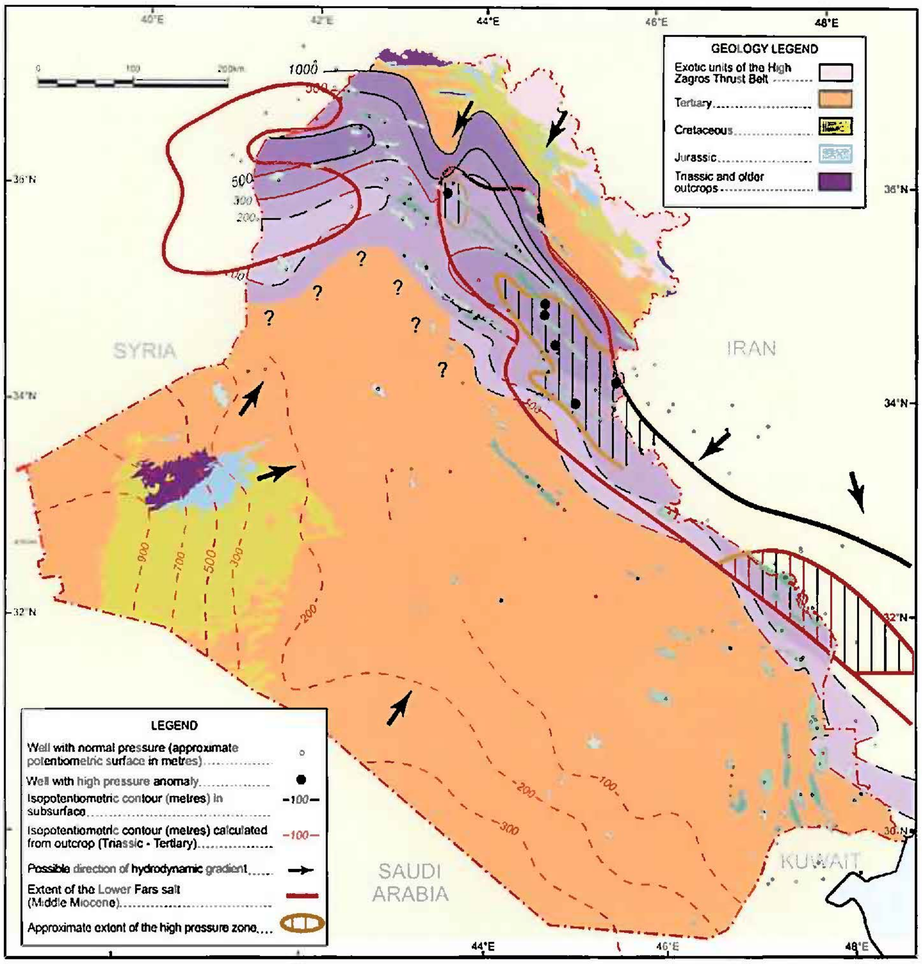

Fig. 9.6.18. Approximate potentiometric surface map of the Cenozoic in Iraq. Contour intervals shaded purple. After Al-Mashadani, 1986.

Basin. The upper 120 m of the formation is normally pressured. The overpressure transition zone is about 100 m thick, and the overpressured zone above the normally pressured carbonate reservoirs is 600 m thick (Al-Mashaani, 1986).

Salinity maps show three hydrological basins in Iraq (Fig. 9.6.19) with differing aquifer characteristics. The basins are the Mesopotamian basin between Kirkuk and Amara; and two basins (Sinjar-Sufaiyah, and Khleisia-Tel Hajar) located in the NW. Freshwater has penetrated aquifers up to 50 km from their outcrops with salinities of 1000–12,000 ppm recorded in oil exploration wells (Al-Mashadani, 1986). MgCl and $NaSO_4$ water types (which indicate a meteoric origin) occur adjacent to recharge outcrops. Salinities increase towards the basin centres, from 50g/l to 300g/l. Very low SO_4/Cl ratios and CaCl water types indicate protected aquifers (Al-Mashadani, 1986) with limited recharge of formation waters. These are largely confined aquifers with high pressures. Locally the presence of MgCl and $NaSO_4$ in waters on the basin margin indicate a meteoric input (Al-Mashadani, 1986).

In and beneath the Lower Fars evaporite, the Miocene and Oligocene aquifers are very saline with salinities up to 300,000 ppm (Fig. 9.6.19).

Biodegradation of oils by bacteria transported with the freshwater has led to deterioration in oil quality of the already heavy oils generated by marginally-mature source rocks.

Case Study

Kirkuk field

The super-giant *Kirkuk* field is located 92 miles (147 km) SE of Mosul (Fig. 9.6.13). The structure is a NW-SE trending anticline, 61 miles long by up to 2.5 miles wide (97 km by 4 km). The geology of the NE flank of the structure is clearly visible at the surface; the SW flank lies below alluvium of the Lesser Zab River. The Kirkuk anticline has three culminations — from NW to SE the Khurmala, Avanah and Baba Domes – which are at depths of 2500 ft (762 m), 2000 ft (610 m) and 1000 ft (305 m), respectively. Closure is at least 600 m given a column height of approximately 2000 ft (610 m) at the Baba Dome (IPC, 1956). Oil produced is 36.7° API (Al-Naqib *et al.*, 1971).

There are three main pay zones in the *Kirkuk* field: a First Pay of Cenozoic limestones; a Second

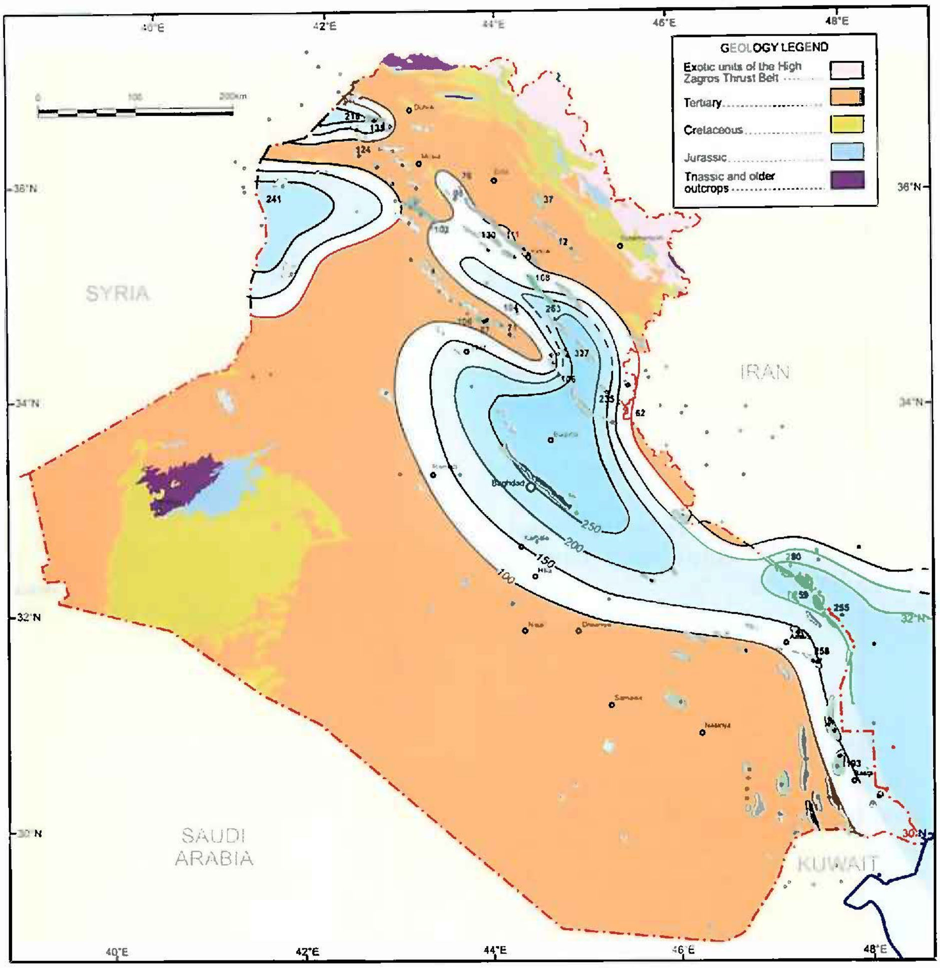

Fig. 9.6.19. Isosalinity map of Cenozoic aquifers in Iraq (salinity in g/litre). Contour intervals shaded blue. After Al-Mashadani, 1986.

Pay of fractured Late Cretaceous marls and limestones (Shiranish Formation); and a Third Pay of Middle Cretaceous limestones. Of these, the First Pay is the most important. High matrix porosities and well-developed fractures interact to form an excellent dual-porosity system. The First Pay is sealed above by the clays and evaporites of the Miocene Lower Fars Formation.

Oil in-place in the Baba and Avanah Domes has been estimated to be about 32.5 billion (B) brl (Saidi, 1987) with 25 B brls in matrix porosity and 7.5 B brls in fractures (including fissures and caverns). Verma *et al.* (2004) estimated reserves of 25 B brl originally recoverable and proven; and 10.8 B proven yet to be recovered plus 8.22 TCF gas. Cumulative oil production from *Kirkuk* field to the end of 2007 is estimated to be 15.5 B brl plus 5.4 TCF gas (Verma *et al.*, 2004).

Production history

The geology of the Kirkuk area was first mapped in detail in 1925-1926. The structure was identified as a large-scale anticline with a thrust fault on one flank. The first well was located between two surface seeps (*Baba Gurgur-1*) and came in as a gusher in 1927 (see *page 13*). The field went on production in 1934 at a rate of 80,000 b/d (Al-Naqib *et al.*, 1971). By 1939, 54 wells had been completed but all except six and one observation well were plugged in 1941 as a result of military activities during World War 2. Operations resumed at the end of the War, and by 1954 some 111 wells had been completed: of the non-plugged wells, 46 were producers and 17 were observation wells (15 for water, two for gas) (Daniel, 1954).

The initial GOR was 200-220 cu. ft/brl (IPC, 1956). There was no initial free gas in the Baba and Avanah Domes due to undersaturation, although a gas cap was present at Khurmala. Al-Naqib *et al.* (1971) suggested that the Baba Dome was undersaturated at the time of discovery because of the surface gas seeps which have been known in the Kirkuk area since antiquity (Plate 9.6.3).

Original reservoir pressure at a subsea depth of 1500 ft (457 m) was 1075 psig (Al-Naqib *et al.*, 1971) (Fig. 9.6.20). During the initial phase of natural depletion, the reservoir pressure declined to 775 psig (Al-Naqib *et al.*, 1971). Production resulted in such a drop in formation pressure that a gas cap had developed in the Baba Dome; by 1951, a gas cap was also developing in the Avanah Dome (IPC, 1956). It became clear that some form of pressure maintenance was required, and a plan was developed to inject gas from the nearby *Bai Hassan*

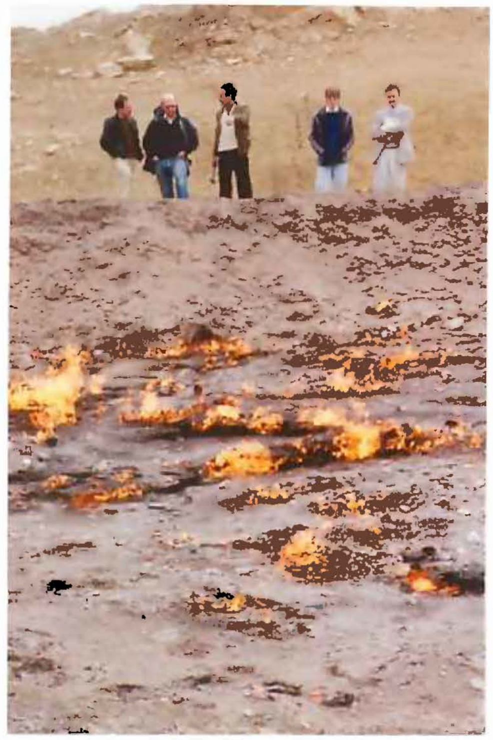

Plate 9.6.3a, b. Field photos of the "Eternal Fires" at Kirkuk:
(a) with oilfield installations in the background.
(b) with geologists for scale including A. Horbury and J. C. Goff (at right).
Photos by R. Cleverly.

field. However, test flooding of cores indicated that water injection was a better long-term method of pressure maintenance. Gas injection started in November, 1957 and continued until November 1961, by which time the water injection facilities had been installed. The average injection rate of 180 MM scfg/d was approximately the reservoir volume equivalent of 650,000 b/d of oil (Al-Naqib *et al.*, 1971). Gas injection caused the GOC to fall to about 1300 ft (396 m) SS by 1961. Water injection started in April, 1961 using water extracted from the Lesser Zab River. Injection was partly by gravity with some assistance from pumps according to the elevation of the injector wells (Al-Naqib *et al.*, 1971).

The original plan for a peripheral water flood with injectors sited downflank just below the OWC was abandoned because the first well (*K-121*) failed to encounter the expected sufficient fracturing on the flanks of the structure to allow flow of water. Injectors were then concentrated in the Amshe saddle area between the Avanah and Baba Domes, where they could make maximum use of the crestal fracturing and matrix porosity in the reservoir unit itself (Al-Naqib *et al.*, 1971). In the 1960s, three more wells were drilled and two further wells were turned over to water injection. A total injection rate of 1,100,000 b/d water was achieved by the early 1970s.

Within a few months of the start of water injection, there was a measurable rise in the OWC up to 20 miles (32 km) distant from the injectors in the Amshe saddle (Fig. 9.6.21). It was recorded that the water could spread freely some 28 miles (45km) along the NE flank and 24 miles (38 km) along the SE flank of the structure. Because the waterflood was not even, it was decided to place an injector on the Tarjil plunge of the Baba Dome in 1969; this

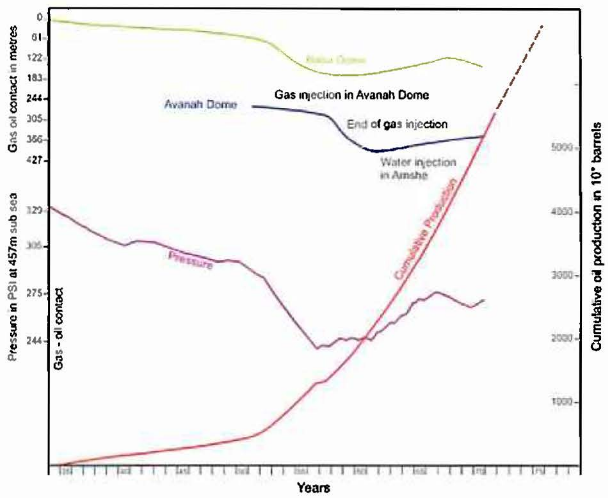

Fig. 9.6.20. Production history for the *Kirkuk* field. From Al-Naqib *et al.*, 1971.

well (*K-185*) started injection of 80,000 b/d water in February, 1970 (Al-Naqib *et al.*, 1971).

The initial OWC in Baba Dome (which extends beneath the Amshe saddle) was at about 2250 ft (686m) SS (Saidi, 1987). The OWC in the Khurmala Dome is higher than the lowest part of the saddle that separates the Khurmala Dome from the Avanah Dome. The original OWC was in general flat (Al-Naqib *et al.*, 1971) (Fig. 9.6.21).

Due to the intense fracturing in the Main Pay carbonates, there is almost instantaneous transmittal of pressure drops over great distances (Daniel, 1954) and pressure response to production occurs throughout the entire field in only a few hours (Daniel, 1954; IPC, 1956).

Acidisation was used on producing wells that revealed high bottom-hole differential pressures after

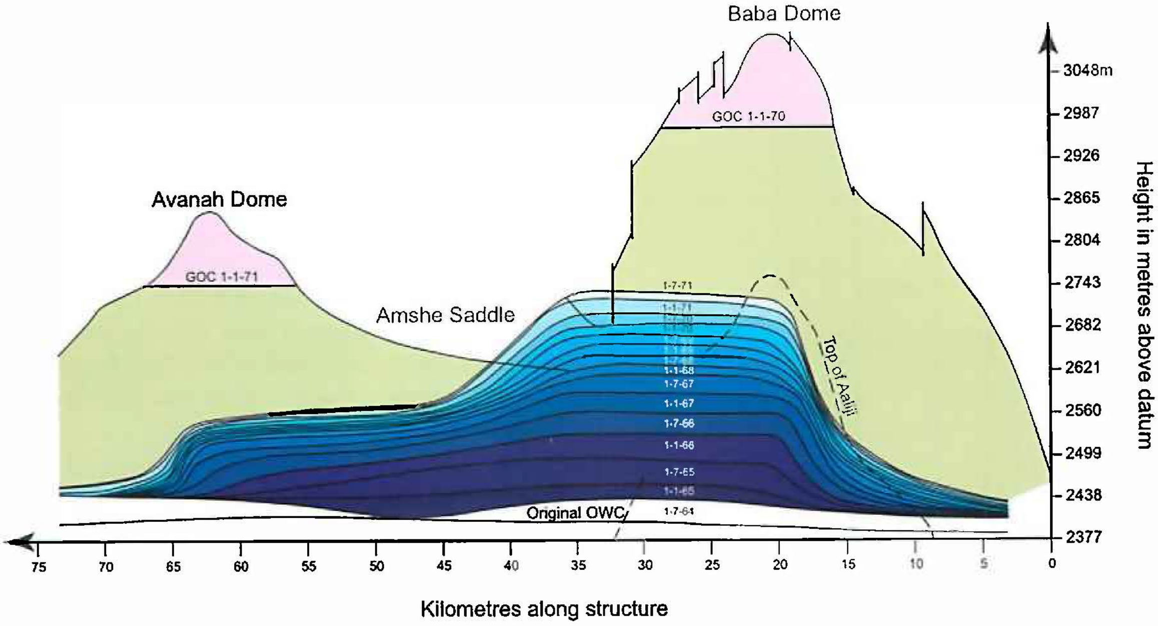

Fig. 9.6.21. Graph showing the progressive rise in the OWC at *Kirkuk* throughout the 1960s. Note that injection was concentrated in the Amshe saddle area. After Al-Naqib *et al.*, 1971.

production tests. Most of the wells were completed barefoot, since the reservoir was considered to lack permeability barriers (Daniel, 1954).

Stratigraphy

The principal reservoir is the Cenozoic Kirkuk Group (First or Main Pay, Main Limestone) (Fig. 9.6.22) which dominates production and which, throughout most of the field, rests on the Paleocene-Eocene Aaliji Formation, a shaly, impermeable limestone which serves as a caprock for underlying Cretaceous reservoirs. The Kirkuk Group reservoir is part of a NW-SE trending, 250 mile long barrier reef belt ranging in age from middle Eocene to Miocene; the palaeoshoreline lies to the NE. The lithostratigraphy of the Kirkuk Group is described on page 257 (Fig. 8.16). There is a divergence of around 15° between the trend of the reef-belt and the axis of the Kirkuk anticline.

In the Kirkuk structure, the First Pay comprises different Cenozoic units in the three culminations. At Khurmala, the First Pay consists of Eocene nummulite bank and back-reef carbonates. At the Avanah Dome, it consists of middle-late Eocene nummulite bank to Oligocene backreef carbonates; and at Baba Dome, Oligocene carbonates (IPC, 1956; Dunnington, 1958).

Al-Naqib *et al.* (1971) estimated the total thickness of the First Pay to be about 1200 ft (366 m), although the thickness depends on the transition of reservoir limestones to underlying basinal shales. However net pay is reduced to below 300 m due to permeability variations, due for example to partial karstification (IPC, 1956).

Al-Naqib *et al.* (1971) identified ten "porosity" or flow units in the Main Limestone, A to J, as follows:

Baba Dome

Unit A: Bajawan Formation: 37 m thick, mainly back-reef/lagoonal, dense porcellanous limestone.
Unit B: Porous Bajawan/Baba Formation: 31 m thick; mainly dolomitised fore-reef limestone, includes the basal part of the reef if porous.
Unit C: Shurau Formation: 21 m thick; mainly back-reef to lagoonal limestones, low permeability.
Unit D: Sheikh Alas Formation: 37 m thick; mainly fore-reef limestone, often dolomitised, good porosity and permeability.
Units E, F, J: Tarjil, Palani (Oligocene) and Jaddala (Eocene) Formations: 259 m thick; low permeability marly (basinal) units.

Avanah Dome

Units A and C: thinner than at Baba Dome (6 m and 9 m, respectively);
Units B and D: Absent
Unit G: Dense Avanah Formation: 46 m thick; back-reef/lagoonal limestones with some reefal carbonates. Very low porosity and permeability.
Unit H : Porous Avanah Formation: 137 m thick on average (up to 198 m); shoal limestones with some reefal carbonate, locally dolomitised; good porosity and permeability.
Unit I: Khurmala Formation: over 152 m thick; back-reef / lagoonal limestones, frequently dolomitised, and low permeability.

The original OWC at Avanah was above the base of the Khurmala Formation. The base of the Main Limestone is taken at the base of Unit J, although the effective base of the reservoir is probably above this level (Al-Naqib *et al.*, 1971).

These ten units were divided by Al-Naqib *et al.* (1971) into two rock types — an upper group (G1) consisting of porosity units A, B, C and D on the

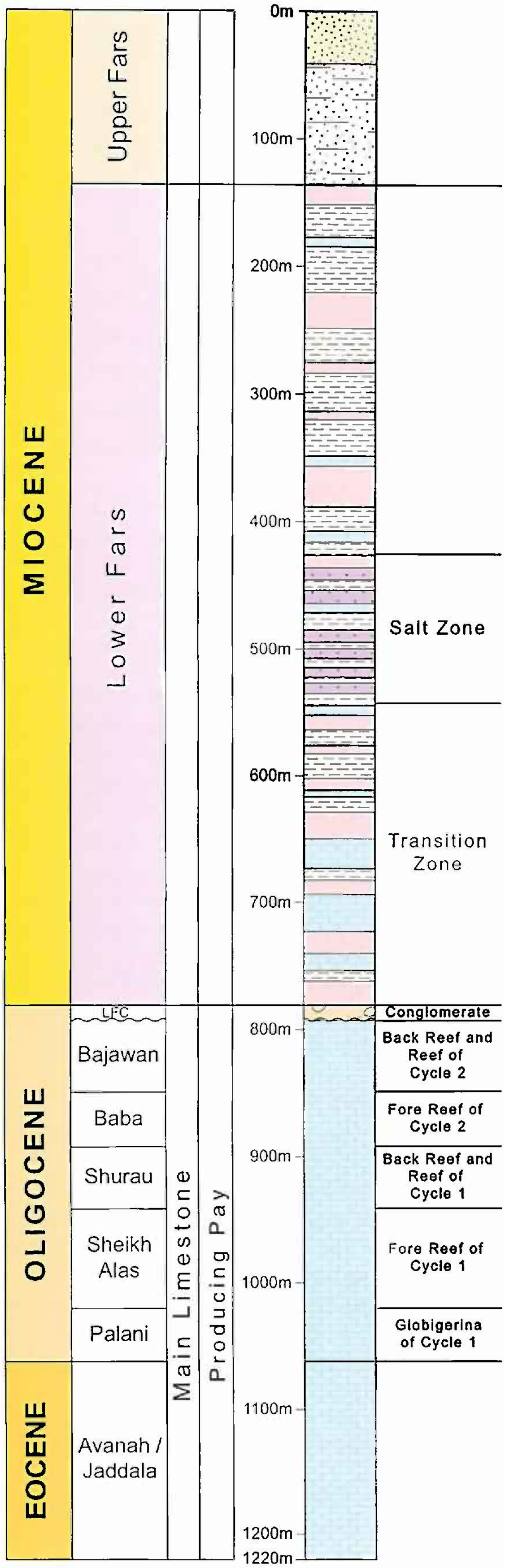

Fig. 9.6.22. Simplified stratigraphy of the shallow stratigraphic succession in the *Kirkuk* field (after Daniel, 1954). LFC: Lower Fars Conglomerate.

Baba Dome, and porosity units G and H on the Avanah Dome; and a lower group, G2, consisting of units E, F and J on the Baba Dome, and porosity unit I on the Avanah Dome. Rock type G1 had a higher matrix porosity and a much higher fracture intensity than G2. G1 had an average gross thickness of 410 ft (125m) in the Baba Dome (Oligocene limestones), and up to 800 ft (244m) in the Avanah Dome (Eocene limestones). G2 has an average gross thickness of 850 ft (260 m) in the Baba Dome (Oligocene and Eocene fine grained basinal limestones) and > 500 ft (152 m) in the Avanah Dome (Eocene fine-grained dolomitic limestones).

Fracturing and voids

Although few km-scale faults are present at *Kirkuk*, frequent joints and minor breaks cut across the reservoir complex in all directions (Daniel, 1954; IPC, 1956). These fracture systems are not present in neighbouring anticlines (IPC, 1956). Early drilling logs indicated the presence of major cavities, and a diversity of materials including camel thorn, straw, cotton seed hulls, bundles of reeds and old gunny sacks, together with cement mud and gelling mixtures were pumped down-hole in an attempt to plug them, not always with success (Daniel, 1954).

Five categories of void were recognized (Daniel, 1954), namely: normal faults (*see below*); solution caverns (*see below*); tension fissures, which occur in the Main limestone in the crest of the Kirkuk anticline as a result of Late Tertiary folding; joints, which are numerous but which have not been extensively studied (in two wells, *Kirkuk-19* and *Kirkuk-30*, joints occur every 4–8 ft (1.2 to 2.5 m) of core); and stylolites which although oil-stained, were thought also to act as seals (Dunnington, 1958).

Normal faults, associated with breccia and slickensides in cores, caused stratigraphic cut-out which was often difficult to identify in the Main Limestone. Faults could however be identified from production data such as (gas) saturation isobars (Freeman and Natanson, 1959). The main fault trends, NNW-SSE and WNW-ESE, cut obliquely across the structure. The largest fault was mapped for 13 miles (21 km) and has 650 ft (198 m) of displacement. Faults must be younger than mid Miocene since they cut the Lower Fars Formation. Daniel (1954) and Dunnington (1958) suggested that the faults may have acted as conduits for the migration of oil into the Main Pay reservoir. Surface gas seeps, such as the "Eternal Fires" (Plate 9.6.3), are indirectly sourced via these faults which reach the Transition Beds of the Lower Fars Formation; these strata are in turn connected to the surface by shallow thrust faults on the crest of the anticline.

Caverns can be divided into two vertical and lateral types. Vertical caverns are confined to backreef and reef facies, which may be karstified

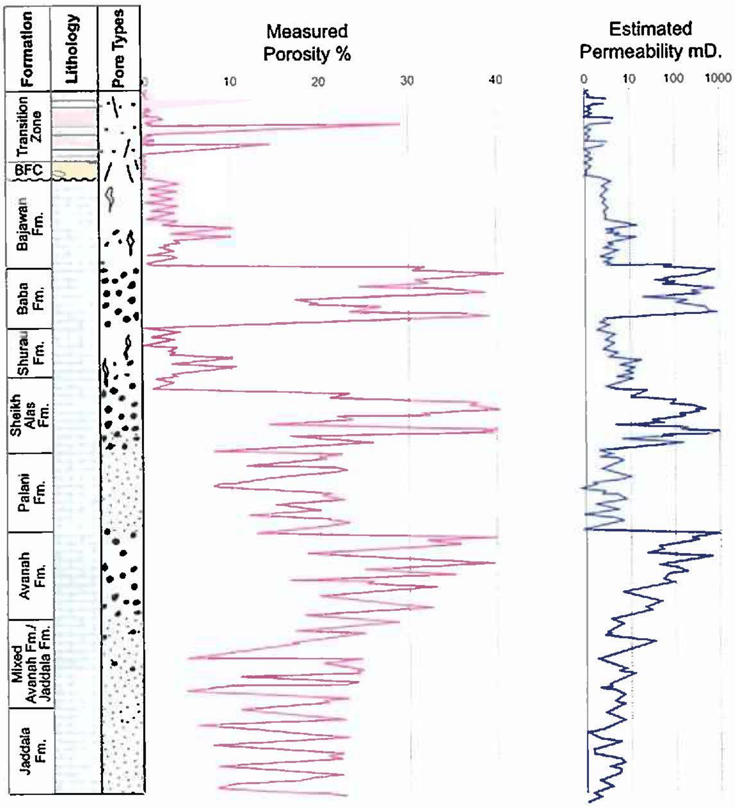

Fig. 9.6.24. Summary of reservoir systems in the *Kirkuk* field, with a schematic representation of pore types, porosities and permeabilities and formation thicknesses (compiled after various authors). Key to pore types: fine dots - microporosity; large dots - vugs; fine lines - fractures; double lines - fissures.

due to solution along joint planes. Blue clay and pebble fills indicate that these were open solution conduits (swallow holes) when beds were exposed to erosion before deposition of the Basal Fars Conglomerate. Lateral caverns are found in fore-reef beds below the porcellanous back-reef and reef facies, or hard dense conglomeratic beds. Dissolution occurs where there is a permeability contrast, encouraging lateral flow of meteoric waters and solution of relatively porous (e.g. fore-reef) deposits. The presence of caverns may explain the huge volumes of lost circulation which were sometimes reported at Kirkuk. In one instance, a 14 ft (4.3 m) timber spacer thrown downhole reportedly rotated on its axis and then floated back up to the surface (Daniel, 1954). The caverns may also explain the production rates of 30,000 b/d for bottom-hole drawdown pressures of only 3 or 4 psi (Daniel, 1954).

Fractures tend to be open in the crestal parts of the Kirkuk structure, which allows not only gas segregation but also the development of convection within the gas cap. This results in a continual loss of gas from solution in the oil a long way downflank, below the depth at which saturation levels are normally attained (Freeman and Natanson, 1959). In the Baba Dome, the gas cap has played a disproportionately large part in displacement of oil downwards since there has been relatively little movement of edge waters.

Porosity and permeability

The matrix poroperm characteristics of the First Pay (Daniel, 1954) are summarized in Table 8.1 (and Fig. 9.6.23). The best reservoir characteristics occur in fore-reef facies (porosity up to 36%; permeability up to 1 Darcy). Jassim and Al-Gailani (2006) reproduced a porosity and permeability profile through the Oligocene reservoir at *Kirkuk* (Fig. 9.6.2c). The stratigraphic section in this profile indicates it is from a well in the SE part of the Baba Dome. The maximum porosity in the Baba Formation forereef limestones was 25%; average porosities in this profile were about 15%.

9. PETROLEUM SYSTEMS

vii. Concluding comments

Much of Iraq is currently at a low level of exploration maturity and understanding of the country's petroleum systems is still at an early stage. This understanding has been hampered by insufficient publications on source-rock intervals and oil-source correlations, although recent studies (e.g. Al-Ameri *et al.*, 2009a,b) have added important data to the public domain. It is recommended here that data obtained from future exploration programmes is systematically collected and analysed to better define the rock units in which hydrocarbons have been generated, migrated and trapped. The petroleum systems concept can then be used to define exploration plays which share a common source rock.

The Precambrian-Palaeozoic succession in Iraq contains frontier exploration plays. Current understanding of the **Palaeozoic petroleum system** is based largely on data on adjacent countries. The Lower Palaeozoic section in Iraq is only known from two exploration areas (*Khleisia* and *Akkas*), from water wells in the Western Desert, and from very limited outcrops in Iraqi Kurdistan. A Lower Silurian (lower Llandovery) source rock has been identified at *Khleisia* and *Akkas*, but its extent away from these areas is unknown. There is insufficient knowledge of the distribution of reservoirs and seals in the complex Silurian – Permian stratigraphy to define hydrocarbon migration pathways. The timing of generation from the Silurian and other potential Palaeozoic source rocks is poorly understood because of uncertainties in burial and thermal histories. The influence of regional unconformities of Late Devonian and Late Carboniferous age on the Palaeozoic petroleum system will become clearer as exploration for Palaeozoic targets proceeds. Ordovician and older source rocks may prove to be significant in the future. Gas-bearing Ordovician reservoir rocks have been encountered at *Akkas*, and this may encourage future gas exploration in western Iraq.

Knowledge of the **Triassic petroleum system** in Iraq is based on data from a few deep exploration wells in NW Iraq, recently-published analyses of thin, Triassic bituminous carbonate source rocks, and preliminary results of recent exploration in Iraqi Kurdistan. The Triassic petroleum system is present in a thick succession of tight carbonates, marls and evaporites with thin dolomite reservoir units. It may locally contain stacked reservoir and source horizons, but there is currently insufficient data to describe Triassic plays except in general terms. A better description of these plays will require an improved understanding of the stratigraphic architecture of the Triassic intrashelf basins and their surrounding platform margins.

Few exploration wells have targeted Jurassic exploration objectives in Iraq. Early results from deep drilling in SE Iraq, at Samawa, and recent drilling in Iraqi Kurdistan strongly suggest that commercial Jurassic discoveries will be made in the future. However, it is important to appreciate some significant differences between the Jurassic succession of the Gotnia Basin and the well-known Jurassic plays of the Gulf countries to the south. Reservoirs of the Arab Formation of Saudi Arabia have not yet been found to extend into Iraq. The **Jurassic petroleum system** in Iraq may prove to be largely dependant on the formation of secondary porosity during deep, burial-related dolomitization, and the creation of fractures during periods of tectonic deformation which in part overlapped in time with hydrocarbon generation and overpressuring. The regional seal at the top of the Jurassic petroleum system probably varies in quality and in places may have been ruptured, allowing leakage of oil into the overlying Cretaceous petroleum system. Middle – Upper Jurassic source rocks may thus have charged both "Jurassic" and "Cretaceous" petroleum systems in different parts of Iraq. Very large volumes of heavy oil have probably been generated from Jurassic source rocks in the western parts of the Jurassic source kitchen.

The **Cretaceous petroleum system** is locally well explored in Iraq. However, further work is required to correlate Cretaceous oils to their parent source rocks, and to investigate the potential for stratigraphic traps. The stacked Cretaceous exploration plays of SE Iraq are now well understood but their respective source rocks are uncertain. The Mishrif, Zubair and Yamama oil reservoirs in SE Iraq contain oils of different quality. Each reservoir system has evidently been charged by different source rocks, and/or from source kitchens of different maturity. Rich source rocks of late Tithonian – earliest Cretaceous age have recently been identified. However, analyses of potential Albian source rocks, which are probably present in Iraq, are needed. Upper Cretaceous source rocks have not yet been identified in Iraq. Important lateral changes in Cretaceous source-rock organofacies and thickness may occur, and data obtained from drilling on structural highs may be unrepresentative of source rock quality in depocentres. Stratigraphic traps along the western margin of the present-day Mesopotamian Basin, which is comparatively undeformed, will require favorable updip facies changes e.g. from platform-margin carbonates into tight lagoonal carbonates, dip reversals (such that basinal facies can act as lateral seals), or onlap of reservoirs onto sealed unconformity surfaces. Exploration for these plays will be facilitated by improved stratigraphic resolution linked to high resolution seismic data.

Finally, the Tertiary play system in Iraq relies on vertical oil and gas migration through the regional-scale unconformity at the base of the Tertiary megasequence AP10. Migration probably occurred through fractures either during primary migration from Jurassic and Cretaceous source rocks, or by remigration of hydrocarbons trapped in Cretaceous reservoirs. Locally, in anticlines with very large vertical closures, hydrocarbon columns may extend via fractures systems from Tertiary to Cretaceous reservoirs. In the Folded Zone of NE Iraq, exploration for Eocene - Miocene reservoirs sealed by Middle Miocene evaporites and marls has proceeded for almost eighty years. However, there are many aspects of the Tertiary play system which require further study. A better understanding of Tertiary reservoirs at the margins and in the interiors of large-scale carbonate platforms will aid prediction of reservoir quality and the potential for stratigraphic traps. In addition, the factors controlling the heavy oil belt along the western margin of the Mesopotamian Basin require further study, in particular the relative roles of generation and expulsion of relatively immature oils from source rocks, and biodegradation.

10. THE PETROLEUM GEOLOGY OF IRAQ: FUTURE CHALLENGES

The petroleum industry in Iraq faces a number of challenges which must be overcome if future oil exploration and production is to be optimised. Challenges are here grouped into three categories. The first set of challenges reflect the need to update the geological and petroleum-geological understanding of Iraq. A gap in technical understanding has emerged and widened over the past two or three decades due to Iraq's relative isolation from the global petroleum industry. Challenges in the second category relate to the exploration and production cycle. Finally, a number of challenges concerning specific stratigraphic intervals are identified and discussed.

1. Principal challenges

Stratigraphy

The stratigraphy of Iraq is still largely based on work by IPC geologists dating from the 1940s and 50s (summarised in the *Iraq Lexicon*) and the results of a later regional survey programme by the State Organization of Minerals. A key advance in petroleum geology since the 1980s has been the development of sequence stratigraphy. A preliminary sequence stratigraphic scheme for the Cretaceous succession in southern Iraq was published by Sadooni and Aqrawi (2000), and Iraqi stratigraphy was integrated into the regional sequence stratigraphic framework compiled by Sharland *et al.* (2001). In the present book, an attempt has been made to define Phanerozoic sequences in more detail. However, these sequences should not be considered as definitive since they were largely defined from the published literature. Examination of original material will allow a much better correlation of Iraqi sequences with those described elsewhere. A major challenge is therefore the rigorous adoption of sequence-stratigraphic concepts and methodologies utilising new seismic and outcrop data. Once complete, this will facilitate improved interpretations of Iraq's petroleum geology.

Structure

The detailed structural subdivisions of Iraq, the geometry of the various Palaeozoic unconformities and the top of the basement in Iraq, as presented by Buday and Jassim (1987) and Jassim and Buday (2006a), were defined primarily from interpretation of gravity and magnetic data. Although the resulting maps give a first-order understanding of these structural features, detail is lacking. Existing seismic data only poorly images the pre-Permian stratigraphy and structure. The top of the basement can only be identified in parts of the Western Desert by using the Cambrian Burj Limestone as a proxy (as noted by Jassim, 2006c). Areas where Silurian source rocks were removed by Palaeozoic erosion cannot yet be mapped confidently. It will therefore be of great importance to compare the basement depth, structural subdivisions, unconformities and major fault zones identified by Jassim and Buday (2006a) with structures newly interpreted from high-resolution seismic data. These structural challenges must be overcome before a more rigorous interpretation of the geological structure of Iraq can be made.

Production paradigm

At least 80% of past Iraqi production has come from two prolific reservoirs – the Main Limestone of *Kirkuk* field (discovered in 1927), and the Zubair Main Pay of *Rumaila* field (discovered in 1953). A major challenge facing the Iraq petroleum industry will be to increase production from other proven reservoir units such as the Mishrif and Yamama Formations in the SE of the country, the Miocene, Eocene and Upper Cretaceous reservoirs in the NE, and deeper Jurassic, Triassic and Palaeozoic reservoirs in the west. The use of enhanced oil recovery techniques from known reservoirs will also be important. In existing fields, application of high-resolution 3D seismic should allow improved definition of traps, fault compartments, and in some cases of reservoir architecture. This may lead to reserves growth through increase in STOIIP and improved targeting of production and injection wells leading to higher recovery factors.

2. Challenges associated with exploration and production

Future exploration in Iraq may need to consider themes which were not addressed in previous E&P strategies. New themes include:

New geographic frontiers:
Exploration of under- and unexplored areas is required. These areas include the Western Desert (and the border areas with Syria, Jordan and Saudi Arabia), Iraqi Kurdistan, the western margins of the Mesopotamian Basin, and the Iraqi offshore in the NW part of the Gulf.

New stratigraphic frontiers:
Exploration programmes should target the Jurassic, Triassic and Palaeozoic petroleum systems, since many structures have not been drilled below the Cretaceous.

New trap concepts:
New regional seismic data should carefully be integrated with well and outcrop studies to identify trap types other than the well-known SW-NE trending "Zagros" anticlines and the north-south trending "Central Arabian" mega-highs of SE Iraq. New structural traps may include tilted fault blocks, flower structures, minor inversion structures and horst blocks between inverted basins. Stratigraphic traps may include isolated carbonate build-ups, or carbonate platform margins passing updip into basinal shales and marls. Subtle stratigraphic traps may also occur including karst reservoirs, low-relief shoals and reefs, hydrothermal dolomite plumes, and siliciclastic basin-floor fans. Areas where these untested structural and stratigraphic traps are likely to be present should therefore be identified for detailed exploration. Previous exploration strategies in Iraq have largely been based on drilling surface anticlines and simple buried structures defined with 2D seismic data.

Petroleum System concepts:
New geochemical data is required to identify source rocks more accurately and to perform oil-to-source rock correlations. Analysis and interpretation of Iraq's petroleum systems will help to guide future exploration strategy. This will be particularly important for the exploration of the Palaeozoic section of western Iraq, and in the evaluation of heavy oil plays along the western margin of the Mesopotamian Basin.

Improved sedimentological models:
Extensive coring is required in new wells to supplement the archive core data-base which was badly damaged after the events of 2003. New core data is required to construct detailed sedimentological models which are required for reservoir characterisation. Outcrops in Iraqi Kurdistan and the Western Desert should be studied in detail in order to build reservoir analogue models. Work on outcrops in neighbouring countries may be necessary where the Iraqi exposures are not adequate. Thus for example, Palaeozoic exposures in Jordan and NW Saudi Arabia may be used for the calibration of fields and opportunities in western Iraq.

Reservoir architecture and geomodelling:
A better understanding of reservoir architecture will help to maximize oil recovery. This will require the routine use of modern techniques including 3D seismic in complex production areas, the acquisition of cores and the use of modern logging suites, together with the implementation of modern concepts such as sequence stratigraphy, high resolution biostratigraphy and chemostratigraphy.

3. Challenges relating to particular stratigraphic intervals

Palaeozoic

The Palaeozoic succession in Iraq is under-explored and poorly known; it requires evaluation with new seismic and well data.

The deeply-buried Megasequence AP1 (Infracambrian or Vendian to Lower Cambrian) has not yet been drilled in Iraq. It may have significant petroleum potential by analogy with the Infracambrian succession of Oman. Deep drilling in western Iraq would be required to investigate and define source rock presence and reservoir quality.

The lower part of Megasequence AP2 (Lower Cambrian to Upper Ordovician) has not yet been penetrated by the drill. The upper part of the megasequence has been penetrated in wells in the *Akkas* discovery and in *Qaim-1* and *Khleisia-1*, but only limited geochemical or sedimentological studies of the succession have so far been published. Seismic imaging of the Palaeozoic sequences will be required to evaluate the interpretation of this interval presented by Jassim (2006).

Application of techniques that have not been used previously in Iraq may help to locate zones of enhanced reservoir quality. For instance, regional diagenetic studies may be used to investigate the formation of chlorite coatings on quartz grains which inhibit silica overgrowth formation; the spatial and temporal controls on this process of porosity preservation are not well defined.

Biostratigraphic studies of Lower Palaeozoic rocks in Iraq will be required as new wells are drilled in order to define (or re-define) standard type sections following the work of Dunnington *et al.* (1959) and Al-Hadidy (2007). At present, there are conflicting ages for some stratigrapic units and nomenclature is confusing. Thus, the Llanvirn-Llandeilo ages of units at the base of wells *Akkas-1* and *Khleisia-1*, as interpreted by Al-Hadidy (2007), are inconsistent with the Arenig-Tremadoc ages given by Baban (1996) and Al-Ameri and Baban (2000, 2002). These issues are of importance when predicting the presence or absence of facies in the deeper stratigraphy from seismic data where well data is absent.

A critical factor for the Middle Silurian - Lower Devonian Megasequence AP3 will be accurate mapping of preserved Silurian source rocks beneath the Late Devonian and Late Carboniferous unconformities. New regional seismic data will be required to map the subcrop pattern at these unconformities and to establish the distribution of the preserved Silurian succession. Modelling the pre-Upper Devonian subcrop will also help define stratigraphic traps in the Lower Palaeozoic succession. An understanding of the burial history of the base-Silurian will help to model the timing of hydrocarbon generation from the Silurian source rocks, which is of critical importance in the context of the timing of trap formation.

Future studies should also investigate reservoir rocks within the uppermost Silurian to Middle Devonian portion of the Megasequence, equivalent to the Tawil and Jauf Formations of Saudi Arabia. These have not yet been studied in Iraq.

Future studies of Megasequence AP4 should focus on improved characterization of both potential source rocks (e.g. the Ora Shale Formation) and reservoir rocks (e.g. the Pirispiki and Kaista Formations and Harur Limestone Formation). Palaeontological issues are important, because the megasequence appears to be dominated by Tournaisian and older units in northern Iraq while the biota reported from the Western Desert appear to be mostly Viséan or younger; lateral relationships need to be studied more thoroughly. The precise distribution of the megasequence is not known. Much of the succession may have been eroded during Late Carboniferous tectonism, particularly over the Salman Zone (Jassim, 2006a,c). Further studies using modern seismic data will be required to check these preliminary observations.

The Ga'ara Formation sandstones of Megasequence AP5 are potential reservoir rocks throughout western Iraq. Detailed stratigraphic, palynological and sedimentological studies are required in order more accurately to subdivide this unit, which may be as young as Middle Triassic in some areas. Studies are also required to characterize the reservoir quality and distribution of the formation.

Permian-Liassic

The Upper Permian – lowermost Triassic Chia Zairi Formation is under-explored throughout Iraq. This Khuff-equivalent, thick dolomitic limestone potentially forms an important gas reservoir in parts of the country. However, the Iraqi stratigraphy appears to be characterized by considerably lower porosities than that in the Gulf area. Diagenesis and the timing of hydrocarbon charge versus porosity occlusion are therefore likely to control prospectivity. The maximum depth of economic reservoir quality must be determined in order to assess the potential of this interval in deeply-buried parts of eastern and southern Iraq. Detailed sequence stratigraphic schemes and depositional models are required for the carbonate facies and their transition into both anhydrites and siliciclastics. Such models will allow better calibration of seismic stratigraphic models and thereby better define overall palaeogeography and facies distributions.

The Triassic petroleum system which is proven in NW Iraq (*Alan, Sufaiyah* and *Butmah* fields) requires careful re-evaluation as it may extend to other parts of the country. The distribution of subtle depocentres controlling source and reservoir quality requires assessment. Source rocks may be present in the centres of these depressions and optimum reservoir facies may occur on their margins. Improved understanding of the distribution, types and effectiveness of Triassic source rocks and the controls on reservoir quality are needed, based on new well (log and core) data. Attention should be focused on intervals that are oolitic, or strongly dolomitised, or collapse-brecciated due to evaporite-dissolution, as well as on limestones that have been karstified. These types of potential reservoir occur within the Mirga Mir, Geli Khana and Kurra Chine Formations. Secondary issues include predicting the sealing capacity of intraformational shales, argillaceous limestones and evaporites, and the extent and reservoir quality of interbedded continental to shallow-water and deltaic sandstones (Minjur facies) with a westerly provenance; these are productive in Syria. A more detailed chrono- and sequence-stratigraphic scheme should be created for the Triassic using techniques that have successfully been applied in neighbouring countries but have not been widely used in Iraq, such as palynology, conodont biostratigraphy and Sr isotope stratigraphy.

The Rhaetian – Aalenian succession (Baluti to Alan Formations of the Stable Shelf, and the Sarki and Sehkaniyan Formations in the Folded Belt) has no proven hydrocarbon potential in Iraq. However, reservoir potential may occur in oolitic, sandy, dolomitic or fractured intervals charged by overlying Jurassic or underlying Triassic source rocks. Pay zones are likely to be thin, but it is possible that multiple pays may occur. A productive interval in Kuwait (Marrat "C" Member oolites) may extend into Iraq.

Middle - Upper Jurassic

The present lack of exploration success in the Jurassic petroleum system of Iraq is unexpected given the abundance of source rocks, particularly since the system has produced large quantities of oil in neighbouring countries. If exploration and production challenges can be overcome, Jurassic reservoirs in Iraq could provide an important future supply of light oil and associated gas, particularly in the south of the country.

The Jurassic petroleum system in Iraq is more complicated than was first thought. Source rocks are overlain by evaporite seals, and conventional reservoirs appear to be best developed in platform margins that are in general laterally equivalent to the main source kitchens and the main sealing facies. This contrasts with Saudi Arabia, where sealed reservoirs often directly overlie Jurassic source rocks. Data from Saudi Arabia and Kuwait, and outcrops in Iran, suggests that lateral facies and diagenetic transitions affecting reservoir quality in the platformal area may also occur over short distances. There is currently insufficient Jurassic well data to assess lateral variations in reservoir quality.

Future work on the Jurassic should focus on defining the genesis and location of porous dolomitic carbonates in both massive carbonate intervals and in units within the younger evaporite-dominated stratigraphy. Prediction of lateral variations in the reservoir quality of dolomites in the Najmah Formation will be difficult, since dolomitising fluids have probably invaded the platform margin at specific locations controlled by stratigraphic architecture and geological structure. High resolution seismic data will be required to locate the Mid-Upper Jurassic carbonate platform margin, and to image dolomitised bodies within and behind this margin. Prediction of oolitic banks and coral-stromatoporoid build-ups or massive dolomite bodies may be possible from their seismic character. An understanding of seismic geometries and seismic stratigraphy will also help to map the extent of potential traps. The few wells that have been drilled into the Jurassic platform may have failed in the past because trap geometry and position of sealing facies were unsuitable.

The prolific Arab Formation reservoirs of northern Saudi Arabia may extend into SE Iraq, as suggested by lithofacies and hydrocarbon shows in the Jurassic section in well *Abu Khema-1* on the Rimthan Arch. However, controls on the distribution of reservoirs in this formation and thus the extent of the play fairway in Iraq are uncertain.

Exploration for fractured Jurassic source rocks and dolomitic reservoirs in Iraq will require a multidisciplinary approach. Reservoir quality in fractured source rocks is likely to be controlled by the development of well-connected fracture systems formed as a result of high pore pressure gradients during oil generation, and folding over major structural highs. 3D seismic data will be required to identify these fracture systems. High-angle wells could target the fractured Sargelu and Naokelekan Formations, but the high pore pressure gradients in southern Iraq present formidable drilling challenges.

In NW Iraq, the Jurassic section subcrops a regional unconformity at the base of the Cretaceous (Dunnington *et al.*, 1959). It is probably not sealed regionally because of the heterolithic nature of the various overlying (onlapping) formations. In the Folded Zone, large-scale leakage of oil from dolomite reservoirs in the Sargelu Formation up into the Cretaceous succession may have occurred during Tertiary folding and thrusting. Many of the traps in the Folded Zone in Iraq are likely to be structurally complex and difficult to image.

Cretaceous

The Cretaceous petroleum system is the most important in Iraq (Sadooni and Aqrawi, 2000) and is among the richest in the world. Most of Iraq's hydrocarbon reserves occur within the Cretaceous succession, particularly in the Mesopotamian Basin. This petroleum system has been successfully explored using "conventional" methods in the past, and to build on this legacy will require a strong analysis of existing paradigms. The identification of new subtle Cretaceous plays will require high resolution seismic data and a better understanding of the controls on source and reservoir quality. In northern Iraq, future work should aim thoroughly to investigate the Cretaceous succession both in the Folded Zone, and below producing Tertiary reservoirs. Outcropping Cretaceous rocks in Iraqi Kurdistan should be carefully studied as analogues for subsurface reservoirs.

The Yamama/Garagu Formations have a wide distribution in Iraq. Particularly in southern Iraq, they contain a relatively thick section of porous oolitic and skeletal limestones (Sadooni and Aqrawi, 2000). However these lithologies form a challenging reservoir; a better understanding of their microporous character and complex diagenesis is required. The reservoir forms an important deep pay zone in southern Iraqi fields such as *West Qurna* and *Nasiriya*, but reservoir quality is variable.

Basin-margin carbonate build-ups with potential for stratigraphic or combination traps may occur in the Shu'aiba, Mauddud, Mishrif and possibly Hartha/Tayarat Formations adjacent to the open-marine Balambo Basin facing eastwards, or in intrashelf basins within the western parts of the platform. Similar plays are already proven, or are in production, in Saudi Arabia, Qatar and the UAE and Oman. These margins require accurate mapping using high-resolution 3D seismic which will identify irregularities that may represent stratigraphic traps. Mapping may also locate lowstand platforms in front of the main margin which likewise could possess stratigraphic trapping potential. Isolated carbonate build-ups may prove to be a significant play. Build-ups may have developed during phases of platform drowning (generally from the Cenomanian onwards), and locally on palaeotectonic highs within depressions such as the Najaf Intrashelf Basin. They may also have developed on the outer parts of carbonate ramps which were elevated due to salt movement, such as build-ups within the Yamama-Garagu system.

The two major siliciclastic reservoir units, the Zubair and Nahr Umr Formations, are underexplored outside SE Iraq. An improved sequence stratigraphic understanding of these units is needed in order both to optimise reservoir description in producing fields and to assess the potential for stratigraphic exploration plays. Stratigraphic traps may be located updip from the major producing structures, although predicting seal integrity may be difficult as net sand content increases westwards.

New plays may also be identified in existing exploration areas as additional well and seismic data becomes available. In mature exploration areas where major four-way dip closures have largely been drilled, stratigraphic trap opportunities in shelf carbonates will become more important. New data will allow the development of more sophisticated depositional models and thus a reduction of the risks associated with stratigrapic trap definition. The Hartha Formation is relatively underexplored. It contains oil in the northern part of the *East Baghdad* field. The formation has also produced oil in western Iraq (in the Kifl area), in an area located outside the main Cretaceous oil plays (Sadooni and Alsharhan, 2004). Other targets include possible mud mounds in the Yamama Formation and dolomite reservoirs in the Mauddud Formation which also has major exploration potential in SE Iraq.

Several Cretaceous carbonate plays in basinal settings are underexplored. The Sa'di-Tanuma-Khasib sequence that contains large volumes of oil in central Iraq at *East Baghdad* has proven to be a target in *Ahdab* and *Dhefria*. Fractured basinal micritic carbonates are potential reservoirs in the Dokan to Shiranish Formations of northern Iraq. Lastly, the thick flysch of the Tanjero Clastic Formation in Iraqi Kurdistan covers large areas in the Folded Zone. It is highly heterogeneous with significant lateral facies variations. The succession includes potential reservoir units (shallow- and deep-marine sandstones, reefal carbonates); intercalated shales may act as caprocks. These formations require a more refined stratigraphic subdivision and chronostratigraphic calibration both at outcrop and in the subsurface.

Tertiary

The Tertiary play system is dominated by the *Kirkuk* field and it is unlikely that this will be surpassed by any single field in the future. However, considerable potential still exists within the Tertiary succession. Additional fields may still be found producing from platform-margin carbonates. In Iraqi Kurdistan, the Pila Spi Formation occurs at outcrop as a porous and often karstified platform-top unit that may be sealed in the subsurface by the Lower Fars Formation. There has been only limited exploration for this Eocene play. However it has recently been proven successful in the *Taq Taq* and *Tawke* discoveries. In the basin centre, the main challenges are in the thin, shelfal carbonate reservoirs of the Miocene Jeribe and Euphrates Formations. These reservoirs need careful management as they are strongly layered (due to interbedded thin anhydrites), contain heavy oil, and have very low reservoir pressures in shallow structures.

New plays may be found in the Tertiary succession. The reservoir potential of the Transition Beds in the Lower Fars Formation requires further evaluation. Isolated platforms of Paleocene and Eocene shelf carbonates are known which are overlain, and thus sealed, by younger basinal carbonates (e.g. on Jebel Sinjar in Iraq, and Jebels Abd El Aziz and Bishri in Syria). If such platforms nucleated on buried inversion structures, they could form significant stratigraphic traps. Clastic-rich units in the Mesopotamian Basin are poorly understood. The Kolosh, Khurmala and Gercus Formations may contain sealed reservoir units.

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Fadhil Sadooni *(fsadooni@qu.edu.qa)* has a Ph.D in petroleum geology (carbonate reservoir characterization) from the University of Bristol. He worked for 13 years as an exploration geologist with the Iraq National Oil Company and was involved with much of the exploration effort in Iraq during the 1970s and '80s. Fadhil has also worked in the petroleum industry in SE Asia and has taught at the Universities of Yarmouk (Jordan), Qatar and the UAE where he was the Chairman of the Geology Department for five years. He now works as an advisor in the office of the Vice-President For Research, Qatar University. Fadhil's research focuses on carbonate reservoirs and microbial sediments.

Andrew Horbury *(andy@cambridgecarbonates.co.uk)* is a co-owner and director of Cambridge Carbonates Ltd. He received a Ph.D in carbonate sedimentology from the University of Manchester in 1987. From 1986 until 1992, he worked with BP Exploration. His first major project with the company was a study of NW Iraq with Jeremy Goff and Fadhil Sadooni (then at OEC). As observed by the project manager Guy Stubbs, this was when he "hatched out of his egg". Presently, Andrew is involved in many consultancy projects on Iraq and has a strong interest in the Tethyan geology of Mexico. He co-authored the GeoArabia Special Publication 2 *"Arabian Plate Sequence Stratigraphy"* and was largely responsible for the contributions on northern Arabia in that volume. He dedicates his part of the present book to the memory of his late mother, Barbara Denise Horbury (1929-2009), who inspired him to study geology through her interest in landscapes and painting.

Jeremy Goff *(goffj@bp.com)* graduated in geology from Oxford University in 1976. He has worked for BP Exploration for 34 years and is currently a senior geological consultant. He has worked on oil exploration and production projects in the UK and Norwegian sectors of the North Sea, Canada and Angola, and in BP's Global Basin Analysis and Unconventional Hydrocarbon Resource teams. Since 1986, he has worked extensively on the Middle East and has managed interdisciplinary joint exploration and production studies with the national oil companies of several countries in the region, including Iraq. He has a particular interest in the tectonostratigraphic evolution of the northern margin of the Arabian Plate, unconventional Jurassic source rock and dolomite exploration plays, and Palaeozoic tight gas reservoirs. He was co-editor with Saad Jassim of the book "Geology of Iraq" published in 2006.

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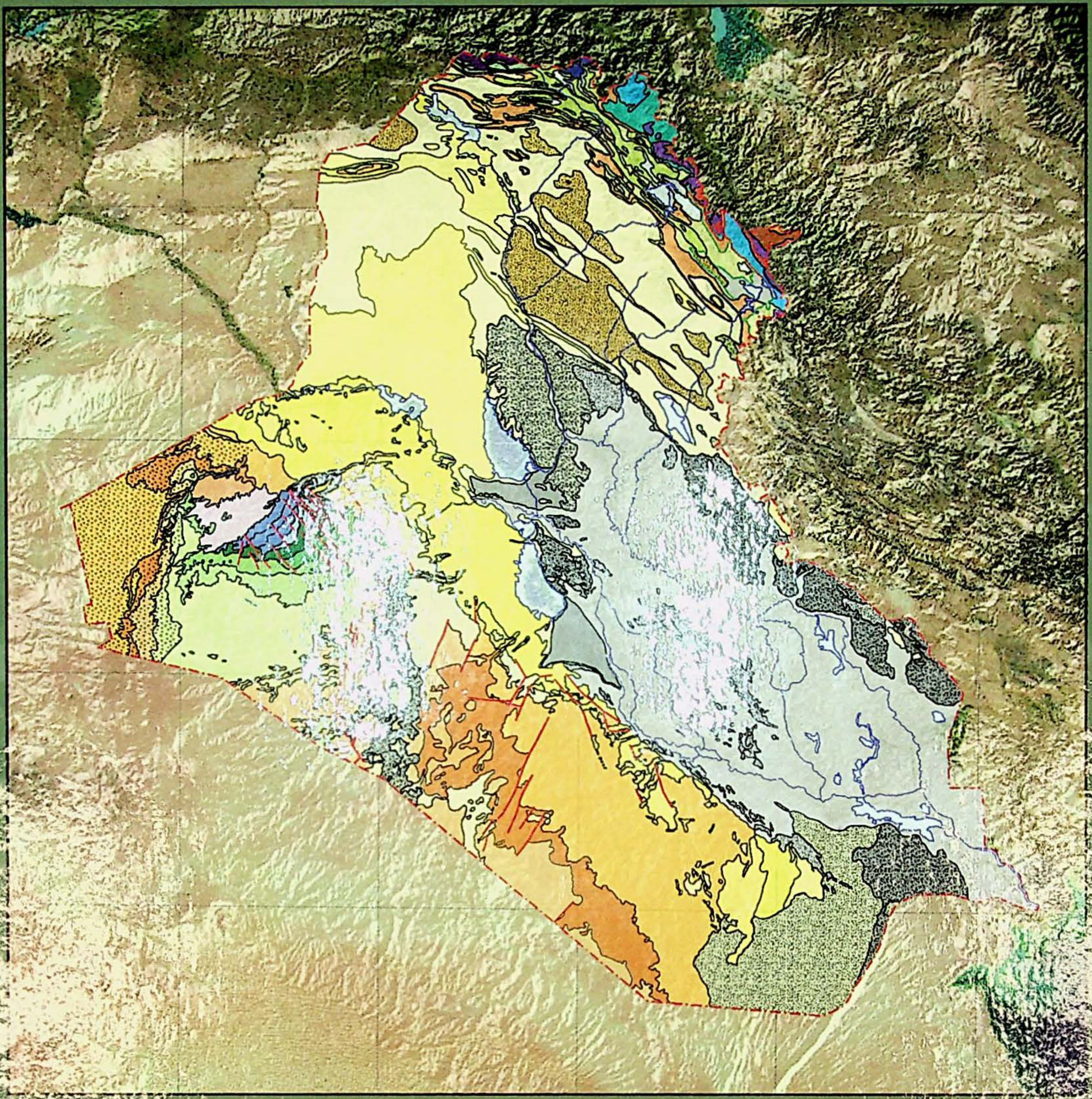

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