Chapter 1

Introduction to the Jurassic Arabian Intrashelf Basin

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Abstract: The Jurassic Arabian Intrashelf Basin provides the setting for the world’s greatest conventional oil reserves, including the world’s largest oilfield, the supergiant Ghawar field. The stratigraphic interval corresponding to the development and infill of the Arabian Intrashelf Basin is from the uppermost Dhruma Formation to the top of the Hith Anhydrite Formation, spanning the late Bathonian–early Callovian to Tithonian. Many areas of the intrashelf basin have been well described in recent years and the stratigraphic succession has been defined in sequence concepts, but the regional development of the intrashelf basin has not been well synthesized. This Memoir builds on published data to give a regional interpretation of the geological evolution of the Arabian Intrashelf Basin. This introductory chapter reviews some of the earlier work, summarizes the key events and elements in the geological history of the Arabian Intrashelf Basin and gives a brief review of the history of petroleum exploration in this region. It is intended to serve as an extended abstract to introduce the general setting and summarize the contents of this Memoir, including some of the proposed revisions of depositional models, correlations and the sequence nomenclature, providing a context for considering and evaluating each subsequent chapter. The themes summarized in this chapter are documented and discussed in much greater detail in the subsequent chapters of this Memoir.

This Memoir is organized as follows: Chapter 2 (Wilson 2020a) summarizes the structural history of the basin. Chapter 3 (Wilson 2020b) summarizes the lithostratigraphy, biostratigraphy, $^{87}\text{Sr}/^{86}\text{Sr}$ dating and sequence stratigraphy. Chapter 4 (Wilson 2020c) illustrates the depositional geometry around and across the basin. Chapters 5 (Wilson 2020d) and 6 (Wilson 2020e) further discuss, evaluate, integrate and interpret the data presented in Chapters 2–4 (Wilson 2020a, b, c) interval by interval. The themes include the influence of changes in sea-level and the global climate and the effects of subtle tectonics during each phase of basin formation and on the intrashelf basin rim. The illustrations include a regional summary cross-section, cross-sections illustrating the depositional geometry of specific areas and facies maps at different phases of the development and infill of the intrashelf basin. The facies maps presented here are more regionally detailed than earlier published versions. Chapter 7 (Wilson 2020f) is a discussion of the implications for exploration. Chapter 8 (Wilson 2020g) summarizes this Memoir, including comparisons with the global eustatic sea-level curve. Each chapter is written to stand alone and the subdivisions are geological and not segregated by geography.

Figure 1.1 is a Google Earth image of the Arabian region with the country borders and major tectonic features labelled. The general area of the Arabian Intrashelf Basin is shown, as well as the southern portion of the generally coeval, but very different, Gotnia–Mesopotamian Basin to the north, which is known as the Lurestan Basin in Iran (Murris 1980). The Arabian Intrashelf Basin may extend southwards into the Rub‘ al-Khali area. Major present day geographical features include the huge Rub‘ al-Khali sand dune region, the Precambrian Arabian Shield, the Zagros fold belt and the thrust sheets adjacent to the Arabian plate boundary in Oman. Paleozoic to Cretaceous outcrops border the Arabian Shield and the Zagros fold belt, variably onlapping one another and dipping to the east. The Jurassic outcrop is c. 800 km long in Saudi Arabia. Other Jurassic outcrops are found in the Zagros folds and the Musandam thrust sheets. The Jurassic outcrops in Oman are in Tethys shelf to ocean floor facies. Erosional outliers of the intrashelf basin rim facies occur in Ras Al-Fajairah, in the eastern United Arab Emirates (UAE). Jurassic outcrops and rift basins also occur in Yemen, but are not covered in this Memoir.

Figure 1.2 summarizes the extent and key elements of the Arabian Intrashelf Basin as interpreted in this Memoir. It is based on the many references cited, discussed and illustrated in this Memoir. The basin is largely defined by the area of source rock deposition shown in olive brown. It may have extended further into the Rub‘ al-Khali area. Note that this map shows the general setting early in the basin’s history. The proportion of shallow subtidal facies to basin centre deeper water facies expanded and contracted within each subsequent depositional sequence. These five figures are included to orient those new to the area to the important features and terminology of this region.

General setting of the Arabian Intrashelf Basin

Figure 1.2 summarizes the extent and key elements of the Arabian Intrashelf Basin as interpreted in this Memoir. It is based on the many references cited, discussed and illustrated in this Memoir. The basin is largely defined by the area of source rock deposition shown in olive brown. It may have extended further into the Rub‘ al-Khali area. Note that this map shows the general setting early in the basin’s history. The proportion of shallow subtidal facies to basin centre deeper water facies expanded and contracted within each subsequent depositional sequence. These five figures are included to orient those new to the area to the important features and terminology of this region.

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the rim than the inner edge of the broad shelf bordering the Neotethys Ocean. In this Memoir, the term Rimthan Arch is used only where it separates the Gotnia Basin from the Arabian Intrashelf Basin. The Jurassic intervals in the west onlapped older strata, and possibly even the Precambrian shield, but have been eroded. The present day outcrop belt in Saudi Arabia is largely in inner ramp facies. Late in the Jurassic a land barrier, a very low angle unconformity, developed in Oman and the eastern UAE (Rousseau et al. 2006; Grelaud et al. 2012) and in Iran, as evidenced by an unconformity noted by Gollesstaneh (1965, 1974), Setudehnia (1978) and Motaharian et al. (2014).

Previous studies in this region

Facies maps for selected intervals were presented by Grabowski and Norton (1995). Hughes-Clarke (1988) and Rousseau et al. (2006) synthesized the Jurassic of Oman and Forbes et al. (2010) wrote a lexicon for Oman. Summaries of the petroleum geology of the region include Cantrell et al. (2014, Saudi Arabia), Chaube and Al-Samahiji (1995, Bahrain), van Buchem et al. (2014, Qatar), Alsharhan et al. (2014a, Abu Dhabi), Bordenave (2014, Iran), Droste (2014, Oman) and Alsharhan et al. (2014b, Kuwait). Broader regional summaries include Alsharhan and Kendall (1986), Alsharhan and Magara (1994) and Ziegler (2001). De Keyser and Kendall (2014) showed depositional models for the development and infill of the Arabian Intrashelf Basin that are similar to those presented in this Memoir, but differ in some details.

Recent studies of the Saudi Arabia outcrops have added considerable detail to the outcrop section. These include isotope studies by Al-Mojel et al. (2018) and Eltom et al. (2018), the Hanifa sequences by Fallatah and Kerans (2018) and the Jubaila outcrop by El-Asmar et al. (2015).

The sequence stratigraphy for the region was proposed initially by Le Nindre et al. (1990) and de Matos and Hulstrand (1995, Abu Dhabi), regionally expanded using the Galloway system of maximum flooding surfaces in Sharland et al. (2001) and later modified in many papers, most recently by Tang et al. (2016). A sequence stratigraphy of the important Arab-D reservoir has been proposed by Handford et al. (2002) and Lindsay et al. (2006). Al-Husseini (1997, 2009) and Al-Husseini and Matthews (2005), Al-Husseini et al. (2006) evaluated the revisions and provided modifications to the 2001 concepts, including tying events to orbital forcing cycles, in a proposed Arabian orbital stratigraphy. Enay et al. (1987, 2009) remapped the outcrop belt, revising earlier age dating of Arkell (1952). Hughes (2004a, b) has provided extensive documentation and revision of the micropaleontology within Saudi Arabia. De Matos and Hulstrand (1995), de Matos and Hulstrand (2001) and de Matos and Walkden (2000) documented micro- and other fossils within Abu Dhabi.

Regarding broader issues of relevance that impact this study, and using a new geological timescale, McArthur et al. (2012) and Gradstein et al. (2012) made significant revisions to the time spans of the Mid and Upper Jurassic stages, which have not been changed to date. Dromart et al. (2003) proposed the late Callovian–early Oxfordian glacial lowstand, which occurred during a crucial time in the origin of the intrashelf basin and the deposition of the main source rock interval. Donnadieu et al. (2011) proposed a model for the end-Carolinian break in shallow water carbonate production, the resulting glacial lowstand and a change in seawater chemistry facilitating source rock deposition.

Ayres et al. (1982) is a summary of the 1973–77 major joint Aramco-Chevron evaluation of source rocks in Saudi Arabia, which was the first study to identify and map source rocks in that country. In that project, L.W. Slentz of Chevron Research and this author sampled from TD (total depth) to surface every wildcat well, every stratigraphic test well (36 wells) and all deeper field wells drilled up to that time in Saudi Arabia. The samples were screened for total organic carbon, followed by further analyses of the potential source rock intervals. The main source rock associated with the Tuwaiq Mountain and...
Hanifa intervals was first identified by Slentz and Chevron laboratory manager R.W. Jones’ analyses and interpretation. The previous interpretation had been that the oil was sourced by lateral migration from within the Jubaila and Arab-D (reservoir) intervals (Arabian American Oil Company Staff 1959). The actual analyses had shown only very low (<1%) total organic carbon in the Jubaila–Arab-D interval, except for thin beds of moderate richness in some wells at the base of the Jubaila Formation in the intrashelf basin.

Slentz continued with the geochemical evaluation and this author regionally correlated and mapped the thickness and richness of the main source facies using well logs and thin sections of cores and cuttings. R.M. Christensen used Lopatin techniques to model maturation and also evaluated the chromatographic data. The resulting net source rock by this author and later published in Ayres et al. (1982), first defined the areal extent of the intrashelf basin in the Eastern Province of Saudi Arabia, which was Aramco’s main operating area at that time. In this Memoir, this isopach is combined with source rock data for the intrashelf basin to the east to provide a framework for the regional interpretation of the intrashelf basin.

More recent papers and abstracts describing the source rock in the various areas are discussed and used to supplement this early work in the relevant chapters. These include Frei (1984), Lehner et al. (1984), Wilson (1984), Droste (1990), Cole et al. (1994), Carrigan et al. (1995), Al-Suwaidi et al. (2000), Al-Ibrahim (2014), Al-Ibrahim et al. (2017), Alansari et al. (2016) and Lindsay et al. (2015, 2016). Many other references are cited in this Memoir and the data and interpretations in all of these are used to document, evaluate and interpret the events that created the Arabian Intrashelf Basin and its vast hydrocarbon resources.

**Wireline logs**

Despite the many references available for this area spanning more than 600 × 1000 km, remarkably few wireline logs have been published for the entire upper Dhruma to top Hith interval. Of those that have been published, many are only gamma ray logs. Wilson (1985) published an FDC-CNL log and gamma ray log for the interval in the Qatif field in
Saudi Arabia. Handford et al. (2002) published five well logs from almost the complete interval in Saudi Arabia. Hohman et al. (2005) published four Saudi Arabia and seven Qatar gamma ray and porosity logs for the Tuwaiq Mountain and Hanifa formations. Saner and Abdulghani (1995) published gamma ray and porosity logs for the Tuwaiq Mountain and et al. (2005) published four Saudi Arabia and seven Qatar from almost the complete interval in Saudi Arabia. Hohman Saudi Arabia. Handford Names of oil and gas

Fig. 1.3. Names of oil and gas fields in the region. Fields coloured green and red are sourced from the Arabian Intrashelf Basin. Where the Upper Jurassic anhydrite seals thin and become ineffective in eastern Abu Dhabi, some of the oil and gas in Lower Cretaceous reservoirs is interpreted as sourced from the Jurassic (Yin et al. 2018).

The lack of well logs does make a regional interpretation and summary more difficult, but not impossible. There are many published pieces of data, variably documented, that can be assembled as pieces of the puzzle posed by the Arabian Intrashelf Basin, although important details are often missing. Mattner and Al-Husseini (2006) discuss some of these difficulties in the context of an Aptian geology question.

General terminology

In older lithic descriptions, the Brankamp and Powers (1958) and Powers (1962) terms calcarenite and calcarenitic limestone are used, which roughly correspond to the now commonly used Dunham (1962) terms of grainstone and wackestone to packstone, respectively.

The edge of the intrashelf basin shallow water facies is referred to as the intrashelf basin rim or simply as the rim. This is not to be confused with the ramp model term rimmed ramp, which implies a steep margin, possibly with reefs at the edge. Deposition in the sequences that formed the Arabian Intrashelf Basin was largely in ramp settings, but generally with low depositional gradients. There is some variation in the nature of the edge of the shallow water ramp. These variations are described in their appropriate context in this
Fadhili reservoirs in the Dhruma of Saudi Arabia are from pre-Lower Sic in the Gotnia Basin. The oil in the Faridah and Sharar reservoirs in Kuwait have oil sourced from the Jurassic reservoirs below the Saudi Jurassic outcrop, unless otherwise noted, shelf refers to the broad Tethys margin shelf.

Field names and fields probably sourced from the Arabian Intrashef Basin facies

The fields shown in green or red in Figure 1.2 contain oil or gas that is likely to have been sourced from the Arabian Intrashef Basin source rock. The oil in Jurassic reservoirs below the upper Dhruma reservoir includes Marrat oil in Kuwait (Yousif and Nouman 1997), which is not coloured green because most Jurassic reservoirs in Kuwait have oil sourced from the Jurassic in the Gotnia Basin. The oil in the Faridah and Sharar reservoirs in the Dhruma of Saudi Arabia are from pre-Lower Fadhil–Uwainat Dhruma source rocks (Ayres et al. 1982; Tang et al. 2016). The oil in these reservoirs has only been reported for the Faridah and Sharar fields, but there may be other locations.

Other fields coloured yellow in Figure 1.2 have oil or gas from other source rocks, such as deeper Paleozoic oil and gas in western Saudi Arabia. The North field offshore Qatar and Iran has Permian Khuff gas, as do the Ghawar and some of the other anticlinal structures. The fields in northern Saudi Arabia and in Kuwait have oil largely in Mid Cretaceous reservoirs, possibly sourced from Kazhdumi Mid Cretaceous source rocks (Ayres et al. 1982; Lehner et al. 1984). The fields shown near the south ends of the Ghawar and Khurais fields and near and under the Saudi Jurassic outcrop have Silurian sourced oil and gas in Paleozoic reservoirs. The oil and gas in Iran may have been sourced from Jurassic and Cretaceous source rocks. The fields in the western UAE and Oman (the Fahud–Lekhwair area) have oil in Mid Cretaceous reservoirs derived from Cretaceous source rocks. The smaller fields in the central Oman Ghaba salt basin have oil in Upper Paleozoic and Mesozoic reservoirs. In south Oman, there is Paleozoic oil in glacial sediments, partly (?) sourced from InfraCambrian source rocks (Beydoun 1987). This summary is extracted from Beydoun (1987), Alsharhan and Naim (1997), Cantrell et al. (2014), Bordenave (2014) and other references listed on Figure 1.2

Introduction to the stratigraphic nomenclature

A major goal of this Memoir is to clarify the various stratigraphic relationships within the area of the Arabian Intrashef Basin, which is confined to Saudi Arabia, Bahrain, Qatar, the UAE and Oman.
Lithostratigraphic Nomenclature, Also Maximum Flooding Surfaces, Sharland et al. 2001 as modified in this memoir.

Fig. 1.5. Lithostratigraphic nomenclature. The left-hand side shows both the early age dating of the section in Saudi Arabia, which was adopted in other country areas, and the more recent dating in Enay et al. (1987) and Al-Husseini (2009) used in this Memoir. In this Memoir, the main interval of the source rock is interpreted to be a lowstand deposit. Modified Sharland et al. (2001) maximum flooding surfaces are also included on the left-hand side. This chart is repeated in Wilson (2020b, Fig. 3.1, Chapter 3, this Memoir). The intervals in Kuwait have been dated using nanofossils, but comparable data are not known to be available for the interval in Saudi Arabia, hence precise age correlations to Kuwait are not shown in this chart. A general consensus of the correlations is shown in Figure 3.7 in Wilson (2020b, Chapter 3, this Memoir).

It is important to understand the different nomenclatures and different interpretations used in the Gulf countries. Nomenclatures were first established early in the exploration of this region and vary from country to country; in some cases they even vary within a given country. Despite this complexity in nomenclature, there is remarkable lithostratigraphic continuity, especially around the basin rim, in the underlying Dhruma Atash–Lower Fadhili–Uwainat reservoir facies and in the Jubaila and Arab–Hith formations at the top. The stratigraphic interval within the deeper basin itself is more complex. Another issue has been the initial use of layer cake lithostratigraphic terminology, which tends to obscure lateral facies changes between the intrashelf basin centre and its rim. Figure 1.5 shows the Jurassic stratigraphic nomenclature. On the left-hand side are the ages in the older literature as given in Powers (1968) and the dating used in this Memoir.

Figures 3.7 & 11.3 show depth–temperature profiles at the time of the maximum flooding surfaces denoted by the arrows on the chart. Figure 3.7 shows the Jurassic stratigraphic nomenclature. On the left-hand side are the ages in the older literature as given in Powers (1968) and the dating used in this Memoir.

Sugden et al. (1975), in their Lexique Stratigraphique for Qatar, observed that the conflicting nomenclatures evolved in early exploration as a result of physical isolation and a lack of communication between the petroleum geologists working for different companies in different countries. More recently, as can be seen for Qatar in van Buchem et al. (2014) and other papers discussed in this Memoir, the Saudi Arabian formation names have increasingly become intermixed with the earlier company and country nomenclatures, making the basic lithostratigraphy even more confusing, especially when comparing older literature with newer papers.

Arabian Intrastrat Shelf and adjacent Gotnia–Mesopotamian Intrastrat Shelf Basin

The Arabian Intrastrat Shelf section is located stratigraphically between the Jurassic Upper Dhruma Atash–Lower Fadhili–Uwainat interval and the top of the Hith (Anhydrite) Formation. A separate intrastrat basin of similar age in Kuwait and Iraq is the Gotnia–Mesopotamian Intrastrat Shelf Basin, but its lithofacies are very different even where similar stratigraphic names are used, with deeper water facies followed by thick salt intervals (Kadar et al. 2015). The portion of the Gotnia–Mesopotamian Basin in Iran is known as the Lurestan Basin. The name Gotnia Basin by itself is used to refer to the area of the basin in Kuwait, the southern edge of Iraq and at the NE edge of Saudi Arabia. The section in Iran in areas close to the Arabian Intrastrat Shelf is included in the Surmeh Group (Setudehnia 1978).

Age dating

The age dating used in this Memoir is strongly based on the extensive remapping and palaeontology of the Saudi Arabia Jurassic outcrop by Enay et al. (1987), who modified the earlier ages summarized in Powers (1968) and revised the ammonite zones of Arkell (1952). Microfossils in the outcrop and subsurface are strongly controlled by the facies.
 Numerous papers by Hughes on Saudi Arabia since the year 2000 (e.g. Hughes 2000, 2004a, b, 2008; Hughes et al. 2008) have extended the stratigraphic ranges of many of the microfossils used for dating the Mid- and Late Jurassic ages of the section across the region. De Matos (1997) and de Matos and Hulstrøm (1995) are the most thorough biostratigraphic studies of Abu Dhabi (as noted by Al-Suwaidi and Aziz 2002). However, the microfossils they cite for age determination in parts of the section are among those whose age ranges have been extended or otherwise altered by more recent work. The apparent discordant ages between Abu Dhabi and Saudi Arabia of the Tuwaiq Mountain and Hanifa intervals are therefore not supported by more recent data and require revision and reassessment. In other areas, such as in Qatar (Sugden et al. 1975) and Oman (Hughes-Clarke 1988), the dating of the section was originally based on correlation with Powers (1968), but has been revised to some degree, as in Droste (1990).

$^{87}\text{Sr}/^{86}\text{Sr}$ dating has also been used and is reviewed and evaluated in Chapter 3 (Wilson 2020), including adjustment, where possible, to the revised geological timescale (McArthur et al. 2012). Unfortunately, most of the published $^{87}\text{Sr}/^{86}\text{Sr}$ data cannot be reliably used for age dating as a result of the types of sample and lack of analytical detail. In many cases, the actual $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are not given, so they cannot be compared to revised versions of the global $^{87}\text{Sr}/^{86}\text{Sr}$ curve.

**Carbonate intrashelf basins**

An important concept essential to understanding the sequences and history of carbonate-dominated intrashelf basins is that the rapid aggradation of shallow water facies around the rim and local tectonics can separate the deposition within a basin from more regional or global influences. This may result in a basin becoming cut-off and slightly restricted during highstands of sea-level, and even more restricted during lowstands. Two coeval intrashelf basins in the same region may show drastically different depositional patterns. The late Bathonian to Tithonian intervals in the Arabian Intrashelf Basin and the Gotnia–Mesopotamian Basin are comprised of lithofacies sequences that are very different, as shown by comparing the depositional facies in the stratigraphic section of the Arabian Basin with the Gotnia Basin section shown in Yousif and Nouman (1997), Al-Moraikhi et al. (2014) and Kadar et al. (2015). These facies–stratigraphic differences are discussed in Chapter 3 (Wilson 2020). An enclosed basin may also have a less diverse fossil assemblage and a salinity and water chemistry significantly different from those of the global ocean.

Carbonate intrashelf basins form by a mixture of tectonics and differential carbonate deposition. The Bajocian–Bathonian Dhruma Formation below the strata of the Arabian Intrashelf Basin is an example of deposition in an intrashelf basin formed largely by tectonics, with significant development of relief beginning in the Triassic and continuing into the Early Jurassic, illustrated by de Matos (1997, his fig. 2.11) and Fig. 2.6 (Wilson 2020a, Chapter 2, this Memoir). The lower Dhruma intervals filled the tectonic relief with upwards-shallowing sequences, each of which filled the available accommodation space without forming a distinct rim around the basin. Once the accommodation space had been filled, the middle to upper Dhruma units blanketed the area.

**Main premises and new interpretations**

In the Arabian Intrashelf Basin region, as is so often the case in other regions, few ideas and interpretations are truly new or unique. Although this applies to the concepts presented in this Memoir, some of the proposed explanations as to how these all fit together are new. The main premises put forth in this Memoir are as follows.

- The Arabian Intrashelf Basin is a unique, complete hydrocarbon system.
- The Arabian Intrashelf Basin formed within Abu Dhabi, Qatar, Bahrain, the edge of Oman, and Saudi Arabia as one single basin in the Callovian, within the relatively open marine Tethyan shelf but 200–300 km from its outer edge. It was initiated by a major transgression coupled with minor subsidence. The subsidence was associated with Tethys passive margin drift and rifting.
- There are two areas in the single intrashelf basin where the Mid and Upper Jurassic section is slightly thicker, which have been termed the Rub’ al-Khali Basin in the east and the Arabian Basin in the west (Ayres et al. 1982; Ziegler 2001). However, despite many references to the Qatar Arch separating the two (e.g. Cole et al. 1994; Ziegler 2001; Lindsay et al. 2006), at most there was only a slight ridging with subtle thinning between the two areas during this time period and any depositional effect is subtle. Van Buchem et al. (2014) stated that the Qatar Arch was not an active structural high and therefore not a major factor during the Mid- and Upper Jurassic. De Keyser and Kendall (2014) also showed the Arabian Intrashelf Basin as a single basin.
- Within and around the rim of the single intrashelf basin, there are identifiable coeval depositional and tectonic events both around the margins and in the basin. Because of many of these events, which formed the Arabian Intrashelf Basin depositional sequences, have previously been assigned to different ages in different areas around the basin, much of this Memoir consists of documentation, discussion and revisions as to how these events are either coeval and/or of different ages than were generally documented in the earlier literature on the area.
- Biostratigraphic and $^8{\text{Sr}}/^{86}{\text{Sr}}$ dating provide a very general idea of the ages, but in most cases are not precise enough for definitive age dating. These general ages are used in conjunction with the interpretation and correlation of the coeval depositional events to define sequences and the evolution of the intrashelf basin. The depositional sequences as defined in earlier work are reviewed and correlated with the basin-wide events and, in some cases, suggested modifications are presented.
- On the relatively open marine Tethyan shelf, with rising sea-levels and a greenhouse climate, a very productive shallow water carbonate factory built the Tuwaiq Mountain Formation carbonate rim (Hadiya reservoir), forming the intrashelf basin. An end-Callocovian–early Oxfordian lowstand ended the shallow water carbonate progradation, leaving a huge basinal area surrounded by the subaerially exposed Tuwaiq Mountain Formation rim.
- The global end-Callocovian into early Oxfordian lowstand brought restricted conditions favouring cyanobacteria–microbial carbonate intrabasinal deposition, which resulted in an exceptionally organic-rich, petrographically unique laminated carbonate source rock within the intrashelf basin. By contrast, other published interpretations ascribe the onset of source rock deposition to anoxic conditions developed with rising sea-levels. A model (Dromart et al. 2003; Donnadieu et al. 2011) for the lowstand having a glacial origin is discussed in the context of source rock deposition.
- Late in the Jurassic, the deposition of the Arab–Hith carbonate–evaporite sequences was controlled by a balance between eustatic sea-level fluctuations, the development
of a land barrier on the broad Tethys shelf and a subtle westwards tilt. Previous interpretations have not fully acknowledged the importance of the land barrier.

The following sections briefly summarize these main premises in the context of the depositional sequences.

**Arabian Intrashelf Basin intervals and sequences**

*Schematic cross-section showing stratigraphic relationships*

Figure 1.6 is a schematic, roughly to scale, cross-section across the basin from the northern offshore waters of Bahrain and Qatar to the outcrop in Saudi Arabia. This summarizes the general interpretation of the intrashelf basin interval documented and discussed in this Memoir, interpreted from many sources, including: Enay et al. (1987, 2009) (Saudi outcrops); Ayres et al. (1982) (within the basin, east–west, Saudi Arabia); McGuire et al. 1993 (eastern rim); Chalbi and Al-Samahiji (1995) (Bahrain, also this author, unpublished Bahrain offshore reports 1985–86, cited in Chalbi and Al-Samahiji); van Buchem et al. (2014) (Qatar); and de Matos (1994, 1997); de Matos and Hulstrand (1995); Al-Silwadi et al. (1996), Al-Suwaidi and Aziz (2002) (Abu Dhabi). The original cross-sections are shown in Chapter 4 (Wilson 2020c). This schematic cross-section shows a transit where the intrashelf basin symmetry is well preserved. Elsewhere, the rim facies of the eastern margin (UAE, Oman) were partly eroded during the Late Jurassic.

**Upper Dhruma Formation–Dhruma Atash Sequence: the foundation for the formation of the intrashelf basin**

Prior to the development of the intrashelf basin, the Upper Dhruma Atash–Lower Fadhili–Uwainat shallow water carbonates blanketed the area, forming a very broad, low-relief platform (de Matos 1997; Murris 1980; Rousseau et al. 2006; Tang et al. 2012; De Keyser and Kendall 2014).

**Tuwaiq Sequence: development of the intrashelf basin**

Sea-level rise and some subsidence began the deposition of the Tuwaiq Mountain Formation depositional sequence (MFS J40), which begins at the base of the uppermost Dhruma Hisyan Member. Slightly greater subsidence in what became the basin centre created enough relief for aggradation and progradation to form the shallow intrashelf basin rim. The subsidence was probably due to both earlier sediment loading and subtle tectonic processes. The tectonic contribution was probably associated with westward drift as the Tethys Ocean continued to develop. In the basin, deeper water facies with benthic forams and the tiny bivalve *Bositra buchi* accumulated, as documented in Hughes (2004a, b; Hughes et al. 2008). The deeper water facies are occasionally slightly organic-rich. The Tuwaiq Mountain rim facies in the Saudi outcrop include build-ups rich in stromatoporoids with corals and coralline algae. On the basin rim in the subsurface, the shallow water facies comprise the Hadriya reservoir with grainstone facies (e.g. Powers 1968; Ayres et al. 1982; McGuire et al. 1993; de Matos 1997; Tang et al. 2012; Lindsay et al. 2015). The Upper Fadhili reservoir below the
Hadiya reservoir pinches out into the deeper water basin centre carbonate facies (Powers 1968). The Upper Fadhili facies may represent facies of a highstand systems tract of a higher order Tuwiq Mountain interval sub-sequence formed in an early phase of sea-level rise, or it may simply be distal facies of the Hadriya reservoir. The Hadriya reservoir facies prograded basinwards in the highstand regressive systems tract phase, but do not extend as far into the basin as the Upper Fadhili.

Source rock deposition during a major lowstand sequence
(Lower Hanifa lowstand systems tract)

The source rock interval is shown as olive brown in Figure 1.6. Most published interpretations of the source deposition attribute it to a deep-water facies at least partly coeval with the Tuwiq Mountain basin rim facies and deposited during a sea-level highstand, with the deeper intrashelf basin centre becoming anoxic. By contrast, the interpretation favoured in this Memoir is for the source rock facies to be post-Tuwiq Mountain and formed when the intrashelf basin was restricted by a widely recognized global end-Callovian lowstand, which continued into the Oxfordian. During this lowstand, the margins were exposed and shallow water carbonate deposition was repressed. The intrashelf basin was restricted, but enough circulation from the Tethys Ocean persisted to prevent major evaporite deposition. The richest source rock deposition across the Arabian Intrashelf Basin began abruptly, always showing a very pronounced and sharp basal contact, as indicated in core and well logs. It is event-driven and not a product of a gradual change. The source rock is a unique organic-rich carbonate laminite facies with minimal clay, typically characterized by micropeloidal (silt-sized) microgranstone laminae interlaminated with very organic-rich laminae. The micropeloids are interpreted as calcified cyanobacterial cells and the organic matter as intrabasinal and microbial in origin. Kendall et al. (2007) also interpreted a cyanobacterial origin for the organic matter. The considerable documentation to support this lowstand interpretation is presented in subsequent chapters and compared with the highstand systems tract interpretation and with global factors. Recovery from the lowstand was characterized by a gradual, but episodic, decrease upwards in organic richness and a slow return to more normal marine intrashelf basin facies. An upwards-shallowing transition from highstand deposition of source rock would be similar. Other factors distinguishing the lowstand interpretation favoured in this Memoir v. the highstand systems tract interpretation are evaluated in the following chapters.

Hanifa sequence(s): return to normal marine deposition

By the mid-Oxfordian, the rise in sea-level had returned more normal marine conditions to the intrashelf basin rim and centre. In outcrop, the Hanifa shallow water facies include oolitic grainstone, with stromatoporoid facies present, but less prominent than in the older underlying Tuwiq Mountain Formation. Enay et al. (1987) documented that the fossil diversity in the outcrop is much lower in the Hanifa Formation than in the Tuwiq Mountain Formation, indicating that slight restriction continued throughout Hanifa deposition. Progradation of the Hanifa facies into the basin formed the Hanifa reservoir, which extends further basinwards than the Hadriya reservoir of the upper Tuwiq Mountain. By late Hanifa deposition, the deeper water remnant of the basin was much smaller in area than in earlier Hanifa times and was shifted eastwards due to faster progradation and infill from the west.

In this Memoir, this is attributed to dominant wind direction at the time and resulting higher energy levels in the west (Fig. 1.9). A late Hanifa lowstand resulted in the deposition of beds of subaqueous anhydrite in the remnants of the intrashelf basin centre and a disconformity on the basin rim. The Hanifa sequences shown are similar to the interpretation summarized in Al-Husseini (2009), except that MFS 150 is placed higher in this Memoir, in the interval where the organic richness decreases. Two informal members are defined in the Hanifa Formation in outcrop: the lower Hawtah and the upper Ulayyah (Enay et al. 1987). Sharland et al. (2001) also proposed a local MFS J60 within the Hanifa, which has been interpreted as representing the Ulayyah interval (e.g. Simmons et al. 2007).

Post-Hanifa westwards tilt and subsidence

At end-deposition of the Hanifa sequence, the Hanifa shallow water rim facies would have been near sea-level around the intrashelf basin rim. Concomitant with the Jubaila transgression, westward structural tilt provided accommodation space. This subtle structural tilt continued into the early Tithonian. A greater thickness of Jubaila intrashelf basin facies rich in lime mud was deposited to the west, whereas in the east the deposition of shallow water carbonate facies was almost continuous. In the west, updip of the present day outcrop in Saudi Arabia, shallow water facies may have been more prevalent in the Jubaila.

Jubaila: Arab-D sequence

Sea-level rise and some subsidence again expanded intrashelf basin deposition, with the Jubaila facies rich in lime mud grading upwards to the shallow water facies of the Arab-D reservoir. In the outcrop, the shallow water facies are divided into two members. The top of the Jubaila Formation is taken within the lower portions of the Arab-D reservoir. Progradation into the basin was again initially from the margins, but, as the basin filled, the directions of progradation became more complex, forming shoals and variably isolated remnant areas of slightly deeper water. In the latest stages, the energy levels became low, the deposition of higher energy facies ceased and only shallow lagoonal remnant basins remained. These basins were filled by lime mud and the initial deposition of the Arab-D anhydrite.

Handford et al. (2002), Lindsay et al. (2006) and Al-Husseini (2009) assigned two third-order sequences to the Jubaila–Arab-D and Tang et al. (2016) described the Jubaila–Arab-D as a composite second-order sequence. This subdivision into two third-order sequences is usually difficult in the subsurface, but there is evidence for this subdivision in the western Saudi Arabia outcrops.

Late Jurassic Tethys margin land barrier

In the east, a land barrier formed adjacent to the Tethys Ocean as a very low angle unconformity. The interpretation of Rousseau et al. (2006) is that this unconformity first began to develop in the Callovian and that it was a major factor in the formation of the Arabian Intrashelf Basin. However, this is an isolated interpretation made in the context of its eastern setting and does not take into consideration its relationship with the rest of the intrashelf basin area. The interpretation in this Memoir is that the Tethys margin land barrier began later. This is because the mid-Callovian Tuwiq Mountain rim developed at the same time and in the same way in all other
areas around the entire rim, far away from where the land barrier later formed. The Hanifa Formation is also similar around the basin rim. Eastwards in the UAE, Grelaud et al. (2012) and Razin et al. (2012) showed Dhruma, Tuwaiq Mountain, Hanifa and Jubailah (?) facies truncated at this unconformity, whereas the Kimmeridgian (Arab Formation) and Tithonian at some times onlapped and at other times were exposed and partially eroded. The land barrier extended further northwards around the basin into Iran (Gollesstanneh 1965, 1974; Setudehnia 1978; Motaharian et al. 2014). Cooper et al. (2016) interpreted the uplift as due to a mild compressive phase in the Late Jurassic. Torsvik and Cocks (2016) showed that the opening of the Atlantic Ocean, beginning late in the Jurassic, may have generated a subtle compressive force far to the east of the Atlantic rift. Murris (1980, his fig. 12) also recognized a land barrier, but interpreted it as confined to the Oxfordian and early Kimmeridgian.

Other interpretations (e.g. Al-Silwadi et al. 1996; Alsharhan et al. 2014a, b) have shown the Late Jurassic eastern margin of the intrashelf basin to be open to the Tethys Ocean, but the land barrier interpretation is preferred in this Memoir (discussed in Chapters 5 (Wilson 2020d) and 6 (Wilson 2020e)).

This Memoir interprets this mild uplift in the east and westwards tilt as possibly Kimmeridgian and Tithonian and as a significant factor in the deposition of the Arab–Hith evaporites. The uplift and westwards tilt episodically isolated the Arabian Intrashelf Basin and also the Gotnia–Mesopotamian Basin from the Tethys Ocean, with additional fluctuations superimposed by eustatic sea-level rise and fall.

**Arab-C to the Hith carbonate–evaporite sequences**

By the end of Arab-D deposition, the Arab-D anhydrite completed the infill of the intrashelf basin, leaving a broad and very flat evaporite platform across the intrashelf basin area roughly at sea-level (Wilson 1975). The lower sequence boundaries are at the base of the evaporites. The evaporites are interpreted as formed by the influx of seawater, with the flooding baffled by the land barrier, resulting in the deposition of gypsum. As the sea-level rise progressed, the waters became fresh enough to allow shallow water carbonate deposition, forming the Arab-C to Arab-A carbonate reservoirs. The Arab-C to Arab-A sequences show thinning of the carbonate intervals and thickening of the anhydrites westwards and/or southwards from the eastern intrashelf basin rim (e.g. Magara et al. 1993; Al-Silwadi et al. 1996). To the east in Abu Dhabi and northwards into Iran (Setudehnia 1978), the anhydrites pinched out or were eroded. The proportion of anhydrite also decreases onto the Rimthan Arch. The Hith Anhydrite Formation formed a thick seal, but intra-Hith carbonate beds increase in frequency to the east. The carbonate intervals are shallow subtidal to lagoonal and peritidal. The shallow subtidal facies are often seen as thin, transgressive oolitic beds.

**Arabian Intrashelf Basin: a unique depositional feature**

The overall intrashelf basin sequence contains a prolific source rock, several reservoir intervals, and remarkably extensive and effective gypsum–anhydrite seals. Continued Tethyan shelf subsidence and Cretaceous and Tertiary sedimentation buried the Arabian Intrashelf Basin facies deeply enough to allow maturation of the source rock. The timing of maturation was such that oil migrating from the exceptionally rich source rock was available to charge the reservoirs during the Late Cretaceous–Miocene development of the huge anticlinal structures. Overall, including its limited geographical and stratigraphic extent, the Arabian Intrashelf Basin formed a self-contained hydrocarbon system and became the most prolific discrete hydrocarbon system in the world.

**Plate tectonic setting and implications: Mid- to Late Jurassic**

Figure 1.7 shows the general location of the Arabian plate as Pangaea separated into Gondwana and Laurasia, with the Arabian Intrashelf Basin on the broad shelf adjacent to the Neotethys Ocean (Torsvik and Cocks 2016). The Neotethys Ocean was well developed by the Mid-Jurassic, with the Arabian plate occupying a passive margin. Figure 1.7 shows the incipient opening of the Atlantic Ocean and the separation of India from the Arabian plate in the Oxfordian.

**Palaeolatitude**

A palaeolatitude of 10° S is shown in Figure 1.2, which was plotted using a palaeolatitude calculator (Fig. 1.8). Palaeolatitudes are important because the various depositional models proposed in the literature and used or revised in this Memoir require a knowledge of the location of the palaeowind and storm belts and the associated wind directions, strengths and wave energy levels and the likelihood of hurricanes impacting the area. Various sources give different palaeolatitudes and palaeowind directions. Al-Husseini (1997) showed the Berri field in Saudi Arabia to be at c. 10° S. Sharland et al. (2001, their fig. 3.26, citing several sources) show the equator crossing the southern tip of the Qatar peninsula during much of the AP7 Jurassic megasequence. Handford et al. (2002), Lindsay et al. (2006) and Cantrell et al. (2014) show the general area of the Ghawar field in the Kimmeridgian at c. 5° S. Al-Nazghah (2011) shows that the equator during the Kimmeridgian trended slightly SW from the base of the Qatar peninsula.

Figure 1.8 shows a plot of palaeolatitudes from the Bathonian to Tithonian for a point in the Arabian Intrashelf Basin. The palaeolatitudes were determined for the present latitude and longitude of (24.8978° N, 49.7321° E) in the Ghawar field, using the palaeolatitude calculator in van Hinsbergen et al. (2015, Figure 1.8) and Torsvik et al. (2012). The ages are based on the 2012 geological timescale (Gradstein et al. 2012, unchanged by 2019), including 95% confidence limits. The reference point is near the northern end of the Ghawar field. The calculator indicates little change in latitude from the Arabian plate in the Oxfordian.

**Palaeotradewind direction, wave energies and water circulation**

Figure 1.9 compares the setting of the Arabian Intrashelf Basin with the palaeotradewinds (5–30° SE). (https://ocean service.noaa.gov/education/tutorial_currents/04currents2.html). The palaeolatitudes would have placed the easterly and southern margins of the intrashelf basin on the most sheltered side of the fringing shallow shelf rim. By contrast,
on the western and northern margins, the trade winds blowing across several hundred kilometres of open water within the intrashelf basin would have exposed those areas to much higher wave energies. In addition, daily heating of exposed areas updip from the present day western outcrops would have generated sea breezes, further enhancing the wave energy. The area would have been at relatively humid latitudes until the Tithonian drift to the south, which would have placed the area on the edges of the latitudes of present day deserts.

The Arabian Intrashelf Basin was a huge body of water separated from the open Neotethys Ocean by the broad Tethyan shelf. The fossil diversity after the development of the Tuwaïq sequence was lower (Enay et al. 1987) throughout the rest of its history. However, as can be seen in Enay et al. (1987) and in the various papers by Hughes and others cited in this Memoir—except for the source rock interval—there was still a wide range of organisms, suggesting that the waters in the basin were only slightly different from normal seawater during much of this time. A partial analogue is the present day Arabian Gulf, with slightly increased salinities and a less diverse fauna and flora than the Indian Ocean and Red Sea (Barnes et al. 1981).

The specific location of passages through which water would have flowed into the Arabian Intrashelf Basin from the Tethys Ocean has never been defined. The wind directions create a general flow across the shelf (as shown in Figure 1.9), which would provide an influx of water during times of rising sea-level and highstands. Lindsay (2014) stated that there were accessways (broad channels) in Arab-D time. Some access may have existed across the Rimthan Arch to the Gotnia–Mesopotamian Basin, but wind-driven currents would have forced water into the Gotnia–Mesopotamian Basin rather than vice versa. The Gotnia–Mesopotamian Basin itself became increasingly restricted during much of the Mid- and Late Jurassic, as indicated by the lack of fossil diversity in the
Sargelu, Naokelekan–Najmah and the Gotnia–Barsarin evaporite intervals (Dunnington et al. 1959; Kadar et al. 2015; this author, in multi-client reports; PGA et al. 1988, 2003). The effect of tidal flow is not known. There may have been distinct channels across the broad shelf that have not yet been detected due to the regionally sparse well control, the lack of high-resolution seismic data in the areas where these may have existed, and erosion in the Late Jurassic adjacent to the Tethys Ocean.

Lindsay (2014), Lindsay et al. (2006) and other workers have suggested that very strong hurricanes struck the area and were important in the depositional architecture because the basin is located on the western side of the almost global fetch of the Tethys Ocean. Unless the area was further south than the palaeolatitude calculations indicate, storms may have been significant, but not extraordinary. Figure 1.10 shows the tracks and intensity of all tropical storms recorded since records were first kept (from the National Oceanic and Atmospheric Administration website: https://www.ncei.noaa.gov/news/inventory-tropical-cyclone-tracks). Most tropical storms form along 10° latitude and track west, eventually turning and strengthening away from the equator. They obtain their strength from the circulation enhanced by the Coriolis force, which is zero close to the equator. Although the Arabian Intrashelf Basin was at the margin along which the strongest storms would have begun to form much further east, the storms would have drifted to the south by the time they reached the longitude of the Arabian Intrashelf Basin.

Normal latitudes of evaporite deposition

Gordon (1975) stated that present day evaporites and those deposited as far back as the Permian are restricted between 50° latitude and the 10° boundary of the equatorial zone, which extends c. 10° from the equator. The palaeolatitudes in Figure 1.8 are used in this Memoir. The Arabian Intrashelf Basin was at the margin along which the strongest storms would have begun to form much further east, the storms would have drifted to the south by the time they reached the longitude of the Arabian Intrashelf Basin.
paralleling the equator and/or find an alternative explanation. The website of the evaporite specialist John Warren gives a model for isolated intracratonic evaporite basins (www.saltworkconsultants.com/ancient-platform.html).

**Intertropical Convergence Zone**

A latitude of 10° generally marks the entry into the Intertropical Convergence Zone (ITCZ) (Waliser and Somerville 1994). The ITCZ is the zone near the equator where easterly trade winds from both sides of the equator converge and decrease in strength. It is usually a humid zone with frequent rainfall and its location and other features fluctuate. The northern half of the Arabian Intraself Basin would have been in the ITCZ. Isotopic signatures (δ18O) indicating meteoric diagenesis were found by Al-Mojel et al. (2018) at the disconformities on top of the Tuwaq Mountain and Hanifa formations. Bray (1997), Bray and Rankey (2002) and Lindsay et al. (2006) found evidence for vadose diagenesis. This author has observed that early leaching is not uncommon in carbonates in the area (e.g. Wilson 1985). Although the setting of the Arabian Intraself Basin has, in general, been interpreted as very arid, its palaeogeographical location suggests otherwise.

**Exploration history**

This section focuses on the discoveries of Jurassic oil sourced in the Arabian Intraself Basin, beginning with Saudi Arabia. This history is important in understanding how the remarkable continuity of the Arabian Intraself Basin geology has been obscured because it was initially defined in different ways in different countries and oil exploration companies.

**Saudi Arabia and Bahrain**

This summary of exploration in Saudi Arabia is extracted from Powers et al. (1966), Beydoun (1987), Alsharhan and Nairn (1997), the book Discovery (Stegner 2007) and accounts from geologists this author worked with in Aramco from 1973 to 1981. This is a brief history because the subject is complex and is covered well in, for example, Beydoun (1987) and Alsharhan and Nairn (1997).
Tracks and Intensity of All Tropical Storms

![Hurricane Intensity Scale](https://www.ncei.noaa.gov/news/inventory-tropical-cyclone-tracks)

**Fig. 1.10.** This image is a track of all known tropical storms/hurricanes (also known as typhoons and cyclones) in modern times from the US National Oceanic and Atmospheric Administration website: [https://www.ncei.noaa.gov/news/inventory-tropical-cyclone-tracks](https://www.ncei.noaa.gov/news/inventory-tropical-cyclone-tracks). The greatest number of hurricanes form near 10° north or south of the equator, drift westwards and gradually turn away from the equator. With clockwise rotation south of the equator the strongest winds are on the south sides of those storms, where the winds blow in the direction of the westward drift. The Coriolis force is a major factor, generating the rotation and the general movement from westwards to southerly. The Coriolis force changes from zero to a very low level between the equator and latitudes 10° north or south of the equator, hence the storms form as shown. As the Coriolis force is unlikely to have been much different in the Jurassic, a similar setting in the north of the equator, hence the storms form as shown. As the Coriolis force is unlikely to have been much different in the Jurassic, a similar setting in all likelihood existed in the Arabian Intra-shelf Basin area, most of which would have been on the periphery of the hurricane belt.

Oil in the Arabian Peninsula area was first discovered in Bahrain’s Awali field in 1932 after a concession had been granted in 1929 to Standard Oil of California (Chevron). The Awali field is in a large surface structure with topographic relief, forming an elongate and prominent jebel (hill). The reservoirs discovered were in the Cretaceous zones (Beydoun 1987), although the oils were later found to have migrated upwards from the Jurassic along fractures.

On clear days, the prominent Dammam dome jebel on the Saudi Arabian coast could be seen from Bahrain, prompting speculation of a structural trap similar to the Bahrain Awali field. Chevron pursued a limited concession in Saudi Arabia, which was granted in 1933 for 66 years. A team was sent in and the first well in Saudi Arabia was drilled in 1935 on the Dammam dome. Texas Oil (Texaco) joined with Chevron in 1937. Tests in the Cretaceous zones (which were productive in Bahrain) were disappointing, a result which continued as several more wells were drilled. At the same time, reconnaissance exploration teams were criss-crossing eastern Saudi Arabia. To the west, in the Jurassic outcrops, they found Dhahiri, a cavern at the contact of the Hith Anhydrite with the overlying Cretaceous Sulaiy Formation, and recognized that the anhydrite seal over shallow water carbonates showed a potential Jurassic play. The Dammam dome drilling was just about to be abandoned when it was decided to deepen the seventh well. It was drilled through the newly discovered Hith Anhydrite and found a gas cap and oil in the Arab Formation. Shortly thereafter, the Dammam–7 well was producing several thousand barrels of oil a day.

After the Dammam discovery, field parties mapped the region further. Structure drilling was used to delineate some apparent surface anticlines and seismic work began. In 1939, the concession was extended to cover the entire area of sedimentary rocks in Saudi Arabia. The Abu Hadriya field was discovered in 1939 and the Abqaig field in 1940. The big prize – the Ghawar field – was not discovered until 1948, first in the north end Ain Dar area and then far south at its southern end at Haradh. The structure was so large that only during 1951–53, after the northern Fazran tip and the middle Uthmaniyyah, Shedgum and Hawiyah areas were drilled, was it determined that it really was a single structure and the world’s largest oilfield: 250 km long and later shown to be 30 km wide, with 396 m (1300 ft) of oil column (Alsharhan and Nairn 1997; Affi 2005).

Other discoveries were made over the same years and in subsequent years. The first offshore oil was found in 1951 in the supergiant Safaniya field, which has oil primarily in Cretaceous siliciclastic reservoirs. Its northern extension in Kuwait is known as the Khafji field. The Safaniya–Khafji field is located on the north side of, but adjacent to, the Rimum Arch and is in the separate Gotnia Basin.

In 1944 the name of the company became the Arabian American Oil Company (Aramco) and in 1948 Standard Oil of New Jersey (Exxon) and Socony Vacuum (Mobil) bought shares in Aramco. The Saudi Arabia government acquired a 25% share in 1973, increasing to 100% ownership in 1980 when the company became Saudi Aramco. The chronology of further discoveries before 1987 is included in Powers et al. (1966) and in Beydoun (1987).

Chronology is only part of the story because the discovery and development of the Saudi oil reserves is one of the most compelling stories in petroleum exploration. In the early days, the teams sent to Saudi Arabia had to build their initial base in Dhahran. Those doing fieldwork had to be adventurers who were willing to learn to survive and navigate in the desert, learning to drive in the sand by adapting wide aircraft tyres with the circular tread to stay on top of the soft sand, and learned from, and their lives depended on, their Saudi Bedouin guides. Travel across the deserts was slow-going and parties had to be self-sufficient and spend long times out in the field. Fieldwork was either curtailed or totally stopped in the hotter summer months. The entire region had to be surveyed and often the weather conditions made establishing precise locations difficult. Structure drilling to Tertiary horizons was extensively used until 1961 to identify and further delineate prospects (Powers et al. 1966). A picture of the geology gradually evolved. Work continued during the Second World War, although fears of invasion hung over the operation. The only actual war incident was a bombing raid targeting Bahrain by four Italian planes from Ethiopia in an ambitious long-range attack. One plane separated from the others and bombed Dhahran, but none of the bombs did any significant damage, as described in the Aramco World magazine (http://archive.aramcoworld.com/issue/197604/air.raid.a.sequel.htm).

So much oil had been discovered by the late 1950s that the four owner companies, according to anecdotes among Aramco geologists, had become concerned about the cost of developing new discoveries when the known reserves would last far beyond the end of their 1999 concession agreements. As a result, a programme of drilling off-structure stratigraphic test wells was begun, ultimately resulting in 36 deep wells that provided valuable geological control. Some areas were relinquished, so that by 1976 Aramco was operating in one large area in the Eastern Province and another large area in Rub’ al-Khali adjacent to Abu Dhabi and Oman, where the Kidan Jurassic gas fields and the Shaybah Aptian Shuaiba oil had been discovered. Other smaller areas with structures had also been retained.

As a result of the increased demand for oil and shortages in North America, a massive effort began to increase exploration, field development and the Saudi Arabian infrastructure, with Aramco heavily involved in all of this. The turnaround was underway when this author arrived in Dhahran in 1973, a week before the October 1973 Arab–Israeli war, the resulting
oil embargo and the huge jump in the price of oil. At that time, only one production geologist was assigned to the entire Gha-
war field, whose primary task was to document new data from the Arab-D cores in the field and maintain other aspects of the geological database. Soon after, the four parent companies became deeply involved in work on the fields and Aramco’s exploration staff was increased. The expansion continued throughout the 1970s and accelerated after the Saudi government acquired 100% ownership. Saudi Aramco was again given exploration rights to the entire country. A large, modern and well-equipped research laboratory was established and the geological and geophysical staff increased. The end result was that many more aspects of the geology were extensively doc-
umented from the 1970s onwards.

Over this same period, universities in Saudi Arabia (and the other Arabian Gulf countries) began to offer geology degrees. Gulf area citizens were also sent to study in other countries. Today, most of the geologists conducting research and explo-
ration there are from the Gulf countries. More recently, Saudi Aramco has begun to evaluate non-conventional plays, includ-
ing those in the main Jurassic source rock (Lindsay et al. 2016), and possible stratigraphic traps (Tang et al. 2016; Alha-
warj et al. 2016).

Qatar
This Qatar summary was extracted from Beydoun (1987), Alsharhan and Nairn (1997) and Sugden et al. (1975). The Anglo–Persian oil company was given a concession in Qatar in 1935 and later became the Petroleum Development Company of Qatar (PDQ). Oil was discovered in the Dukhan field in 1939. Years later, Shell made the offshore discovery of the Idd Al-Shargi field in 1960 and three other discoveries not long after, including the supergiant North Dome Permian gas field. In 1953, PDQ became the Qatar Petroleum Company (QPC). The government company, the Qatar General Petroleum Company, obtained 60% ownership of the QPC and Shell areas. Later, in the 1980s, Wintershall and Sohio obtained areas to explore. Oil in the offshore region is largely in the Arab-D reservoir and the onshore oil is in the Dukhan field. There is also a small area with Arab Formation oil in the North Dome field.

UAE
This UAE summary was extracted from Beydoun (1987), Alsharhan and Nairn (1997) and Yin et al. (2018). Regionally in the UAE, the Trucial Coast Petroleum Development Company (owned by the Iraq Petroleum Company (IPC) con-
sortium) acquired a concession in 1936. The first discovery onshore Abu Dhabi, the Bab-Murban structure, was made in 1954. The company became the Abu Dhabi Petroleum Company and offshore exploration was conducted by the Abu Dhabi Marine Areas company. The IPC relinquished the Tru-
cial Coast areas and other companies moved in. Some discoveries have been made in all of the emirates except Fujairah, which is on the Gulf of Oman–Arabian Sea.

Fields with Jurassic oil include Abu Al-Bukhsh, Al-Bateel, Al-Bunduq, Arzanah, Belbazem, Bu Jufair, Bu Tini (gas and condensate), Dlana, Ghasha, Hail (gas and condensate), Mubarraz (gas), Nasr, Satah, Umm al Anbar, Umm Al-Salsal and Yasir. Sharjah’s Sajaa field has Late Jurassic gas and con-
densate, which is sealed by the Cretaceous Nahr Umr shales. Most of these have hydrocarbons in the Arab zones, with some also having hydrocarbons in the Uwainat and Lower Araej reservoirs. In general, hydrocarbons where the Arab–
Hith anhydrite seals are effective are interpreted as sourced from the lower Hanifa source rock. Zakum and other fields have oil in early Cretaceous Thamama reservoirs, which, above where the Jurassic anhydrite seals thin and pinch out to become ineffective, may be sourced from the Jurassic. Cret-
eaous oil is also interpreted as sourced from the Bah and Shi-
lafet Cretaceous source basins. Yin et al. (2018) provide a recent summary of the UAE petroleum systems.

Oman
Oman probably does not have Jurassic oil, but exploration in Oman has given additional data for understanding the intra-
shelf basin, as in Rousseau et al. 2006. Initial exploration, which began in 1937, was by the IPC operating as Petroleum Development of Oman. Except for Shell, the IPC partners left Oman in the 1950s after drilling several dry holes. Discoveries were ultimately made in three main areas: the Fahud salt basin in the central northern area (closer to the Abu Dhabi and Saudi Arabia boundaries, with oil in Cretaceous reservoirs); the cen-
tral Oman Ghaba salt basin (oil in Upper Paleozoic and Meso-
zoic reservoirs); and in parts of the south Oman salt basin (with oil in Paleozoic reservoirs) (Beydoun 1987). Other companies have obtained areas in licensing rounds, including Elf, Japex and Occidental Petroleum, with some discoveries.

Exploration history and our understanding of the regional geology
The varied exploration history in this region, contributed to by so many different companies, which, among themselves, were potential competitors for concessions and market share, is a major reason why the stratigraphic terminology is so complex and regional synthesis has been so slow to develop. Since 1994, many publications in GeoArabia and conferences originated by Gulf Petrolink have considerably improved geological communication between the various countries and companies. An interesting and sometimes frustrating quirk in the document-
ation of the petroleum geology of the area is due to early British and American influences: well depths, well logs and thicknesses are in feet, whereas surface measurements are metric. However, in some publications, metric measurements are used or intermixed for the subsurface and we need to be care-
ful when reading the literature to identify which measurement system is used. Scale errors are also not uncommon in pub-
lished illustrations.

| Country          | Barrels of oil |
|------------------|----------------|
| Bahrain          | 108 000 000    |
| Iran             | 155 600 000    |
| Iraq             | 147 233 000    |
| Kuwait           | 101 500 000    |
| Oman             | 5373 000 000   |
| Qatar            | 25 244 000 000 |
| Saudi Arabia (2016, 2018) | 266 260 000 000 |
| Syria            | 2 500 000 000  |
| United Arab Emirates | 97 800 000 000 |
| Yemen            | 3 000 000 000  |

*Sources: Oil and Gas Journal (2018) and Saudi Aramco Facts and Figures, 2016 – booklet handed out at the American Association of Petroleum Geologists ICE (October 2017, London, UK).
Reserves

The latest estimates of remaining recoverable Middle East oil reserves are published every December in the Oil and Gas Journal. The countries in which a very large proportion of their oil is sourced from the Jurassic Arabian Intrashelf Basin (as defined in Figs 1.2 and 1.3) are shown in bold in Table 1.1.

The proportion of Jurassic-sourced oil in the UAE is not known because some of the oil in this country is from Cretaceous source rocks (Yin et al. 2018). Saudi Arabia has oil from sources in the Gotnia Basin in the north and from Cretaceous source rocks in the NE (Ayres et al. 1982; Lehner et al. 1984), but the largest proportion of the Saudi Arabia oil is from the Jurassic Arabian Intrashelf Basin. Oil reserves in Bahrain are largely or entirely sourced from the lower Hanifa source rocks, but are largely in Cretaceous reservoirs as a result of leakage through the Jurassic anhydrite seals along faults. Gas reserves are not included in Table 1.1 because much of the gas in countries with Arabian Intrashelf Basin source rocks is found in Paleozoic reservoirs.

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