Middle to Upper Jurassic Saudi Arabian carbonate petroleum reservoirs: biostratigraphy, micropalaeontology and palaeoenvironments

Geraint Wyn ap Gwilym Hughes

ABSTRACT

Recent work has improved understanding of the benthic foraminiferal stratigraphic and palaeoenvironmental ranges of the Middle to Upper Jurassic reservoir-containing carbonates of Saudi Arabia. The entire Jurassic succession includes the Marrat, Dhruma, Tuwaïq Mountain, Hanifa, Jubaila and Arab formations that terminate with a succession of evaporites, the final, thickest unit of which is termed the Hith Formation. This study focuses on selected carbonate members studied from the Dhruma Formation and above, and includes the Lower Fadhili, Upper Fadhili, Hanifa and Arab-D reservoirs. The Hadriya and Manifa reservoirs are not considered. An ascending order of tiered deep-to shallow-marine foraminiferal assemblages has been determined for each formation and applied to distinguish both long- and short-term palaeobathymetric variations. The *Lenticulina-Nodosaria*-spicule dominated assemblage characterises the deepest mud-dominated successions in all formations. The consistent presence of *Kurnubia* and *Nautiloculina* species suggests only moderately deep conditions, considered to be below fair-weather wave base and shelfal. A foraminiferally-depleted succession then follows that is characterised by encrusting and domed sclerosponges, including *Burgundia* species, in the Tuwaïq Mountain, Hanifa and Jubaila formations. This assemblage is followed, in the Hanifa and upper Jubaila formations, by a biofacies dominated by fragments of the branched sclerosponge *Cladocoropsis mirabilis*, together with *Kurnubia* and *Nautiloculina* species and a variety of indeterminate simple miliolids. *Pseudocyclammina lituus, Alveosepta powersi/jacardi* and *Redmondoides lugeoni* are present within this assemblage. A slightly shallower, possibly lagoon-influenced assemblage is developed in the Hanifa and Arab formations that include *Cladocoropsis mirabilis, Kurnubia* and *Nautiloculina* species and the dasyclad algae *Clypeina sulcata* and *Heteroporella jaffrezi*. A further shallower assemblage, found only in the upper Arab-D Member, is characterised by the presence of *Mangashtia viennoti, Clypeina sulcata* and *Cladocoropsis mirabilis*. This assemblage is gradually supplemented by “*Pfenderina salernitana*” and is interpreted as slightly shallower conditions in the upper Arab-D. A very shallow assemblage in the uppermost Arab-D is characterised by the presence of *Trocholina alpina*, which is then followed by an intertidal assemblage of cerithid gastropods and felted calcareous algae in which foraminifera are typically absent.

These various microbiofacies have provided depositional and potential reservoir stratification. A phenomenon termed “palaeobathymetric compression” has been observed in which depositional cycles are enhanced by rapidly shallowing upwards tiered biofacies that encompass less than 3m of sediment thickness but represent in excess of 20m of water depth reduction. This is attributed to short-term rapid lowering of sea level, and may be considered as the microfaunal signals of high frequency forced regressions.

INTRODUCTION

As Jurassic carbonates have economic importance in the Middle East region, their petrographic properties have received considerable attention. In general, the Saudi Arabian Jurassic carbonate hydrocarbon reservoirs were examined for microfauna during early investigations (Bramkamp and Steineke, 1952; Steineke and Bramkamp, 1952; Powers, 1962; 1968; Powers et al., 1966), but these studies were primarily aimed at their stratigraphic use. More attention is now paid to the diachronous nature of local stratigraphic ranges of shallow-marine species. Sequence stratigraphic interpretations begin
to reveal that platform carbonates, previously considered to have accumulated in an aggradational fashion, can display considerable complexity resulting from sea-level induced progradational and retrogradational trends. Such complexities now require a search for additional information to identify and constrain the palaeoenvironmental variations and determine the high-resolution depositional cyclicity of the reservoir carbonates. Environmental sensitivity of benthic foraminifera, combined with associated microfossils and macrofossils, provides a potentially valuable technique for determining subtle variations in the depositional environment and also providing a proxy for sea-level fluctuations.

The present study is based on in-house micropalaeontological studies by Saudi Aramco of hundreds of thin sections from Middle to Upper Jurassic carbonate reservoirs. Additionally, samples were collected from measured sections of reservoir equivalent facies exposed along the outcrop belt. The four carbonate reservoirs considered in detail in this study include the Lower Fadhili, Upper Fadhili, Hanifa and Arab-D; the Hadriya Reservoir has not yet been analysed in detail. Comments are based on an examination of the outcrop west of Riyadh where macropalaeontology and limited micropalaeontology have been carried out. The Hanifa

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**Figure 1: Lithostratigraphy of the Dhruma to Hith formations.** There is no biostratigraphic control for the Arab and Hith formations. The Arab Formation is informally divided into four members D to A. The entire succession from the Dhruma to Hith forms megasequence AP7 of Sharland et al. (2001).

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Formation contains the Hanifa Reservoir within the upper part, equivalent to the informal Ulayyah member, and has been micropalaeontologically examined in the Khurais and Abqaiq subsurface. Micropalaeontology of the shallow stratigraphic well Wadi Laban-1 and outcrop samples from Jabal Abaqayn and the Tuwaiq Mountain roadcut west of Riyadh have supplemented the results presented herein. The Jubaila Reservoir, locally developed within the lower Jubaila Formation, and within the informal J1 member, has not been examined micropalaeontologically and is not included in this study. The upper part of the Jubaila Formation, equivalent to the informal J2 unit, contains the lower part of the Arab-D Reservoir. The Arab-D Reservoir continues into, and occupies most of, the carbonates of the Arab-D member of the Arab Formation.

As most of the information presented is based on subsurface investigations of specific carbonate reservoirs, it should be remembered that future investigations of the non-reservoir facies of the carbonates in the outcrop belt may provide supplementary palaeoenvironmental information to enhance that presented herein.

Many of the foraminiferal species encountered in this study require additional taxonomic investigation in order to determine their cladistic evolutionary paths. It is hoped that their illustration will further assist future micropalaeontological application for reservoir characterization within the region.

**PREVIOUS WORK**

**Lithostratigraphy**

The Middle and Upper Jurassic succession in Saudi Arabia include the Dhruma, Tuwaiq Mountain, Hanifa, Jubaila, Arab and Hith formations (Figure 1) (Bramkamp and Steineke, 1952; Steineke and Bramkamp, 1952; Powers, 1962, 1968). These formations carry different names in other Middle East countries that renders regional correlations and palaeoenvironmental interpretations difficult. Regional equivalents are discussed and clarified by Beydoun (1988, 1991), Alsharhan and Nairn (1997), Al-Husseini (1997) and Sharland et al. (2001). The term Dhruma is retained across the Middle East, although its members are given different names. The Tuwaiq Mountain Formation is termed the Sargelu in Kuwait, and the Upper Araej in Qatar and the United Arab Emirates (UAE). The Hanifa Formation is termed the Najmah in Kuwait, and Diyab in Qatar and the UAE. The undifferentiated Jubaila and Arab-D formations are termed the Fahalil in Qatar, but the Arab Formation is termed the Asab in the UAE.

**Sequence Stratigraphy**

A sequence framework based on the global eustatic sequences of Haq et al. (1988) for the Middle and Upper Jurassic of Saudi Arabia has been suggested by Le Nindre et al. (1990) and Vaslet et al. (1991). It is comprised of the sequences LZA 1.1 to LZA 2.2 (Lower and Middle Dhruma formation), and LZA 3.2 to LZA 5.4 (Upper Dhruma to Sulaiy formations). Al-Husseini (1997) correlated this framework for the Gulf region.

A maximum flooding-based stratigraphy (Galloway, 1989) has been proposed by Sharland et al. (2001). It implies the presence of a number of sequences within this succession with maximum flooding surfaces:

- MFS J110 (147.0 Ma, late Tithonian) in the Hith Formation
- MFS J100 (150.75 Ma, late Kimmeridgian) near base Arab-A carbonate (picked in Arab-A in Figure 4.49, but indicated as Arab-B in Tables 4.73 and 4.74 of Sharland et al., 2001);
- MFS J90 (151.25 Ma, late Kimmeridgian) near base Arab-B carbonate;
- MFS J80 (151.75 Ma, late Kimmeridgian) near base Arab-C carbonate;
- MFS J70 (152.75 Ma, late Kimmeridgian) in lower Jubaila Formation;
- MFS J60 (154 Ma, early Kimmeridgian) in upper Hanifa Formation;
- MFS J50 (156 Ma, mid-Oxfordian) in lower Hanifa Formation;
- MFS J40 (162 Ma, mid-Callovian) in Hisyan Member, Dhruma Formation;
- MFS J30 (168 Ma, early Bathonian) in Middle Dhruma Formation.
Major unconformities are present at the base of the Dhruma Formation (Aalenian to late Toarcian), possibly intra-Dhruma (Callovian to late Bathonian), and between the Hith and Sulaiy formations (lower Tithonian). Disconformities, based on sedimentological features and rapid changes in biofacies character, are present at the contacts of the Atash and Hisyan members of the Dhruma Formation, between the Tuwaiq Mountain and Hanifa formations and between the Hanifa and Jubaila formations. Micropalaeontological characteristics of selected Jurassic unconformities have been discussed by Meyer and Hughes (2000).

Reservoirs

The carbonate reservoirs examined for micropalaeontology include the Lower Fadhili (Dhruma Formation, Atash Member), Upper Fadhili (lower Tuwaiq Mountain Formation), Hanifa Reservoir (upper Hanifa Formation) and Arab-D (upper Jubaila Formation and Arab-D Member of the Arab Formation) reservoirs (Figure 1). The Hadriya (upper Tuwaiq Mountain Formation) and Manifa (Hith Formation) reservoirs have not been investigated but are the subject of current study.

The most significant aspect of this study follows an observation of micropalaeontological tiering. The tiering refers specifically to an ascending stacking order of particular foraminiferal and calcareous algal species, together with macropalaeontological elements where they exist. Although the palaeoenvironmental preferences of the individual species are difficult to determine with reference to extant equivalent species, morphologically similar forms do provide guidance. This indirect support is reinforced when such species are presented in an orderly vertical succession that is consistent with the expected deepening- or shallowing-upwards trend using sedimentological evidence.

Of particular interest is the repetition of such tiered successions, especially when they form cycles between two and three metres thick, but represent a palaeobathymetric transition in excess of ten to twenty metres. This phenomenon is especially well developed in the Upper Jurassic successions, but has also been observed in the Late Permian Khuff carbonates, Early Cretaceous Yamama carbonates and Neogene carbonate formations of Saudi Arabia (Hughes; internal Saudi Aramco reports). In the Hanifa Formation, for example, basal mudstone beds containing abundant siliceous sponge spicules are interpreted to have accumulated at least below fairweather wave base in a ramp setting. These are conformably overlain, at the top of the depositional cycle, by peloidal and foraminiferal grainstones of shallow marine origin. Notwithstanding the effects of sediment compaction, the two to three metres of sediment represent a shallowing episode of possibly 20 metres. This phenomenon is here termed “palaeobathymetric compression” and represents a forced palaeobathymetric reduction with the biofacies displaying a rapid “catch-up” character. The repetitious nature of this phenomenon leads one to conclude an allocyclic, high frequency eustatic control. Within the reservoirs, such micropalaeontologically determined cyclicity is well suited for integration with sedimentological observations and possible wireline log fluctuations that provide depositional as well as potential reservoir stratification. The repeated succession of “palaeobathymetrically compressed” cycles represents high frequency eustatic cycles that should be considered as parasequences.

In the following discussions, it should be emphasised that many of the micropalaeontological assemblages are evident on at least two levels of scale within the formations and their contained reservoirs. In most cases, a deeper lower part is considered as linked with a transgressive dominated phase, while the incidence of shallow marine forms in the upper part is correspondingly attributed to highstand shallowing. Both phases are successively represented by couplets that are considered to represent depositional sequences such as the Dhruma Formation (Hisyan Member) to Tuwaiq Mountain Formation, Hawtah to Ulayyah members of the Hanifa Formation, the lower (J1) to upper (J2) members of the Jubaila Formation and within the Arab Formation.

The strength of micropalaeontology in analytically dissecting the reservoirs and their host formations lies in the ability to provide independent evidence for otherwise cryptic palaeobathymetric and palaeoenvironmental variation. Confident subdivision of the reservoirs can be accomplished by this approach using closely spaced core samples, preferentially less than six inches apart in key stratigraphic cored sections.
Biostratigraphy

The stratigraphic ranges of the Middle East Jurassic benthic foraminiferal species are relatively poorly known. Ten biozones with their diagnostic marker species are proposed for the late Callovian to Tithonian succession of Yemen by Simmons and Al-Thour (1994). Whittaker et al. (1998) provide stratigraphic ranges for most of the commonly found benthonic foraminifera within the region, especially for Iraq and Saudi Arabia. Supplementary ranges are discussed by Tasli (2001), and Clark and Boudagher-Fadel (2001), including assignment of the Jurassic succession to the algal Salpingoporella sellii subzone of the foraminiferal Kurnubia palastiniensis zone. Foraminiferal stratigraphic ranges for the Upper Jurassic succession in Abu Dhabi are confined to the Arab Formation (de Matos, 1994). Hughes (1996) suggested three biofacies and 16 bioevents for the Kimmeridgian to Tithonian Arab-D Reservoir, comprising the upper part of the Jubaila Formation and the lower part of the Arab Formation in Saudi Arabia.


Taxonomy

The taxonomy of the warm-water Jurassic benthic foraminifera of the Middle East is not fully established; although the most commonly encountered species are moderately well understood and documented. Fundamental taxonomic papers on Saudi Arabian agglutinated species include Redmond (1964, 1965), Banner (1970) and Maync (1965). In this study, the taxonomic uncertainty of Pfenderina salernitana, of Cretaceous age sensu stricto (Septfontaine, 1988), is the reason for placement within inverted commas. The most recent taxonomic assessments of the shallow-marine species of the region, but excluding Saudi Arabia, include Banner and Highton (1990), Banner and Whittaker (1991), Banner et al. (1991), Whittaker et al. (1998) and Clark and Boudagher-Fadel (2001). Calcareous algae have received little previous attention except by Okla (1987) and Hughes (2003). Corals have been recorded by Powers (1962) and El-Asa’ad (1991).

Palaeoenvironment

During the Middle and Late Jurassic, the Arabian Peninsula was located on the southern margin of the Tethys Ocean, and was the site of an extensive shallow marine platform (Murris, 1980; Le Nindre et al., 1987; Enay et al., 1993; see review by Al-Husseini, 1997). The western margin of this platform is not clearly defined owing to removal of the coastal facies by erosion, but it is considered to lie in the vicinity of the present-day eastern margin of the Arabian Shield (Figure 2 a,b). Scattered across the platform were localized deeper areas considered to be intra-shelf basins, and localised highs that formed the sites of sclerosponge (stromatoporoid) and coral banks.

The palaeoenvironmental significance of the Middle East benthic foraminifera is the least well known, although individual species have received attention in the Mediterranean region (Derin and Reiss, 1966; Pelisse and Peybernès, 1983). The palaeoenvironment containing various complex-walled agglutinated species is briefly considered by Banner and Highton (1990), Alveosepta species by Banner and Whittaker (1991) and Trocholina species by Manicelli and Coccia (1999). More detailed information on Saudi Arabian foraminiferal assemblages has been presented by Hughes (1996, 1998, 2000, 2001, 2002a, b, c, 2004a, b), Meyer et al. (2000) and Al-Dhubeeb (2001, 2002a, b). All studies are based on detailed analysis of the vertical successional occurrence of the various species, in samples from cored oil well and exposed sections, and their relationship to the host carbonate fabrics. Jurassic calcareous algae have been discussed with reference to coeval foraminifera and their palaeoenvironmental significance by Hughes (2003).

Palaeoenvironmental analysis of microfauna and microflora of Middle to Upper Jurassic carbonates is based on an interpretation of the semi-quantitative analysis of thousands of thin sections. The
thin sections were prepared from core plugs of subsurface samples, collected 6 inches apart from exploratory and development cores in the Ghawar, Khurais and Berri oilfields of eastern Saudi Arabia. In addition, samples were analysed from each bed in measured sections of the Jubaila from the outcrop belt of the Tuwaiq Mountain escarpment of central Saudi Arabia.

Six palaeoenvironmental regimes have been defined, including: (1) the open marine/intrashelf basin; (2) transitional basin-shoal; (3) shoal complex; (4) deep lagoon; (5) shallow lagoon; and (6) shore-intertidal. The entire Middle and Upper Jurassic succession is considered to have been deposited upon
a broad, shallowly submerged rimmed marine shelf or platform with intra-shelf basins, such as the interior of the modern Great Bahama Bank, and is best termed a shelf lagoon in the sense of Bates and Jackson (1980). These categories are used in the following discussion of the palaeoenvironmentally significant biofacies distribution. Reference is made to palaeobathymetry with relation to normal wave base, and regimes 2 to 6 would lie within normal wave base. For calibration purposes, Saudi Aramco’s hydrological data at Marjan indicate normal wave base to be 10m, with one year storm wavebase at 49m. The open marine regime would lie at water depths in excess of 10m, and probably in excess of 50m, as these sediments are interpreted to have received the products of occasional storms rather than continued reworking by wave action (sensu Sharland et al., 2001).
Figure 4: The west flank of the Tuwaiq Mountain Escarpment west of Riyadh city, in the Dirab area, exposes the naturally-weathered contact between the Dhruma and Tuwaiq Mountain formations. The uppermost Hisyan Member of the Dhruma Formation is exposed here and is considered to be genetically linked with the overlying Tuwaiq Mountain Formation, as the transgressive component of the upper Dhruma – Tuwaiq Mountain sequence. Note the pair of thin recessive beds towards the upper part of the Tuwaiq Mountain Formation, equivalent to a level slightly above the top of the left pinnacle, that represents two dark grey beds illustrated in Figure 11.

BIOSTRATIGRAPHY AND PALAEOENVIRONMENTS

Lower Fadhili Reservoir, Atash Member, Upper Dhruma Formation

Stratigraphy
The Upper Dhruma Formation has been subdivided by Powers et al. (1966) into the lower yellow-brown limestone of the Atash Member, and upper yellow-brown shales of the Hisyan Member. The Atash Member is correlated with the Lower Fadhili reservoir of eastern Saudi Arabia. The Dhruma Formation underlies the Tuwaiq Mountain Formation (Figures 1, 3 and 4). In this study, the open marine, ammonite-rich Hisyan Member is considered to be genetically associated with the Tuwaiq Mountain Formation. The underlying ammonite-barren Atash Member is considered to genetically represent the shallowest and final sediment of the Dhruma sequence. The uppermost stromatoporoid-dominated facies of the Tuwaiq Mountain Formation, equivalent to unit T3 of Enay (1987) is host to the Hadriya Reservoir in eastern Saudi Arabia.

Age
The Upper Dhruma Formation is of Middle Jurassic, mid-Callovian age. Although no ammonites have been recovered from the Atash Member, earlier age determinations included late Bathonian based on the presence of the brachiopod *Eudesia* sp. (Arkell, 1952) in the lower part, and late Callovian for the upper part based on the presence of an echinoid assemblage (Kier, 1972). These determinations have been improved by later biostratigraphy based on ammonites, nautiloids, brachiopods, ostracods and calcareous nannofossils. A Middle Callovian age is concluded for the overlying Hisyan Member of the Upper Dhruma (Enay et al., 1987; Fischer et al., 2001) based on the presence of the ammonite *Grossooviria kontkiewiczi*, *Erymnoceras schoenbachii* and *Pachyerymnoceras* spp. that define equivalence with the northwest European ‘carinatum’ ammonite zone. Nautiloids recovered from the overlying Hisyan Member include *Eutrephoceras globosum*, *E. aff. douvillei*, *Cenoceras saoudense*, *Paracenoceras*
Figure 5: Lower Fadhili Reservoir biocomponents (width of photomicrograph indicated in mm); (1) costate gastropod QTIF-67 (#1033) (1mm); (2) non-costate gastropod QIRD-8 (#386) (2mm); (3) Cayeuxia sp. QTIF-67 (#956) (2mm); (4) Cayeuxia sp. QIRD-8 (#348) (8mm); (5) simple coral QIRD-8 (#387) (4mm); (6) sponge spicule QTIF-67 (#1033) (1mm); (7) Bositra buchi QIRD-8 (#384) (1mm); (8) microbialite QTIF-67 (#973) (2mm); (9) oncolith QIRD-8 (#363) (8mm); (10) Cladocoropsis mirabilis fragment QIRD-8 (#362) (2mm); (11) Cladodoropsis mirabilis fragment QIRD-8 (#348); (12) Ophthalmidium sp. QIRD-8 (#381) (1mm); (13) Pfenderina trochoidea QTIF-67 (#1011) (1mm); (14) Pfenderina trochoidea QTIF-67 (#1023) (2mm); (15) cf. Satorina apuliensis QTIF-67 (#1023) (2mm).
Figure 6: Lower Fadhili Reservoir biocomponents (width of photomicrograph indicated in mm);
(1) Trocholina elongata QIRD-8 (#377) (2mm); (2) Trocholina elongata QTIF-67 (#878) (2mm);
(3) Trocholina elongata QTIF-67 (#1033) (1mm); (4) Ammobaculites sp. QTIF-67 (#989) (2mm);
(5) Nautiloculina oolithica QIRD-8 (#387) (1mm); (6) Nautiloculina oolithica QTIF-67
(#1011) (1mm); (7) Pfenderina salernitana QTIF-67 (#1038) (2mm); (8) Pfenderina salernitana
QIRD-8 (#374) (1mm); (9) Redmondoides lugeoni QIRD-8 (#385) (1mm); (10) Redmondoides lugeoni
QTIF-67 (#805) (2mm); (11) Redmondoides lugeoni QTIF-67 (#1038) (2mm); (12) Redmondoides lugeoni
QIRD-8 (#348) (1mm); (13) Redmondoides sp. cf. rotundata QTIF-67 (#1038) (2mm); (14) Valvulina sp.
QTIF-67 (#959) (2mm); (15) indeterminate planispiral species QIRD-8 (#361) (2mm).
Figure 7: Lower Fadhili Reservoir biocomponents (width of photomicrograph indicated in mm); (1) Trochamijiella gollehstanehi QTIF-67 (#965) (2mm); (2) Trochamijiella gollehstanehi QTIF-67 (#956) (2mm); (3) Trochamijiella gollehstanehi QTIF-67 (#926) (2mm); (4) Trochamijiella gollehstanehi QTIF-67 (#921); (5) Trochamijiella gollehstanehi QTIF-67 (#892); (6) Trochamijiella gollehstanehi QTIF-67 (#1005) (2mm); (7) Trochamijiella gollehstanehi QTIF-67 (#1017) (2mm); (8) Trochamijiella gollehstanehi QIRD-8 (#356) (2mm); (9) Trochamijiella gollehstanehi QTIF-67 (#903) (2mm); (10) Trochamijiella gollehstanehi QTIF-67 (#1023) (2mm); (11) Trochamijiella gollehstanehi QTIF-67 (#1033) (1mm); (12) Trochamijiella gollehstanehi QIRD-8 (#364) (2mm); (13) Trochamijiella gollehstanehi QIRD-8 (#385) (2mm); (14) Parurgonia caelinensis QTIF-67 (#956) (2mm); (15) cf. Pseudocyclammina sp. cf. lituus QIRD-8 (#351) (2mm).
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Figure 8: Suggested palaeoenvironmental model for Middle to Late Jurassic biocomponents (note that many of the species from the deep lagoon/shelf to bank environments can be present as storm-transported debris within the intra-shelf basin biofacies).
Figure 9: Diagrammatic distribution of selected biocomponents within the Middle to Late Jurassic lagoon - intrashelf basin environments.

Figure 10: The Tuwaiq Mountain Escarpment, roadcut, west of Riyadh city (N 24°31.63'; E 46°23.71') showing a succession of thin beds with the lower Tuwaiq Mountain Formation. Note the twin recessive dark beds in the distance, in the fresh roadcut surface.

Figure 11: Middle part of the Tuwaiq Mountain Formation (T2 unit of Enay, 1987) showing the two distinctive recessive, burrowed beds with Thalassinoides spp. This is a fresh roadcut surface.

Figure 12a and 12b: Upper part of the Tuwaiq Mountain Formation (T3 unit of Enay, 1987) and equivalent to the Hadriya Reservoir showing sclerosponge bioherm in fresh roadcut surface. This is the first of a succession of extensive sclerosponge bioherms that characterise the upper part of the formation. These bioherms seem to develop during the upper part of high frequency depositional cycles. Individual reefs up to approximately 45 feet high and 150 ft in diameter have been recorded in this area (Steineke et al., 1958). Note the presence of chert nodules in the beds beneath the bioherm, the slight sag in the darker beds resulting from loading of the bioherm on probably poorly consolidated sediments. The bioherm consists of domal and platey stromatoporoids, with an outer cover of compound corals, same location as Figure 10.
Figure 13: Stromatoporoid bioherm in a naturally weathered location in the upper Tuwayq Mountain Formation (unit T3), approximately 100m south of the roadcut in Figure 12.

Figure 14: Stromatoporoid bioherm in a naturally weathered location in the Upper Tuwayq Mountain Formation, approximately 150m south of the roadcut in Figure 12. Height of exposed stromatoporoid bioherm in centre of image is approximately 5m.

_sulcatum, Cymatonautilus collignoni_ and _Aulacenceras arabicum_ (Tintant, 1987). Brachiopods from the Atash Member include _Ceririthyris bihinensis, C. africana, Eudesia cardioides_ and _Birmirhynchia nazeri_. Those from the Hisyan Member include the Callovian species _Daghanithynchia daghaniensis, Kutchirhynchia gregoryi_ and _Biennithyris barringtoni_ (Almeras, 1987). Ostracods from the Atash Member are of moderately high diversity (22 species) and include _Amicytheridea triangula, Cytherelloides aazourensis_ and _Dhrumaella cardaensis_, all of which are of Middle Callovian age (Depeche et al., 1987). Middle Callovian ostracods have been recovered from the Hisyan Member (Depeche et al., 1987) and including _Virgulacytheridea sherifensis_ and _Trichordia cf. triangula_. Calcareous nannofossil species provide evidence for the _Stephanolithion bigoti_ Zone confirming a middle Callovian age for the Upper Dhruma. These include _Zeugrhabdotus erectus, Waiztnaueria manitae, Ethmolithus cf. gallicus Polyporhabdus escaii and Stephanolithion bigoti_ (Manivit, 1987).

Foraminiferal evidence, using the ranges of Whittaker et al. (1998), provides a lower to middle Callovian age, based on the presence of _Pfenderina trochoidea_ and _Redmonidoidea_ species in the lower part and of _Kurnubia_ species in the upper part of the reservoir. On regional evidence and correlation, Sharland et al. (2001) have proposed a maximum flooding surface within the Hisyan Member of the upper Dhruma Formation (MFS J40) dated as 162 Ma, mid-Callovian.
Biofacies
The Lower Fadhili carbonates contain moderately diverse foraminiferal assemblages that suggest a shoaling upwards succession (Figures 5-7). These include the localized distribution of *Ophthalmidium* spp., *Pfenderina trochoidea*, *Satorina apuliensis*, *Trocholina elongata*, *Ammobaculites* spp., *Nautiloculina oolithica*, “*Pfenderina salernitana*”, *Redmondoides lugeonii*, *Redmondoides* sp. cf. rotundata, *Valvulina* sp. *Trochamijiella gollehstanehi*, *Paruronia caelensis* and *Pseudocyclammina* cf. lituus. Other biocomponents include *Bositra buchi*, *Cladocoropsis mirabilis*, costate and non-costate gastropods, *Cayeuxia* spp., simple corals sponge spicules, microbialite concretions and oncoliths. Dasyclad algae are locally present and are dominated by *Salpingoporella annulata* (Hughes, 2003).

Sclerosponges, commonly referred to as stromatoporoids, are defined as calcified demosponges (Vacelet, 1985) these being sponges (Phylum Porifera) that have skeletons composed of spongin, or a mixture of spongin and siliceous (“spicule”) spicules. Calcified demosponges contain a massive basal layer of aragonite or calcite below the spongin layer. This basal layer enables fossilization to occur even though the spongin layer quickly disintegrates into spicular remnants upon death. Abundant *in-situ* stromatoporoid specimens are considered to be indicative of water depths shallower than 10 m (Toland, 1994).

Palaeoenvironment
Recent foraminiferal studies within Saudi Aramco have refined the undifferentiated subtidal depositional environment for the Upper Dhruma suggested by Enay et al. (1987). The foraminiferal, dasyclad and sclerosponge distribution suggests a moderately shallow, lagoonal environment in which localized shoals of branched sclerosponges were present, between which deeper parts of the lagoon became dominated by spicule-secreting sponges during periods of sea level rise. An interpretation of the palaeoenvironmental preferences for each biocomponent, based on their vertical distribution and biofacies association, is represented in Figure 8. A diagrammatic representation of the various depositional environments is illustrated as Figure 9. The absence of ammonites within the Atash Member is noteworthy as they are common in the underlying Middle Dhruma D7 unit, or informal Mishraq Member and in the overlying Hisyan Member (Enay, 1987). This suggests shallow marine depositional conditions.

Upper Fadhili Reservoir, lower Tuwaiq Mountain Formation

Stratigraphy
The Tuwaiq Mountain Formation was first defined by Steineke et al. (1958), as a cliff-forming, resistant, coral and stromatoporoid-bearing limestone (Figures 3, 10-14) overlying a softer, less resistant shale-dominated Hisyan Member of the Upper Dhruma Formation. This characteristic limestone was later described by Powers et al. (1968) as being clearly distinguished from the underlying olive-green shale of the upper Dhruma Formation. Powers (1968) recorded a thickness of 230 m for the Tuwaiq Mountain Formation, noting a disconformable contact with the underlying Dhruma Formation and a conformable contact with the overlying Hanifa Formation. The Tuwaiq Mountain Formation has been informally subdivided by Enay et al. (1987) into, in ascending order, the T1, T2 and T3 units, that equate with the informal Baladiyah, Maysiyah and Daddiyah members respectively. The dark grey mudstone beds within the Tuwaiq Mountain Formation in outcrop (Figures 10-11) may represent proximity to the maximum flooding zone of the Formation, or at least to those of hierarchically subordinate parasequences superimposed on the Dhruma (Hisyan) to Tuwaiq Mountain sequence. Preliminary palynological evidence indicates a mixture of land – derived palynomorphs and marine dinoflagellates (John Filatoff, oral communication). The Upper Fadhili reservoir lies within a grain-rich facies of the lower Tuwaiq Mountain Formation while the Hadriya Reservoir lies within the grain-rich, stromatoporoid-associated upper Tuwaiq Mountain Formation. In the Tuwaiq Mountain Formation outcrop, the upper member is characterised by a succession of prograding stromatoporoid bioherms (Figures 12-14) with intervening “meadows” of branched stromatoporoids (Powers et al., 1966). Chert nodules within the middle part of the stromatoporoid-bearing beds may represent the products of sponge spicule concentrations deposited during the maximum flooding of parasequences.
Figure 15: Upper Fadhili Reservoir biocomponents (width of photomicrograph indicated in mm); (1) "Kurnubia" wellingsi transverse section BRRI-234 #144 (1mm); (2) Meyendorffina bathonica tangential vertical section BRRI-234 #144 (2mm); (3) Meyendorffina bathonica axial vertical section BRRI-234 #144 (2mm); (4) Siphovalvulina sp. BRRI-234 #295 (1mm); (5) Valvulina sp. BRRI-234 #170 (1mm); (6) Valvulina sp. BRRI-234 #162 (2mm); (7) Redmondoides lugeoni BRRI-234 #209 (1mm); (8) Reophax sp. BRRI-23 #340 (2mm); (9) Pfenderina trochoidea BRRI-234 #302 (1mm); (10) unidentified planispiral foraminifera BRRI-234 #223 (2mm); (11) unidentified planispiral foraminifera BRRI-234 #223 (1mm); (12) cf. Timidonella sarda or Anchispirocyclina lusitanica BRRI-234 #150 (4mm); (13) Nodosaria sp. BRRI-24 #1127 (1mm); (14) Nodosaria sp. BRRI-23 #389 (1mm); (15) Nodosaria sp. BRRI-23 #357 (1mm).
**Biofacies**

Carbonates associated with the Upper Fadhili reservoir facies contain a variety of biocomponents, each of which contributes to assemblages that are considered to have palaeoenvironmental significance (Figures 15-16). Benthic foraminifera include undifferentiated nodosariids, *Lenticulina* spp., *Bolivina* spp., *Trocholina elongata*, *Kurnubia palastiniensis*, *K. wellingsi*, *Nautiloculina oolithica*, *Valvulineria* sp., *Redmondoides lugeoni*, *Pfenderina trochoidea*, *Meyendorffina bathonica*, and *Trockhamijiella gollesstanehi*. Scleropores include the branched species *Cladocoropsis mirabilis* together with stratified forms. Monaxon and tetraxon sponge spicules are locally present, with the filamentous bivalve *Bositra buchi* and juvenile brachiopods. Calcareous algae from the Tuwaiq Mountain Formation have been described by Okla (1987) and Hughes (2003).

**Palaeoenvironment**

The Upper Fadhili Reservoir lies in the lower, or T1, unit of the Tuwaiq Mountain Formation, consisting of a grainstone-dominated shelf environment for which Enay et al. (1987) concluded a back reef depositional environment. Recent work by Saudi Aramco on the Upper Fadhili reservoir from Berri field, offshore Saudi Arabia has revealed a variety of depositional environments, based mostly on an interpretation of the foraminiferal and associated fossil and microfossil assemblages (Figures 8 and 9). The Hadriya Reservoir is located within the upper part of the Formation, or T3 unit, and is dominated by astromaporid-bank-dominated facies.

The pelagic bivalve *Bositra buchi* is abundant in certain parts of the Upper Tuwaiq Mountain Formation. They have been used to deduce a deep, open marine depositional environment in which a low sedimentation rate prevailed. This allowed the slow accumulation, and concentration of very thin-walled bivalves, and is consistent with the palaeoenvironmental interpretation of such accumulations of *Bositra buchi* and its related species *Lenticula humilis* in central Italy (Conti and Cresta, 1982; Conti and Stefano, 2001). Duff (1978) argues against a pendent seaweed-attached or free-swimming habit based on the absence of a byssal notch and of strong muscle scars respectively. Conti and Cresta (1982) suggest a benthic mode of life within low-energy settings. Their abundance is due to localized blooms and rapid colonization of an environment with little niche competition. In addition, these thin bivalve beds are accompanied by monaxon and tetraxon sponge spicules and dwarf or juvenile, costate brachiopods. This association is considered to be typical of deep-marine, normal salinity conditions with limited carbonate production and sediment input. These conditions would be expected during a rapid marine transgression and during a maximum flooding event when possibly suboxic conditions excluded other organisms that would have either devoured or diluted the concentration of these three characteristic and mutually compatible biocomponents. Open marine biofacies, deposited below wave-base, include species of *Lenticulina*, *Nodosaria* and *Bolivina*.
Figure 16: Upper Fadhili Reservoir biocomponents (width of photomicrograph indicated in mm); (1) *Lenticulina* sp. tangential vertical section BRRI-234 #184 (1mm); (2) *Lenticulina* sp. axial vertical section BRRI-234 #300 (1mm); (3) *Lenticulina* sp. axial vertical section BRRI-9 #320 (1mm); (4) *Nautiloculina oolithica* BRRI-5 #129 (1mm); (5) *Textularia* sp. BRRI-234 #150 (1mm); (6) stromatoporoid BRRI-133 #844 (8mm); (7) simple coral BRRI-234 #174 (4mm); (8) *Cayeuxia* sp. BRRI-234 #293 (2mm); (9) juvenile brachiopod BRRI-234 #321 (1mm); (10) *Bositra buchi*, sections of abundant disassociated valves BRRI-234 #275 (1mm); (11) *Bositra buchi*, tangential commissural section BRRI-234 #376 (2mm); (12) *Bositra buchi*, transverse section BRRI-23 #641 (8mm); (13) sponge spicules dominated by tetraxons BRRI-234 #271 (2mm); (14) tetraxon sponge spicule oblique section BRRI-234 #354 (1mm).
Figure 17: The Hanifa Formation, exposed in a small wadi north of the Riyadh - Mecca highway (N 24°31.49'; E 46°25.123'). Note the smooth profile of the lower part of the Hanifa Escarpment, and the more resistant, cliff dominated upper part resulting from the increase in quartz-bearing grainstones. The Jubaila Formation forms low hills above the Hanifa.

Figure 18: The Hanifa Formation, as exposed in a roadcut in the Riyadh – Mecca Highway through the Tuwaiq Mountain Escarpment, west of Riyadh city (N 24°31.454'; E 46°24.805'). Note the regular cyclic nature of the bedding that characterises the Hanifa Formation.

The shoal complex includes platey, domed and branched sclerosponges, of which the platey and domed forms are interpreted to represent the distal, higher energy regime of the shoal, probably above wave base. The branched sclerasteroid Cladocoropsis mirabilis is typically found with dasyclad algae and is interpreted to have occupied a lower energy environment within the sheltered, bank-flank region of the lagoon. In cores, the presence of the branched form stratigraphically above the domed forms and is interpreted to represent either a deepening event or progradation of the bank-bank facies.

The deep lagoon biofacies displays the highest species diversity, and includes Meyendorffina bathonica, Trochamijiella gollesstanhi, Redmondoides lugeoni, Kurnubia wellingsi, Praekurnubia sp., Pfenderina trochoidea, Valvulineria sp., Trocholina elongata and Nautiloculina oolithica. The calcareous alga Arabicodium aegagrapiloides and Clypeina species are typical components. Fragments of stromatoporoids are often associated with this biofacies close to shoals. A shallow-lagoon environment is concluded for the sparse biofacies in which Nautiloculina oolithica, branched coral, large, robust echinoid spines.

Hanifa Reservoir, Hanifa Formation

Stratigraphy
The Hanifa Formation (Bramkamp and Steineke and Steineke, 1983; Powers et al., 1966; Powers, 1968) is divided into the lower and upper members, namely the Hawtah and Ulayyah respectively (Vaslet et al., 1983; Enay et al., 1987). It is well stratified and displays regular alternations of thicker, massive beds and thinner beds (Figures 17 and 18). According to Denis Vaslet and Yves le Nindre (oral communication, November, 2002), their mapping criterion for the Tuwaiq Mountain - Hanifa contact was placed at the top of the large stromatoporoid reefs. The palaeoenvironmental interpretations of
selected outcrops are based on the lithology. These outcrop sections have been interpreted for their palaeoenvironmental significance, based on the lithology by Moshrif (1984). The Hawtah Member is approximately 57 m thick, typically clayey and has bioclastic carbonates with rare sclerosponges. The overlying Ulayyah Member is approximately 71 m thick, contains more grainstones, corals and stromatoporoids than the Hawtah Member and develops reservoir properties in the subsurface.

**Age**

An Oxfordian age is assigned to the Hanifa Formation based on the presence of the ammonite *Euaspidoceras cf. catena perarinatum* (Enay et al., 1987; Fischer et al., 2001) that is characteristic of the *plicatilis* ammonite zone. The nautiloid *Paracenoceras aff. hexagonum* (Tintant, 1987) also confirms a mid-Oxfordian age. Brachiopods consistent with an early to mid-Oxfordian age (Almeras, 1987) from the Hawtah Member include *Somalirhynchia africana*, *Somalithyris bihendulensis* and *Rhynchonella hadramautensis*. The nannofossil species *Vekshinella stradneri* makes its first appearance in the Hawtah Member and is consistent with an early to mid-Oxfordian age; a late Oxfordian age is deduced for the upper Ulayyah Member. Recent investigation by the author within the Khurais field (Hughes, 2001) has revealed the presence of *Pseudocyclammina lituus* and *Alveosepta jaccardi* which suggest a late Oxfordian age using the stratigraphic ranges of Whittaker et al. (1998).

Based on regional evidence and correlation, Sharland et al. (2001) have proposed a maximum flooding surface in the lower part of the Hanifa Formation (MFS J50, 156 Ma, mid Oxfordian) and in shales of the upper Hanifa Formation (MFS J60, 154 Ma, early Kimmeridgian).

**Biofacies**

The Hanifa Formation displays a moderately low foraminiferal species diversity that includes undifferentiated nodosariids, *Lenticulina* spp., *Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Pseudomarssonella* species, *Alveosepta jaccardi*, *Pseudocyclammina lituus*, undifferentiated miliolids and biserial agglutinated forms (Figure 19). Sclerosponges include the branched species *Cladocoropsis mirabilis* together with stratified forms. Monaxon and tetraxon sponge spicules are locally present, as are valves of juvenile brachiopods. Dasyclad algae are well represented by *Clypeina sulcata*.

**Palaeoenvironment**

An upward transition from inner lagoon, back reef to reef palaeoenvironmental trend is suggested by Enay et al. (1987). Foraminiferal assemblages from the outcrop at Jabal Abaughayn and in the subsurface of the Abqaiq and Khurais fields of Saudi Arabia provide evidence for a variety of sub-environments (Figures 8 and 9). Deep, open marine conditions below wave base are typified by the presence of *Lenticulina* spp., *Nodosaria* spp., *Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Pseudomarssonella* species, juvenile costate brachiopods, and sponge spicules. Open-marine, moderately deep-marine conditions are typified by agglutinated foraminifers that include *Alveosepta powersi*, *Pseudocyclammina lituus*, *Kurnubia palastiniensis* and *Nautiloculina oolithica*.

The shoal complex includes both domed and branched sclerosponges, of which the domed form is interpreted as being typical of the distal, higher-energy regime of the shoal, probably above wave base. The branched sclerosponge *Cladocoropsis mirabilis* is typically found above the domed form, and interpreted to have formed in the relatively sheltered lagoonal shoal flank at or above wave base. In Khurais field, there is good evidence to support the existence of a series of southerly-prograding stromatoporoid bank complexes. A deep lagoon environment is interpreted for the *Kurnubia palastiniensis* and *Nautiloculina oolithica*-dominated assemblage, in conjunction with the well-represented dasyclad alga *Clypeina sulcata* and the encrusting alga *Thaumatoporella parvoexcisulifera*. In the studied sections, no shallow marine, miliolid-dominated sediments have been encountered.

**Arab-D Reservoir, Jubaila Formation**

**Stratigraphy**

The Jubaila Formation (Bramkamp and Steineke and Steineke, 1952; Powers et al., 1966; Powers, 1968; Manivit et al., 1985) is divided into a lower unit Ju1 and an upper Ju2 unit (Enay et al., 1987) (Figures 20 and 21). It unconformably overlies the Hanifa Formation (Meyer and Hughes, 2000).
and is approximately 130 m thick (D. Vaslet, oral communication, 2002). According to Denis Vaslet and Yves le Nindre (oral communication, November, 2002), their mapping criterion for the Hanifa - Jubaila contact was placed at the base of the reworked coral-bearing beds that overlie oncolites of the uppermost Hanifa Formation. The lower unit consists of mudstones and intraclastic, peloidal packstones and wackestones, with numerous encrusted hardgrounds. The upper part of the Jubaila, at the same exposure, displays an increasing presence of sclerosponges with corals, all of which are considered allochthonous (Meyer, 2000). In the Helwah region south of Riyadh, exposures at the head of Wadi Helwah display in-situ domed sclerosponges (Figures 22 and 23) and corals (Figure 24) that are based on a bed rich in displaced fragments of sclerosponges and corals.
Figure 20: The Jubaila Formation, looking south into Wadi Laban, a tributary valley of Wadi Hanifa. Note the well-developed, smooth scree-dominated profile of the lower part, resulting from the less resistive, mud-dominated sediments equated with J1. The upper third of the exposure forms highly resistive, often vertical, cliffs that are related to the increasingly grain-dominated texture. The trace fossil *Zoophycus* sp. has been found in the basal part of this exposure (Hughes et al., in preparation).

Figure 21: (a) The upper Jubaila carbonates as exposed in the road section west of Riyadh. The mud-filled dissolution feature of (?) Holocene age that follows the bedding in the lower part of this fresh roadcut separates the storm-dominated lower Jubaila from the upper section that is characterised by stromatoporoid and coral-filled channels. This event is approximately equivalent to the subsurface boundary between reservoir zones 3 and 2b in Ghawar. A bed containing fragments of the branched stromatoporoid *Cladocoropsis mirabilis* is present towards the top of this exposure. The top of this exposure marks the top of the Jubaila Formation, but the Arab-D Formation is not preserved at this locality. (b) Close-up of karst feature within the upper Jubaila Formation, showing remains of *Thalassinoides* burrows. The feature is bed-conformable at its upper surface, but crosses beds in the lower part. Much of the cave is filled with red mud.
Figure 22: In situ domed stromatoporoid cf. Burgundia sp. in the upper Jubaila Formation, Wadi Helwah, Hawtah region (N 23° 28.173; E 46° 52.101).

Figure 23: Stromatoporoid cf. Burgundia sp. in the upper Jubaila Formation, Wadi Dirab roadcut, west of Riyadh. Note the well-defined growth laminae. This specimen lies within a stromatoporoid-filled channel and is not in-situ; the apparent way-up position is fortuitous, and is surrounded by smaller stromatoporoid fragments in random orientation.

Figure 24: The upper Jubaila Formation at Wadi Helwah, Hawtah region (N 23° 28.173; E 46° 52.101) displaying in-situ erect coral overlying a bed containing transported stromatoporoids and corals. Note this specimen is located on the same bed as the stromatoporoid in Figure 22.
Age
A Kimmeridgian age is assigned to the Jubaila Formation based on the presence of the ammonite species *Perisphinctes jubailensis* in the lower part of the formation (Enay et al., 1987), and the nautiloids *Paracenoceras wepferi* and *P. ex gr. moreausum* (Tintant, 1987). Age-supportive foraminifera encountered in surface and subsurface studies by the author include *Alveosepta jaccardi*, *Kurnubia palastiniensis*, *Trocholina palastiniensis*, “*Pfenderina salernitana*”, *Mangashia viennoti*, in the absence of *Redmoinoides* species, *Pfenderina trochoidea* and *Riyadhella regularis*. Specimens of *Zoophycos* have been identified within the lower part of the Jubaila Formation in Wadi Laban, east of Riyadh, but are not sufficiently well preserved to enable age determination as suggested by Olivero (2003, Figure 15).

Based on regional evidence and correlation, Sharland et al. (2001) have proposed a maximum flooding surface within the lower part of the Jubaila Formation (MFS J70, 152.75Ma, late Kimmeridgian).

Biofacies
In recent investigations of surface sections at Wadi Laban, Wadi Nisah and in the subsurface of the Khurais and Gha`war fields by the author, the Jubaila Formation displays a moderately low foraminiferal species diversity that includes undifferentiated nodosariids, *Lenticulina* spp., *Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Alveosepta jaccardi*, undifferentiated miliolids and biserial agglutinated forms. Allochthonous sclerosponges include the branched species *Cladocoropsis mirabilis* together with domal forms such as *Burgundia* spp. Monaxon and tetraxon sponge spicules are locally present, as are valves of juvenile brachiopods (Figures 25-27).

Trace fossils identified from the Lower Jubaila in Wadi Laban include *Zoophycos* spp., *Teichichnus* spp., *Asterosoma* spp., *Planolites* spp., *Nereites* spp., *Chondrites* spp., *Cylindrichnus* spp., *Skolithus* spp., *Rhizocorallium* spp. and *Thalassinooides* spp. (Dr. R. Goldring, Reading University, UK and Dr. A. Taylor, Ichron, UK oral communication, 2000).

Palaeoenvironment
A lagoon palaeoenvironment is suggested by Enay et al. (1987) for the Jubaila Formation. Foraminiferal and associated calcareous algal and stromatoporoid assemblages from the outcrop in the Tuwaiq Mountain Escarpment, west of Riyadh and in the subsurface of the Gha`war and Khurais fields, provide evidence for a variety of sub-environments (Figures 8-9). Moderately deep marine conditions, below fairweather wavebase and with normal salinity are typified by the presence of *Lenticulina* spp., *Nodosaria* spp., *Dentalina* spp., *Pseudomarssonella* spp., monaxon and tetraxon sponge spicules and juvenile costate brachiopods. The presence of *Kurnubia palastiniensis* and *Nautiloculina oolithica* is of limited palaeoenvironmental significance, as they are present in most of the Jubaila biofacies. Fragments of *Cladocoropsis mirabilis* and domed or platy encrusting sclerosponges are locally present and attributed to storm-triggered transportation from a shallower setting as tempestites or carbonate turbidites. A deep shelf environment is suggested by the trace fossil *Zoophycos* spp. that is well represented in the outcrop belt and is not considered to have occupied lagoonal environments after the Middle Jurassic. *Rhizocorallium* spp. is also present and was confined to a shelfal environment during the Middle to Late Jurassic (Dr. R. Goldring, Reading University, UK oral communication, 2000).

The coral and stromatoporoid-filled channels exposed in the road cut west of Riyadh, and confined to the upper part of the Jubaila Formation (Figures 28 and 29) suggest transport of shallow marine biocomponents into the deeper setting. Fragments of the branched stromatoporoid *Cladocoropsis mirabilis* are common and localised towards the top of the Jubaila Formation in the Jubaila roadcut on the Riyadh – Mecca highway near Wadi Dirab (Figure 30). Progressive narrowing and deepening of the channels towards the top of the Jubaila exposure at this locality suggests progradation of the channel complex (Figure 31). It is important to note that the rare presence of fragmented branched *Cladocoropsis mirabilis* and domed stromatoporoid interpreted as storm-derived, in the lower Jubaila in the subsurface of Gha`war imply a contemporaneous relatively local source of shallower marine stromatoporoids in the region. An *in-situ* source for this shallower biofacies has been only discovered near Hawtah (Figure 24). As with the Hanifa Formation, the restricted, deeper part of the open-marine regime is characterized by the presence of alveolar-walled agglutinated *Alveosepta powersi*. The ubiquitous species *Kurnubia palastiniensis* and *Nautiloculina oolithica* are also present. The
Figure 25: Arab-D Reservoir biocomponents (width of photomicrograph indicated in mm)  
(1) Coptocampylodon lineolatus axial vertical section HWYH-363 # 43 (1mm); (2) Coptocampylodon lineolatus axial vertical section HWYH-363 # 19 (1mm); (3) Coptocampylodon lineolatus transverse section HWYH-363 (30V) (1mm); (4) Clypeina sulcata vertical axial section; HWYH-363 # 69 (2mm); (5) Clypeina sulcata transverse section HRDH-737 (#69) (2mm); (6) Cayeuxia sp. HWYH-363 # 30 (2mm); (7) Thaumatoporella parovesciculifera HWYH-363 (#78) (1mm); (8) Thaumatoporella parovesciculifera HWYH-363 # 69 (1mm); (9) Thaumatoporella parovesciculifera HWYH-363 # 49 (1mm); (10) Burgundia sp. HWYH-363 #121 (8mm); (11) Cladocoropsis mirabilis, axial section HWYH-363 (6194.5) (2mm); (12) Cladocoropsis mirabilis, axial section of branch termination HWYH-363 #66 (8mm); (13) Cladocoropsis mirabilis, sagittal transverse section HWYH-363 (#101); (14) Cladocoropsis mirabilis, oblique transverse section HWYH-363 # 70 (8mm); (15) tetraxon sponge spicule HWYH-363 # 215 (2mm).
Figure 26: Arab-D Reservoir biocomponents (width of photomicrograph indicated in mm)
(1) Spiroloculina sp. oblique transverse section HWYH-363 # 31 (1mm); (2) Quinqueloculina sp. transverse section HWYH-363 # 19 (1mm); (3) Pfenderina salernitana, tangential vertical section HWYH-363 # 19 (1mm); (4) Valvulina sp., vertical axial section HWYH-363 # 50 (1mm); (5) Valvulina sp., vertical axial section HWYH-363 # 31 (1mm); (6) Siphovalvulina sp., vertical axial section HWYH-363 # 31 (1mm); (7) Siphovalvulina sp., vertical axial section HWYH-363 # 19 (1mm); (8) Mangashtia vienotti, transverse section HWYH-363 # 30 (1mm); (9) Alveosepta jacardi/powersi HWYH-363 # 25 (4mm); (10) Alveosepta sp. cf. powersi HWYH-363 # 25 (1mm); (11) cf. Iraqia sp., axial vertical section HWYH-363 #119 (1mm); (12) cf. Dobroginella sp., tangential vertical section; (13) Trocholina alpina, tangential axial section HWYH-363 # 19 (1mm); (14) Nautiloculina oolithica, tangential axial section HWYH-363 # 19 (1mm); (15) Nautiloculina oolithica, tangential axial section HWYH-363 # 19 (1mm).
Figure 27: Arab-D Reservoir biocomponents (width of photomicrograph indicated in mm) 
(1) *Kurnubia palastiniensis*, axial section HWYH-363 # 150 (2mm); (2) *Redmondoides lugeoni* HWYH-363 # 151 (1mm); (3) polymorphinid HWYH-363 # 59 (1mm); (4) *Lenticulina* sp. vertical section HRDH-737 (#155) (2mm); (5) *Lenticulina* sp. oblique axial section HRDH-737 (#151) (1mm); (6) cf. charophyte HWYH-363 # 89 (1mm).

Figure 28: Jubaila roadcut showing a wide, shallow stromatoporoid-filled channel, Wadi Dirab roadcut, west of Riyadh.
shallowest depositional facies in the Jubaila Formation includes *Kurnubia palastiniensis*, *Nautiloculina oolithica*, with rare, *Clypeina sulcata*, miliolids, and scattered fragments of laminated and branched stromatoporoids and corals and suggests proximity to a shoal complex.

**Arab-D Reservoir, Arab Formation**

**Stratigraphy**

The Arab Formation consists of four members (Steineke and Bramkamp and Steineke, 1952; Powers et al., 1966; Powers, 1968), named in ascending vertical succession as D, C, B and A. Each member consists of a lower carbonate and an upper evaporitic section, although the anomalously thick evaporite associated with the Arab A Member is called the Hith Formation (Figure 31). Surface exposures are limited, and the formation has been defined on its subsurface characteristics. The
Arab-D reservoir spans the upper part of the Jubaila Formation, and the carbonates of the Arab-D Member. The base of the Arab-D Member of the Arab-Formation is micropalaeontologically placed at the base of consistent *Clypeina* species and *Thaumatoporella parvovesiculifera* (as *Polygonella incrustata*) in the type section (Powers et al., 1966, p.D62). Although this event can be consistently detected in the Ghawar subsurface, it is less easily detected in the outcrop samples. According to Denis Vaslett and Yves le Nindre (oral communication, November, 2002), their mapping criterion for the Jubaila - Arab contact was placed at the uppermost limit of stromatoporoids. This would place the top of the Jubaila at the top of the section exposed in the studied Riyadh - Mecca roadcut. At this same location, an extensive, stratibound, clay-filled cave complex within a bed of dedolomite (F.O. Meyer oral communication) is well developed in the Jubaila (Figure 21), and its association with intensive *Thalassinoides* burrows suggests possibly preferential dissolution of less-resistant burrow-fill sediment. Large sclerosponge fragments make their first stratigraphic appearance above this feature along the Riyadh-Mecca roadside in the Tuwaiq Mountain roadcut west of Riyadh. Nannofossil evidence (O. Varol, oral communication, 2003) suggests a shallowing event that corresponds to the surface between reservoir zones 2 and 3 of the Arab-D reservoir. It is stressed, however, that this nannofossil evidence is based on environmentally controlled exclusion of the open marine coccolith *Cyclagelosphaera omanica* (Dr. O. Varol, written communication, 2003) and does not necessarily represent a true extinction and therefore precludes an isochronous interpretation. A diachronous relationship with a similar event observed in Ghawar cannot be discounted, and is considered herein to be a preferred interpretation.

**Age**

Neither ammonites nor coccoliths have been recovered from the Arab-D Member, and the age is based on benthic foraminifera. The presence of *Alveosepta jaccardi, Kurnubia palastiniensis, Mangashtia viennnoti, Trocholina palastiniensis, Everticyclammina hedbergi/virguliana* and *Pfenderina salernitana* provide an undifferentiated Kimmeridgian age.

Based on regional evidence and correlation, Sharland et al. (2001) have proposed maximum flooding surface: (1) near the base of the carbonates of the Arab-C Member (MFS J80, 151.75Ma, late Kimmeridgian), (2) near the base of the carbonates of the Arab-B member (MFS J90, 151.25Ma, late
Kimmeridgian), (3) possibly (author’s interpretation) near the base of the carbonates of the Arab-A Member (MFS J100, 150.75Ma, late Kimmeridgian), and (4) within the Hith Formation (Figure 31) (MFS J110, 147Ma, late Tithonian).

**Biofacies**

Benthic foraminifera recovered from the Arab-D Member Ghawar and Khurais include *Nautiloculina oolithica*, *Kurnubia palastiniensis*, *Pfenderina salernitana*, *Trocholina palastiniensis*, *Mangashtia viennoti*, undifferentiated miliolids, and undifferentiated biserial agglutinated species (Figures 25-27). A variety of dasyclad algae include *Clupeina sulcata*. Sclerosponges include the branched species *Cladocoropsis mirabilis* and undifferentiated domed or platy encrusting forms. Towards the top of the Arab-D reservoir in Ghawar, microfaunal diversity decreases rapidly and a depleted, cerithid gastropod-dominated microbiocenosis is present. It is considered to represent a low intertidal environment. Of regional palaeoenvironmental significance is the absence of the shallow marine foraminifera “*Pfenderina salernitana*, *Mangashtia viennoti*, *Trocholina palastiniensis*, and the calcareous algae *Thaumatoporella parvovesiculifera* and *Clupeina sulcata*, from the Jubaila exposed in the Dirab road cut. These forms are present within the Jubaila of the Ghawar subsurface, and are also present in the Arab-D Member of the Arab Formation exposed above the Jubaila Formation at Wadi Helwah near Hawtah.

**Palaeoenvironment**

A sabkha palaeoenvironment is suggested by Enay et al. (1987) for the Arab Formation. Foraminiferal assemblages from the outcrop in the Tuwaiq Mountain Escarpment and in the subsurface of the Ghawar and Khurais fields, however, provide evidence for a variety of sub-environments (Figures 8 and 9).

The deepest biofacies of the Arab-D Member represents a deep lagoon, normal salinity setting and includes *Kurnubia palastiniensis*, *Nautiloculina oolithica*, laminated stromatoporoids, *Cladocoropsis mirabilis*, *Clupeina sulcata* and *Thaumatoporella parvovesiculifera*. A slightly shallower lagoon subtidal setting includes “*Pfenderina salernitana*, *Mangashtia viennoti*, *Trocholina alpina* and undifferentiated simple miliolids. A hypersaline, intertidal environment is characterised by undifferentiated simple miliolids, costate, cerithid-like gastropods, bivalve and brachiopod debris, and algal laminae.

**CONCLUSIONS**

The following conclusions are based on observations made on the reservoir-associated sections of the Middle and Upper Jurassic formations encountered during industrially applied, rather than academic, micropalaeontological studies. It is conceivable that the trends observed may require modifications after more extensive studies of closely-sampled measured sections from the outcrop belt (currently in progress). Micropalaeontological tiering, or vertical stacking orders typically display biofaces that track shoaling-upwards trends. Stacking ordering of the respective species and their associations, together with limited sedimentological information, have enabled palaeoenvironmental interpretations to be deduced. These are based on the peculiarities of foraminiferal wall structure and comparisons to genera of modern analogues where possible. Figures 8 and 9 summarise the distribution of the palaeobathymetrically-sensitive species used in this study.

The deepest parts of each of the depositional cycles represented by the Tuwaiq Mountain, Hanifa and Jubaila formations display a similar microbiocenosis that consists of monaxon and tetraxon spicules, species of *Lenticulina* and *Nodosaria*, with sparse *Dentalina*, together with juvenile costate brachiopods. The pelagic bivalve *Bositra buchi* is only present in this biofacies in the Tuwaiq Mountain Formation. These species are commonly found in association with species that are typically found in the lagoon setting. Forms such as *Kurnubia palastiniensis* and *Nautiloculina oolithica* may either have a very wide palaeoenvironmental tolerance, or their presence may be attributed to an allochthonous, tidal or storm-derived cause. Of these, the former is considered more likely because of their ubiquitous presence. The assemblage considered herein to typify the relatively deeper regime probably represents episodes of marine transgression when the most open marine, normal salinity and unrestricted environmental conditions persisted. Episodic events characterised by concentrations of spicules and *Bositra buchi* suggest low carbonate production rates. The resulting concentration of pelagic elements,
and of those that did not secrete a continuous shell or test, may represent condensed beds related either to rapid transgression and a ‘catch-up’ carbonate setting, or the acme of a cycle-scale transgression. In the Tuwaiq Mountain Formation, these events are repeated and have been integrated with the sedimentology to deduce depositional cycles from which reservoir layers have been suggested. This association provides evidence to support the concept that *B. bucchi* was not restricted to shallow marine conditions, but was more representative of low energy conditions at water depths below wave base.

A relatively shallower environment within the open-marine unrestricted regime (but deeper than the sclerosponge shoals below fair-weather wavebase and within the carbonate factory) contains a depleted equivalent of the assemblage described above. It contains *Alveosepta jaccardi, A. poworsi, Pseudocyclammina lituus* and *Everticyclammina* spp. The reason for the predominance of large, complex-walled agglutinated species is uncertain, but may be explained by the rapid colonisation of an environment in which input of storm- and tide-derived bioclastic debris was common, as these forms are considered as allochthonous.

The shoal complex within the studied sections is always represented by the presence of sclerosponges (stromatoporoids sensu Wood, 1987), minor corals and few microbiocomponents. Stratigraphically, in core samples, the laminated, domed and encrusting sclerosponges underlie the branched *Cladocoropsis mirabilis*. Interpretation of the depositional environments of both extinct stromatoporoid types can be assisted by using their morphological similarity to domal and branched corals (see Figure 9 in James, 1983). The domal forms would represent a shoal crest or flank, with moderate to high wave energy, and with rates of sedimentation prevailing above fairweather wave base. The branched *Cladocoropsis mirabilis* would be expected to occupy lower energy conditions with high rates of sedimentation such as on the lee side of a stromatoporoid shoal. The macrotiering or vertical succession represented in cores may, therefore, represent progradation of a lee or lagoonal *Cladocoropsis mirabilis* facies over the encrusting and dome-shaped stromatoporoids of the shoal crest. Many authors have suggested that stromatoporoid morphology is strongly influenced by the pattern of sedimentation (e.g. Swan and Kershaw, 1994) which is in agreement with the present study.

The deep lagoon association includes the benthic foraminifera *Trocholina elongata, Redmondoides lugeoni, Meyendorffina bathonica, Trochamijiella gollesstanhi, Pfenderina trochoidea, Kurnubia wellingsi, Praekurnubia* sp., *Valculineria* sp. *Kurnubia palastiniensis* and *Nautiloculina oolithica*. Sparse, simple miliolids are also present within this association. Other biocomponents include *Clupeina sulcata* and *Thaumatoporella parvoesiculifera*.

The shallow lagoon assemblage is typified by undifferentiated simple miliolids. These include *Kurnubia palastiniensis, Nautiloculina oolithica, Pfenderina salenritana, Pfenderina trochoidea, Mangashtia viennoti*, undifferentiated biserial agglutinated forms and *Trocholina alpina* with common *Clupeina sulcata*. Upwards within this succession, *Mangashtia viennoti* becomes rare to absent, followed by *Pfenderina salenritana* and finally *Trocholina alpina*, which is believed to represent gradually-shallowing conditions. The uppermost biofacies typically contains rare undifferentiated simple miliolids, cerithid gastropods and felted algal laminae. It is believed to represent intertidal, shoreline conditions.

In addition to the observation of environmentally and stratigraphically significant biotiering of micro- and macrobiofacies, the phenomenon of “palaeobathymetric compression” has been interpreted for parasequences where the vertical palaeobathymetric range requires considerable water depth reduction. This is greater than that represented by the palaeontologically-calibrated parasequence thickness, even after decompaction has been considered, and could be considered as a palaeoenvironmental manifestation of forced regression.

The variety of biofacies and the high frequency of bioevent transition provide valuable independently-gained events for intra-reservoir stratification in multi-well studies. Lateral biofacies variations provide a unique contribution for palaeodepositional environmental reconstruction. Although not discussed herein, their integration with sedimentological, petrographic, petrophysical and wireline log data, significantly improve efforts to develop depositional and reservoir-facies models within fields as well as assisting in the formulation of geocellular models for reservoir simulation.
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ABOUT THE AUTHOR

Geraint Wyn Hughes is Senior Geological Consultant and Leader of the Carbonate Systems Support Group in Saudi Aramco’s Geological Technical Services Division. He gained BSc, MSc, PhD and DSc degrees from Prifysgol Cymru (University of Wales) Aberystwyth and in 2000 he received the Saudi Aramco Exploration Professional Contribution award. His biostratigraphic experience includes 10 years with the Solomon Islands Geological Survey, and 10 years as Unit Head of the Middle East-India region for Robertson Research International. Wyn’s professional activities are focused on integrating micropalaeontology with sedimentology to enhance the sequence stratigraphic understanding of Saudi Arabian hydrocarbon reservoirs. He maintains links with academic research as an Adjunct Professor of the King Fahd University of Petroleum and Minerals, Dhahran. He is a reviewer for GeoArabia, and a member of the British Micropalaeontological Society, the Dhahran Geoscience Society, the International Fossil Alga Association and the Cushman Foundation for Foraminiferal Research.

geraint.hughes@aramco.com

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