Biofacies and palaeoenvironments of the Jurassic Shaqra Group of Saudi Arabia

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ABSTRACT: The Jurassic succession in Saudi Arabia consists of seven formations, forming the Shaqra Group, of which most are carbonate and some are partly evaporitic, and is of economic importance because it hosts twelve hydrocarbon reservoirs, including the Arab-D Reservoir within the world's largest oilfield at Ghawar. The Minjur-Marrat formational boundary marks the Triassic-Jurassic boundary, of which the Marrat is dated as Toarcian. A significant unconformity separates this unit from the overlying Dhruma Formation, of Bajocian to Bathonian ages. The Tuwaiq Mountain Formation, of Callovian age, overlies the Dhruma Formation, with reduced hiatus. The Hanifa Formation, of Oxfordian age, is separated from the Tuwaiq Mountain Formation by a minor hiatus, as are the successive Jubaila, Arab and Hith formations, of Kimmeridgian to Tithonian ages. The Jurassic-Cretaceous boundary is currently placed within the lower part of the overlying Sulaiy Formation.

A combination of semi-quantitative micropalaeontological and macropalaeontological analysis of closely-spaced thin sections from these carbonates displays a tiered relay of clearly defined microbiofacies cycles. These cycles reveal palaeoenvironmental trends that subdivide the succession into parasequences, transgressive and highstand systems tracts that are not always evident from the sedimentology alone. The biofacies approach to elucidating palaeoenvironmental variations of the Shaqra Group provides significant insights to the Jurassic history of the Arabian Plate, as well as serving to explain the origin and stratigraphic location of hydrocarbon reservoirs, seals and potential source rocks.

The Shaqra Group spans at least 36 Ma, and qualifies as a second order depositional sequence, within which the formations can be considered as third order sequences. Better chronostratigraphic constraint of the depositional sequences reveals elevated subsidence rates for the Dhruma, Tuwaiq Mountain and Hanifa formations that can be related to established episodes of global plate readjustment. Tectonoeustatic and possibly glacioeustatic controls on depositional cyclicity probably exerted an influence on the major unconformities within the Shaqra Group.

INTRODUCTION

As the host rocks for the largest oilfield in the world, and to numerous stratigraphic levels that host subsidiary hydrocarbon reservoirs, the Shaqra Group ranks as the most economically significant lithostratigraphic unit of Saudi Arabia. Although the group has received attention during early and more recent regional geologic mapping, its commercial value has led to it being better understood in the subsurface than in outcrop. The relationship between the component forma-

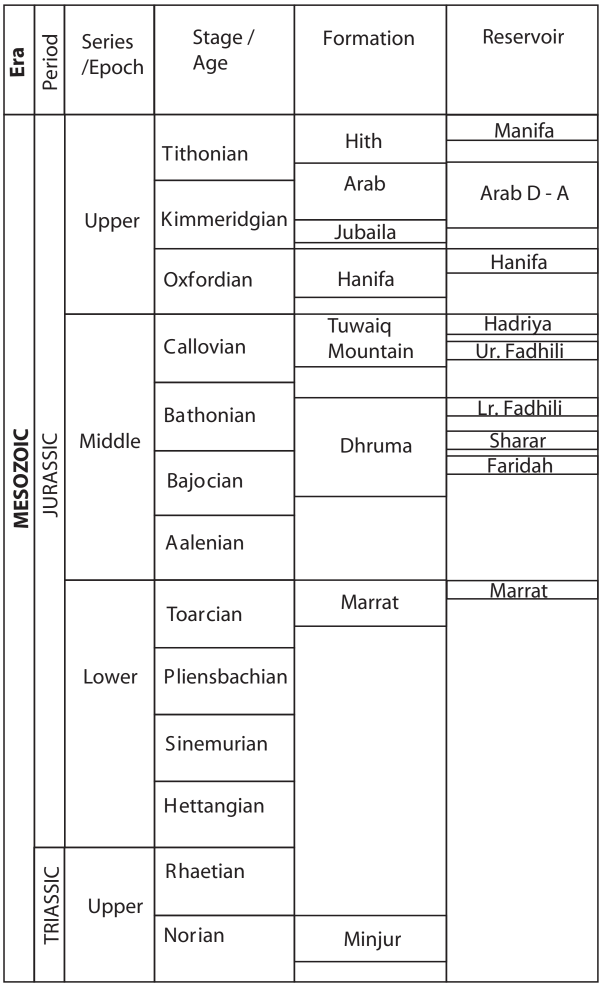

Fig. 1. Lithostratigraphy and chronostratigraphy of members of the Shaqra Group of Saudi Arabia. The chronostratigraphy is based on Gradstein *et al*. (2004), the lithostratigraphy is modified from Enay (1987) and the global sea level is from Haq and Al-Qahtani (2005).

tions and their subsurface equivalents has been improved by relatively recent biostratigraphy and the palaeoenvironmental variations of each have been significantly enhanced by intensive micropalaeontological studies. This contribution focuses on the new micropalaeontological aspects of each formation and their refined palaeoenvironmental implications.

LITHOSTRATIGRAPHY

The lithostratigraphy of the seven formations that constitute the Shaqra Group was established by Powers (1968) and Powers *et al*. (1966) and later modified by the detailed quadrangle-based geological map series in the numerous publications by Vaslet *et al*. (1983, 1984, 1991), Manivit *et al*. (1985a, 1985b, 1986) and summarised by Enay (1987), Le Nindre *et al*. (1990), Al-Husseini (1997) and Sharland *et al*. (2001).

The Shaqra Group lies unconformably upon the Minjur Formation, of Late Triassic age, and is overlain by the Sulaiy Formation, of Berriasian age. It is comprised of, in ascending stratigraphic order, the Marrat, Dhruma, Tuwaiq Mountain, Hanifa, Jubaila, Arab and Hith formations. These formations are separated by hiatuses of which the duration progressively decreases, as displayed in Fig. 1 where they are calibrated with the latest chronostratigraphy of Gradstein *et al*. (2004). By applying orbital stratigraphic control, Al-Husseini and Mathews (2005, 2006) have assigned the Early Jurassic succession to a second order Arabian Orbital Stratigraphy sequence $DS^2$13, the Middle Jurassic succession to $DS^2$12 and the Upper Jurassic succession to $DS^2$11.

If considered as one supercycle, the approximate 36 Ma duration of the Shaqra Group, including the duration of the numerous hiatuses, would classify it as a 2nd order cycle using the criteria of Vail *et al*. (1991), and the component formations would qualify as 3rd order cycles.

The Jurassic formations consist predominantly of carbonates, although evaporitic sediments become more prevalent in the Kimmeridgian and Tithonian Arab and Hith formations. Unlike the underlying red sandstone-dominated Minjur Formation, siliciclastics are uncommon in the carbonate-dominated Shaqra Group and mostly confined to the northern and southern margins of the outcrop belt where near-shore palaeoenvironments are inferred.

The Lower Jurassic succession includes the Marrat Formation, 102.5 m thick, that lies unconformably on the Triassic Minjur Formation, and consists of interbedded marine sandstone, carbonate and claystone deposits that are Toarcian or older in age. It is informally subdivided into lower (36.5 m), middle (41.8 m) and upper Marrat (24.2 m).

The Middle Jurassic is represented by the Dhruma and Tuwaiq Mountain formations. The Dhruma Formation, as defined here, is 336 m thick and lies unconformably on the Marrat Formation. It is mainly composed of carbonate in the subsurface, carbonate and claystone in the central part of the outcrop area, and siliciclastics in outcrops to the north and south. It was originally defined with seven informal units D1 to D7 (Manivit *et al*. 1990) that include 143 m of units D1 and D2 of the lower

Dhruma, 193 m of units D3 to D6 of the middle Dhruma and 111 m of unit D7 of the upper Dhruma. Recent reexamination of the upper Dhruma and Tuwaiq Mountain Formation, partly suggested by Hughes (2004c) and confirmed through discussion in early 2006 with Dennis Vaslet (Bureau of Mineral Resources, Paris), would place the mud-dominated D7 unit of the Dhruma genetically within the basal Tuwaiq Mountain Formation. The newly defined Tuwaiq Mountain Formation lies unconformably on the Dhruma Formation (D6) and consists mostly of shallow-marine lagoon and stromatoporoid carbonates of Middle to Late Callovian age with a combined thickness of 295 m. In addition to the D7 unit, the Tuwaiq Mountain Formation includes three originally defined informal members that include 32 m of unit T1 or Baladiyah, 56 m of unit T2 or Maysiyah and 96 m of T3 or Daddiyah.

The Upper Jurassic succession consists of the Hanifa, Jubaila, Arab and Hith formations. The Hanifa Formation lies disconformably upon the Tuwaiq Mountain Formation, is 126 m thick and consists of a lower muddy carbonate unit and an upper stromatoporoid and lagoonal carbonate lithofacies. It has been informally subdivided into up to 66 m of the lower Hawtah Member (H1), and up to 74 m of the upper Ulayyah Member (H2). The Jubaila Limestone (J) lies disconformably upon the Hanifa Formation and consists of moderately deep marine carbonates in the lower part that is overlain by a shallow marine stromatoporoid-associated assemblage. In the outcrop belt, the carbonates pass into sandstones to the south and northwest. It consists of two informal members that include 50 m of the lower J1 and 35 m of the upper J2 member. The Arab Formation is approximately 54 m thick in outcrop and consists of four stacked carbonate-evaporite cycles, named Arab-D to Arab-A in ascending order. The Hith Anhydrite, consists mostly of anhydrite but has an upper carbonate unit, as described by Hughes and Naji (2009). It is 90 m thick at the outcrop and represents the evaporitic part of the Arab-A carbonate-evaporite couplet (Powers *et al.* 1966).

BIOSTRATIGRAPHY

The Shaqra Group is entirely of Jurassic age (Fig. 1), spans the Toarcian to Tithonian, and each formation in the outcrop and subsurface has been dated with moderately refined accuracy using a combination of macrofossils, microfossils and nannofossils. The biostratigraphic evidence is based on ammonites (Enay *et al.* 1987), nautiloids (Tintant 1987), brachiopods (Almeras 1987), ostracods (Depeche *et al.* 1987), nannofossils (Manivit 1987; Varol personal communication), gastropods (Fischer *et al.* 2001), foraminifera (Hughes 2004 a-c) and calcareous algae (Okla 1987; Hughes 2005) together with a variety of data in Manivit *et al.* (1990). Fischer *et al.* (2001) provides an excellent summary of the various age-diagnostic macrofossil species and their chronostratigraphic assignment as used in this paper, and the reader is referred to that publication because space does not allow such detail here.

The Lower Jurassic succession contains ammonites in the upper part of the lower Marrat and the middle Marrat that provide an Early Toarcian age (Serpentinum Zone), and a Middle Toarcian age (Bifrons Zone) for the basal part of the upper Marrat. The upper Marrat has not yielded any age-indicative forms.

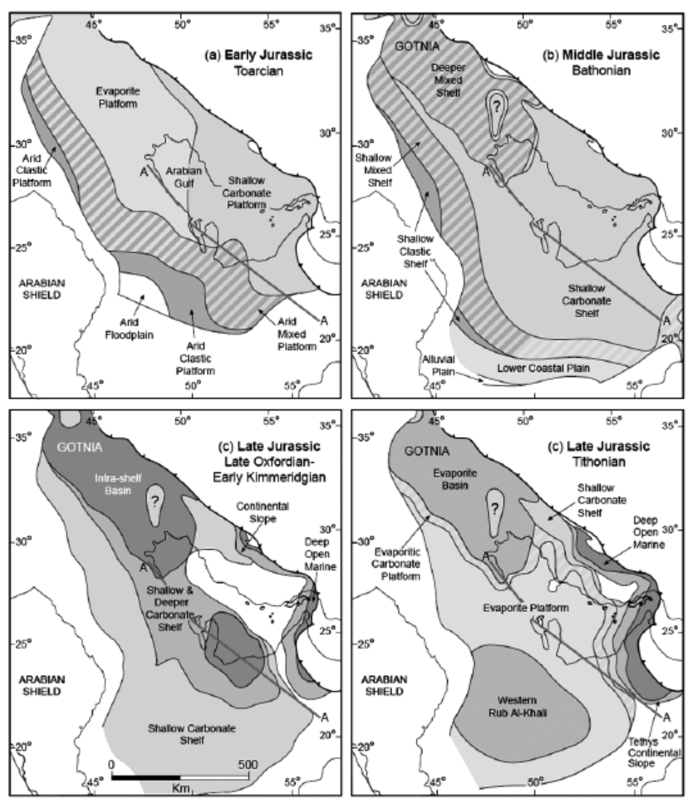

Fig. 2. Jurassic environments of deposition in the Middle East (Murris 1980), redrawn by Al-Husseini (1997).

	Intertidal	very shallow lagoon/ shelf	shallow lagoon/ shelf	deep lagoon/ shelf	back bank	bank	fore - bank	intra-shelf basin
costate gastropods								
non-costate gastropods								
microbialites								
oncoliths								
Ophthalmidium sp.								
Spiroloculina sp.								
cf. Charophytae								
Trocholina alpina								
Quinqueloculina sp.								
„Pfenderina" salernitana								
„Pfenderina" trochoidea								
Alveosepta jaccardi		?						
Alveosepta jaccardi/powersi		?						
Trocholina elongata		?						
Mangashtia vienotti								
cf. *Satorina apuliensis*								
Redmondoides lugeoni								
Redmondoides sp. cf. *rotundata*								
Valvulina sp.								
cf. *Pseudocyclammina* sp. cf. *lituus*								
Ammobaculites sp.								
Trochamijiella gollehstanehi								
Parurgonia caelinensis								
Siphovalvulina sp.								
Reophax sp.								
Meyendorffina bathonica								
Cayeuxia sp.								
Coptocampylodon lineolatus								
Siphovalvulina sp.								
cf. *Iraqia* sp.								
cf. *Dobroginella* sp.								
Cladocoropsis mirabilis								
Clypeina sulcata								
Thaumatoporella parvovesiculifera								
simple corals								
compound corals								
Nautiloculina oolithica								
Kurnubia palastiniensis								
"Kurnubia" wellingsi								
massive stromatoporoids								
Burgundia sp.								
Nodosaria sp.								
Lenticulina sp.								
Astacolus sp.								
polymorphinids								
tetraxon sponge spicules								
monaxon sponge spicules								
juvenile brachiopods								
Bositra buchi								

Fig. 3. Palaeoenvironmental interpretation of the major microfossil and selected macrofossil components of the Shaqra group of Saudi Arabia (adapted from Hughes, 2004c). All italicised species are foraminifera with the exception of *Cladocoropsis mirabilis, Burgundia* sp. (stromatoporoid); *Clypeina sulcata* (dasyclad alga); *Thaumatoporella parvovesiculifera* (alga); *Bositra buchi* (bivalve).

The Middle Jurassic succession includes the Dhruma and Tuwaiq Mountain formations, of which the Dhruma Formation, with its D1-D6 units, is Lower Bajocian to Middle Callovian. The D1 unit is Lower Bajocian (upper part of the Discites Zone to lower part of the Laeviuscula Zone). The basal part of D2 is dated as late Early Bajocian (earliest of the Humphriesianum Zone) and the upper part, known as the Dhibi Limestone Member, is Late Bajocian (Niortense Zone). The basal and middle parts of D3 are Late Bajocian (*Ermoceras mogharense* fauna and *Thambites* fauna), but the upper part and member D4 are Early Bathonian (Zigzag Zone) together with member D5 (Aurigerus Zone). Member D6 contains an endemic ammonoid fauna and two species of nautiloids (Tinant 1987) that suggest an Early Bathonian age, although brachiopods suggest a Late Bathonian age. Unit D7, now assigned to the Tuwaiq Mountain Formation, includes the lower Atash Member and Middle Callovian nannofossils, and supports a stratigraphic hiatus that spans the Middle Bathonian to basal Middle Callovian at the D6-D7 (middle Dhruma – Tuwaiq Mountain) boundary. The upper Hisyan Member is Middle Callovian (Coronatum Zone) based on ammonites, nautiloids, brachiopods and nannoflora. Evidence for the Coronatum Zone persists into the Tuwaiq Mountain Formation members T1, T2 and basal T3, but the upper part of T3 is Upper Callovian age (Athleta Zone), based on ammonoids and nannoflora.

The Upper Jurassic includes the Hanifa, Jubaila, Arab and Hith formations. Within the Hanifa Formation, the lower part of the Hawtah Member is Lower Oxfordian (?) based on brachiopods and the middle and upper parts of the Member are Middle Oxfordian (Plicatilis Zone) based on ammonites, nautiloids and nannoflora. The Ulayyah Member is Upper Oxfordian in its basal part, based on the occurrence of foraminifera *Alveosepta jaccardi* and brachiopods, and may extend into the Kimmeridgian (?Hypselocyclum Zone) if the echinoid evidence is reliable. The Jubaila Limestone is considered as Early Kimmeridgian in age because of nautiloids and endemic ammonites that resemble Early Kimmeridgian species. The Arab Formation microfaunal associations suggest a Kimmeridgian to Tithonian age. The Hith Anhydrite is considered as Tithonian based on its stratigraphic position.

BIOFACIES AND PALAEOENVIRONMENTS

Rather simple palaeoenvironmental maps for selected Jurassic ages have been published by Murris (1980), Ziegler (2001) and Al-Husseini (1997), based on generalised and sparse lithological evidence. That by Murris is included here as Fig. 2. These authors conclude that, during the Jurassic, the Arabian Peninsula was located on the southern margin of the Tethys Ocean, and was the site of an extensive shallow marine platform. The western margin of this platform is not clearly defined owing to removal of the coastal facies by subsequent erosion, but it is interpreted to lie in the vicinity of the present-day eastern margin of the Arabian Shield. Scattered across the platform were localised deeper areas considered to be intra-shelf basins flanked by basin margins colonised predominantly by stromatoporoid banks with subsidiary corals.

Although palaeoenvironmental interpretation of Jurassic microfossils, especially of foraminifera, is very limited, its contribution to small and large-scale palaeoenvironmental reconstruction is considerable. The most significant studies of Tethyan Jurassic foraminifera include those of Pelissie and Peybernes (1983), Pelissie *et al.* (1983), Derin and Gerry (1975), Banner and Highton (1990), Banner and Whittaker (1991), Hughes (1996, 2004c) and Mancinelli and Coccia (1999). Recent developments in stromatoporoid palaeoenvironments are summarised by Toland (1994), Leinfelder (2001) and Leinfelder *et al.* (2005). Fig. 3 displays a summary of the interpreted depositional environments based on various studies by the author.

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 shelf conditions, considered to be below fair-weather wave base. A foraminiferally depleted succession then follows that is characterised by encrusting and domed stromatoporoids, including *Burgundia* species, in the Tuwaiq 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 stromatoporoid *Cladocoropsis mirabilis*, together with *Kurnubia* and *Nautiloculina* species and a variety of indeterminate simple miliolids. *Pseudocyclammina* sp. cf. *lituus, Alveosepta jaccardi/po-*

wersi 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* foraminiferal species and the dasyclad algae *Clypeina sulcata* and *Heteroporella jaffrezoi*. 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 is gradually supplemented by ''*Pfenderina*" *salernitana* and is interpreted to represent 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.

The Marrat Formation contains very low diversity microfauna that consist of gastropods and brachiopods; no foraminifera have yet been recovered. This assemblage is interpreted to represent a shallow subtidal to intertidal environment.

The Dhruma Formation contains moderately diverse foraminiferal assemblages that include the localized distribution of *Ophthalmidium* spp., "*Pfenderina*" *trochoidea*, ? *Satorina apuliensis*, *Trocholina elongata*, *Ammobaculites* spp., *Nautiloculina oolithica*, "*Pfenderina*" *salernitana*, *Redmondoides lugeoni*, *Redmondoides* sp. cf. *rotundata, Valvulina* sp., *Trochamijiella gollehstanehi*, *Parurgonia caelinensis* and *Pseudocyclammina* sp. cf. *lituus*. Other biocomponents include *Bositra buchi, Cladocoropsis mirabilis,* costate and non-costate gastropods, *Cayeuxia* spp., corals, sponge spicules, microbialite concretions and oncoliths. Dasyclad algae are locally present and are dominated by *Salpingoporella annulata*. Abundant *in-situ* stromatoporoid specimens are considered to be indicative of water depths shallower than 10 m (Toland 1994). The foraminiferal, dasyclad and stromatoporoid distribution suggests a moderately shallow, lagoonal environment in which localized shoals of branched stromatoporoids were present, between which deeper parts of the lagoon became populated by spicule-secreting sponges during periods of sea level rise.

The Tuwaiq Mountain Formation contains benthic foraminifera that include undifferentiated nodosariids, *Lenticulina* spp., *Bolivina* spp., *Trocholina elongata, Kurnubia palastiniensis, K. wellingsi, Nautiloculina oolithica, Valvulineria* sp., *Redmondoides lugeoni, Praekurnubia* sp., "*Pfenderina*" *trochoidea, Meyendorffina bathonica,* and *Trochamijiella gollehstanehi*. Stromatoporoids include the branched species *Cladocoropsis mirabilis* together with stratified forms. Monaxon and tetraxon sponge spicules are locally present, with the very thin shelled bivalve *Bositra buchi* and juvenile brachiopods. Calcareous algae from the Tuwaiq Mountain Formation have been described by Okla (1987) and Hughes (2005). The T1 unit of the Tuwaiq Mountain Formation consists of a grainstone-dominated shelf environment whereas the T3 unit is dominated by a stromatoporoid bank 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. Open marine biofacies, deposited below wave-base, include species of *Lenticulina, Nodosaria* and *Bolivina*. The shoal complex includes platy, domed and branched stromatoporoids, of which the platy and domed forms are interpreted to represent the distal, higher energy regime of the shoal, probably above wave base. *Cladocoropsis mirabilis* is typically found with dasyclad algae and is interpreted to have occupied a lower energy environment within the sheltered, bank-flank area of the lagoon. The deep lagoon biofacies displays the highest species diversity, and includes *Meyendorffina bathonica, Trochamijiella gollehstanehi, Redmondoides lugeoni, "Kurnubia" wellingsi, Praekurnubia* sp., "*Pfenderina*" *trochoidea, Valvulina* sp., *Trocholina elongata* and *Nautiloculina oolithica*. The calcareous alga *Arabicodium aegagrapiloides* and *Clypeina* species are typical components. A shallow-lagoon environment is concluded for the sparse biofacies in which *Nautiloculina oolithica*, branched coral, large and robust echinoid spines are present.

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* sp. cf. *lituus*, undifferentiated miliolids and biserial agglutinated forms. Stromatoporoids include *Cladocoropsis mirabilis* together with platy forms. Monaxon and tetraxon sponge spicules are locally present, as are valves of juvenile brachiopods. Dasyclad algae are well represented by *Clypeina sulcata*. 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 foraminifera that include *Alveosepta jaccardi, Pseudocyclammina* sp. cf. *lituus*, *Kurnubia palastiniensis* and *Nautiloculina oolithica*. The shoal complex includes both domed and branched stromatoporoids, of which the domed form is interpreted as being typical of the distal, higher-energy regime of the shoal, probably above wave base. *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. 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 parvovesiculifera*. In the studied sections, no shallow marine, miliolid-dominated sediments have been encountered.

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 stromatoporoids include *Cladocoropsis mirabilis* together with domal forms such as *Burgundia* spp. Monaxon and tetraxon sponge spicules are locally present, as are valves of juvenile brachiopods. 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., *Skolithos* spp., *Rhizocorallium* spp. and *Thalassinoides* spp. A deep shelf environment is suggested by the trace fossil *Zoophycos* spp. as this genus is not

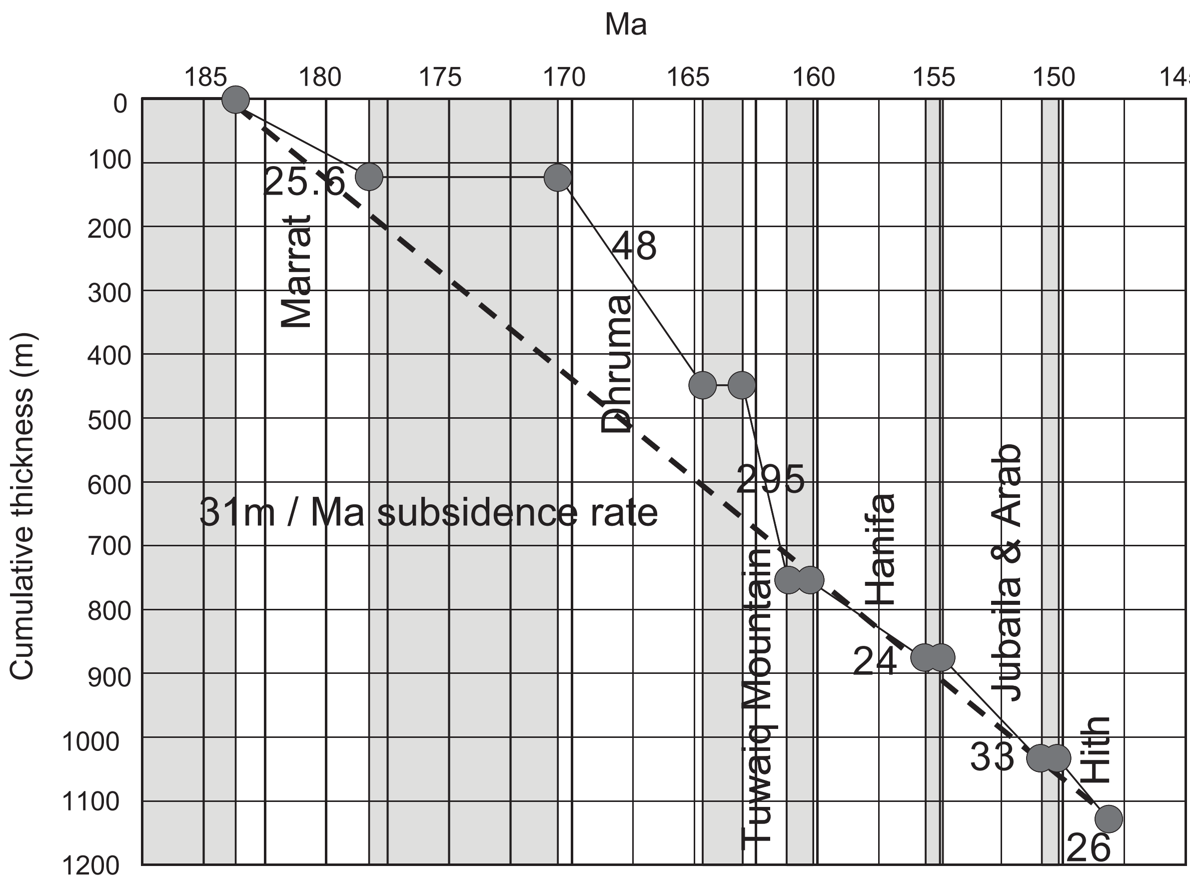

Fig. 4. Subsidence rates for individual formations of the Shaqra Group; shaded area represents duration of unconformities. Note the accelerated rate of subsidence during the deposition of the Dhruma, Tuwaiq Mountain and Hanifa formations.

Sea-level rise	Sea-level fall	Shaqra Group	Tectonoeustatic cause	AP and GSS (Sharland *et al.* 2001)	AROS (Al-Husseini and Matthews 2005)
	Tithonian	Hith		AP8 GSS 110	SB 10
Late Oxfordian to Kimmeridgian	Late Oxfordian to Kimmeridgian	Hanifa to Arab	Rifting associated with inital breakup of Gondwana and formation of Indian Ocean	AP7 GSS 100-60	SB 11
Middle Callovian		Tuwaiq Mountain	Rifting associated with initiation of C. Atlantic sea floor spreading	AP7 GSS 50	SB 11
	Bathonian				
Late Bajocian					
Early Bajocian		Dhruma		AP7 GSS 40-20	SB 12
	Aalenian		Rifting associated with initiation of S. Atlantic sea floor spreading		SB 12
Early Toarcian		Marrat	Rifting associated with initiation of S. Atlantic sea floor spreading	AP6	SB 12
Early Pliensbachian					SB 13
Early Sinemurian					
Early Hettangian					
	Latest Rhaetian	Top Minjur	Rifting associated with Pangea break-up		

Fig. 5. Major sea-level changes during the Latest Triassic and Jurassic (from Hallam 2001), Arabian Plate megasequences and genetic stratigraphic sequences (GSS) of Sharland *et al.* (2001) and Arabian Orbital Stratigraphy (AROS) of Al-Husseini and Matthews (2005). Grey areas represent major unconformities.

considered to have occupied lagoonal environments after the Middle Jurassic. *Rhizocorallium* spp. is also present and was confined to a shelf environment during the Middle to Late Jurassic (R. Goldring, Reading University, UK oral communication, 2000). Moderately deep marine conditions, below fairweather wavebase and with normal salinity are supported 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 Jubaila biofacies. Fragments of *Cladocoropsis mirabilis* and domed or platy encrusting stromatoporoids are locally present and attributed to storm triggered transportation from a shallower setting as tempestites or carbonate turbidites. The coral and stromatoporoid-filled channels exposed in the road cut west of Riyadh, and confined to the upper part of the Jubaila Formation, suggest transport of shallow marine biocomponents into the deeper setting. Progressive narrowing and deepening of the channels towards the top of the Jubaila exposure at this locality suggests progradation of the channel complex, with common fragments of *Cladocoropsis mirabilis* localised towards the top of the Formation. As with the Hanifa Formation, the restricted, deeper part of the open-marine regime is characterized by the presence of alveolar-walled agglutinated *Alveosepta jaccardi*. The ubiquitous species *Kurnubia palastiniensis* and *Nautiloculina oolithica* are also present. The shallowest depositional facies in the Jubaila Formation contains *Kurnubia palastiniensis* and *Nautiloculina oolithica* with rare, *Clypeina sulcata*, miliolids, and scattered fragments of laminated and branched stromatoporoids and corals, which suggests proximity to a shoal complex.

Benthic foraminifera recovered from the Arab-D Member include *Nautiloculina oolithica, Kurnubia palastiniensis, "Pfenderina" salernitana, Trocholina alpina, Mangashtia viennoti*, undifferentiated miliolids and undifferentiated biserial agglutinated species. A variety of dasyclad algae include *Clypeina sulcata*. Stromatoporoids include *Cladocoropsis mirabilis* and undifferentiated domed and platy encrusting forms. Towards the top of the Arab-D microfaunal diversity decreases rapidly and a depleted, cerithid gastropod-dominated microbiofacies is present. It is considered to represent a low intertidal environment. 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, Clypeina 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, cerithid-like costate gastropods, bivalve and brachiopod debris and algal laminae.

Carbonates from the upper part of the Hith Formation, as well as from the interbedded carbonates and evaporites in the "transitional" unit contain a sparse foraminiferal assemblage (see Hughes and Naji 2009 this volume) that includes *Redmondoides lugeoni*, *Trocholina alpina* and various miliolids and valvulinids. Their association with stromatolites and ostracod-dominated grainstones suggests shallow marine deposition within generally adverse, possibly hypersaline environments.

HYDROCARBON SIGNIFICANCE

The Shaqra Group is well-exposed along the central Arabian outcrop belt, but forms the world's largest reservoirs in the subsurface of eastern Saudi Arabia. Twelve hydrocarbon reservoirs are hosted within the group (Fig. 1) that include the Marrat, Faridah, Sharar, Lower and Upper Fadhili, Hadriyah, Hanifa, Arab D to A and the Manifa. Most of these reservoirs are developed in grainstone facies associated with the late highstand systems tracts of each formation. The Faridah and Sharar reservoirs are related to highstand grainstones of high frequency sequences within the Dhruma Formation. Source rock is well represented in the Shaqra Group, as the Tuwaiq Mountain and Hanifa formations are known to have excellent source rocks that developed within the intra-shelf basins during the Callovian and Oxfordian (Carrigan *et al*. 1995). Reservoir seals are also well developed and formed by transgressive mudstones that characterise the basal parts of each formation.

DISCUSSION

The seven component formations of the Shaqra Group provide a unique insight to the depositional history of the Jurassic Period represented in Saudi Arabia. Features of particular significance include the presence of six major unconformities, the progressive decrease hiatus duration and the gradual development of evaporitic facies. Age constraint on each sequence-bound formation is provided by a variety of biostratigraphic marker species, resulting in a high-resolution chronostratigraphy.

The Jurassic succession of Saudi Arabia has been interpreted within various sequence stratigraphic frameworks by Le Nindre *et al*. (1990), Al-Husseini (1997), Sharland *et al*. (2001) and Haq and Al-Qahtani (2005) of which most relate the succession to the eustatic sea level curve of Haq *et al*. (1988). The influence of orbital forcing has been considered by Al-Husseini and Mathews (2005, 2006). If the Shaqra Group represents one complex depositional cycle, then it seems inconsistent that the most extensive unconformites coincide with the interpreted transgressive part when sea level would be expected to be rising at a high rate. It seems similarly inconsistent that fewer and shorter unconformities are associated with the interpreted highstand and possibly early lowstand when sea level fall should be more conducive for unconformities of greater duration. Is it possible that the Shaqra Group represents the result of three sequences, namely the "Marrat sequence", the "Dhruma-Tuwaiq Mountain sequence" and the "Hanifa-Jubaila-Arab-Hith sequence ?". Sharland *et al*. (2001) subdivided the succession into three Arabian Plate (AP) megasequences, of which AP6 extends from the Upper Permian to the Lower Jurassic, AP7 includes the entire Middle and Upper Jurassic, and AP8 from the uppermost Jurassic to the Upper Cretaceous. This scheme also includes

Formation	Thickness (m)	Oldest age	Ma	Youngest age	Ma	Duration Ma	Subsidence rate (m/Ma)
Hith	90	Tithonian	150.5	Tithonian	147	3.5	26
Jubaila and Arab	139	early Kimmeridgian	155	Kimmeridgian	150.8	4.2	33
Hanifa	140	Early Oxfordian	161	Late Oxfordian	155.7	3.3	42
Tuwaiq Mountain	295	Middle Callovian	163	Middle Callovian	161	2	147
Dhruma	336	Early Bajocian	171	Late Bathonian	164	7	48
Marrat	102.5	Early Toarcian	183	Middle Toarcian	178	5	20.5

Fig. 6. Thickness and estimated absolute age duration for each formation, and used to generate the subsidence rates in Fig. 4.

a series of genetic stratigraphic sequences (GSS) (Fig. 5). There is no doubt that the component formations represent cycles of sea-level rise and fall, and their coincidence with the global Jurassic cycles of Hallam (2001) is remarkable (Fig. 5). Hallam (2001) attributes these major sea-level episodes to tectonoeustacy and not to glacioeustacy. Dromart *et al.* (2003) however, attributes the Middle Callovian rise to a temperature optimum followed by a drastic climatic decline leading to continental ice production during the Late Callovian. This view is also suggested by Tremolada *et al.* (2006). A new Arabian Orbital Stratigraphy (AROS) framework has been proposed by Al-Husseini and Matthews (2005) in which the Jurassic succession includes four second order sequences that include, in ascending stratigraphic order, the ? Pliensbachian SB 13 (base Marrat), the Toarcian-Aalenian-Early Bajocian SB 12 ("supra-Marrat"), the Middle Callovian-Oxfordian SB11 (Hanifa/Tuwaiq Mountain) and the Tithonian to Berriasian SB10 (Hith-Sulaiy). Further consideration is required to reconcile the various events and understand the various tectonoeustatic and possibly glacioeustatic controls on the Jurassic sedimentation and episodes of non-deposition on the Arabian Plate.

Palaeoenvironmental interpretation of each formation has been optimised by thin-section micropalaeontology of field and core samples. Tiered patterns of microfossil distribution reflect palaeoenvironmental gradients that especially provide palaeobathymetric trends. The presence of increasingly deeper biofacies reflects a microfacies deposited during a relative marine transgression, whereas those of increasingly shallower character reflect marine regressive conditions linked to the latter part of a depositional autocycle. Such cycles are considered to represent possibly 4th order parasequences that were superimposed on the 3rd order formational cycles. Fig 4 and 6 illustrate the estimated subsidence rates, excluding decompaction, of each formation of the Shaqra Group based on the latest available absolute dating for each Formation. Thicknesses are based on those measured at the type sections along the outcrop belt, and cannot be used to represent rates that would be expected in local intrashelf basins that may have occupied other parts of the Arabian Platform. Rates are shown for the Marrat (25.6 m/Ma), Dhruma (48 m/Ma), Tuwaiq Mountain (147 m/Ma), Hanifa (42 m/Ma), Jubaila and Arab (33 m/Ma) and Hith (26 m/Ma). These provide an average subsidence rate of 31 m/Ma for the Toarcian to Tithonian. The apparent, although questionably anomalous, high rate of subsidence during deposition of the Tuwaiq Mountain Formation may explain the concentration of source rocks within this Formation (Carrigan *et al.* 1995). Sharland *et al.* (2001) place their tectonic megasequence AP6-AP7 boundary between the Marrat and Dhruma formations, with the entire Dhruma to Hith succession falling within AP7. They attribute post-rift subsidence as a cause for accelerated intra-shelf basin development during three episodes, namely the Early Bajocian, Middle Callovian and Middle Oxfordian that coincide with the Dhruma, Tuwaiq Mountain and Hanifa elevated rates of subsidence.

Studies into the regional palaeoenvironmental variations of each of the formations of the Shaqra Group are being planned in the style of the recently completed Hanifa investigation (see Hughes *et al.* 2009, this volume). Such studies rely heavily on the palaeoenvironmental sensitivity of microfossils, and provide important guides to assist the prediction of palaeoenvironments away from well control and the outcrop belt.

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