# Oxfordian biofacies and palaeoenvironments of Saudi Arabia

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**ABSTRACT:** The Hanifa Formation in Saudi Arabia consists of a succession of carbonates, over 100 m thick, that were deposited during the Late Jurassic. It consists of two depositional sequences represented by the lower Hawtah Member and an upper Ulayyah Member, respectively. The Hawtah Member is assigned an Early (?) to Middle Oxfordian age, based on brachiopod, nautiloid and coccolith evidence. The Ulayyah Member is assigned a Late Oxfordian age based on ammonite, nautiloid, coccolith and foraminiferal evidence.

Detailed study of the microbiofacies and lithology of the late highstand succession of the Ulayyah sequence in 41 cored wells distributed across the Kingdom was aimed at determining the most suitable locations for porous and permeable grainstone accumulation as lithofacies hosts the Hanifa Reservoir elsewhere in the region. A range of palaeoenvironments has been determined, based on integrated biofacies and lithofacies, that include shallow lagoon packstones and foraminiferal dominated grainstones and deep lagoon wackestones and packstones with *Clypeina*/*Pseudoclypeina* dasyclad algae. In addition, a series of basin-margin, shoal-associated biofacies are present that include stromatoporoid back-bank packstones and grainstones with the branched stromatoporoid *Cladocoropsis mirabilis*, bank-crest grainstones with encrusting and domed stromatoporoids. A few wells also proved the presence of intrashelf basin-flank mudstones and wackestones containing sponge spicules, deep marine foraminifera and coccoliths.

This study provided control to delimit an intrashelf basin with an irregular margin situated in the east-central part of the Saudi Arabian portion of the Arabian Plate carbonate platform during Late Oxfordian. The basin is flanked by a belt of stromatoporoid banks that pass laterally into a back-bank facies before developing into a lagoon facies. There is no evidence for the shoreline of this basin, although the presence of rare charophytes in the northwest testifies to possible proximity of fluviatile input. The grainstone dominated basin margin facies presents good hydrocarbon reservoir facies and its juxtaposition to intrashelf basinal sediments with potential source rock character provides exciting new prospects in areas hitherto uninvestigated for hydrocarbon reservoirs.

## INTRODUCTION

The study was initiated by Saudi Aramco to provide a core-based map of the various depositional settings that existed during the deposition of the Hanifa Formation over Saudi Arabia, for the purpose of defining the regional distribution of potential reservoir facies and also areas of possible source rock accumulation. Acquisition of such data provides valuable guidance

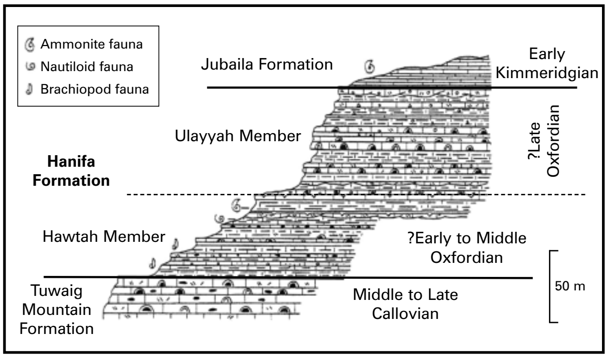



Fig. 1. Diagramatic representation of the Hanifa Formation, based on the Wadi Dirab locality (adapted from Vaslet *et al.* 1991, fig. 3).

to locate exploration targets, and for focusing seismic surveys in remote frontier areas. The Hanifa Formation extends from the outcrop belt, west of Riyadh, into the subsurface beneath the Arabian Gulf. The area included in this study has attempted to sample as many locations within the outcrop and subcrop, within the time constraint of the project. To achieve this goal, well locations were carefully selected for core availability and geographic distribution, together with published and otherwise documented data from within and peripheral to the study area. Analytical work included sedimentological study of nearly 1000m of core from 41 cored wells and semi-quantitative micropalaeontology of 3021 thin sections of core plugs. Selected samples from various wells were submitted for calcareous nannopalaeontological analysis to assist correlation.

Early stratigraphic studies on the Hanifa Formation in Saudi Arabia include Bramkamp and Steineke (in Arkell 1952), Powers *et al.* (1966) and Powers (1968), in which the age, thickness and contact relationships with the underlying Tuwaiq Mountain Formation and the overlying Jubaila Formation were described. Vaslet *et al.* (1983) recognised two members, the Hawtah and Ulayyah, within the Hanifa at outcrop and used this lithostratigraphic nomenclature in all successive publications resulting from the Saudi Arabian geological mapping project. Sequence stratigraphic interpretations of the Jurassic succession include Le Nindre *et al.* (1990a, b), Sharland *et al.* (2001) and Hughes (2004a-c, 2006, 2007). Mattner and Al-Husseini (2002) interpreted the Hanifa Formation to consist of two 3$^{rd}$ order sequences, equivalent to the Hawtah and Ulayyah members respectively. Using an orbital-forcing approach, Al-Husseini *et al.* (2006) maintain this interpretation and have further subdivided the Hawtah and Ulayyah members into five and seven 4$^{th}$ order cycles respectively. The biofacies characteristics and sedimentological evidence support consideration of the Hawtah and Ulayyah members as two separate sequences.

Previous regional palaeoenvironmental interpretations for the Hanifa Formation include Murris (1980), Moshrif (1984), Al-Husseini (1997) and Ziegler (2001) for which very limited palaeoenvironmental detail is presented other than an approximate shoreline and an undifferentiated shallow carbonate platform. Droste (1990) described the Hanifa Formation in Qatar, where intra-platform, basinal laminated, dark, organic-rich lime-mud wackestones and local anhydrites are present. Aspects of the Hanifa stratigraphy, lithology and palaeoenvironment are described by de Matos and Hulstrand (1995). The Hanifa Formation accumulated in a relatively shallow depression that represents a typical example of an intrashelf basin which formed within the interior of an extensive broad epeiric, shallow-water carbonate platform termed the "Arabian Hanifa Intrashelf Basin" (Aigner *et al.* 1989). The bathymetry of this basin is considered to have been responsible for the deposition of prolific source rocks in the Upper Jurassic of Eastern Arabia. Intrashelf basins develop as a result of a rapid eustatic sea level rise in which carbonate margins build up around an isostatically sagged deeper basin floor while the sedimentary fill continues at a slower rate of sedimentation (Read 1985). Strohmenger *et al.* (2004) provided a sequence-constrained study of the Hanifa Formation in Abu Dhabi, and related it to the J60 and J70 sequence boundaries of Sharland *et al.* (2001). Subsidence of the Hanifa Formation has been examined by Le Nindre *et al.* (2003) and Hughes (2006, 2007). A palaeoenvironmental interpretation of outcrop and well-based data has been provided by Hughes (2004a-c) and Hughes *et al.* (2006, 2007).

## LITHOSTRATIGRAPHY

The Hanifa Formation forms one of seven formations that constitute the Shaqra group of Saudi Arabia (Manivit *et al.* 1990). It overlies the Tuwaiq Mountain Limestone Formation with apparent paraconformity in the outcrop and is disconformably overlain by the Jubaila Formation, as evidenced by a pebble conglomerate in exposures in Wadi Birk. It has been defined from

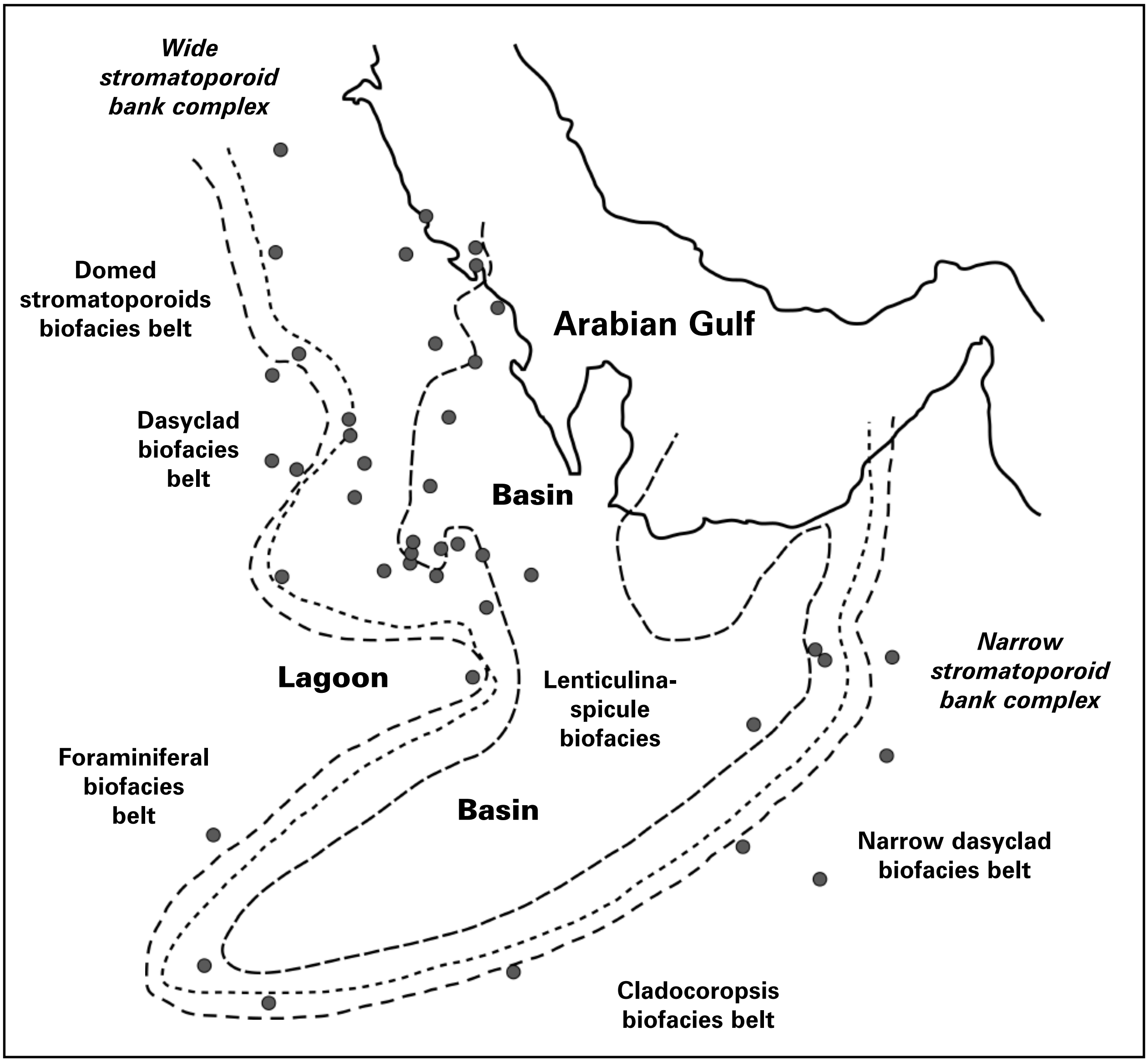



Fig. 2. Distribution of study wells (dots) and interpreted palaeoenvironmental province boundaries (dashed lines) for the regional upper Hanifa Formation (Ulayyah Member) for part of the Arabian Platform during the Late Oxfordian. Dots indicate study well locations.

exposures in Saudi Arabia (Powers *et al.* 1966; Powers 1968), where the reference section (N24°57'48", E46°11'29") consists of a lower wackestone to packstone succession, 94.4 m thick, and contains colonial corals in the lower part. The upper unit consists of an 18.9 m thick succession of packstones and grainstones. The top of the Hanifa is described by Powers as "marked by a massive bed of oolite-pellet calcarenite". Recent examination of this contact has revealed, in Wadi Birk, an oyster-encrusted, iron-stained surface overlain by a bed containing rounded carbonate pebbles of the basal Jubaila (Franz Meyer, oral communi-cation). In the roadside exposures west of Riyadh, the top of the Hanifa Formation is characterised by thin beds of coated pelloidal grains with abundant nerineid gastropods.

Regional mapping by Vaslet *et al.* (1983, 1984a and b, 1991) and Manivit *et al.* (1984) has enabled subdivision of the Hanifa Formation into two members as shown in Figures 1 and 3. The Hawtah Member, also termed H1, was measured as being 57 m thick and abruptly overlies the Tuwaiq Mountain Formation, and begins with a yellow clayey limestone containing a brachiopod fauna, and continues with more indurated beds of gray

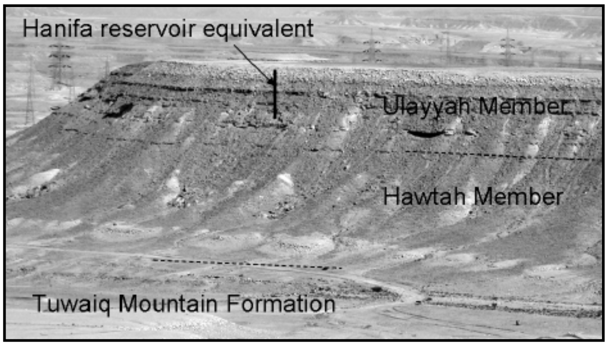



Fig. 3. Hanifa Formation exposed west of Riyadh, on the north side of the Mecca-Riyadh highway. Note the interpreted Hawtah and Ulayyah members and, at the top in rectangle, the approximate location of grainstones equivalent to the Hanifa Reservoir. The wadi (valley) floor coincides with the Tuwaiq Mountain and Hanifa Formation contact. The top of the exposure is the top of the Hanifa Formation.

bioclastic limestone and nodular limestone with corals and ammonites. It is mud-dominated, and forms the characteristically recessive lower slopes of the escarpment. The top of the Hawtah Member is formed by an oyster-rich bed informally termed the "*Nanogyra* lumachelle" (Vaslet *et al.* 1983, 1984a and b). The Ulayyah Member, also termed H2, is 71 m thick, is grainier than the Hawtah, and the contact is placed at the base of a series of brown, cross-bedded, pelletoid and bioclastic packstones/grainstones. Vaslet *et al.* (1983) describe the Ulayyah Member "with a carbonate-pebble conglomerate base filling channels in the Hawtah Member", an observation that is critical evidence to support the presence of a sequence boundary between both members. The Ulayyah Member forms resistant cliffs of the upper escarpment and contains a greater proportion of calcareous algae, stromatoporoids and corals and is considered to represent the Hanifa highstand. Le Nindre *et al.* (1990a) and Manivit *et al.* (1990) have described red-stained surfaces at the top of the Hanifa Formation, in addition to reworking at the base of the Jubaila Formation. The topmost beds of the Ulayyah in outcrop display abundant coated gastropods of *Nerinea* sp.

The maximum duration of the Hanifa Formation would be 5.5 Ma, based on the recently revised absolute time scale of Gradstein *et al.* (2004), and would thus qualify as a third order sequence following the criteria of Goldhammer *et al.* (1990), but not with the 2.0-2.8 Ma duration estimated by Matthews and Frohlich (2002). This estimated duration of the Hanifa Formation compares well with the 4.86 Ma duration estimated by Al-Husseini *et al.* (2006) based the Arabian Orbital Stratigraphy (AROS) framework of Al-Husseini and Matthews (2005), using the glacioeustatic driver as explained by Matthews and Frohlich (2002).

## BIOSTRATIGRAPHY

The Oxfordian age of the Hanifa Formation has been determined from exposures using a variety of macrofossils, microfossils and nannofossils. Brachiopods from the Hawtah Member include *Somalirhynchia africana, Somalithyris bihendulensis,* and *Terebratula bicanaliculata* (Manivit *et al.* 1985), and indicate an Early to Middle Oxfordian age. Fischer *et al.* (2001) documents the gastropod fauna of the Hanifa Formation, but these do not provide additional chronostratigraphic information. Almeras (1987) while providing a comprehensive review of the Early and Middle Jurassic brachiopod faunas of Saudi Arabia, did not include the Hanifa. The middle and upper parts of the Hawtah Member are Middle Oxfordian based on the presence of the ammonite *Euaspidoceras* cf. *catena perarmatum* (Vaslet *et al.* 1983; Enay *et al.* 1987) and the nautiloids *Paracenoceras* aff. *arduennense, P. macrum* and *P.* aff. *hexagonum* (Tintant 1987); no Early Oxfordian ammonites have been found and Enay (oral communication, 2006) is convinced that the Early Oxfordian is not present, and dismisses the brachiopod evidence as being significant. Micropalaeontological evidence for age determination is sparse. The absence of the benthonic foraminiferal species *Trocholina elongata* is used to suggest an Oxfordian age, if not environmentally excluded despite the presence of other *Trocholina* species, as this species is common in the underlying Callovian Tuwaiq Mountain Formation (Hughes 2005). The calcareous nannofossil coccolith evidence for age determination from the outcrop samples is not conclusive (Manivit 1987), but recovery from recently drilled shallow cores from the WLBN-1 well in Wadia Laban, west of Riyadh, and the road cut on the Mecca-Riyadh highway, west of Riyadh indicates an Oxfordian age, based on the presence of *Cyclagelosphaera deflandrei, Crepidolithus crassus* and *Watznaueria manivitae*. Of these species, *Cyclagelosphaera deflandrei* and *Watznaueria manivitae* has been found to be of greatest value in the studied wells because they are not present above the Hanifa Formation. This study confirms the previous stratigraphic restriction of *Watzaueria manivitae* to the Hawtah Member (Manivit 1987), and would support an Early

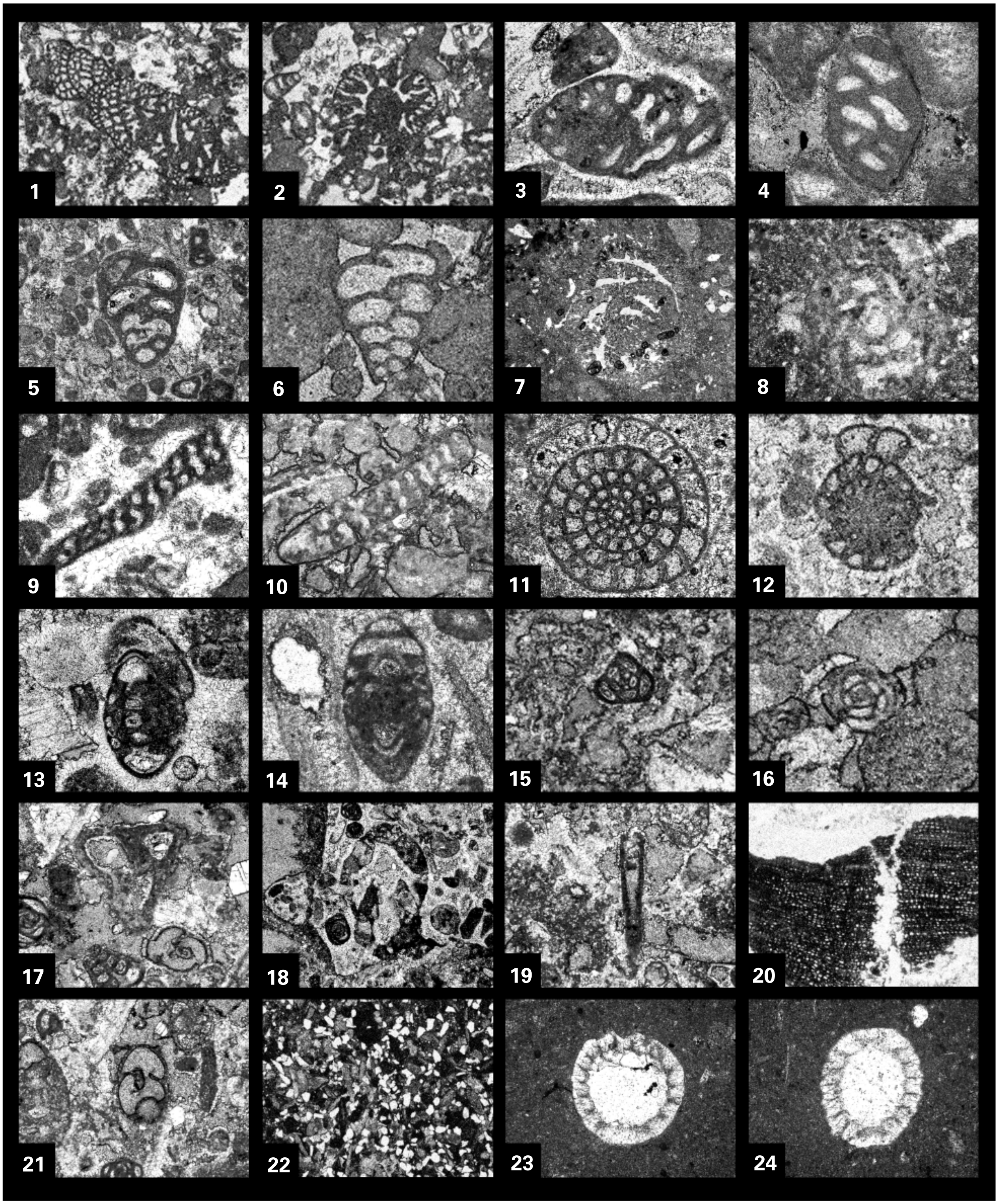
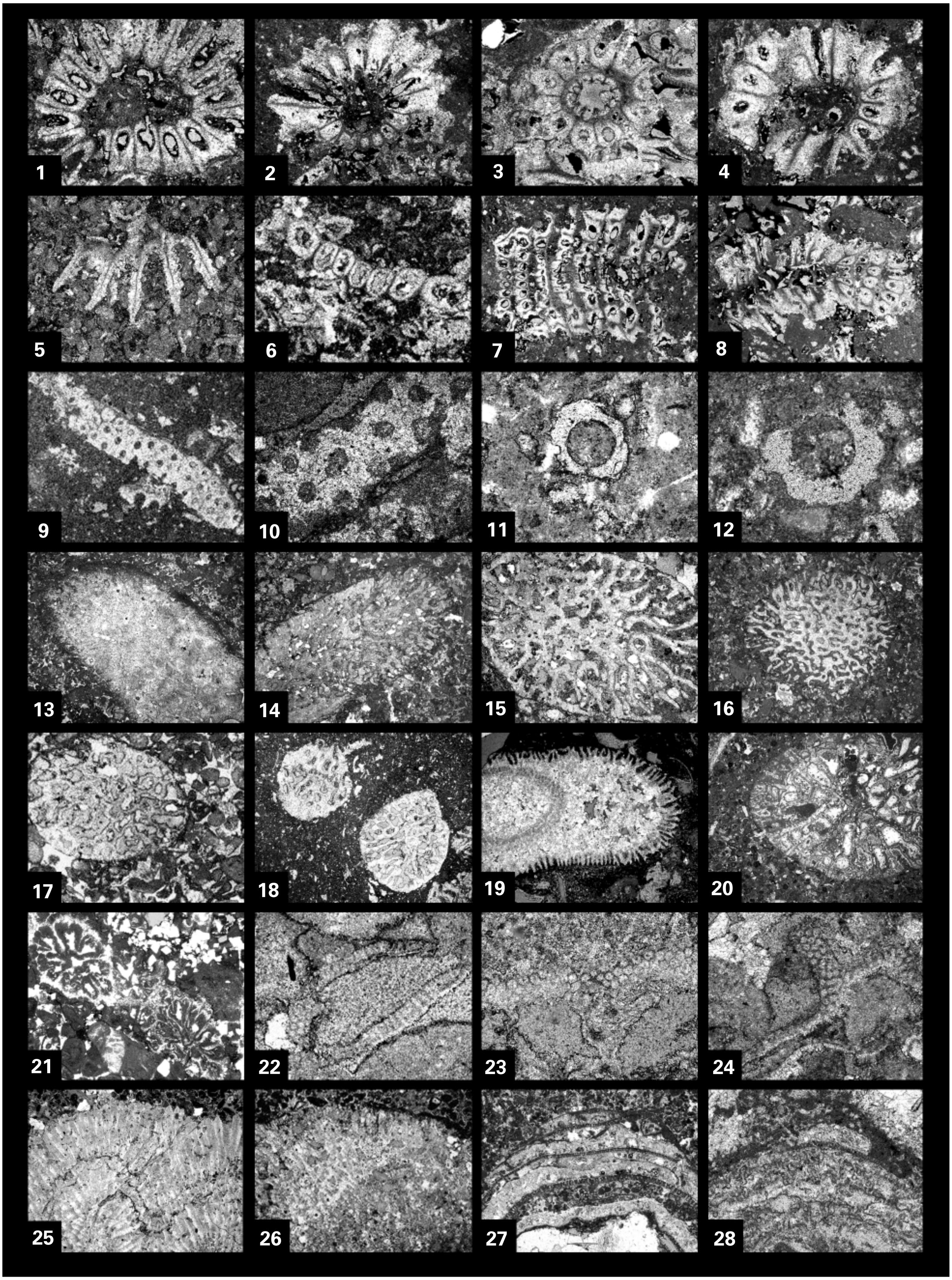



Plate 1
Biocomponents of the "foraminiferal biofacies", width of image given as (mm) after each image description: 1-2 – *Kurnubia palastiniensis* (Henson) (2 mm); 3-4 – *Palaeopfenderina salernitana* (Sartori and Crescenti) (0.8 mm); 5-6 – *Redmondoides lugeoni* (Redmond) (0.8 mm); 7-8 – *Alveosepta jaccardi* (Schrodt) (2 mm); 9-10 – *Levantinella egyptiensis* Fourcade, Mouty and Teherani (0.8 mm); 11-14 – *Nautiloculina oolithica* (Mohler): 11-12 – axial equatorial sections (0.8 mm), 13-14 – transverse sections (0.8 mm); 15-16 – *Quinqueloculina* spp. (0.8 mm); 17 – *Tritaxia* sp. (0.8 mm); 18 – *Reophax* sp. cf. *horridus* (Schwager) (2 mm); 19 – *Aeolisaccus kotori* Radoicic (0.8 mm); 20 – wood fragment (4 mm); 21 – *Bulimina* sp. (0.8 mm); 22 – quartz-rich packstone (4 mm); 23-24 – Charophyte oogonia (0.8 mm).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Oxfordian age for this member (Bown 1998), although the age assignment of this locally-defined species has been calibrated with evidence that still remains questionable, as discussed above.

The Ulayyah Member is Late Oxfordian in its basal part, based on the presence of *Paracenoceras* aff. *sulcatum* (Tintant 1987). The coccolith *Stephanolithion bigotii*, of Oxfordian to Early Kimmeridgan age, is present within the maximum flooding zone, together with an influx of *Ellipsagelosphaera britannica* and *Lotharingius crucicentralis*. *Lotharingius crucicentralis* is not younger than intra-Late Oxfordian (Bown 1998). The common and consistent presence of the *Alveosepta jaccardi* (Schrodt) throughout the Ulayyah Member provides a Late Oxfordian age (Manivit *et al.* 1984; Manivit *et al.* 1985; Hughes 2004c), although rare specimens have been reported by Manivit *et al.* (1985) in the Hawtah. A Late Oxfordian age has been assigned to part of the Ulayyah Member based on brachiopods (Boullier, in Manivit *et al.* 1990) while upper part of the Member yielded echinoid faunas including *Pygurus smelthei* and *Polycyphus parvituberculatus* (Clavel, in Manivit *et al.* 1985, 1990) that suggest an Early Kimmeridgian age (?Hypselocyclum Zone).

## BIOCOMPONENTS

The Hanifa Formation has yielded a variety of biocomponents in thin section, including microfossils and numerous macrofosssil fragments, the most representative being illustrated in Plates 1-3. Variations in their relative abundance and composition provide significant information regarding the variations in the depositional setting of the Hanifa sediments. Semi-quantitative micropalaeontological analysis of thin-sections has revealed a number of discrete biofacies and these have been used to interpret regional variations in the depositional setting. The information gained from the sedimentological analysis has been integrated with the micropalaeontological data to determine the depositional environments for the studied sections. Grainstones are typically found in association with the stromatoporoid bearing sediments, but are also found within the shallow lagoon sediments. Mudstones and wackestones are typical of the intra-shelf basin depositional facies, and packstones are found associated with the *Clypeina*-bearing sediments typical of the deeper lagoon. In addition, the relative abundance and diversity of coccolith nannofossils has been used as an indicator for the degree of open marine influence. The significance of ascidian spicule calcareous nannofossils has yet to be fully understood in terms of palaeoenvironmental significance.

Foraminifera are well-represented in most samples, with high recovery and high diversity, except for those deposited in the basinal setting where diversity is very low. Agglutinated foraminifera predominate over less well-represented miliolid and calcareous species. The foraminifera have been the most useful, in combination with the stromatoporoids and calcareous algae, for discriminating subtle differences in the interpreted palaeoenvironment. Foraminiferal aspects of the Hanifa Formation in well samples and from outcrop have been published by Hughes (2004a, b, c; 2005) and presented by Dhubeeb and Hughes (2005).

Dasyclad algae are well-represented in many of the studies sections, and are mostly assignable to *Pseudoclypeina distomensis* Barattolo and Carras (Hughes 2005). These delicate forms are interpreted to occupy moderately deep, normal salinity parts of the lagoon, where low energy conditions predominate (Banner and Simmons 1994). These forms are typically preserved as disaggregated fronds, except in the northwestern part of the study area, where entire stems and branches are preserved.

Brachiopod and echinoid fragments are common components of the Hanifa carbonates, of which the latter are present both as plate fragments and discrete spines. The smaller, highly “spoked” spines seem to be preferentially concentrated within the

Plate 2
Biocomponents of the “dasyclad algal biofacies” (images 1-12), “*Cladocoropsis* biofacies” (images 13-24) and “encrusting/domed stromatoporoid biofacies” (images 25-28), width of image given as (mm) after each image description. 1-10 – *Pseudoclypeina distomensis* Barattolo and Carras: 1 – transverse section of thallus (0.8 mm), 2-5 – transverse sections of thallus (2 mm), 6 – sagittal section of thallus (2 mm), 7-8 – axial sections (4 mm), 9 – transverse section of stem (8 mm), 10 – transverse section of stem (0.8 mm); 11-12 – *Salpingoporella dinarica* moulds (0.8 mm); 13-18 – *Cladocoropsis mirabilis* Felix oblique axial sections of branch (8 mm): 15 – transverse section of branch (4mm), 16 – transverse section of branch (8mm), 17 – transverse section of branch (4 mm), 18 – transverse section of branch (8 mm); 19 – branched coral, axial section (8 mm); 20-21 – branched coral: 20 – axial section (8 mm), 21 – transverse section (4 mm); 22 – *Thaumatoporella parvovesiculifera* (Raineri) (8 mm); 23-24 – *Thaumatoporella parvovesiculifera* (Raineri) (0.8 mm); 25-26 – domed stromatoporoid (8 mm); 27-28 – domed stromatoporoid (0.8 mm).

mudstones and wackestones. Ostracods are rare. Monaxon sponge spicules are present within certain wackestones and packstones of the lagoonal biofacies, but are also well-represented in the mudstones and wackestones that are interpreted to represent the basinal sediments. In the basinal setting, the monaxon spicules are accompanied by tetraxon forms, and are typically associated with sparse microfaunal assemblages.

Stromatoporoids present within the Hanifa Formation include unspeciated encrusting, dome-shaped forms that resemble *Burgundia ramosa* Pfender, based on the criteria of Wood (1987) and fragments of branched forms here assigned to *Cladocoropsis mirabilis* Felix. From work on the preferred palaeoenvironment of both forms in the Saudi Arabian Middle and Upper Jurassic carbonates (Hughes 2004c), together with the limited published data on Tethyan stromatoporoid carbonates (Leinfelder 2001; Leinfelder *et al.* 2005), it is concluded that the stromatoporoid morphotypes indicate a response to variations in environmental energy levels. The existing model proposes that the domed stromatoporoids have adapted to higher energy conditions such as would be expected on the oceanward flanks of a bank margin. As with branched corals such as *Acropora cervicornis, A. palmata* and species of *Porites* and *Goniolithum*, the branched stromatoporoids would be expected to occupy the relatively lower energy, not necessarily deep, relatively sheltered region within the lagoon, on the leeward side of the stromatoporoid bank. A "back-reef" environment has been suggested for branched stromatoporoids by Turnsek *et al.* (1981).

Corals are, when compared to stromatoporoids, poorly represented in the Hanifa. The relative low abundance of corals has been attributed by Leinfelder *et al.* (2005) to significantly higher temperatures over Arabia, based on the palaeoclimate model of Sellwood *et al.* (2000). The inferred presence of considerably overheated waters within a climatic belt with annual mean surface water temperatures exceeding 28°C may explain the occurrence of pure stromatoporoid assemblages, as they are considered to have a greater tolerance to warmer waters; their tolerance to hypersaline conditions is not fully understood. As filter feeders with minimal photosynthetic requirements, the inferred ability of stromatoporoid sponges to occupy muddier waters beyond the tolerance range of corals may be another significant factor worthy of consideration. It is of interest to speculate on the effects of the Middle Oxfordian thermal minimum and the warming stage of 3-4°C during Middle to the Late Oxfordian, as described by Lecuyer *et al.* (2003). Such data require reconciliation with the evidence for glacial conditions in the Late Callovian as suggested by Dromart *et al.* (2003).

## BIOFACIES

Inspection of the micropalaeontological and macropalaeontological assemblages has revealed a preferred coincidence of certain species and other biocomponents within the studied part of the Hanifa Formation. These groups of biocomponents are interpreted to represent a response to variations in environmental conditions, mostly related to hydraulic energy levels and possibly light penetration. Five biofacies have been determined for the upper Ulayyah Member in this regional study, and are based on the coexistence of selected, environmentally-sensitive and significant species and their relative abundance. The recognition of such biofacies has been instrumental in constructing the depositional map for the upper Hanifa across the entire region (Fig. 2).

### Foraminiferal biofacies (A)

Biofacies A (Pl. 1) is characterised by high foraminiferal species diversity and recovery, in which the main component species include *Kurnubia palastiniensis* (Henson), *Redmondoides lugeoni* (Redmond), *Alveosepta jaccardi* (Schrodt), *Levantinella egyptiensis* Fourcade, Mouty and Teherani, previously misassigned to the Cretaceous species *Mangashtia viennoti* (Kaminsky 2004), *Quinqueloculina* spp., *Palaeofenderina salernitana* (Sartori and Crescenti) and *Nautiloculina oolithica* (Mohler) with scattered coarsely agglutinated forms that resemble *Reophax horridus.* It should be noted that rare, robust specimens of *Lenticulina* spp. are found within this biofacies, and testify to the moderately wide palaeobathymetric tolerance of this species during the Late Jurassic. This genus is also present within the low diversity deep marine biofacies described below, where its association with triaxon and tetraxon spicules, *Bositra buchi* (Roemer) and calcareous dinocysts confirm a deep marine setting. Brachiopod and echinoid debris are common throughout. Stromatoporoids and dasyclad algae are absent, but the above species are

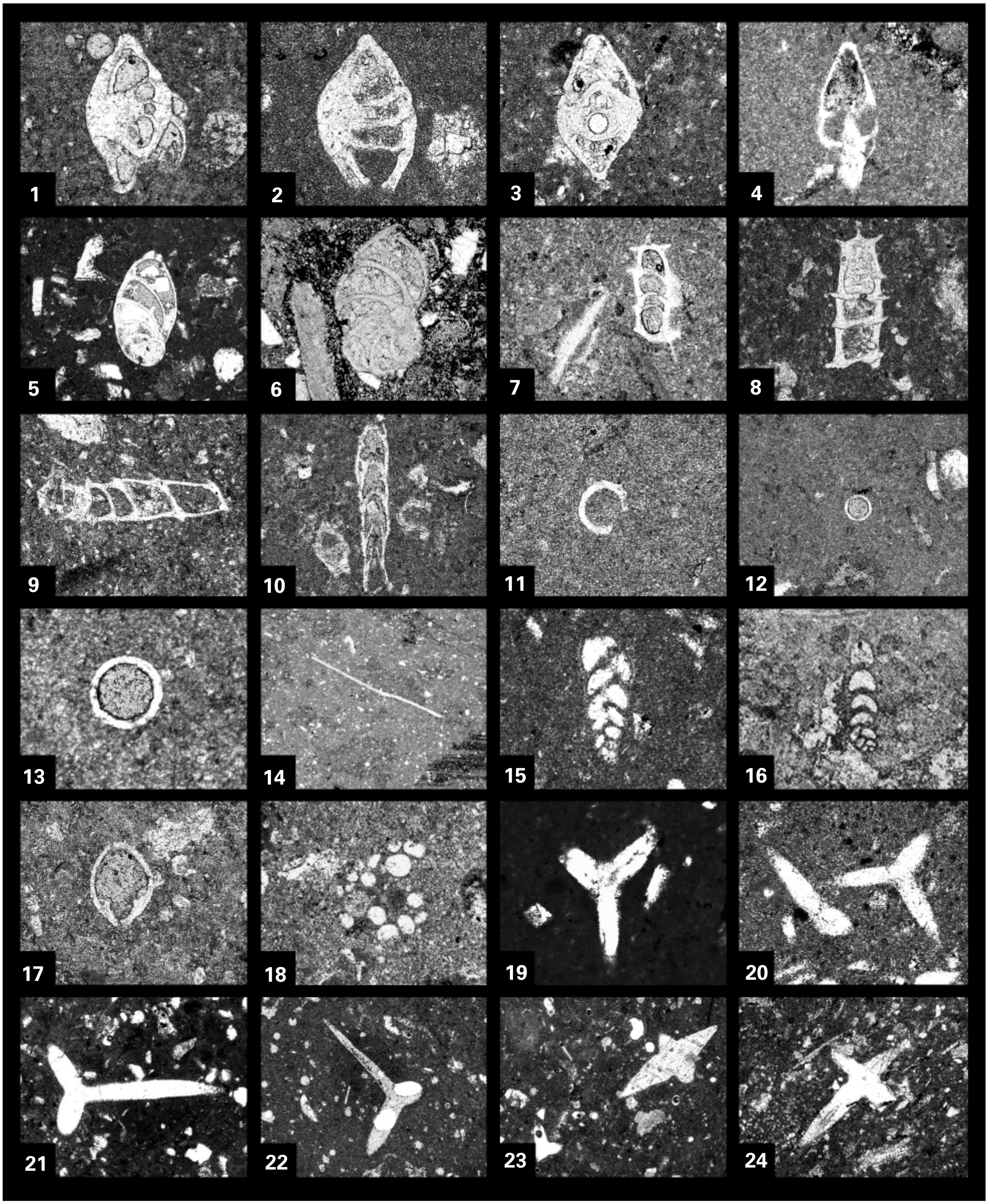


Plate 3

Biocomponents of the "*Lenticulina* and spicule biofacies", width of image given as (mm) after each image description. 1-4 – *Lenticulina sublenticularis* (Schwager) (0.8 mm); 5-6 – *Astacolus* cf. *vacillantes* Espitalie and Sigale (0.8 mm); 7-9 – *Nodosaria* spp. (with rimmed suture) (0.8 mm); 10 – *Nodosaria* sp. (0.8 mm); 11-13 – calcareous dinocysts (0.8 mm); 14 – *Bositra buchi* (Roemer); 15 – *Bolivina* sp. (0.8 mm); 16 – *Bigenerina* sp. (0.8 mm); 17 – juvenile brachiopod (0.8 mm); 18 – spicule cluster (0.8 mm); 19-20 – triaxon sponge spicules (0.8 mm); 21-22 – triaxon sponge spicules (2 mm); 23-24 – tetraxon sponge spicules (2 mm).

also found together with such forms in the deeper lagoon and back-bank facies. At certain localities, such as in the northwest, quartz grains and fragments of wood are present that, together with charophyte oogonia, provide evidence for proximity to a source of terrestrially-derived sediment.

**Foraminiferal-dasyclad biofacies (B)**

Biofacies B (Pl. 2: 1-12) consists of a combination of most of the biofacies described for Biofacies A, but accompanied by dasyclad algae. The well-preserved forms indicate that there has been little sediment transport and disturbance, as these fragile forms are easily disarticulated. Moderately deeper or protected conditions within the lagoon are interpreted from the lower energy conditions, possibly below fair-weather wave base.

**Cladocoropsis biofacies (C)**

Biofacies C (Pl. 2: 13-24) is characterised by the presence of the branched stromatoporoid assigned to *Cladocoropsis mirabilis* Felix together with the encrusting algal form *Thaumatoporella parvovesiculifera* (Raineri) and rare branched corals. Branched stromatoporoids are considered to have required moderately low energy conditions in order to avoid breakage, and are considered to have best developed in the distal part of the lagoon, in the lee of a bank, where the direct higher wave energy would be dampened. Branched corals occupy a similar niche today, and their distribution has provided support to the palaeoenvironmental interpretation of these extinct stromatoporoids. The branching growth probably represents a response to the need for accelerated vertical growth within an area where the sedimentation rate was relatively high and this was, therefore, a survival strategy. It is noted here that the branching tendency of many corals appears to be a strategy for rapid regrowth in an area where fragments may be prone to breakage due to periodically elevated energy conditions (Leinfelder, oral communication; Lirman 2000; Wallace 2004). Biocomponents of Biofacies A and B are also present within this facies.

**Encrusting/domed stromatoporoid biofacies (D)**

Biofacies D (Pl. 2: 25-28) is characterised by the presence of the massive, domed and encrusting stromatoporoid forms, with comparatively rare corals. These forms are considered to have best developed in association with high energy grainstone banks with ooids, where the direct wave energy would be effective in inhibiting most biological activity. Domed encrusting corals occupy a similar niche today, and their distribution has provided support to the palaeoenvironmental interpretation of these extinct stromatoporoids.

**Lenticulina-spicule biofacies (E)**

Biofacies E (Pl. 3) is characterised by the presence of smaller foraminifera species that are normally considered to occupy deeper marine environments. These include species resembling *Lenticulina sublenticularis* (Schwager) and *Astacolus vacillantes* Espitalie and Sigale*, Nodosaria* spp.*,* various polymorphinids and agglutinated forms such as *Bigenerina* spp. and the ubiquitous *Kurnubia palastiniensis* (Henson). Rare valves of the pelagic bivalve *Bositra buchi* (Roemer) are also present within this biofacies. In addition, this fine-grained, mudstone and wackestone lithofacies is characterised by the presence of common to locally abundant and various sponge spicules that include monaxon, triaxon and tetraxon types. This biofacies is confined to the central part of the study area. Barren mudstones are also included within this biofacies.

## PALAEOENVIRONMENTAL INTERPRETATION

The Hawtah and Ulayyah members of the Hanifa Formation represent two third order sequences (Al-Husseini *et al.* 2006) of which the upper part of the Ulayyah Member, here studied, represents late highstand conditions. Palaeoenvironmental subdivisions based on the various biofacies range, in order of water depth control related to increasing distance offshore, from foraminiferal lagoon, *Clypeina/Pseudoclypeina* lagoon, *Cladocoropsis* (branched stromatoporoid) back-bank/lagoon, stromatoporoid bank complex to foraminiferal-spicule intra-shelf basin.

Fig. 2 is an interpretation of the distribution of palaeoenvironments, based on characteristic biofacies and lithofacies. Facies boundaries have been drawn between wells that have different biofacies. An orderly biofacies progression is evident, grading from proximal lagoon, to deeper dasyclad lagoon, to back-bank *Cladocoropsis* lagoon and the higher energy domed stromatoporoid–ooid grainstone shoals. Where study well density is relatively high, delineation of such environmentally-controlled biofacies is relatively easy, such as in the north-west part of the study area. Towards the south, however, the wells are widely spaced and the placement of the facies boundary lines is more tentative. In the south-east, the data by Strohmenger *et al.* (2004) assisted definition of these palaeoenvironments.

The overall picture is one in which the study area consists of an intra-shelf basinal complex that is flanked by shallow lagoons on the west and south sides. The margin of the intra-shelf basin complex is defined by the change from deep marine wackestones and mudstones to stromatoporoid grainstones that accumulated on the high energy shoal complex. The east flank of the basin complex is poorly constrained, and relies upon the published work by de Matos and Hulstrand (1995) and Strohmenger *et al.* (2004). For the region adjacent to Qatar, Droste (1990) describes the Hanifa as consisting predominantly of organic rich mudstones with minor evaporites that suggests that deep, restricted marine conditions prevailed. The width of the stromatoporoid complex is a function of the combination of Biofacies C and D, because the separation of the domed stromatoporoid grainstone facies and the back-bank *Cladocoropsis* grainstone and packstone facies is expected to be transitional and difficult to locate without closer well spacing. The width of the combined branched and domed/encrusting stromatoporoid belt is remarkably wide along the northwest flank of the basin complex, and contrasts markedly with the interpreted narrow belt that flanks the southwesterly corner of the interpreted elongate arm of the basin.

For the first time, a broad interpretation of the palaeoenvironmental variations of the Hanifa Formation within Saudi Arabia has been generated that has been based on objective, rock-based evidence. There is, of course, much room for future refinement of this depositional model by insertion of additional wells. The depositional model provides considerable information for the palaeogeographers as well as for the hydrocarbon explorationists. Delineation of a grainstone facies belt with reservoir potential provides possible exploration targets once their location has been further refined by seismic data. The presence of mud-dominated intra-shelf basin facies will allow geochemists to delimit possible source rock accumulation locations, as the Hanifa Formation and the underlying Tuwaiq Mountain Formation are known to have considerable source rock potential (Carrigan *et al.* 1995).

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