Saudi Arabian Late Jurassic and Early Cretaceous agglutinated foraminiferal associations and their application for age, palaeoenvironmental interpretation, sequence stratigraphy, and carbonate reservoir architecture

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ABSTRACT

Saudi Arabian Upper Jurassic and Lower Cretaceous carbonates constitute the world's largest hydrocarbon reservoirs. Optimum exploitation of these reservoirs is highly dependent upon an understanding of intra-reservoir flow layers that are mostly related to primary depositional layers. Within these apparently monotonous carbonate reservoirs, such stratification is not readily discernible by logs or lithofabric alone but often can be resolved by integration with closely-spaced, semi-quantitative micropalaeontological data derived from core samples and measured exposures.

The Hanifa, Jubaila and Arab Formations represent an extensive development of Late Jurassic (Oxfordian - Tithonian) platform carbonates. Palaeoenvironmental interpretation of the agglutinated foraminifera *Kurnubia palastiniensis* and *Alveosepta jaccardi* from the Hanifa and Jubaila Formations and of *Kurnubia palastiniensis, Alveosepta jaccardi, Mangashtia viennoti, Pfenderina salernitana* and *Trocholina alpina* in the Arab-D suggests gradually shallowing conditions passing from middle neritic through to shallow inner neritic water depths. A thick anhydrite unit of possible salina origin overlies the carbonates and terminates this particular depositional megacycle.

The Yamama and Shu'aiba Formations are of Early Cretaceous, Berriasian-Valanginian and Aptian age respectively. The Yamama Formation displays low microfossil diversity with three acme events of well-represented *Pseudocyclammina lituus*, together with *Trocholina elongata* and the dasyclad alga *Salpingoporella annulata*. The vertical succession of assemblages suggests a gradually shallowing depositional environment. The Shu'aiba Formation is of Early Aptian age with rich biocomponent assemblages that are dominated by rudist bivalves, calcareous algae and benthonic foraminifera. The agglutinated foraminifera *Palorbitolina lenticularis, Praechrysalidina infracretacea, Debarina hahounerensis* and *Vercorsella arenata* are moderately well represented at certain levels. Localised hedbergellid planktonic foraminifera provide evidence for regional marine transgressions.

The apparently cyclic distribution of the agglutinated assemblages is considered within a sequence stratigraphic context. Identification of intra-reservoir depositional layers has been facilitated by an integration of the micropalaeontological data with gamma and density logs and sedimentology.

INTRODUCTION

The Upper Jurassic and Lower Cretaceous lithostratigraphy of Saudi Arabia includes a variety of lithologies, ranging from carbonates, siliciclastics and evaporites. The Hanifa, Jubaila, Arab, Yamama and Shu'aiba Formations of Saudi Arabia represent extensive, relatively thick carbonate accumulations of stable shelf origin. As they form the world's largest hydrocarbon reservoirs they are of great economic and strategic importance. The recent detailed micropalaeontological analysis is an attempt to improve understanding of the reservoir layering and thereby optimise economic exploitation of these reservoirs. As sedimentary particles, fossils are known to be indicators of the dynamics of sedimentation and depositional environments that may aid in the recognition of sequences and their boundaries.

The Hanifa Formation forms the Hanifa Reservoir, the upper Jubaila and Arab-D carbonates together form the Arab-D Reservoir, the Yamama Formation forms the Upper Ratawi Reservoir and the Shu'aiba forms the Shu'aiba Reservoir. In this study, the Hanifa, Jubaila and Arab Formations have been sampled from the Tuwaiq Escarpment exposures and from the subsurface in the Ghawar Field; samples from the Yamama and Shu'aiba Formations are derived from the subsurface of the Safaniya and Shaybah Fields respectively.

This investigation has led to the discovery that the locally rich, though low diversity, palaeontological components display certain associations. Agglutinated foraminifera constitute a considerable proportion of these assemblages and the study offers new information on their preferred faunal and floral associations. Despite the abundance of published

In: Hart, M.B., Kaminski, M.A., & Smart, C.W. (eds) 2000. Proceedings of the Fifth International Workshop on Agglutinated Foraminifera. *Grzybowski Foundation Special Publication*, 7, 149-165.

data on Middle Eastern foraminifera, there is minimal information concerning the palaeoenvironmental preferences of Jurassic and Cretaceous Middle East benthonic foraminifera from shallow carbonate environments, with the exception of Banner & Simmons (1994). Upper Jurassic and Lower Cretaceous reservoir rocks crop out extensively within the Middle East and are, therefore, readily available for analysis. The reservoir rocks have been cored extensively and are also available for study. There is, however, a lack of detailed information concerning the intra-reservoir distribution of biocomponents, and negligible information on the environmental factors that controlled biocomponent distribution. Certain hydrocarbon reservoirs with high production rates initially submit to exploitation without the need for micropalaeontological interpretation beyond the initial pioneer studies designed specifically related to providing gross stratigraphic relationships. Further, the computerisation of subsurface data has facilitated seismic and wireline log interpretation by development geologists so that the detailed results of micropalaeontological data have been ignored. The search for a solution to unexpected reservoir flow behaviour in mature carbonate reservoirs has recently necessitated an improved understanding of their internal stratal architecture. With the advent of sequence stratigraphy, the simple layer-cake approach to subdividing carbonate reservoirs into equi-thickness hydrocarbon flow layers has become questionable. It is with these problems in mind that there has been a resurgence in micropalaeontological contribution, within certain oil companies, as a necessary tool for depositional environment interpretation, layering schemes for reservoir rocks, depositional layer correlation, integration with seismic interpretation, wireline log correlation and reservoir modelling.

The present study has revealed that foraminifera and associated microfauna and microflora display well-defined and limited stratigraphic positions within the Upper Jurassic and Lower Cretaceous carbonates of Saudi Arabia. These associations may be explained in terms of sequence stratigraphy and it is this approach that is being used to define depositional layers and potential hydrocarbon flow layers in extensive Saudi Arabian oil fields. The Hanifa, Jubaila, Arab-D, Yamama and Shu'aiba Formations are carbonates that have received such micropalaeontological attention in the past few years and the following discussion will illustrate the various ways in which improved understanding of the depositional layering and palaeoenvironment has resulted from such studies.

PREVIOUS WORK

Only a few publications exist on the shallow marine agglutinated foraminifera of Late Jurassic age and these include Derin & Reiss (1966), Derin & Gerry (1975), Pelissie *et al.* (1985) and Sartorio & Venturini (1988). Middle Eastern shallow marine carbonate agglutinated foraminifera have been considered by Redmond (1964, 1965), Powers (1962), Bozorgnia, (1964), Banner & Highton (1990), Banner & Whittaker (1991), Banner *et al.* (1990), Simmons & Al-Thour (1994), de Matos (1994), and Whittaker *et al.* (1988). Middle Eastern Early Cretaceous foraminifera from selected formations have been described by Simmons & Hart (1987), Simmons (1994) and Hughes (1997; 1998a; 1998b).

. Precise palaeoenvironmental interpretation of the microfaunas is precluded by the absence of extant counterparts. Nevertheless, numerous studies have suggested preferred palaeoenvironments for Late Jurassic and Early Cretaceous benthonic foraminifera and associated fossils, of which Banner & Simmons (1994) provide the best attempt to objectively assign palaeobathymetric ranges for certain Early Cretaceous forms based on light-penetration predictions for the Early Cretaceous seas. Other attempts include Derin & Reiss (1966), Pelissie and Peybernes (1982), Pelissie *et al.* (1985), Brooks (1985) and Sartorio & Venturini (1988).

METHODOLOGY

The results here presented are based on an analysis of over 3000 core plugs and field samples. Core plugs and field samples have been studied for the Arab Reservoir, but only core plugs were available for analysis from the Hanifa, Yamama and Shu'aiba Formations. Core plug analysis has been at an average of 6-inch spacing. The Arab-D and upper part of the Hanifa carbonates have been sampled from the extensively cored sections in the Ghawar Field. The lower part of this section is well exposed along the Tuwaiq Escarpment and especially within Wadi Nisah. The Yamama carbonates have been analysed only in cores from the subsurface in the Safaniya Field. The Shu'aiba Formation is poorly exposed in Saudi Arabia (Vaslet *et al.*, 1991) and analysis has been confined to core plug thin sections.

Foraminiferal identification has been assisted with reference to Loeblich & Tappan (1987), Sartorio & Venturini (1988) with calcareous algae being identified using Elliott (1960; 1968); Granier (1986), Okla (1991), Bodrogi *et al.* (1993) and Schindler & Konrad (1994). All biocomponents have been identified and recorded semi-quantitatively, using a four-category abundance scheme. The data, with relative diversity, was plotted on Excel spreadsheets and converted to true vertical scale displays with gamma, density, neutron, porosity and permeability traces.

LITHOSTRATIGRAPHY

The following brief lithostratigraphic descriptions (Figure 1) of the Upper Jurassic and Lower Cretaceous carbonates are based on Powers (1968) and Vaslet *et al.* (1991). The most recently available age determinations are also included in this section, especially the reappraisal of benthic foraminifera by Whittaker *et al.* (1998).

AGE	FORMATION	RESERVOIR
Aptian	Shu'aiba	Shu'aiba
Barremian	Biyadh	Zubair
Hauterivian	Buwaib	Buwaib
Valanginian	Yamama	Ur. Ratawi
Valanginian - Berriasian	Sulaiy	Lr. Ratawi
Tithonian	Hith	Manifa
Tithonian - Kimmeridgian	Arab	Arab A - D
Lr. Kimmeridgian	Jubaila	Arab D -Jubaila
Lr. Kimmeridgian – M. Oxfordian	Hanifa	Hanifa

Figure 1.. The lithostratigraphic position of the Upper Jurassic to Lower Cretaceous Formations and reservoirs of Saudi Arabia.

The Hanifa Formation in the studied subsurface samples includes basal calcareous shales and black impure limestones, cream, grey and brown aphanitic and oolite-pellet, packstone, with a total thickness of 180m. Less resistant mudstones and wackestones of the Jubaila Formation conformably overlie the oolitic calcarenites. In the Riyadh area, the Formation is subdivided into a lower Hawtah Member (57 m thick) and an upper Ulayyah Member (71 m thick) (Vaslet *et al.*, 1991).

The Jubaila Formation is defined as a cream to yellow, tight, partially dolomitised aphanitic limestone with occasional beds of pellet-skeletal calcarenitic limestone and tightly cemented calcarenite, with a total thickness of 145 m. The type section is divided into two informal units, J1 (56 m thick) and J2 (60 m thick) (Le Nindre *et al.*, 1990), with the contact between this formation and the overlying Arab Formation placed at the transition upwards into clean, brown, skeletal calcarenite.

The Arab Formation is composed of four Members, termed D to A in ascending order, each of which includes a carbonate - anhydrite couplet; the uppermost anhydrite, that would normally be considered to be the A anhydrite, is called the Hith Formation. The definition of the Arab Reservoir causes additional confusion as it includes the uppermost carbonates of the Jubaila Formation. The top of the Hith Formation is unconformably overlain by the Sulaiy Formation, which is in turn overlain by the Yamama Formation. Discussions continue regarding the sequential relationship of these anhydrite beds to the underlying carbonates.

The Yamama Formation conformably overlies the Sulaiy Formation, the contact of which is marked by a change from cream, bioclastic, bioturbated limestone to yellowish, clayey limestone interbedded with brown bioclastic calcarenite. The Yamama Formation is 45.5 m thick at the type locality and consists of alternating calcarenite with thin interbeds of aphanitic and calcarenitic limestone. Powers (1968) described the reference section but additional recent investigations include those of Vaslet *et al.* (1991) and Shebl & Alsharhan (1994). The latter study outlines six microfacies associations from the Al Qusay 'an upland exposure, but these have no relationship to the detailed microfacies seen in the currently studied subsurface cored material. In the field, Vaslet *et al.* (1991) describes the upper part of the Yamama Formation as being very bioturbated and interrupted by several hardgrounds.

The Shu'aiba Formation is defined as a chalky, dolomitic limestone up to 100 m thick. In Saudi Arabia it overlies sandstones of the Biyadh Formation and its limestone equivalent and is overlain by the shales of the Nahr Umr Formation of the Wasia Group. Siliciclastics of the Biyadh Formation are replaced by carbonates in the Shaybah region of Saudi Arabia, the Emirates and Oman.

AGE

Age determination has been based mostly on macrofossils from exposures in Saudi Arabia (Enay, 1987). The stratigraphic ranges of benthonic foraminifera of the Middle East have recently been reviewed and upgraded by Whittaker *et al.* (1998). Husseini (1997) provides a recent review of the varied publications concerning the age of the Jurassic carbonates of the Arabian Gulf. Of the carbonates considered in the present study, planktonic foraminifera have only been recovered from parts of the Shu'aiba Formation, in contrast to lithostratigraphic equivalents in Oman and the United Arab Emirates. Absolute ages based on thin section are difficult to determine because the lithostratigraphic units are below the stratigraphic resolution provided by benthonic foraminifera.

Hanifa Formation (Middle Oxfordian - Early Kimmeridgian)

A Middle Oxfordian to Early Kimmeridgian age has been proposed for the Hanifa Formation by Vaslet *et al.* (1991). A Middle Oxfordian age is provided for the Hawtah Member by the ammonite *Euaspidoceras* gr. *catena-perarmatum* and the large nautiloid *Paracenoceras* aff. *hexagonum*. Lower to Middle Oxfordian brachiopods include *Somalirhynchia africana*, *Somalithyris bihendulensis* and *Rhynchonella hadramautensis*. Nautiloid and echinoid faunas in the Ulayyah Member suggest a Late Oxfordian to Early Kimmeridgian age, the boundary between the Oxfordian and the Kimmeridgian being placed at the Hawtah-Ulayyah contact (Vaslet *et al.*, 1985; Tintant, 1987; Manivit, 1987). Stromatoporoid evidence (Toland, 1994), however, indicates a Middle to Late Oxfordian age for the Hanifa Formation equivalent in the Emirates, based on the presence of *Promillepora pervinquiri*, *Acrostroma damesini*, *Steineria somaliensis* and *Shuqraia hudsoni*.

Jubaila Formation (Lower Kimmeridgian)
An Early Kimmeridgian age is assigned to the Jubaila Formation (Vaslet *et al.*, 1991), based on ammonite and brachiopod evidence. The lower half of unit J1 has yielded ammonites that include the Early Kimmeridgian endemic species *Perisphinctes* aff. *jubailensis*.

Arab Formation (Kimmeridgian - Tithonian)
In a review of the Arab Formation, Al-Silwadi *et al.* (1996) indicate a broad Kimmeridgian to Tithonian age, with the Arab-D being confined to the Kimmeridgian, although Al-Hussein (1997) indicates the possibility of the Arab-D ranging from the Kimmeridgian to Tithonian. Whittaker *et al.* (1998), in their review of Middle Eastern formations, place the Arab Formation within the range of Middle Kimmeridgian to the basal part of the Upper Tithonian. The presence of *Pfenderina salernitana* in the uppermost part of the Arab-D member would certainly restrict its age to not younger than Early Tithonian; recognition of the potentially useful *Alveosepta powersi* is difficult within randomly oriented thin sections. The Arab Formation is dated as undifferentiated Kimmeridgian - Tithonian, based on isotope studies of the oxygen ($\partial^{18}O$ = +13.3) and sulphur ($\partial^{34}S$ = +17.1) (Vaslet *et al.*, 1991) in a sample of anhydrite from Dahl Hith, that indicates a latest Jurassic age. The stromatoporoid assemblage is imprecise and includes the first appearance of *Burgundia ramosa* together with most of the Middle - Late Oxfordian species, except for *Actinostromarianina praesalevensis* and *Parastromatopora libani*; an Early Kimmeridgian age is suggested for the Arab-D Member by $^{87}Sr/^{86}Sr$ isotope data (Toland, 1994).

Yamama Formation (Valanginian)
The Yamama Formation was assigned a Valanginian age by Powers (1968) based on the presence of *Everticyclammina eccentrica*, *E. elegans* and *Pseudocyclammina cylindrica*, but these species are now known to be of no refined chronostratigraphic significance. A latest Berriasian to Early Valanginian age is presented by Vaslet *et al.*, (1991) based on the presence of the calcareous nannofossils *Rucinolithus wisei*, *Kokia borealis* and *Nannoconus sabinae* and also on the presence of the echinoid *Pygurus yamamaensis*. Micropalaeontological evidence for the age of the underlying Sulaiy Formation is poor and based mainly on stratigraphic position above the Tithonian age Hith Formation. In the samples currently analysed from Saudi Arabia, calpionellids were apparently environmentally excluded. In Ras Al Khaimah, the onset of 'platform slope' sedimentation is dated as intra-Berriasian, using calpionellids (Toland *et al.*, 1993). The calpionellid species *Calpionella alpina*, *C. elliptica*, *Crassicollaria parvula* and *Calpionellopsis oblonga* in the stratigraphically equivalent Rayda Formation of Oman (Simmons & Hart, 1987; Simmons, 1994; Aziz & El-Sattar, 1997) indicate a Middle Berriasian age equivalent to Zone D1 (Remane, 1985; Rehakova & Michalik, 1997).

Shu'aiba Formation (Aptian)
The Aptian age of the Shu'aiba Formation was originally assigned by Powers (1968), based apparently on stratigraphic position. An Early Aptian age for the Shu'aiba Formation in Oman was suggested by Simmons & Hart (1987) and Simmons (1994), based on *Palorbitolina lenticularis*. An Early to early Middle Aptian age has been provided by Harris *et al.* (1984) and an Early to Middle Aptian age by Alsharhan & Nairn (1986). The age of the Shu'aiba has most recently been reviewed by Witt and Gokdag (1994), in which the Shu'aiba Formation in northern Oman has been assigned an Early to Late Aptian age. The Early Aptian age is based on the presence of *Palorbitolina lenticularis*, *Praeorbitolina cormyi* and *Orbitolina (Mesorbitolina) lotzei* and an Early Aptian rudist association (Masse, 1992). The Late Aptian age is based on the presence of *Orbitolina (Mesorbitolina) texana* and *Orbitolina (Mesorbitolina) parva*. Recent analyses of the rudists (Skelton *et al.*, in press) and foraminifera (Hughes, 1997;, 1998a,b, 1999; Hughes *et al.*, 1999) of the Shu'aiba Formation in the Shaybah Field in Saudi Arabia indicate only an Early Aptian age. Calcareous nannofossil evidence (Varol, *pers. comm.*), however, confirms a Late Aptian age for the upper part of this formation. The rudist assemblages are of typical Early Aptian affinity and include *Glossomyophorus costatus*, *Offneria murgensis* and *Agriopleura blumenbachi*. The Early Aptian species *Eoradiolites plicatus* has not been recorded from the Shu'aiba Formation in the Shaybah Field, but has been identified in Oman (Russell, 1996). Of the orbitolinids, only *P. lenticularis* has been identified from analysis of randomly orientated specimens in thin section.

AGGLUTINATED FORAMINIFERAL ASSOCIATIONS AND PALAEOENVIRONMENTAL INTERPRETATION

As many Mesozoic genera are extinct and displayed unique wall structures, it is difficult to directly apply the environmental preferences of modern forms to assist palaeoenvironmental interpretation. Nevertheless, certain microfossil associations, sedimentology and log traces assist in guiding palaeoenvironmental interpretation as discussed below.

Late Jurassic (Middle Oxfordian - Tithonian)
Within the Hanifa, Jubaila and Arab-D Formations, agglutinated foraminifera include *Kurnubia palastiniensis*, *Pfenderina salernitana*, *Mangashtia viennoti*, *Alveosepta jaccardi*, *Pseudocyclammina* spp., *Gaudryina* spp. and *Textularia* spp. They are found within assemblages that contain *Nautiloculina oolithica*, undifferentiated simple miliolids, *Trocholina alpina* and species of *Lenticulina*, *Nodosaria* and undifferentiated polymorphinid - like forms. In addition, these formations include stromatoporoids, *Cladocoropsis*

mirabilis and the calcareous algae *Clypeina jurassica*, *Heteroporella jafferezoi* and *Thaumatoporella parvovesciculifera*. Oligosteginids, monaxon and tetraxon sponge spicules are also present. Figures 2 - 4 illustrate the stratigraphic distribution of agglutinated and calcareous foraminifera and associated microfossils from the Hanifa, Jubaila and Arab-D Formations. Figures 5 and 6 illustrate the stratigraphic distribution of agglutinated and calcareous foraminifera and associated microfossils from the Yamama and Shu'aiba Formations.

Hanifa Formation (Middle Oxfordian - Early Kimmeridgian)

The Hanifa Formation (Figure 2) consists predominantly of mudstones with subsidiary wackestones and the foraminiferal assemblage of the lower 70m is characterised by the rare to frequent (1 - 2 specimens per thin section) presence of *Alveosepta jaccardi* in the presence of echinoid spines. *Kurnubia palastiniensis* is present but mostly absent from this lower section. In the upper approximately 60m, *Kurnubia palastiniensis* and *Textularia* spp. gradually replace *Alveosepta jaccardi*. The miliolid foraminifer *Nautiloculina oolithica* typically co-occurs with *K. palastiniensis* and there is also an increase in the presence of sponge spicules and calcareous, multilocular globose forms considered to be polymorphinid foraminifera.

DEPTH	Shallow -> Deep				
AGGLUTINATED FORAMINIFERA					
Textularia spp.				X	
Kurnubia palastiniensis				X	X
Alveosepta jaccardi					X
CALCAREOUS BENTHONIC FORAMINIFERA					
Nautiloculina oolithica				X	
Nodosaria spp.				X	
polymorphinids				X	X
CALCAREOUS ALGAE					
oligosteginids					X
VARIOUS MICROFOSSILS					
Spicules					X

Figure 2. The stratigraphic distribution of selected foraminifera and associated microfossils in a cored section from the Hanifa Formation.

The Hanifa Formation contains low diversity and low abundance microfossil assemblages; the laminated and massive bioturbated sections relate to deep anoxic and shallower oxic conditions respectively (Heydari *et al.*, 1997). The formation is characterised by the common presence of finely-laminated, organic-rich layers in which bioturbation is absent, that alternate with massive mudstones in which bioturbation has homogenised the primary stratification (Savrda & Bottjer, 1991). These features suggest deposition under low energy conditions within a moderately deep basin, below storm wave base with anoxic episodes (Droste, 1980) that may be supported by the relative predominance of *A. jaccardi*. A palaeobathymetric interpretation in terms of informal depth zones is illustrated in Figure 2. The gradual replacement of *A. jaccardi* by *K. palastiniensis* in the upper, bioturbated massive part of the Formation may indicate a response to shallower conditions with improved circulation. It is difficult to determine if the scattered presence of *K. palastiniensis* within the lower *A. jaccardi*-dominated section represent autochthonous, stressed individuals or if they were transported into the deeper parts of the basin from the shallower oxygenated flanks.

Jubaila Formation (Early Kimmeridgian)

The Jubaila Formation is also predominantly a mudstone, but this passes vertically into a succession of mudstones with interbedded fining-upwards wackestone-mudstone beds. The Hanifa - Jubaila contact is marked by the reappearance of *A. jaccardi* and an increase in the abundance of *N. oolithica*, polymorphinids and sponge spicules. The Jubaila Formation (Figure 3) is characterised by the consistent presence of *A. jaccardi*, *K. palastiniensis* and *Textularia* spp. Coexisting non-agglutinated foraminifera include the miliolid *N. oolithica* and the rotalids *Lenticulina* spp., *Nodosaria* spp. and thin-walled, globular forms considered as polymorphinids. Non-foraminiferal biocomponents include oligosteginids, sponge spicules and the localised presence of rare fragments of the stromatoporoid *Cladocoropsis mirabilis*, the dasyclad alga *Clypeina jurassica* and corals.

The marked increase in diversity and abundance of biocomponents within the Jubaila Formation mudstones and wackestones, when compared with those of the underlying Hanifa Formation, together with the consistent presence of *A. jaccardi*, *K. palastiniensis*, *Textularia* spp. suggest oxygenated conditions. A palaeobathymetric interpretation in terms of informal depth zones is illustrated in Figure 3.

Moderately deep water is suggested by the presence of the non-agglutinated foraminiferal species of *Lenticulina* and *Nodosaria*, together with the consistent presence of oligosteginids and sponge spicules. The fining-upwards nature of the beds suggests that the coarser wackestones were transported into the muddy, low energy environment and this suggests water depths greater than wave base. Individual beds have been sampled in the field and these tend to display a concentration of K. *palastiniensis*, *Textularia* spp. and *N. oolithica* at the base of each bed, although *A. jaccardi* is often present throughout the entire bed. This distribution suggests that *A. jaccardi* may be autochthonous whereas *K. palastiniensis*, *Textularia* spp. and *N. oolithica* may be allochthonous and result from episodic transportation from a shallower environment and would imply that *A. jaccardi* occupied a deeper life habit than *K. palastiniensis* and *N. oolithica*. Further evidence for transport of shallower forms into the deeper environment is provided by the localised presence of *C.*

mirabilis, C. jurassica and coral debris, as such shallower forms are well-represented in the relatively shallower carbonates of the overlying Arab-D Member of the Arab Formation.

DEPTH	Shallow - >Deep						
AGGLUTINATED FORAMINIFERA							
Textularia spp.					x	x	x
Kurnubia palastiniensis					x	x	x
Alveosepta jaccardi							x
CALCAREOUS BENTHONIC FORAMINIFERA							
Nautiloculina oolithica				x	x	x	x
Nodosaria spp.						x	x
Lenticulina spp.						x	x
polymorphinids							x
CALCAREOUS ALGAE							
Clypeina jurassica				x			
oligosteginids					x	x	x
VARIOUS MICROFOSSILS							
Spicules						x	x
STROMATOPOROIDS							
Cladocoropsis mirabilis				x			
stromatoporoids (*Shuqria* spp.)				x			

Figure 3. The stratigraphic distribution of selected foraminifera and associated microfossils in a cored section from the Jubaila Formation.

Arab-D Member of the Arab Formation (Kimmeridgian - Tithonian)

The Arab-D Member of the Arab Formation consists of mudstones, packstones and grainstones, together with many dolomitised layers. The contact between the Jubaila Formation and the Arab-D Member of the Arab Formation approximates with the last uphole presence of *A. jaccardi*, oligosteginids, sponge spicules and species of *Lenticulina, Nodosaria* and consistently present polymorphinids. *K. palastiniensis, Textularia* spp. and *N. oolithica* are present throughout most of the Arab-D Member and are progressively accompanied upwards through the succession by *Mangashtia viennoti* and *Pfenderina salernitana* (Figure 4). Non agglutinated foraminiferal species that typify this Member include undifferentiated simple miliolids and *Trocholina alpina*; the latter species displays its first uphole appearance before that of *M. viennoti*. The sclerosponge *Cladocoropsis mirabilis* is consistently present, together with the dasyclad *Clypeina jurassica*.

Biocomponent diversity and abundance is relatively high throughout the Arab-D carbonates and these aspects gradually increase upwards. A palaeobathymetric interpretation in terms of informal depth zones is illustrated in Figure 4. Coarsening-upwards textures are common and considered to represent the effects of progressive shallowing. The absence of *A. jaccardi* and species of *Lenticulina* and *Nodosaria*, oligosteginids and sponge spicules suggest shallower water depths than those of the Jubaila Formation.

DEPTH	Shallow -> Deep					
AGGLUTINATED FORAMINIFERA						
Textularia spp.	x	x	x	x	x	
Gaudryina spp.	x	x	x	x	x	
Pfenderina salernitana		x	x			
Mangashtia viennoti			x			
Pseudocyclammina sp.				x		
Kurnubia palastiniensis				x	x	
CALCAREOUS BENTHONIC FORAMINIFERA						
thick-walled miliolids	x	x	x	x	x	
Nautiloculina oolithica		x	x	x	x	
Trocholina alpina		x	x			
CALCAREOUS ALGAE						
T. parvovesciculifera		x	x	x	x	
Heterolepa jafferezoi			x	x		
Clypeina jurassica			x	x		
Salpingoporella spp.				x	x	
STROMATOPOROIDS						
Cladocoropsis mirabilis			x	x	x	
stromatoporoids (Shuqria spp.)					x	

Figure 4.. The stratigraphic distribution of selected foraminifera and associated microfossils in a cored section from the Arab-D carbonate.

The progressively ascending appearance of certain species is not a simple arrangement, as they are initially represented by sporadic, localised minor occurrences that gradually increase in their vertical extent and abundance until a consistent presence is developed towards the top of the section (Hughes, 1996). This distribution pattern suggests either that downslope transport is responsible, or that the cycle shallows sufficiently to enter the palaeobathymetric tolerance of the particular species. The increase in the incidence and intensity of the presence of these species up section suggests a possible gradual shallowing of the site of deposition that is related to the gradual approach of a prograding shallower part of the basin. In all wells studied, the uphole consistent presence of *M. viennoti, P. salernitana, T. alpina, C. mirabilis, C. jurassica* and *T. parvovesciculifera* is preceded by isolated local occurrences of these species. The presence of grainstones within the upper part of the member suggests high-energy conditions that are possibly associated with deposition shallower than wave base. The Arab-D carbonate member is overlain by the Arab-D anhydrite. Current interpretations range from this evaporite being of sabkha origin (Wilson, 1985; Wood & Wolfe, 1968) and thereby terminating the shallowing upwards trend of the carbonates, to one in which they represent a subaqueous saltern-like accumulation (Lapointe, 1991).

Yamama Formation (Berriasian - Valanginian and Aptian)

The Yamama Formation contains the following agglutinated foraminifera: *Pseudocyclammina lituus, Everticyclammina elegans, Palaeodictyoconus* spp., *Praechrysalidina* spp., *Textularia* spp., *Valvulina* spp. and cf. *Bramkampella* sp., of which *P. lituus* is the most consistently represented (Figure 5). The calcareous species *Trocholina elongata* is well represented, together with the dasyclad algae *Salpingoporella annulata* in the uppermost part of the studied section.

DEPTH	Shallow - Deep				
AGGLUTINATED FORAMINIFERA					
Palaeodictyoconus spp.				x	x
Praechrysalidina spp.	x	x	x	x	x
Textularia spp.	x	x	x	x	x
Pseudocyclammina lituus				x	x
CALCAREOUS BENTHONIC FORAMINIFERA					
Trocholina elongata			x	x	
miliolids	x	x	x	x	
Nautiloculina oolithica	x	x			
CALCAREOUS ALGAE					
Lithocodium aggregatum	x	x			
Salpingoporella annulata	x	x	x		
Salpingoporella dinarica	x	x	x		
VARIOUS MICROFOSSILS					
stromatoporoids	x				
bivalves	x	x	x	x	x
echinoid debris	x	x	x	x	x

Figure 5. The stratigraphic distribution of selected foraminifera and associated microfossils in a cored section from the Yamama Formation

The Yamama Formation displays three well-defined, isolated agglutinated events in which *Pseudocyclammina lituus* is well represented. A palaeobathymetric interpretation in terms of informal depth zones is illustrated in Figure 5. A number of associations is evident and includes the lower *P. lituus* assemblage that grades upwards into the *P. lituus - Trocholina elongata* assemblage. A shallower assemblage includes *P. lituus, T. elongata* and *Palaeodictyoconus* spp. The uppermost of the three *P.lituus*-dominated assemblages includes *Salpingoporella annulata* together with an increase in the incidence of gastropods and macrofossil debris and suggests the most shallow, lagoonal environment. As the three *P. lituus* - dominated sections correlate well with high gamma ray values, it is considered that they represent the deepest facies represented in the Formation and that the Yamama Formation consists of at least three shoaling-upwards successions. The calcareous alga *Lithocodium aggregatum* is scattered throughout most of the succession, but stromatoporoids are confined to the upper part of the lowermost unit. Records from the exposure (Vaslet *et al.*, 1991) describe numerous bioturbated surfaces encrusted with oysters that suggest hard-ground development within the succession.

Shu'aiba Formation (Aptian)

The Shu'aiba Formation (Figure 6) contains the following agglutinated foraminifera: *Palorbitolina lenticularis, Debarina hahounerensis, Praechrysalidina infracretacea, Vercorsella arenata* and various species of *Textularia*. The calcareous benthonic species *Trocholina alpina* is locally represented, together with the planktonic species *Hedbergella planispira* and *Hedbergella delrioensis*. Calcareous algae are well represented and include *Lithocodium aggregatum, Salpingoporella dinarica* and *Coptocampylodon lineolatus*. Recently identified rudists include *Glossomyophorus costatus, Offneria murgensis, O. nicolinae, Agriopleura blumenbachi, Horiopleura distefanoi*, and *Himeralites douvillei* (Skelton *et al.*, 1997; Hughes, 1999)).

DEPTH ZONE	Shallow - Deep							
AGGLUTINATED FORAMINIFERA								
Textularia spp.				x	x	x	x	
Palorbitolina lenticularis				x	x	x	x	
Debarina hahounerensis							x	
Praechrysalidina infracretacea							x	
Vercorsella arenata							x	
Choffatella decipiens							x	
CALCAREOUS BENTHONIC FORAMINIFERA								
thick-walled miliolids				x	x			
Trocholina alpina						x	x	
Lenticulina spp.								x
discorbids								x
Nodosaria & Dentalina spp.								x
thin-walled miliolids								x
PLANKTONIC FORAMINIFERA								
Hedbergella spp.								x
CALCAREOUS ALGAE								
Lithocodium aggregatum						x	x	
Salpingoporella dinarica							x	
Coptocampylodon lineolatus							x	
Oligosteginids								x
VARIOUS MICROFOSSILS								
Spicules								x
Pteropods								x
RUDISTS								
Offneria murgensis	x							
aff. *Pachytraga* spp.		x						
Glossomyophorus costatus			x					
Agriopleura blumenbachi				x				

Figure 6.. The stratigraphic distribution of selected foraminifera and associated microfossils in a cored section from the Shu'aiba Formation.

Carbonates of the Shu'aiba Formation in the Shaybah Field of Saudi Arabia are cream to white and overlie a regionally extensive and distinctive dark grey, orbitolinid limestone that is informally considered to be a facies equivalent of the sandstones of the Biyadh Formation. A palaeobathymetric interpretation in terms of informal depth zones is illustrated in Figure 6. The Biyadh equivalent packstones

consist predominantly of *Palorbitolina lenticularis* but also contains rare planktonic foraminifera and oligosteginids. They are overlain by planktonic-rich mudstones, together with species of *Lenticulina*, *Nodosaria* and keeled discorbids that suggest a moderately deep marine environment that grades into wackestones with rare planktonics and *Lithocodium aggregatum*. The regionally extensive character of the Shu'aiba Formation terminates at the top of this unit, as a response to localised rudist bank development that may be founded upon localised faulted highs. An extensive lagoon developed in certain areas, in which *L. aggregatum* flourished with *Palorbitolina lenticularis* and *Trocholina alpina* and passes upward into a miliolid-dominated assemblage. Planktonic foraminifera are rare and restricted to thin transgressive layers within the lagoonal succession.

The expanding rudist bank complex supported few foraminifera, except on the lagoonal flanks where *P. lenticularis* existed at depths too shallow for *L. aggregatum* but too deep for the elevator rudist *Glossomyophorus costatus*. The elevator rudist *Offneria murgensis* dominates the very shallow bank crest facies and the high-energy conditions precluded foraminiferal colonisation. In the deeper parts of the region, offshore to the rudist bank complex, agglutinated foraminifera include *Palorbitolina lenticularis*, *Lenticulina*, *Nodosaria* and keeled discorbids. The uppermost part of the Shu'aiba Formation in the Shaybah Field consists mostly of an extensive lagoon that is characterised by an agglutinated foraminiferal assemblage containing *Debarina hahounerensis*, *Vercorsella arenata* and *Praechrysalidina infracretacea*. The elevator rudist *Agriopleura blumenbachi* is well developed within this facies, although *G. costatus* and *O. murgensis* form rudist bank complexes along the margin of this extensive deep lagoon. There is a clear tendency for the height of the orbitolinid cone to increase upwards within the succession and this trend follows that described by Vilas *et al.* (1995) where the lower flatter forms inhabited relatively deeper environments with reduced light penetration.

PALAEOENVIRONMENTAL INTERPRETATION OF SELECTED SPECIES

Late Jurassic

Alveosepta jaccardi (Hanifa Formation)
Foraminiferal association: *Kurnubia palastiniensis*, *Nautiloculina oolithica*, polymorphinids and *Textularia* spp.
Algal association: none.
Various: rare bivalve debris, echinoid debris.
Published palaeoenvironment: 'circalittoral-outer infralittoral; inner infralittoral-mediolittoral' (Pelissie *et al.*, 1984).
Palaeoenvironment: interbedded massive mudstones and thin, organic-rich, laminated beds, moderately deep marine, associated with transgressive systems tracts with periodic suboxic events.

Alveosepta jaccardi (Jubaila, absent from Arab-D)
Foraminiferal association: *Bolivina* spp., *Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Lenticulina* spp., *Nodosaria* spp., polymorphinids, *Textularia* spp.
Algal association: oligosteginids; allochthonous *Clypeina jurassica*.
Various: sponge spicules, bivalve debris, echinoid debris, allochthonous fragments of stromatoporoids, *Cladocoropsis mirabilis* and corals.
Published palaeoenvironment: 'circalittoral-outer infralittoral; inner infralittoral-mediolittoral' (Pelissie *et al.*, 1984).
Palaeoenvironment: bioturbated massive mudstones, moderately deep marine, below wave base but within storm base effect. Shallower than Hanifa palaeobathymetry and considered to be associated with transgressive systems tracts.

Kurnubia palastiniensis (Hanifa Formation)
Foraminiferal association: Sporadically distributed with *A. jaccardi*, but absent from the anoxic to suboxic mudstones. *Textularia* spp. and *N. oolithica* are sparse except towards the upper part of the Formation.
Algal association: none.
Various: Inconsistent bivalve and echinoid debris; oligosteginids rare.
Published palaeoenvironment: shallow marine, intertidal (Brooks, 1985), 'infralittoral' (Pelissie & Peybernes, 1982), 'middle infralittoral - inner infralittoral' (Pelissie *et al.*, 1984).
Palaeoenvironment: interbedded massive mudstones and thin, organic-rich, laminated beds, moderately deep marine, associated with transgressive systems tracts with periodic suboxic events.

Kurnubia palastiniensis (Jubaila Formation)
Foraminiferal association: *Alveosepta jaccardi*, *Bolivina* spp., *Nautiloculina oolithica*, *Lenticulina* spp., *Nodosaria* spp., polymorphinids, *Textularia* spp.
Algal association: oligosteginids; allochthonous *Clypeina jurassica*.
Various: sponge spicules, bivalve debris, echinoid debris, allochthonous fragments of stromatoporoids, *Cladocoropsis mirabilis* and corals.
Published palaeoenvironment: shallow marine, intertidal (Brooks, 1985), 'infralittoral' (Pelissie & Peybernes, 1982), 'middle infralittoral - inner infralittoral' (Pelissie *et al.*, 1984).
Palaeoenvironment: bioturbated massive mudstones, moderately deep marine, below wave base but within storm wave base. Shallower than Hanifa palaeobathymetry and considered to be associated with transgressive systems tracts.

Kurnubia palastiniensis (Arab-D Member)
Foraminiferal association: *Pseudocyclammina* spp., *Textularia* spp., *Pfenderina salernitana*, *Gaudryina* spp., *Nautiloculina oolithica*, *Praechrysalidina* spp. and miliolids.
Algal association: *Clypeina jurassica*, *Heteroporella jafferezoi* and *Thaumatoporella parvovesciculifera*

Various: *Cladocoropsis mirabilis*, bivalve debris, echinoid debris, stromatoporoids, *Cladocoropsis mirabilis* and corals.
Published palaeoenvironment: shallow marine, intertidal (Brooks, 1985), 'infralittoral' (Pelissie & Peybernes, 1982), 'middle infralittoral - inner infralittoral' (Pelissie *et al.*, 1984).
Palaeoenvironment: moderately shallow to very shallow marine wackestones and packstones within wave base and probably lagoonal. Consistently present, but typically not present within very shallow marine conditions approaching the top of the Member. Abundance increases at cycle boundaries.

Mangashtia viennoti (Arab-D Member; absent from Hanifa and Jubaila Formations)
Foraminiferal association: *Pseudocyclammina* spp., *Textularia* spp., *Pfenderina salernitana*, *Gaudryina* spp., *Nautiloculina oolithica*, *Praechrysalidina* spp. *Trocholina alpina* and miliolids.
Algal association: *Clypeina jurassica*, *Heteroporella jafferezoi* and *Thaumatoporella parvovesciculifera*.
Various: *Cladocoropsis mirabilis*, bivalve debris and echinoid debris.
Published palaeoenvironment: inner platform - shoals (Brooks, 1985).
Palaeoenvironment: moderately shallow marine wackestones and packstones within wave base of lagoon. Consistently present within the highstand systems tract, but allochthonous, penecontemporaneously transported forms often sporadically present within deeper marine mudstones associated with cycle boundaries. Typically sporadically present within very shallow marine conditions approaching the top of the Member.

Pfenderina salernitana (Arab-D Member; absent from Hanifa and Jubaila Formations)
Foraminiferal association: *Pseudocyclammina* spp., *Mangashtia viennoti*, *Textularia* spp., *Gaudryina* spp., *Nautiloculina oolithica*, *Praechrysalidina* spp., *Trocholina alpina* and miliolids.
Algal association: *Clypeina jurassica*, *Heteroporella jafferezoi* and *Thaumatoporella parvovesciculifera*.
Various: *Cladocoropsis mirabilis*, bivalve debris and echinoid debris.
Published palaeoenvironment: shallow marine, inner and outer shoals (Brooks, 1985), inner - middle 'infralittoral' (Pelissie & Peybernes, 1982), lagoon, internal platform, inland of oolitic platform (Pelissie *et al.*, 1984).
Palaeoenvironment: moderately shallow marine wackestones and packstones within wave base of lagoon. Consistently present within the highstand systems tract, but allochthonous, penecontemporaneously transported forms often sporadically present within deeper marine mudstones associated with cycle boundaries. Typically sporadically present within very shallow marine conditions approaching the top of the Member.

Lower Cretaceous

Pseudocyclammina lituus (Yamama Formation)
Foraminiferal association: *Trocholina elongata*, *Palaeodictyoconus* sp.
Algal association: *Salpingoporella annulata*.
Published palaeoenvironment: shallow marine (Banner and Simmons, 1996).
Palaeoenvironment: moderately shallow marine - below wave base.

Palaeodictyoconus sp. (Yamama Formation)
Foraminiferal association: *Pseudocyclammina lituus*, *Trocholina elongata*.
Algal association: *Salpingoporella annulata*.
Published palaeoenvironment: shallow marine (Banner & Simmons, 1996).
Palaeoenvironment: moderately shallow marine - below wave base to within wave base.

Palorbitolina lenticularis (Shu'aiba Formation)
Foraminiferal association (open platform): planktonic foraminifera (*Hedbergella* spp.), miliolids, *Lenticulina* spp., *Debarina hahounerensis*, *Everticyclammina hedbergi*, *Textularia* spp., *Praechrysalidina infracretacea* (rare), and *Vercorsella arenata* (rare).
Rudist/algal association (open platform): *Salpingoporella dinarica*.
Foraminiferal association (back barrier - lagoon): *Trocholina alpina*, *Textularia* spp., miliolids, *Debarina hahounerensis* and *Praechrysalidina infracretacea*.
Rudist/algal association (back barrier - lagoon): *Lithocodium aggregatum*, *Glossomyophorus costatus* (rare).
Foraminiferal association (fore-barrier): *Textularia* spp.
Rudist/algal association (fore-barrier): *Lithocodium aggregatum*.
Published palaeoenvironment: outer platform (fore-reef) and distal internal platform (back-reef) (Peybernes *et al.*, 1979; Sartorio & Venturini, 1988). Ecologically ubiquitous, carbonate shelf and outer basin (Moullade *et al.*, 1985). Warm, shallow; especially abundant in muddy settings of pure carbonates; dominant except for small foraminifera, isolated rudists, corals or brachiopods (Vilas *et al.*, 1995).
Palaeoenvironment: *Palorbitolina lenticularis* is found in a variety of palaeoenvironments, ranging from lagoon, distal back-barrier and proximal fore-barrier, as well as in the deeper open marine platform setting. As indicated above, the foraminifera and associated fossils coexisting with *P. lenticularis*, together with a regional interpretation of sediment types, assist in determining the various palaeoenvironments in which *P. lenticularis* is found. Of significance is the association of high trochoid forms of *P.lenticularis* with shallower marine settings, such as in the distal back-barrier and of low trochoid forms in the deeper environments, as also noted by Vilas *et al.*, (1995).

Debarina hahounerensis (Shu'aiba Formation)
Foraminiferal association: *Praechrysalidina infracretacea, Vercorsella arenata, Palorbitolina lenticularis, Textularia* spp., *Everticyclammina hedbergi*, miliolids, and planktonic foraminifera (*Hedbergella* spp.).
Rudist/algal association: *Lithocodium aggregatum, Salpingoporella dinarica*, aff. *Pachytraga* spp., *Offneria murgensis, Agriopleura blumenbachi.*
Published palaeoenvironment: none.
Palaeoenvironment: moderately deep lagoon to rudist back barrier; deep open marine platform/shelf with open marine influence.

Praechrysalidina infracretacea (Shu'aiba Formation)
Foraminiferal association: *Debarina hahounerensis, Vercorsella arenata, Palorbitolina lenticularis, Textularia* spp., *Everticyclammina hedbergi*, miliolids, and planktonic foraminifera (*Hedbergella* spp.).
Rudist/algal association: *Lithocodium aggregatum, Salpingoporella dinarica*, aff. *Pachytraga* spp., *Offneria murgensis, Agriopleura blumenbachi.*
Published palaeoenvironment: none.
Palaeoenvironment: moderately deep lagoon to rudist back barrier.

Vercorsella arenata (Shu'aiba Formation)
Foraminiferal association: *Debarina hahounerensis, Praechrysalidina infracretacea, Palorbitolina lenticularis, Textularia* spp., *Everticyclammina hedbergi*, miliolids, planktonic foraminifera (*Hedbergella* spp.).
Rudist/algal association: *Lithocodium aggregatum, Salpingoporella dinarica*, aff. *Pachytraga* spp., *Offneria murgensis, Agriopleura blumenbachi.*
Published palaeoenvironment: none.
Palaeoenvironment: moderately deep lagoon to rudist back barrier; deep open marine platform/shelf with open marine influence.

SEQUENCE BOUNDARY RECOGNITION USING FORAMINIFERAL ASSEMBLAGES

The established hierarchy of sequence stratigraphic cycles considers cratonic onlap-offlap cycles as first order, with a duration greater than 50 Ma. and second order transgressive-regressive cycles have a duration of 10 - 50 Ma. Third order cycles have a duration of 0.5 - 5 Ma. and can be subdivided into systems tracts and fourth to sixth order cycles are parasequence or Milankovitch cycles (Read *et al.*, 1995). Of these, the first to third order cycles can be adequately resolved by global biostratigraphic marker species, but the fourth order and smaller cycles are resolved only within a regionally-based biozonation scheme (Copestake, 1993). It is at this level that micropalaeontological biostratigraphy is of most value in elucidating carbonate reservoir stratification.

The Hanifa, Jubaila, Arab-D, Yamama and Shu'aiba Formations are each less of than 5 Ma duration and would be considered, therefore, as 3rd order sequences; micropalaeontologically-determined cyclic events may represent autocycles or parasequences of at least fourth order. Sequence recognition within carbonates has been described in the key publications by Sarg (1988), Schlager (1992), Handford & Loucks (1993), Emery & Myers (1996), Kerans & Tinker (1997) and Read *et al.* (1995). Interpretation is assisted by the recognition of the three important thresholds of shoreline (sea level), fair-weather wave base (20 - 40 feet) and storm wave base (100-250 feet). Exceptions to this water energy - depth relationship are the lower wave energies found in shallow protected lagoons, back-reefs and back-barrier settings.

Criteria for sequence boundary and maximum flooding surface recognition have been described from the deep marine siliciclastic setting of the Gulf of Mexico (Armentrout & Clement, 1990; Armentrout *et al.*, 1990). Biocomponent variability has rarely been used, however, to assist sequence boundary determination of carbonates. Exceptions include the Saudi Arabian Cretaceous and Jurassic (Le Nindre *et al.*, 1990) and the Upper Jurassic of Yemen (Toland *et al.*, 1994).

Autochthonous palaeontological assemblage components of shallow marine carbonates owe their characteristics to the same processes that produced depositional sequences and systems tracts. It is possible that palaeontological analogues of system tracts and maximum flooding surfaces may be identified that would provide a new dimension in assisting genetic unit recognition in such carbonates leading to 'sequence biostratigraphy' (Posamentier & Goodman, 1992; Brett, 1995).

Palaeobathymetry and system tract recognition in carbonate environments has to be carefully considered, because relatively slow marine transgressions may not cause a significant deepening in areas where high productivity maintains a 'keep up' situation. Rapid transgressions do, however, seem to be able to cause variable effects on carbonate productivity, causing 'catch-up' situations that are often accompanied by the influx of planktonic foraminifera and oligosteginids and the inhibition of the moderately shallow fauna and flora. Where planktonic organisms are absent, due to shallow water depths, increases in microfaunal abundance and diversity assist in locating maximum flooding zones. The presence of allochthonous shallow marine forms, such as fragments of stromatoporoids, *Cladocoropsis mirabilis* and *Clypeina jurassica* are of value in positioning cycle, or parasequence, boundaries in sections where such forms are not consistently present. Palaeobathymetric control on the distribution of agglutinated foraminifera and possible sequence stratigraphic context in Saudi Arabian Upper Jurassic and Lower Cretaceous carbonates is discussed below and illustrated in Figures 7 and 8.

Late Jurassic

The Hanifa Formation

The economic aspects of a sequence stratigraphic interpretation of the Hanifa Formation have been considered by Kompanik *et al.* (1993) and McGuire

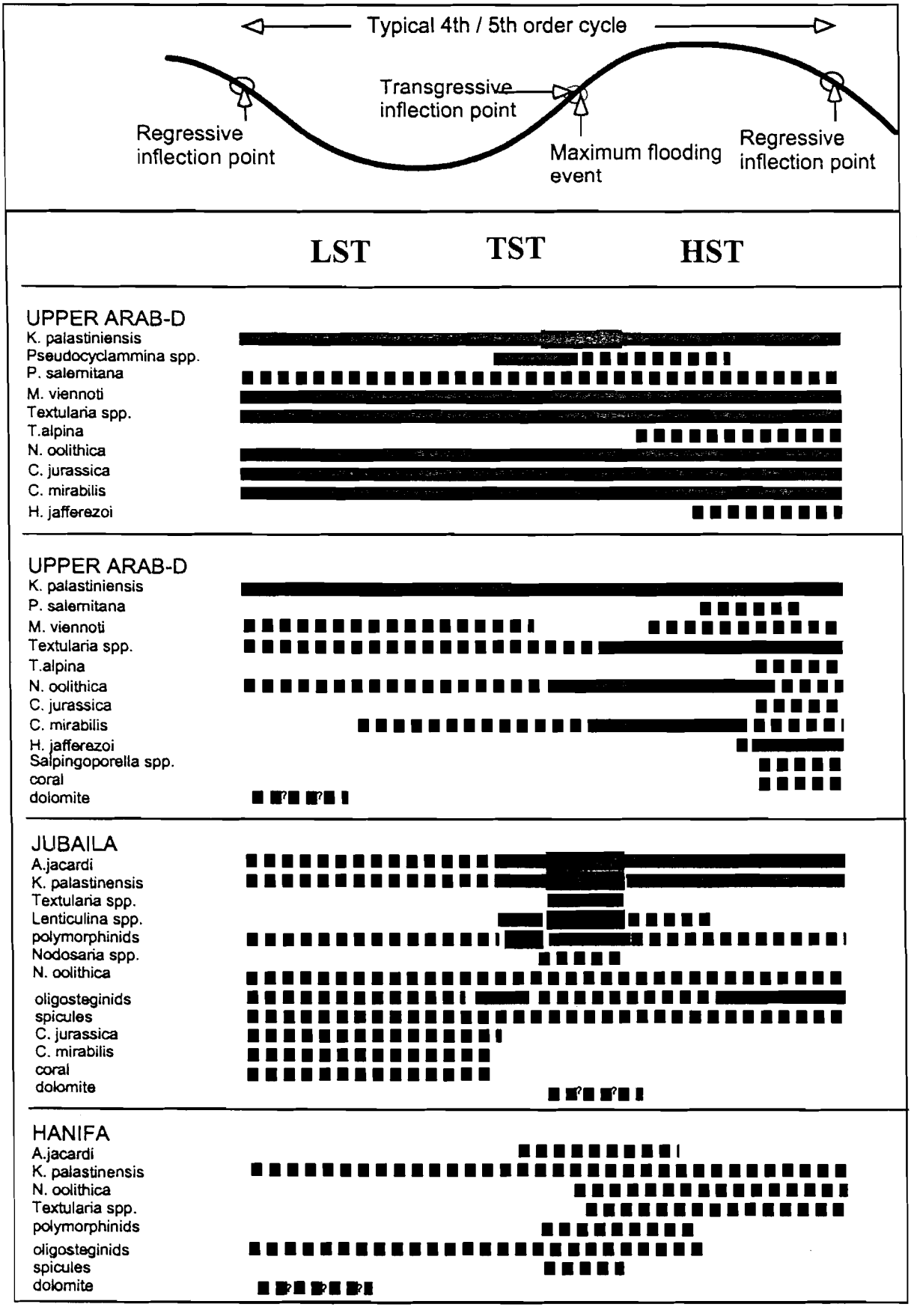

Figure 7. Suggested relationship between the various foraminifera and associated microfossils and eustatically-controlled variations in sea level (Hanifa, Jubaila, Arab-D).

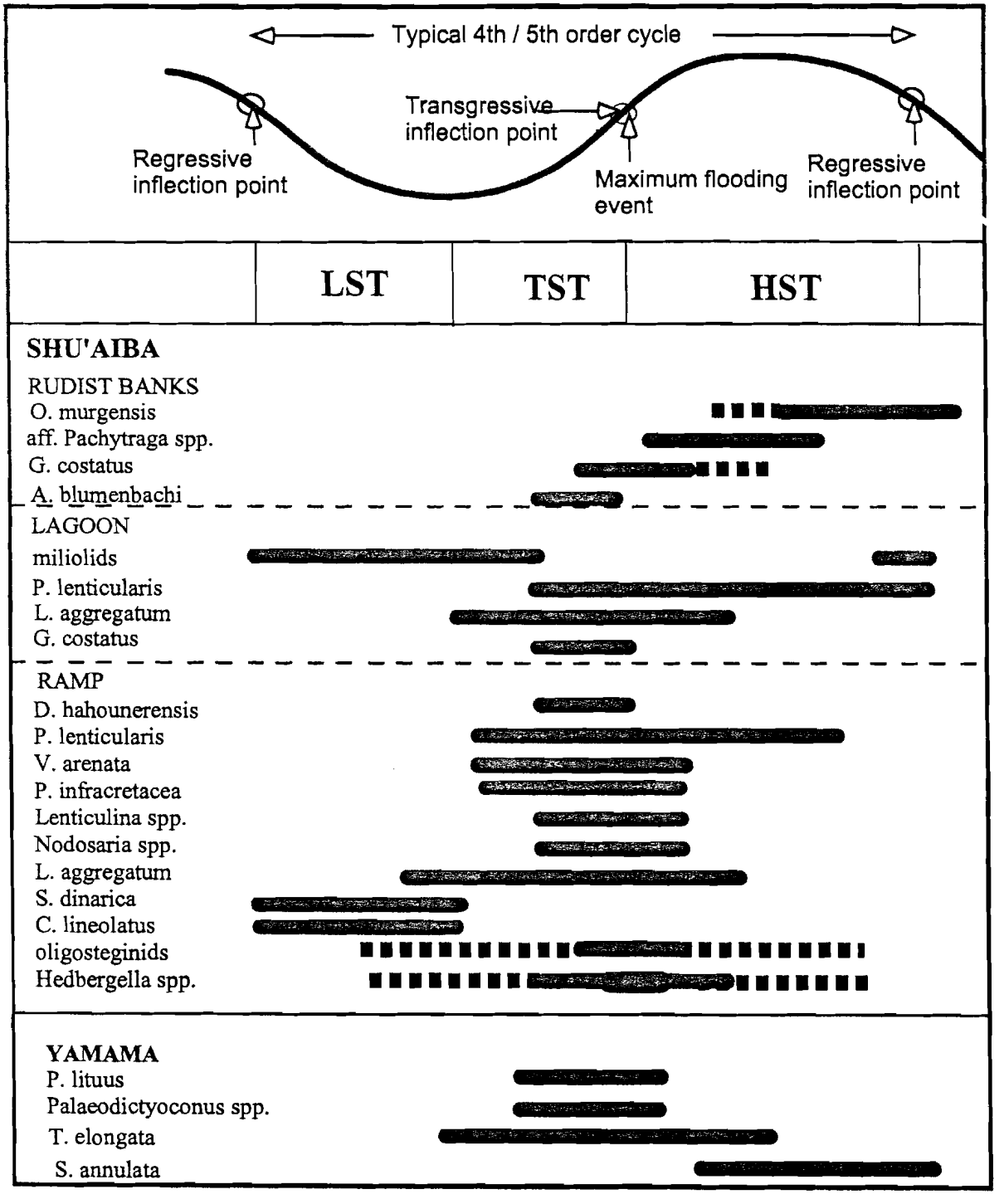

Figure 8. Suggested relationship between the various foraminifera and associated microfossils and eustatically-controlled variations in sea level (Yamama, Shu'aiba).

et al. (1993). This formation has been considered to be the product of two cycles, each consisting of a low and high-energy phase, based on lithological variations (Okla, 1983; Moshrif, 1984; Le Nindre *et al.*, 1990). Integration of agglutinated foraminiferal distribution, other microfossil distribution, lithology, gamma and porosity logs suggests the presence of two shoaling upward successions. The localised presence of *Alveosepta jaccardi* coincides with elevated gamma log values, lower porosity values and muddiness and suggests deeper conditions that may be explained in terms of a maximum flooding zone. Sponge spicules are recorded from such events within this and other wells. *K. palastiniensis, Textularia* spp. and the calcareous foraminifera *Nautiloculina oolithica* with echinoid debris tend to be concentrated in the intervening sections and may be associated with highstand conditions and gradual shallowing

approaching the sequence boundary. Within the Hanifa Formation at this locality, the low sea level associated with the sequence boundary is not considered to have caused emergence, because of the absence of well-developed shallow marine forms.

A. jaccardi is here considered to have flourished in the deeper, episodically suboxic conditions associated with the marine transgression and maximum flooding and therefore to be considered autochthonous. Spicules and globular 'polymorphinid' forms are also considered to be associated with, but not confined to, these conditions. All other forms, including *K. palastiniensis* and *Textularia* spp. are mostly considered allochthonous and to have been transported into the site of deposition by storms or enhanced wave base reworking during the lower sea levels associated with highstand.

Jubaila Formation

The concentration of *A. jaccardi* with associated *Lenticulina* and *Nodosaria* species, calcispheres and spicules and a general absence of allochthonous shallower marine forms in the Jubaila Formation indicates deep conditions typical of a transgressive systems tract. The concentration of *A. jaccardi* within this zone represents an ecological epibole, or acme zone, associated with the maximum flooding zone. The localised presence of allochthonous shallow marine stromatoporoid and coral debris possibly indicates shallower conditions associated with a late highstand prior to submarine cycle boundaries, possibly representing 4th order cycles or smaller (Figure 3). The marked uphole termination of the *Lenticulina-Nodosaria*-calcisphere-spicule assemblage is considered to mark another sequence boundary.

Arab-D Member

The Arab-D carbonates display a stacked arrangement of shoaling upward cycles that are superimposed upon an overall shoaling upwards succession (Figure 4). It is difficult, therefore, to recognise sequence boundaries within this entire continuous succession, although the marked absence of the deeper marine forms at the base of the Arab-D represents a significant decrease in bathymetry that may be associated either with the onset of highstand conditions or a sequence boundary. Cryptic systems tracts are possibly present in the numerous shoaling upwards units that characterise the Arab-D and probably represent autocycles (*sensu* Ginsburg, 1971; Goldhammer *et al.*, 1990; Schlager, 1992) or parasequences.

Early Cretaceous

Yamama Formation

Neither calpionellids nor planktonic foraminifera have been identified in the Yamama Formation, but the three events in which *Pseudocyclammina lituus* predominate are attributed to three episodes of deepening. The gamma-ray peaks that coincide with the base of the *P. lituus* occurrences have been identified by the author as possibly represent maximum flooding events. The underlying elevated gamma signal is suggested to be associated with a sequence boundary, above which the transgressive succession is often dominated by *Palaeodictyoconus* spp. The presence of stromatoporoids below the influx of *P. lituus* suggests possible association with shallower conditions of the late highstand or lowstand systems tracts. Intermediate depths are characterised by the presence of *Palaeodictyoconus* sp. and *Trocholina elongata*.

Shu'aiba Formation

Hedbergella spp. are present as isolated occurrences within the Shu'aiba representing incursion epiboles (Brett, 1995) and an influx of deeper marine forms associated with a maximum flooding surface (Figure 6). The *Palorbitolina lenticularis* - and *Praechrysalidina infracretacea* - dominated agglutinated assemblage of the Biyadh Formation passes rapidly upwards into a deeper, *Hedbergella* - dominated assemblage at the base of the Shu'aiba Formation. This transition is rapid and possibly represents a cycle boundary, with a planktonic-dominated transgressive zone merged with the maximum flooding zone. The deeper conditions associated with this marine transgression continued to support *D. hahounerensis, Textularia* spp. and *V. arenata* but reduced *P. lenticularis* and miliolids and inhibited *Everticyclammina. hedbergi, P. infracretacea*, oligosteginids, *L. aggregatum* and *Salpingoporella dinarica*.

CONCLUSIONS

The Hanifa, Jubaila, Arab-D and Shu'aiba Formations of Saudi Arabia are carbonate sediments that were deposited under variable palaeobathymetric conditions that represent the Oxfordian to Kimmeridgian, Berriasian and Aptian respectively. Variations in the foraminifera, calcareous alga and associated microfauna and microflora indicate that these carbonates did not maintain a 'keep up' production rate, and therefore were subject to episodes of variable palaeobathymetry. Postulation of depth preferences of the agglutinated foraminifera is based on their vertical arrangement combined with mutually occurring calcareous foraminifera and algae and larger biocomponent fragments.

The Hanifa and Yamama Formations display rather similar, low diversity and low abundance micropalaeontological associations. The Jubaila, Arab-D carbonates and Shu'aiba Formations contain higher species diversity and abundance. The Hanifa and Yamama equivalents are source rocks within the Gulf region and they may represent unusual palaeoenvironmental conditions associated with marine stagnacity.

The closely spaced, semi-quantitative micropalaeontological data have been integrated with sequence stratigraphic principles to produce a series of depth-controlled palaeontological associations. The examples provided by this study will assist correlation of well sections and by the recognition of

sequence stratigraphic systems tracts, should assist the prediction of facies migration, by progradation, retrogradation or aggradation and thereby improve the prediction of more favourable reservoir facies.

This study is considered to be ongoing and refinements of the depth ranges and relationship to systems tracts are to be expected.

ACKNOWLEDGMENTS

The results presented in this paper are based on Saudi Arabian samples studied as part investigations within the Geological R&D Division to support Saudi Aramco's exploration and development activities. Thanks are extended to Saudi Aramco for providing permission to publish the data. Editorial comments by J.A.Al-Jallal, S.Al-Hajri and J. Filatoff, of the Geological Research and Development Division of Saudi Aramco, and by M. Simmons of Aberdeen University, are gratefully acknowledged.

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FAUNAL AND FLORAL REFERENCE LIST OF SAUDI ARABIAN LATE JURASSIC TAXA

Agglutinated foraminifera

Alveosepta jaccardi (Schrodt, 1894)
Levantinella egyptiensis Fourcade, Arafa & Sigal, 1997
Mangashtia viennoti Henson, 1948
Kurnubia palastiniensis Henson, 1948
Pfenderina salernitana Sartori & Crescenti

Calcareous benthonic foraminifera

Trocholina alpina (Leupold, 1935)
Nautiloculina oolithica Mohler, 1938

Calcareous algae

Clypeina jurassica Favre and Richard, 1927
Heteroporella jafferezoi Bernier, 1984
Thaumatoporella parvovesciculifera

Stromatoporoid

Cladocoropsis mirabilis Felix

Ammonites

Euaspidoceras gr. *catena-perarmatum* (Sowerby)
Paracenoceras aff. *hexagonum* (Sowerby)
Perisphinctes aff. *jubailensis* Arkell

Brachiopods

Somalirhynchia africana Weir
Somalithyris bihendulensis Muir-Wood
Rhynchonella hadramautensis Stefanini

Stromatoporoids

Promillepora pervinquiri Dehorne
Acrostroma damesini Hudson
Steineria somaliensis Zuffardi-Comerci
Shuqraia hudsoni Wood
Burgundia ramosa Pfender
Actinostromarianina praesalevensis Zuffardi-Comerci
Parastromatopora libani Hudson

FAUNAL AND FLORAL REFERENCE LIST OF SAUDI ARABIAN EARLY CRETACEOUS TAXA

Agglutinated foraminifera

Pseudocyclammina lituus (Yokohama, 1890)
Palaeodictyoconus sp.
Palorbitolina lenticularis (Blumenbach, 1805)
Praeorbitolina cormyi Schroeder,
O. (Mesorbitolina) lotzei Schroeder, 1964
O. (Mesorbitolina) texana (Roemer, 1852)
O. (Mesorbitolina) parva Douglas, 1960
Debarina hahounerensis Fourcade *et al.*, 1972
Praechrysalidina infracretacea Luperto Sinni, 1979

Vercorsella arenata Arnaud-Vanneau, 1980
Calcareous benthonic foraminifera
Trocholina elongata
Trocholina alpina (Leupold, 1935)
Planktonic foraminifera
Hedbergella planispira (Tappan, 1940)
Hedbergella delrioensis (Carsey, 1926)
Calcareous algae
Lithocodium aggregatum Elliott, 1956
Salpingoporella annulata Carozzi, 1953
Salpingoporella dinarica Radoicic, 1975
Coptocampylodon lineolatus Elliott, 1963
Rudist molluscs
Glossomyophorus costatus Masse, Skelton and Sliskovic
Offneria murgensis Masse
Agriopleura blumenbachi (Studer)
Eoradiolites plicatus Conrad
Echinoderms
Pygurus yamamaensis Kier 1972
Calcareous Nannofossils
Rucinolithus wisei Thierstein, 1971
Kokia borealis Perch-Nielsen, 1988
Nannoconus sabinae Perch-Nielsen, 1988
Calpionellids
Calpionella alpina Lorenz, 1902
Calpionella elliptica Cadisch
Calpionellopsis oblonga (Cadisch)
Crassicollaria parvula Remane