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A New Bioevent Stratigraphy of Late Jurassic Arab-D Carbonates of Saudi Arabia

Geraint Wyn Hughes
Saudi Aramco

ABSTRACT

A series of fine-scale biofacies cycles are recognised by the application of semi-quantitative micropalaeontological analysis of cores in eight wells from the reservoir carbonates from the Arab-D and upper Jubaila formations in Saudi Arabia. They are of Kimmeridgian - Tithonian age, and form the primary producing reservoir of the world's largest single continuous reservoir located in the Ghawar field of Saudi Arabia. Three new composite biozones are identified that include a basal, deep marine Biozone D3 with fining-upwards cycles which equate, in part, with the Jubaila Formation. Biozone D2 was deposited in shallower conditions of the lower Arab-D carbonate, and Biozone D1 deposited in a very shallow marine environment of the upper Arab-D carbonate; both zones contain multiple coarsening-upwards cycles. Numerous additional bio-events, of potential subzonal value, are detected within these broad zones, and are considered to be related to discrete shoaling-upwards responses to transgressive episodes. The proposed scheme differs significantly from that erected for the Arab-D Formation in offshore Abu Dhabi.

Carbonates of the Arab-D member are concluded to be composed of a series of high frequency palaeobathymetric changes which were superimposed upon an extensive carbonate platform. Gradual shallowing of the platform resulted possibly from a reduction in subsidence rate, a fall in sea level, rise in carbonate productivity rate or a combination of these. The latest episode of very shallow marine carbonate sedimentation terminated with the deposition of the Arab-D evaporites.

INTRODUCTION

The Arab-D is the primary producing reservoir in the world's largest single, continuous reservoir located in the Ghawar field of Saudi Arabia (Figure 1). Log interpretation and other studies are being used routinely to improve our understanding of the depositional-reservoir layer association, and thus assist in optimising the engineering activities involved in reservoir exploitation. These disciplines will now be supplemented by that of applied micropalaeontology, an approach which has essentially been bypassed since the early days of the field's discovery and is considered to provide an important contribution to resolving the otherwise cryptic layering of the reservoir.

This paper describes the fundamentals of applied micropalaeontology used in the development of this carbonate reservoir, and departs from the conventional use of micropalaeontological data for age and palaeoenvironmental interpretation. Cores of the grain-dominated Arab-D carbonate, with up to 13% of sheet-like dolomite beds, up to maximum of 15 feet thick, in the 'Ain Dar, Shedgum and Uthmaniyah areas of Ghawar field were analysed from eight wells using high resolution micropalaeontology in which all biotic skeletal fragments are recorded semi-quantitatively. This approach has revealed the presence of a number of zones based on microfaunal and microfloral events which provide a highly sensitive environmental history for the deposition of the carbonates, the majority of which are laterally traceable between adjacent wells.

Bioevent diachroneity is suggested between the studied wells despite the relatively short distance between them, and a progradational process is inferred. The bioevent diachroneity implies that the presence of certain marker species is facies controlled, and associated with the gradual migration of an environmental facies belt into deeper parts of the basin. Such bioevents do not, therefore, represent time-lines. This paper will review previous work on the Arab-D reservoir and introduce a new biostratigraphic scheme which has revealed potentially valuable insights into such layering schemes.

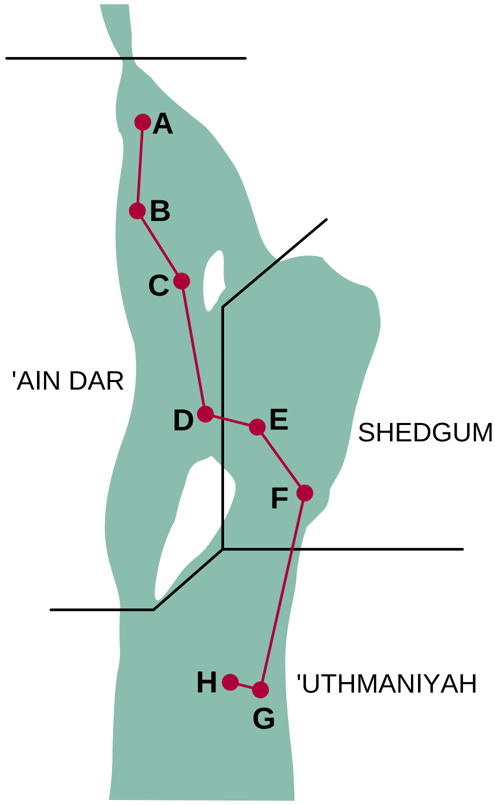


Figure 1: Location of the Ghawar field in Saudi Arabia, with localities of the study wells in the 'Ain Dar, Shedgum and 'Uthmaniyah areas.

ARAB-D RESERVOIR LITHOSTRATIGRAPHY

The Arab-D Reservoir includes the upper part of the carbonate mudstones of the Jubaila Formation (Figure 2), and the overlying carbonates of the entire Arab-D of the Arab Formation (Steineke and Bramkamp, 1952; Powers, 1962, 1968). The boundary between these two formations is conformable and represents a transition from mudstones to clean packstones. The Arab Formation is of Upper Jurassic, Upper Kimmeridgian to Lower Tithonian, age (Le Nindre et al., 1990; de Matos and Hulstrand, 1995) and is overlain by the massive anhydrite of the Hith Formation through a transitional contact characterised by an increase in thickness and frequency of anhydrite beds. The Arab Formation is composed of four members, commencing at the base with the Arab-D Member, and proceeding through Arab-C, -B and -A members upwards through the formation. Each member consists of a lithological couplet, i.e. the Arab-D carbonate and the Arab-D anhydrite, which represents a cyclic transition upwards from shallow marine carbonates through to marginal marine evaporites, now preserved as anhydrite. The upper anhydrite couple of the Arab-A Member is the thickest, and has been designated the Hith Formation instead of the Arab-A anhydrite, and is accepted as representing the closing cycle of the repeated carbonate - evaporate succession of the Arab Formation (Powers, 1968).

PREVIOUS WORK

The only detailed biostratigraphic analysis of the Arab-D Formation from Saudi Arabia prior to the present study was by Powers (1962), based on thin section carbonate analysis at approximately 6 inches spacing. The number of biocomponents identified by Powers was restricted to eight elements, and his interpretation on their vertical distribution was therefore limited. Significant biostratigraphic studies from the later Arab members have, however, been made by de Matos (1994), de Matos et al. (1994) and Simmons and Al-Thour (1994), and lithostratigraphic and depositional environmental contributions for the Arab Formation include Wilson (1985), Meyer and Price (1993), Alsharhan and Whittle (1995), Bouroullec and Meyer (1995), Saner and Abdulghani (1995) and Yousif and Nouman (1995). Sequence stratigraphic interpretations of the Arab-D are limited, and include Le Nindre et al. (1990) and Azer (1995) and, for the slightly older Hanifa Formation, Kompanik et al. (1993), McGuire et al. (1993) and de Matos and Hulstrand (1995).

The biozonation scheme suggested for offshore Abu Dhabi by Al-Silwadi et al. (1996) assigns upper *Kurnubia jurassica* and lower *Everticyclammina virguliana* biozones to the Arab-D, but these cannot be applied within Saudi Arabia because of the marked difference in bioassemblage characteristics. For example, *Clypeina jurassica*, *Pfenderina salernitana* and *Kiliania* spp. are well represented in the Saudi Arabian Arab-D, whereas these species are only present in the Arab-C of offshore Abu Dhabi.

METHODOLOGY

The technique applied in this study was an attempt to independently fingerprint the stratigraphic section based on the micropalaeontological response to subtle environmental variations, and to later establish an order of biosequences with a higher resolution, palaeoenvironmentally-guided stratigraphic interpretation than in any previous study. Cores from eight wells (A to H) have been examined from the 'Ain Dar, Shedgum and 'Uthmaniyah fields from which a total of 1,863 thin sections were analysed, with 6 inch sample spacing in two of the wells (E and F).

In the other six wells, average sample spacing is 12 inches. Each thin section had been described petrographically, and was analysed for micropalaeontology, with the abundance of all identifiable bioclasts being recorded semi-quantitatively. All species have been displayed on a true-vertical scale biostratigraphic chart, with gamma, density, neutron, lithology, porosity and permeability traces as well as foraminiferal species diversity and abundance, associated microfaunal / microfloral diversity and abundance and total bioclast diversity. Correlation of biocomponent events, including first, last and multiple downhole occurrences, were made by visual inspection; other available data were compared at a later stage.

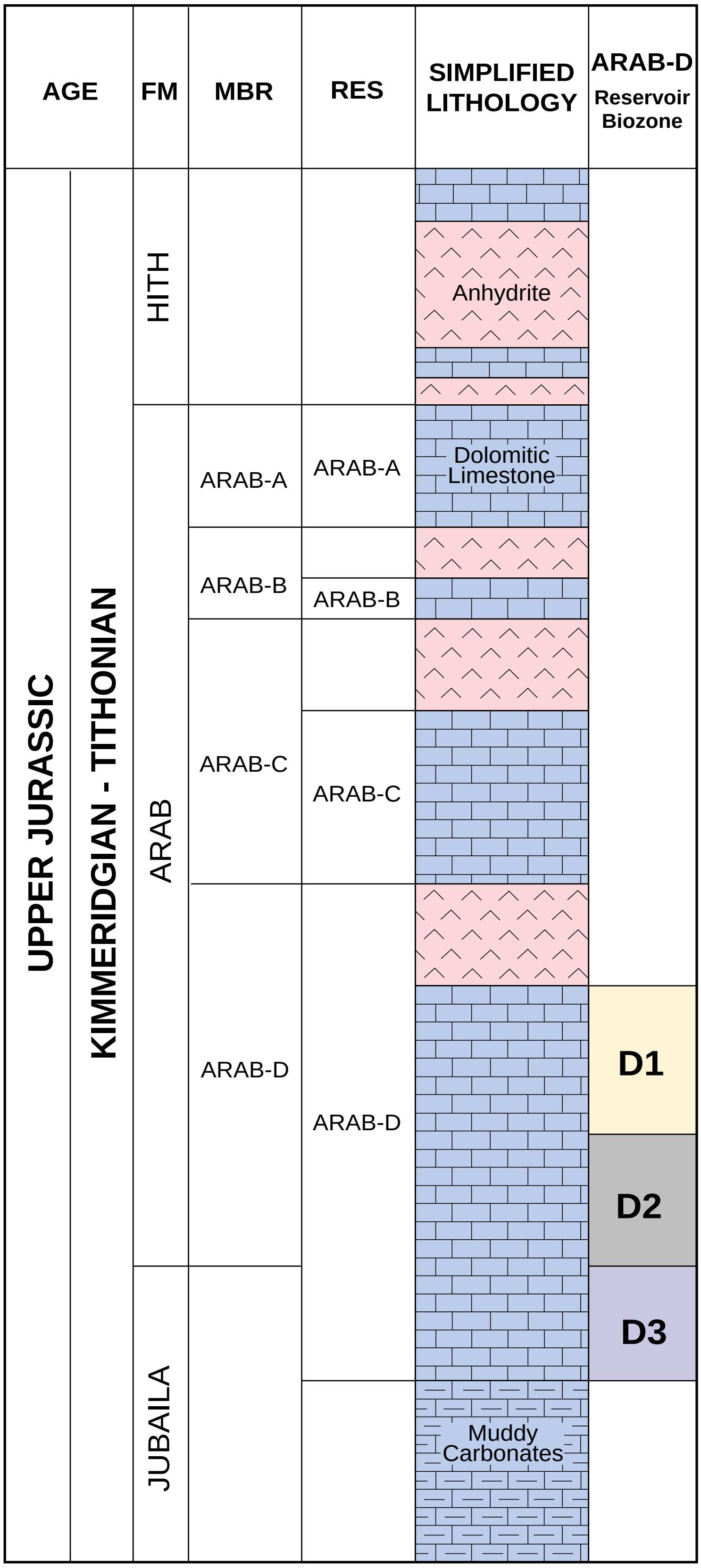


Figure 2: Stratigraphy and simplified lithology of the Jubaila, Arab and Hith formations.

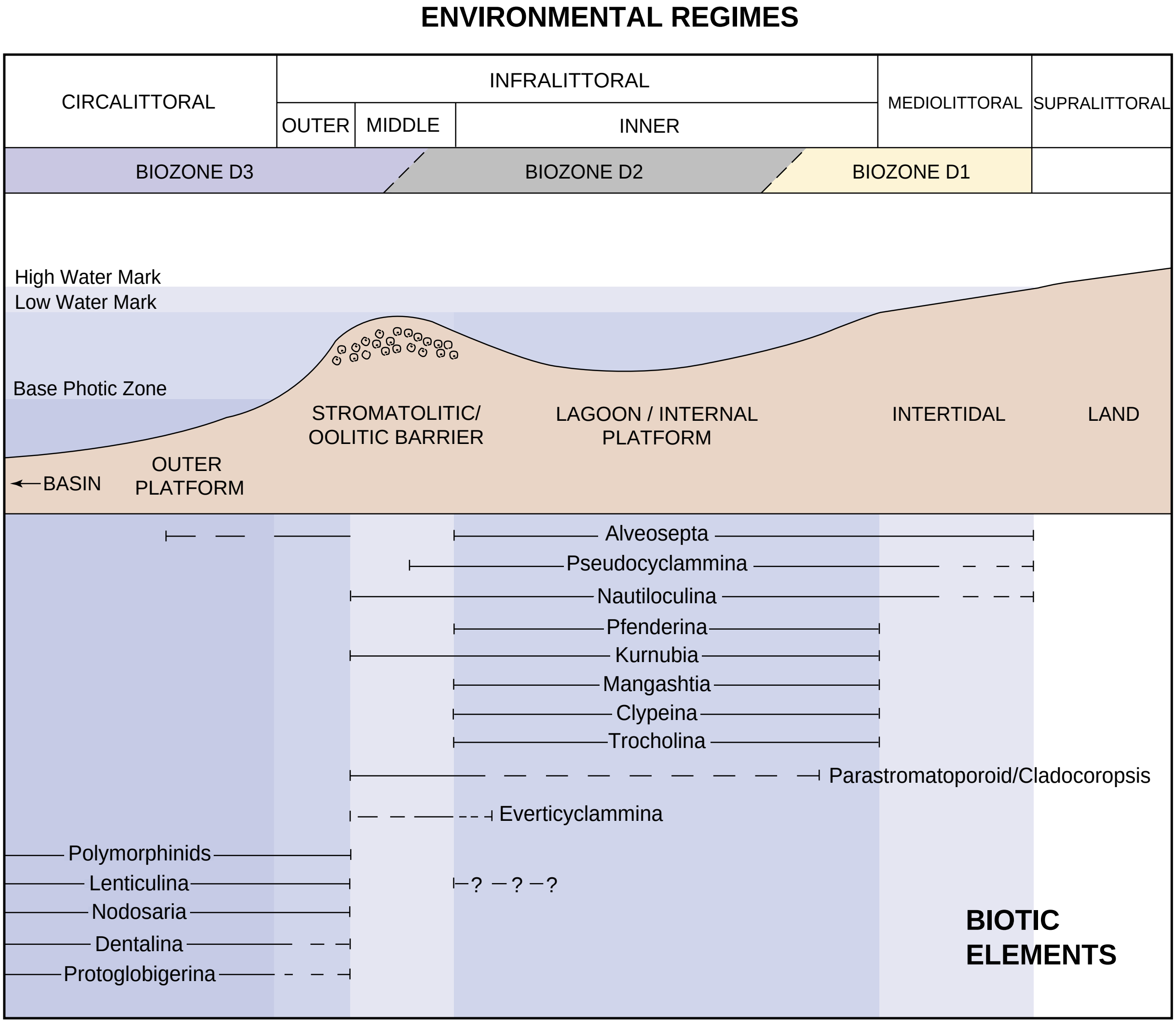


Figure 3: Model for the palaeoenvironmental distribution of various micropalaeontological forms within the Arab-D reservoir.

BIOCOMPONENTS

The current palaeoenvironmental inter-pretation of micropalaeontological elements of the Arab-D reservoir in the studied wells (Figure 3) is based upon a limited number of relevant publications (Derin and Gerry, 1975; Pelissie and Peybernes, 1982; and Pelissie et al., 1983), together with various associations of the biocomponents.

A variety of microfaunal, microfloral and fragments of macrofaunal and macrofloral elements exist within each study well. Figure 4 illustrates the vertical distribution of selected forms within wells A to H, and these events in adjacent wells have been used to identify three major biozones as illustrated in Figure 5. The most significant elements are illustrated in Plate 1.

A number of micropalaeontological elements display localised, and therefore stratigraphically important, vertical variations in both presence and abundance, within the studied well sections. These include *Clypeina jurassica, Cylindroporella sugdeni, Deloffrella quercifolipora, Heteroporella jaffrezoi, Salpingoporella annulata* and *Thaumatoporella parvovesciculifera* and the stromatoporoid *Cladocoropsis mirabilis*. Entire discs of *Clypeina jurassica* were recorded separately as possible indicators of degree of post mortem transport.

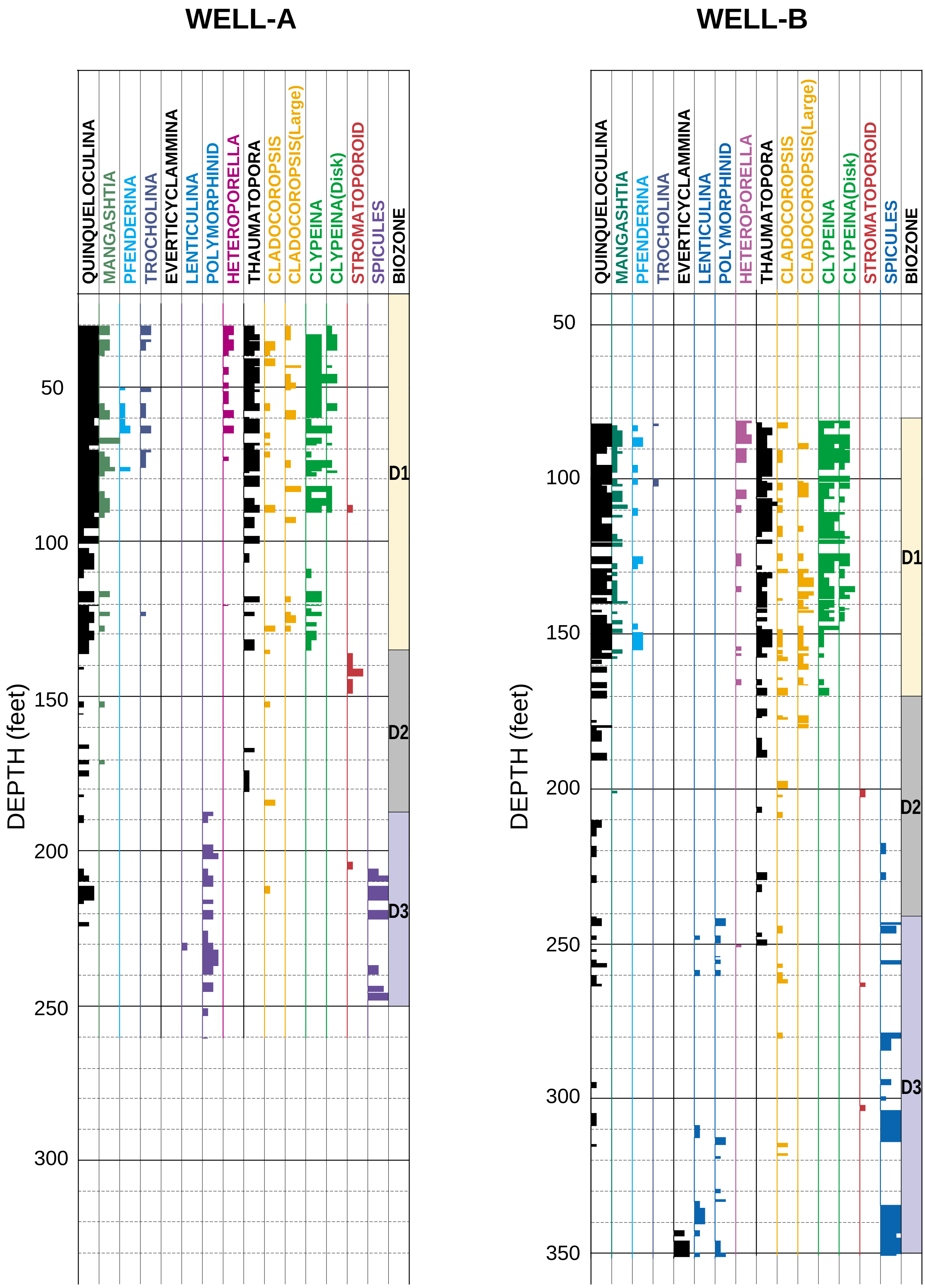


Figure 4: Micropalaeontological variation of selected forms and biozones within wells A to H (continued on pages 422 to 424).

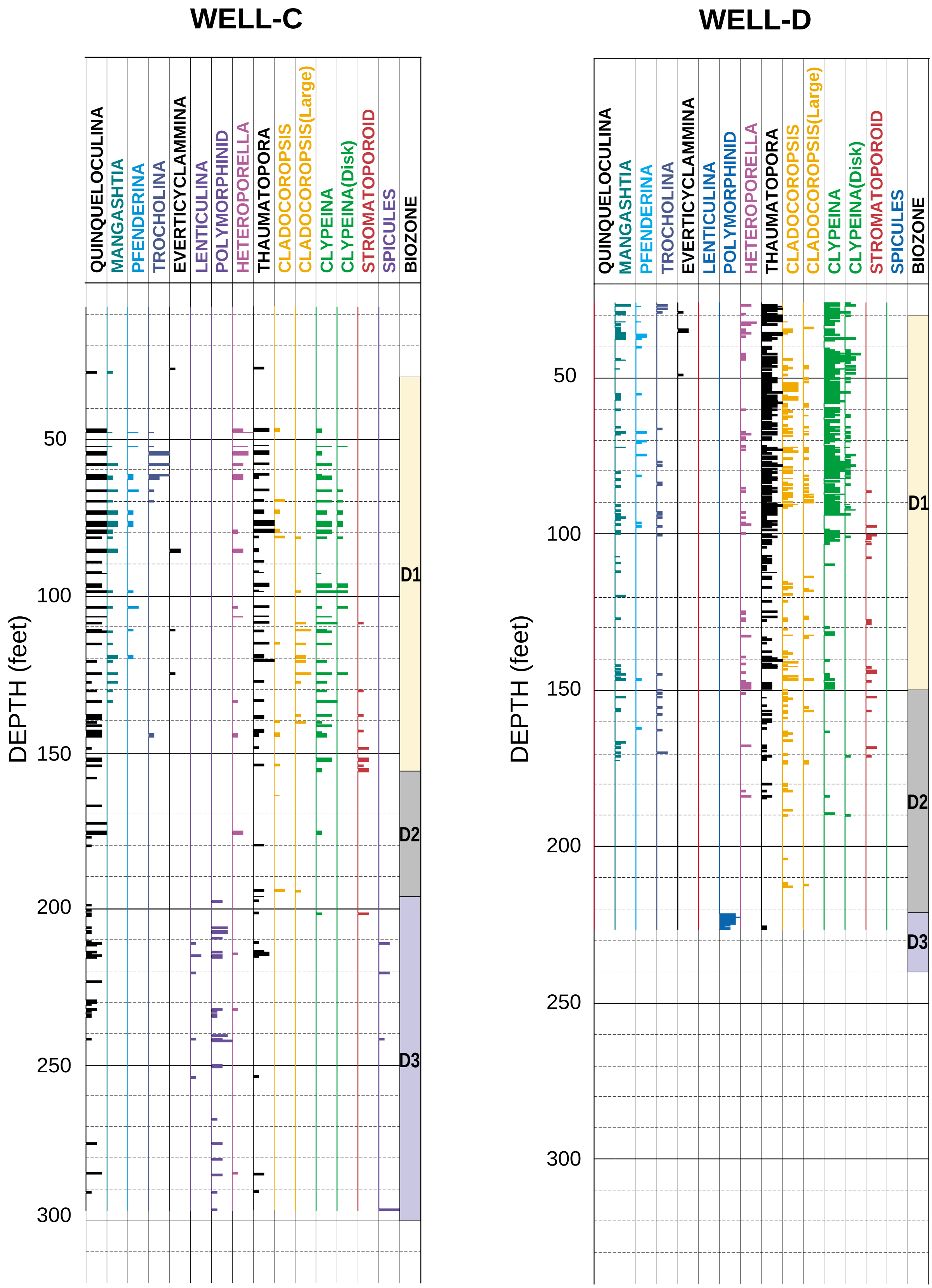
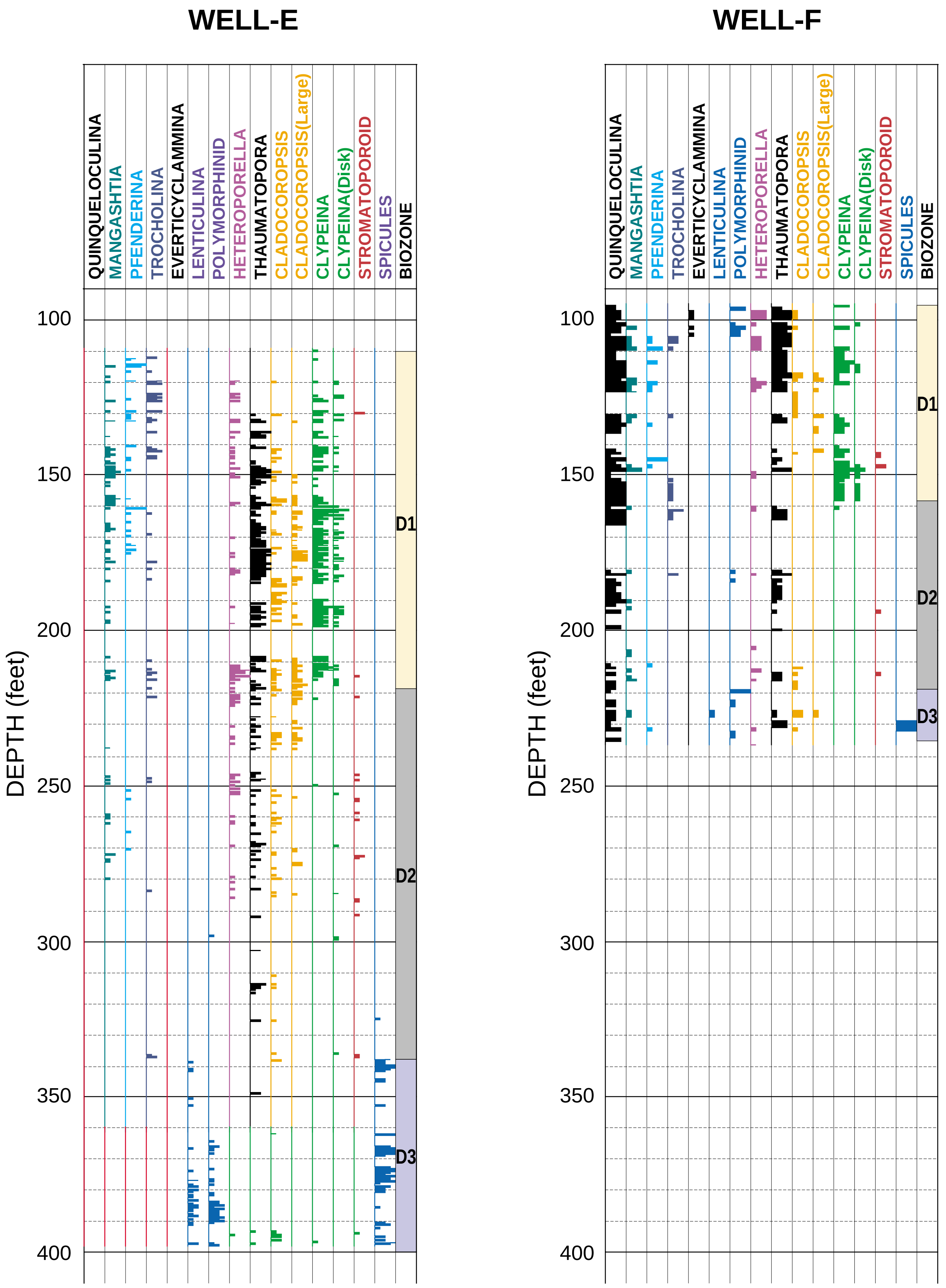


Figure 4: (continued)



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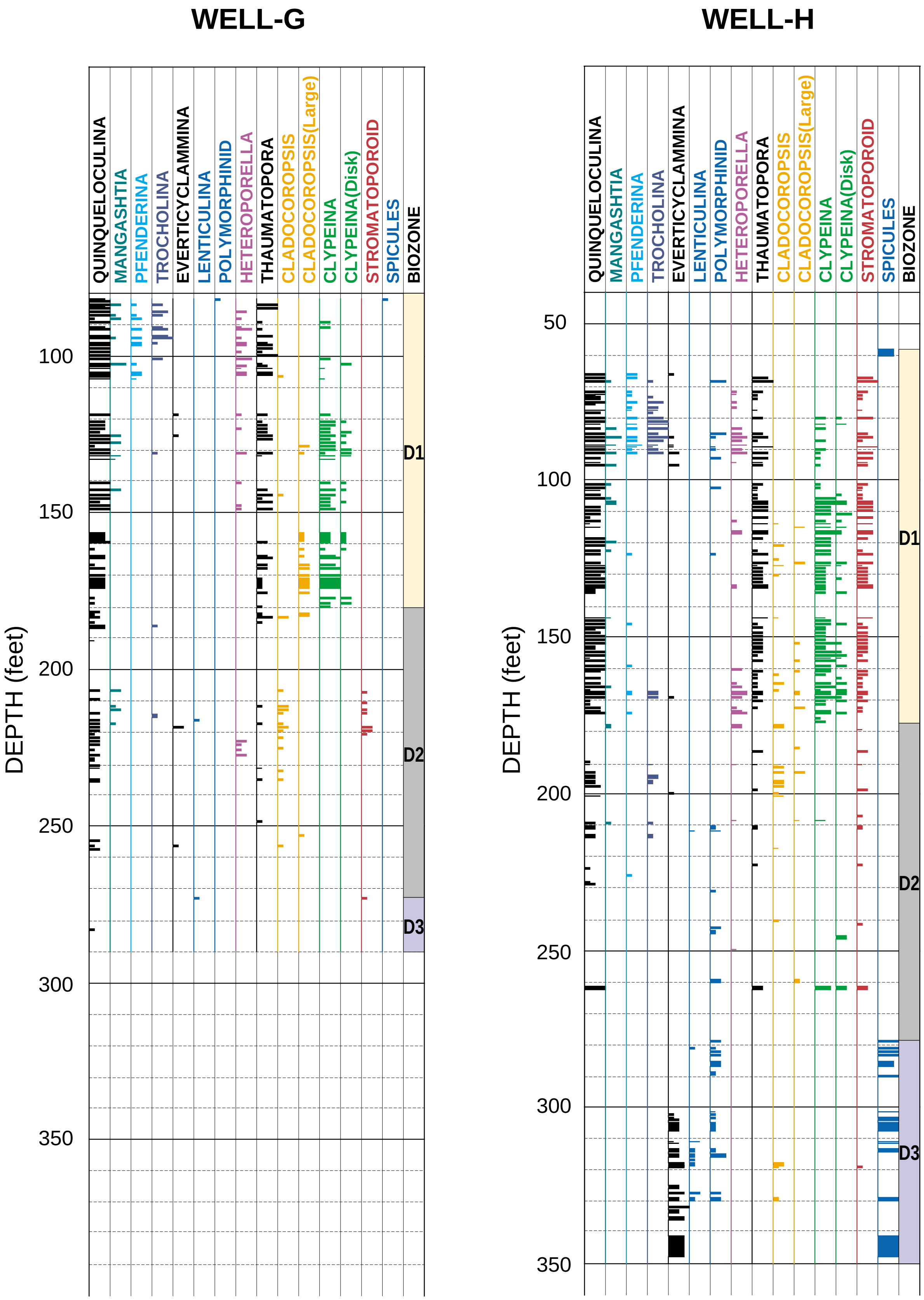

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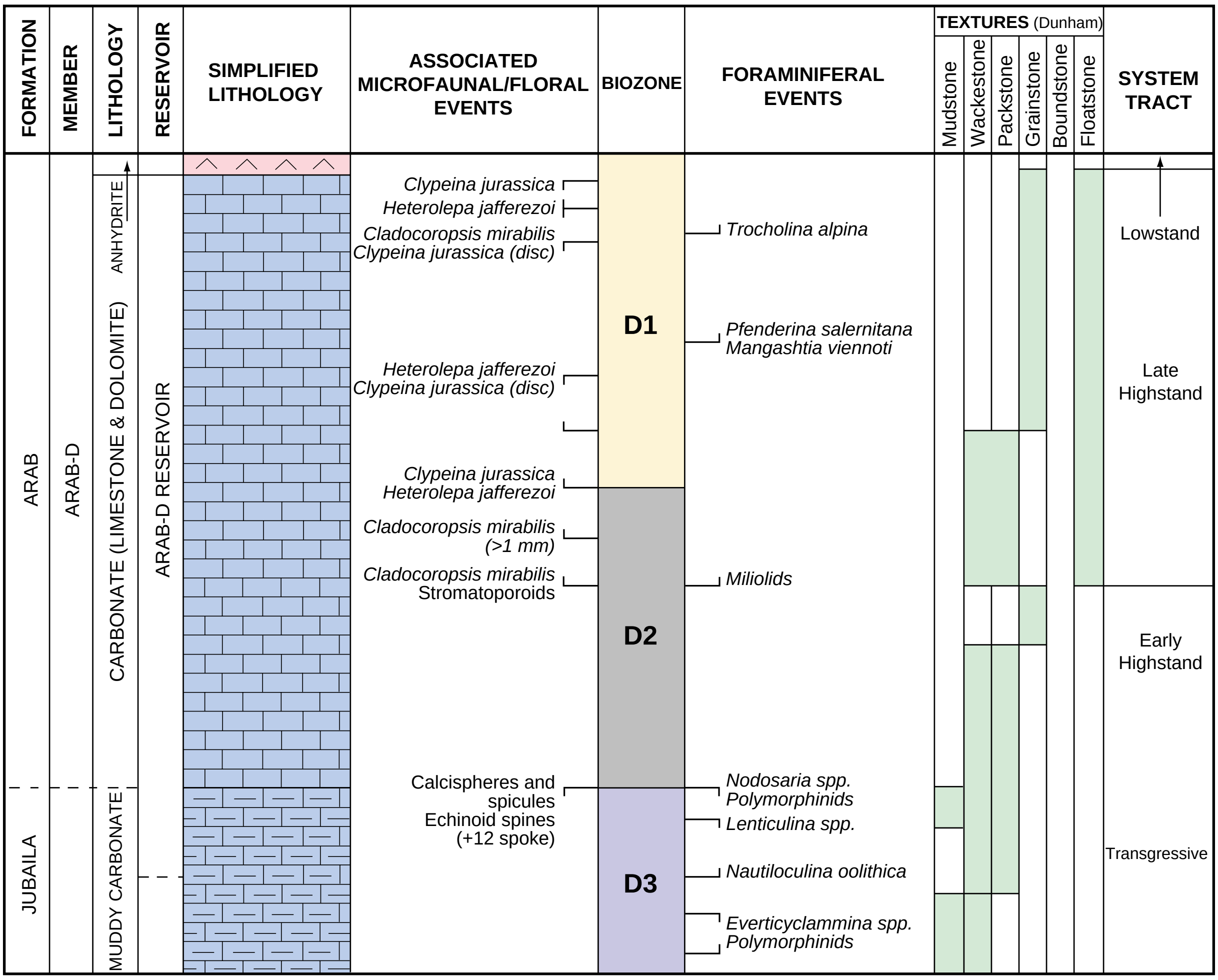


Figure 5: Microfaunal/floral and foraminiferal events detected within the carbonates of Arab-D reservoir.

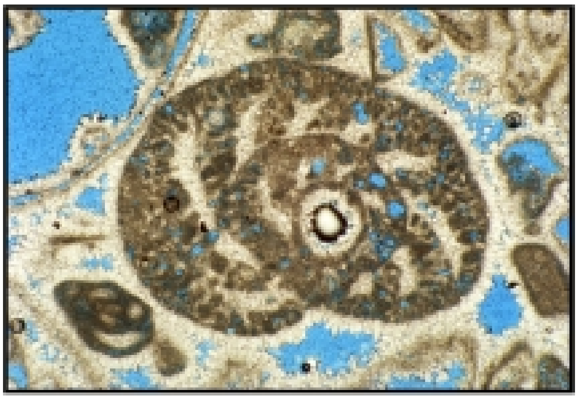
Benthonic foraminifera include undifferentiated simple miliolids, *Alveosepta jacardi/powersi, Kurnubia palastiniensis, Mangashtia viennoti, Nautiloculina oolithica, Pfenderina salernitana Pseudocyclammina* sp. and *Trocholina alpina*. In addition, the localised distribution of smaller calcareous benthonic foraminiferal genera, including *Lenticulina* spp., *Nodosaria* spp., *Stilostomella* spp. and undifferentiated polymorphinids were also recorded. Non-foraminiferal faunal bioclasts include calcispheres and a variety of sponge spicules, bivalve, bryozoan, gastropod and worm tube fragments together with echinoid debris, of which small spines with greater than 10 ribs were recorded separately.

MICROPALAEONTOLOGICAL LAYERING AND PALAEOENVIRONMENTAL INTERPRETATION

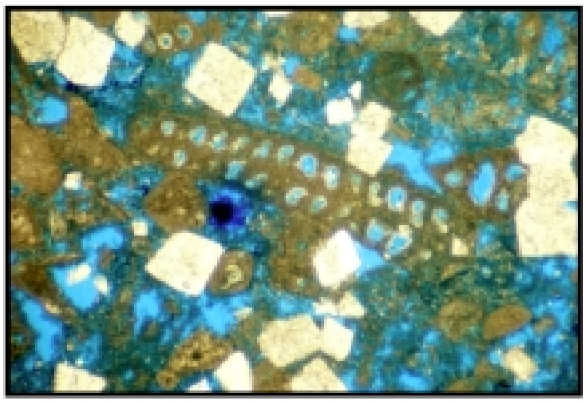
Recent interest in the palaeobiological stratification of the Arab-D Reservoir, which includes the Arab-D Member carbonates and of the upper Jubaila Formation, results from the need for an improved understanding of the reservoir/depositional layers and their regional continuity. High resolution micropalaeontological analysis has revealed the presence of numerous microfaunal and microfloral events which may serve as guides for the calibration of core-based lithological variations and well-logs, and to identify regionally traceable depositional layers. The carbonates of the Arab-D Reservoir contain a moderately high diversity of species, of which benthonic foraminifera are typically dominant; bivalve, echinoid, calcareous algae and stromatoporoid debris is also well represented. *Kurnubia palastiniensis* and *Nautiloculina oolithica*, echinoid and bivalve debris persist throughout the reservoir section, and are therefore of limited correlation value. Stratigraphic distribution of the non-persistent species, however, defines three major bio-assemblages which permit the designation of three local biozones D1, D2 and D3, in descending stratigraphic order (Figure 6). Biozone D3 is restricted to the deep marine biofacies which approximates with the Jubaila Formation. Biozones D2 and D1 are within the Arab-D carbonates. There is also a potential for recognising consistently present biofacies subdivisions within these biozones, and these may well prove to provide useful subzones to the existing scheme.

PLATE 1

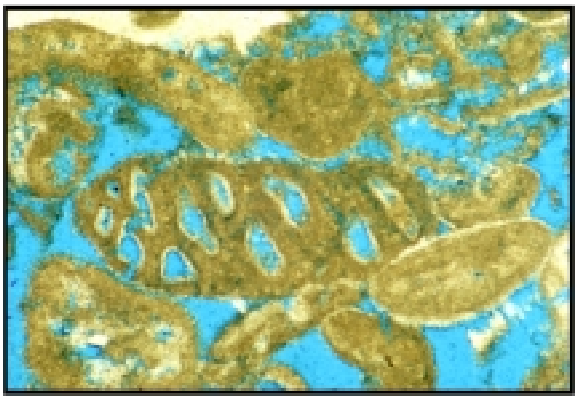
Photomicrographs of Selected Biocomponents of the Arab-D Reservoir



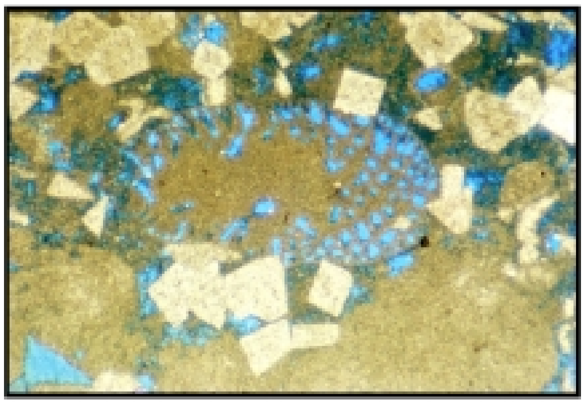
Alveosepta sequana/jacardi. (1.0 mm diameter)



Mangashtia viennoti (1.0 mm length)

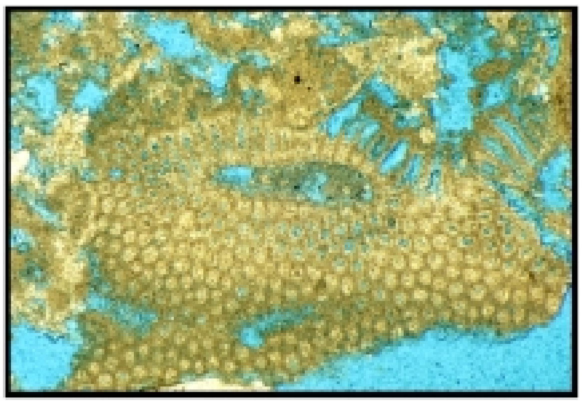


Pfenderina salernitana (0.58 mm length)

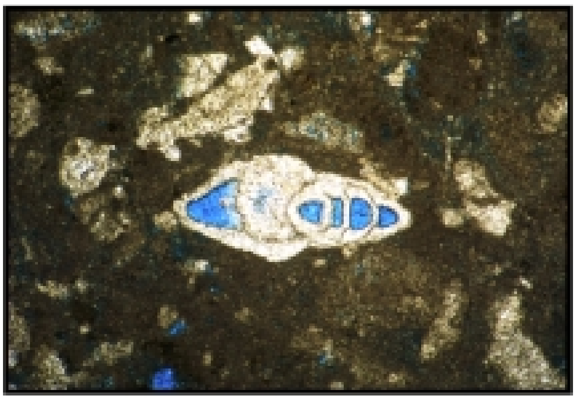


Kurnubia palastiniensis (0.75 mm length)

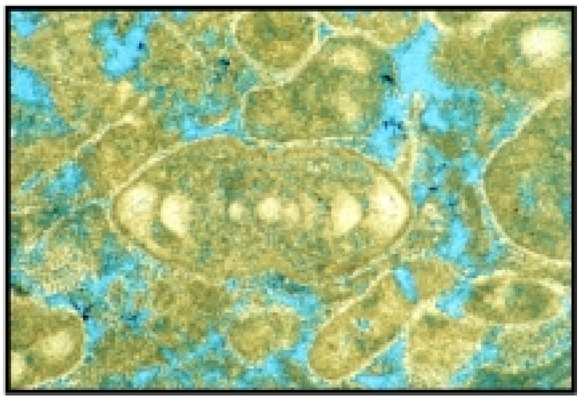
Cladocoropsis mirabilis (2.94 mm maximum width)



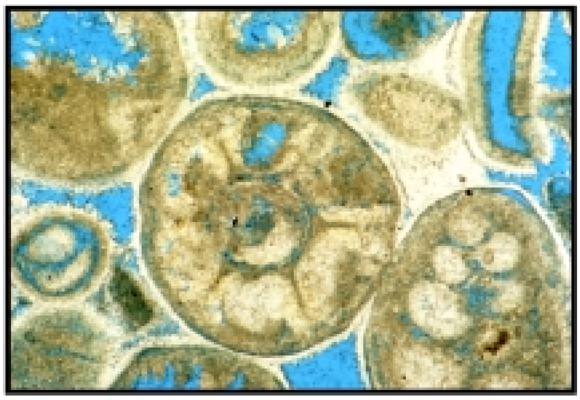
Thaumatoporella parvovesciculifera (0.94 mm maximum width)



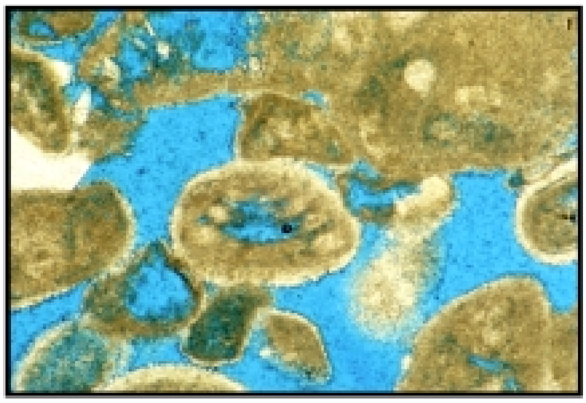
Lenticulina sp. (0.48 mm diameter)



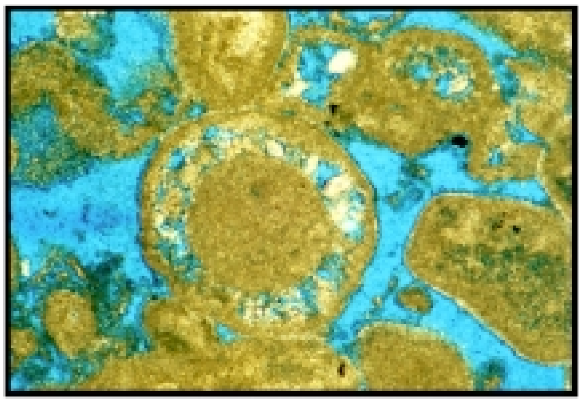
Nautiloculina oolithica (0.56 mm diameter)



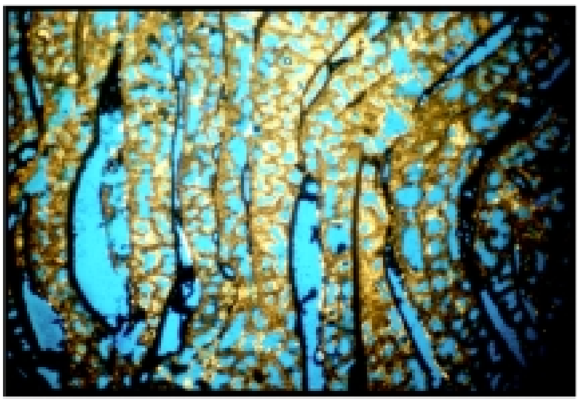
Clypeina jurassica (0.47 mm disc diameter),



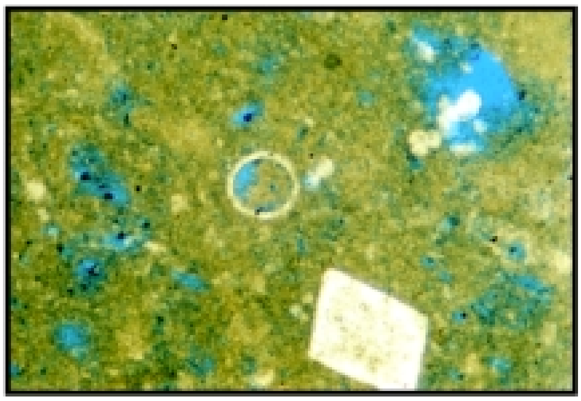
Trocholina alpina (0.4 mm diameter)



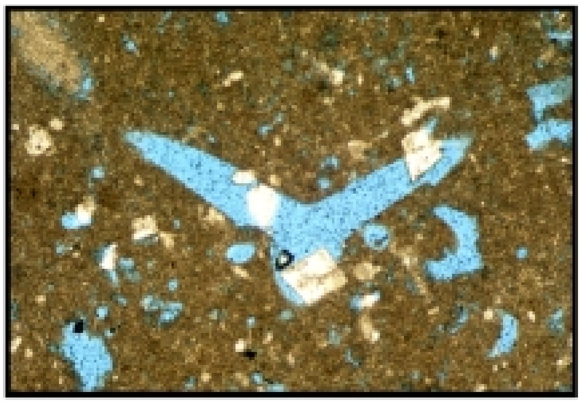
Heteroporella jafferezoi (0.46 mm diameter)



Stromatoporoid



Calcisphere (0.1 mm diameter)



Sponge spicule (0.58 mm maximum dimension)

Biozone D3 (upper Jubaila Formation)

A lower section of the Arab-D reservoir, which includes the upper part of the Jubaila Formation and, at some localities the basal Arab-D carbonates, is characterised by species of *Lenticulina*, smooth and hispid *Nodosaria* species, *Bolivina* species, indeterminate polymorphinids, *Alveosepta jacardi/powersi*, calcispheres, monaxon and tetraxon sponge spicules, intensively-ribbed echinoid spines and smooth and hispid calcispheres (Figure 6). These are considered to represent in situ deeper marine forms into which allochthonous shallower marine forms, such as *Kurnubia palastiniensis* and *Nautiloculina oolithica*, were continually transported. Large bivalve fragments and miliolids are locally present at levels that seem to coincide with packstones, and form the lower parts of upwards grading, mudstone-dominated cycles that are considered to be storm-generated distal turbidites (Meyer and Price, 1993). These were deposited under low energy, normal salinity conditions below storm wave base and are interpreted to represent deposition at water depths well in excess of 25 meters, and possibly into the middle or outer shelf, based on the presence of species of *Lenticulina*, hispid nodosarids and *Everticyclammina* (Johnson, 1975; Murray, 1991).

Figure 6: Vertical micropalaeontological variations within individual depositional layers characteristic of the lower, middle and upper parts of the Arab-D reservoir.

Biozone D2 (Arab-D carbonate, lower part)

The deeper marine benthonic foraminiferal species that characterise Biozone D3 of the underlying mud-dominated section of the Jubaila Formation are absent within Biozone D2, the base of which approximates with the base of the Arab-D carbonates. Species that maintain a constant presence within Biozone D2 include *Kurnubia palastiniensis, Nautiloculina oolithica*, echinoid and bivalve debris, scattered stromatoporoids and *Cladocoropsis mirabilis*, and miliolid foraminifera (Figure 6). Cycles are evident in which the upper parts typically contain *Pfenderina salernitana, Trocholina alpina, Praechrysalidina* sp., *Mangashtia viennoti*, elongate *Textularia* spp., *Thaumatoporella parvovesciculifera, Heterolepa jafferezoi, Salpingoporella* spp. and rare *Clypeina jurassica.* This biozone consists predominantly of wackestones and packstones with thin intermittent mudstones which are arranged in upward-cleaning facies assemblages and include 'muddying upward beds'. Dolomite has preferentially replaced the mudstones. A carbonate shelf environment is interpreted, with alternating low and moderately high energy, probably the result of periodic shoaling to within the zone of wave agitation. Regional evidence suggests that the shelf may have evolved into an extensive shelf lagoon under the influence of a stromatolitic and / or oolitic rim to the east.

With reference to Figure 4, it is apparent that Biozone D2 displays a variable thickness across the area, with the shorter sections being present at localities A, B, C and F; thicker sections of this biozone are present at D, E, G and H. A possible explanation of this variation is that the deeper marine conditions were terminated earlier at the sites where the shallower biofacies of Biozone D2 are thicker. This interpretation thus suggests that deeper marine conditions of Biozone D3 persisted longer at localities where Biozone D2 is thinnest.

Biozone D1 (Arab-D carbonate, upper part)

Biozone D1 contains the persistence of certain species which were present in Biozone D2, and include *Kurnubia palastiniensis, Nautiloculina oolithica,* echinoid and bivalve debris and miliolids (Figure 6). It is, furthermore, characterised by the consistent presence of *Pfenderina salernitana, Trocholina alpina, Mangashtia viennoti, Thaumatoporella parvovesciculifera, Heterolepa jafferezoi* and *Clypeina jurassica*, that are typically restricted to the upper parts of cycles within the biozone. The upper parts of each cycle within Biozone D1 are characterised by the presence of *Praechrysalidina* spp., *Pseudocyclammina* spp., *Spiroloculina* spp., *Cylindroporella sugdeni* and short, stubby forms of *Textularia* spp. Packstones predominate and suggest moderately high energy conditions, and water depths within the effects of wave base i.e. considerably shallower than 15 meters and possibly intertidal towards the uppermost part prior to the deposition of the anhydrites. A shallow carbonate shelf environment of normal marine salinity is thus concluded. The Arab-D carbonates are overlain by Arab-D anhydrites, which are barren of foraminifera. The 'post Arab-D stringer', within the anhydrite, is a carbonate which contains bio-components similar to those of the upper section described above.

It is possible to detect the component cycle boundaries within most of the studied sections (Figure 7) and these present potentially correlatable datums for event, depositional and reservoir stratigraphy. The individual event characteristics, although too numerous to list here, include the multiple local top and bottom occurrences of the biocomponents listed in Figures 5 and 6. The relatively short distance between the study wells would lead one to suspect that the micropalaeontological events should be isochronous, within geological terms. There is evidence, however, that the base of Biozone D2 represents a shallowing event which progressively took place across the region at different times. This is further supported by the delayed appearance of *Clypeina jurassica, Pfenderina salernitana* and *Kilania* sp. until the Arab-C Member offshore Abu Dhabi (Al-Silwadi et al., 1996). Figure 7 also illustrates the validity of biostratigraphic correlation between adjacent wells, with other biostratigraphic events taking over, in relay fashion, linking other neighbouring wells where different bioevents are present.

SEQUENCE STRATIGRAPHIC INTERPRETATION

Sequence stratigraphic interpretation of shallow marine carbonates based upon the technique of high-resolution micropalaeontology, as described in this study, is a new approach in an attempt to decipher the cryptic layering of carbonate reservoirs. The sequence stratigraphic interpretation of bioevents identified in the Arab-D reservoir is based exclusively upon the micropalaeontological component

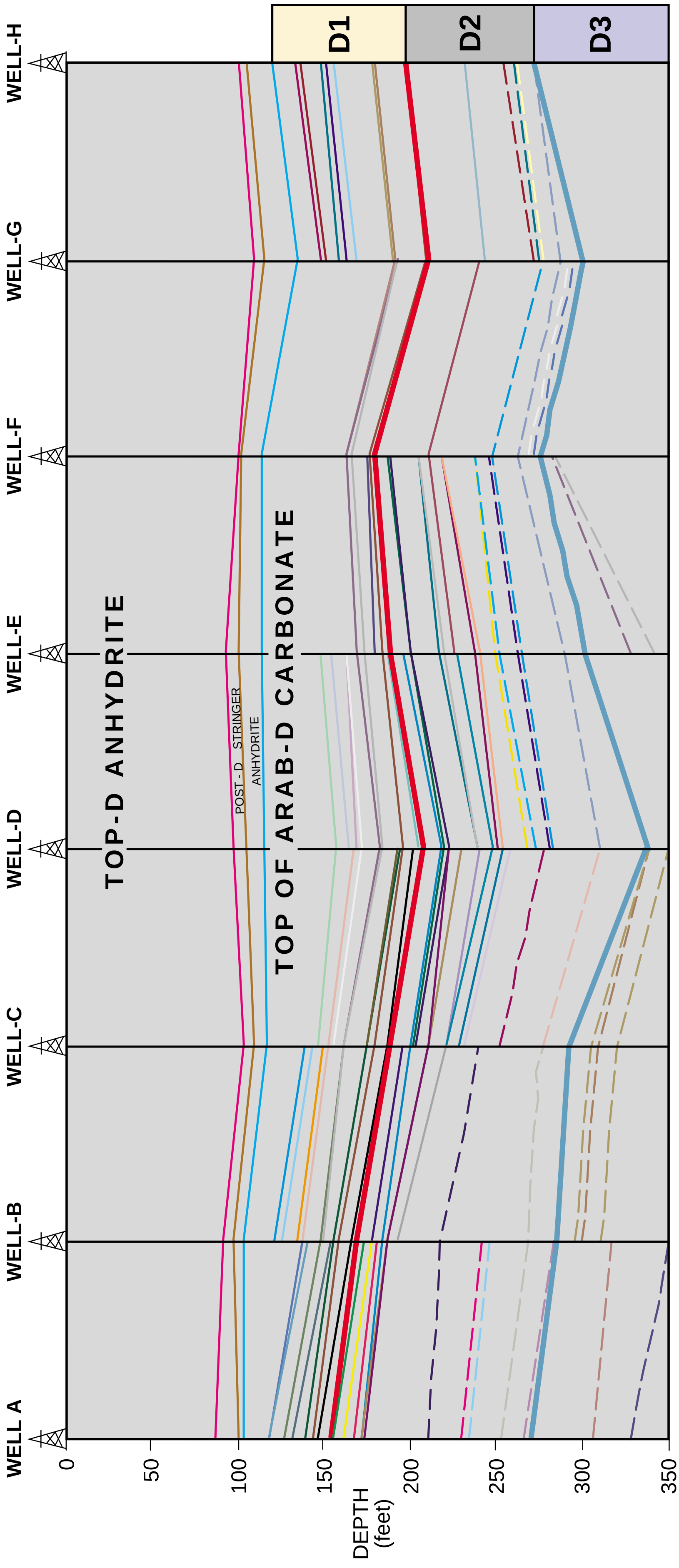


Figure 7: Correlation of the main micropalaeontologically-determined events between the studied well sections of the Arab-D reservoir.

variability and diversity, following the style previously used only for deep marine siliciclastic sediments (Armentrout, 1990; Armentrout and Clement, 1990; Armentrout et al., 1990). Carbonates of the Arab-D Reservoir are considered to represent progressive infilling of an intra-shelf basin and display biocomponent responses to transgressive, early and late highstand components of a major eustatic cycle, possibly of third-order magnitude (Le Nindre et al., 1990). The micro-cyclic nature of the bio-components within the studied section, on a scale of between 4 and 35 feet (1 - 11 m approximately), suggests that they possibly represent fourth- or fifth-order eustatic cycles superimposed on the third-order cycle, and which assist important parasequence stacking patterns to be recognised. Hydrocarbon reservoirs in platform carbonates commonly show that reservoir layers occur within 1 to 15 m thick, upwards coarsening lithofacies units, which were the response of upwards shallowing depositional environments (Harris et al., 1993).

Although there is an apparent 'layer-cake' character to the bioevent correlation (Figure 7), and apparent absence of a diachronous, laterally migrating belt of progressively shallower biofacies basinward, the variation in relative depth in the Arab-D carbonate of Biozones D3 and D2 (Figure 4) suggests that shallower conditions commenced earlier at well localities D, E, G and H, which are situated in an approximately axial position within the present Ghawar structure. At localities A, B, C and F, along the flanks of the structure, the shallower conditions of Biozone D2 apparently developed later. This implies that the deeper marine sediments of the uppermost part of Biozone D3 were accumulating on the flanks of the structure at the same time that shallower marine sediments of Biozone D2 were accumulating along the axis. From this axial position, the shallower marine sediments of Biozone D2 gradually prograded laterally into the deeper marine regions on both sides of the depositional high. Alternatively, it is possible that higher sedimentation rates and/or subsidence rates took place preferentially on the flanks, resulting in a thicker D2 zone. Unfortunately, only two of the study wells have been cored deep into Biozone D3, but in wells B and H, the presence of *Everticyclammina* at a similar stratigraphic level suggests that the deep marine sediments were possibly deposited in extensively similar palaeobathymetric conditions. This biozone is interpreted to have occurred during a major marine transgression, as there is no evidence for shallowing up within the assemblages, and a transgressive systems tract may be interpreted and searched for in detailed seismic studies.

The finer-scaled cyclic layers within Biozones D2 and D1 display well-defined upwards variations in the micropalaeontological assemblage components, abundance and diversity. In Biozone D2, this shallowing upwards trend suggests a delayed response to a rapid rise in sea level, and that carbonate productivity was capable of 'catching-up' with the new sea level. The bioassemblages in Biozone D1 are less well differentiated, however, and the absence of moderately deep marine species - such as *Cladocoropsis mirabilis* and *Salpingoporella* sp. suggest deposition in persistently shallower water, possibly less than 5 m, (Banner and Simmons, 1994) with possibly higher rates of productivity - or slower rates of periodic eustatic sea level rise, enabling these carbonates to 'keep-up' with the rising sea level. The absence of anhydrites within Biozone D1 suggests that if emergence took place, it was short-lived and insufficient for sabkhas to become established. Micropalaeontological assemblages of the Arab-D carbonates display progressively shallower conditions, and are considered to represent aggradational and progradational deposition resulting from highstand conditions. Biozone D2 displays the effects of shallowing upwards cycles within an episodically fluctuating sea level which was never very shallow. Shallow marine foraminifera are only sporadically present, and always at the top of each shoaling upwards cycle, and therefore represent the shallowest sea level attained during that particular depositional episode.

The first consistent uphole occurrence of *Clypeina jurassica* and an abundance of miliolids locate the boundary between Biozones D2 and D1. The sporadic occurrence of this species within Biozone D2 may be the result of lateral reworking from axially-positioned shallow areas which shed fragments of this species into deeper flank areas, thus heralding the inevitable arrival of the prograding shallower, *Clypeina*-dominated environment.

The mud-lean packstones and grainstones at the top of the Arab-D carbonates, together with the overlying anhydrites, are considered to represent shallower sediments of late and latest highstand respectively, and proximity to the end of the Arab-D sequence. The anhydrites were deposited within an extensive supratidal sabkha environment which terminated the deposition of carbonates. It is possible that these anhydrites were also diachronous and prograded into the gradually shallowing Arab-D carbonate basin.

An alternative view held by some workers is that the anhydrites represent sabkha conditions of the next lowstand, and are separated from the Arab-D carbonates by a sequence boundary. The micropalaeontological evidence of decrease species diversity and predominance of hypersaline-tolerant species within the uppermost carbonates of the Arab-D would tend to be more consistent with a transitional, increasingly hypersaline environment which would be expected to have prevailed prior to the establishment of the extreme, biotically-hostile sabkha conditions associated with the latest highstand. In the Emirates, limited information provided by de Matos (1994) indicates that basal carbonates of the Arab-C contain deeper marine elements similar to those recovered from the uppermost Biozone D3 of the present study, and would therefore support a transgression commencing at the top, rather than base, of the Arab-D anhydrite. Basal Arab-C carbonates within the Ghawar area have not been analysed in the method outlined in this study, and this should take place in order to elucidate the positioning of the sequence boundary.

CONCLUSIONS

Gradual shallowing of the Arab-D reservoir carbonates has been confirmed by high resolution, semi-quantitative, polyphyletic micropalaeontological analysis. Superimposed upon this macro-shallowing feature are a hitherto unrecognised fine-scale series of biocycles which reflect repetitive micro-shallowing events and changes in sea-level during the deposition of the carbonate sediments. Three composite biozones are identified, of which the lower is mostly restricted to the Jubaila Formation and the upper two lie within the Arab-D carbonate.

The lower biozone (D3) consists of a grading-upwards succession of muddy carbonates in a deep marine environment within possibly outer ‘infralittoral’ water depths into which coarser-grained shallow marine debris was periodically transported.

A middle biozone (D2) consists of mudstones to occasional grainstones with moderately deep marine bioassemblages which episodically display shallower marine bioforms, and are considered to represent shallowing upwards depositional layers that were deposited within the deeper waters of an inner ‘infralittoral’ shelf lagoon. Sediments of this biozone are interpreted to have been deposited earlier along the crest of the Ghawar region, and to have prograded into the deeper marine environment along the flanks of the regional high.

The upper biozone (D1) was deposited in shallow marine conditions within the shallow ‘infralittoral’ regime of a shelf lagoon, with the consistent presence of shallow marine bioassemblages. The trend towards ever-shallowing conditions culminated at the top of the carbonate depositional phase by the deposition of anhydrites. The small-scale biofacies cycles, and potential biosubzones, are readily correlatable between adjacent wells, up to 40 km apart.

It is considered that these small cycles may provide a new tool for the recognition of depositional cycles within the Arab-D, and thereby assist the lateral modelling of reservoir layers which has been hitherto hindered by poor log variation and by the irregular development of dolomite beds.

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ABOUT THE AUTHOR

Geraint Wyn Hughes *holds PhD, MSc and BSc degrees from the University College of Wales, Aberystwyth, and has been a Micropaleontologist/Stratigrapher with Saudi Aramco for the past 4 years. He has over 20 years experience in stratigraphy, of which 10 years were with the Solomon Islands Geological Survey, and 10 years of biostratigraphic consultancy of North Africa, the Middle East, Australasia, the Americas and the North Sea with Robertson Research in Singapore and the United Kingdom. He is a Fellow of the Cushman Foundation for Foraminiferal Research, and a member of the British Micropaleontological Society and the Dhahran Geological Society.*

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