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New Insights into Regional Correlation and Sedimentology, Arab Formation (Upper Jurassic), Offshore Abu Dhabi

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ABSTRACT

Correlation uncertainties within the Arab Formation reservoirs of the Ghasha-Bu Tini field were resolved with a combined biostratigraphic and lithostratigraphic study. A chronostratigraphic framework was established based on the type and reference localities elsewhere on the Arabian Peninsula. Construction of a regional biozonation scheme for the entire Arab Formation resulted in a downward shift of the Arab C-D unit boundary by approximately 100 feet in the field, which was reconcilable with a lithological change from anhydrite to dense limestone at that stratigraphic horizon.

As a result of the modified Arab C-D boundary, younger boundaries in the Arab Formation were adjusted. These secondary adjustments were assisted by the identification of lithological markers such as thrombolitic horizons, charophytic bands and distinctive anhydrite layers. These horizons were constrained (in a broad sense) by the new biozonation scheme. Ghasha-4 is introduced as a candidate reference well for the Arab Formation of western Abu Dhabi and could be used to adjust reservoir boundaries in other fields. In this manner, not only could regional consistency be ensured, but further insights in exploration could be gained.

Evidence for the occurrence of subaqueous sulphate deposits is discussed. Subaqueous anhydrites comprising palisades of subvertically orientated nodules exist at all levels within the upper Arab Formation, but the case is made for thicker, nodular anhydrites interbedded with subtidal stromatolites also having formed subaqueously.

INTRODUCTION

Ghasha-Bu Tini field is located in western offshore Abu Dhabi (Figure 1) and measures 40 by 37 kilometers (km). It was discovered in 1970 and 14 exploration and appraisal wells have been drilled to date with spacing varying from 3.7 to 9 km. The field contains several stacked reservoirs within the Arab Formation but their hydrocarbon types vary both vertically and laterally, which raised significant concerns regarding the adequacy of the reservoir layering scheme that had traditionally been governed by correlations of anhydrite layers.

The seismic definition of the Arab Formation reservoirs in Ghasha-Bu Tini is extremely poor and so seismic stratigraphy could not be used to resolve their internal architectures. Instead, a study which combined biostratigraphical, sedimentological, fluid and test analysis was undertaken. This paper summarises the geological aspects of the study which was completed during 1990. It discusses its impact on regional correlations and re-assesses traditional sedimentological interpretations and stratigraphic significances of some anhydrite layers within the Arab Formation.

LITHOSTRATIGRAPHY

The stratigraphic nomenclature of the Upper Jurassic (Figure 2) in the Arabian Peninsula has been historically complex and confused. This stems from: (1) inconsistent correlations across political borders where lithostratigraphic names may change without appropriate change in facies/lithology; (2) different lithostratigraphic schemes within a country introduced by different oil companies; (3) the imprecise manner in which certain lithostratigraphic units have been defined and mis-correlated across a region.

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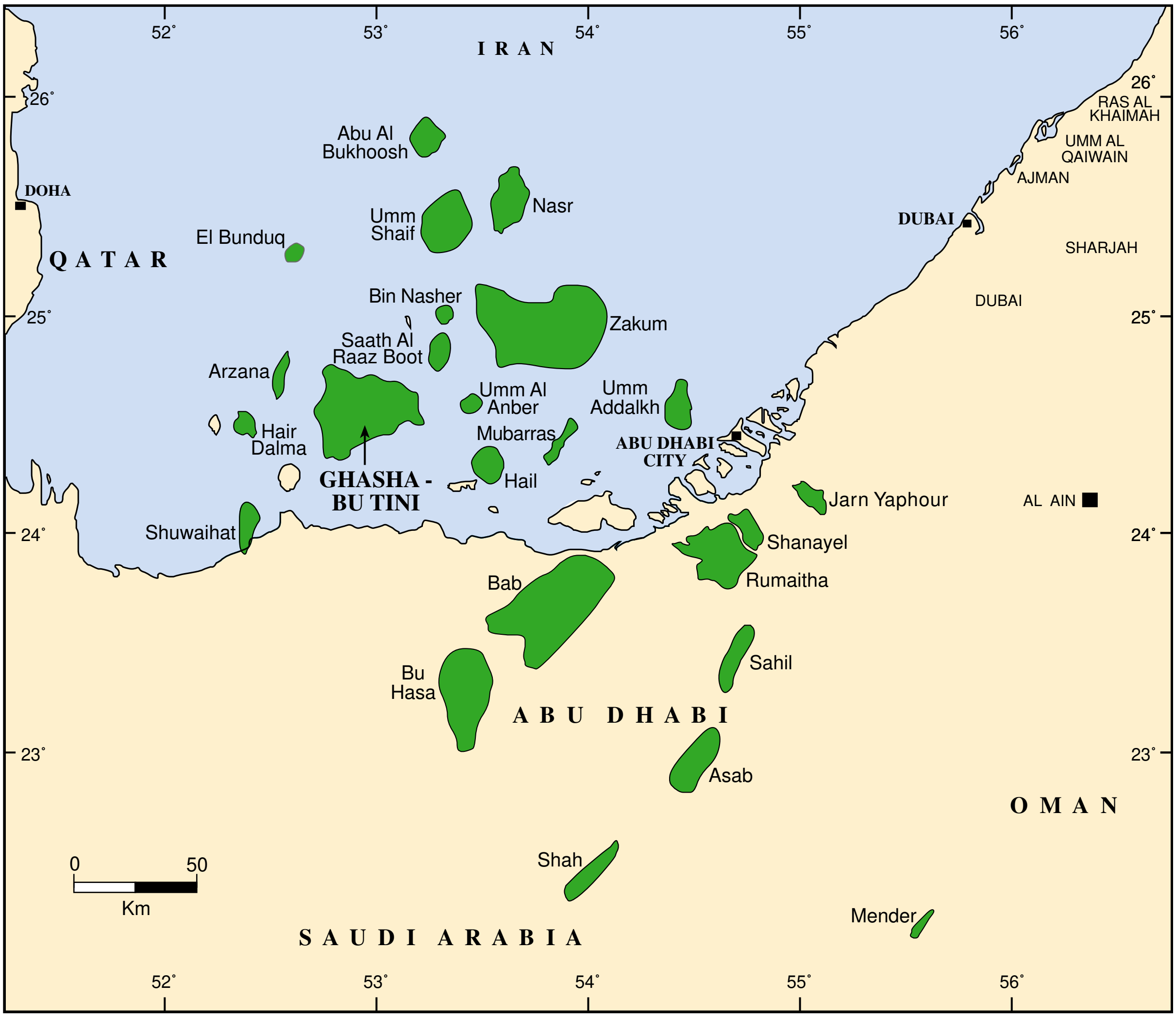

Figure 1: Location Map

Figure 3 summarises the historical usages of the published terminologies. Most of the differences have occurred in the pre-Arab stratigraphy (de Matos, 1994) but it is not the intention of this paper to address these problems. There has fortunately been consistency in the usage of the term, Hith Formation, to describe the thick anhydrites which cap the Arab Formation at the top of the Upper Jurassic; and in the practice of subdividing the Arab Formation into four producing units (A,B,C and D) separated by dense lithological units, although the placing of unit boundaries has not always been consistent.

The terms "Hith" and "Arab" were introduced in Saudi Arabia to describe the cyclic carbonates and anhydrites which form important reservoirs and seals in the eastern part of that country. They were fully described by Powers (1968) who used Dammam-7, Saudi Arabia, as the type well for the Arab Formation. The similarity between the succession in Saudi Arabia and western and central Abu Dhabi led to the informal adoption of Arab and Hith formations by operating companies in Abu Dhabi. However, a separate nomenclature was introduced in Qatar (Sugden and Standring, 1975) which also came to be used in parts of Abu Dhabi. The term Hith Formation was retained in Qatar for the major evaporitic unit at the top of the sequence, while the Arab Formation equivalent sediments were subdivided into two formations: the Qatar Formation and the Fahahil Formation. Nevertheless, modern workers in Qatar use the original A, B, C and D nomenclature in describing the Arab Formation.

Thick anhydrites subdivide the Arab Formation of Saudi Arabia and Qatar into the four producing units, but anhydrites are not abundant within the producing units. Intra-unit anhydrites are more common (though often discontinuous) in western offshore Abu Dhabi where they generally increase in thickness and frequency upwards within the Arab A, B and C producing units. These successive intra-unit anhydrite beds generally extend progressively eastwards (Hawas and Takezaki, 1995) before pinching

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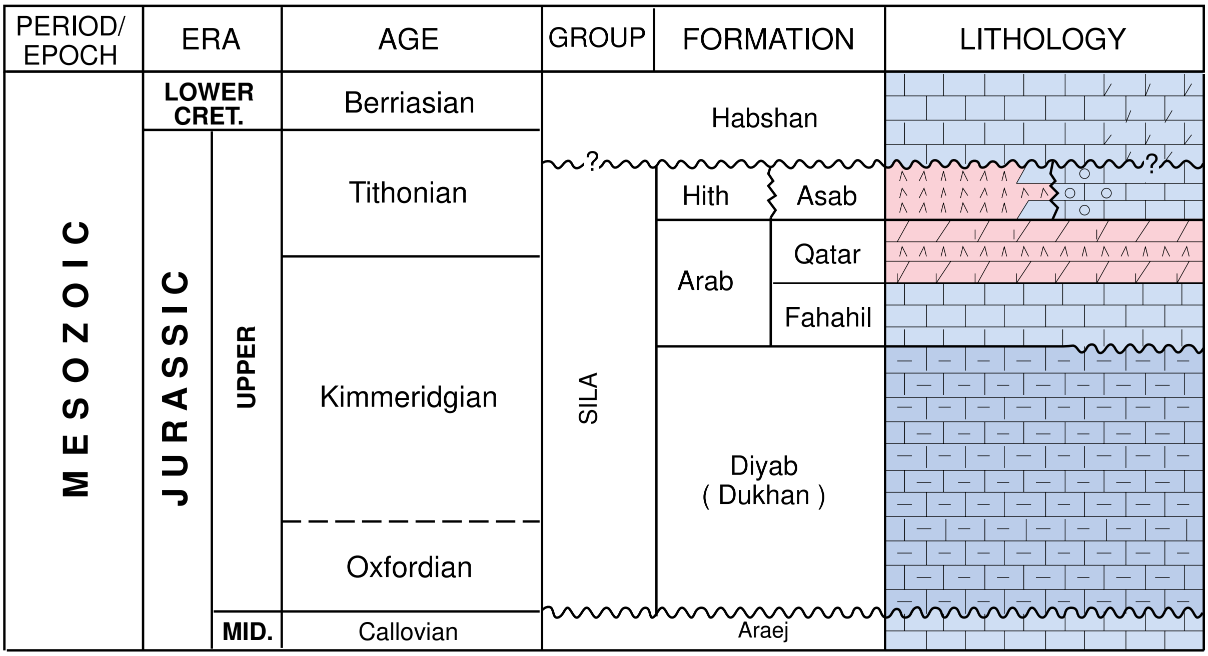

Figure 2: Summary stratigraphic column for the Upper Jurassic sediments of Abu Dhabi.

out into laterally equivalent carbonates (Figure 4). These gross lateral lithology changes are clearly evident even within the Ghasha-Bu Tini field. The Arab Formation is not present over eastern offshore Abu Dhabi.

Conversely, thin dolomite beds occur within the inter-unit anhydrites (Upper, Middle and Lower Anhydrites) of the Arab Formation and also within the Hith Formation. These dolomites are common within the lower Hith Formation of Ghasha-Bu Tini field and have led to uncertainties on where to place the Arab-Hith boundary. For the purpose of this study, the boundary was chosen at the top of the uppermost field-wide porous dolomite in Ghasha-Bu Tini.

In Abu Dhabi, the Arab Formation represents part of a large shallowing-upwards cycle with the Arab D dominantly representing relatively shallow water, subtidal sediments which have prograded over deeper water, organic-rich, intra-shelf basinal deposits of the Diyab Formation. In northern Abu Dhabi, the upper Arab D is highly anhydritic. As in Ghasha-Bu Tini, there is often a sharp log break at the Arab-Diyab boundary which may indicate a minor discontinuity in sedimentation. The succession of the overlying Arab units reflects increasingly restricted, eastwards prograding carbonate parasequences with peritidal and lagoonal sediments becoming dominant and increasingly associated with anhydrites. The overlying Hith Formation represents the final phase of the restriction towards the end of Jurassic time. It forms the maximum eastwards extension of the evaporites and the Hith edge approximately demarcates the two main Abu Dhabi play fairways of the pre-Hith Arab Formation and post-Hith Thamama Group (Hawas and Takezaki, 1995).

Interbedded halite and anhydrite within the Gotnia Formation forms the Arab Formation equivalents northwestwards, near Kuwait (Ali, 1995). The Asab Oolite and carbonate grainstones of the Asab Formation (an informal term) are lateral equivalents of the Arab and Hith formations in eastern Abu Dhabi (Figure 4), but whether or not the Asab Oolite is stratigraphically as old as the top of the Arab D is uncertain. Strontium isotope evidence (including some Bu Tini data) showing that the Asab Oolite is stratigraphically equivalent to the Hith Formation and the Arab A was presented by de Matos (1994). Correlations are complicated by possible erosion and/or non-deposition of latest Jurassic sediments in eastern Abu Dhabi. These grainstones are interpreted as proximal to the edge of a rimmed shelf and pass even further east into shelf slope carbonates in Oman. Contrary to the interpretation by Alsharhan and Whittle (1995), they are not lateral equivalents of the Mender Glauconite of southeast Abu Dhabi, which contains calpionellids of unequivocally Berriasian age (unpublished research by M.D.Simmons) and forms part of the initial transgressive systems tract and maximum flooding surface of the lowermost sequence within the overlying Thamama Group.

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Underlying the Asab Formation in eastern Abu Dhabi and Dubai are clean carbonates which persist downwards to include the lateral equivalents of the Arab D and basinal Diyab Formation of western Abu Dhabi. These limestones form part of the Dukhan Formation (Figure 2), although locally the Arab equivalent section may also be referred to as Arab Formation or Asab Formation. In Dubai these sediments are referred to as the Fateh Formation. The precise correlation of these units to the Hith-Arab succession of western-central Abu Dhabi therefore remains problematic. A detailed discussion of the Upper Jurassic stratigraphy of onshore Abu Dhabi was provided by de Matos and Hulstrand (1995).

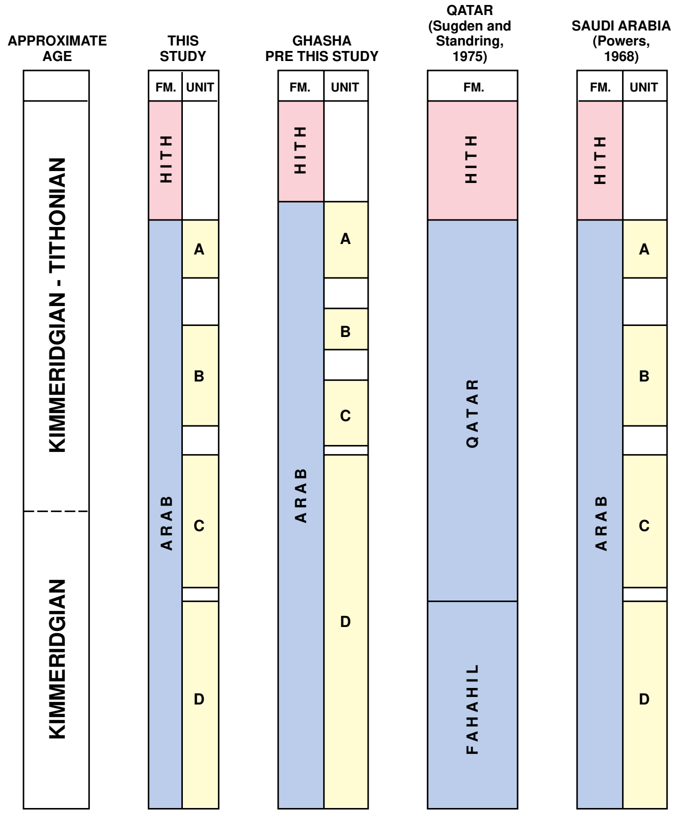

Figure 3: Historical uses of Upper Jurassic lithostratigraphic terminology.

The causes of Arab Formation cyclicity have been related to climatic and eustatic sea level fluctuations (Alsharhan and Kendall, 1986) but it seems likely that the tectonic events which led to Late Jurassic uplift and erosion in the Oman Mountains were at least partly responsible for rapidly fluctuating sea levels in the region of the Arabian Peninsula. Both tectonics and eustacy probably played a role in governing the pattern of sedimentation, but it is noteworthy that Kimmeridgian-Tithonian (the age of the Arab Formation) sediments throughout the Tethyan region often display a marked cyclicity. However, correlation with the eustatic sea level curve of Haq et al. (1987) is difficult because of the lack of precise biostratigraphic control. Correlation of the Arab Formation is possible on a local scale (see below) but precise correlation to the ammonite zones within the Kimmeridgian and Tithonian stages is not yet possible.

Arab Formation correlations have historically relied upon the use of anhydrite marker layers due to the general absence of fossils in the upper Arab strata. The anhydrites have been regarded traditionally as prograding sabkha deposits since Wood and Wolfe (1969) introduced the concept of the "ideal" sabkha cycle. However, the gross lateral variations within the Arab and Hith formations of Ghasha-Bu Tini led to possible mis-correlations both locally and regionally. Such problems may have led to the apparently inconsistent distribution of hydrocarbons in Ghasha-Bu Tini.

BIOZONATION

Supported by detailed sedimentological descriptions of several thousand feet of slabbed cores (Figure 5), the biostratigraphy of the Arab Formation from 13 Ghasha-Bu Tini wells was studied in order to: (1) constrain fieldwide wireline log correlations; (2) recognise the diachroneity of facies belts using chronostratigraphic correlation methods; (3) determine the depositional environments. Samples for biostratigraphic analysis were studied in thin-sections from the cores due to the indurated nature of the carbonates. The entire fossil assemblage was studied including: foraminifera, calcareous algae and macrofossil fragments. The general sedimentary microfacies was also recorded for each sample.

There are few publications concerning the Upper Jurassic micropalaeontology of the region. Banner and Wood (1964) included the Arab and Hith formations in their review of the Umm Shaif field, while Bozorgnia (1964), Sampo (1969) and Kalantari (1986) have illustrated Upper Jurassic microfossils from Iran. Powers (1962) illustrated and discussed some microfossils from the Arab D of northeast Saudi Arabia, while Redmond (1964, 1965) described a number of foraminifera from Jurassic sediments of Saudi Arabia for the first time. This work has been revised in part by Enay et al. (1987), Banner and

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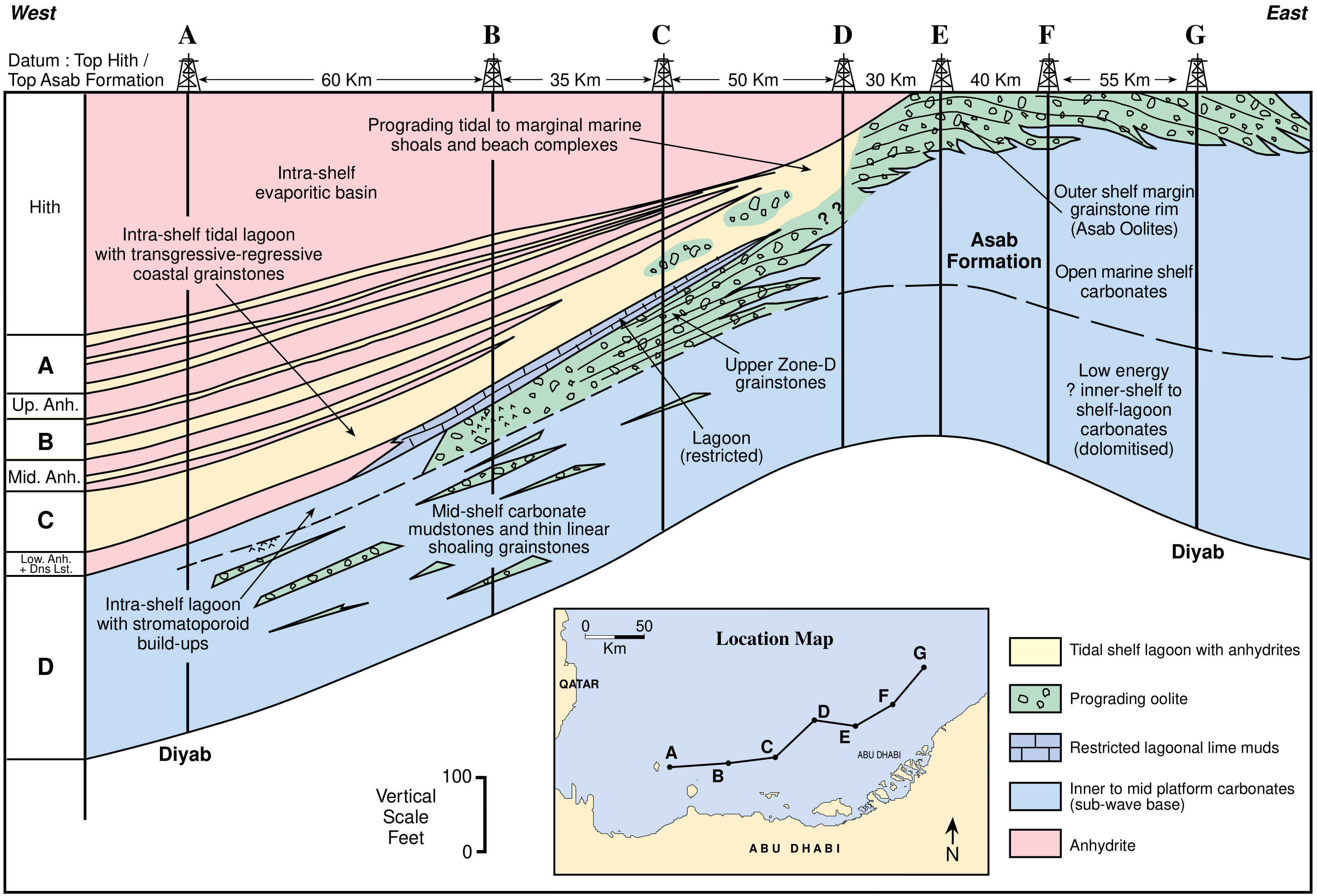

Figure 4: Schematic east-west cross-section of the Arab and Hith formations, Abu Dhabi. Note: Datum is possibly affected by erosion with the amount of truncation increasing to the east. Facies relationships are schematic.

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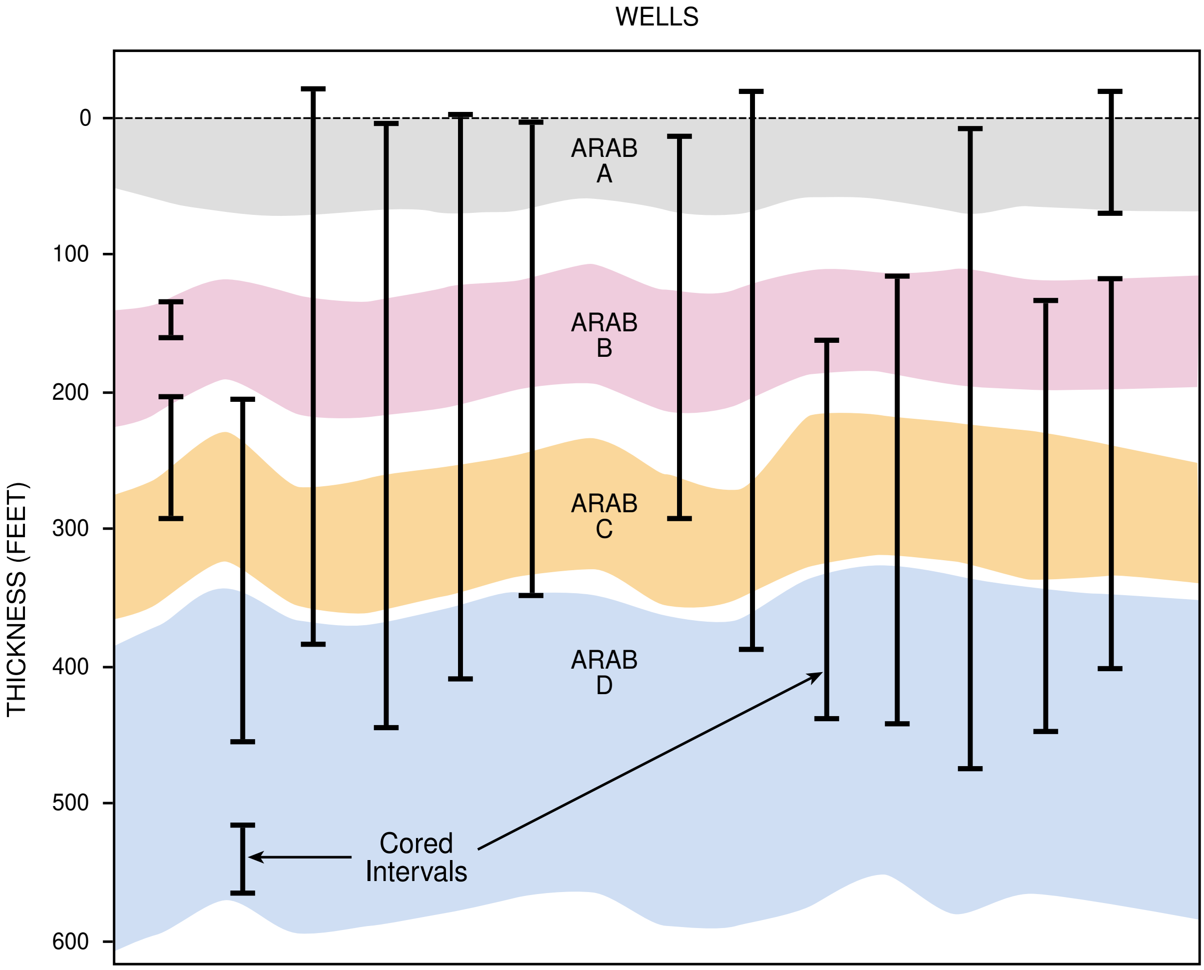

Figure 5: Ghasha-Bu Tini field core coverage. All cored intervals shown in brackets.

Whittaker (1991) and Banner et al. (1991). Many of the foraminifera first described by Redmond occur in the Arab Formation of Abu Dhabi. Toland (1994) and de Matos (1994) have provided recent data on the palaeontology and biostratigraphy of the Arab Formation in Abu Dhabi. Alsharhan and Whittle (1995) also list taxa found in the succession.

The following biozonation scheme is based upon experience acquired regionally as well as on data from Ghasha-Bu Tini. Ghasha-4 is chosen as a candidate reference well for the Arab Formation in western Abu Dhabi (Figure 6). Consistent with de Matos (1994), one of the main implications of this study is that the Arab C-D boundary had previously been picked approximately 100 ft too high in Ghasha-Bu Tini. Consequently, regional log correlations led to the lowering of the Arab B-C and Arab A-B boundaries in Ghasha-Bu Tini (Figure 3). It is therefore stressed that the following references to these Arab Formation units are done so in the context of the revised boundaries within the field.

Graphic Correlation Technique

During the course of the study, a new biozonation scheme which includes all the biostratigraphic data was developed using the semi-quantitative Graphic Correlation Technique (Figure 7; Shaw, 1964; Miller, 1977; Sweet, 1979; Harper and Crowley, 1984; Edwards, 1984 and 1985; Simmons, 1994). The technique can be summarised as one where (well or outcrop) sections are graphed against each other using fossil extinctions (tops) and inceptions (bases) as a means of developing a gradient line of correlation, which should also honour known isochronous events (for example, certain lithological markers). A Composite Standard Reference Section (CSRS) is developed which shows the maximum range of all the fossil taxa used. The CSRS can also be divided into an almost infinite number of units of equal duration which have time significance. These can be correlated to other sections by the line of correlation. Fossil ranges

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in the CSRS are progressively maximised by incorporating data from other sections.

The method has the advantage that it considers all the palaeontological data available, and thus diminishes the effects of facies control on fossil ranges and correlation. Note that because the correlation assumes a linear rate of rock accumulation there may be drawbacks to using this method in sequences where this is highly variable. However, in carbonate shelf settings such as those in which the Arab Formation of Abu Dhabi was deposited, rock accumulation rates can be considered to be relatively uniform.

This technique was successfully employed although a limiting factor was the paucity of data points with which to construct a line of correlation. Despite the higher resolution of the new scheme compared to previous schemes, it remains relatively coarse for the required correlations. Average resolution is about 520,000 years which, although very high for Mesozoic shelf carbonates, can be compared with wireline log cycles that probably have a duration of tens of thousands of years. The reason for this disparity in resolution is simply that there are few microfossils in the Arab Formation which have suitably short chronostratigraphic ranges.

Biozonation schemes generally use extinctions (tops) and inceptions (bases) of species to define zones, although local acmes are used in a few cases. Problems are introduced because, for example, the upper occurrences of a species in any given well may not be at its absolute top. In Ghasha-Bu Tini field, tops could be artificially lower and bases artificially higher because of: (1) sample spacing; (2) facies control; (3) diagenetic alteration and masking. This limits the reliability of correlating biozones. These factors do not imply that biozonal correlations are completely invalid. Such correlations are useful when dealing with major lithological units over broad regions (for example, the Arab C unit over the Ghasha-Bu Tini field).

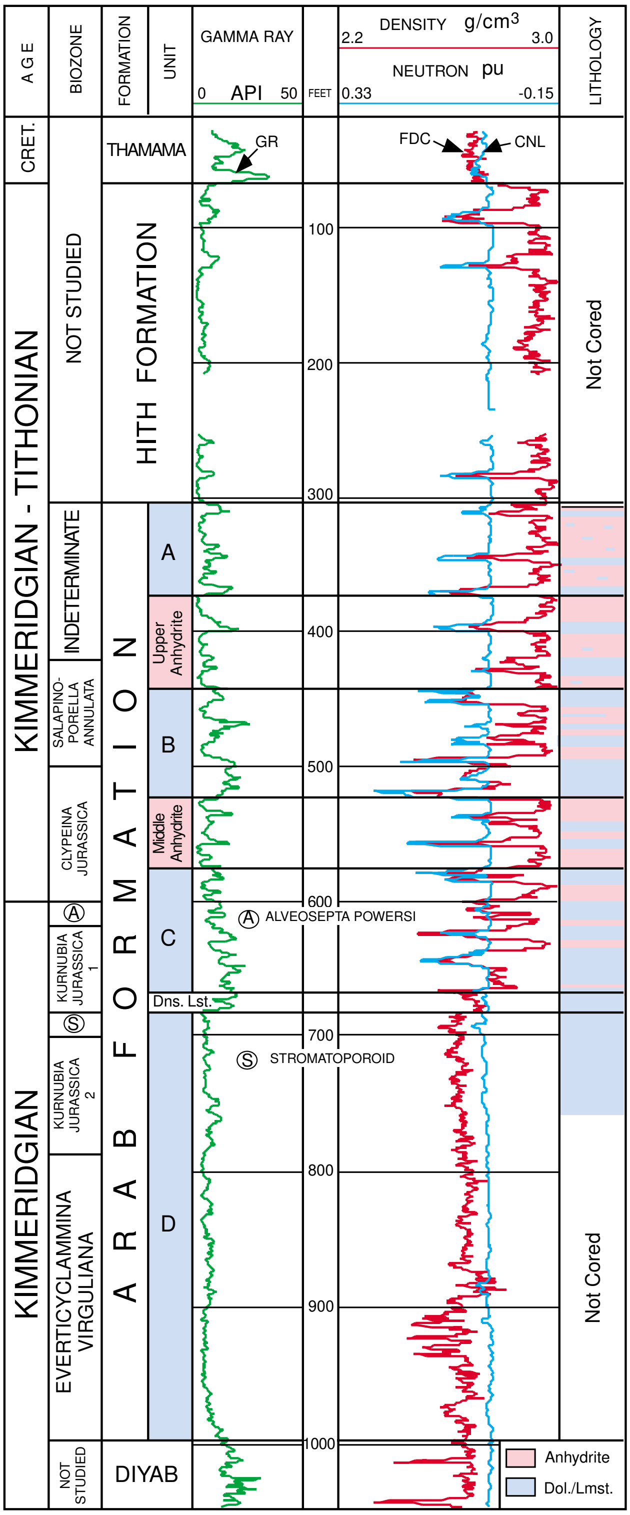

Figure 6: Ghasha-4: a candidate reference well for the Arab Formation of west-central AbuDhabi.

The lines of Composite Standard Time Units (CSTUs) suggest that, within the resolution of the study, no significant diachronism is taking place within the Arab Formation across the Ghasha-Bu Tini field. Although the facies belts represented within the Arab Formation must be diachronous to a certain degree, the migration of facies is occurring at a rate beyond current resolution across the study area. This might imply a strong eustatic control on sedimentation during the time of deposition. It also allows for a high degree of confidence in the wireline log correlations and leads to a better understanding of the hydrocarbon variations for compositional modelling within the field.

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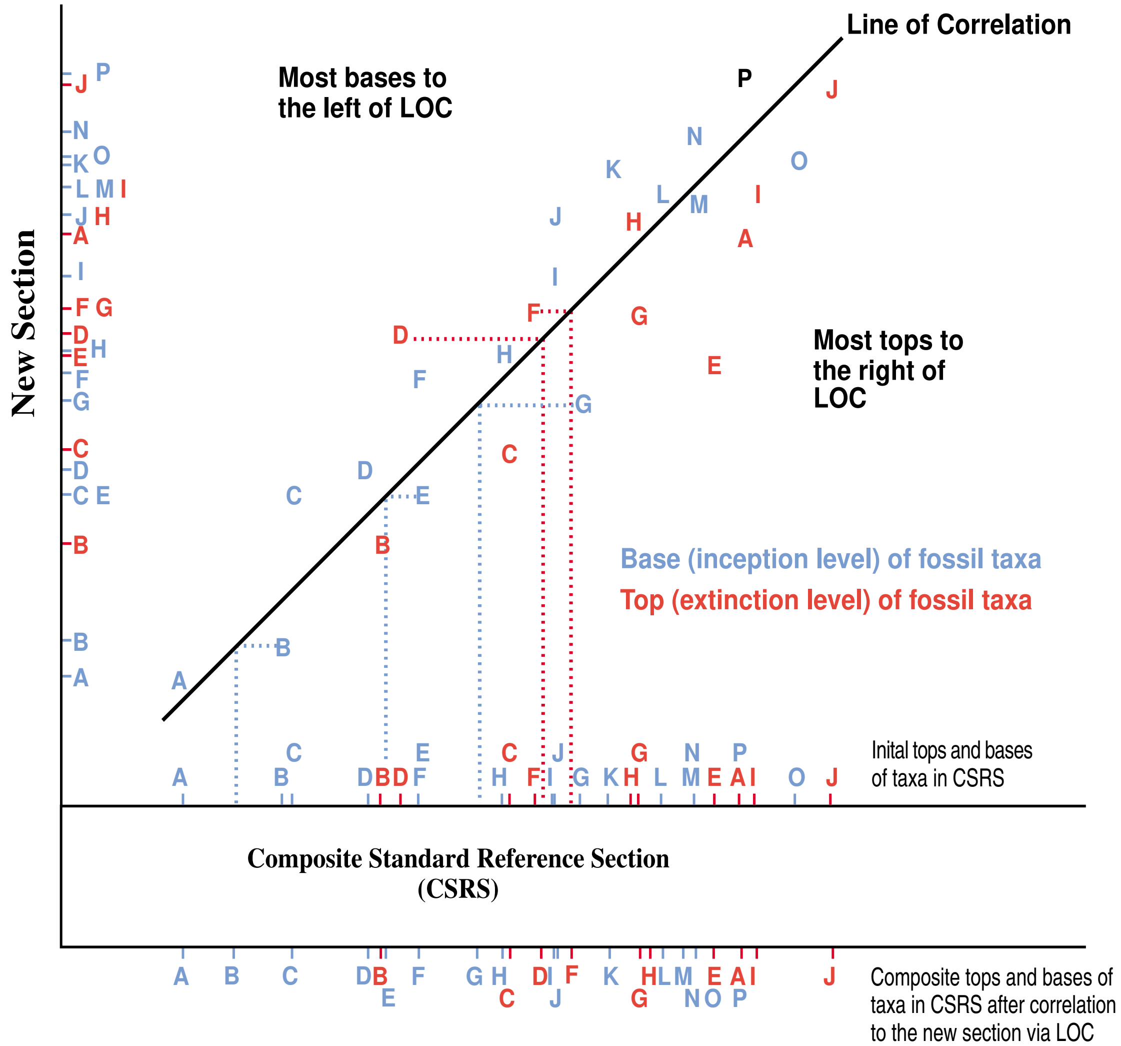

Figure 7: Simplified example of Graphic Correlation to extend fossil ranges in the Composite Standard Reference Section (after Simmons, 1994). Equal subdivisions of the Composite Standard Reference Section (CSRS) can be referred to as Composite Standard Time Units (CSTUs). These form the basis for correlation between sections.

Biozonation Scheme for the Arab Formation

Seven main biozones were recognised in the Arab Formation, as well as an indeterminate zone immediately beneath the Hith Formation (Figure 8). These are discussed below in descending order. All zones except the indeterminate zone have their tops defined by the first downhole occurrence of the defining fossil species. The zonation scheme has been developed using the Graphic Correlation Technique together with regional knowledge of microfossil stratigraphic ranges. Key fossils are illustrated in Figure 9.

Indeterminate Zone

This zone is barren of fossils and its age is estimated as Kimmeridgian-Tithonian based upon the age of the underlying and overlying strata. The interval equates with the Arab A and the Upper Anhydrite.

Salpingoporella annulata Zone

S. annulata (Figure 9a) also occurs in the lower Thamama Group (Early Cretaceous). The top of this zone can also be recognised on the first downhole occurrence of Jurassic forms of *Nautiloculina* sp. (Figure 9b). Assemblages are sparse and also include *Prethocoprolithus* sp. (Figure 9c), textulariids, miliolids and occasional ostracods. There are common *Hydrobia* gastropods at some levels. The age is interpreted as Kimmeridgian-Tithonian based upon the underlying and overlying strata. The zone equates with the greater part of the Arab B.

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***Clypeina jurassica* Zone**

The sparse assemblages present in this zone include *C. jurassica* (Figure 9d), *S. annulata, Nautiloculina* sp., *Riyadhella* spp., valvulinids, textulariids and miliolids. The highest occurrence of *Pfenderina salernitana* occurs near the base of this zone, but it is not a frequently encountered taxon. *Clypeina jurassica* is a typical Kimmeridgian-Tithonian species (Bassoullet et al., 1978), thus the age of the zone is assumed to be Kimmeridgian-Tithonian in the absence of definite Kimmeridgian indicators. The zone equates with the lower part of Arab B and the upper part of Arab C.

***Alveosepta powersi* Zone**

This contains a faunal assemblage which is similar to the overlying zone but is more diverse and also includes *Alveosepta powersi* (Figure 9e), *Kiliania* MDS1 (Figure 9f) and *Cylindroporella arabica. Kiliania* MDS1 is a previously undescribed species of *Kiliania*. The presence of *A.powersi* indicates an age no younger than Kimmeridgian (Banner and Whittaker, 1991). This zone equates with a level in the upper part of Arab C.

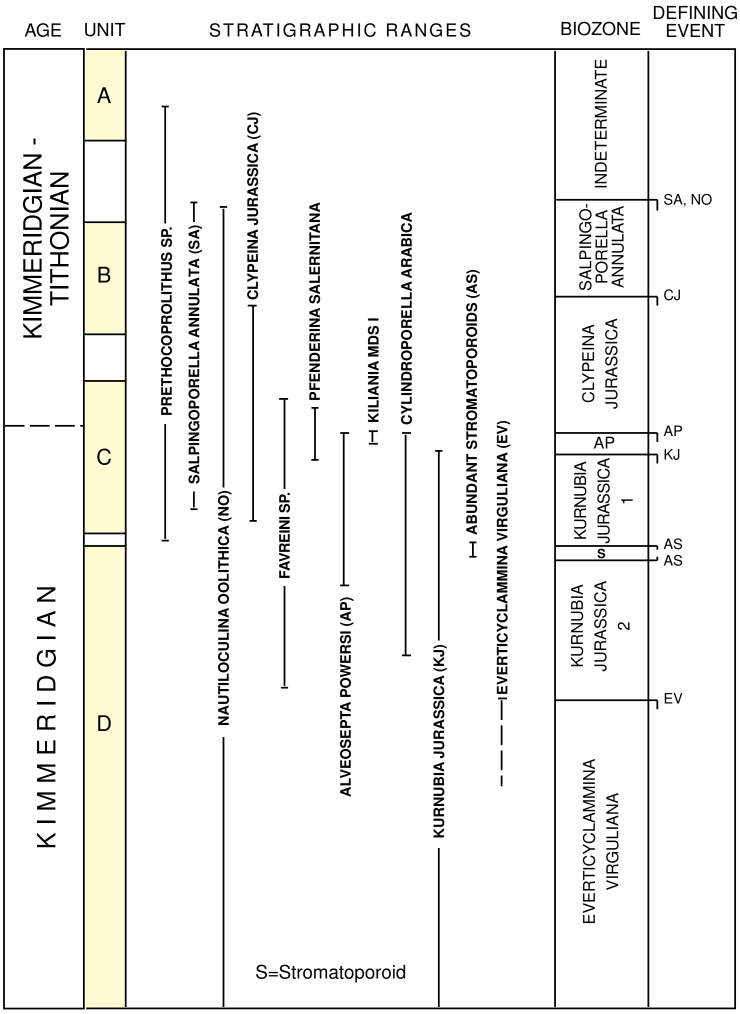

Figure 8: Biozonation scheme for the Arab Formation.

***Kurnubia jurassica* Zone 1**

A fairly diverse microfossil assemblage is present including *K. jurassica* (Figure 9g), *A. powersi, C. arabica, Favreina* sp., *Prethocoprolithus* sp., *C. jurassica, Nautiloculina* sp., *S. annulata, Riyadhella* spp., *Redmondoides* spp., valvulinids and various small textulariids and miliolids. There also occurs an acme event of *S. annulata* which has some local correlation value. The above assemblage indicates a Kimmeridgian age and the zone correlates with the lower part of the Arab C .

Stromatoporoid Zone

The assemblage is dominated by stromatoporoids including: *Shuqraia zuffardi, Burgundia trinorchi* (Figure 9h), *Promillepora pervinquieri* and *Cladocoropsis mirabilis*. It forms the topmost part of the Arab D in Ghasha-Bu Tini. This assemblage has also been recognised by Kawaguchi (1991), de Matos (1994) and Toland (1994) and is assigned a Kimmeridgian age.

***Kurnubia jurassica* Zone 2**

This zone contains relatively sparse assemblages but includes *K. jurassica, A. powersi, C. arabica, Favreina* sp., *Nautiloculina* sp., *Riyadhella* spp., valvulinids, textulariids and miliolids. The assemblage is of Kimmeridgian age and the zone equates with the upper part of the Arab D.

***Everticyclammina virguliana* Zone**

Sparse assemblages from this zone include *Everticyclammina virguliana* (Figure 9i), *K. jurassica, Nautiloculina* sp., miliolids, textulariids and lituolids. A Kimmeridgian age is indicated and the zone equates with the lower part of the Arab D. It is possible that with further study a richer assemblage would be recorded and lead to additional zonal subdivision. *E. virguliana* is known to be no older than Kimmeridgian (Simmons and Al-Thour, 1994).

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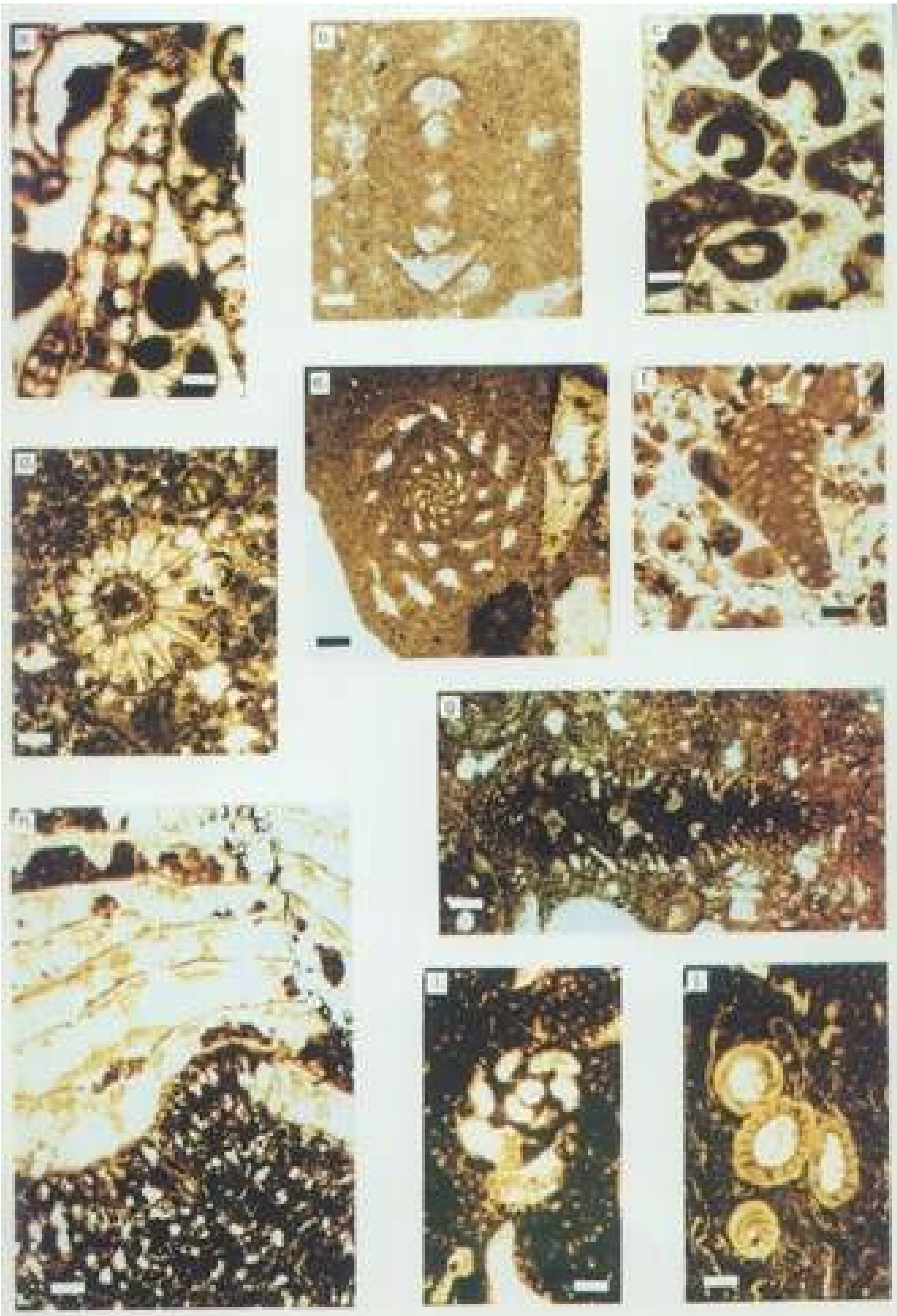

Figure 9: a) ***Salpingoporella annulata*** **(scale: 0.2mm), b)** ***Nautiloculina*** **sp. (scale:0.07mm), c)** ***Prethocoprolithus*** **sp. (scale: 0.05mm), d)** ***Clypeina jurassica*** **(scale: 0.4mm), e)** ***Alveosepta powersi*** **(scale: 0.2mm), f)** ***Kiliania*** **MDS1 (scale:0.1mm), g)** ***Kurnubia jurassica*** **(scale: 0.2mm), h)** ***Shuqraia zuffardi and Burgundia trinorchi*** **(scale: 0.3mm), i)** ***Everticyclammina virguliana*** **(scale:0.15mm), j) charophytes from an Arab B bituminous mudstone (scale: 0.3mm).**

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LITHOLOGICAL MARKERS

While the above biozonation scheme provided a valuable framework for placing the Arab Formation units in their correct stratigraphic position regionally, it did not provide sufficiently tight control for detailed intra-unit correlations. Lithological markers were required to achieve this although they had to be very distinctive to avoid repeating severe miscorrelations such as those already discussed. They could also be constrained by the biozonation described above. The need for such markers became increasingly important towards the top of the Arab Formation where fossils are rare because of the restricted depositional environments imposed by the increasingly evaporitic nature of the basin. Three key lithological markers were recognised in the form of thrombolites, charophytic horizons and layers of subvertical anhydrite nodules.

Thrombolites (Aitken, 1967) are distinctive cryptalgal lithologies which are usually attributed to microbial (blue green algal or cyanobacterial) activity. They differ from stromatolites in not possessing laminations and characteristically portray a clotted or digitate appearance. They may develop in intertidal or subtidal environments and under normal marine or schizohaline conditions (Kirkham, 1977). They may occur as laterally continuous beds or packets of beds which are traceable over hundreds of square kilometers and their conspicuous textures render them particularly useful as potential lithological markers. Thrombolites were recorded only from the Arab C in several Ghasha-Bu Tini wells (Figure 10). While these horizons could not be used for precise correlations, they nevertheless provide a distinct lithofacies which is readily recognisable and possibly diagnostic only of the Arab C.

A thin bituminous mudstone, only a few centimeters (cm) thick, containing a rich assemblage of charophyte oogonia was recorded within a thick anhydrite near the top of the Arab B in most Ghasha-Bu Tini wells (Figure 9j). Although some Jurassic charophytes may have been tolerant of relatively high salinities (Burne et al., 1980; Racki, 1982), charophytes are generally used as indicators of fresh water environments and so their abundance in the above mentioned mudstone provides an excellent field-wide marker. Charophytes were not found at other stratigraphic levels within the Arab succession of Ghasha-Bu Tini although de Matos (1994) recorded them from the "Dense Limestone" (at the Arab C-D boundary) of the Arab Formation in Bab field.

Horizons comprising subvertical anhydrite nodules provided the most distinctive lithological markers (Figure 11). Individual vertical nodules rarely exceeded 2 cm in width and 10 cm in height but are sometimes grouped to form stacked palisade textures sometimes exceeding 45 cm in total thickness. Compaction has often caused them to lean over in unison but this does not mask their distinctiveness. Such anhydrite nodules are interpreted as replacements of contemporaneous, subvertical gypsum crystals which developed subaqueously at sediment-water interfaces (Kendall, 1979b) within highly saline, marine lagoons or salinas. Three such horizons were recognised within the Arab A and B of all the Ghasha-Bu Tini wells where cores exist at the relevant horizons (Figure 5). They can be readily correlated on logs and bracketed the charophyte horizon which was therefore given added merit as a marker.

The discovery of the distinct charophyte and sub-vertical anhydrite markers, near the top of the Arab Formation, was instrumental in removing pre-existing correlation uncertainties near the Arab-Hith boundary across the field. The boundary (as defined above) was lowered by more than 10 ft in several wells mainly over the eastern part of the field. Whereas it was previously suspected that the Arab-Hith boundary was diachronous across the field, these markers illustrated that the boundary was in fact isochronous within Ghasha-Bu Tini.

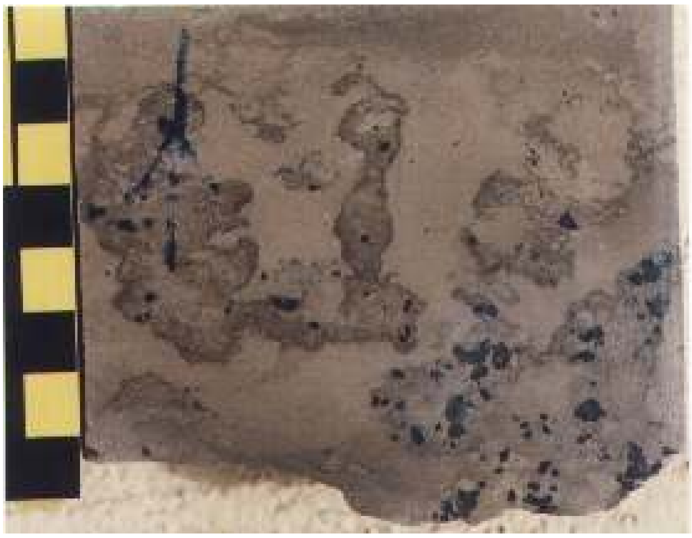

Figure 10: Arab C thrombolites showing vaguely digitate morphology. Scale is in centimeters.

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Figure 11: Cores from part of the Upper Anhydrite, Arab Formation, showing 24 feet of nodular, laminated and enterolithically folded anhydrite. Note the significant thickness of vertically continuous anhydrite. Note also the well developed subvertical anhydrite nodules at approximately 10,375 feet.

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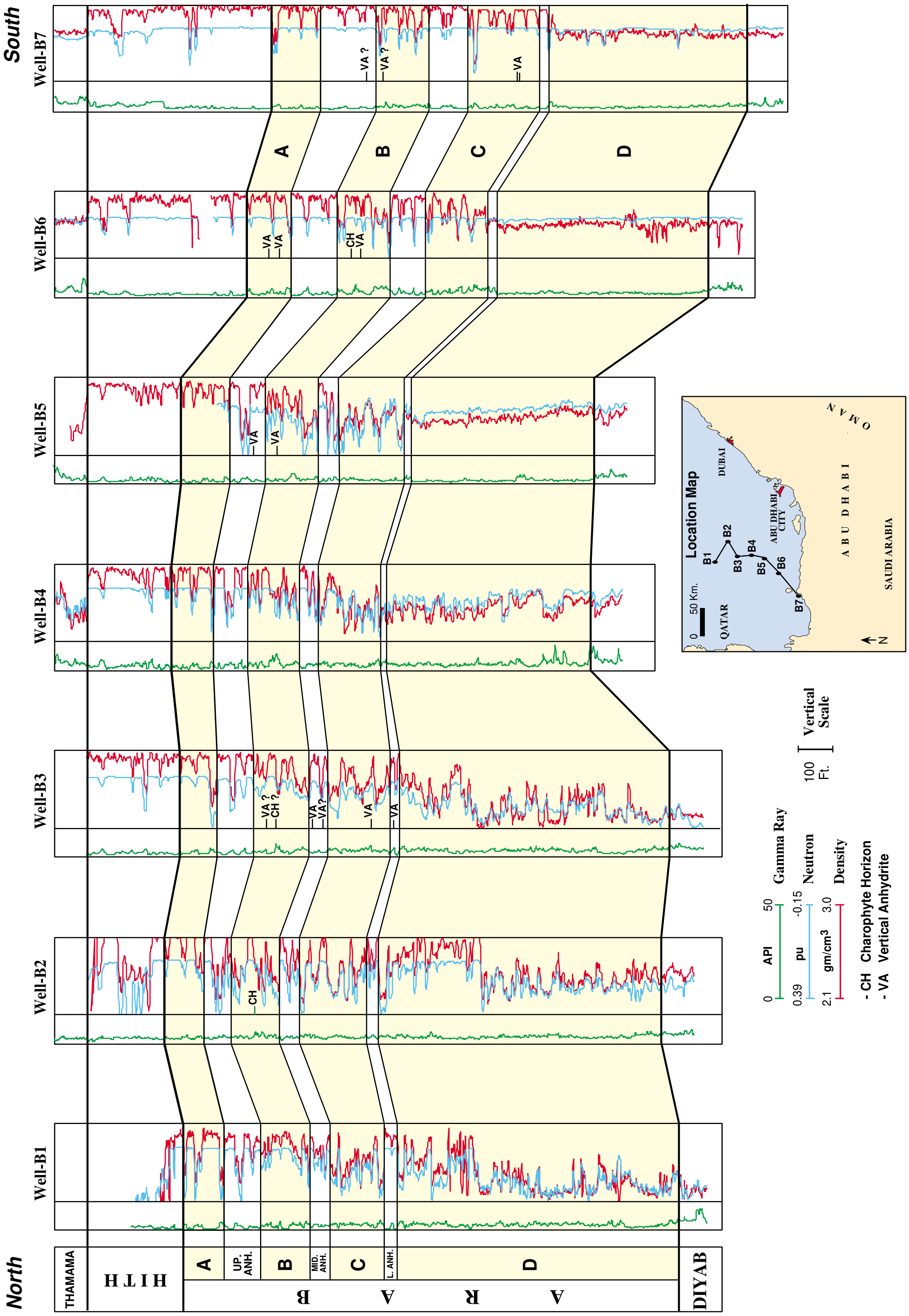

Figure 12: North-south log correlation of the Arab Formation, offshore Abu Dhabi.

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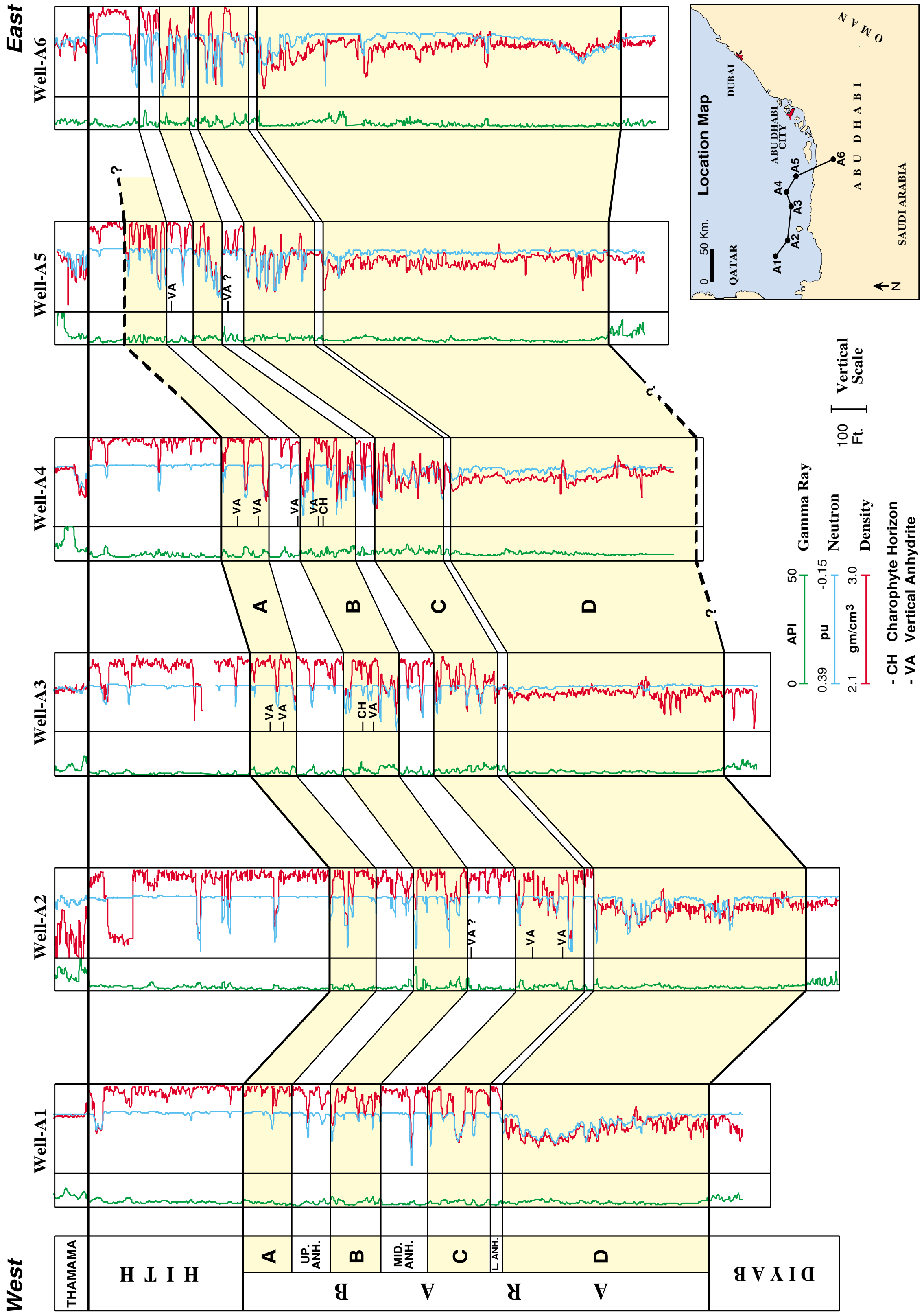

Figure 13: West-east log correlation of the Arab Formation, offshore Abu Dhabi.

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DISCUSSION

Implications for Regional Correlations

Log correlations within the Arab Formation of Abu Dhabi are notoriously difficult (Figures 12 and 13; Lapointe and Karakhanian, 1990). The Ghasha-Bu Tini field's location within the centre of the offshore Arab Formation play fairway of western Abu Dhabi renders it key to understanding the stratigraphy of this area.

It is important to re-emphasise the previous conclusion of de Matos (1994) that the anhydritic interval separating Arab C and D in Saudi Arabia, Qatar and western Abu Dhabi passes eastwards into a distinctive carbonate (the "Dense Limestone") in central and eastern Abu Dhabi. In El Bunduq field, for example, this interval is represented by a 20 ft thick anhydrite (Honda et al., 1989) which passes laterally into the 12 ft thick, ostracod-rich "Dense Limestone" in Ghasha-Bu Tini field. Non-recognition of this facies change led to previous mis-correlations within the field due to a preference to correlate thick anhydrites.

It is highly likely that, in view of the need to lower the Arab Formation zonal boundaries in Ghasha-Bu Tini, similar significant adjustments will also be necessary in the neighbouring fields. It may be wrong to assume that hydrocarbon pools assigned to specific units in neighbouring fields are in truly stratigraphically equivalent strata. The stratigraphic context of each field should be re-examined and any adjustments made accordingly so that a consistent regional stratigraphic framework is established for future exploration. However, it may be impractical from a production point of view to re-adjust Arab unit boundaries in fields where often decades of production history has accrued. The existing boundaries are so engrained that chaos would ensue if they were changed simply to satisfy geological correctness. Nevertheless, such mis-correlations cannot be ignored by explorers if they are to fully understand the sequence stratigraphic development of the Upper Jurassic play fairway(s).

The biozonation described herein is applicable to those parts of Abu Dhabi where the succession is similar to Ghasha-Bu Tini. It is after all a development of similar, well established biozonations formulated on the basis of studies done elsewhere such as in Saudi Arabia, Qatar, Oman and Yemen. It is also entirely possible that the lithological markers discussed above (or similar ones) are correlatable elsewhere in the region. As examples, we know of unpublished records of thrombolitic horizons in the Arab C of Qatar. They have also been recorded from Umm Shaif. The same Arab B charophyte-rich horizon discussed above has been correlated 100 kilometers north of Ghasha-Bu Tini to Nasr field. Many instances of possibly correlatable sub-vertical anhydrite nodules exist in other Abu Dhabi Arab Formation reservoirs of, for instance, Abu Al Bookoush, Nasr, Umm Shaif, Bin Nasher, Hair Dalma and others. Such anhydrites also occur deeper in the sequence in Arab C (for example, at Shuwaihat field).

Implications for Depositional Modeling

Since Wood and Wolfe (1969) first described the Arab Formation anhydrites as being analogues to the Holocene coastal sabkha sulphates of the United Arab Emirates, many authors have described the Arab Formation as comprising prograding, stacked parasequences capped by sabkha anhydrites. The traditional Arab Formation model has therefore assumed rapid regional sabkha progradations over distances exceeding a thousand kilometers (Leeder and Zeidan, 1977).

Kinsman (1969) calculated that Holocene sabkhas of the Emirates coast had prograded seawards at the rate of 1 to 2 meters per year. However, anhydrites are by no means ubiquitous within these Holocene sabkhas. They are certainly not as widespread as many geologists are led to believe from the literature. The bulk of the sulphates are restricted to the sabkhas near Abu Dhabi island (Butler, 1970) .

Ptigmatically folded, enterolithic anhydrite is generally regarded as highly indicative of sabkha anhydrites but these are relatively uncommon in the Arab Formation. Chicken-wire textures typical of coastal sabkha deposits (Butler et al., 1982) are far more common in the Arab Formation. Some isolated anhydrite nodules are possibly replacements of large, penecontemporaneous lenticular gypsum crystals such as those typically developed within the buried middle intertidal sediments of parts of the present day Emirates coastline. Some of the more massive Arab Formation anhydrites are undoubtedly replacements of upper intertidal gypsum mush layers.

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Many (or most) of the anhydrite layers are certainly of sabkha origin with anhydrite having developed by replacement of gypsum or by direct precipitation within the sabkha sediment. Their intimate associations with peritidal deposits (for example, stromatolites) are highly supportive of this type of origin. However, present-day sabkha sulphate layers rarely exceed about a meter because capillary zones within which they form do not exceed such thickness (Patterson and Kinsman, 1981). Butler et al. (1982) recorded 2.4 m (7.87 ft) thick sabkha beds containing anhydrite nodules although they did not clarify the anhydrite percentage or degree of nodule packing.

Kendall (1979a) stated that several supratidal units could coalesce to generate thick evaporites. A common argument against thick, massive, sabkha anhydrite formation is that the capillarity required to sustain the development of such thick anhydrites would not be possible in the low permeabilities created by the anhydrite development. Contradicting this is the evidence of Hawas and Takezaki (1995) who described Miocene sabkha anhydrites up to 13 ft thick, with porosities and permeabilities as high as 31.3% and 410 milliDarcies respectively, at burial depths of 58 ft near Abu Dhabi. A 63% decrease in solid phase volume, potentially increasing porosity (in competition with compaction), during dehydration of gypsum to anhydrite (Bath et al., 1985) could have contributed to such high values. Peebles et al. (1995) invoked a similar origin for the high porosities and permeabilities in the same rocks, but it is not yet clear why these anhydrites and associated petrophysical characteristics have been so well preserved below the water table where rehydration would be expected (R. Peebles, personal communication). Capillarity would surely be maintained in such lithologies but these early diagenetic petrophysical characteristics may have been untypical of the Arab Formation anhydrites.

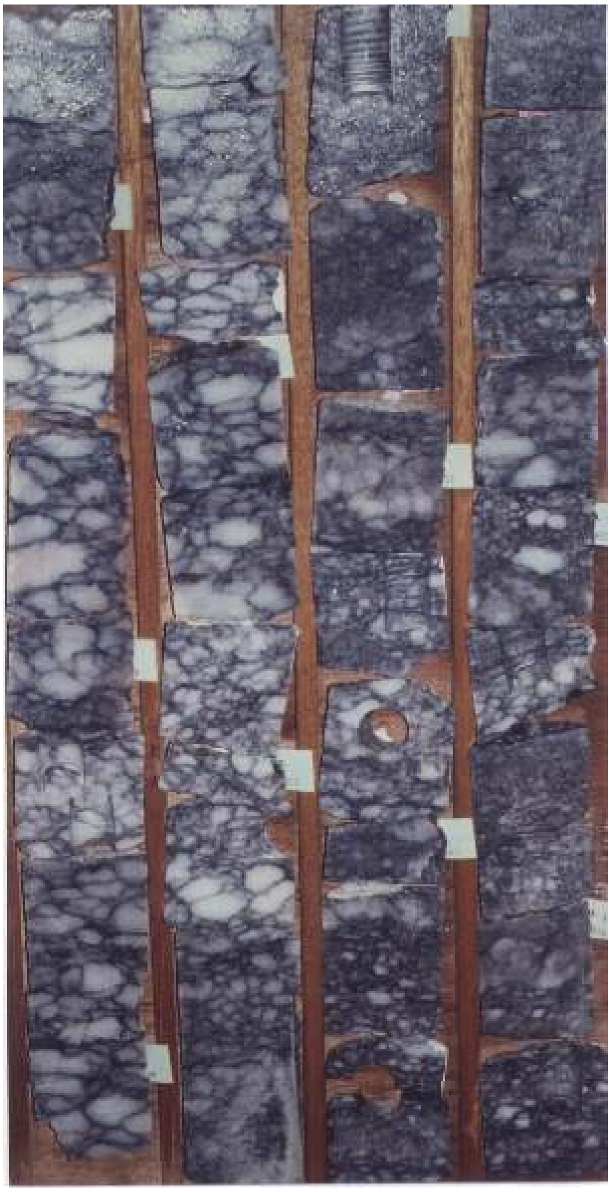

Figure 14: Thick nodular anhydrite showing typical chicken-wire textures in four inch diameter, slabbed cores from the Arab Formation, western Ghasha-Bu Tini field.

Warren and Kendall (1985) stated that an unequivocal interpretation of sabkha anhydrites can only be based on the occurence of a trinity of subtidal, intertidal and erosion capped supratidal sediments. If the Arab Formation represents a stacked succession of parasequences capped by supratidal anhydrites, one would expect to see common evidence of at least the transgressive system tracts overlying deflation surfaces (truncated anhydrites). Convincing examples of these occurences are distinctly lacking in the thicker Arab Formation anhydrites. They also argued that the tendancy to form sabkha anhydrites greater than a meter must be rather exceptional. The fact that the Arab Formation anhydrites commonly exceed two or three meters in thickness therefore suggests an alternative origin seems likely for these thicker beds.

While the Holocene sabkha processes certainly explain many of the Arab Formation anhydrites, it is likely that other processes were also active (Lapointe and Karakhanian, 1990; Lapointe, 1991). Their normal association with lagoonal and peritidal deposits argues against deep water origins for these thick anhydrites and yet there is evidence for subaqueous sulphate precipitation. It is interesting to note that Peebles et al. (1995) interpreted most of the above mentioned Miocene sulphate deposits as having

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formed in large, hypersaline lagoons and ephemeral lakes (salinas) as opposed to the interpretation by Hawas and Takezaki of them being exclusively of sabkha origin. Warren and Kendall (1985) and Azer and Peebles (1995) recorded subtidal or subaqueous evaporites in the upper Arab Formation but their degrees of continuity and correlation potential over significant distances has never before been demonstrated. The ability to extensively correlate palisades of subvertical anhydrite nodules, which are indicative of former subaqueous gypsum growth in highly evaporitic lagoons or salinas, has important bearing upon the sedimentological model. Such vertical anhydrite nodules are typically associated with thick (sometimes exceeding 20 ft) massive anhydrites (lacking matrix) which could in turn have been of mainly salina origin (Figures 11a and b). These massive beds may contain anhydritised laminites representative of subaqueous microbial mats. It is stressed that they are usually entirely nodular with chicken-wire textures (Figure 14) and comparable to the subaqueous anhydrites described by Wardlaw and Christie (1975). Wanless and Dravis (1989) described analogous salina sulphate deposits comprising interbedded gypsum-algal laminae and massive to nodular gypsum from West Caicos and Providenciales.

Figure 15: Patterned dolomite in four inch diameter, slabbed core from the Arab Formation, western Ghasha-Bu Tini field.

Salinas (no size connotation implied) could easily have developed during deposition of the Arab Formation by isolation of lagoons or from slight relative sea level rises causing marine flooding of the extensive, low relief coastal sabkha plains which probably existed. The continuous sulphate layers thus produced could have been initiated almost instantaneously over very large regions, which contrasts sharply with the comparatively slow rate of development implied for the prograding sabkha sulphates. The semi-permanence of the resulting shallow salinas (maintained by episodic marine flooding or leakage of marine water through the salinas' margins) could have led to subaqueous gypsum beds accumulating under the evaporitic conditions which prevailed and they, in turn, could have been fringed and capped by prograding sabkha anhydrites. Evidence of these related sabkhas is provided by occurrences of enterolithic folding within the abnormally thick anhydrites (Figures 11).

The tendency to form salina deposits increased with time during Arab Formation deposition. This is reflected not only in the increased proportions and thicknesses of anhydrite layers towards the top of the Arab Formation, but also in the decreasing diversity and diminishing faunal and floral populations. Ultimately, the overlying Hith Formation formed the most extensive and thickest salina sulphate deposits (Alsharhan and Kendall, 1994) totalling over three hundred feet thick in western Abu Dhabi and beyond.

The flooded area would have been an intra-shelf rimmed basin. Its broad, low relief rim persisted across central Abu Dhabi throughout the upper Arab Formation (probably prograding eastwards) and was the site of most frequent sabkha anhydrite development during Arab A, B and C deposition. This rim may have begun to manifest itself during upper Arab D deposition in northern offshore Abu Dhabi. Contemporaneous salt diapirism may also have created localized sites of sabkha sulphate development. West of the rim, the proportion of subaqueous sulphates are thought to increase whereas eastwards the succession is dominated by more open marine carbonates of the Asab Oolite and Asab Formation.

In fact, the evaporitic nature of the upper Arab Formation was even greater than is evident today. Much of the original gypsum was removed penecontemporaneously by sulphate reducing bacteria as indicated by the very common occurrence of patterned dolomites (Figure 15; Dixon, 1976; Kendall, 1977). This facies type is particularly abundant over western Ghasha-Bu Tini and has been observed as a common constituent of the upper Arab Formation in other fields (for example, Umm Shaif and Nasr). They are usually devoid of bioclasts and frequently show evidence of internal slumping under subaqueous or

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water logged conditions. They are often cryptalgal, and so many Arab Formation stromatolitic intervals may be subtidal rather than intertidal in origin.

Wood and Wolfe (1969) recognized nine "ideal" sabkha cycles at Umm Shaif whereas Azer and Peebles (1995) recognized nineteen in offshore Abu Dhabi. This large difference could be interpretational or due to sedimentological variability. Kirkham and Twombley (1995) illustrated the extreme lateral variability of both the Arab Formation depositional cycles and the analogous Emirates coastline and sabkha plain. The "ideal" sabkha cycle is comparable with only limited parts of the Emirates coastline. Lapointe (1991) observed the lack of "ideal" sabkha cycles in the Arab Formation but Kendall (1979a) developed four hypothetical variations on shoaling-upwards cycles capped by supratidal deposits. In other words, progradational sabkha sequences need not be capped by anhydrites. Nevertheless, it seems reasonable to fundamentally re-assess the process of assigning parasequences to the Arab Formation in a sequence stratigraphic approach to understanding its depositional history - especially if some of the regionally correlatable anhydrites are no longer accepted as being of sabkha origin. As sabkha anhydrites are displacive (and replacive?) in origin, they may totally mask depositional characteristics. If the thick anhydrites of the Arab Formation are of sabkha origin, how many parasequences actually occur within a massive anhydrite? On the other hand, if they are of salina origin they could form part of a transgressive system tract rather than the top of a high stand system tract within each parasequence or depositional cycle.

CONCLUSIONS

A new biozonation scheme was constructed for the Arab Formation using the Graphic Correlation Technique which focuses on the inceptions and extinctions of all faunal and floral groups present. This scheme drew on experiences gained from regions beyond Abu Dhabi. The technique provided meaningful correlations and showed that, within the resolution available, there is little diachronism within the Arab Formation across the Ghasha-Bu Tini field. The biozones enabled lithologic markers (thrombolites, charophytic mudstone, and beds of subaqueous, subvertical anhydrite nodules) to be constrained. The lithological markers were particularly useful in resolving the position of the Arab-Hith boundary over Ghasha-Bu Tini. The new biozonation supports the independent conclusions of de Matos (1994) that the Arab C-D boundary had previously been picked too high due to the non-recognition of the anhydrite separating these two units passing eastwards into the "Dense Limestone" over west-central parts of Abu Dhabi. Consequently, the overlying Arab Formation unit boundaries have been re-adjusted downwards on the basis of revised regional correlations. As Ghasha-Bu Tini is central to the offshore Arab Formation play fairway, the new biozonation scheme combined with lithologic markers could be used to help standardise the Arab Formation correlations regionally to better constrain sequence stratigraphic studies. Finally, the evidence for extensive salina-derived sulphates in the upper Arab Formation requires a fundamental re-assessment of the depositional models to properly constrain the sequence stratigraphy.

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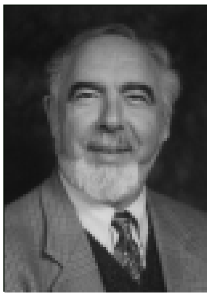

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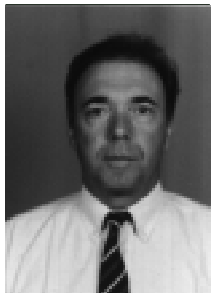

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