High-resolution Sequence Stratigraphic Architecture of Barremian/Aptian Carbonate Systems in Northern Oman and the United Arab Emirates (Kharaib and Shu’aiba Formations)

Frans S.P. van Buchem, Bernard Pittet¹ and Heiko Hillgärtner, Institut Français du Pétrole, Jürgen Grötsch² and Abdullah I. Al Mansouri, Abu Dhabi Company for Onshore Oil Operations, Ian M. Billing³, Henk H.J. Droste⁴, W. Heiko Oterdoom⁵ and Mia van Steenwinkel, Petroleum Development Oman

ABSTRACT

A regional sequence stratigraphic model for the Kharaib and Shu’aiba formations (Barremian, Aptian) is proposed based on outcrop and subsurface transects in Oman and the United Arab Emirates. The model shows distinct variations in depositional facies and geometrical patterns in relation to third-order sequences. The sedimentary systems evolved from a low-angle carbonate ramp (Kharaib Formation), to an organic-rich intrashelf basin surrounded by carbonate platforms (Hawar Member and Lower Shu’aiba), to a clay-dominated sedimentation restricted to the intrashelf basin (Upper Shu’aiba). Eustatic sea-level changes and, to a lesser extent, local tectonic controls influenced the development of the systems. This high-resolution sequence stratigraphic model has implications for both exploration and production strategies.

This study presents a revised sedimentological facies interpretation based on detailed outcrop observations with geological constraints provided by a regional well-log correlation from Oman and the United Arab Emirates. Time control was provided by biostratigraphy (including new nannofossil data), and carbon isotope stratigraphy. Four third-order depositional sequences bounded by regional exposure surfaces were defined that are composed of at least two higher-order sequences (fourth- and fifth-order).

Depositional sequences I and II have a flat ramp setting. The typical ecological succession was orbitolinid and/or miliolid wackestone-packstone deposited in a low-energy, inner ramp environment during early transgression; a mixed-fauna mudstone-wackestone in an open lagoon during maximum flooding and early highstand; and a rudist/miliolid wackestone-packstone-grainstone-framestone of the succeeding late highstand in a high-energy, inner- to mid-ramp environment. The doubling in thickness of the sequences from Oman to Abu Dhabi is attributed to differential subsidence. The Sequence III succession was somewhat similar, but differences were caused by the creation of the intrashelf Bab Basin, and by well-developed microbial boundstones. The basin morphology was primarily due to differential accumulation rates and tectonism was of only minor importance. Rapidly aggrading and backstepping microbial boundstones formed the platform, whereas condensed sedimentation and the accumulation of carbonate source rocks occurred in the basin. Highstand deposits were primarily grainy, high-energy rudist-dominated facies. The sequence ended with a forced regressive wedge along the basin margins. Sequence IV was restricted to the Bab Basin and sedimentation consisted of a clay-rich infill phase. At that time, the Oman and Abu Dhabi platforms were exposed on both sides of the basin. Nannofossils dated this major relative fall in sea level to the early-late Aptian.

¹ Present address: University of Lyon, France
² Present address: Shell Gas Abu Dhabi BV, Abu Dhabi, United Arab Emirates
³ Present address: Saudi Aramco, Dhahran, Saudi Arabia
⁴ Present address: Carbonate Research Center, Sultan Qaboos University, Muscat, Oman
⁵ Present address: Lundin Sudan Ltd., Khartoum, Sudan
INTRODUCTION

The Kharaib and Shu’aiba formations of Barremian and Aptian age contain one of the most prolific petroleum systems of the Middle East (Alsharhan and Nairn, 1997). In the United Arab Emirates and Oman several giant fields, such as Asab, Bab, and Bu Hasa; and Al Huwaisah, Lekhwair, and Yibal, respectively, belong to the Kharaib/Shu’aiba system. With the production history of these fields gradually becoming mature, an increasing interest is being shown in their high-resolution geological architecture. This knowledge is important for the construction of reservoir characterization models (input of geometries and reservoir facies dimensions) and for correlation between fields (which may lead to the identification of common rock types in terms of pore system characterization). Our study has developed a model for the regional sequence stratigraphic architecture of the Kharaib and Shu’aiba formations based on outcrop and subsurface data from northern Oman and the United Arab Emirates (Figure 1).

Many studies have been published on the Kharaib and Shu’aiba formations during the past 20 years, but they are almost exclusively based in the subsurface, and often limited to an individual country, region or field (see overviews in Alsharhan and Nairn, 1997; Hughes, 2000). Similarly, several lithostratigraphic and biostratigraphic investigations have been made of outcrops in northern Oman, where time-equivalent rocks crop out (Glennie et al., 1974; Simmons and Hart, 1987; Scott, 1990; Pratt and Smewing, 1993; Simmons, 1994; Masse et al., 1997, 1998). These studies have been complemented by the regional mapping of the French Bureau de Recherches Géologiques et Minières on behalf of the government of the Sultanate of Oman (Beurrier et al., 1986; Le Métour et al., 1986; Rabu et al., 1986). However, our work is the first to have integrated outcrop and subsurface data.

In recent years, a variety of sequence stratigraphic studies have been made. Azer and Toland (1993) and Boichard et al. (1995) proposed sequence stratigraphic interpretations for the upper part of the Thamama Group (the Kharaib and Shu’aiba formations) of offshore Abu Dhabi. Sequence stratigraphic work on well logs (M. van Steenwinkel, unpublished internal Shell report RKRS.92.GY1, 1992) in combination with the paleontological work of Witt and Gökdag (1994) confirmed the presence of the Aptian-aged Bab Basin in northwestern Oman. Vahrenkamp (1996) proposed depositional sequences in the Shu’aiba Formation based on carbon isotope stratigraphic work. Recently, Sharland et al. (2001) have proposed a subdivision of the Phanerozoic rock record of the Arabian Plate, using Maximum Flooding Surfaces (MFS) as the key correlation surfaces. We will discuss to what extent our results correspond and differ with their interpretations.

Our study has combined for the first time

• An integration of outcrop (Oman) and subsurface data (Oman, Abu Dhabi);
• A regional data set that covers the main paleogeographical features in the area during the Aptian: the Bab Basin and the bordering carbonate platforms in Oman and Abu Dhabi; and
• Multidisciplinary integration of sedimentology, paleontology, organic geochemistry, paleoecology and sequence stratigraphy (but excluding seismic).

In two related papers, specific aspects of the Barremian and Aptian rocks in the outcrops of northern Oman are highlighted. Pittet et al. (2002) dealt in detail with the sedimentology, high-resolution sequence subdivision, and cyclostratigraphy of the Kharaib and Shu’aiba deposits in Jebel Akhdar and Jebel Madar, and Hillgärtner et al. (in press) presented the Barremian-Aptian evolution of the eastern Arabian Plate margin that is fully exposed in the Nakl area of northern Oman.

Our paper aims to

• Exploit the subseismic-scale information on stratal geometries provided by the exceptional outcrops in the northern Oman Mountains (Jebel Akhdar, Adam Foothills), and in Ra’s Al-Khaimah.
• Control large-scale depositional geometries by using regional wireline log correlations, completed with core descriptions.

• Propose a regional high-resolution sequence stratigraphic model, which is predictive with respect to the depositional geometries and the distribution of the sedimentary facies (including the reservoir, source rock and seal facies).

• Evaluate the controlling factors on this sedimentary system.

• Demonstrate the petroleum geological implications of the study, with the possible consequences for exploration and production in this stratigraphic interval elsewhere in the region.

**GEOLOGICAL SETTING**

The Kharaib and Shu’aiba formations of Barremian and Aptian age were first defined in the subsurface (see Glennie et al., 1974; Alsharhan, 1985; Hughes Clarke, 1988; Alsharhan and Nairn, 1997). The Kharaib Formation was defined in well Kharaib-1 in Qatar. The reference section in Oman is the Lekhwair-7 well, which includes a thin Hawar shale member at the top (Hughes Clarke, 1988). The

![Figure 1: Paleogeographic map of early Aptian for the eastern part of the Arabian Plate. Outline of the Bab Basin is based on the present study and Vahrenkamp (1996). Locations of outcrop and subsurface transects (Enclosure: Figures 8, 10, 14) are shown. Well 15 is Lekhwair-7 (see Figure 9).](https://pubs.geoscienceworld.org/geoarabia/article-pdf/7/3/461/4566726/vanbuche.pdf)
The age of the Kharaib is estimated to be Barremian to Aptian as the fossil content is not fully diagnostic. The Shu’aiba Formation was first defined in well Zubair-3 in Iraq. The reference section in Oman is the Lekhwair-7 well for the basinal Shu’aiba, and the Al Huwaishah-2 well for the rudist Shu’aiba (Hughes Clarke, 1988). The age of the Formation is Aptian to earliest Albian. A distinction between a carbonate dominated Lower Shu’aiba and an argillaceous Upper Shu’aiba was made by Hughes Clarke (1988).

The formations are excellently exposed in northern Oman around the Jebel Akhdar window, in several small anticlinal structures in the Adam Foothills, and in the northern part of the United Arab Emirates around Ra’s Al-Khaimah (Figure 1). The lithostratigraphic terminology used in the subsurface has also been applied to the outcrops. Generally speaking, this is very straightforward and the only possible cause for confusion is the Hawar shale member that changes laterally in character and thickness from more shaly toward the north (offshore Abu Dhabi and Qatar; Boichard, 1995; Vahrenkamp, 1996) to more carbonate-dominated in the outcrops of northern Oman. Age determinations of the outcrop sections correspond to those obtained in the subsurface. The Lower Kharaib is of early Barremian age, the Upper Kharaib of late Barremian/early Aptian, the Lower Shu’aiba is early Aptian—but the entire late Aptian is missing in Wadi Mu’aydin (Simmons and Hart, 1987; Simmons, 1994; Immenhauser et al., 1999; Figure 2).

The Kharaib and Shu’aiba formations are part of the authochthonous Mesozoic carbonate successions of the Arabian Plate. They were buried along the Oman margin to a depth of about 8 km during ophiolite obduction in the Late Cretaceous and were exposed by Miocene uplift and deformation (Beurrier et al., 1986; Le Météour et al., 1986; Rabu et al., 1986; Hanna, 1990). In western Oman and Abu Dhabi, which was beyond the obduction front, maximum burial is estimated to have been about 2,000 to 3,000 m (Terken, 1999).

Figure 2: Schematic regional stratigraphic cross-section through the Lower and mid Cretaceous in Oman and Abu Dhabi showing the lithostratigraphic nomenclature. (Modified after Pratt and Smewing, 1993, and Masse et al., 1997).
The Early Cretaceous evolution of the eastern Arabian Plate is schematically presented in a regional cross-section in Figure 2. The infill of the Rayda basin is simplified as an overall progradation of the Habshan-Lekhwair-Salil system (for more details see Haan et al., 1990; Landmesser and Saydam, 1996; Aziz and Abd El-Sattar, 1997; Lebec et al., 2002; Droste and van Steenwinkel, in press). Infill was followed by an aggradational phase with the deposition of the carbonate platforms of the Kharaib and Shu’aiba formations. The clays of the Nahr Umr Formation separate the platforms from the overlying Natih Formation, except along the Neo-Tethys ocean margins where they pass laterally into carbonates (Masse et al., 1996, 1997; Immenhauser et al., 1999). A feature of both the Shu’aiba and Natih formations was the creation of organic-rich intrashelf basins (van Buchem et al., 1996, 2002; Droste and van Steenwinkel, in press).

The paleogeographical evolution of the area was presented in Murris (1980) and Vahrenkamp (1996), and shows the creation of the Bab intrashelf basin during the early Aptian. The late Aptian age of the Bab Basin sediments in Abu Dhabi has been reported by Hassan et al. (1975) based on ammonites, and more recently in Oman by Witt and Gökdag (1994) based on benthic foraminifera and nanofossils.

The shallow-water carbonates of the Kharaib and Shu’aiba formations are characterized by the benthic foraminifera Orbitolina and abundant rudists, and is typical of platform facies in the Neo-Tethys realm during the Barremian-Aptian. The rudist-dominated facies is known elsewhere as the Urgonian Facies (e.g. in France, Arnaud-Vanneau and Arnaud, 1990; Hunt and Tucker, 1993; in Spain, García-Mondéjar, 1990; Ruiz-Ortis and Castro, 1998; Vennin and Aurell, 2001), whereas orbitolinid-dominated facies types are commonly named the Orbitolina-beds in France and Switzerland (e.g. Arnaud-Vanneau and Arnaud, 1990; Funk et al., 1993).

METHODS AND MATERIALS

We have adopted high-resolution sequence stratigraphy as a powerful technique by which to describe the stratigraphic architecture of sedimentary systems. Examples in the literature of similar usage can be found in van Wagoner et al. (1988), Homewood et al. (1992), Loucks and Sarg (1993), Read et al. (1995), and Homewood and Eberli (2000). The theoretical principles of cyclostratigraphy by de Boer and Smith (1994) and Strasser et al. (1999) have also been applied. The subdivision of depositional sequences into five orders, which fall into a general time framework, is followed here (Vail et al., 1991; Haq et al., 1987). The orders of sequences of relevance for this study are second-order of 3 to 50 millions of years (my) duration, third-order (0.5–3 my), fourth-order, also referred to as high-frequency cycles, parasequences or genetic sequences (0.5–0.08 my), and fifth-order (0.08–0.02 my). Their definition is based on the notion of geological time, and they are the result of tectonic, tectonoeustatic, eustatic, or glacioeustatic mechanisms (Vail et al., 1991).

The applied methodology can be summarized in the following steps:

(a) Detailed (1:50-scale) macroscopic sedimentological and paleontological descriptions of outcrop sections and subsurface cores; observations of discontinuity surfaces, stratal patterns, and geometries at outcrop.

(b) These observations were complemented in this study with the following laboratory analyses: semiquantitative microscopic analysis of the microfacies; Rock-Eval VI analysis (mineral and organic carbon), carbon (C) and oxygen (O) stable-isotope analyses; outcrop gamma-ray spectrometry; and biostratigraphy.

(c) Environmental facies interpretation.

(d) One dimensional analysis of the depositional sequences and the establishment of a sequence hierarchy (i.e. stacking-pattern analysis).

(e) The construction of 2- to 3-D correlation schemes.

(f) Sequence stratigraphic model.
### Table 1: Facies Classification and Interpretation (see enclosure: Figure 10 for legend)

<table>
<thead>
<tr>
<th>Facies Association and General Environmental Interpretation</th>
<th>Depositional Environment</th>
<th>Sedimentary Features</th>
<th>Depositional Features</th>
<th>Other Common Features</th>
<th>Sedimentary Features</th>
<th>Other Common Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b Total facies</td>
<td>Studied subtidal or beach environment</td>
<td>Low-angle cross-bedding, cross-bedding, bioturbation, nannofossil, bioclasts</td>
<td>Laminites, dolomitization</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b BioconstructedPlatform</td>
<td>Protected relict platform</td>
<td>Cross-bedding, bioturbation, nannofossil, bioclasts</td>
<td>Lithocodium-Bacinella association</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 High-energy shallow-water</td>
<td>Internally subtidal</td>
<td>Low-angle cross-bedding, cross-bedding, bioturbation, nannofossil, bioclasts</td>
<td>Laminites, dolomitization</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4a Open lagoon and ramp</td>
<td>Open lagoon and ramp</td>
<td>Cross-bedding, bioturbation, nannofossil, bioclasts</td>
<td>Lithocodium-Bacinella association</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4b Agglutinated carbonate</td>
<td>Agglutinated carbonate</td>
<td>Cross-bedding, bioturbation, nannofossil, bioclasts</td>
<td>Lithocodium-Bacinella association</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Facies Description

<table>
<thead>
<tr>
<th>Facies</th>
<th>Texture</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b Total facies</td>
<td>P-G</td>
<td>Mixed low-energy facies</td>
</tr>
<tr>
<td>2b Bioconstructed Platform</td>
<td>GR</td>
<td>Mixed low-energy facies</td>
</tr>
<tr>
<td>3 High-energy shallow-water</td>
<td>GR</td>
<td>Mixed low-energy facies</td>
</tr>
<tr>
<td>4a Open lagoon and ramp</td>
<td>GR</td>
<td>Mixed low-energy facies</td>
</tr>
<tr>
<td>4b Agglutinated carbonate</td>
<td>GR</td>
<td>Mixed low-energy facies</td>
</tr>
</tbody>
</table>

#### Sedimentary Features

<table>
<thead>
<tr>
<th>Facies</th>
<th>Sedimentary Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b Total facies</td>
<td>Laminites, dolomitization</td>
</tr>
<tr>
<td>2b Bioconstructed Platform</td>
<td>Lithocodium-Bacinella association</td>
</tr>
<tr>
<td>3 High-energy shallow-water</td>
<td>Lithocodium-Bacinella association</td>
</tr>
<tr>
<td>4a Open lagoon and ramp</td>
<td>Lithocodium-Bacinella association</td>
</tr>
<tr>
<td>4b Agglutinated carbonate</td>
<td>Lithocodium-Bacinella association</td>
</tr>
</tbody>
</table>

#### Depositional Environment

<table>
<thead>
<tr>
<th>Facies</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b Total facies</td>
<td>Internally subtidal</td>
</tr>
<tr>
<td>2b Bioconstructed Platform</td>
<td>Protected relict platform</td>
</tr>
<tr>
<td>3 High-energy shallow-water</td>
<td>Internally subtidal</td>
</tr>
<tr>
<td>4a Open lagoon and ramp</td>
<td>Open lagoon and ramp</td>
</tr>
<tr>
<td>4b Agglutinated carbonate</td>
<td>Open lagoon and ramp</td>
</tr>
</tbody>
</table>

#### Other Common Features

<table>
<thead>
<tr>
<th>Facies</th>
<th>Other Common Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b Total facies</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
</tr>
<tr>
<td>2b Bioconstructed Platform</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
</tr>
<tr>
<td>3 High-energy shallow-water</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
</tr>
<tr>
<td>4a Open lagoon and ramp</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
</tr>
<tr>
<td>4b Agglutinated carbonate</td>
<td>Rare bioclasts, microfossils, peloids, oncoids, tuberoids, Lithocodium-Bacinella association, corals, stromatoporoids</td>
</tr>
</tbody>
</table>
In order to obtain information on subseismic-scale geometries and facies variations, the Kharaib and Shu’aiba formations were studied in five outcrop sections in northern Oman and in Ra’s Al-Khaimah (Figure 1). The subsurface dataset consisted of 30 wells forming an east-west profile including the eastern (Oman), and the western (Abu Dhabi) side of the Bab Basin. The transect starts close to one of the outcrop sections in the Adam Foothills (Jebel Madar). Cores from six wells were described. An offshore well in Abu Dhabi (Well-A, Figure 1) has been included to aid correlation with the literature (Boichard et al., 1995; Sharland et al., 2001).

To improve the dating of the Bab Basin sediments, nannofossil biostratigraphic age determinations were made on 220 samples from nine wells, five of which gave results (see Figure 11). Samples from the Wadi Mu’aydin section in the northern Oman Mountains (see Figure 9a), and the Lekhwair-7 well (see Figure 7), in addition to three other wells (see Figure 11) were measured to establish a carbon isotope stratigraphy. Bulk powder samples were prepared using a medium-sized drill. The Wadi Mu’aydin and Wadi Bani Kharus outcrop sections were logged with a handheld portable outcrop natural gamma-ray spectrometer in order to help correlation with the subsurface. Spectral gamma-ray analysis using a portable, suspended, 4-channel, natural gamma-ray spectrometer (Exploranium GR 320, GPS-21 detector) provided 1-minute measurements in four values (Total Gamma-ray count; Potassium (%); Uranium (ppm) and Thorium (ppm). Fifty-three samples from the Lekhwair-7 well (see Figure 7) were analyzed with the Rock-Eval VI for carbonate content, Total Organic Carbon (TOC), Hydrogen Index, and Oxygen Index.

SEDIMENTOLOGY

On the basis of faunal content, texture, sedimentary structures, and lithological composition observed in outcrop and core material, 21 facies were defined. Their characterization and environmental interpretation are presented in Table 1. For more detailed information on the outcrop facies, the reader is referred to Pittet et al. (2002). The facies are grouped in three Facies Associations that are interpreted in terms of depositional environments that differ with respect to one or several of the following conditions: bathymetry, hydrodynamic energy, and trophic level.

Facies Association 1: Low-energy, Muddy, Intertidal to Shallow-subtidal Environment

This environment is subdivided in two subenvironments based on a difference in the faunal assemblages.

Facies Association 1a: Miliolid-dominated clay-poor carbonate mudstones to wackestones—interpreted as an oligotrophic environment

Facies Association 1a is characterized by common to abundant miliolids and calcareous algae in association with peloids, echinoderm fragments, gastropods, oncoids and rudist fragments in pure calcareous wackestone and packstone textures. Bioturbation was common, as shown by *Thalassinoides* burrows (Figure 3b). Bedding is at the decimeter- to meter-scale. Miliolids are typical of shallow-platform to inner-ramp settings with slightly elevated salinity. Facies Association 1a is interpreted as an oligotrophic (minor nutrient input) environment.

Facies Association 1b: Orbitolinid/calcareous algae-dominated argillaceous wackestone to packstones—interpreted as a mesotrophic environment

Facies Association 1b is characterized by clay and the common occurrence of the benthic foraminifera *Orbitolina* in association with calcareous algae and echinoderms in wackestone to packstone textures. Bioturbation was common (*Thalassinoides*). Bedding is typically at the decimeter scale (Figures 3e, 4a).

In contrast to miliolids, orbitinolids could live in a variety of environments, with estimated water depth ranging from several meters to 50 m (e.g. Arnaud-Vanneau and Arnaud, 1990; Banner and Simmons 1994; Vilas et al., 1995; Hughes, 2000; Vennin and Aurell, 2001). Thus, the association with depth-indicative fauna and sedimentological features needs to be taken into account in the interpretation...
Figure 3: Facies and bedding-patterns of third-order sequences I and II (upper part of Lekhwair Formation and Lower and Upper Kharai) in Wadi Mu’aydin; see also Figure 9a. (a) Sequence I (upper part of Lekhwair Formation and base of the Lower Kharai). Massive bed at top (~13 m) is grainy and rudist-rich, and represents the best reservoir facies. Beds at base are thinner, and consist of muddier bioturbated facies capped by firm grounds. (b) Lagoonal mudstone/wackestone cycles (Transgressive Systems Tract: TST) at base of Sequence I (upper part of Lekhwair). Note burrows (arrows) penetrating down from firm-ground surface (hammer head on surface). (c) Rudist packstone and rudstone shoals (Highstand Systems Tract) at top of Sequence I (base Lower Kharai; Wadi Nakhr). (d) Sequence II, showing a thickening-upward bed-stacking pattern (1) culminating in a massive bed. Brown bands (2) near middle of bed are bioturbated layers with dolomitized burrow systems; toward the top are rudist packstones and rudstone beds (3). This pattern can be traced throughout the Jebel Akhdar area (see Pittet et al., 2002). (e) Lagoonal orbitolinid-rich wackestone/packstone cycles (early TST). Note firm-ground surfaces that cap cycle tops (arrows). (f) Detail of firm-ground surface with burrows filled partly by orbitolinid packstone and partly by calcite.
Figure 4: Facies and bedding patterns of third-order Sequence III (Hawar Member and Lower Shu’aiba) in Wadi Mu’aydin; see also Figure 9a. (a) Overview of lower part (Transgressive Systems Tract: TST) of Sequence III (Hawar Member); note well-developed decimeter-scale bedding pattern. (b) Bedding pattern style at top of Hawar Member: alternation of carbonate wackestone beds and bioturbated (Thalassinoides) argillaceous packstone (orbitolinid-rich) interbeds. (c) Detail of bioturbated (Thalassinoides) orbitolinid-rich wackestone and packstone interbeds. (d) Overview of middle and upper parts of Sequence III (Lower Shu’aiba). Note massive appearance of microbial boundstones (TST) and meter-scale bedding of rudist and benthic foraminiferal grainstones and rudstones (Highstand Systems Tract: HST). (e) Detail of channel incision (HST, upper part of Lower Shuaiba). (f) Traction current cross-bedding in channel fill: note fining-up trend.
of their depositional environment. In general, in Facies Association 1b, orbitolinids are abundant, small (millimeter-scale) and flat. They occur in close association with calcareous algae (*Permocalculus*; determination by M. Simmons) and echinoderms. Both orbitolinids and calcareous algae show evidence for reworking, as suggested by the different degrees of preservation (unaltered to completely micritized). Changes in size and abundance of the orbitolinids occur at the decimeter-scale. The greatest abundance and size of discoidal orbitolinids occur in argillaceous, bioturbated (*Thalassinoides*), limestone interbeds, whereas in more calcareous limestones they are generally smaller and associated with abundant miliolids and mono- and biserial foraminifera. In more proximal areas, such as the Hawar Member in the Jebel Madar area (Figures 5 and 6), orbitolinid-rich layers alternate at the decimeter-scale with intertidal microbial laminites and show desiccation features, multiple centimeter-scale layers with rip-up-clasts, and wave ripples (Figure 6), all indicative of a tidal-flat environment. At the top of the Lower Kharaib Formation, firm grounds are associated with calcite-filled burrow systems (Figure 3f) and are interpreted as evidence for ephemeral exposure.

By analogy with Holocene large benthic foraminifera, some authors consider orbitolinids to be symbiont-bearing and thus light-dependent organisms (Hottinger, 1982, 1996, 1997; Banner and Simmons, 1994; Immenhauser et al., 1999; Simmons et al., 2000). They consider orbitolinid morphology to be a function of water depth, with larger and flatter forms (discoidal) in deeper water, and smaller and conical forms in shallower water. In addition, Hallock (1985) observed that large size is only advantageous under oligotrophic conditions, that is, when food resources are limited. As an alternative hypothesis, Vilas et al. (1995) suggested that terrigenous runoff increased nutrient supply, thereby favoring fast-growing organisms with asexual reproduction (r-type reproducers; Birkelund, 1988) such as orbitolinids.

Our observations show the following: (1) A relationship between detrital influx (mesotrophic conditions), orbitolinid abundance and the functional morphology of the orbitolinid foraminifera; (2) A general depositional environment in the range between intertidal to (shallow) subtidal (tidal-flat deposits in Jebel Madar; rudist-filled channel deposits in Wadi Bani Kharus); and (3) An alternation at the decimeter scale of argillaceous, orbitolinid-rich interbeds with more calcareous (less clayey), miliolid-dominated beds.

The presence of the tidal-flat deposits and miliolid-dominated beds, intercalated between the orbitolinid beds, excludes the possibility that the entire Facies Association was related to a relatively deep-water environment. Similarly, it is highly unlikely that the decimeter-scale variations in orbitolinid abundance and morphology are the result of high-amplitude sea-level fluctuations in a greenhouse environment. This means that the alternations must be attributed to high-frequency paleoenvironmental changes, probably as a result of a waxing and waning clay influx. The morphological adaptation of the orbitolinids can thus be a reaction to the varying turbidity: larger forms during periods of clay influx, and smaller forms during periods of pure carbonate sedimentation. Alternatively, the link between orbitolinid abundance and morphology with detrital influx can be explained by high-nutrient input favoring fast-growing r-type opportunity species (Birkelund, 1988; Villas et al., 1995). In addition, the detrital influx may have inhibited the reproduction of other carbonate-producing organisms (Hallock and Schlager, 1986), and resulted in the low accumulation rates.

In summary—the detrital influx; the biotic association of discoidal orbitolinids, calcareous algae and echinoderms; the frequent reworking; the bathymetric constraints; in combination with an epiphytic way of life proposed for orbitolinids (Arnaud-Vanneau, 1976)—suggests a depositional environment for the orbitolinid beds of algal meadows in a shallow-platform top to inner-ramp setting, with local storm reworking, and detrital and nutrient input from the land.
Figure 5: Overview of the Hawar Member in outcrop in Jebel Madar: a typical example of Facies Association 1b (see text) with closely alternating beds of orbitolinid-rich packstone, miliolid-dominated beds, and intertidal facies with mud cracks and rip-up clasts (see Figure 6 for details). The environmental interpretation is of a very shallow subtidal to intertidal setting, with local evidence of temporary exposure (Exp. 1 to 3). See Table 1 for facies codes.
Figure 6: Details of tidal-flat facies in the Hawar Member of Jebel Madar. 
(a) Plan view of mud cracks and rip-up clasts; Exposure level 3 in Figure 5; 
(b) Desiccation cracks and wave ripples; Exposure level 3 in Figure 5; 
(c) and (d) Polished slabs of rip-up clasts and desiccation cracks in homogenous carbonate mudstones, 
alternating with very fine bioclastic grainstone and packstone; Exposure level 1 in Figure 5.

Facies Association 2: Low-energy, Muddy and/or Microbial, Shallow- to 
Deep-subtidal Environment

Two subenvironments were distinguished based on the faunal assemblage.

Facies Association 2a: Mixed fauna, mudstone to wackestone
Facies Association 2a is characterized by low-energy deposits of mudstones and wackestones having 
a diverse faunal association of orbitolinids, bivalves, gastropods, rudists, and echinoderms. Miliolids 
are rare, mono- and biserial foraminifera are common, as are orbitolinids (mainly conical forms), and 
Choffatella and some lenticulids are present. Locally, more grainy levels of debris occur and truncate 
the low-energy muddy facies. These are interpreted as tempestites. In general, bedding is poorly 
developed. Locally bioturbated layers contain dolomitized burrow systems (Figure 3d). The diversified 
fauna, the scarcity of high-energy facies, and the predominantly muddy texture of the sediment suggest 
normal open-marine conditions in the deep subtidal range above storm wave base in the open lagoon 
of a platform or in a mid-ramp environment.

Facies Association 2b: Microbialites, micro-encrusters and rudists-in-life-position 
boundstone and oncoids
Facies Association 2b is characterized by an abundance of microscopic encrusting structures formed 
by microbial organisms, such as cyanobacteria and other bacteria, fungi, and green algal filaments. 
They may form dense networks in association with rudists, corals and stromatoporoids, and with 
other micro-encrusters such as foraminifera, bryozoans, red alga, sponges, serpulids, Bacillariella and
Lithocodium. Locally, they occur as large oncoids embedded in a muddy wackestone facies. They are interpreted as having inhabited a fairly wide range of water depths, including algal mats in the supratidal mudflats, but mostly as bioconstructors in the subtidal domain (Figure 4d).

Microbial and micro-encrusting associations have significance in terms of the depositional environment (Leinfelder et al., 1996; Schmid, 1996; Dupraz and Strasser, 1999). Abundant microbial/micro-encrusting activity commonly relates to high, but not excessive, nutrient conditions (Leinfelder, 1992). A Bacinella-Lithocodium association is interpreted as a well-oxygenated, very shallow-water environment with normal marine salinity, whereas leiolitic and thrombolitic crusts might point to higher nutrient levels and somewhat deeper water (Dupraz and Strasser, 1999).

**Facies Association 3: High-energy, Grainy Intertidal to Shallow-subtidal Environment**

Facies Association 3 is dominated by rudists (mostly debris; both caprinids and radiolitids), miliolids and mono- and biserial foraminifera, in association with calcareous algae, echinoderms, oncoids and peloids. Both high- and low-energy deposits formed in this environment. Muddy rudist biostromes and muddy miliolid wackestones and packstones occur adjacent to well-sorted, erosive and cross-bedded channel deposits, with rudist rudstone channel lags (Figure 4e, 4f), and laminated miliolid grainstones that are interpreted as beach deposits. The sediment contains very little to no siliciclastic material. The bedding pattern is very irregular, and laterally discontinuous due to the high energy of this environment. The setting is oligotrophic, and an intertidal to shallow subtidal range is proposed.

**Facies Association 4: Intraslab Basin Environment**

Two sub-environments are distinguished based on the difference in lithological composition and faunal content.

**Facies Association 4a: Nannoconid-dominated, organic-rich carbonate mudstones and wackestones**

Facies Association 4a is characterized by carbonate mudstones to wackestones containing a poor macrofauna and very little clay (Figure 7). A characteristic of these deposits is the occurrence of organic-rich interbeds that in Lekhwair-7 contain up to 4.13 percent Total Organic Carbon of marine type-II origin (Hydrogen Index between 400 and 650) in an immature stage (maximum temperature < 435°F). Nannoconids are the dominant faunal elements. A decimeter- to meter-scale bedding pattern is present in the core. Water depths for these basinal deposits is based on the geometrical reconstruction of the intrashelf basin (Enclosure: Figure 8), and may have attained a maximum of about 70 m.

**Facies Association 4b: Argillaceous, coccolith/nannoconid-rich mudstones to marls**

An alternation of argillaceous carbonate mudstones to wackestones and carbonate-rich claystones is typical of Facies Association 4b (Figure 7). The carbonate-rich layers contain abundant nannoconids, whereas the more clayey layers contain large numbers of coccoliths. Locally, miliolid and foraminiferal grainstones occur that are interpreted as tempestite lobes on the slopes of shoals in the intrashelf basin (Witt and Gökdag, 1994). Wind directions are likely to have influenced the disposition of these slopes and shoals. The water-depth estimation is based on the geometrical reconstruction of the intrashelf basin (Enclosure: Figure 8) and a maximum water depth of about 40 m is proposed.

**SEQUENCE STRATIGRAPHY**

**Outcrop Correlation**

Geometrical information at the subseismic scale, such as bedding pattern, stratal geometries, and lateral facies change, plays a vital role in the construction of predictive geological models. For this reason, the Kharaib and Shu’aiba formations have been studied in four outcrops in northern Oman and one in Ra’s Al-Khaimah (Figure 1). This work was published by Pittet et al. (2002), and ample illustrations
### Bio. Sedimentological Logs

**Stage:**

- Lower Aptian
- Upper Aptian

**Formation:**

- Nahr Umr

**Member:**

- Kharaib
- Lower Shu‘aiba
- Upper Shu‘aiba (Bab member)

**Bedding:**

- See Figure 10

**Texture (see Legend):**

- Open lagoon
- Carbonate, organic matter-rich intrashelf basin
- Argillaceous intrashelf basin (Tempestite lobes)

**Lithology:**

- Barremian
- Lower Aptian
- Upper Aptian

**Mineralogy Interpretation:**

- Bioclastic M
- Orbitolina/W
- Miliolids/M-W
- Intraclasts
- Mudstones

**General facies:**

- Bars and channels, rudist biostromes
- Protected lagoonal, carbonate-marl beds, thin organic matter-rich inter layers
- Marl-limestone alternation
- Coccoliths in argillaceous beds; nannochondrids in carbonate beds; ammonites
- Bioclastic M with thin organic matter-rich inter layers

**Depositional environment:**

- Intrashelf basin
- Subtidal
- Intertidal
- Supratidal
- Exposure

**Stable Isotopes:**

<table>
<thead>
<tr>
<th>Zones</th>
<th>Nannochondrid</th>
<th>%TOC</th>
<th>%CaCO3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 6b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 6a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 5a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 4a</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**STABLE ISOTOPES**

- δ13C

**Barremian**

- Lower Aptian
- Upper Aptian

**Lower Kharaib**

- Lower Shu‘aiba
- Upper Shu‘aiba (Bab member)

**Upper Kharaib**

- Lower Shu‘aiba
- Upper Shu‘aiba (Bab member)

**Base Lower Aptian (Witt and Gokdag, 1994)**

- Nannochondrid Stage
- Bio. Sedimentological Logs
- Mineralogy Interpretation
- Stable Isotopes

**INTERPRETATION**

- Density
- Neutron
- Gamma-Ray
- %TOC
- %CaCO3

**ΣINTERPRETATION**

- Density
- Neutron
- Gamma-Ray
- %TOC
- %CaCO3

**Mineralogy**

- Bioclastic M
- Orbitolina/W
- Miliolids/M-W
- Intraclasts
- Mudstones

**General facies:**

- Bars and channels, rudist biostromes
- Protected lagoonal, carbonate-marl beds, thin organic matter-rich inter layers
- Marl-limestone alternation
- Coccoliths in argillaceous beds; nannochondrids in carbonate beds; ammonites
- Bioclastic M with thin organic matter-rich inter layers

**Depositional environment:**

- Intrashelf basin
- Subtidal
- Intertidal
- Supratidal
- Exposure

**Stable Isotopes:**

- δ13C

**Downloaded from https://pubs.geoscienceworld.org/geoarabia/article-pdf/7/3/461/4566726/vanbuche.pdf**
are provided of the sedimentary facies and the bedding pattern at different scales. These results are briefly summarized here to provide the reader with the essential information required for the understanding of the sequence stratigraphic model proposed in this paper.

As an example of the logging procedure, the composite log of the Wadi Mu‘aydin outcrop section is shown as Figure 9a, and documented with outcrop photographs of the bedding pattern and facies (see Figures 3 and 4). Outcrop data is presented in a regional correlation (Enclosure: Figure 10), which has an orientation that is along strike with respect to the platform geometries, and roughly parallel to the paleocoastline of the Neo-Tethys ocean (Figure 1). The datum for correlation is the top of Sequence II.

Three large-scale depositional sequences are distinguished based on bedding pattern, facies succession, and subaerial exposure surfaces. The bedding pattern is very similar in all of the outcrop sections, and much like that seen in Wadi Mu‘aydin (Figure 9b). A systematic alternation is observed between decimeter-scale, horizontally bedded intervals, and decameter-thick, massive limestone beds. These units can be readily correlated over distances of tens of kilometers (Enclosure: Figure 10). The sedimentary facies also show a repetitive pattern of a succession of the three Facies Associations in all the studied outcrop sections. A general evolution is as follows:

(a) A low-energy, muddy, shallow-subtidal to intertidal environment (Facies Association 1) deepens to

(b) a more open-marine environment (subtidal domain) with mud-dominated open lagoons and local storm beds (Facies Association 2a); or the development of extensive microbial-dominated boundstone facies (Facies Association 2b). In both cases shallowing leads to

(c) a high-energy, grainy environment, also in the shallow-subtidal to intertidal domain (Facies Association 3).

Thus, based on facies succession and bedding pattern the three large-scale depositional sequences are defined in the outcrop sections (Enclosure: Figure 10).

The boundaries of the sequences mark a dramatic change in the sedimentary facies, and are locally accompanied by evidence of subaerial exposure. The base of Sequence I is placed at a sharp facies change from rudist-dominated grainstones and rudstones to a miliolid-dominated mudstone and wackestone. Locally, for example in the Wadi Mu‘aydin section, this surface is accentuated by mud cracks that testify to ephemeral exposure. The lower part of Sequence I is characterized by Facies Association 1a, with miliolid-dominated mudstones and wackestones in decimeter- to meter-thick beds that are intensely bioturbated at the top (dolomitized Thalassinoides burrows; Figure 3b), and locally contain algal laminites (Wadi Bani Kharus, Jebel Madar; Enclosure: Figure 10). They are interpreted as shallow subtidal to intertidal sediments, deposited during early transgression. Locally during late transgression, slightly deeper-water facies (Facies Association 2a) are present, as in Wadi Nakhr and Wadi Mu‘aydin, and are interpreted as open lagoonal facies in the subtidal domain. The highstand of this sequence is characterized by thicker bedding (Figure 3a) and grainier, high-energy, rudist- and miliolid-dominated deposits of Facies Association 3 (Figure 3c), interpreted as shallow subtidal to intertidal deposits.

Figure 7 Facing page: Completion log of the Lekhwair-7 well, located in the center of the Bab intrashelf basin (see Figure 1 for location). This is the reference well for the Kharaib and Shu‘aiba formations of Oman (Hughes Clarke, 1988). Note the change in the intrashelf basinal facies from the organic-rich carbonate deposits in the upper part of Sequence III, to the clay-rich organic-matter-poor intrashelf basinal facies in Sequence IV (see Neutron and Density logs, and the decrease in carbonate content). This lithological change is accompanied by a change in the carbonate producers in the Bab Basin—dominated by nannoconids in Sequence III and coccoliths in Sequence IV (see text for further explanation). It is also taken as the boundary between the Lower and Upper Shu‘aiba. The core description uses the facies color code of Table 1. In the gamma-ray log: a, b, etc., represent small-scale cycles correlatable at the scale of the Bab Basin (see Enclosure: Figure 8). TOC = Total Organic Carbon
Figure 9: Composite log and outcrop photograph of the Wadi Mu’aydin section.
(a) Composite log: sedimentological observations based on macrofacies, microfacies and bedding pattern analysis; outcrop gamma-ray spectrometry log; $\delta^{13}$C isotope curve; and environmental interpretation. The color code of the facies is that in Table 1. Depositional Environments: Sub. = subtidal; Inter. = intertidal; Supra. = supratidal; Exp. = exposure.
(b) Outcrop photograph of the Kharib and Shu’aiba formations in Wadi Mu’aydin (vehicle for scale at bottom left). Lithostratigraphic nomenclature and sequence subdivisions are shown. Detailed photographs of this section are given in Figures 5 and 6. Note that the characteristic bedding pattern can be traced throughout the Jebel Akhdar area (Enclosure: Figure 10; see also Pittet et al., 2002).
The base of Sequence II is also marked by an abrupt change in texture and fauna with orbitolinid- and miliolid-rich argillaceous wackestones overlying the rudist and miliolid grainstones of Sequence I. Eroded coral heads at the top of Sequence I are evidence of early cementation that was followed by a slight erosional phase (ravinement surface). The lower part of Sequence II is characterized by abundant discoidal orbitolinids (Figure 3e) in association with calcareous algae, typical of Facies Association 1b. This facies is bedded at decimeter-scale, with cycle tops commonly capped by well-developed firmground surfaces, perforated by calcite-filled burrow systems (Figure 3f). A distinct thickening-upward stacking pattern can be seen in outcrop (Figure 3d). Facies Association 1b is interpreted as a very shallow, low-energy, platform-top environment deposited during early transgression. During late transgression, an open lagoonal environment existed, with grainy tempestite deposits locally occurring in the mudstone and wackestone facies. Brown, dolomitized, Thalassinoides bioturbated layers are interpreted as condensed horizons of reduced sedimentation rates that probably marked the time of maximum deepening (Figure 3d). High-energy, gravelly rudist and miliolid facies of Facies Association 3 represent the highstand deposits. This facies migrated over the platform. It first appears in the sections closest to the ocean margin as meter-scale cross-bedded grainstones in Wadi Barakah and as a relatively thick rudist-dominated unit in Wadi Bani Kharus, whereas in Wadi Mu’aydin and Jebel Madar it is much thinner (Enclosure: Figure 10).

The base of Sequence III is also placed at an abrupt change in facies (from Facies Association 3 to 1b; Enclosure: Figure 10) and a change in bedding style (massively bedded to decimeter-scale bedded). The lower part of the sequence is characterized by an abundance of discoidal orbitolinids and calcareous algae in decimeter-scale bedded argillaceous packstone to wackestone of Facies Association 1b (Figures 4a,b,c). This interval has a thickness of up to 25 m, a specific texture and faunal content, and is readily correlated between outcrop sections (Enclosure: Figure 10). We have named this interval the Hawar Member (see below for discussion). In Jebel Madar, algal laminites, mud cracks, and rip-up clasts are evidence of ephemeral subaerial exposure in a tidal-flat environment (Figures 5 and 6). During late transgression, microbial encrusting organisms formed in association with thick rudist boundstone deposits (Figure 4d). In the Wadi Rahaba section, more open-water conditions prevailed at this time. The highstand deposits of Sequence III are rudist- and miliolid-dominated grainstones, rudstones, and framestones that formed bars, channels, rudist biostratums and beach deposits (Figures 4d,e,f). In the Wadi Mu’aydin section, a well-developed channel system with coarse-grained channel lags of rudist debris, bi-directional cross-bedding and a fining-upward trend occurs (Figures 4e,f). Facies Association 1b was interpreted as a high-energy shallow platform-top environment. The upper boundary of Sequence III is an iron-encrusted hardground overlain by the clayey orbitolinid facies of the Nahr Umr Formation.

Thickness variations are relatively subtle in the Jebel Akhdar region (Enclosure: Figure 10), with the Wadi Mu’aydin and Wadi Nakhr sections about 40 m thicker than those at Jebel Madar and Wadi Bani Kharus. The thickest succession is in Wadi Rahabah, where significant thickening has occurred particularly in Sequence III that is twice as thick as in Jebel Akhdar. Evidence for ephemeral subaerial exposure and reduced thickness can be seen at the base of Sequence I in Wadi Bani Kharus, and at the base of Sequence III in Jebel Madar. Local variations in accommodation space, most probably the result of synsedimentary tectonic activity by differential subsidence, seems to have had a slight influence on the paleogeography.

The ages of the outcrop sections have been determined using the existing literature. The Barremian/Aptian boundary is placed just below the top of the Upper Kharai. The Shu’aiba Formation in outcrop is probably only of early Aptian age, with a major time gap representing most of the late Aptian (Scott, 1990; Simmons, 1994; Masse et al., 1997, 1998; Immenhauser et al., 1999). A carbon-isotope curve measured in Wadi Mu’aydin shows a negative shift at the base of Sequence III in the lower part of the Hawar Member (Figure 9a). This shift is characteristic of the early Aptian (Weissert et al., 1998), and has been observed elsewhere in northern Oman (Wagner, 1990; Vahrenkamp, 1996; Grötsch et al., 1998). It provides supporting evidence for the biostratigraphic dating. Following the time scale of Hardenbol et al. (1998), the three sequences together represent about 9 my, which suggests that they are on the third-order scale of Vail et al. (1991).
In Wadi Mu’aydin and Wadi Bani Kharus, spectral gamma-ray measurements were made at outcrop in order to correlate with the subsurface (Enclosure: Figure 8). The results for the Wadi Mu’aydin section (Figure 9a) show that the total gamma-ray signature was mainly produced by fluctuations in the Uranium (U) content, and that the Potassium (K) and Thorium (Th) contents are low. The highest gamma-ray values were measured in the transgressive parts of the sequences. This corresponds very well with the downhole wireline signature, which also shows increases in these intervals (Enclosure: Figure 8). These higher values were probably due to an increase in U bound by organic matter, and to a lesser extent by an increase in the clay content as only small increases in the K and Th contents were measured (Figure 9a). In addition, the signature obtained from the outcrop seems to individualize some of the smaller-scale sequences.

Subsurface Correlation

The subsurface study was based on 28 wells (Figure 1). For 12 of these, facies information was available (Enclosure: Figure 8), either through core material (wells 10, 15, 16, 19, 20, 22, 25 and 26) or cuttings (wells 1, 3, 6, 9). The well transect was chosen to cover both margins of the Bab intrashelf basin. An example of a typical ‘Bab Basin’ well is Lekhwair-7 (Figure 7), that is described briefly here. The core material of Lekhwair-7 covers half of Sequence II, and parts of sequences III and IV.

The facies succession and sequence organization for Sequence II, as documented in the core, resembles closely that seen in outcrop (see Figure 9a). Significantly, toward the top of Sequence II, traces of paleosoil are preserved in soil-filled rhizoliths that testify to subaerial exposure. Only the lowest part of Sequence III is similar to the outcrop sections, where decimeter-scale bedded orbitolinid/miliolid-dominated wackestones and packstones (‘upper dense’ unit in company usage) overlie a grainy rudist facies of Sequence II (Figure 7). These are replaced after a few meters by microbial boundstones and mixed-fauna wackestones, which change rapidly at 1,238 m into calcareous mudstones composed for the most part of nannoconids that alternate with thin argillaceous interbeds containing organic matter (Figure 9). This succession is interpreted as deepening upward overall. From exposure at the base of Sequence III, the succession becomes a shallow-subtidal to intertidal orbitolinid-miliolid facies, deepening through a thrombolitic microbial facies to the subtidal domain of an open lagoon setting, and eventually to an intrashelf basin in which organic matter accumulated and there was nannoconid productivity.

The boundary between sequences III and IV is positioned at a sharp lithological change (1,218 m in Figure 7), where a dramatic increase of the clay content (up to 40%) occurs. This can be seen in the carbonate measurements and the neutron log and the Formation Density Compensator (FDC) log. The organic-matter content of Sequence IV is generally low and the higher TOC values are due to live oil (Figure 7). The surface marking this dramatic change in the sediment flux was also interpreted as a sequence boundary by M. van Steenwinkel (unpublished Internal Shell report RKRS.92.GY1, 1992). Typical alternating bedding at the decimeter to meter scale of carbonate and clay-rich beds occurs in Sequence IV and is accompanied by a change in the faunal composition. Nannoconids dominate in the carbonate-rich beds, but they are nearly absent in the argillaceous beds that are dominated by coccoliths. In the upper part of the section, tempestite deposits consist of packstones and grainstones of miliolid and other small benthic forams. This facies evolution is interpreted as being due to the gradual infilling of the intrashelf basin as shallow-water deposits prograded into the basin.

Nannofossil biostratigraphic age determinations were successful in samples from five wells in the Bab intrashelf basin. The results are summarized in Figure 11. The age determinations were based on the nannoconid zonation established by Deres and Achertéguy (1980), and the coccolith zonation of Thierstein (1976). The lower Aptian corresponds to nannoconid zone 5 (Nannoconus bucheri) and the Chioistozygus litteratus coccolith zone, and the upper Aptian to the Parahabdolithus angustsus coccolith zone, and to nannoconid zone 6 (Nannoconus boletus), subdivided into a lower (zone 6a) and upper part (zone 6b). The Albian corresponds to nannoconid zone 7 (Nannoconus donnatensis) and coccolith zones Prediscosphaera cretacea and Eiffellithus turrisaefifili.

The position of the early/late Aptian boundary was determined in wells 16, 22, 24, and 26 (Figure 11). The results show that the upper part of Sequence III is of earliest late Aptian age (nannofossil zone 6a).
Figure 11: Summary diagram of the three types of time constraints on the regional correlation: biostratigraphic information (nannofossils, rudists, orbitolinids), chemostratigraphy (carbon isotope curve), and sequence stratigraphy (third-order depositional sequences, separated by subaerial exposure surfaces). Note that the late Aptian of the Abu Dhabi carbonate platform margin may be a sedimentary wedge similar to one interpreted on the Oman margin of the Bab Basin. More data is needed to confirm the extent of these deposits. See Figure 1 for location of wells.
and that the clay-rich sediments of the Bab Basin, the Upper Shu’aiba of Hughes Clarke (1988), are of late Aptian age (nannofossil zone 6b). Compared to the dates given for the Lekhwair-7 well in Witt and Gökdag (1994), the early/late Aptian boundary has moved down to the lithological boundary between the Lower and Upper Shu’aiba. Of significance is the presence of earliest late Aptian sediments on top of the Shu’aiba platform in Abu Dhabi well 26 (Figure 11). Carbon isotope curves have been measured in four wells (10, 16, 22, 26). The typical early Aptian shift toward lower values, as observed in the pelagic domain by Weissert et al. (1998) and reported for the Arabian Platform by Wagner (1990) and Vahrenkamp (1996), was found in all of them (Figures 7, 9, and 11).

The regional east-west wireline log correlation extends from near the Jebel Madar outcrops in Oman to western Abu Dhabi (see Figure 1). The spacing between the wells varies from 15 to 85 km. The datum is the top of Sequence II (Enclosure: Figure 8). Where cores or cuttings were available (in 12 of the 28 wells), the sequences were defined on the faunal content and texture, as in the outcrops. In uncored wells, it was based on the gamma-ray, sonic and neutron-log signatures, which were interpreted by comparison with cored wells.

Four sequences were defined. Sequences I and II have a typical gamma-ray log signature, with more variable and higher values at the base and a very flat response in the upper part. Facies control in several wells confirmed that the lower part consists of argillaceous miliolid and/or orbitolinid wackestones, whereas the flat gamma-ray log corresponded to calcareous open lagoonal deposits and high energy-rudist deposits at the top (Enclosure: Figure 8). The thickness of sequences I and II doubles in a westward direction, from 20 to 40 m, and from 35 m to 75 m, respectively. The log correlations suggest flat ramp systems with very little relief, findings supported by the absence of seismic geometries in these intervals in Petroleum Development Oman (PDO) and Abu Dhabi Company for Onshore Oil Operations (ADCO) data.

The architecture of Sequence III is more complicated, with the creation of the Bab intrashelf basin. The log signatures show evidence for significant lateral facies variation, and a basin morphology and dipping clinoforms have been observed on seismic lines of PDO and ADCO (Fisher et al., 1994). Based on the geometries reconstituted by the well-log correlations, three units can be distinguished. The first one, indicated in dark green in Figure 8 of the Enclosure, is very flat and can be traced along the entire length of the transect. It corresponds to the early transgression. The facies evolved laterally and vertically from orbitolinid- and calcareous algae-dominated muddy facies at the base throughout the transect, to an open lagoonal environment on the site of the future Bab Basin (wells 16, 19, 20, 22), and to the aggradation of shallower-water facies in more proximal areas (e.g. Jebel Madar and well 26).

The second unit (light green in Figure 8 of the Enclosure), shows clinoform geometries in the eastern part of the transect that have been identified by correlating maximum flooding surfaces of medium-scale cycles based on the log signatures. Since the position of the transect is perpendicular to the Bab Basin coastline and the Neo-Tethys ocean coastline (Figure 1), it is well suited to bring out the internal geometries of the Shu’aiba platform in Oman. Five clearly expressed flooding surfaces can be traced from the basin margin between wells 12 and 13, to well 1 in the east adjacent to Jebel Madar (Enclosure: Figure 8). The platform developed in successive transgressive phases as a result of differential sedimentation. The flooding surfaces delineate the platform geometries, which evolved from a retrogradational, to aggradational, to progradational style. Microbial boundstones and large, conical orbitolinid wackestones dominated proximal-slope facies during the retrogradational phase. Distal, intrashelf basin facies show a clear cyclicity in the gamma-ray logs, especially in the western part of the transect. The gamma-ray signature is a reflection of alternating organic-rich, clayey levels with limestone beds (see Figure 7). The maximum flooding surface of the third-order sequence (Enclosure: Figure 8) is put at the change from retrogradation to progradation, following M. van Steenwinkel (unpublished internal Shell report RKRS.92.GY1, 1992). Facies in the prograding part are grainy rudist-dominated packstones, grainstones and rudstones. Dipmeter measurements confirm a westward progradation, with dip angles of up to 30° (Enclosure: Figure 8, wells 8 and 9). In Abu Dhabi on the western side of the Bab Basin, the transect was parallel to the paleocoastline and so provided no information on the internal platform geometries.

In Abu Dhabi, the top 20 to 30 m of the Shu’aiba-platform sediments in well 26 constitute the third unit (yellow-green in Figure 8 of the Enclosure) and have been dated as late Aptian based on nannofossils.
(Figure 11). This unit can be correlated along strike with the neighboring wells 25 and 27 (Enclosure: Figure 8). No information is available as to how far this unit continues onto the platform. In Saudi Arabia, an early Aptian age for the Shu’aiba platform is generally accepted (Hughes, 2000). On the eastern side of the basin, no sedimentation occurred on top the lower Aptian platform, except for an anomalously thick succession in well 8. This 30-m-thick unit can be correlated in strike direction (parallel to the paleocoastline) with a package that is clearly defined on the gamma-ray log of wells 9 to 12. In well 11, this package is dated late Aptian based on Orbitolina (Yibal well, Witt and Gökdag, 1994). There is therefore evidence for an upper Aptian wedge of rudist facies along the eastern and western margins of the Bab Basin. An estimate can be made of the water depth in the intrashelf basin by following the top boundary of Sequence III from the platform into the basin. The actual thickness difference, without correction for compaction, is approximately 90 m in Sequence III on the western margin (between wells 25 and 24), and 70 m on the eastern margin (between wells 12 and 13). In general, a westward increase in thickness occurs in Sequence III, with the Oman Platform having a total thickness of about 90 m, and the Abu Dhabi Platform about 160 m (Enclosure: Figure 8).

Sequence IV, the Upper Shu’aiba of Hughes Clarke (1988), is restricted to the intrashelf Bab Basin. It is characterized by a meter-scale bedding pattern in gamma-ray logs that can be recognized in most of the intrashelf basinal wells (Enclosure: Figure 8). The bedding pattern is essentially a reflection of the clay content (see core description in Figure 7). No organic-matter accumulation of any significance is found in this sequence. The layer-cake bedding pattern can be followed from the eastern part of the basin as far as the Sahil area (well 21; Figure 1), where the bedding disappears, and a pure claystone succession remains (wells 24 and 23). We suggest that this variation was the result of intrashelf basinal water currents, probably controlled by dominant wind directions. Water depth during Sequence IV is estimated to have been several tens of meters. Two shallowing-up cycles were identified in core material. In well 24, shallowing-up is marked by a mixed fauna of rudists, corals, and an abundance of small and large orbitolinids, whereas in the east, in well 16 (Figure 7) the presence of miliolid-rich storm deposits suggests progradation. The deeper-water deposits are alternating limestone beds and marls.

Sequence Stratigraphic Model

A sequence stratigraphic model is proposed on the basis of the following:

- The sequence stratigraphic subdivision as determined from outcrop sections and core material;
- Biostratigraphic information available in the literature and new age determinations presented in this study;
- Carbon-isotope stratigraphy; and
- A regional log correlation.

This model is represented in a two-dimensional west-east cross-section, showing the facies distribution and the stratal geometries (Figure 12), and in a set of block diagrams illustrating the stepwise paleogeographical and environmental evolution (Figure 13). The block diagrams represent the southeastern part of the Arabian Plate from northern Oman to the United Arab Emirates.

Sequences I and II

Depositional sequences I and II have a comparable bedding pattern and an identical ecological succession. Three facies associations are recognized:

1. Orbitolinid and/or miliolid wackestone-packstones, representing a low-energy platform-top environment, were deposited during the early transgression;
2. Mixed-fauna mudstones and wackestones, characteristic of an open-lagoon environment, were deposited during the maximum flooding and early highstand; and
3. Rudist/miliolid wackestones, packstones, grainstones and framestones, interpreted as a high-energy, shallow platform-top environment, were deposited during the late highstand.
Figure 12: Sequence stratigraphic model for the Barremian/Aptian in northern Oman and Abu Dhabi. Four depositional systems are identified: the carbonate ramps of Barremian age (sequences I and II; Kharaib Formation); the starved organic-rich intrashelf basin and fringing carbonate platforms of lower Aptian age (Sequence III, Lower Shu’aiba); the clay-filled intrashelf basin of upper Aptian age (Sequence IV, Upper Shu’aiba); and the mixed carbonate-siliciclastic shelf of Albian age (Nahr Umr Formation). OM = organic matter.
**CARBONATE RAMP SYSTEMS (Kharai Formation)**

<table>
<thead>
<tr>
<th>Sequence I</th>
<th>Sequence II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early TST</strong></td>
<td><strong>Early TST</strong></td>
</tr>
<tr>
<td>Shallow miliolid lagoon</td>
<td>Shallow miliolid lagoon</td>
</tr>
<tr>
<td>Deep ramp</td>
<td>Deep ramp</td>
</tr>
<tr>
<td>Channel</td>
<td>Channel</td>
</tr>
<tr>
<td>Muddy, low-energy ramp</td>
<td>Muddy, low-energy ramp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>MFS</strong></th>
<th><strong>MFS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Open lagoon</td>
<td>Open lagoon</td>
</tr>
<tr>
<td>Local small shoals</td>
<td>Local small shoals</td>
</tr>
<tr>
<td>Shallow miliolid lagoon</td>
<td>Shallow miliolid lagoon</td>
</tr>
<tr>
<td>Deep ramp</td>
<td>Deep ramp</td>
</tr>
<tr>
<td>Muddy to grainy, medium-energy ramp</td>
<td>Muddy to grainy, medium-energy ramp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Late HST</strong></th>
<th><strong>Late HST</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Open lagoon</td>
<td>Open lagoon</td>
</tr>
<tr>
<td>Rudist shoals</td>
<td>Rudist shoals</td>
</tr>
<tr>
<td>Ooid shoals</td>
<td>Ooid shoals</td>
</tr>
<tr>
<td>Tempestites</td>
<td>Tempestites</td>
</tr>
<tr>
<td>High-energy lagoon</td>
<td>High-energy lagoon</td>
</tr>
<tr>
<td>Grainy, high-energy ramp</td>
<td>Grainy, high-energy ramp</td>
</tr>
</tbody>
</table>

- **Open muddy lagoon, with Thalassinoides burrows and tempestites**
- **Microbial mounds**
- **Rudist shoals**
- **Shoal**
- **Ooid shoals**
- **Tempestites**
- **Tidal creeks**
- **Shoal**
- **Sea grass meadows**
- **Orbitolinids**
- **Beach**
- **Muddy, low-energy ramp**
- **Muddy to grainy, medium-energy ramp**
- **Muddy to grainy, high-energy ramp**
- **Shallow miliolid lagoon**
- **Deep ramp**
- **Channel**
Figure 13: Block diagrams illustrating the paleogeographical evolution of the depositional system during the Barremian and Aptian. Note the facies evolution occurring in the early Transgressive Systems Tract (TST) and the Maximum Flooding Surfaces (MFS) in sequences I to III. The facies association typical for the Highstand Systems Tracts (HST) did not change. The approximate location of the subsurface (red) and outcrop (green) transects and the main geographical units are indicated in the legend. The sedimentological features are not drawn to scale.
No seismic geometries have been identified in the Kharaib Formation (ADCO and PDO personal communications) of the studied area, and no deeper-water, intrashelf basinal facies have been found in outcrop or core. The deepest-water conditions were recorded in offshore Abu Dhabi, where an outer ramp facies with nannoconoids was reported by Boichard et al. (1995). Based on these observations we interpret sequences I and II to be a very flat ramp system. In Sequence II, a high-energy, grainy environment was present for most of the time on the Neo-Tethys ocean side, and only migrated over the entire platform during the highstand (Figure 13). A gentle synsedimentary differential subsidence is invoked to explain the regional thickness difference observed in Sequence II.

Sequence III
In Sequence III, the topography changed dramatically with the creation of an intrashelf basin. During early transgression, the facies were comparable to those found at the base of Sequence II with decimeter-scale bedded orbitolinid and calcareous algal packstones and wackestones. This facies type can be traced throughout the area, but some changes in the faunal composition and thickness do occur. Evidence for the shallowest water depth is found in Jebel Madar, where orbitolinid beds intercalate with tidal-flat deposits and miliolid-rich beds (Figure 5). Somewhat deeper-water conditions existed in areas such as the Shaybah field where planktonic foraminifera occur (Hughes, 2000). In the Jebel Akhdar area, intermediate water depths have been interpreted, as neither mudflat facies nor planktonic foraminifera occur.

These observations are important as, firstly, it shows that the Kharaib platform had some topographic relief prior to flooding by Sequence III, and secondly, it is proof that the presence of the orbitolinid facies by itself is not a conclusive environmental indicator. The orbitolina facies are only a few meters thick in the subsurface at the location of the Bab Basin (Figure 7; Enclosure: Figure 8), but attain a thickness of about 20 m in outcrop (Figure 9; Enclosure: Figure 10). In the basin, the facies is overlain by a deepening-upward trend of microbial boundstones to open-lagoonal mudstones and wackestones (Figures 7, 12). This lateral variation in thickness and facies can be explained as a sedimentary response to a slow rise in sea level that caused a retrograding trend in the Bab Basin, and a time-equivalent aggrading trend in the more proximal domains of the outcrop sections (Figure 12).

This initial facies differentiation was further accentuated by differential sedimentation rates in the proximal domain and intrashelf basin, probably as a result of an increase in the rate of sea level rise during the late Transgressive Systems Tract (TST). Organic matter accumulated in the starved intrashelf basin (up to 4% TOC; Figure 7) in association with nannoconid muds, to form a carbonate source rock. In the proximal domain, the interval is characterized by the abundance of microbial encrusting organisms such as Lithocodium and Bacinella, which are the bonding elements in the construction of the carbonate platform (Enclosure: Figure 10). The contemporaneous accumulation of organic matter associated with microbial activity is interpreted as an indication of mesotrophic conditions at this time. Thus, by making use of a slight relief present on the platform, the dynamic processes of the sedimentary system created intrashelf basin morphology through differential sedimentation rates. It is possible that the initial relief was controlled by the presence of the underlying salt that may have reacted to a compressional regime that began in the Aptian.

During the subsequent highstand, high-angle clinoforms of grainy, rudist/miliolid sediments prograded into the intrashelf basin (see dipmeter measurements in Enclosure 1: Figure 8). Well-developed channel systems, rudist-debris bars and well-sorted laminated grainstone beds are evidence of the shallow-water (subtidal to intertidal) environment at the top of the platform (Figure 4). Similar facies were observed in well 26. Toward the Bab Basin margin, rudist accumulations are several tens of meters thick. Evidence for a forced regressive wedge around the margin of the basin is supported by the biostratigraphic dating of early late Aptian sediments in Oman and Abu Dhabi.

Sequence IV
During Sequence IV times, the platforms on both sides of the Bab intrashelf basin became exposed, and sedimentation was restricted to the basin itself and to the Neo-Tethys margin (Figure 13). The exposure was most likely the result of a major eustatic fall in sea level of about 50 m (not corrected for compaction; Enclosure: Figure 8). Evidence for the fall is provided by
(a) the younger age of these deposits (late Aptian; Figure 11);

(b) the presence of two shallowing-up sequences within the Bab Basin (observed in well 24), and onlap geometries of basinal deposits against the platform margin (e.g. Witt and Gökdag, 1994; Grötsch et al., 1998);

(c) the exposure surfaces on top of the Shu’aiba platforms in Oman, Abu Dhabi and Saudi Arabia; and

(d) the sudden increase in clay, indicating a major change in the sedimentary system.

This sea-level fall happened during the earliest late Aptian at the base of nannoconid zone 6b. The sedimentation in the intrashelf basin became clay-dominated and no organic matter was preserved. Layer-cake bedding patterns of meter-scale cycles of clay-limestone alternations can be traced for long distances (Enclosure: Figure 8). A pure claystone wedge in wells 23 and 24 may be explained by either trade-wind-controlled water currents in the intrashelf basin, a local point-source of clay material beyond the exposed carbonate platform, or a combination of both. The infill sequence was terminated by prograding cycles in the east that shed mililoid tempestite lobes into the basin (well 16, Figure 7) and by the installing of an Orbitolina-dominated shallow-platform setting in the west (well 24). No evidence for subaerial emergence has been found here and it is unlikely that a time gap exists between the Shu’aiba and the Nahr Umr shales in the intrashelf basin (Witt and Gökdag, 1994).

**DISCUSSION**

**Ecological Change and Depositional Sequences**

One of the most interesting results of this study is the recognition of ecological change and faunal successions both at the scale of third-order sequences and, on a longer time scale, during the Barremian and Aptian.

The first three third-order depositional sequences have a similar stratigraphic succession to the three Facies Associations. The discoidal orbitolinid- and mililoid-dominated Facies Association 1 occurred during early transgression; the mixed, diversified biota/microbialites, micro-encrusters and rudists in-life-position Facies Association 2 was formed during late transgression and early highstand; and the rudist, mililoid, mono- and biserial foraminifera Facies Association 3 is of late highstand. The third-order sequences are bounded by exposure surfaces, and their overall environmental evolution is interpreted as a symmetrical deepening/shallowing trend. Water depths both at the base and the top of the sequences were shallow subtidal to locally intertidal, but the faunal assemblage and textures are dramatically different and interfingering of facies has only been observed for Facies Associations 2 and 3.

In the Lower Shu’aiba Formation of the Shaybah field in southern Saudi Arabia, Hughes (1997, 2000) observed a similar tripartite faunal succession. The ‘lower Shu’aiba’ has a flat morphology dominated by *Palorbitolina lenticularis* and *Lithocodium aggregatum* in association with subordinate miliolids and rare planktonic foraminifera. The ‘middle Shu’aiba is of lagoonal to open marine facies, dominated by an association of *Lithocodium aggregatum*, various rudist species and benthic foraminifera in the proximal domain, and by planktonic foraminifera in the open-marine environment. The ‘upper Shu’aiba’ is characterized by a more grainy facies composed of a rudist-dominated lower layer and an foraminiferal-dominated upper layer. Hughes did not provide a geometrical framework for his biofacies observations, but the faunal succession is strikingly similar to that seen in Oman and Abu Dhabi, suggesting that the same sequence stratigraphic model may be applicable.

We suggest that the influence of paleoenvironmental factors other than accommodation space, such as the trophic level and clay input, strongly controlled the facies succession. The orbitolinids, which in the studied area are commonly associated with abundant calcareous algae and echinoderms in slightly argillaceous, very muddy limestones, were probably deposited under mesotrophic conditions in a low-energy environment. Conversely, the rudist and mililoid-dominated, grainy, pure limestone facies indicate oligotrophic (lower trophic) conditions in a relatively high-energy environment.
Changes in the trophic level and clay input might be related to variable humidity patterns during sea-level changes. During early transgression, increased weathering rates induced by heavier rainfall, and clay mobilization caused by flooding of the exposed platforms, may have contributed to the creation of mesotrophic conditions favorable for the development of orbitolinids. The occurrence of orbitolinids at several locations around the Neo-Tethys has been reported during the first episode of the Aptian transgression (Arnaud-Vanneau and Arnaud, 1990; Funk et al., 1993; Raspini, 1998; Bernaues, 2000). In contrast, the high-energy rudist-dominated environment experienced a negligible influx of terrigenous material, possibly as the result of a drier climate. The grainy rudist-dominated facies of the upper Barremian and lower Aptian are so typical of the Neo-Tethys shorelines that they have received an internationally recognized facies name. It is known as the Urgonian in France (Arnaud-Vanneau and Arnaud, 1990), in Switzerland (Funk et al., 1993), in Italy (Raspini, 1998), in Spain (Ruiz-Ortiz and Castro, 1998; Bernaues, 2000), and in Mexico (Bonnet, 1952). Thus, the regional continuity of the argillaceous orbitolinid facies and of the grainy rudist-dominated facies provides supporting evidence for a controlling factor that surpasses the local setting.

Faunal change not only occurred at the scale of the third-order sequence, but also at the second-order scale. During the course of the four successive third-order sequences, three major changes in the faunal assemblage occurred. Firstly, the appearance and gradual increase in numbers of the benthic foraminifera *Orbitolina*. Orbitolinids occur throughout the upper Barremian to the mid Cenomanian, and are present in many different environments (e.g. Arnaud-Vanneau, 1987; Simmons et al., 2000). However, they are most abundant in the early transgressive deposits of the third-order sequences in Oman (base of sequences II and III), and in the Albian Nahr Umr shales they may form up to 50 percent of the sediment. This stepwise increase of abundance of the orbitolinids is interpreted as the result of the gradual occupation of an ecological niche by this pioneering r-type species. A relationship between clay input and mesotrophic conditions is, in our opinion, the most plausible explanation for the proliferation of the orbitolinids, and suggests a link to regional controlling factors such as climate, superposed on the third-order sea-level fluctuations.

The second faunal change occurred during the late transgression-early high stand of Sequence III (early Aptian). It is characterized by the widespread occurrence of microbial boundstones and the time-equivalent accumulation of organic matter in the adjacent intrashelf Bab Basin. The coeval deposition of the microbial boundstone in the proximal domain and the accumulation of organic matter in the basin are also interpreted as a biological expression of a changing depositional environment. The accumulation of organic matter in the Bab intrashelf basin is time-equivalent to the Oceanic Anoxic Event 1a, during which organic matter accumulated worldwide (Bralower et al., 1994; Weissert et al., 1998). Both tectonic activity (plate reorganization, major basalt extrusion in the Ontong plateau in Java, and increased CO2 emissions), and possibly related worldwide climatic changes during the Aptian, have been invoked as the controlling factor of changes in the deep- and shallow-water depositional environments (e.g. Larson, 1991; Bra,lower et al., 1994).

The third faunal change occurred at the boundary between sequences III and IV, when sedimentation was restricted to the Bab intrashelf basin in the early late Aptian. During Sequence III, nannoconids were the main contributors to the Bab Basin deposits that consist of a hemipelagic carbonate mud with thin organic-rich interbeds (Figure 7). Sequence IV, however, is characterized by an alternation of limestone and argillaceous interbeds, and does not contain organic matter. Coccolithophorids are abundant in the clay-rich layers, whereas the carbonate beds are dominated by nannoconids. Nannoconids are opportunistic forms (Busson and Noël, 1991) of relatively oligotrophic and unstable conditions (Coccioni et al., 1992; Erba 1994), whereas coccoliths are generally considered to be communities living in stable mesotrophic conditions. This suggests that during Sequence IV, the carbonate beds in the Bab Basin were deposited during periods of good water mixing and minimal clay supply. On the other hand, clayey layers may correspond to periods of clay influx and more stable (stratified) conditions in the water column during which each coccolith community could occupy its own ecological niche (Mattioli, 1997). In addition, nannoconids are generally restricted to epicontinental seas of low latitude (Busson and Noël, 1991). This may suggest that apart from clay supply and water mixing, changes in water temperature may have influenced nannoconid occurrence and abundance, whereas coccolithophorids are found in a wider latitudinal spectrum and may survive in lower water temperatures.
This study illustrates two important aspects of sequence stratigraphy related to carbonate systems: ecological change, occurring at different time scales; and sequence boundary expression by a dramatic change in the sedimentary system. McDonough (1996) and Homewood (1996) invoked ecological change or faunal partitioning at the scale of third-order sequences. Van Buchem et al. (1996, 2002) documented a replacement of the faunal assemblage in the intrashelf basin domain during third-order depositional sequences of Cenomanian age. However, as yet no conclusive studies have been published proving this hypothesis in the platform domain. Here, we have demonstrated for the first time that the replacement of faunal assemblages during the course of a third-order sequence can occur in the shallow-water environment. It may be that this phenomenon is the exception rather than the rule, and that changing climate and increased tectonic activity (such as during the Barremian and APTian), are needed to create the conditions for such a well-expressed ecological succession. Detailed studies in other periods of known climatic change are needed to confirm this hypothesis.

Schlager (1991) advocated the importance of dramatic changes in the sedimentary system as indicators of sequence boundaries. He stressed that in carbonate environments in particular this is an important criteria since the system is extremely sensitive to changes in the depositional environment. In this study, we have two examples of this:

1. The change from Facies Association 3 (grainy, rudist facies) to Facies Association 1 (muddy orbitolinid-dominated facies) across the top boundaries of sequences I, II and III in the platform domain; and
2. The change from Facies Association 4a (organic-rich carbonate basinal facies) to 4b (organic-poor, clayey basinal facies) across sequence boundary III to IV in the intrashelf basin.

**Sequence Stratigraphic Architecture**

The stratigraphic organization in carbonate systems is not only dependent on the variations in accommodation but also, importantly, on changes in the faunal assemblages as a result of environmental controls. In this particular case, the recognition of a systematic logic in the faunal succession formed the basis for the sequence subdivision. This observation has not been reported in the literature before, since studies were limited to either the Kharaib or Shu’aiba formations, or did not include a regional transect (e.g. Boichard et al., 1995; Witt and Gökdag, 1994; Vahrenkamp, 1996). Based on the regional context, the larger stratigraphic interval considered, and the combination of outcrop and subsurface data, we propose a revision of the environmental interpretation of the orbitolinid beds and, as a result, a revised sequence stratigraphic interpretation.

The orbitolinid beds, corresponding to the lower ‘dense’ units in the subsurface, and the Hawar Member as defined in outcrop (Enclosure: Figure 14), are interpreted by us as having been deposited during early transgression over a land surface that had some relief. The main deepening event (the lower Aptian third-order MFS) occurred later when the Bab Basin was created through differential sedimentation. Our interpretation is as follows:

- The base of Sequence III is a regional subaerial exposure surface as shown by root traces in Abu Dhabi wells, the lowstand wedge observed in the Nakhl area (Hillgärtner et al., in press), supported by the dramatic change from Facies Association 3 to Facies Association 1b.

- The orbitolinid facies alternate with very shallow-water facies, including miliolids and tidal-flat deposits in the Hawar Member in the Jebel Madar area. In the Upper Kharaib of Jebel Akhdar, they are found in association with firm grounds that have calcite-filled burrow systems. Orbitolinid facies are reported to contain planktonic forams in the Shaybah field (Hughes, 2000). However, relief was probably minimal, as is suggested by the good correlation of meter-scale cycle packages with other locations (Pittet et al., 2002).

- The orbitolinid facies are slightly argillaceous. The origin of this clay fraction could be both reworked clays of the exposed platform and exposed siliciclastic sources to the west in what is now Saudi Arabia (Murris, 1980). Mobilization of terrigenous material during early transgression is a common phenomenon; however, during maximum flooding, siliciclastic depocenters tend to occur more nearshore, hence causing the deposition clay-poor HST sediments.
Both from the point of view of sedimentary facies and geometrical control, the maximum deepening in the Shu’aiba Formation occurred not in the orbitolinid facies but in the Bab Basin where organic-rich limestone facies and abundant nannoconids and planktonic foraminifera occur (Figure 7 and Enclosure: Figure 8). Correlations in the Oman Platform show an unambiguous retrograding, aggrading and prograding geometry above the orbitolinid beds (Enclosure: Figure 8). Placing the maximum flooding surface of the Aptian in the orbitolinid facies would imply that the microbial facies were deposited in deep water, and that they gradually filled the accommodation space—this is difficult to match with the observed platform geometries.

Evidence for the relationship between the Aptian isotopic signature and relative sea-level fluctuations was provided by Grötsch et al. (1998). As a proxy for relative sea-level variations, they used cycle-stacking patterns (Fisher plots) measured in carbonate platforms in Greece and Mexico. During the earliest early Aptian, little accommodation was created on these platforms and the carbon isotope signature was very low. However, a positive carbon isotope shift was accompanied by an increase in bed thickness, interpreted as a relatively rapid rise in sea level. A similar evolution is interpreted at the base of Sequence III, with decimeter-bedded orbitolinid facies having been deposited in a phase of reduced accommodation, whereas the thick-bedded, aggrading microbial boundstones were laid down during a rapid rise in sea level (Figure 15).

Note that we advocate caution in the interpretation of depositional environments based only on microfacies without having supporting evidence from sedimentary structures and the overall architecture of the depositional system.

Compared to previous work, our sequence stratigraphic interpretation of the Kharaib Formation (sequences I and II) comes close to those proposed by Boichard et al. (1995) and Sharland et al. (2001) (Figure 15). We differ from Sharland et al. (2001) and Davies et al. (2002; this issue) in the position of the MFS in sequences I and II (their K50 and K60). We place them slightly higher in the succession, in the open lagoonal facies rather than at the top of the orbitolinid/miliolid facies (Figure 15).

Sharland et al. (2001) may have misplaced the K50 MFS in the Lekhwair-7 well (their Figure 4.56) and in the Wadi Mu’aydin section (their Figure 4.53) since the Lower Kharaib is clearly expressed in both and correlates well with the offshore Abu Dhabi well-A, as is shown in Figure 14 of Enclosure. The lower part of Sequence II in that well consists of facies that are of deeper-water origin (nannoconid shaly limestone) than are observed in other wells and sections; this suggests the presence of some relief in the area of well-A at the time.

In the interpretation of the Shu’aiba Formation, opinions differ more fundamentally. Boichard et al. (1995) distinguished three medium-scale sequences in the Shu’aiba. They did not interpret the strong facies change in the basinal facies as a sequence boundary, but recognized the difficulty of deciding on the order of these sequences (fourth- or third-order). Sharland et al. (2001) and Davies et al. (2002; this issue) proposed two maximum flooding surfaces in the Shu’aiba Formation: the K70, of early Aptian age, corresponding to the Hawar shale; and the K80, of mid Aptian age, corresponding to the top of the organic-rich basinal facies in the Lower Shu’aiba (Enclosure: Figure 14; and Figure 15). Their interpretation was based on the assumption that the Bab Basin morphology is essentially of tectonic origin, and therefore they consider that the maximum eustatic flooding is located in the Hawar Shale unit (Davies et al., 2002). We propose a third-order MFS of the depositional sequence encompassing the whole of the Lower Shu’aiba. In the Bab Basin, it is placed at the base of the organic-rich intrabasinal limestones (Figure 7), and in the platform domain at the top of the microbial boundstone facies (Figure 9a). This surface comes close to the MFS 80 of Sharland et al. (2001), but we interpret their K70 as being a higher-order maximum flooding surface, probably fourth-order. Our interpretation corresponds to that proposed by M. van Steenwinkel (Unpublished internal Shell report RKRS.92.GY1, 1992) on the Oman side of the Bab Basin. Our arguments are as follows:
Figure 15: Chronostratigraphy of Barremian-Aptian in Oman and Abu Dhabi. Timescale based on Hardenbol et al. (1998). Carbon isotope curves are simplified versions of those presented in Figure 9a (Oman platform) and Figure 7 (Bab Basin). The sequence interpretation from this study is compared with that of Sharland et al. (2001). See text for discussion.
• We do not see evidence for a predominantly tectonic control of the Bab intrashelf basin. On the contrary, equal thicknesses of the strata between the limestone marker bed at the base of the Nahr Umr and the top of Sequence II (Figure 11), suggest that there was no differential subsidence.

• In the shallow-water domain, the Lower Shu‘aiba facies succession is comparable to that in sequences I and II, suggesting that we are dealing with a similar type of depositional sequence (Enclosure: Figure 10). Consequently, we interpret the Lower Shu‘aiba facies succession (including the creation of the Bab intrashelf basin), as the response of the sedimentary system to a predominantly eustatic-controlled relative sea-level rise. As a result, the Bab Basin facies represent the deepest-water conditions of this depositional sequence.

• A similar mechanism of a dominantly eustatic-controlled origin of intrashelf basin to platform topography has also been invoked for the Cenomanian/Turonian carbonate platforms (Natih Formation) in northern and central Oman (van Buchem et al., 1996, 2002; Droste and van Steenwinkel, in press).

At this point, we need to refer to a possible cause of confusion. The Hawar Shale was originally defined in well logs as the shaly unit underlying the Shu’aiba carbonates and overlying the Dense A unit (see, for instance offshore Abu Dhabi well-A in Figure 14 of Enclosure). In outcrop, however, the Hawar Member corresponds to the decimeter-bedded orbitolinid interval that separates the Shu’aiba and Upper Kharaib limestone beds (Figure 9b, and outcrop logs in Figure 14 of Enclosure). Put in a sequence stratigraphic context, the Hawar Member, as defined in outcrop, corresponds to the ‘upper dense’ unit and the Hawar Shale in the subsurface; and together they represent the early transgressive deposits of Sequence III (Enclosure: Figure 14). This illustrates the lateral variation in facies that occurred at the time.

### Controlling Factors

The sedimentation pattern in the Barremian and Aptian is the result of an interplay of accommodation (eustacy and tectonism) and environmental changes, such as clay influx and trophic conditions. Indications of variations in accommodation are provided by the environmental interpretation of the facies (water depth) and by the thickness of the sequences. The first three depositional sequences show a complete infill of the accommodation space in the platform domain. Interestingly, the thickness of the three sequences doubles each time; for example, in Jebel Madar Sequence I is 20 m thick, Sequence II is 40 m, and Sequence III is 80 m, although the facies succession remains the same. Three explanations are possible: either the sequences have a similar duration, but the sedimentation rate increases; or the sedimentation rate is constant and the duration of the sequence increases; or a combination of both. Based on a cyclostratigraphic counting of fourth- and fifth-order sequences, the second interpretation is favored (Pittet et al., 2002) that supposes a constant sedimentation rate, and thus a constant creation of accommodation space. An intriguing question is why did the sedimentary system develop the same sedimentation pattern (fauna and Facies Associations) over increasingly longer periods of time? The answer will require more work and comparisons with sedimentation patterns of the same time interval in other locations.

Tectonism played only a minor role during deposition of the sequences. Gentle regional differential subsidence is invoked to explain the increase in thickness of sequences II and III from southeastern Oman to northwestern Abu Dhabi ((Enclosure: Figure 8; and Figure 11). A punctuated change in plate stress occurring during the early Aptian may have activated deep-seated salt basins, thus creating some relief on the Arabian plate, and notably a slight depression at the location of the future Bab Basin. This small variation in sea-floor topography was then accentuated by differential sedimentation rates.

Environmental control at various scales has been proposed above. One was at the scale of the third-order sequences, when conditions seem to have been different during the transgressive and the highstand phases giving rise to different faunal assemblages, and another was on a longer time scale that covered the Barremian and Aptian. Numerous studies have demonstrated global climatic changes occurring in this time interval. A climatic evolution from arid-warm to humid-warm with a temperature maximum during the early Aptian, is now generally accepted (e.g. Weissert, 1989; Larson, 1991; Weissert and Lini, 1991; Erba, 1994).
Implications for the Petroleum System

This study has several important implications for the understanding of the Kharaib and Shu’aiba petroleum systems.

Firstly, it provides a regional time framework based on biostratigraphy, chemostratigraphy (carbon isotope curve), and sequence stratigraphy that allows for correlation between fields with more certainty, and points out similarities and differences in their reservoir layering (Enclosure: Figure 14). The regional correlation also serves to select relevant outcrop analogs to study, for instance, subseismic geometries and heterogeneities in reservoir facies. As a result, the Kharaib outcrops in northern Oman can be considered as excellent outcrop analogs for time-equivalent reservoirs in the subsurface in Oman and the United Arab Emirates with the result that subseismic-scale observations on reservoir unit geometries can be made. The outcrops of the Shu’aiba Formation at the same location are, however, only of relevance for those fields that are located at the margin or in the platforms bordering the Bab Basin; for example, Yibal, Bu Hasa, Shaybah.

Within this time framework, a geological model is proposed that is predictive with respect to the regional distribution and large-scale geometries of the different sedimentary facies. This is of immediate relevance for the understanding of the distribution, geometries, and heterogeneities in reservoir, seal, and source rock facies, and thus for both exploration and reservoir characterization studies.

Reservoir characteristics at the large-scale are controlled by the overall geometries of the depositional system: very flat carbonate ramp systems in sequences I and II; a platform and intrashelf basin system in Sequence III; and sedimentation restricted to the intrashelf basin in Sequence IV (Figures 12, 13). These morphologies controlled the distribution and size of the grainy reservoir facies. Within the third-order sequences, the best reservoir facies are the grainy rudist-rich packstones and grainstones and rudstones of Facies Association 3 that were deposited during the highstands (Figure 15).

The intraformational seals, or ‘dense’ units in ADCO and PDO usage (Enclosure: Figure 14), correspond to the early transgressive deposits of sequences II and III. They are very muddy, may be slightly argillaceous and contain mainly benthic foraminifera (mostly orbitolinids and miliolids). The dense unit at the base of Sequence II (KLD; Dense B) is continuous throughout the study area, and its typical gamma-ray signature can be traced over hundreds of kilometers in the subsurface and outcrops (see outcrop gamma-ray logs in Enclosure: Figures 10, 14). The dense unit at the base of Sequence III (KUD; Dense A), shows much more lateral facies change, due to the formation of the Bab Basin, and varies significantly in thickness (Enclosure: Figures 10, 14). Consequently, the seal capacities can be expected to vary significantly at a regional scale. The lithological and geometrical differences between these dense zones can be explained by differences in the carbonate systems: Sequence II is a flat ramp, whereas in Sequence III a platform and intrashelf basin produced a much more complicated pattern of lateral facies change and depositional geometries (Figure 12).

These differences also explain why time-equivalent deposits of the Lower Shu’aiba in Sequence III are source rocks. The intrashelf basin topography created conditions, such as a stratified water column and a slow water circulation, that were suitable for the deposition of organic-rich source-rock material. The observation that source rocks accumulated in the Bab Basin during transgression is typical of intrashelf basins in the Mesozoic carbonate systems elsewhere in the Arabian Plate (e.g. Murris, 1980; Droste, 1990; van Buchem et al., 1996; 2002; Sharland et al., 2001; Droste and van Steenwinkel, in press).

CONCLUSIONS

The main conclusions of this study are as follows:

- In a regional transect across the Oman and Abu Dhabi platforms bordering the Bab Basin, four third-order depositional sequences covering the Barremian and Aptian stages are identified and correlated. A high-resolution sequence stratigraphic cross section is presented that integrates for the first time outcrop and subsurface data.
• In the first three third-order sequences, a systematic ecological succession of three Facies Associations is observed. They are (a) a discoidal orbitolinid- and miliolid-dominated Facies Association 1 deposited during early transgression; (b) a mixed, diversified biota/microbialites, micro-encrusters and rudists in-life-position Facies Associations 2 (late transgression and early highstand); and (c) a rudist, miliolid, mono- and biserial foraminifera Facies Association 3 (late highstand).

• The stratigraphic architecture evolved from a flat carbonate ramp-type system during sequences I and II, to a platform and organic-rich intrashelf basin system in Sequence III, and in Sequence IV the carbonate platforms were exposed and a mixed carbonate/clay sedimentation was confined to the Bab intrashelf basin.

• The high-resolution sequence stratigraphic model provides a regional time framework for comparing different oil fields, and identifying outcrop analogs. The Kharaib Formation outcropping in the northern Oman Mountains was shown to be an excellent analog for reservoirs in this formation in Abu Dhabi. The Shu'aiba Formation in Oman, however, may only serve as an analog for fields that are located on the Shu’aiba platform or at its margin, and not for the Shu’aiba facies in the Bab intrashelf basin.

• Within this time framework, the proposed geological model is predictive with respect to lateral facies changes and the depositional geometries of reservoir, seal, and source rock facies.

ACKNOWLEDGMENTS

This study by the Institut Français du Pétrole (IFP) was sponsored by the Abu Dhabi Company for Onshore Oil Operations (ADCO) and Petroleum Development Oman (PDO). Both companies support the conclusions of this paper. Publication is by kind permission of the Abu Dhabi National Oil Company, ADCO, PDO and the Ministry of Oil and Gas of the Sultanate of Oman. We thank Omar Al-Jeelani and Khalil Al-Mohsen from ADCO; Abdullah Al-Habshy, Ali Al-Jahadmi, Magda Al-Kharusi, Mohamed Al-Mamary and Hisham Al-Siyabi from PDO; Philippe Razin, University of Bordeaux; and Guy Desaubliaux, Olivier Lerat and Philip Bassant of IFP for their help in data collection. Nannofossil dating was by Carla Muller, stable Carbon and Oxygen isotope measurements were made at the isotope laboratory of M. Joachimski at the University of Erlangen, Germany, and organic geochemical analyses at the Organic Geochemistry Laboratory of IFP in Rueil-Malmaison, France. Initial drafting work was by Y. Montéon, A. Nakou and N. Doizelet, and photography of Figures 6c,d was by D. Foucault. The quality of the manuscript was much improved by the thorough reviews of GeoArabia’s referees Peter Sharland, Mike Simmons, Dave Casey, and Roger Davies. We also thank GeoArabia’s editors for improving the manuscript. The design and drafting of the final figures was by Gulf PetroLink.

REFERENCES


ABOUT THE AUTHORS

Frans van Buchem is Senior Research Scientist and Project Leader in the Geology-Geochemistry Division of the Institut Français du Pétrole (IFP). He was awarded an MSc in Geology and an MSc in Biology by the University of Utrecht, The Netherlands, and a PhD in Geology by the University of Cambridge, UK. Frans joined IFP in 1990. His main fields of research are carbonate petroleum systems, including the sedimentology of carbonates and organic matter, sequence stratigraphy, and reservoir characterization. He has been involved in extensive research in the petroleum provinces of western Canada, the western USA, Mexico, and North Africa, and is an expert on Cretaceous carbonate systems of the Middle East. Frans was recently awarded the Medal of Merit of the Canadian Society of Petroleum Geologists. He is an editorial board member and reviewer for several international journals.

Corresponding author: frans.van-buchem@ifp.fr
Bernard Pittet is a Lecturer in Sedimentology at the University of Lyon, France. He was awarded a PhD by the University of Fribourg, Switzerland in 1996. His specialist field is high-resolution sequence stratigraphy and cyclostratigraphy of carbonate depositional sequences. Bernard spent one year with the Institut Français du Pétrole working on outcrop analogs of the Lower Cretaceous Kharaib and Shu’aiba platforms of Oman and the United Arab Emirates.

Heiko Hillgärtner is a Research Scientist at the Institut Français du Pétrole, which he joined in 2002. He was awarded a PhD by the University of Fribourg, Switzerland, in 1998. His specialist field is high-resolution sequence stratigraphy and cyclostratigraphy of mixed carbonate-siliciclastic systems. Previously, Heiko spent postdoctoral years with the Institut Français du Pétrole and the Free University of Amsterdam working on the quantification of Lower Cretaceous reservoir bodies.

Jürgen Grötsch is working for Shell Gas Abu Dhabi. He was previously employed as a G & G Coordinator with Shell Abu Dhabi assigned as a Consultant to the Abu Dhabi National Oil Company. He received his MS degree from Universität Erlangen in Germany in 1987. Following a research post at Scripps Institution of Oceanography, San Diego, he received a PhD from Universität Erlangen in 1991 for a study on the evolution of Cretaceous carbonate platforms. Following a postdoctoral fellowship at Universität Tübingen, Jürgen joined Shell International Exploration and Production as a Seismic Interpreter. Later, he was assigned to Shell Exploration and Production Technology and Research as a Production Geologist. There, Jürgen worked mainly on the application and development of novel 3-D modeling techniques for carbonate reservoirs with emphasis on the integration of 3-D seismic and outcrop analogues. He has provided technical services to operating companies in Oman, Abu Dhabi, Venezuela, Kazakhstan, Malaysia, and the Philippines, and is an Editor and Reviewer for several international journals.

Abdullah Al-Mansouri is a Reservoir Geologist in the Abu Dhabi Company for Onshore Oil Operations (ADCO). He obtained a BSc in Geology from Al-Ain University, United Arab Emirates in 1995. From 1995 to 1999, he was an Operations Geologist in ADCO and from 2000 to 2001 he worked as a Reservoir Geologist. Abdullah has conducted reservoir studies and presented papers at regional conferences. He is a member of the Emirates Society of Geoscience. and his main area of professional interest is carbonate sedimentology.
Ian Billing is employed by Saudi Aramco as a Geological Specialist attached to the Geological Research and Development team. He has a BA in Geology from Oxford University and a PhD from Durham University (1991). He then joined Shell International, working on Russian geology before being assigned to the Carbonate Research Group at Rijswijk. It was here that he gained an interest in carbonate reservoir correlation and characterization, including studies of Cretaceous isotope stratigraphy in the Middle East. This work continued with a secondment to Petroleum Development Oman, before he left the Shell group and joined PanTerra Geoconsultants in The Netherlands.

Mia van Steenwinkel is a Senior Geologist/Seismic Interpreter in the Frontier Exploration Asset of Petroleum Development Oman (PDO). She was awarded a PhD from the University of Leuven in Belgium. Prior to joining PDO in 1992, Mia worked as a Carbonate Geologist with Shell Research in The Netherlands. At PDO, she has worked as a Production/Operations Geologist on the Natih, Fahud, and Al Huwaisah carbonate fields.

Henk Droste is Geoscience Advisor for the JVR Centre for Carbonate Studies at Sultan Qaboos University, Oman. He is also a member of the Carbonate Development Team with Shell Exploration and Production Technology in Rijswijk. Henk has an MSc in Geology from the University of Amsterdam, The Netherlands. He was previously employed by Petroleum Development Oman as a Sedimentologist in the Exploration Laboratory, a Geologist/Seismic Interpreter in Exploration, a Production Geologist, and Team Leader of the Regional Studies and Geological Services Team. Henk has also worked as a Carbonate Geologist with Shell Research in The Netherlands and as a Sedimentologist in the Regional Studies Team of Shell Expro in London.

W. Heiko Oterdoom is employed by Lundin Sudan Ltd. Heiko was educated at Berkeley and Zürich and was awarded a PhD in Petrography from the Federal Institute of Technology, Zürich in 1981. He has exploration experience as a Regional Geologist with Shell in oil shales, the North Sea-Norwegian Sea, and the Far East. He joined Petroleum Development Oman in 1995 as a Senior Exploration Geologist in diverse functions ranging from operational stratigraphy and geological studies to frontier exploration. Heiko is a licensed guide to the Dutch tidal flats.

Manuscript Received March 20, 2001
Revised April 20, 2002
Accepted April 24, 2002
Comparative schema of sedimentological facies, depositional sequences, lithostratigraphic nomenclature, and reservoir units for wells and outcrops from offshore Abu Dhabi to Jebel Musait Oman.

Figure 8: Regional well correlation from the United Arab Emirates to Oman.

Figure 14: Comparative schema of sedimentological facies, depositional sequences, lithostratigraphic nomenclature, and reservoir units for wells and outcrops from offshore Abu Dhabi to Jebel Musait Oman.

References:


Enclosure to Accompany
High-Resolution Sequence Stratigraphic Architecture of Barremian-Aptian Carbonate Systems in Northern Oman and the United Arab Emirates (Kharib and Shu’iba Formations)


Figure 8: Regional well correlation from the United Arab Emirates to Oman.

Figure 14: Comparative schema of sedimentological facies, depositional sequences, lithostratigraphic nomenclature, and reservoir units for wells and outcrops from offshore Abu Dhabi to Jebel Musait Oman.