Barremian-lower Aptian Qishn Formation, Haushi-Huqf area, Oman: a new outcrop analogue for the Kharaib/Shu’aiba reservoirs

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ABSTRACT

Limestones of the middle Cretaceous Qishn Formation are exposed in the Haushi-Huqf area of Oman. These carbonates preserved reservoir properties due to shallow burial and an arid post-exhumation climate. This characteristic makes the Qishn Formation an excellent outcrop analogue for the Upper Kharaib and Lower Shu’aiba oil reservoirs in the Interior Oman basins. The aim of this paper is to provide a broad overview of results from an industry-oriented field study recently performed in the Qishn Formation outcrops belts. The comparison of these results with studies undertaken in the Northern Oman Mountains and the Oman Interior subsurface is the topic of ongoing research.

The age of the Qishn Formation is middle Barremian to mid-early Aptian, the Hawar Member (equivalent) is earliest Aptian in age. The paleo-environments recorded range from the tidal mudflat to the argillaceous platform setting (outer ramp) below the storm wave base. In terms of sequence stratigraphy, four large-scale transgressive-regressive cycles of Cretaceous age (Jurf and Qishn formations) were distinguished. Sequence I, a dolomitized succession termed Jurf Formation, is the equivalent of the Lekhwair, the Lower Kharaib and possibly older Cretaceous units. Due to pervasive early dolomitization, the Jurf Formation is not further considered here. Sequence II, forming the base of the overlying Qishn Formation represents the equivalent of the Upper Kharaib, portions of Sequence III the Hawar Member, and Sequence IV is the equivalent of the Lower Shu’aiba. At least two lower orders of cycles are superimposed on these four sequences.

Total porosity with a mean of 19.3% (s = 8.74%) and permeability with a mean of 6.36 mD (s = 6.57 mD) characterize the Qishn Formation limestones. Overall, the correlation of porosity and permeability is better for regressive (highstand) deposits than for the transgressive limestones. The lateral variability (>100 m) of porosity and permeability values within specific intervals is substantial and matches or even exceeds stratigraphic variability. Spectral gamma ray logs from Qishn Formation recorded in the outcrops are dominated by the U spectrum and to a lesser degree by the Th spectrum.

Qishn Formation carbonates in the Haushi-Huqf High are extensively fractured. The outcrops studied display very widespread systematic jointing with dominant NW-SE to WNW-ESE trends. A second, subordinate system results in a potentially highly interconnective network. Joints are strictly confined to specific beds or groups of beds and have regular spacing of between 6 and 18 cm. Joints are related to regional stress fields and do not show significant changes (in density or direction) in the vicinity of folds or faults. Faults are typically organized in corridors consisting of up to several metre-wide zones with swarms of discrete fault planes. Fault gauges are very rarely observed, but where present, form discontinuous, 10s of cm long lenses.
INTRODUCTION

The Barremian and Aptian Kharaib and Shu’aiba formations and the Cenomanian Natih Formation represent major petroleum reservoirs in the Middle East (e.g. Le Métour et al., 1995; van Buchem et al., 1996; Alsharhan and Nairn, 1997; Sharland et al., 2001; van Buchem et al., 2002a, b). Outcrop analogues of these subsurface reservoirs allow for a detailed investigation of the facies architecture and structures of carbonate bodies and allow access for easy sampling as in Oman. This approach is particularly valuable for areas where oil fields are geologically complex. The exposures of Cretaceous successions at Jabal Akhdar and the Adam Foothills in Oman are considered as some of the best places for outcrop analogue studies. Consequently, numerous industry-oriented field projects have focused on outcrops in Northern Oman and their correlation with the subsurface (e.g. van Buchem et al., 1996; Masse et al., 1997; Hughes, 1997; Hughes, 2000; Immenhauser et al., 2001; Sharland et al., 2001; van Buchem et al., 2002a, b; Davies et al., 2002; Pittet et al., 2002; Hillgärtner et al., 2003). In contrast, the low-relief Barremian/Aptian remote outcrop belts in the Haushi-Huqf High of Central Oman (Jurf and Qishn formations) rising from barren and sand-swept sabkha plains have previously attracted limited interest (Figure 1).

As a reservoir analogue, the Haushi-Huqf Qishn Formation limestones have three major advantages when compared to the Northern Oman Kharaib/Shu’aiba outcrop belts: (1) The western Haushi-Huqf High outcrop belts are close (about 50 km; Figure 1) to the Shu’aiba fields in the Ghaba Salt Basin. (2) The carbonates of the Qishn Formation in the Haushi-Huqf High have well preserved reservoir properties in terms of rock porosity and permeability due to shallow burial. (3) The geotectonic evolution of the western Haushi-Huqf High is related to that of the subsiding domains, i.e. the nearby Salt Basins. Consequently, observations and interpretations derived from these outcrops can be extrapolated in a meaningful way to the subsurface.

This paper summarizes results of an industry-oriented field project undertaken between March 2001 and June 2002 with focus on the outcrops of the Qishn Formation in the western and southern Haushi-Huqf High in Oman. It is beyond the scope of this paper to document all aspects of this study in detail. Therefore, specific topical papers will focus on aspects such as sequence stratigraphy, rock properties and diagenesis, the impact of discontinuity surfaces on reservoir compartmentalization and the relation between fracturing, facies and carbonate diagenesis. We furthermore do not place the findings shown here in the context of previous sequence stratigraphic models or subsurface data. This must be the topic of future compilations that build on the data presented here.

REGIONAL GEOTECTONIC SETTING AND PREVIOUS WORK

During the middle Cretaceous, the Arabian Peninsula was located approximately at latitude 8º south, i.e. in the tropical realm (Hughes, 2000). Owing to the globally high sea level (Hardenbol et al., 1998), broad portions of the Arabian craton were flooded and carbonate rocks were deposited on an extensive platform upon which sedimentary rocks span the Late Permian to early Turonian (e.g. Murris, 1980; Alsharhan and Nairn, 1986). The Barremian through early Aptian Jurf and Qishn formations of the Haushi-Huqf High of Oman form part of these autochthonous shelf deposits. Beydoun (1964) originally defined the Qishn Formation in South Yemen. This formation name was subsequently adapted to the Barremian-Aptian outcrops in the Haushi-Huqf High of Oman (Dubreuilh et al., 1992; Montenat et al., 2003). The Qishn Formation exposed in the Haushi-Huqf High largely corresponds to the Upper Kharaib (including the Hawar Member) and the Lower Shu’aiba formations of northern Oman (Figures 1 and 2).

The carbonate rocks of the Qishn Formation onlap the approximately north-south running Haushi-Huqf High (Figure 1; Ries and Shackleton, 1990; also termed ‘Khufai anticline’ by Dubreuilh et al., 1992). To the west, the strata dip gently (2-3º) towards the Interior Oman Basin where the carbonate rocks of the Qishn Formation thicken and are associated to the Kharaib and the Lower Shu’aiba formations of the Interior Oman subsurface (Hughes Clarke, 1988). In contrast, the Kharaib/Shu’aiba oil fields in the Interior Oman subsurface (Ghaba Salt Basin, Musallim slope and Fahud Salt Basin), are located in a shallow intrashelf basin in a paleo-bathymetrically deeper setting compared to that of the Qishn Formation. Local features such as salt domes (Cambrian Ara Group), and structural highs
possibly related to regional strike-slip faults, affect and complicate the overall basin geometry (Peters et al., 2003). The uplift of the Haushi-Huqf High itself, apparently complementary to the coeval subsidence of the Ghaba Salt Basin to the west and the Masirah Trough to the east (Immenhauser et al., 2000c), commenced in the infra-Cambrian and was intermittently reactivated until the Late Cretaceous (Ries and Shackleton, 1990; Loosveld et al., 1996). Two field areas were investigated during this project: a northern outcrop belt near Wadi Jarrah and a southern outcrop belt near Wadi Baw (west of Duqm); in total, an area of about 120 x 10 km (Figure 1).
METHODS AND MATERIALS

Stratigraphic sections (~1,500 section m-k-z) from the two outcrop areas (Figure 1) form the backbone of this study. Outcrop observations, rock samples, and thin sections provided material for petrographic and facies investigations. Non-skeletal components, skeletal components, foraminifera, and algae were analyzed semi-quantitatively with numbers indicating their relative abundance: 0 = absent, 1 = present, 2 = frequent, 3 = abundant, 4 = dominant, in analogy with the nomenclature applied by van Buchem et al. (2002a, b). The depositional facies was investigated in the field, and observations complemented by thin-section petrography. Criteria applied for the interpretation of specific depositional environments included the level of hydrodynamic energy, sedimentary structures and textures, biota, their paleo-ecology, trace fossils, and diageneric alteration. The limestone classification is according to Dunham (1962).

Discontinuity surfaces (Clari et al., 1995; Hillgärtner, 1998) i.e. marine hard- and firmgrounds, subaerial exposure surfaces and composite surfaces (Immenhauser et al., 2000a, b) were recorded stratigraphically and traced laterally between sections. Combined with the facies under and overlying these surfaces, discontinuities acted as pinning points for sequence stratigraphic interpretation, and their lateral continuity as well as their impact as baffles and thus their significance with regard to reservoir compartmentalization were investigated.

The sequence stratigraphic interpretation applied in this study follows basic concepts as proposed by, for example, Sarg (1988) or Hanford and Loucks (1993), and principles of high-resolution sequence stratigraphy described in Strasser et al. (1999) or van Buchem et al. (1996). The sequence stratigraphic model is based on the interpretation of bathymetric trends defined by the vertical facies evolution. Characteristic discontinuities (Hillgärtner, 1998) and bioturbation intensity are used to interpret phases of omission, sedimentary condensation, and subaerial exposure.

The stratigraphy of the Qishn Formation is based on macrofossils, particularly rudist bivalves and on detailed thin section microfossil analyses (calcareous algae and foraminifera). Chemostratigraphy was applied to refine the stratigraphic framework. Carbon-isotope ratios were measured from matrix micrite subsamples from five sections. Refer to Immenhauser et al. (2001) for details of the analytical procedure. Strontium-isotope stratigraphy was performed from low-Mg calcite shells of screened rudist specimens, selected for their pristine trace element composition (Sr, Mg, Mn, Fe). Refer to Steuber (2001) for details of the analytical procedure. Ages are derived according to Gradstein et al. (1994).

Porosity and permeability data of Qishn Formation limestones were measured from 237 pseudo-core plugs. 147 plugs were collected in the southern field area (Wadi Baw in Figure 1) and 90 plugs from the northern field area (Wadi Jarrah in Figure 1). Due to the steep outcrop (cliff) faces, most plugs were drilled horizontally, i.e. approximately parallel to bedding planes. Where possible, vertical (approximately perpendicular to bedding planes) plugs were taken as well. Four sections were logged with a portable natural gamma-ray spectrometer (Exploranium GR 320, GPS-21 detector). Measurement intervals were five-minutes, and sampling increments 0.5 m. Measurements are provided in Potassium (%), Uranium (ppm) and Thorium (ppm).

Distributed fractures (joints) were investigated in several outcrops chosen among areas and sections investigated for sedimentological studies. Several stations were surveyed in each locality, producing more than 1,000 measurements of faults planes with striations, joints and folds. The vertical distribution of fractures in the stratigraphic column was analyzed and is shown diagrammatically. The spatial orientation of the fractures is displayed on stereographic projections and treated statistically in appropriate diagrams to provide a quantitative description. At key outcrops, the exact 3-D position of fractures along bands of given width and orientation was described, resulting in data on the spacing between fractures. Faults were analyzed in all localities where present. The distribution of single fault planes within fault zones was described to constrain their 3-D architecture. Fracture densities were measured at various distances from the fault zone itself to assess the degree of fracturing associated with such faults (to identify the background deformation related to distributed fracturing). We have used paleostress indicators such as conjugate faults, to assess the position of maximum and minimum horizontal axes and their relation with systematic joints.
STRATIGRAPHY OF THE QISHN FORMATION IN THE HUQF

The earliest Cretaceous deposits overlying the unconformity on the Jurassic Mafraq/Dhruma formations in the Haushi-Huqf High (sequence boundary between AP8 and AP7, 149 Ma according to Sharland et al., 2001) are probably late Berriasian in age, and correspond to a rise in sea level that resulted in shelf deposition of the Kahmah (Thamama) Group until the early Aptian (Dubreuilh et al., 1992).

The base of the Kahmah Group is composed of a ~30 m-thick succession, the Jurf Formation, which unconformably overlies the Jurassic, Permian, Triassic, Paleozoic or Proterozoic formations (Figure 2). The Jurf is poorly dated (possibly Berriasian-Valanginian) at the base and extends through the Hauterivian and well into the Barremian (Le Métour et al., 1995). Portions of the Jurf may correspond to the Lekhwair and Kharaib formations of northern Oman. It is furthermore possible that the Raydah, Salih and Habshan formations of Northern Oman have at least in part a chronostratigraphic equivalent in the Jurf Formation of the Haushi-Huqf High (Figure 2). In the study area, the Jurf consists essentially of marly limestones and dolomites with algal laminae, attesting to a restricted intertidal to tidal environment of deposition (Platel et al., 1992; Dubreuilh et al., 1992; Immenhauser et al., 2001). The Jurf Formation is regionally capped by an iron-stained, nodular discontinuity surface (perhaps the K60 surface, the Lower/Upper Jurf boundary according to Sharland et al., 2001) and overlain by the Qishn Formation. Due to its pervasive early dolomitization, the Jurf Formation is a poor analogue to the primarily calcitic rocks of the correlative subsurface reservoirs and thus not further considered here.

In the study area, the Qishn Formation consists of shales, open platform (outer ramp) carbonates, high-energy and intertidal platform top deposits. In Wadi Jarrah (northern Haushi-Huqf High), the Qishn Formation reaches a total stratigraphic thickness of about 75 m, whereas in the southern Haushi-Huqf High (Wadi Baw), a stratigraphic thickness of about 65 m was found. The Qishn Formation is capped by a regionally significant unconformity (hereafter termed ‘top-Qishn Formation unconformity’) that represents a considerable hiatus (more than 5 my) spanning portions of the early and the late Aptian (Figure 2). The surface referred to here occurs within the AP8 sequence between K80 and K90 MFS in Sharland et al. (2001). Sharland et al. (2001) mention this surface in their text and indicate it on Enclosure 2b (late Aptian unconformity) but it is not part of their scheme based of maximum flooding surfaces. The carbonates underlying the discontinuity become progressively older from the Interior Oman Basin towards the Haushi-Huqf High (Figure 3). In the Haushi-Huqf High, the Qishn Formation is either conformably overlain by the orbitolinid-rich shales of the Albian Nahr Umr Formation, or unconformably by the cross-bedded siliciclastic deposits of the Campanian Samhan Formation (Figure 5; Dubreuilh et al., 1992).

Figure 2: Cretaceous chronostratigraphy of Oman. Qishn, Shu’aiba and Kharai Formation and Hawar Member are shown in light blue.
The post-depositional (late Aptian through Recent) evolution of the Jurf and Qishn Formation carbonates was marked by repeated phases of burial, regional tilting, uplift, erosion and re-burial. The stratigraphic succession is characterized by numerous hiatus. The argillaceous Albian Nahr Umr Formation is often truncated, and younger stratigraphic units unconformably overlie the remnants of the Nahr Umr or rest directly on the Qishn Formation (Figures 5 and 6). The top unconformity of the Qishn Formation itself is a regional unconformity that truncates all Mesozoic units south of the Haushi-Huqf, and overlies eroded Palaeozoic sedimentary units in the subsurface.

It is beyond the scope of this paper to provide a detailed account of the post-lower Aptian evolution of the Haushi-Huqf High. Figure 6 summarizes some of the main geotectonic events from the late Aptian to Recent. The Tertiary record in the study area is scarce and the reader should refer to Dubreuilh et al. (1992), Le Métour et al. (1995), or Immenhauser et al. (2000c) for more regional information.

**TIME FRAMEWORK**

**Biostratigraphy**

The following section refers to the sequence stratigraphic subdivision of the Qishn Formation in large-scale sequences II to IV as discussed in this paper. The pervasively dolomitized Sequence I, the Jurf Formation, is not considered here. See Figures 7 and 8 for an overview of depositional environments and sequence stratigraphic organization.
Calcareous algae and foraminifera in sections D-005, S-001 and S-008

**Calcareous algae** in Sequence II include: *Hensonella dinarica* (Radoicic), *Cylindroporella ivanovici* (Sokac), *Salpingoporella* cf. *muehlergii* (Lorenz), *Carpathoporella fontis* (Patrulius) and representatives of the genera *Terquemella* and *Neomeris*.

**Foraminifera** in Sequence II include: *Praechrysalidina infracretacea* Luperto Sini, *Palorbitolina lenticularis* (Blumenbach), *Choffatella* cf. *crucensis* (Renevier), *Debarina hahounerensis* Fourcade and Raoult, *Vercorsella scarcellai* (De Castro), *Vercorsella* cf. *arenata* Arnaud Vanneau, *Buccinrenatula hedbergii* (Maync) and *Arenobulimina curvicostata* Arnaud Vanneau. Of special interest is the presence of a primitive form of the genus *Voloshinoides*. The only described pre-Albian-Cenomanian species of this genus (see Barnard and Banner, 1980) is *Voloshinoides murgensis* Luperto Sini and Masse (Luperto Sini and Masse, 1993a, b) from the lower Aptian of Southern Italy, characterized by a well developed subepidermal network. Similar forms are present in the Upper Kharaib Formation of Jebel Madar. Sequence II also records a representative of the genus *Involutina*. This form, identical to 'Glomoinvolutina apuliae' Luperto Sini and Masse (nomen nudum), is also present in the Kharaib and Shu’aiba formations at Jebel Akhdar. This assemblage of dasycladales and foraminifera has a broad Barremian and lower Aptian significance (Arnaud Vanneau, 1980; Luperto Sini and Masse, 1986; 1993a, b; Masse et al., 1998a, b). Most of these taxa are present in the upper Kharrai and Shu’aiba formations from northern Oman (Simmons and Hart, 1987; Simmons, 1994; Witt and Gökdag, 1994; Masse et al., 1998a, b) and Saudi Arabia (Hughes, 2000).

The biota of Sequence III is comparable to the one of Sequence II but due to intertidal episodes its diversity tends to decrease. Sequence IV also shows a very similar assemblage with a tendency toward low diversity. *Voloshinoides murgensis* is present in Sequence IV as well as advanced forms of *Nezzazata*. These two species were also found in the Shu’aiba Formation at Jebel Akhdar.

**Rudist bivalves**

*Glossomyophorus costatus* Masse, Skelton and Sliskovic was collected in Wadi Baw and Wadi Jarrah (Figure 1), mainly in sequences III and IV where they form common dense monospecific biostromes. *Offneria nicolinae* (Mainelli) and *Offneria murgensis* Masse are found in sequences III and IV. A form recently described from Saudi Arabia, *Oedomyophorus shaybahensis* Skelton (Skelton, in press) was also identified in Sequence III, and is associated with *Offneria murgensis*.

**Discussion of biostratigraphic results**

Data from northern Oman show that the Shu’aiba Formation is characterized by a *Palorbitolina-Praeorbitolina* association (Witt and Gökdag, 1994). This association has an upper lower Aptian (Bedoulian) biostratigraphic significance. *Montseciella arabica*, *Eoparorbitolina transiens* and *Praeorbitolina* were not recorded in the Haushi-Huqf High thus precluding a detailed biozonation similar to those of northern Oman. In the Haushi-Huqf High region the presence of *Voloshinoides murgensis* in Sequence IV suggests a possible equivalence of the corresponding interval within the Lower Shu’aiba Formation in northern Oman. Assuming that this correlation is correct, sequences II and III might be the equivalent to the Upper Kharrai Formation including the Hawar Member (Figure 8).

In northern Oman, the *Offnerianicolinae – Offneriamur gensis – Glossomyophorus costatus* assemblage was recorded in the Upper Kharrai and Shu’aiba formations (Masse et al., 1998a, b). *Offneria arabica* Chartrousse and Masse and *Offneria italica* Masse were found in the ‘rudist member’ of the Shu’aiba Formation at Jebel Madar (Chartrousse and Masse, 1998) and Akhdar (Masse et al., 1998a, b). Similarly, *Agriopleura* was recorded in the upper part of the Shu’aiba from the Nahkl zone (Masse et al., 1998a, b) and *Agriopleura* is also documented from the Shaybah field in Saudi Arabia (Hughes, 2000).

The rudist assemblage of the Qishn Formation is thus similar to the rudists of the upper Kharrai and Shu’aiba Formation from northern Oman and Shaybah field in Saudi Arabia.

**Summary of biostratigraphic age constraints**

Biostratigraphic evidence thus suggests that the Qishn Formation is an equivalent of the Upper Kharrai and Lower Shu’aiba formations from northern Oman, the United Arab Emirates and Saudi Arabia. The
biostratigraphic range is tentatively given as uppermost Barremian and lower Aptian. Sequences III and IV are indisputably lower Aptian in age, whereas Sequence II might possibly belong to the uppermost Barremian and/or the lower Aptian. The absence of some typical upper lower Aptian markers may be due to environmental restriction or to the absence of the corresponding sedimentary record.

**Chemostratigraphy**

**Strontium-isotope stratigraphy**

The outer shell layer of rudists consists of diagenetically stable low-Mg calcite (LMC) and has shown to be a reliable archive of Sr isotope ratios of Cretaceous seawater, when sufficient care is taken to evaluate diagenetic alteration (Steuber, 2001; Steuber et al., 2002). A steep gradient of $^{87}\text{Sr}/^{86}\text{Sr}$ values of Cretaceous seawater from the late Barremian to the late Aptian allows precise stratigraphic correlation within this interval (Figure 4a). Only a limited number of rudist specimens from the Qishn Formation were suitable for Sr isotope stratigraphy. Typically, but not generally, diagenesis shifts $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to more radiogenic (i.e. higher) values. This is also observed in the analyzed samples (Figure 4b). Bulk rock samples have highest $^{87}\text{Sr}/^{86}\text{Sr}$ values, and visibly altered rudist shells have higher values than well preserved specimens. High Mn and Fe concentrations are frequently considered to indicate diagenetic alteration (McArthur, 1994), but low concentrations of these elements even in bulk rock samples of the Qishn Formation show that elemental concentrations are not very useful for screening the present set of samples. Obviously, samples with Sr concentration in the range characteristic for early Cretaceous low-Mg calcite (Steuber and Veizer, 2002) have lowest Sr isotope values (Figure 4b). A small scatter of Sr isotope values of these samples, respectively, from the three studied stratigraphic intervals provides additional evidence for the retention of the original seawater composition (McArthur, 1994). Numerical ages are derived from mean values of these best-preserved samples using the ‘look-up’ table of McArthur et al. (2001). Upper and lower age limits were obtained by adding two standard errors of the mean values of isotopic results to the statistical uncertainty of the seawater curve (Howarth and McArthur, 1997). The results (Figure 4) indicate that: (1) m 28 of Section S-018 (Sequence III) falls

![Figure 4](https://pubs.geoscienceworld.org/geoarabia/article-pdf/4566773/imnhsr.pdf)
in the latest Barremian (~122 Ma); (2) m 3.5 of Section D-007 (Sequence IV) falls in earliest Aptian (~120 Ma); and (3) the top of the Al Huwaisah-2 core of the Lower Shu’aiba in Oman falls into the late early Aptian (~118 Ma).

**Carbon-isotope stratigraphy**

Carbon-isotope stratigraphy is commonly used to date lower Aptian carbonate rocks. The positive shift in $\delta^{13}C$ related to the oceanic anoxic (Selli) event 1a (OAE-1a) is a clear event marker of late early Aptian age recognized from many carbonate platforms worldwide (e.g. Vahrenkamp, 1996; Erbacher and Thurow, 1997; Grötsch et al., 1998; Weisert et al., 1998). Furthermore, a prominent negative carbon isotope shift just above the Barremian/Aptian boundary was documented (Figure 3; Vahrenkamp, 1996; Jenkyns and Wilson (1999)).

The positive $\delta^{13}C$ excursion related to OAE-1a is well recorded in Oman in sections at Jabal Madar and Jabal Akhdar (Immenhauser et al., 2000a, b; van Buchem et al., 2002a, b) and in many lower Shu’aiba cores elsewhere in the region (Vahrenkamp, 1996). Carbon-isotope chemostratigraphy from four sections in the Haushi-Huqf High, however, provided no evidence of this excursion in the Qishn Formation (Figure 3). Based on this observation and on strontium-isotope stratigraphy, we now conclude that the Qishn Formation in the Haushi-Huqf High does not reach the stratigraphic level with the positive excursion in $\delta^{13}C$ (Figure 3). In contrast, the negative shift in $\delta^{13}C$, just above the Barremian/Aptian boundary, is present in all isotope sections measured in the Qishn Formation. This earliest Aptian shift to lower values must not be confused with shifts in rock intervals that show evidence for late meteoric alteration.

Particularly significant near-surface alteration of rock properties occurred during subsequent phases of increased precipitation, since meteoric water has a rapid and pervasive impact on the porosity and

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**Figure 5:** Schematic lithostratigraphic columns of the Cretaceous successions as exposed in the Wadi Jarrah (I and II) and Wadi Baw (III) study area. Hatching represents hiatus. Red surfaces indicate regional unconformities at base and top of the Qishn Formation. WSW dip of strata is exaggerated. Not to scale.
<table>
<thead>
<tr>
<th>Framework Chronologic</th>
<th>Geotectonic Events</th>
<th>Illustration (Stratigraphic thickness: not to scale)</th>
<th>Key to Symbols Color Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenomanian (Natih) and Albian (Nahr)</td>
<td>Ongoing transgression and deposition of the Nahr Umr Formation (seal facies) and possibly the Natih Formation.</td>
<td><img src="image1" alt="Illustration" /></td>
<td>sea level Natih Fm Nahr Umr Fm Horizontal scale: ~kms</td>
</tr>
<tr>
<td>Late Aptian</td>
<td>Regional truncation and peneplanation of the top of the Qishn Formation. Truncation probably took place under continental conditions. Peneplanation probably occurred during transgression (marine hardground).</td>
<td><img src="image2" alt="Illustration" /></td>
<td>Top Qishn unconformity (marine hardground) Horizontal scale: ~kms</td>
</tr>
<tr>
<td>Early/Late Aptian boundary</td>
<td>Possibly large-scale regional folding (100 km scale). Tectonism is probably related to uplift in SW Arabia. Locally, folding might result in extensional faulting (km's-scale).</td>
<td><img src="image3" alt="Illustration" /></td>
<td>Uplift and faulting (?) See Figure 14 for marker beds. Large-scale regional folding (?) Horizontal scale ~100 km</td>
</tr>
<tr>
<td>Middle Barremian to lower Lower Aptian (Qishn Formation) Berriasian to Middle Barremian (Jurf Formation)</td>
<td>Deposition of the Jurf and Qishn formations.</td>
<td><img src="image4" alt="Illustration" /></td>
<td>Sea level Qishn Fm Marker beds (cf. Figure 14) Jurf Fm Horizontal scale: ~kms</td>
</tr>
<tr>
<td>Pliocene/Holocene humid intervals</td>
<td>Pervasive meteoric diagenesis and karsting of those portions of the Qishn Formation that form the exposed upper interval of table mountains unaltered in the adjacent plain (topographic effect).</td>
<td><img src="image5" alt="Illustration" /></td>
<td>Top Qishn unconformity (marine hardground) Unaltered Qishn Meteoric diagenesis and karsting Horizontal scale ~100 km</td>
</tr>
<tr>
<td>Late Campanian to Maastrichtian</td>
<td>Tilting (2-3°) of Shamhan Formation after the Campanian. Emplacement of eastern ophiolite belt and Batin nappes. Deposition of the Fiq and Filim formations.</td>
<td><img src="image6" alt="Illustration" /></td>
<td>Tilting, possibly faulting, erosion Qishn Formation Erosion Fiq/Filim formations Horizontal scale ~100 km</td>
</tr>
<tr>
<td>Early Campanian</td>
<td>Renewed transgression and deposition of the Shamhan Formation. Shamhan transgression leads to erosion and truncation of the Natih and Nahr Umr formations.</td>
<td><img src="image7" alt="Illustration" /></td>
<td>Erosive transgression Samhan rudist limestones Samhan siliciclastics Horizontal scale ~100 km</td>
</tr>
<tr>
<td>Turonian Coniacian, Santonian</td>
<td>The emplacement of the Senail Ophiolite and the Hawasina Complex in northern Oman (Turonian-Campanian) results in uplift, tilting, and local erosion of the (Natih?), Nahr Umr, and Qishn formations in the Huqf area.</td>
<td><img src="image8" alt="Illustration" /></td>
<td>Erosion (unconformity) Uplift, tilting, erosion (tilting not to scale) Horizontal scale ~100 km</td>
</tr>
</tbody>
</table>

Figure 6: Schematic overview of the Berriasian to Holocene geotectonic evolution of the Cretaceous successions in the study area. Cartoons are numbered 1 through 11 from old to present day.
Barremian-lower Aptian Qishn Formation, Haushi-Huqf area, Oman

permeability properties of carbonate rocks (Land, 1970). Alternating dry and humid phases took place throughout the Cenozoic and the most recent humid intervals ended approximately 117 ky and 6.2 ky ago respectively (Figure 6; Burns et al., 1998). This recent meteoric lithification of the Qishn Formation is restricted to rock intervals that are easily recognized by their completely cemented, dense appearance in outcrops. This is often accompanied by karst pipes, silex nodules and locally by bean iron ores. These altered intervals are situated at the exposed tops of table mountains (Figures 5 and 6) whereas their stratigraphic counterparts exposed as low-relief outcrops in the adjacent plains, suffered no alteration (Figures 4 and 5). Only those intervals not affected by meteoric lithification were investigated as analogues of the subsurface units.

In the subsurface, the earliest Aptian shift to lower values coincides with the Hawar Member of the Kharaib Formation (Figure 3; Vahrenkamp, 1996). The combination of Sr-isotopes, carbon-isotope stratigraphy, and biostratigraphic data from this study, from the lower Shu’aiba Formation in the subsurface (Vahrenkamp, 1996), and from Northern Oman (Immenhauser et al., 2000a, b) provides an improved temporal resolution of the Qishn Formation in the Haushi-Huqf High (Figure 3).

Summary of the time framework

- Biostratigraphic and chemostratigraphic results point to a middle Barremian to mid-early Aptian age for the Qishn Formation.
- The carbonate rocks just beneath the top-Qishn Formation unconformity, from Sr-isotope evidence, are earliest Aptian in age. This is approximately 2 my older than the age of the Lower Shu’aiba unconformity both in the Interior Oman subsurface and in the Northern Oman Mountains. There, this unconformity coincides with the early/late Aptian boundary.
- The Hawar Member (equivalent) in the Qishn Formation is earliest Aptian in age.
- The Qishn Formation thus overlaps, in time, with the Upper Kharaib and portions of the Lower Shu’aiba.

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY

Sedimentology and Depositional Environments

Five main depositional environments, each with a number of standard facies types, were established. They are based on field observations, the paleo-ecology of faunal associations, the hydrodynamic regime, regional facies correlations, and thin-section and slab analysis (Figure 7 and Table 1). For clarity and ease of comparison with previously published work, we use a facies terminology and color code (Table 1) comparable to van Buchem et al. (2002b; p. 466) who described the Kharaib and Shu’aiba formations in the Northern Oman Mountains. The five following depositional environments, with characteristic biota were distinguished within the Qishn Formation (Figure 7 and Table 1).

Tidal flat depositional environment

The tidal flat environment comprises two facies types. 1a: Mudflat facies with sedimentary features such as chalky algal laminites, abundant desiccation cracks, birds eyes, sheet cracks, tepee structures, and rootlets. Typical biota are shell debris, some pelecypods, echinoderm fragments, ostracods, miliolid foraminifera and green algae; and 1b: Sandflat facies composed of fine, laminated and locally reworked peloidal or miliolid packstone to grainstones with rare cross-beds. Facies 1b is often rich in very small miliolid foraminifera.

The restricted inner platform depositional environment

The restricted inner platform environment comprises two facies types. 2a: Wackestones with a restricted fauna, notably shell debris, pelecypods, spiculae, agglutinating and miliolid foraminifera, and green algae; and 2b: Argillaceous wackestones with a restricted fauna comprising basically the same biota as 2a but in a more shaley facies.

High-energy, platform-top depositional environment

The high-energy, platform-top environment comprises three facies types. 3a: High-energy cross-bedded pack- to grainstone with peloids and small oncoids and patches of rudstone. The typical biota comprises
Table 1: Overview of facies classification and interpretation. Numbers indicate the relative abundance of non-skeletal and skeletal components: 0 = absent, 1 = present, 2 = frequent, 3 = abundant, 4 = dominant. For texture legend see Enclosure.

<table>
<thead>
<tr>
<th>Facies Code</th>
<th>Color Code</th>
<th>Facies/Key Biota</th>
<th>Texture</th>
<th>Skeletal and Non-Skeletal Components</th>
<th>Depositional Environment</th>
<th>Facies Associations and their Depositional Environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td></td>
<td>Laminites and mudflat facies</td>
<td>M-W, W minor: M-P, P</td>
<td>Peloids 2, shell debris 2-3, pelecypods 1-2, echinoderms 1-2, ostracods 1-2, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Tidal mudflat</td>
<td>1 Tidal flat</td>
</tr>
<tr>
<td>1b</td>
<td></td>
<td>Peloidal/miliolid facies</td>
<td>P-G, G minor: W-P</td>
<td>Micrite envelopes 1-2, pelecypods 1-2, shell debris 2, echinoderms 1-2, agglutinating foraminifera 2-2</td>
<td>Tidal sandflat</td>
<td>2 Restricted platform</td>
</tr>
<tr>
<td>2a</td>
<td></td>
<td>Restricted fauna</td>
<td>W</td>
<td>Shell debris 2-3, pelecypods 2-3, spiculae 2, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Restricted marine platform top</td>
<td>3 High energy platform</td>
</tr>
<tr>
<td>2b</td>
<td></td>
<td>Argillaceous restricted fauna facies</td>
<td>W</td>
<td>Shell debris 2-3, pelecypods 2-3, spiculae 2, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Restricted marine platform top</td>
<td>4 Open marine platform (bioconstructed)</td>
</tr>
<tr>
<td>3a</td>
<td></td>
<td>High-energy facies</td>
<td>F-G, G, G-P</td>
<td>Peloids 2-3, oncoids 2-3, micrite envelopes 1-3, gastropods 1-2, pelecypods 1-2, oysters 1-3, shell debris 1-2, echinoderms 1-2, agglutinating foraminifera 2-3, miliolids 1-2, green algae 1-3</td>
<td>Platform top</td>
<td>5 Deep platform, storm influenced</td>
</tr>
<tr>
<td>3b</td>
<td></td>
<td>High-energy Lithocodium/Bacinella oncoid facies</td>
<td>F-G, G, G-P</td>
<td>Peloids 2, oncoids 3-4, micrite envelopes 1-2, gastropods 2-3, echinoderms 1-3, shell debris 1-2, echinoderms 1-2, agglutinating foraminifera 1-3, miliolids 1-3</td>
<td>Platform top</td>
<td>6 Argillaceous, open marine platform</td>
</tr>
<tr>
<td>3c</td>
<td></td>
<td>High-energy rudist-dominated facies</td>
<td>F, F-R</td>
<td>Peloids 1-2, oncoids 1-2, micrite envelopes 2, oyster 1-2, shell debris 2-3, echinoderms 2-3, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2, matrix: packstone</td>
<td>Platform top</td>
<td>7 Deep platform</td>
</tr>
<tr>
<td>4a</td>
<td></td>
<td>Rudist biostrom facies</td>
<td>F-B</td>
<td>Peloids 1-2, pelecypods 2, oyster 2, shell debris 2-3, echinoderms 2-3, agglutinating 1-2, foraminifera 1-1, miliolids 1</td>
<td>Open marine platform (bioconstructed)</td>
<td>8 Deep platform</td>
</tr>
<tr>
<td>4b</td>
<td></td>
<td>Coral-dominated facies</td>
<td>F-B</td>
<td>Massive coral heads embedded in grainedstone, packstones of lagoonal facies and brecias</td>
<td>Open marine platform (bioconstructed)</td>
<td>9 Open marine platform (bioconstructed)</td>
</tr>
<tr>
<td>4c</td>
<td></td>
<td>Oyster (Chondrodonta) floatstone</td>
<td>F (R)</td>
<td>Peloids 1-3, micrite envelopes 1-3, gastropods 1-2, pelecypods 2, rudists 1-3, shell debris 2-3, echinoderms 1-2, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Open marine platform</td>
<td>10 Open marine platform (bioconstructed)</td>
</tr>
<tr>
<td>4d</td>
<td></td>
<td>Diverse fauna facies (low energy)</td>
<td>P, P-W, W</td>
<td>Gastropods 1-2, pelecypods 1-3, shell debris 2-3, echinoderms 1-2, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Open marine platform, below storm-wave base</td>
<td>11 Open marine platform (bioconstructed)</td>
</tr>
<tr>
<td>4e</td>
<td></td>
<td>Diverse fauna (intermittently agitated)</td>
<td>P, P-G</td>
<td>Peloids 2-3, pelecypods 2-3, oysters 1-2, shell debris 2-3, echinoderms 2-3, agglutinating foraminifera 1-2, miliolids 1-2, green algae 1-2</td>
<td>Open marine platform, below fair-weather wave base, but within the reach of storm waves</td>
<td>12 Deep platform, below storm wave</td>
</tr>
<tr>
<td>4f</td>
<td></td>
<td>Orbitolina dominated facies, locally marly</td>
<td>P-W, P-G</td>
<td>Orbitolina 4, peloids 2-4, pelecypods 2, oysters 1-2, shell debris 2-3, echinoderms 1-3, agglutinating foraminifera 1-2, miliolids 1-3, green algae 1-2</td>
<td>Open marine platform</td>
<td>13 Deep platform</td>
</tr>
<tr>
<td>4g</td>
<td></td>
<td>Bioconstructed Lithocodium/Bacinella facies</td>
<td>B</td>
<td>Peloids 1-2, oncoids 2, micrite envelopes 2, orbitolinids 1-2</td>
<td>Open marine platform (bioconstructed)</td>
<td>14 Deep platform</td>
</tr>
<tr>
<td>5a</td>
<td></td>
<td>Hummocky cross-stratification facies</td>
<td>G, P-G</td>
<td>Peloids 3-4, shell debris 2-3, echinoderms 2-3, miliolids 1-3, green algae 2</td>
<td>Deep platform, storm influenced</td>
<td>15 Deep platform, storm influenced</td>
</tr>
<tr>
<td>5b</td>
<td></td>
<td>Muddy, argillaceous facies</td>
<td>M, M-W, W</td>
<td>Peloids 1-2, shell debris 1, echinoderms 2</td>
<td>Deep platform, below reach of storm waves</td>
<td>16 Deep platform, below reach of storm waves</td>
</tr>
<tr>
<td>5c</td>
<td></td>
<td>Spiculite facies</td>
<td>W, W, P</td>
<td>Peloids 1-2, shell debris 2, echinoderms 2-3, ostraecoda 2</td>
<td>Deep platform</td>
<td>17 Deep platform, below reach of storm waves</td>
</tr>
</tbody>
</table>
Figure 7: Overview of paleo-depositional environments recorded in the Qishn Formation of the Haushi-Huqf High. Facies types (e.g. 4a, 5d etc.) are indicated. Refer to Table 1 for more detail. See Enclosure for key to symbols. FWWB= fair-weather wave base; SWB= storm-weather wave base; HCS= hummocky cross stratification.

gastropods, oysters, echinoderms and various shell debris; 3b: high-energy grainstone and reworked Lithocodium/Bacinella floatstone (oncoidal floatstone); 3c: Rudist bivalve grainstone to floatstone (common rudists are Glossomyophorus costatus, while Agriopleura and Monopleura species are found more rarely). Offneria occurs in the uppermost levels of the Qishn Formation (mainly Offneria nicolinae and less frequently Offneria cf. murgensis). Rudists are fragmented and displaced in this high-energy environment.

**Open marine platform (inner/mid ramp) depositional environment**
The open marine platform depositional environment comprises seven different facies types. The shallower facies are, 4a: Rudist biostromes (Glossomyophorus, Agriopleura and Monopleura) mainly of floatstone facies. Rudists may be in situ or slightly transported; 4b: Coral facies. Colonial corals (Actinastrea pseudominima major MORICOWA; det. H. Löser, Hermosillo) colonize firmgrounds and dominate the sessile lagoonal facies; 4c: Oyster (chondrodonta-like) floatstone; 4d: Bioturbated wackestone to packstone with a diverse open marine fauna gastropods, pelecypods, oysters, echinoderms, agglutinating foraminifera (Choffatella decipiens), miliolid foraminifera, and green algae. Deeper facies, below storm-wave base, are; 4e: Bioturbated packstones to grainstones with a diverse open marine fauna as listed under 4d. The sediments were deposited below fair-weather wave base but within the reach of storm waves (intermittently agitated); 4f: Orbitolina-dominated facies, in some localities, orbitolinids (and other foraminifera such as Choffatella decipiens) are less abundant and the facies is more marly; and 4g: Lithocodium/Bacinella bindstone facies, laminated or mottled with in situ algal-microbial growth structures that are in places associated with orbitolinid-rich open-marine facies. At other localities, the Lithocodium/Bacinella bindstone facies forms several meter sized mound structures associated with coarse high-energy grainstone/rudstone of facies type 3b.

**Deep platform (outer ramp) depositional environment**
The deep platform depositional environment comprises three facies. 5a: ‘Deep’ platform deposits with storm-induced well-washed grainstone layers and hummocky cross stratification. The typical biota is shell debris, echinoderms, ostracods and scarce miliolid foraminifera; 5b: Argillaceous, burrowed mud- and wackestones deposited below the reach of storm waves; and 5c: Wacke- and packstones with abundant sponge spiculae.
SEQUENCE STRATIGRAPHY

Facies analysis in the various sections indicates changes in accommodation of at least three different orders of magnitude, distinguished in a purely descriptive way as small-, medium-, and large-scale depositional sequences. This approach is similar to that described by van Buchem et al. (1996; 2002a, b). Deposited on the Haushi-Huqf High, the Qishn Formation comprises transgressive to highstand facies tracts (e.g. Mitchum and Vail, 1977) or transgressive-regressive cycles at higher frequencies only. The oldest of the low-frequency cycles of the Shu’aita is represented, also by transgressive to highstand systems tracts. In these asymmetrical upper shoreface to lithoral sequences, lowstand deposits are absent. As a consequence of the relatively little accommodation over the proximal shoulder of the Haushi-Huqf High, stratigraphic units have thus tabular geometries and may be traced laterally over considerable distances. Facies trends indicating a deepening and shallowing of depositional environments are termed respectively transgressive and highstand (regressive) deposits (indicated TS and HS in Figures 8 through 14; Embry, 1993). The maximum flooding ‘surfaces’ do not record very deep bathymetry, but the relatively deepest or most open-marine facies represent an ‘interval’ of maximum flooding (indicated MFI in Figures 8 through 14). Sequence boundaries (SB in Figures 8 through 14) generally are discontinuity surfaces with evidence for subaerial exposure and /or a break in sedimentation and an inversion in the bathymetric trend within the shallowest depositional environments.

Discussion of Results
Origin of deepening-shoaling cycles. Stratigraphic sections were correlated by laterally tracing prominent discontinuity surfaces and marker beds wherever possible. The regional correlation of the studied sections shows that most of the observed bathymetric cycles extend over 100 km parallel (north-south) to the facies belts and are thus obviously regional in scale (Figures 8 through 14). This is strong evidence that these deepening-shoaling facies trends record relative sea-level (allocyclic) changes rather than lateral shifts of sediment bodies (autocyclic; e.g. Wilkinson et al., 1996).

Hierarchy and stacking of sequences. The three different scales of superposed depositional sequences observed in the Qishn Formation are interpreted to reflect relative sea-level cycles of different durations and amplitudes. Locally, thin transgressive-regressive sequences (<1 m) might possibly represent an even lower (smallest scale) depositional system. These are superposed on what we termed small-scale (1-3 m in thickness) depositional sequences. These smallest sequences (<1 m), however, usually pinch out over some 10s to some 100s of m, and since their regional scale or allocyclic origin could not be demonstrated, they are not further considered here.

The superposition of cycles of sea-level change of different magnitudes leads to a forcing of the characteristics of facies composition of higher order sequences (e.g. Guillocheau, 1991; Strasser et al., 1999). Therefore, facies and facies successions in a higher-order (smaller-scale) sequence in the transgressive part of a lower-order (larger-scale) sequence will differ from those in a smaller scale sequence in the regressive part (Figure 8). Below we summarize some of these differences as observed in the Qishn Formation.

Large-scale sequences within the Qishn Formation are approximately 10 to 30 m thick and commonly show clear facies successions reaching from intertidal to deep subtidal depositional environments (Figures 8 to 10). Large-scale sequences are delimited by well-expressed discontinuity surfaces with evidence for subaerial exposure. Four large-scale sequences were identified and correlated.

Sequence I contains largely the Jurf Formation (probably the equivalent of the Lekhwair and lower Kharaib formations). It represents the first Cretaceous transgression (Valanginian to Barremian) onto the older successions and commonly is represented by dolomitized limestones (Figures 8 to 10). Slightly more argillaceous deposits characterize the lower part of the sequence. Towards the top Jurf/base Qishn Formation, an overall low accommodation potential is indicated by repeatedly occurring tidal flat deposits (standard facies type 1; cf. Figures 8 to 10). An alternative interpretation is that the stacked tidal flats represent the early transgressive phase. This because tidal flats rarely ever prograde, they aggrade. Nevertheless, field evidence suggests that the main sequence boundary is above these tidal flat deposits.
**Sequence II** is characterized by transgressive, high-energy shoal deposits at its base, overlain by well-characterized (nodular, strongly bioturbated), marly maximum flooding deposits (Figures 8 to 10). The main maximum flooding surface of sequence II is a firm- to hardground (condensed horizon) of a regional extent (Figures 8 to 10). Beneath this discontinuity, the facies is represented by an overall shallow-water environment. Above the discontinuity, a more argillaceous, deeper-water facies is present (Figures 8 to 10). The shoaling part of Sequence II is marked by open-platform deposits capped by a tidal flat succession with evidence for repeated subaerial exposure.

**Sequence III** is somewhat different since the depositional environment is entirely dominated by very shallow marine deposits indicative of a high energy environment. Tidal flat deposits and locally *in situ* rudist lithosomes form the transgressive part. Shallow, open-platform deposits characterize the deepest part, whereas gradual infilling of accommodation space is indicated by high-energy shoals (standard facies type 3) overlain by tidal flats (Figures 8 to 10). The top of the sequence is formed by a regionally extensive, composite surface with abundant evidence for intermittent subaerial exposure related to the tidal flat environment and minor evidence for long-term, terrestrial subaerial exposure. Omission (i.e. hardground formation), related to the subsequent flooding of the carbonate platform, is suggested by borings perforating the discontinuity surface.

**Sequence IV** forms the top of the Qishn Formation in the Haushi-Huqf High. It commences with tidal flat deposits and gradually deepens into open platform deposits of the upper Qishn Formation (Figures 8 to 10). In the southern study area (Wadi Baw), the turnover from deepening to shoaling is characterized by a marly, recessive facies indicating protected platform settings, with thin grainstone layers from intermittent storm agitation. An influx of fine argillaceous sediment, particularly in the southeast, characterizes this interval (Figures 8 to 10). The source of this argillaceous material might be eroded argillaceous sedimentary rocks or exposed basement rocks further south towards Yemen. The shoaling trend of Sequence IV starts with prominent *in situ* rudist lithosomes (Figures 8 to 10). The topmost few meters beneath the regional unconformity that caps the Qishn Formation are mainly composed of high-energy facies (standard facies type 3). In the southern area (Wadi Baw; cf. Figures 8 to 10), this interval is formed by coarse, reworked intraclasts (*Lithocodium/Bacinella* oncoids) indicating the highest hydrodynamic level observed in the study area (standard facies type 3). In the southeastern extremity of the study area, where the topmost meters of the Qishn Formation are preserved *Lithocodium/Bacinella* bindstones and mounds (standard facies type 4) are associated with the high-energy facies.

**Medium-scale sequences.** Large-scale sequences are made up of two to four medium-scale sequences with thicknesses ranging between 4 and 10 m (Figure 11). The four large-scale sequences build up twelve medium-scale sequences. The deepening and shallowing trends in these twelve sequences are generally more subtle, and are sometimes difficult to recognize in one single section. Many of these more subtle facies trends, however, are regionally correlatable and the sequences are commonly delimited by well-marked discontinuity surfaces indicating changes in the depositional system, such as abrupt shifts of facies belts.

Figure 11 illustrates two examples of medium-scale sequences that are superposed on sea-level trends related to large-scale cycles. The lower medium-scale sequence in the highstand of large-scale sequence III is dominated by shallow, high energy and tidal flat deposits (Figure 11). Bathymetric changes within this sequence are interpreted to be in the order of a few meters only. The well-expressed basal surface is erosional, locally with indications of channeling and subaerial exposure. Stacked tidal flats indicate a keep-up setting. The continuous infill of the accommodation space dominates the transgressive part of the sequence. The overlying rudist-rich shoals and lagoonal sediments were deposited in the relatively deepest bathymetric setting reflecting a few meters water depth and correspond to a maximum flooding zone. Comparably thin tidal flats abruptly overlie lagoonal sediments in the top part of the sequence. Root horizons superimposed on channels suggest repeated subaerial exposure at the upper sequence boundary. This points to decreasing accommodation at both the large-scale and shorter term trends.

The upper medium-scale sequence (Figure 11) forms the initial transgressive part of large-scale Sequence IV. This sequence displays a completely different facies evolution with transgressive tidal flats that gradually display a deepening of depositional environments towards an open-marine condition. Water depth is estimated to have not exceeded 30 m (cf. Figure 7). Only locally, a slight shallowing towards the top of the sequence is reflected in a trend towards more restricted facies.
Upper sequence boundary is formed by a polygenic discontinuity suggesting omission and erosion, probably at the wave base. Coral-rich deposits that grew on the discontinuity surface typically indicate a subsequent transgressive phase and deepening in these environments. The upper sequence boundary was probably never subaerially exposed since the medium-scale sea-level drop was attenuated by the large-scale transgressive trend. In contrast to the medium-scale sequence that formed in the longer term highstand, creation of accommodation space here continuously exceeded sedimentation rate.

Small-scale sequences (Figure 12) commonly show stratigraphic thicknesses between 1 and 3 m and are bound by discontinuity surfaces. Locally, the limits of small-scale sequences may not be clearly defined due to significant lateral changes in the bounding surfaces. Furthermore, outcrop conditions and slight facies contrasts may additionally hamper their identification in the field. The correlation of all sections, however, via marker beds and marker surfaces allows establishing a coherent high-resolution framework of small-scale sequences across the entire study area (i.e. ~ 100 km). Twenty-eight small-scale sequences are superposed on large-scale sequences II through IV of the Qishn Formation (the equivalents of Upper Kharai and Lower Shu’aiba formations) and these can be correlated across the study area (Figures 8 to 10). These small-scale sequences are labeled II.1, II.2, etc. within for instance large-scale Sequence II (Figures 8 to 10). Small-scale sequences show a broad spectrum of facies evolution and stacking patterns depending on their position within larger-scale trends. Two end member examples of small-scale sequences are presented in Figure 12.
The first example (Figure 12a; portions of section S-001) is taken from a generally shallow marine (a few meters deep) depositional environment, and involves relative changes in sea level in the order of a few meters only. Accommodation space was filled in rapidly and entirely. The sequence overlies a discontinuity surface in a tidal flat environment, which shows evidence for subaerial exposure. Strong erosion during the subsequent transgression led to intense reworking and local formation of a relief. The transgressive sediments overlying this surface are rich in large solitary coral heads in growth position, in places encrusting the discontinuity itself. This is a very typical feature of the Qishn Formation and was observed along many sequence boundaries. Lagoonal sediments that shallow up into tidal flat laminites form the deepest part of the sequence. The top sequence boundary is a composite surface with evidence for: (1) intermittent exposure and erosion in a tidal flat setting, followed by (2) terrestrial subaerial exposure and finally by (3) marine flooding expressed in the field as an omission surface with borings.

The second example (Figure 12b), is from a deeper depositional environment than section S-001. In this case, the small-scale sequence is superposed on medium-and large-scale maximum flooding of the early highstand. The underlying sequence boundary is a firm- to hardground colonized by a coral fauna. The transgressive deposits overlying this firmground are argillaceous and characterize the open platform setting below the storm wave base. The highstand of this small-scale sequence is more calcareous, open marine, deposited below storm-wave base. Subsequently, sediment accumulation raised the seafloor to within the reach of storm currents. The capping discontinuity is an erosion or omission surface.

**Lateral variability of sequences.** The sequence stratigraphic framework is correlatable across the entire Qishn Formation outcrop belt in the western Haushi-Huqf High (Figure 13). The thickness of sequences, the evolution of facies types within these sequences, and characteristics of the bounding discontinuity surfaces, however, do vary laterally.

Commonly, over distances of several hundred meters, sequences of all scales show only minor lateral thickness variations. These thickness variations do not indicate zones of differential subsidence but can be attributed to local differences in paleo-topography and intervals characterized by non-deposition or minor erosion. Facies variations between the northern and southern study area suggest slightly deeper depositional environments and an increased argillaceous input in the southern Haushi-Huqf High (Sequence IV; Figure 13). In the southern study area (Wadi Baw), the transgression

![Figure 12: Details of small-scale sequences. (a) Small-scale sequence superposed on the early transgression stage of a medium and large-scale sequence. (b) Small-scale sequence superposed on the maximum flooding to early highstand stage of a medium and large-scale sequence. SWB = storm-weather wave base.](https://pubs.geoscienceworld.org/geoarabia/article-pdf/4566773/imnhsr.pdf)
of the Jurf Formation over the older successions apparently occurred later than in the north as indicated by several missing small- and medium-scale sequences at the base (Figure 10). The large-scale facies evolution in the entire field area is very constant and suggests that the sections all have a similar relative position to the Haushi-Huqf structural high, with homogeneous subsidence rates. This agrees with the overall north-south orientation of the outcrop belts approximately parallel to the inferred paleo-facies zones of this portion of the Barremian/Aptian Arabian platform.

Lateral facies variations within small- and medium-scale sequences are more common in depositional environments where numerous microfacies types coexist or alternate, for example at the limits between different facies belts. The controlling factors are accommodation space and the level of hydrodynamic energy. In a system with very low accommodation, paleo-topography will be minimal and smeared out constantly. Qishn Formation facies in such environments are dominated by laterally continuous tidal flats and restricted lagoonal sediments (e.g. Figure 8, lateral continuous tidal flat intervals on top of Sequence II and at base of Sequence III). Occasionally, channels and small high-energy storm deposits are preserved. Discontinuity surfaces are laterally continuous, but in the field they do show differences in terms of their appearance due to the variable sub-environments (i.e. facies) of the underlying tidal flat environment and due to differential erosion.

In more distal systems, where more accommodation space was available, the average level of hydrodynamic energy was higher and some degree of topographic variability was created leading to a differential infill of the available space. The result is a higher degree of lateral facies variability (e.g. Figure 8, regressive trend of Sequence IV). Facies types change laterally between open platform, high-
energy shoals, bio-constructed carbonate bodies, and tidal flats. Discontinuity surfaces often show a limited lateral extent and/or significant variety.

In deeper settings and lower hydrodynamic levels, small-scale sea-level changes did not induce significant shifts in facies belts. Here, lateral facies changes in small and medium sequences are low (Figure 8, maximum flooding zone of Sequence II) and discontinuity surfaces tend to be of a wide lateral extent with consistent indications of omission.

THE TOP-QISHN FORMATION UNCONFORMITY

The top-Qishn Formation unconformity and its diagenetic evolution are of special interest as this is a regionally significant marker surface overlain by the Nahr Umr Formation, the seal overlying the Shu’aiba reservoirs. The top-Qishn Formation unconformity is the same discontinuity that caps both the Shu’aiba reservoirs in the Interior Oman subsurface, and the Shu’aiba outcrops in northern Oman (Immenhauser et al., 1999; 2000b, c). In the southern field area (Wadi Baw), where the section directly underneath this surface is well exposed, the diachronous nature of the discontinuity is documented (Figure 14). In a transect less than 20 km in length, the rocks beneath the surface are systematically older from southeast to northwest, i.e. a difference of 5 m section in thickness (Figure 14). The discontinuity itself is a flat to undulating marine hardground surface with circumstantial evidence for a subsequent short subaerial exposure stage (Immenhauser et al., 2000b). Based on observations from recent settings, processes that take place at or beneath the wave base are commonly unable to account for the planar erosion of several meters of (at least in part lithified) carbonate sediments. In carbonate depositional environments, subaquatic erosion commonly first leads to some degree of winnowing at the seafloor and then to the formation of a marine hardground that precludes further erosion (Shinn, 1969). The marine hardground surface at the top of the lower Aptian Qishn Formation is probably the last of several phases that cumulatively shaped the top-Qishn Formation (Shu’aiba) discontinuity. Evidence for deep reaching meteoric karsting at this level has not been documented in the Haushi-Huqf High, nor in the extensive outcrop belts of northern Oman. Elsewhere in Oman and the Gulf region, seismic evidence from this interval reveals deep karst features, up to 1 km in width, indicating long-term subaerial emergence of the top Shu’aiba (unpublished PDO reports).

RESERVOIR CHARACTERISTICS OF THE QISHN FORMATION LIMESTONES

Porosity and Permeability Data from Outcrop Core Plugs

In order to quantify the porosity and permeability properties of the Qishn Formation limestones, outcrop (pseudo-) core plugs from Sequence II to base Sequence IV (Figure 15) were drilled in the Wadi Jarrah study area and plugs from Sequence IV (Figure 16) were drilled in Wadi Baw. The data are shown in Figures 15 through 19 and represent total (surface) porosity values. The mean total porosity of the Qishn Formation limestones (n = 344) is 19.3 % with highest values (max) of 36 % and lowest values (min) of 1.5 % (standard deviation s = 6.57 %). The mean permeability of the Qishn Formation limestones is 6.36 mD (max = 58.2 mD; min = 0.12 mD; s = 8.74 mD) when ignoring two extreme values (168 and 680 mD; Figure 19) that are considered non-representative.

The detailed quantification of interparticle and vuggy porosity in the sense of Lucia (1983; 1999) is the focus of a more extensive and detailed diagenesis study under way. The following general observations on the porosity evolution of these rocks are based on thin section petrography, geochemistry and outcrop evidence and summarized as a schematic paragenetic sequence in Figure 20.

Burial History

Qishn Formation limestones preserved porosity/permeability values that match those of Kharaib/Shu’aiba reservoirs in Oman or the United Arab Emirates (Budd, 1989; Moshier, 1989; Al-Awar and Humphrey, 2000; Immenhauser et al., 2002). Exceptions are the lithified uppermost portions of cliff faces of Qishn Formation table mountains (Figures 5 and 6). This lithification is the result of (sub)recent meteoric diagenesis (Figures 5 and 6) that has no analogue in the subsurface and these intervals are
Figure 14: NW-SE transect of upper interval of Qishn Formation in the southern Haushi-Huqf High. The top-Qishn Formation discontinuity (red line on top of sections) is diachronous in km-scale and caps different stratigraphic levels. For legend see Enclosure.
The considerable open porosity of the Qishn Formation limestones is most likely the result of very shallow burial and the overall post-exhumation arid climate. An estimate of the maximum burial depth can be made by interpolating the thickness of all post-Aptian formations in the Haushi-Huqf High (Dubreuilh et al., 1992). This suggests a maximum cumulative stratigraphic thickness of about 420 m of sedimentary rocks deposited atop of the Qishn Formation (not corrected for compaction). This value should be considered as a maximum as for instance the Nahr Umr Formation is commonly truncated by the Samhan Formation and the thickness of the Maastrichtian and Neogene units is much reduced in the study area (Dubreuilh et al., 1992; Immenhauser et al., 2002). A conservative estimate of the burial depth of the Qishn Formation is thus in the order of perhaps 200 m (± 50 m). This assumption is supported by the conspicuous absence of (late) burial cement phases in thin sections under cathode luminescence. It is thus concluded that nearly all of the present-day vuggy porosity is either primary, or apparently the product of early marine, early meteoric, shallow 'burial' or late (exhumation) diagenesis. In contrast, genuine burial phases are absent.

Primary Macro-Porosity

The term early porosity refers to all macroscopic pore space that existed primarily at (or near) the seafloor or that formed due to solution of metastable carbonate phases (aragonite and high-Mg calcite) in the early meteoric or shallow marine settings (Figure 20). Many samples are characterized by a considerable, but now occluded early vuggy porosity.

Figure 15: Plots of total (present-day) porosity and permeability data from three sections in the northern field area (Wadi Jarrah). Data are placed against facies and sequence stratigraphic interpretation. Data points labeled ‘V’ refer to vertically (approximately perpendicular to bedding) drilled plugs.
Winnowed grainstones were cemented by a thin isopachous layer of early marine cement and entered the shallow burial (or the meteoric phreatic) realm with a considerable open interparticle pore system. Much of this porosity has subsequently been occluded by compaction and by stable (low-Magnesium) blocky carbonate cements of shallow marine burial and meteoric origin (Figure 20).

Rudist bivalves comprise an outer, diagenetically stable low-Mg calcite shell and an inner, diagenetically metastable aragonitic shell. The inner aragonitic shell was dissolved during early diagenesis (probably near the sediment surface). This process results in a conspicuous system of open macropores easily observed at the weathered surface of outcrops. In plug thin sections, taken a few tens of centimeters away from the weathered surface, these macropores are often occluded by later blocky low-Mg calcite and internal sediments. This implies that the conspicuous open macroporosity as seen in exposed surfaces is generally the result of surficial weathering and these features are thus not fully applicable to subsurface settings. Nevertheless, Al-Awar and Humphrey (2000) describe substantial leaching of rudist shells and shell fragments from the Ghaba North field in Oman (Figure 20).

Oysters are abundant in many sections and are characterized by wide, flat (low-Mg calcite) shells preserving shelter porosity. However, blocky calcite and internal sediments nearly always occlude this primary shelter porosity (Figure 20).

Meteoric diagenesis, particularly leaching of metastable carbonate phases in the vadose zone, is a common feature related to subaerial exposure surfaces. Nevertheless, leached pores are commonly infilled by vadose silt and occluded by blocky meteoric calcite cement. Root traces are commonly filled with internal sediments (Figure 20).
Immenhauser et al.

Present Porosity

Following previous work (Lucia, 1983) we distinguish: (1) interparticle micro porosity; and (2) vuggy porosity. Interparticle microporosity is visible as a homogenous blue background staining in most impregnated thin sections but it is the scope of a subsequent study to investigate this porosity type in more detail. Vuggy porosity types include: (1) moldic pores related to the dissolution of secondary dolomite rhombs; (2) intrafossil pores (commonly in foraminifera but also in other micritized skeletal components); and (3) solution-enlarged fractures and burrows.

The significance of some of these observations for the Lower Shu’aiba subsurface limestones is questionable; particularly the considerable porosity caused by the dissolution of small euhedral dolomite crystals in the Qishn Formation limestones. This dolomite phase differs from the euhedral to

Figure 17: Permeability-porosity cross-plots from Qishn Formation limestone outcrop plug measurements grouped according to facies. Black circles indicate samples with no permeability data. Black lines are calculated trends. Thin sections represent corresponding facies.
Barremian-lower Aptian Qishn Formation, Haushi-Huqf area, Oman

Lithocodium-Bacinella bindstone

- mean Phi 23.2%
- mean K 8.9 mD
- n=24

Grainstone

- mean Phi 18.6%
- mean K 5.4 mD
- n=15

Lithocodium-Bacinella limestone of the Qishn Formation, Section D-022, sample 6.5, plug 58.
Phi = 19.6%, K = 2.47 mD.

Miliolid/oncoid grainstone of the Qishn Formation, Section D-007, sample 9.45, plug 36.
Phi = 22.1%, K = 4.87 mD.

Figure 17: Continued.

Subhedral, micro-rhombic, low-Mg calcite crystals as described from the Lower Cretaceous in the subsurface of the United Arab Emirates (Budd, 1989; Mosher, 1989) or the Ghaba North field in Oman (Al-Awar and Humphrey, 2000) by its mineralogy and perhaps its origin. Strongly dolomitized Qishn Formation carbonates show the highest porosity and permeability values measured in this study and plot in a relatively narrow field. In the subsurface of Oman, however, there are only a few wells that do show dolomitization in the (lowermost) Shu’aiba. Dolomitization in the Shu’aiba reservoirs is perhaps related to the presence of sink holes (i.e. meteoric water) in the area as interpreted from seismic. It is thus conceivable, that outcrop-restricted dolomitization is the product of meteoric water related to one or several climatically humid phases (Figures 5 and 6).

This implies that moldic pores related to the dissolution of secondary (meteoric) dolomite rhombs are of minor significance in the subsurface. In contrast, intra-fossil/component vuggy pores, solution-enlarged fractures and burrows, and leaching of rudist shells are features described from the Shu’aiba...
Figure 18: Correlation of large-scale sequences with porosity-permeability data. Overall, the correlation of Phi-K data is better for limestones deposited during the regressive (highstand) portion of a cycle. Black circles refer to measurements with no permeability data, red circles refer to vertically drilled plugs. Refer to enclosure for color code. Black lines are calculated trends.
Barremian-lower Aptian Qishn Formation, Haushi-Huqf area, Oman

Relation between Depositional Environment, Facies and Porosity-Permeability Values

Grouping of porosity and permeability data according to facies shows little difference. In contrast, the lateral variability within one depositional unit, in terms of porosity and permeability, is of the same order of magnitude as the stratigraphic variability (Figures 15 and 16). This might reflect the inherent heterogeneity of several facies types lumped into a common (e.g. open platform or tidal flat) depositional environment. Diagenetic processes affect the carbonate rocks irrespective of their depositional environment. As expected, shaley lagoonal and fine-grained tidal flat deposits show, on average, lower mean total porosity (15-20%) than for instance the coarse-grained rudist floatstones (32% mean total porosity).

A more straightforward relation is found, however, when related facies types are grouped (Figure 17). Porosity and permeability data show a coherent distribution according to thin-section facies particularly if those thin-sections that are extensively dolomitized are not taken into consideration (Figure 17). The following facies groups were used: (1) grainstones including bioclastic, oncoidal and peloidal facies; (2) Lithocodium/Bacinella bindstones; (3) Mollusk packstones, particularly oyster and rudist packstones and floatstones; and (4) Miliolid and peloid packstones (Figure 17). The resulting plots by facies are comparable with, for instance, porosity-permeability cross plots by facies in the Shu’aiba reservoirs of the United Arab Emirates (Budd, 1989). This implies that the values obtained from the Qishn Formation outcrop analogues are representative for subsurface reservoirs.

Figure 19: Overview of total porosity and permeability data from the Qishn Formation. Data from all sections are plotted using the top Qishn Formation unconformity as a datum and placed against depositional environments. Dark grey line is calculated five-point-moving average of all data. Refer to Enclosure and figure 7 for key to color code.

in the Northern Oman Mountains and the subsurface of Oman and United Arab Emirates (Budd, 1989; Moshier, 1989; Al-Awar and Humphrey, 2000; Borgomano et al., 2002) and thus of relevance for subsurface reservoirs.
The relationship between large-scale transgressive-regressive cycles and total porosity-permeability was tested in several sections. Overall, the porosity-permeability relationship shows a higher correlation for the regressive (highstand) deposits than for the transgressive deposits. This is illustrated in Figure 18 for section S-034. With respect to medium- and small-scale cycles, the correlation is poor. It is assumed that this latter observation is at least in part related to a sampling bias, i.e. the insufficient number of drill-plugs per medium- and small-scale cycle. The superposition of sea-level cycles of various magnitudes further complicates the direct correlation of porosity-permeability values to specific stages in a regressive-transgressive cycle.

Porosity and Permeability Trends in the Qishn Formation
Figure 19 summarizes total porosity and permeability data from all Qishn Formation data plotted against depositional environment and depth beneath the top Qishn Formation unconformity. Sequences II and III show comparably invariant porosity values. In contrast the permeability increases systematically from Sequence II (top Kharaib equivalent) built by fine-grained open platform limestones, to Sequence III mainly characterized by tidal flat and rudstone facies but drops sharply at the base of Sequence IV. Porosity values of Sequence IV are invariant whereas permeability in the highstand of Sequence IV scatters over a wide range with mean values comparable to Sequence III. Porosity values in Sequence IV are, in a statistically significant manner, higher and show less scatter. The same accounts to some degree for the permeability values of the highstand of Sequence IV. The reason for the

Figure 20: Schematic paragenetic event summary for the Qishn Formation limestones based on field data, thin-section petrography and cement geochemistry. Diagenetic events that took place during or after the exhumation phase, and thus are not compatible with subsurface reservoirs, are indicated in yellow.

Relation between Sequence Stratigraphy and Porosity-Permeability Values
The relationship between large-scale transgressive-regressive cycles and total porosity-permeability was tested in several sections. Overall, the porosity-permeability relationship shows a higher correlation for the regressive (highstand) deposits than for the transgressive deposits. This is illustrated in Figure 18 for section S-034. With respect to medium- and small-scale cycles, the correlation is poor. It is assumed that this latter observation is at least in part related to a sampling bias, i.e. the insufficient number of drill-plugs per medium- and small-scale cycle. The superposition of sea-level cycles of various magnitudes further complicates the direct correlation of porosity-permeability values to specific stages in a regressive-transgressive cycle.

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consistently higher porosity and permeability values of Sequence IV is perhaps the very coarse rudstone facies that builds most of this unit and that has no analogue in sequences I through III.

Spectral Gamma Ray Signature

The spectral gamma ray signature of the Qishn Formation limestones was measured at several sections in order to: (1) test the applicability of gamma ray in the Qishn Formation of the Western Haushi-Huqf High as a correlation tool; (2) to compare facies with total gamma ray and K, U, and Th spectra; and (3) to compare outcrop gamma ray signatures with the gamma ray well logs measured in the Lower Shu‘aiba Formation. Two reference sections illustrate the spectral gamma ray signature of the Qishn Formation in the Haushi-Huqf High (S-030 and D-008; Figure 21).

Discussion of Gamma Ray Data

Overall, gamma ray signatures provided a useful complement for sequence stratigraphic correlations. At a more regional scale, however, the spectral gamma ray signature reflects local variations in argillaceous influx and/or the amount of organic matter. These local features may override the background signature controlled by the overall distribution of more shaley/organic rich units in the large-scale cycles in the Qishn Formation. The more variant gamma ray signals in the southern field area might be related to the overall deeper and more shaley – or more organic rich - facies in this area (Figure 13).

The U and Th spectra dominate the total gamma ray curves (Figure 21). Uranium is commonly linked to organic material. In the case of the Qishn Formation, it appears that the amount of organic material, mainly present in more shaley lithologies, is the cause of the various shifts observed and not the clay content. This must be taken into account when comparing the more calcareous outcrop gamma ray sections with the facies of the Oman Interior subsurface. Nevertheless, in the Oman subsurface the Shu‘aiba gamma ray signal is also controlled by organic matter content, only to the northwest, in the
Bab Basin (Upper Shu’aiba) there are clays. Overall, the gamma ray sections from the Wadi Baw area show more variation, particularly the Uranium and Thorium spectrums, than the sections from the northern field area near Wadi Jarrah. The highest U values are present at the base of both reference sections with at least two major excursions between m 0 and 10 of section D-008 (Figure 21). Similarly, the Hawar Member equivalent in section D-008 is characterized by a shift towards higher values at its base and subsequently decreasing values. The lowest gamma ray values are observed in the uppermost few meters of both sections. These intervals are composed of fully lithified carbonate rocks that have seen pervasive (sub)recent meteoric diagenesis (Figures 5 and 6), suggesting that the low values are a diagenetic artifact.

FRACTURING AND FAULTING OF QISHN FORMATION LIMESTONES

Limestones of the Qishn Formation are affected by widespread fracturing, faulting, and to a much lesser degree by folding, with consequences for geotechnical characteristics of the rocks and thus their reservoir properties. The structural data and their interpretation focus on several aspects that include the morphology and the spacing of fractures that form as Qishn Formation limestones respond to applied stresses. A second important issue of this study includes the relation between fracture pattern, fracture density and limestone facies. A third aspect centred on the tectonic origin of fractures and particularly their relation to folding, to larger-scale faulting, or to regional stresses.

The most common strain-related features in the Qishn Formation outcrop belts are widespread systematic joints, which form systematic and homogeneous sets with regard to their morphology, their distribution in space and their orientation (Figure 22a). In a more limited number of outcrops, fractures are long and irregular (Figure 22b). They are mainly developed in fully lithified layers (post-Cretaceous meteoric diagenesis, cf. Figures 5 and 6) forming the top of table mountains built by Qishn Formation limestones or being linked to intensively (early?) dolomitized intervals at the top of the Jurf and the base of the Qishn Formation. Outcrops of the Haushi-Huqf High are also affected by fault corridors. Folds, typically open with subvertical axial planes, are observed in several outcrops.
Systematic Joints – Morphology and Distribution

Systematic joints occur regionally, and are typically confined to specific intervals of the exposed part of Qishn Formation limestones where they form regular networks of fractures. They are usually straight and long, typically longer than the extension of outcrops (m to a few 10s of m). Joints have very systematic orientations and all investigated localities show a dominant, NW-SE to WNW-ESE trending set (Figure 23). A second joint family is often observed which can be either perpendicular to the first one (Figure 23a) or at small angle (Figure 23b and c). The constant presence of the NW-SE trending family is remarkable because outcrops investigated are several tens of km apart. This implies that this joint direction is of regional significance.

The spacing between joints has a very systematic distribution averaging 6-18 cm (Figure 24a). Because of the presence of more than one set of joints, and the fact that joints are much longer than the typical spacing, intervening blocks have fairly constant dimensions in the order of 10-20 cm.

Vertical sections show that systematic fractures or joints are present in specific beds (Figure 22c), whereas in other beds, they are absent. Terminations at the boundaries of the affected layer are typically abrupt. Fractured intervals show quite constant orientation and spacing between fractures independently from their facies and lithology. More widely spaced fractures can either cross the entire stratigraphic interval, or can gradually disappear with changing lithological characteristics.

Systematic joints are basically found in four intervals within the Qishn Formation. This pattern is consistent over large distances (i.e. 100 km in north-south orientation). The affected intervals often include either single beds or groups of beds. From bottom to top jointed intervals are:

- A 50 cm-thick bundle of open platform bioclastic limestones deposited below wave base at the top of Sequence I (Figure 10).
- An about 1m-thick interval of thinly bedded tidal flat deposits at the top of Sequence III (Figure 10).
- A 5-6 m-thick succession of thickly bedded, coarse gained Lithocodium/Bacinella rudstones, with Lithocodium/Bacinella biomounds in the upper part of Sequence IV (Figure 10).
- The 1.5–2 m-thick, cross bedded rudstones at the very top of Sequence IV (Figure 10).

The origin of systematic joints

Relations with folding. Measurements on two structures, a double plunging anticline with up to 70° steep flanks and an about 2-km-wide anticline marked by gentle flank dips, showed no major differences
between the joint patterns (both density and orientation) present on folded layers and those observed away from the fold itself. We therefore conclude that folding did not produce significant fracturing elsewhere than in the anticlinal hinges.

Relations with fault corridors. No significant modification of fracture density was noted approaching fault zones, and joint patterns and densities close to faults are comparable with those observed several meters or 10s of meters away. It is thus concluded, that fault-related deformation was basically limited to the fault zone itself.

Relations with regional stress fields. Field data demonstrate that joints are not associated with ‘local’ causes and that they must rather be attributed to regional stresses. There are as yet no objective and independent criteria to associate joint sets with directions of principal stresses. While there is a general agreement that joints are formed perpendicular to $\sigma_3$ and parallel to $\sigma_1$ specific cases can be more complex. Other geological structures were therefore analyzed in order to constrain stress trajectory directions which can then be compared with the joints observed. For this purpose, some sets of conjugate faults and open folds from different outcrops were measured. In accordance with the general view, we interpret the dominant NW-trending joint set as parallel to the maximum horizontal stress (e.g. Hancock and Engelder, 1989; Pollard and Aydin, 1988). This is compatible with the opening character of the observed joints (mode I fracturing). The inferred NW-SE direction for the maximum principal stress is different to the one derived for the Present which is more N-S trending. We associate the NW-SE direction of $\sigma_1$ with the Latest Cretaceous to Palaeocene transpression between the Arabian and the Kabul/India plates (e.g. Immenhauser et al., 2000c). Similar directions of the maximum horizontal stress SH have been recently derived by Montenat et al. (2003) and considered to be of a somewhat earlier age, namely Aptian.

Non-systematic Fractures

A second group of joints (Figure 23a) is formed by long fractures (meters to 10s of meters), fairly irregular in trajectory but only partly organized in systematic sets. They appear to be open, but the
effects of surficial weathering and dissolution of fracture filling calcite in these outcrops are unknown. These fractures affect fully lithified rocks such as dolomitized carbonates and, more importantly, the meteorically lithified top few meters of the Qishn Formation exposed in the table mountains (Figures 5 and 6). Although very apparent both in the field and on aerial photographs, these fractures are not relevant for the Kharaib and Shu’aiba reservoirs in the Interior Oman subsurface where limestones escaped dolomitization and meteoric lithification.

**Faults and Fault Corridors**

Although not very common, faults are found in most outcrops of the Qishn Formation. From a morphological point of view they are divided in two groups which correspond to relative displacement.

Faults of the first group are usually sharp with deformation localized in centimeter-thick zones. Sharp faults systematically display limited displacements, in any case less than 2 meters. In places, the fault zones become wider with the presence of centimeter-thick lenses of cataclastic breccias. These are very well cemented and thus completely ‘tight’. Fault planes dip at ~60º but become steeper when they cross particularly competent beds. Faults can also become wider when they intersect beds with pre-existing discontinuities, particularly subvertical joints. In this case, the displacement is distributed over a number of joints (Figure 24b).

In some cases, strain is accommodated by complex fault corridors, which typically form zones 10-20 m in width. These are basically formed by numerous fault planes separating blocks with little deformation. Fault planes are often coalescent and blocks typically measure less than 1 meter in width. Deformation in the fault corridors is essentially confined to the fault planes, and intervening blocks are generally non-fractured. This goes hand in hand with the lack of similar features related to regional deformation outside the fault zone itself. Neither an increase in fracture density, nor a modification of fracture orientation was observed close to the faults.

Fault corridors form topographically conspicuous features in landscape-scale and on aerial photographs. In the southern part of the Haushi-Huqf High (Wadi Baw) they are often strike-slip faults as based on striae. The lack of marker horizons prevents a precise quantification of movement along strike-slip faults, but there is no evidence for significantly large movements. When more than one fault corridor is exposed, they are at distances of several hundred meters.

**Mechanical Stratigraphy**

The stratigraphic distribution of different structural features is quite variable defining a ‘mechanical stratigraphy’. The most apparent feature is that joints (both systematic and non-systematic) are always confined to specific intervals, typically less than few m thick, whereas faults (both localized and as corridors) cross the entire stratigraphic succession. Jointed intervals are consistent over most of the investigated area, i.e. a distance of about 100 km in the N-S extension.

Joints are confined to specific intervals of the stratigraphic column, corresponding to less than 20% of its total thickness. The dichotomy between the complete absence of joints in most of the section and their widespread appearance in specific intervals is apparent but difficult to explain since jointed intervals are substantially different in terms of their lithological characteristics. Joints do not appear in soft rocks (e.g. Ladeira and Price, 1981), which tend to accommodate deformation in a distributed (= ductile) manner (Figure 24c). On the other side, very strong layers are not affected by jointing as their strength is higher than the available stresses. We therefore conclude that the strict confinement of joints to specific stratigraphic intervals requires strongly contrasting mechanical properties of different layers. It is intuitive that such differences were strongest prior to complete lithification and, therefore, joints developed perhaps in an early stage.

In layers, which are prone to jointing, it is possible that joint spacing depends on: (1) the thickness; (2) the mechanical properties of the competent bed; and (3) the thickness of the incompetent beds above and beneath the jointed strata, respectively (Ji and Saruwatari, 1998 and references therein). The spacing of...
joints in the Qishn Formation limestones is remarkably constant within the four intervals in which they are present and a correlation with bed layer thickness can thus be excluded. We conclude that the dominant factors controlling joint spacing are mechanical. According to Ji and Saruwatari (1998), these are the Young’s modulus, the tensile strength and fracture saturation strain of the competent beds as well as the shear modulus of the incompetent layer. We did not measure these parameters in the outcrops of the Haushi-Huqf High. It is, however, remarkable that the jointed layers are very different with respect to their facies and grain size. This implies that grain-size as such is not the controlling mechanism. We propose that the main factor controlling the mechanical properties of the jointed layers and, thus, joint spacing depends on relatively subtle differences in carbonate content of individual beds. Indeed all jointed intervals are basically shale-free. This is expressed morphologically by the fact that fractured beds typically form steep cliffs with well-developed plateaus at their top. A lack of correlation between lithology and joint spacing has also been demonstrated by Ladeira and Price (1981) and Narr and Suppe (1991).

In contrast to joints, faults are observed to cross the entire stratigraphy merely becoming somewhat steeper when traversing more competent layers. This is related to:

- The comparably large amount of displacement associated with faults that cannot be easily accommodated by jointing.
- The possibility that faults developed following complete lithification, that is, in a stage when mechanical differences among layers were much reduced. Indeed, faults in some outcrops are seen to reactivate pre-existing sets of systematic joints.

CONCLUSIONS

- The Qishn Formation, as exposed in the Haushi-Huqf High of Oman, is presented in this study as new outcrop analogue for Kharaib/Shu’aiba subsurface reservoirs.
- Based on biostratigraphy, as well as on carbon and strontium-isotope chemostratigraphy, the Qishn Formation is middle Barremian to mid-early Aptian in age. The equivalent of the Hawar Member within the Qishn Formation, and in the subsurface, is earliest Aptian in age. The underlying dolomitic Jurf Formation is perhaps the time-equivalent of the Lower Kharaib, Lekhwair, Habshan, Salil, and Raydah formations.
- The Jurf and Qishn formations are organized in four major (10-30 m) depositional sequences of which Sequence I represents the dolomitic Jurf Formation. The Qishn Formation is built by three large-scale transgressive-regressive cycles. Sequence II represents the equivalent of the Upper Kharaib, most of Sequence III corresponds to the Hawar Member, and Sequence IV is the equivalent of the Lower Shu’aiba Formation.
- At least two lower orders of higher frequency depositional sequences (medium-scale sequences 4-10 m in thickness and small-scale sequences 1-3 m thick) are superposed on the large-scale sequences. Sequences of these three orders can be correlated throughout the Qishn Formation outcrop belts, i.e. 100 km in north-south extension. The origin of these cycles is therefore probably allocyclic.
- The paleo-environments recorded in the Qishn Formation span from the tidal mudflat to the below-storm wave open platform (outer ramp), overall a shallow setting compared to the more intrashelf basin setting of the Oman Interior basins. The north-south oriented outcrop belts of the Qishn Formation in the Haushi-Huqf High are parallel to the paleo-facies belts of the Barremian-Aptian Arabian Platform in this region.
- The Qishn Formation limestones have preserved their reservoir properties due to shallow burial of perhaps not more than 200 m (± 50 m) and the post-exhumation arid climate. Plugs from the middle and upper Qishn Formation are characterized by fairly high porosity (mean of 19.3%) and permeability values (mean 6.36 mD). Overall, the relation between porosity and permeability is better for regressive (highstand) deposits than for the limestones of the transgressive interval. The lateral variability (>100 m) of porosity and permeability values within specific intervals is substantial and matches or even exceeds that of stratigraphic variability.
- The gamma ray data from Qishn Formation limestones are dominated by the U spectrum and to a lesser degree by the Th spectrum. This is comparable to Shu’aiba gamma ray well logs in Oman that are generally controlled by variable amounts of organic matter.
• Four stratigraphic intervals within the Qishn Formation are affected by widespread pervasive jointing. The cumulative thickness of the fractured layers is <20% of the total thickness of the Qishn Formation.
• Joints in these intervals are extremely systematic as to their spacing, morphology and directions. The dominant direction is NW-SE.
• Joints formed parallel to the maximum compressional axis oriented NW-SE, similar to that of the dominant joint set. The controlling stress field was most likely generated during Maastrichtian to earliest Paleocene transpression along the SE margin of Oman.
• The present paper documents the findings of a field study and their interpretation. These results form the basis for future, more advanced work that must: (1) place these data and their interpretation in a plate-wide stratigraphic context; and (2) link the Qishn Formation outcrops with the Upper Kharaib/Lower Shu’aiba formations in the Interior Oman subsurface.

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REFERENCES

Immenhauser et al.


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