Khuff Sequence KS5 outcrop-equivalents in the Oman Mountains, Sultanate of Oman: Variations to the simple “layer-cake” stratigraphy

Lisa Walz, Thomas Aigner and Bastian Koehrer

ABSTRACT

The Khuff Formation is a major producer of non-associated gas and an exploration target in the Middle East. The Middle Permian to Lower Triassic Khuff carbonates were deposited on a gently inclined epeiric carbonate ramp, which formed on the margin of the Neo-Tethys Ocean. The formation represents a supersequence consisting of transgressive-regressive sequences KS6 to KS1 from oldest to youngest. This paper focuses on a detailed sedimentological analysis of Khuff Sequence KS5 in outcrops in Al Jabal al-Akhdar in the Oman Mountains, Sultanate of Oman. Based on the sedimentological analysis of five outcrop sections, 11 facies types were identified in KS5. These were grouped into six facies associations, which represent environments ranging from a tidal flat to offshore. Based on the 1-D analysis of sequences and their stacking patterns, 2-D correlations were constructed on a scale of several tens of kilometers. These correlations were used to build the framework for 3-D facies models.

In contrast to the typical “layer-cake”-type Upper Khuff sequences KS4 to KS1 in terms of facies associations and cyclicity prominent lateral facies association changes and thickness variations are common in KS5, which makes correlation challenging. Different correlation strategies were tested, all resulting in complex cycle and stratal geometries with cycle pinch-outs and apparent cycle set downlaps/onlaps. Due to the dynamic depositional changes throughout KS5, the lateral extent of shoal-associated grainstones is limited. The appearance of these potential reservoir bodies is mainly governed by paleogeography and stratigraphic position. The observed depositional patterns represent significant variations from a rather simple “layer-cake”-type stratigraphic architecture and are possibly due to effects of differential subsidence on a subregional scale. This study contributes to a more detailed understanding of the Lower Khuff’s reservoir distribution and continuity, which is a key to ensuring future success in Khuff exploration and the efficient recovery in producing fields.

INTRODUCTION

In 1979 the first offshore Khuff gas discovery was made in the Umm Shaif-88 Well in the United Arab Emirates (Alsharhan, 2006). Since then the Middle Permian–Lower Triassic Khuff Formation has become a major producer and exploration target, especially after the discovery of the supergiant Qatar North Field (Bashari, 2005; Figure 1). This paper is part of a larger research project, initiated in 2007 by Qatar Shell, Petroleum Development Oman and Germany’s University of Tuebingen. The project’s objective is to prepare a detailed sequence-stratigraphic and sedimentary characterization of Khuff time-equivalent strata in Al Jabal al-Akhdar in the Oman Mountains (Figures 1 and 2).

In the Al-Jabal al-Akhdar region, Khuff time-equivalent strata can be divided into six transgressive-regressive sequences KS6 to KS1 from oldest to youngest (Koehrer et al., 2010; Figure 3). Recent studies (Al-Husseini and Koehrer, 2013; Obermaier et al., in preparation) interpret the Khuff in terms of four third-order sequences (KS6, KS5, KS4, KS3–KS1) with KS3, KS2 and KS1 representing individual high-frequency sequences (HFS). Based on the sequence-stratigraphic framework developed on the Saiq Plateau reference section, the stratigraphic architecture of Sequences KS1 to KS4 was studied by Koehrer et al. (2011, 2012), Zeller et al. (2011) and Haase and Aigner (2013). Their lithofacies associations show overall “layer-cake”-type geometries at the scale of 10s of kilometers.
Most studies have focused on sequences KS4 to KS1 because they contain the main hydrocarbon-bearing reservoir zones (i.e. K4 to K1 reservoir zones in Qatar). In contrast to KS4 to KS1, the lithofacies associations of the lower, transgressive part of Khuff Sequence KS6 are not “layer-cake” as they were influenced by the initial paleotopography (Bendias et al., 2013). Khuff Sequence KS5 occurs between KS4 and KS6, and the geometry and lateral extent of its lithofacies associations – and thus potential reservoir geobodies – is poorly understood. This study aims to address this uncertainty and investigates the KS5 stratigraphic architecture on a several 10s of kilometer scale in outcrops of Khuff time-equivalent outcrop sections in the Oman Mountains. The general Khuff stratigraphy is shown in Figure 3, and the interval of Khuff Sequence KS5 studied in this paper is highlighted.

STUDY AREA AND METHODOLOGY

Several field seasons in 2008 and 2009 were required to collect the database from the five studied outcrop sections in Al Jabal al-Akhdar (Figure 2, UTM coordinates, Oman 40 Zone, base of sections respectively): Wadi Mistal (N2575342, E570578), Wadi Hedek (N2586590, E589341), Wadi Sahtan (N2580281, E531879), Wadi Bani Awf (N2576149, E547442) and the Saiq Plateau (N2554545, E570159).

The five sections were sedimentologically logged with a resolution of 10 cm. In total 1,080 m of KS5 strata was investigated. Data on lithology, sedimentary structures and textures, facies types, components and rock color were noted. For the determination of facies types, the previously established facies atlas of Koehr et al. (2010) was applied. A number of outcrop photographs were
taken to document the rock character. Standardized logging sheets were used to capture all the data. Rock samples were taken and used for the preparation of a total of 227 thin sections. Those were analyzed following standard petrographic techniques with a transmission light microscope. Natural gamma-radiation of the outcrop strata was measured with a hand-held spectral gamma-ray device (model GS-512, manufactured by Geofyzika, Czech Republic) using a spacing of half a meter with a recording time of 15 seconds.

The concept of dynamic stratigraphy (Aigner, 1985; Kerans and Tinker, 1997; Aigner et al., 1998) was applied as workflow for this research. Based on the 1-D analysis of sequences and their stacking patterns, 2-D correlations were constructed and used to build the framework for the final 3-D digital facies models.
Sequence KS5 was deposited in the late Guadalupian (Middle) Epoch of the Permian Period and is assigned to the Midian Stage based on the occurrence of Upper Midian *Sphantoria sikuoides* and *Shanita amosi* (Koehrer et al., 2010; Forke et al., 2012). The Midian Stage approximately correlates to the Capitanian Stage, which is dated between ca. 265.1 and 259.8 Ma in GTS 2012 (Gradstein et al., 2012) implying the depositional duration of KS5 is about 5.3 million years (Figure 3).

![Figure 3](https://pubs.geoscienceworld.org/geoarabia/article-pdf/18/4/179/4569185/walz.pdf)

Figure 3: General stratigraphic column of the Permian–Triassic Khuff time-equivalent strata in the Oman Mountains. Focus of this study is the KS5 covering the Capitanian Stage. Top KS5 (KS5 to KS4 boundary) coincides with a major regression and the End-Guadalupian mass extinction, which is also visible in the Khuff sedimentary record (modified from Koehrer et al., 2010, 2012). Geological time scale from Gradstein et al. (2012) with tentative correlation to MFS postulated by Sharland et al. (2004).
In the Mid-Permian, the study area was located on the passive continental margin of the Arabian Plate in the Pangea Supercontinent, facing the newly formed Neo-Tethys Ocean (Sharland et al., 2001). The margin consisted of a large epeiric carbonate ramp with very low topographic relief (Alsharhan and Nairn, 1994; Insalaco et al., 2006). Seen in a global context, the Mid-Permian was an era of transitional climate from ice-house to greenhouse conditions (Al-Jallal, 1995). Based on paleobotanical data, Berthelin et al. (2003) suggest an inner-tropical to sub-equatorial latitude for Oman during that time (latitude 30° south). The warm and humid tropical climate showed no marked seasonality.

In this paper the Upper Saiq and Lower Mahil members in the Oman Mountains are considered as time-equivalent to the subsurface Khuff Formation (Glennie et al., 1974; Glennie, 2005). Baud and Richoz (2013) explained that some authors apply a different lithostratigraphic scheme, also attributed to Glennie et al. (1974), in which the Saiq Formation corresponds to the entire Permian–Lower Triassic Khuff Formation, and the Mahil Formation to the overlying Triassic formations. In the range of this research project (this paper as well as Koehrer et al., 2010, 2011, 2012; Pöppelreiter et al., 2011; Zeller et al., 2011; Obermaier et al., 2012; Bendias et al., 2013; Haase and Aigner, 2013), we refer to the lithostratigraphic lower Saiq/Mahil Boundary of Glennie et al. (1974), defined in the type locality of the Saiq Formation on the Saiq Plateau.

In the studied outcrops the lower sequence boundary of KS5 (SB KS5, KS6/KS5 boundary) is picked on top of an up-to 50 cm thick microbial laminite, which can laterally develop into rooted mudstones on a 10 km scale (Bendias et al., 2013). The interval was described as “Microbial Marker 1” by Koehrer et al. (2010). The upper sequence boundary of KS5 (SB KS4, KS5/KS4 boundary) occurs in an interval between KS5 and KS4 that is characterized by a typical “zebra-stripe” pattern, visible from a distance. The pattern results from an intercalation of thick microbial laminites, well-reflected by a very light outcrop color, and intercalated darker bioclastic-rich pack- to grainstones. This interval was referred to as “Microbial Marker 2” by Koehrer et al. (2010). The top sequence boundary SB KS4 of Sequence KS5 is picked on top of the most prominent microbial laminite bed (up to several 10s of centimeters thick) found in all investigated sections.

**SEDIMENTOLOGICAL ANALYSIS**

Making use of the established Khuff facies atlas (Koehrer et al., 2010), Khuff Sequence KS5 comprises 11 facies types (LFT, Figure 4), which can be grouped in six lithofacies associations (LFA). Although the entire KS5 shows various degrees of mimetic replacement (fabric preserving) to complete destruction into finely crystalline (non-fabric preserving) dolomite, the depositional textures, structures and fauna could largely be determined. By the use of white paper for the microscopic analysis the contrasts could be enhanced further. A dolomitization model for the Saiq and Mahil formations in the Oman Mountains is provided by Coy (1997).

**Facies Types**

**Burrowed to vertically rooted mud- to wackestone (LFT 2b)**
Among the mud-dominated facies, lithofacies type 2b (LFT 2b) represents the most commonly observed facies type within KS5 (Figure 5). It commonly shows burrows and rarely root traces. Its indicative light color varies from light grey to bluish and whitish. The bed thickness varies between 10 and 30 cm. Only in the upper regressive part of KS5 it can reach up to 1 m in thickness. It is interpreted as being deposited in a low-energy environment of a shallow subtidal protected inner-ramp with possible periods of exposure. Its associated lithofacies setting is interpreted as a low-energy backshoal (LFA 4A) environment.

**Bioturbated mud- to wackestone (LFT 2c)**
Lithofacies type 2c is mainly found in the Saiq Plateau section, representing offshore deposits (LFA 7) (Figures 4 and 6). Noteworthy is the appearance of chert nodules in this facies types in Wadi Hedek and on the Saiq Plateau where they form the so-called “Chert Marker” (Koehrer et al., 2010). In both locations this interval represents the overall maximum flooding of Sequence KS5. The origin of the
“Chert Marker” bed is not clearly understood at this point and the main siliceous fossil contributors could not be identified. This interval is interpreted as the maximum flooding since it is assumed to be generated by siliceous sponge needles or other siliceous fossils which virtually all reflect open to deeper-marine waters. Possibly, the nodular appearance of the chert hints towards former bioturbation structures, which were chertified during later diageneis.

(a)

<table>
<thead>
<tr>
<th>Group</th>
<th>Facies Type</th>
<th>LFT</th>
<th>Interpretation</th>
<th>LFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud-dominated</td>
<td>Burrowed to vertically rooted mud- to wackestone (LFT 2b)</td>
<td></td>
<td>Deposits of a moderate-energy, shallow subtidal lagoonal setting</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Bioturbated mud- to wackestone (LFT 2c)</td>
<td></td>
<td>Open subtidal deposits of the low-energy outer ramp with strongly varying oxygenation, reduced circulation and low sedimentation rates.</td>
<td>7</td>
</tr>
<tr>
<td>Biogenic-dominated</td>
<td>Microbial laminites (LFT 3a)</td>
<td></td>
<td>Moderate- to high-energy intertidal deposits or shoal exposures</td>
<td>3, 4B</td>
</tr>
<tr>
<td>Grain-dominated</td>
<td>Graded pack- to mudstone Sub-Type A: Graded wacke- to mudstone (LFT 5a1)</td>
<td></td>
<td>Moderate- to high-energy storm deposits above SWB on the windward and leeward side of shoals</td>
<td>4A, 4B, 6</td>
</tr>
<tr>
<td></td>
<td>Graded pack- to wackestone (LFT 5a2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intraclastic packstone with laminite flakes (5b1)</td>
<td></td>
<td>Moderate- to high-energy, adjacent to tidal flats</td>
<td>3, 5</td>
</tr>
<tr>
<td></td>
<td>Poorly sorted pack- to grainstone Sub-Type A: Peloidal-rich pack- to grainstone (5c1)</td>
<td></td>
<td>Deposits of the moderate-energy, deeper subtidal environment</td>
<td>4A, 4B, 6</td>
</tr>
<tr>
<td></td>
<td>Sub-Type B: Bioclast-rich pack- to grainstone (5c2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Well sorted grainstone Sub-Type A: Well-sorted peloidal grainstone (5d2)</td>
<td></td>
<td>Proximal incipient to fully developed shoal complexes within a high-energy, shallow subtidal setting</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sub-Type B: Well-sorted oolitic grainstone (5d1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Skeletal floatstone (5f)</td>
<td></td>
<td>Deeper water, outer ramp deposits below SWB</td>
<td>7</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Lithofacies Association</th>
<th>Depositional Environment</th>
<th>Sedimentary Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFA 3: Tidal flat</td>
<td>Low-energy tidal flats surrounded by higher energy channels, becoming locally evaporitic during more arid phases</td>
<td>Structureless to laminated mudstones, wackestones and packstones, discontinuity surfaces, mudcracks, tepees, microbialites, fenestrae, rare ostracods and gastropods</td>
</tr>
<tr>
<td>LFA 4A: Low Energy Backshoal</td>
<td>Low energy, shallow water, with semi-restricted circulation of marine waters</td>
<td>Moderately to poorly sorted mud/wacke/packstone, intraclasts and oncoids, variably bioturbated, normal grading, clay drapes, mudstone intraclasts, microbial binding, abundant gastropods, thin-shelled bivalves, ostracods, miliolids, algae, peloids, ooids, pellets</td>
</tr>
<tr>
<td>LFA 4B: Moderate Energy Backshoal</td>
<td>Moderate energy, shallow water, with semi-restricted circulation of marine waters, adjacent to shoals</td>
<td>Moderately sorted pack- to grainstones, intraclasts, oncoids, microbial binding, gastropods, bivalves, ostracods, miliolids, algae, peloids, ooids, pellets</td>
</tr>
<tr>
<td>LFA 5: High Energy Shoal</td>
<td>Open circulation, fully marine waters, variable hydrodynamic energies characterizing active shoals, dominated by wave and wind activity</td>
<td>Moderately to well sorted, peloidal and oolitic grainstones, well developed trough and planar cross-stratified, shell debris</td>
</tr>
<tr>
<td>LFA 6: Foreshoal</td>
<td>Moderately low- to locally high-energy, deeper subtidal storm dominated, mid to outer ramp with open circulation of fully marine waters</td>
<td>Moderately to poorly sorted graded wackestones to pack/ grainstones, well developed low-angle lamination and hummocky cross stratification (HCS), normal grading, post event bioturbation, locally hardground development, abundant peloids, shells, intraclasts, foraminifers, crinoids and algae</td>
</tr>
<tr>
<td>LFA 7: Offshoal Basinward</td>
<td>Moderately to low-energy, deep subtidal outer ramp below storm wave base with strongly varying oxygenation, reduced circulation and low sedimentation rates</td>
<td>Poorly sorted skeletal floatstones/packstones and bioturbated mud/wackestones, strong bioturbation including a minor amount of preserved burrows and feeding structures, foraminifers, corals, shells</td>
</tr>
</tbody>
</table>

Figure 4: Atlas for Khuff Sequence KS5: (a) facies types from Koehrer et al. (2010), adjusted according to the appearance in KS5; and (b) identified lithofacies associations in the KS5. Modified from Koehrer et al., 2010.
The Permian represents a time of major chert development in various settings all over the world (e.g. Kakuwa, 1996; Murchey and Jones, 1992; Beauchamp and Baud, 2002). The literature commonly refers to this massive chert appearance all over the globe as the PCE, the Permian Chert Event. In contrast, the Early Triassic is described as a global period of non-production or preservation of chert (ETCG, the Early Triassic Chert Gap). In the case of the “Chert Marker” in KS5, anoxic conditions are not considered to have been present. It is more likely that dysoxic conditions and high siliceous productivity were favored by a changing paleo-oceanographic circulation (e.g. Murchey and Jones, 1992).

**Microbial laminites (LFT 3a)**

Due to the light color and well-preserved lamination the facies type 3a can be readily recognized from a far distance in the field (Figure 7). The characteristic “zebra stripe” pattern at the top of KS5 is created by intercalations of microbial laminites with bioclastic-rich pack- to grainstones and marks the KS5 to KS4 transition. The thickness ranges from 5 cm to 1.5 m in the regressive part of KS5. Its depositional setting is interpreted as either a low- to moderate-energy in a tidal flat association (LFA 3) or adjacent to shoals (LFA 4B) during short-term exposure events (see also discussion in Haase and Aigner, 2013). Depending on the bed thickness, as well as on the facies stacking pattern, these two settings can be distinguished.

**Graded pack- to mudstone with**

**Sub-Type A: Graded wacke- to mudstone (LFT 5a1) and**

**Sub-Type B: Graded pack- to wackestone (LFT 5a2)**

LFT 5a1 as well as LFT 5a2 (Figure 8) represent moderate to high-energy storm sheets above storm-weather wave base. The graded wacke- to mudstones/pack-wackestones show thin interbedding of grainy and muddy beds with wavy lamination. The depositional environment is either foreshoal or backshoal depending on the fossil content and facies stacking pattern.
**Figure 6: Bioturbated mud- to wackestone (LFT 2c).**

**Intraclastic packstone (with laminite flakes) (LFT 5b1)**

The facies type 5b1 (Figure 9) is one of the rarest facies types in Khuff Sequence KS5. It comprises reworked flakes of microbial laminites in a packstone matrix, and is interpreted as a high-energy shallow subtidal storm deposit and assigned to tidal flat areas (LFA 3).
Khuff Sequence KS5, Al Jabal al-Akhdar, Oman

Figure 7: Microbial laminite (LFT 3a).

- characteristic light grey to white outcrop color (a)
- distinctive wavy to crinkly lamination in muddy matrix due to abundant microbial activity (b)
- common fenestral fabrics, often filled with vadose silt (c)
- frequent geopetal fabric (d)
- desiccation cracks/tepees
- low biotic diversity

Interpretation
- low to moderate energy
- inter- to supratidal
- probably high salinity fluctuations
  → tidal flat settings or shoal exposures; long term exposures are represented by desiccation structures

Figure 8: Graded mud- to wackestone and pack- to wackestone (LFT 5a1/5a2).

- wacke-mudstone (5a1) (1) or pack-wackestone (5a2) (2)
- light grey outcrop color
- thin interbedding of grainy and muddy beds
- scoured base, wavy lamination, normal grading
- moderately sorted
- bioturbated tops (5a1)
- skeletal debris, intraclasts, gastropods, peloids, crinoids (a), foraminifers (b)

Interpretation
- moderate to high energy
- storm sheets above SWB
- 5a1 distal storm sheets, 5a2 proximal storm sheets
  → dependant on the biotic assemblage and facies stacking pattern either fore- or backshoal
Poorly sorted pack-to grainstone with
Sub-Type A: mainly peloids (LFT 5c1) and
Sub-Type B: mainly bioclasts (LFT 5c2)
Sub-Type A (LFT 5c1) mainly consists of peloids or cortoids and can be interpreted as a moderate to high-energy deposit, adjacent to shoals (Figure 10). It can be found, depending on the biotic assemblage as well as on the facies stacking pattern, in a moderate-energy backshoal (LFA 4B) association, or in a foreshoal setting (LFA 6). Commonly microbial binding and lumping of grains can be observed in thin sections, hinting towards the moderate-energy backshoal environment due to common microbial stabilization in low- to moderate energy conditions. LFT 5c1 indicates a shallow subtidal to intertidal setting.

Sub-Type B (LFT 5c2) reflects a deeper subtidal environment (Figure 11). Depending on the biotic assemblage, as well as on the facies stacking pattern, it can be assigned either to the backshoal (LFA 4) or the foreshoal environment (LFA 6). In this study, LFA 4 backshoal is split into a low-energy (LFA 4A) and a moderate-energy backshoal environment (LFA 4B), depending on the texture (Figure 4): packstones fall into low-energy setting (LFA 4A), and pack- to grainstones and grainstones in a moderate-energy backshoal setting (LFA 4B). A great variety of skeletal fragments can be observed in LFT 5c2. The backshoal representative of Sub-Type B can mainly be identified by the lack of typical open-marine fauna (corals, echinoderms, allatoconchid bivalves), and the dominance of gastropods, salinity-tolerant foraminifers (e.g. *Shanita amosi*), as well as typical microscopic features such as lumping, encrusting and the common appearance of pellets.

Well-sorted grainstone with
Sub-Type A: mainly peloids (LFT 5d2) and
Sub-Type B: mainly ooids (LFT 5d1)
The well-sorted grainstone types were deposited on a proximal to fully developed shoal or bar complex (LFA 5). Lithofacies Type 5d2 of Sub-Type A is composed mostly of peloids and shows good sorting (Figure 12), ooids, coated grains and less frequently intraclasts. Sub-Type B (LFT 5d1) mainly
**Figure 10: Peloidal pack- to grainstone (LFT 5c1).**

**Description**
- pack- or pack- to grainstone
- mainly composed of peloids
- beige to dark grey outcrop color (1)
- normal grading, erosive bases
- bioturbation and burrowing (a) features
- microbial binding, lumping
- brachiopods, foraminifers (b), bivalves, gastropods, cortoids, coral debris, crinoids, echinoderms, algae (c)

**Interpretation**
- moderate to high energy
- shallow subtidal to intertidal, shoal adjacent
- restricted to high salinity
- dependant on the biotic assemblage and facies stacking pattern: either moderate energy back shoal (2 and 3) or foreshoal

**Figure 11: Bioclastic pack- to grainstone (LFT 5c2).**

**Description**
- pack-, pack- to grain-, grainstone
- mainly composed of bioclasts
- bluish to dark grey outcrop color
- normal grading, erosive bases, low-angle lamination, lumping
- sparse bioturbation and burrowing features
- very poor to moderate sorting (1)
- brachiopods, foraminifers (a), bivalves, gastropods, cortoids, coral debris, crinoids (b), echinoderms, peloids, algae (c)

**Interpretation**
- moderate to high energy
- deeper subtidal
- variable sedimentation rates
- normal marine circulation
- dependant on the biotic assemblage and facies stacking pattern: either back shoal (2) or foreshoal (3)
Description
- grainstones, mainly composed of peloids
- rarely planar and trough cross-bedding
- erosive bases commonly observed with clasts
- rarely showing bioturbated tops, microbial activity, lumping (a)
- well sorted
- rare biotic occurrence and low diversity: algae, foraminifers (b), ooids, cortoids (c), oncoids (d), intraclasts

Interpretation
- high energy
- shallow subtidal
- constant wave agitation, reworking
- high energy shoal or bar complex

Figure 12: Peloidal grainstone (LFT 5d2).

This consists of ooids and subordinate abiotic components (Figure 13). Both facies types commonly show cross-bedding. Their thickness (dm scale) and beige color help with their identification in the field. In most cases a clear differentiation between 5d2 and 5d1 can only be made under the microscope.

**Skeletal floatstone (LFT 5f)**

The skeletal floatstone (LFT 5f, Figure 14) is very common in the lower part of KS5 (up to the overall maximum flooding of KS5), representing exclusively offshoal environments (LFA 7). The main components of the floatstone are either corals or allatoconchid bivalves. The *Allatoconchidae* are a giant bivalve group from the Permian, representing the largest (in size) bivalve group in the Paleozoic (e.g. Aljinovic et al., 2008; Isozaki and Aljinovic, 2009). They are described from only nine areas (Afghanistan, Croatia, Iran, Japan, Malaysia, Oman, Philippines, Thailand and Tunisia; Isozaki and Aljinovic, 2009). The so-far described specimens from Oman (Saïh Hata area) were interpreted as Wordian (Weidlich and Bernecker, 2007). This study shows that the Permian giant bivalve group also extended into the Capitanian in Oman.

The typical coexistence of *Allatoconchidae*, large-tested fusulinid foraminifers (e.g. *Neoschwagerina*) and rugose corals is commonly described as the “tropical trio” (Aljinovic et al., 2008; Isozaki and Aljinovic, 2009). They flourished during the Permian, covering the shallow and warm waters of the Tethyan and Panthalassan oceans. The “tropical trio” did not survive the end-Guadalupian mass extinction at the end of the Capitanian Stage, suggesting that they did not only share the common habitat but also had a common cause of extinction. Possibly they shared common photosymbionts (algae and cyanobacteria), which did not survive a tropical cooling event (“Kamura cooling event”; Isozaki and Aljinovic, 2009). In the investigated outcrops the largest identified allatoconchid bivalve reached a length of about 40 cm.
### Khuff Sequence KS5, Al Jabal al-Akhdar, Oman

**Description**
- grainstones, mainly composed of ooids
- planar (a) and trough cross-bedding
- erosive bases
- rarely followed by microbial cap
- well sorted
- occasional lumping of several ooids (b)
- rare biotic occurrence and low diversity; peloids, coated grains

**Interpretation**
- high energy
- shallow subtidal
- constant wave agitation
  → high energy shoal or bar complex

---

**Figure 13: Oolitic grainstone (LFT 5d1).**

**Description**
- floatstone, packstone, rarely coral boundstone
- grey to dark grey outcrop color
- poor sorting
- main components: corals (coral heads (1)) or *Allatoconchidae* bivalves (2); other skeletal material; foraminifers, bivalves, echinoderms, brachiopods
- huge biotic diversity

**Interpretation**
- subtidal
- open marine
- "level-bottom community"
  → offshoal environment

---

**Figure 14: Skeletal floatstone (LFT 5f).**
Facies Associations and Depositional Model

The Khuff deposits developed on an epeiric carbonate ramp, resulting in extensive facies belts, each characterized by specific lithofacies associations (LFA, Figure 15). These associations were used as input parameters for 3-D facies modeling. In total six associations are identified in Khuff Sequence KS5 (Figure 4): (1) tidal flat (LFA 3); (2) low-energy backshoal (LFA 4A); (3) moderate-energy backshoal (LFA 4B); (4) high-energy shoal (LFA 5); (5) moderate-energy foreshoal (LFA 6); and (6) low-energy offshoal (LFA 7). Extending the Khuff facies associations of Koehrer et al. (2010) an additional moderate-energy backshoal environment was introduced (Figure 16) for Khuff sequence KS5. This facies type is also represented in the Jilh and Sudair equivalent formations in the Oman Mountains (Obermaier et al., 2012) and was also used by Haase and Aigner (2013) for their high-resolution sedimentological investigation of the lower part of Khuff Sequence KS4. It is comprised of deposits mainly associated with the leeward side of the shoal complex with frequent storm washovers and sediment winnowing. Cortoidal/peloidal pack- to grainstones with abundant microbial precipitation are indicative microfacies in this environment.

Foreshoal versus Backshoal Indicators

Since several facies types can be present either in the backshoal side as well as in the foreshoal environment (e.g. bioclastic-rich pack-grainstone, LFT 5c2), explicit skeletal indicators were used to clearly identify the lithofacies associations (c.f. Koehrer et al., 2012, Forke et al., 2012). Based on thin section data, documentation of characteristic skeletal and non-skeletal (Figure 17) particles was found to be useful to distinguish foreshoal from backshoal deposits.

Amongst the non-skeletal particles, microbial lamination is a common feature indicating tidal flat environments or in places a shoal-related algal cap. In general it represents a low-energy environment or respectively a short-term rise of a shoal complex. Often associated with tidal flat and backshoal settings are fenestral fabrics as well as geopetal fabrics and micritic envelopes (cortoids). Although pellets can be seen in a wider range of depositional settings, their main occurrence focuses around a

Figure 15: Three-dimensional schematic facies model for the Khuff platform (modified from Koehrer et al., 2010). The lithofacies associations range in Sequence KS5 is from offshoal to tidal flat. Sabkha and marsh deposits were not identified in the outcrop sections.
low-moderate energy backshoal-related setting. Oncoidal structures are in contrast fairly distinctive for lower-energy backshoal related settings. Ooids and peloids are the most distinctive features for the high-energy shoal environments. So-called ghost structures of leached fossils (mainly of large benthic foraminifers) are indicative for a foreshoal setting.

1-D SEQUENCE-STRATIGRAPHIC ANALYSIS

The 1-D sequence-stratigraphic analysis of the outcrop sections forms the basis for the 2-D correlations as well as for the final 3-D facies model. Based on prominent bounding surfaces as well as on vertical facies trends, a hierarchy of stratigraphic cycles was identified in the outcrops. The adopted sequence-stratigraphic terminology is based on Kerans and Tinker (1997).
Table 1: Micro Particle Indicators

<table>
<thead>
<tr>
<th>Environment</th>
<th>Tidal flat</th>
<th>Low-energy backshoal</th>
<th>Mod-energy backshoal</th>
<th>Shoal</th>
<th>Foreshoal</th>
<th>Offshoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Particles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lamination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenestral fabrics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geopetal structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micritic envelopes (cortoids)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumping of grains, microbial over-growth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oncoids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ooids, peloids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leached fossils (mostly LBF); Ghost structures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 17: Typical non-skeletal foreshoal and backshoal indicators in Khuff Sequence KS5. LBF = large benthic foraminifera. Line spacing wide = less frequent appearance and narrow line spacing = high frequency.
The smallest logged scale is referred to as “small-scale cycles”, representing the deposits of a single base-level cycle. “Medium-scale cycle sets” are interpreted to result from the stacking of genetically related cycles that show a consistent trend (progradational, aggradational or retrogradational). An average of four small-scale cycles builds a medium-scale cycle set. Four “high-frequency sequences” (HFS) were identified in Khuff Sequence KS5. These are based on a very characteristic gamma-ray pattern (especially in upper KS5), showing a bulge shape, as well as on facies trends. They are also represented by genetically related cycle sets that show a consistent deepening trend followed by a shallowing trend. The entire Khuff Sequence KS5 represents one “composite sequence”.

A maximum of 66 small-scale cycles, stacked into 21 medium-scale cycle sets, were logged in Wadi Hedek (272 m vertical section), which represents the thickest overall outcrop section of KS5 in the studied area.

Cycles

The small cycles show an average thickness of five meters. They represent the smallest scale of stratigraphic cyclicity and were continuously interpreted through all the outcrop sections. According to Koehrer et al. (2010) the facies stacking pattern of small-scale cycles allow the identification of several cycle motifs. Koehrer et al. (2010) identified four general cycle motifs, which can all be recognized in KS5: (1) foreshoal cycle motif; (2) shoal-margin cycle motif; (3) shoal cycle motif with subtype shoal cycle motif with microbial cap; and (4) shoal-to-backshoal cycle motif. In this study an additional cycle motif (shoal-margin-to-backshoal motif) is interpreted in KS5 (Figure 16) which was also identified in outcrop studies in Oman corresponding to the lower Khuff Sequence KS4 (Haase and Aigner, 2013) and the Jilh and Sudair formations (Obermaier et al., 2012).

Cycle Sets

An average of four small-scale cycles form a medium-scale cycle set (Koehrer et al., 2010, 2012). These cycle sets vary in thickness from 6 to 20 m. Cycle sets are the first scale of hierarchy that can be recognized in the gamma-ray pattern by showing identifiable trends (cleaning, dirtying, etc.; Note: it was not possible to identify the impact of the dolomitization on the GR values). These trends were used to identify the medium-scale cycle sets in combination with the vertical facies succession. Noteworthy is the change in the gamma-ray pattern over the entire Khuff Sequence KS5 (Figure 18).

In the lower part of KS5, gamma-ray readings are highest during maximum flooding intervals of cycle sets (Figure 18) due to overall high percentage of muddy foreshoal and offshoal facies types. This pattern is reversed upwards in the overall regressive part of KS5, where the maximum gamma-ray signal reflects mud-dominated tidal flat deposits representing sequence boundaries. This reverse signature results from the overall shift of lithofacies associations from a foreshoal setting in the lower part of KS5 to a restricted backshoal setting in the upper part. It illustrates how peak-to-peak correlation solely based on GR values and irrespective of facies information can be highly misleading. The overall highest GR values were measured in tidal flat deposits represented by microbial laminites (see also Koehrer et al., 2010).

High-frequency Sequences (HFS)

KS5 unraveled an additional order of cyclicity. It is referred to as high-frequency sequences (HFS) (Mitchum and Van Wagoner, 1991; Kerans and Tinker, 1997). The HFS can be best identified from gamma-ray patterns that show a typical bulge shape (cleaning trend followed by dirtying trend; Figure 19). They probably represent base-level cycles on a larger scale fitting in-between the medium-scale cycle sets and the entire Khuff Sequence KS5, which is considered as a third-order composite sequence (Koehrer et al., 2010).

Four HFSs were identified in KS5, named HFS4 to HFS1 from bottom to top. Since the HFSs are mainly identifiable from gamma-ray patterns they are most easily recognized where the GR pattern clearly differs between backshoal and foreshoal deposits. This is the case in the overall regressive part
Sequence boundaries reflecting GR peaks
MFS reflecting GR lows
Sequence boundaries reflecting GR lows
MFS reflecting GR peaks

Switch in GR pattern

Figure 18: Demonstration of the switch in GR pattern over the KS5 in Wadi Mistal. See Figure 4 for LFA color coding.

Figure 19: Logged KS5 section in Wadi Mistal showing the four high-frequency sequences (HFS), mainly based on the GR pattern and overall vertical facies associations successions. See Figure 4 for LFA color coding.
of the KS5, where high GR values represent tidal flat or low-energy backshoal environments (sequence boundaries) and low GR values foreshoal environments (maximum floodings). In the transgressive part, the HFSs are mainly highlighted due to the overall vertical trends in depositional environments. The four HFSs can also be recognized in the subsurface (Figure 20), where the GR bulge-shaped pattern is even more prominent (example from the Yibal Field). The more prominent pattern in subsurface is probably due to the more proximal depositional setting compared to the outcrop sections (Figure 1). The recognition of HFSs can therefore contribute to a more robust correlation strategy with the subsurface (Figure 20).

![Subsurface correlation displayed in the exploded sections version](https://pubs.geoscienceworld.org/geoarabia/article-pdf/18/4/179/4569185/walz.pdf)

Figure 20: Subsurface correlation displayed in the exploded sections version (each high-frequency sequence is seen as an individual sequence with a separate flattening surface; in the transgressive HFSs the maximum flooding surfaces are used as flattening surfaces; in the regressive part the sequence boundaries are used as flattening surfaces). The Yibal GR logs were provided by Petroleum Development Oman.
High-frequency Sequence HFS4
The base of the lowermost HFS4 is marked by the “Microbial Marker 1” (Koehrer et al., 2010; Bendias et al., 2013) formed by a thick bed of microbial mats interpreted as upper sequence boundary of Sequence KS6. Compared to the top of the KS5, the base is less prominent and makes a clear identification in the field more difficult.

During the early transgression of HFS4 backshoal-related facies dominate (Figure 21). The first occurrence of foreshoal or even offshoal-related facies is not synchronous throughout the different sections. This may be due to the different positions in the paleogeography or to differential subsidence. There appears to be a relationship to paleohigh structures, which can be observed in the underlying KS6 (Bendias et al., 2013) and might continue to be present through these portions of the stratigraphy. The GR readings of this interval are generally low, showing serrated patterns with subtle trends and little similarity in the different sections. A typical pattern in the transgressive hemisequence is the occurrence of foreshoal facies represented by skeletal floatstones. These consist of large Allatoconchidae bivalves, vertically followed by coral-rich beds, which are interpreted as the maximum flooding interval of HFS4 (Figure 21).

The regressive hemisequence in the more distal sections (Wadi Hedek, Wadi Mistal and Saiq Plateau) shows a high proportion of offshoal and foreshoal-related deposits (Figures 22 and 23). In these sections shoal facies represent the top sequence boundary of HFS4. However, in wadis Sahtan and Bani Awf, the regressive hemisequence of HFS4 is clearly dominated by shoal facies. Here, muddy backshoal deposits represent the sequence boundary. In these sections, a clear dirtying in the GR pattern can be observed towards the sequence boundary.

High-frequency Sequence HFS3
The transgressive part of HFS3 culminates in the overall maximum flooding interval of KS5, dominated by bioclastic-rich foreshoal packstones. The maximum flooding in Wadi Hedek and on the Saiq Plateau is represented by the “Chert Marker” (Koehrer et al., 2010) (Figure 24). In the other sections, the maximum flooding interval is marked by the thickest coral floatstone bed.

In wadis Mistal and Sahtan which represent the most proximal sections, thick shoal deposits are visible in the regressive hemisequence (Figure 22). Muddy backshoal or tidal-flat deposits mark the sequence boundaries. Wadi Mistal shows the clearest dirtying trend in the GR towards the sequence boundary due to facies changes towards proximal muddy backshoal and tidal flat-associated textures.

In the distal sections (Wadi Hedek, Wadi Bani Awf and the Saiq Plateau) higher proportions of foreshoal deposits occur in the regressive hemisequence (Figures 22 and 23). Here, shoal facies represent the sequence boundary. HFS3 is the thinnest HFS, which is probably due to a low carbonate production rate in a foreshoal-dominated environment. This observation supports the placement of the overall KS5 maximum flooding in this interval.

High-frequency Sequence HFS2
HFS2 is the first high-frequency sequence within the overall regression of KS5 (Figure 23). The first occurrence of the miliolid foraminifer Shanita amosi (mostly in HFS2) throughout all sections points to more restricted conditions in a backshoal environment. In Wadi Sahtan, HFS2 and HFS1 are not exposed due to heavy faulting in the outcrops (Figure 22).

In the proximal sections (wadis Mistal and Bani Awf) the transgressive hemisequence is dominated by shoal to backshoal facies, whereas the distal Wadi Hedek and Saiq Plateau sections show foreshoal to offshoal facies (Figures 22 and 23). The maximum flooding interval is represented by foreshoal (Wadi Bani Awf) to offshoal (Saiq Plateau, wadis Mistal and Hedek) deposits in all four sections, which are accompanied by low GR readings.

The regressive hemisequence shows a transition to backshoal-related deposits in wadis Mistal, Hedek and Bani Awf (Figure 22). The Saiq Plateau section shows the highest percentage of foreshoal facies throughout the regressive hemisequence and therefore represents a most distal setting. The upper
Skeletal floatstones composed of coral heads

Thin section, showing an Allatoconchidae bivalve

Skeletal floatstones composed of Allatoconchidae bivalves

Figure 21: Vertical facies succession for the HFS in Wadi Mistal. The offshoal environments are dominated by Allatoconchidae and coral floatstones.
Figure 22: West-east correlation based on the four high-frequency sequences (HFS). The display technique of exploded sections is used to better illustrate the variations in the individual HFSs. HFS3 & 4 were flattened on the MFS as they represent the transgressive phase of KS5. HFS2 & 1 were flattened on the respective SB.
Figure 23: North-south correlation based on the four high-frequency sequences. The display technique of exploded sections is used to better illustrate the variations in the individual HFSs. HFS3 & 4 were flattened on the MFS as they represent the transgressive phase of KS5. HFS2 & 1 were flattened on the respective SB.
sequence boundary is marked by microbial laminites deposited in a tidal flat environment. This major facies shift in all sections is clearly represented by an increasing gamma-ray pattern (Figure 18).

**High-frequency Sequence HFS1**

The transgressive part of the uppermost HFS1 in wadis Bani Awf and Mistal is represented by shoal to backshoal facies (Figure 25). In contrast, in Wadi Hedek and on the Saiq Plateau it consists of mainly foreshoal deposits (Figure 23). The maximum flooding interval (MFI) is composed of shoal facies in Bani Awf whereas in Wadi Mistal a thin foreshoal interval develops. The sections in Wadi Hedek and the Saiq Plateau show offshoal coral floatstones at the MFI. During the regressive hemisequence all sections quickly shift to a backshoal environment (Figure 22 and 23). The uppermost HFS1 is represented by a distinctive gamma-ray pattern (bulge-shaped) in all sections.

**Composite Sequence**

The entire Khuff Sequence KS5 is interpreted as one composite sequence (see also Koehrer et al., 2010). Not all wadi sections expose the entire Khuff Sequence KS5. Wadi Sahtan shows heavy faulting and therefore only the lower part of KS5 is present. In Wadi Bani Awf, the transition from KS6 to KS5 and the maximum flooding interval are not exposed. The section in Wadi Mistal is also incomplete around the maximum flooding interval. The sections in Wadi Hedek and on the Saiq Plateau exhibit the complete KS5 (for Saiq Plateau see also Koehrer et al., 2010 and Al-Husseini and Koehrer, 2013).

Khuff Sequence KS5 shows noticeable lateral thickness variations (Figures 26 and 27). The thinnest complete section is 214 m thick and occurs in the southernmost Saiq Plateau section; the thickest complete section in Wadi Hedek is 272 m thick. Thus a thickness difference of 58 m can be observed on a scale of ca. 38 km. Additionally lateral facies variations are very common throughout the entire KS5 (Figures 22, 23, 26 and 27).

The early transgressive phase of KS5 is dominated by shoal-margin to backshoal cycles and shoal-to-backshoal cycles (Figures 26 and 27). Towards the maximum flooding interval, these cycle types are replaced by foreshoal cycles as well as shoal-margin cycles. In the proximal sections to the west (wadis Sahtan and Bani Awf), the change from the early transgressive phase towards the maximum flooding interval is less prominent. There, the shoal cycle motif is the most dominant cycle motif.

In the proximal sections (wadis Bani Awf, Sahtan and Mistal) the regressive hemisequence of KS5 is dominated by shoal to backshoal, shoal-margin to backshoal as well as shoal-cycle motifs (Figure 26). However, the distal sections to the east and south (Wadi Hedek and Saiq Plateau) show a much higher percentage of foreshoal cycles as well as shoal-margin cycles even in the regressive hemisequence. Only during the late regressive phase, all wadi sections show a similar paleogeographic setting, reflected by shoal to backshoal cycles and shoal-margin to backshoal cycles.

**2-D CORRELATIONS**

Two different correlation strategies were applied in Khuff Sequence KS5.

(a) Correlation of cycle sets (Figures 26 and 27): This correlation strategy does not account for the high-frequency sequences. Only the top and base of KS5 as well as the overall MFS are considered as correlation timelines. This correlation technique allows more flexibility for the correlation of the medium-scale cycle sets.

(b) Correlation of high-frequency sequences and cycle sets (Figures 22 and 23): This second correlation strategy uses the four high-frequency sequences (HFS) as a given framework within which the medium-scale cycle sets were correlated. The correlations are based on an integrated interpretation of gamma-ray patterns as well as on the textural and lithological data from the outcrop sections.
Figure 24: Vertical facies succession for the HFS3 in Wadi Hedek. This HFS includes the overall maximum flooding of the KS5. Chert marker in Wadi Hedek. Maximum flooding surface of the entire KS5.  Cyclic packstones representing foreshoal deposits.
Zebra-stripe top in Wadi Mistal: intercalations of thick whitish microbial laminites and dark thinly bedded bioclastic-rich packstones.

First occurrence of the miliolid foraminifer *Shanita Amosi*, indicating restricted conditions in a backshoal environment.

Figure 25: Regressive part (HFS2 and HFS1) of Khuff Sequence KS5 in Wadi Mistal.
Correlation of Cycle Sets

The base and top of KS5 as well as the overall MFS are considered as timelines between which the cycle sets were correlated. The west-east correlation includes wadis Sahtan, Bani Awf, Mistal and Hedek (Figure 26). Another correlation on a north-south transect includes wadis Hedek, Mistal and the Saiq Plateau section (Figure 27). The overall maximum flooding is used as datum.

West-East Correlation

The west-east correlation (Figure 26) displays thickness variations as well as lateral facies changes. A discontinuous cycle set above the MFS results in an apparent downlap. The lateral changes can be explained by proximal-distal trends as well as differential subsidence.

In the transgressive phase a deepening trend from west to east can be observed (Figure 26). Remarkable is the down-dipping of all correlation lines from Wadi Mistal towards Wadi Bani Awf and Wadi Hedek (dip angles of about 0.01º) (for comparison: present-day Arabian Gulf shows an inclination of 0.03º). These depositional geometries are due to the reduced sediment thickness in Wadi Mistal. According to Bendias et al. (2013) Wadi Mistal represents a paleohigh in KS6 associated with limited accommodation space. This paleotectonic position might still have persisted in the initial transgressive phase of KS5.

Due to the high amount of shoal facies in the late transgressive phase in Wadi Sahtan, the correlation lines show down-dipping towards Wadi Bani Awf (dip angles of about 0.02º). This observation highlights a transition from a high carbonate production in a shoal position towards lower sedimentation rates in a more foreshoal dominated setting.

The early regressive phase is dominated by shoal deposits in wadis Mistal and Sahtan, whereas wadis Hedek and Bani Awf remain in overall foreshoal settings (Figure 26). Based on the more distal settings of wadis Bani Awf and Hedek, the first cycle set above the MFS is not reflected in the sediment record. As a result an apparent downlap onto the maximum flooding (dip angles of about 0.02º towards wadis Hedek and Bani Awf) is visible. In the late regressive phase, Wadi Hedek remains in a foreshoal setting compared to the other sections (wadis Mistal and Bani Awf), which are dominated by shoal to backshoal facies. This observation can be interpreted as a deepening trend from west to east.

Compared to the other sections, the Wadi Mistal section is thickest in the regressive phase due to higher subsidence. As a result, the correlation lines down-dip towards the Wadi Hedek (dip angles of about 0.007º) and Wadi Bani Awf (dip angles of about 0.02º) sections.

North-South Correlation

In the north-south correlation (Figure 27), facies changes can be seen alongside with thickness variations. The interval above the MFS shows a discontinuous cycle set which results in an apparent downlap onto the surface.

The Saiq Plateau section comprises a more distal facies pattern in the early transgressive phase than in the other wadi sections (Figure 27). This suggests a deepening trend in the early rise phase towards the south (Saiq Plateau). The late transgressive phase is dominated by foreshoal to offshoal facies in all three sections showing fairly consistent depositional conditions. The correlation lines show down-dipping geometries from Wadi Mistal towards Wadi Hedek and the Saiq Plateau (dip angles of about 0.01º) highlighting a deepening towards Wadi Hedek and the Saiq Plateau section. A possible paleohigh around Wadi Mistal with reduced accommodation space could explain these depositional geometries.

The early regressive interval remains dominated by foreshoal facies in Wadi Hedek and on the Saiq Plateau (Figure 27). In Wadi Mistal however, shoal-related facies represent the highest percentage. A deepening trend towards the northeast (Wadi Hedek) and to the south (Saiq Plateau) can be interpreted. Upsection, the late regressive phase becomes increasingly dominated by backshoal facies in Wadi Mistal. In Wadi Hedek the shallowing trend is less prominent. The Saiq Plateau still contains
Figure 26: West-east correlation without consideration of the high-frequency sequences.
Figure 27: North-south correlation without consideration of the high-frequency sequences.
the highest amount of foreshoal facies, representing the most distal section. The uppermost cycle sets are dominated by shoal to tidal flat deposits in all sections, illustrating a major sequence boundary. Based on the high sediment accumulation in the shoal setting in Wadi Mistal, the correlation lines show down-dipping geometries from Wadi Mistal to Wadi Hedek and the Saiq Plateau (dip angles of about 0.01°).

**Correlation of High-frequency Sequences and Cycle Sets**

Using the four previously discussed high-frequency sequences as a framework, the five outcrop sections were correlated on the cycle set scale (Figures 22 and 23). The technique of “exploded sections” was used for the correlations so that thickness variations and changing geometries of individual HFSs could be better visualized. The exploded sections permit using different datum horizons for the HFSs. Since HFS4 and HFS3 are part of the overall transgressive hemisequence of KS5, their MFSs are considered the best candidates for regional timelines in a uniform and sustained depositional environment. For the regressive hemisequence HFS2 and HFS1, their upper sequence boundaries were used as datums.

**West-East Correlation**

The W-E transect is about 61 km long and the correlation shows variations in thickness, lateral facies and sequence geometries (Figure 22). The lateral changes may have been caused by a proximal-distal trend and by differential subsidence. The correlation shows lateral cycle set discontinuities in HFS4 and HFS3, apparent downlaps onto the MFSs of HFS4 and HFS3, and an apparent onlap onto the base of KS5 (SB KS5).

In wadis Sahtan and Bani Awf **High-frequency Sequence HFS4** shows a regression-dominated trend in its lowermost part. In wadis Mistal and Hedek it is dominated by transgressive hemisequences (Figure 22). Thus, the proximal shoal-to-backshoal sections show typical shallowing upward sequences (fall-dominated), whereas the sections in a distal foreshoal-to-offshoal setting are marked by rise-dominated sequences. With the MFS as datum, the correlation lines have an eastwards dip, following the paleo-deepening trend towards the east (dip angles from 0.02° to 0.03°).

In the transgressive hemisequence an additional cycle set is observed in Wadi Hedek (dip angle of 0.05°). Higher carbonate production rates in a shoal setting may be the reason for this additional cycle set. In the regressive hemisequence however, the number of cycle sets decreases from west to east (3.5 in wadis Sahtan and Bani Awf; 2.5 in Wadi Mistal; and 1.5 in Wadi Hedek). This cycle set reduction is accompanied by facies association changes from a shoal to an offshoal setting (Figure 28). Due to the distal setting of wadis Mistal and Hedek with limited sedimentation rates, not every sea-level fluctuation may necessarily be reflected in the sedimentary record.

**High-frequency Sequence HFS3** is regression-dominated in wadis Sahtan and Mistal (Figure 22), and symmetrical in wadis Hedek and Bani Awf. It is similar to HFS4, with the proximal sections (wadis Sahtan and Mistal) being fall-dominated. In HFS3 wadis Sahtan and Mistal represent local shoals from which the correlation lines dip towards Wadi Hedek (east) and Wadi Bani Awf, which are in a mostly foreshoal to offshoal setting. The shoal developments are accompanied by increased cycle set numbers in the regressive part (2.5 in wadis Sahtan and Mistal; 1.5 in wadis Hedek and Bani Awf). The additional cycle sets apparently downlap from wadis Sahtan and Mistal to wadis Hedek and Bani Awf (dip angles of 0.02°).

**High-frequency Sequence HFS2** occurs in the regressive part of KS5, and shows fall-dominated sequences in all sections with high proportions of backshoal facies (Figure 22). The upper sequence boundary is used as a datum and leads to down-dipping geometries of the correlation lines from Wadi Hedek (dip angles of 0.03°) and Wadi Bani Awf (dip angles of 0.03°) towards Wadi Mistal. HFS2 is not accessible in Wadi Sahtan. Wadi Mistal has the thickest deposits in HFS2 due to its shoal setting with a higher carbonate production rate. The number of cycle sets is constant in all logged sections.
Figure 28: Facies association changes in the regressive part of the high-frequency Sequence HFS4.
High-frequency Sequence HFS1 occurs in the proximal wadis Bani Awf and Mistal and is fall-dominated (Figure 22). In Wadi Hedek, which is in a more distal setting, HFS1 appears symmetrical. When flattened on the top of KS5 (SB KS4), the correlation lines dip from Wadi Bani Awf (dip angles of 0.01°) and Wadi Mistal (dip angles of 0.02°) towards the east, reflecting a paleo-deepening trend to Wadi Hedek (HFS1 is missing in Wadi Sahtan). The number of cycle sets remains constant on this scale of ca. 60 km. In this HFS, Wadi Hedek revealed the thickest sediment column, probably due to larger accommodation space in a shoal to foreshoal setting.

North-South Correlation
The north-south correlation (Figure 23) based on high-frequency sequences shows, similar to the west-east correlation (Figure 22), thickness variations as well as facies changes (described in the following) and different sequence symmetries. The correlation depicts cycle set discontinuities, and apparent downlaps, in HFS4, HFS3 and HFS2.

High-frequency Sequence HFS4 is transgression-dominated in wadis Hedek and Mistal, and symmetrical in the Saiq Plateau sequence (Figure 23). Since all sections are interpreted in a more distal setting on the Khuff carbonate ramp, the changing cycle symmetry may be interpreted to be caused by differential subsidence. This HFS is flattened on the MFS, resulting in a dip of the correlation lines towards the north (Wadi Hedek) (dip angle of 0.02°).

As observed in the west-east correlation, Wadi Hedek shows an additional cycle set (dip angle of 0.05°) in the transgressive phase, which is probably caused by higher subsidence and increased carbonate production. In the regressive phase, the number of cycle sets is condensed from the Saiq Plateau and Wadi Mistal to Wadi Hedek in the north (2.5 on the Saiq Plateau and Wadi Mistal; 1.5 in Wadi Hedek). Higher subsidence at the Saiq Plateau may have led to a thicker sediment column and therefore higher resolution of the cycle sets.

High-frequency Sequence HFS3 is fall-dominated on the Saiq Plateau and in Wadi Mistal (Figure 23). The fall dominance in Wadi Mistal can be explained (as in the west-east correlation) by its shoal related setting. The Saiq Plateau section consists mainly of foreshoal facies and shows rise-dominance, which might be due to a higher subsidence rate. Wadi Hedek shows a symmetrical sequence. Due to the MFS being used as datum, the correlation lines show dip towards the north (Wadi Hedek) (dip angles of about 0.02°). Similar to HFS4, we observe a reduction of cycle sets in the regressive part of HFS3 from the Saiq Plateau and Wadi Mistal towards Wadi Hedek in the north (2.5 on the Saiq Plateau and Wadi Mistal; 1.5 in Wadi Hedek) (dip angle of 0.02°). Since the Saiq Plateau section ends with backshoal deposits and therefore represents a cycle with completely filled accommodation space, no additional subsidence is needed to explain the increased sediment thickness compared to the more distal Wadi Hedek section where the accommodation space is not completely filled.

High-frequency Sequence HFS2 is dominated by the regressive phase in wadis Mistal and Hedek, whereas the Saiq Plateau section shows a dominance of the transgressive phase (Figure 23). Wadis Mistal and Hedek mainly revealed backshoal facies, representing a proximal setting. The Saiq Plateau section is continuously in a distal foreshoal setting showing a rise-dominated sequence. Using the top sequence boundary as datum, the correlation lines dip towards Wadi Mistal, which represents the thickest section (81 m) in this HFS (dip angles of about 0.03°). The regressive phase shows a cycle set reduction from wadis Hedek and Mistal towards the Saiq Plateau (3.5 in wadis Hedek and Mistal; 2.5 on the Saiq Plateau) (downlapping angle of about 0.03° towards the Saiq Plateau section). Due to the more distal position of the Saiq Plateau accompanied by reduced sedimentation rates, not every sea-level cycle is necessarily reflected in the sediment record.

High-frequency Sequence HFS1 is the uppermost HFS and shows a dominantly regressive phase in Wadi Mistal (Figure 23). In Wadi Hedek and the Saiq Plateau the sections are symmetrical. In all sections backshoal-related facies represent the highest percentage. The upper sequence boundary SB KS4 (top KS5) is used as datum resulting in a dip of the correlation lines towards Wadi Hedek, the thickest sequence in the north (dip angles of about 0.02°). Wadi Hedek is located in the most distal position with the highest available accommodation space, which is completely filled up to the top of KS5. The interpreted cycle sets show constant numbers (4 cycle sets) in this HFS. This observation...
underlines SB KS4 as a major sequence boundary where all the accommodation space is uniformly filled up. At this boundary the paleorelief is at a minimum and the cycles are laterally persistent over the entire study area (60 x 40 km).

**DISCUSSION OF STRATIGRAPHIC ARCHITECTURE**

Independent of the correlation strategy, facies association changes are visible in all correlations (Figures 22, 23, 26 and 27). The correlation based on high-frequency sequences shows more complex depositional geometries and more lateral cycle set discontinuities due to the limited flexibility in cycle set correlations. Both correlation strategies show that Khuff Sequence KS5 displays significant deviations from a “layer-cake”-type stratigraphic geometry as indicated below.

**Lateral Thickness Changes:** The transgressive part of KS5 shows the highest variability around Wadi Mistal where the stratigraphic section is thinnest (74 m). The proposed paleohigh (Bendasia et al., 2013) is still visible in the lower part of KS5. The regressive part of KS5 shows the thickest succession in Wadi Mistal (178 m). In this case it is linked to its highly productive shoal position and probably an increased subsidence rate.

**Lateral Facies Association Changes:** Lateral facies association changes cannot be neglected regardless of the correlation technique. An overall trend of deepening deposits towards the Saiq Plateau and Wadi Hedek can be recognized. Nevertheless, there is no clear proximal-distal trend throughout KS5, but rather a highly dynamic (e.g. differential subsidence) and localized (e.g. paleohigh around Mistal during the transgressive phase) differentiation, which must be treated on an individual basis. The high-frequency sequences were considered as helpful to break down these more dynamic changes.

**Cycle and Strata Geometries:** Correlation scenarios of cycles, cycle sets and high-frequency sequences result in complex lateral cycle patterns, no matter what correlation strategy was applied. Clearly there are lateral facies and thickness changes of single cycles and cycle sets, cycle pinch-outs and apparent cycle set downlaps. These represent subtle stratal geometries, in contrast to a “layer-cake” stratigraphic architecture. These more complex depositional patterns probably resulted from differential subsidence due to active rifting of the Neo-Tethys in Mid-Permian time (Searle, 2007).

**Differential Subsidence Patterns**

To better delineate the influence of differential subsidence, maps were created for each HFS displaying the most abundant facies associations with superimposed thickness maps (Figure 29). The maps were created with Petrel and manually adjusted to match the facies percentages interpreted in the logs.

The map for HFS4 (Figure 29a) shows a local shoal development combined with decreased sediment thickness around Wadi Mistal, which supports the assumption of a paleohigh during the early stage of KS5. The expected proximal-distal trend towards the northwest can be observed from the Saiq Plateau in the south to wadis Bani Awf and Sahtan towards the north. The increased sediment thickness around wadies Sahtan and Bani Awf can most likely be explained by a higher carbonate production rate in a shoal setting and a potentially higher subsidence rate. However the Wadi Hedek KS5 section displays the thickest deposits (88.5 m) and foreshoal dominance. Keeping the additional cycle set and the transgression dominated cycle symmetry in mind, this may only be explained with an increased subsidence rate.

The HFS3 map (Figure 29b) reflects the overall MFI of KS5 with the highest percentage of foreshoal deposits and thinnest deposits of all the HFSs. The thickness variations between the sections are marginal and can be explained without increased subsidence rates. Whereas in HFS4 a paleohigh is present, HFS3 shows a deepening trend towards the south without indicators for a paleohigh.

The HFS2 map (Figure 29c) shows the beginning of the regressive phase with an increasing percentage of proximal facies. Sections in the northwest (wadis Mistal and Bani Awf) have thicker deposits and are dominated by shoal-associated sediments. Since the available accommodation space
Figure 29: Averaged facies associations with superimposed thickness maps for (a) HFS4, (b) HFS3, (c) HFS2 and (d) HFS1.
is completely filled in all sections (tidal flats represent sequence boundaries in all sections) the higher sediment thickness can only be explained by an increased subsidence. The data around Wadi Sahtan is extrapolated.

In the HFS1 map (Figure 29d) the increasing thickness towards the east is accompanied by more distal facies associations. Since the top of KS5 represents a flat datum these trends can be explained without differential subsidence. In every section (Wadi Sahtan section again is extrapolated) the top KS5 (SB KS4) is represented by tidal flat deposits, and therefore the depositional setting is filled-up. This pattern suggests more uniform subsidence patterns and the end of the active rifting phase at the end of the Mid-Permian.

3-D FACIES MODELING

The final step of this study was to generate 3-D facies models in order to evaluate depositional trends in three dimensions, as well as to visualize the continuity of potential reservoir shoal bodies. The two different correlation strategies were modeled using Petrel software.

Petrel Set Up

Using the UTM coordinates from the five outcrop sections, vertical pseudo-wells were generated. The cycle set boundaries, and in some cases MFSs, were used as correlation lines. In the case of HFS-based correlation, 22 cycle-set boundaries and the MFSs of HFS4, HFS3 and HFS2 were used. For the correlation without HFS, 21 cycle-set boundaries and the overall MFS (MFS of HFS2) were used for zonation.

The correlated pseudo-well tops (cycle-set boundaries or MFSs) were used as input data to generate the different surfaces of the model. The Petrel default algorithm “Convergent Interpolation” was applied. Since several surfaces intersected with each other (due to down-lapping and on-lapping geometries of horizons), the generated surface model had to be corrected. For example in the correlation based on HFSs, the base KS5 surface and the overlying surface intersected and had to be merged in the overlapping area. The intersection resulted from the on-lapping horizon on the base KS5 from Wadi Hedek towards the other sections.

The lateral grid increments of the model were set to 1 km in the x and y directions. The generated surfaces were used as inputs to create the grid zones. The zones were divided into layers in order to increase the vertical resolution. Each zone was analyzed, and depending on its thickness and internal vertical heterogeneity, the number of layers was determined. In total, 600 layers (25 horizons) were used. As a last step for the model preparation, the facies data from the input logs were upscaled. Imported lithofacies association data was assigned to the grid cells. The “Most of averaging” Petrel method was chosen.

Facies Modeling

The “Sequential Indicator Simulation” (SIS) Petrel algorithm was used to generate 3-D realizations run for each of the two correlation scenarios. Vertical facies proportion curves were honored and the variogram settings (horizontal and vertical ranges, azimuth and nugget) were chosen specifically for each lithofacies association and zone (e.g. shoal facies were modelled with an extent of 12 x 10 km and an azimuth of 30 displaying a NW-SE direction). Variogram ranges were inferred from the high-resolution 2-D correlations. Twelve different realizations were generated for each zone by varying the seed variable. The different correlation techniques show similar overall facies trends (Figure 30). Nevertheless, in terms of geometries, the different correlation versions show different impact on the final model. The onlapping geometries of the lowermost cycle set in the HFS-based model (Figure 30a) are not present in the model that did not consider HFSs (Figure 30b). Just as the downlapping features onto the MFSs of the respective HFS are not displayed in the model, which neglected the HFS (Figures 30 and 31).
Figure 30: Average of 12 realizations (most-of) with an additional Saiq support pseudo-well to better weigh the lateral facies association changes towards the south. The upper figure (a) shows the results based on the correlation technique with HFS, the lower image (b) is based on the correlation without HFS.

Figure 31: Different geometries of the HFS based facies model (top) and the facies model without HFS (bottom). Both facies models are based on the SIS algorithm. Important cycle boundaries (black lines) and maximum flooding surfaces (dark blue lines) are displayed. The downlapping and onlapping geometries are highlighted. In contrast to the HFS based correlation only one cycle set downlaps onto the overall maximum flooding in the correlation without HFS. The lowermost cycle set does not downlap onto the Base KS5 but thins towards the more distal sections.
Discussion of Facies Modeling

The results of the different correlation techniques show similar overall facies association patterns. The major facies trends are represented in the same manner regardless of the correlation. Major differences can be seen in depositional geometries of KS5 depending on the correlation strategy (Figure 31). The HFS-based model shows several down-lapping surfaces onto the MFSs of their respective HFSs as well as an onlapping surface of the lowermost cycle set away from Wadi Hedek (Figure 31). In contrast the model based on the correlation without HFS shows only one downlap onto the overall MFS of KS5. Also visualized is the thinning of the lowermost cycle set in contrast to the onlapping surface in the HFS-based model. These differences are most obvious in the transgressive phase of KS5. It should be noted that the models based on the correlation of only cycle sets without the HFSs also show the four deepening and shallowing trends in the facies distributions. Although the HFSs were not specifically honored in the correlation, the 3-D models show four major rise-and-fall-hemisequences represented in the facies trends (Figure 32).

The different correlation strategies slightly influence the statistics of the LFA proportions (Table 1). The models based on the correlation without HFS show slightly higher percentages of shoal and shoal-adjacent moderate-energy backshoal facies. In contrast, the HFS-based correlations result in higher percentages of foreshoal facies in the models.

![Figure 32: 3-D facies model based on the correlation without HFS (SIS algorithm). However the four deepening and shallowing trends are still visible in the facies association successions.](https://pubs.geoscienceworld.org/geoarabia/article-pdf/18/4/179/4569185/walz.pdf)

Table 1: Statistics of the LFA proportions of the final models based on the different correlation strategies (SIS: Sequential Indicator Simulation)

<table>
<thead>
<tr>
<th>Environment</th>
<th>SIS with HFS</th>
<th>SIS without HFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Flat</td>
<td>0.96%</td>
<td>0.77%</td>
</tr>
<tr>
<td>Low energy backshoal</td>
<td>7.08%</td>
<td>7.37%</td>
</tr>
<tr>
<td>Mod. Energy backshoal</td>
<td>20.08%</td>
<td>25.43%</td>
</tr>
<tr>
<td>Shoal</td>
<td>28.78%</td>
<td>31.84%</td>
</tr>
<tr>
<td>Foreshoal</td>
<td>39.16%</td>
<td>33.45%</td>
</tr>
<tr>
<td>Offshoal</td>
<td>3.94%</td>
<td>1.15%</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Five outcrop sections of Khuff Sequence KS5 time-equivalent strata (Saiq Formation) were investigated in wadis on the northern flank of the Oman Mountains (Al Jabal al-Akhdar). It is possible to link these additional sections in the sequence-stratigraphic framework developed previously for the Saiq Plateau outcrop reference section. Based on the detailed sedimentological analysis and thin-section investigations eleven lithofacies types were interpreted in KS5. These can be grouped into six lithofacies associations ranging from tidal flat to offshoal. Specific skeletal as well as non-skeletal particles were found to provide indicator criteria to differentiate between texturally often similar foreshoal and backshoal facies types.

The 1-D sequence-stratigraphic analysis of composite Khuff Sequence KS5 revealed several higher orders of cyclicity from cycles to high-frequency sequences (HFS), the latter particularly well marked by very characteristic gamma-ray patterns. Whereas in the foreshoal-dominated lower, transgressive part of KS5 maximum gamma-ray readings correspond to maximum flooding events, maximum gamma-ray signals in the backshoal-dominated upper, regressive part of KS5 reflect muddy tidal flat deposits marking sequence boundaries.

Two different 2-D correlation strategies were applied by using as well as neglecting the four HFSs alongside the cycle sets. The identification of the high-frequency sequences provided additional criteria to reliably correlate sections over a distance of several tens of kilometers, however overall facies trends are represented similarly regardless the correlation strategy. In general, thickness variations and lateral facies association changes between the sections resulted in complex correlation geometries, including apparent cycle set downlaps. These patterns represent significant variations from a simple “layer-cake” stratigraphic architecture and are possibly due to effects of differential subsidence on a subregional scale.

Different 3-D facies models were constructed that clearly display the lateral facies association changes, thickness differences and different depositional geometries. The appearance of shoal facies types, representing possible reservoirs, is mainly governed by paleogeography and stratigraphic position. The proximal sections (in the northwest) show a high percentage of shoal facies throughout KS5, whereas in the more distal sections (in the southeast) the shoal facies appears mainly around sequence boundaries of the HFSs. Due to dynamic lateral facies association changes throughout KS5, the lateral extent of reservoir shoal bodies is limited.

ACKNOWLEDGEMENTS

This study is part of a research project of the University of Tuebingen, sponsored by Shell and Petroleum Development Oman (PDO). We would like to thank Shell and PDO and their focal points Joachim Amthor, Aly Brandenburg, Jean-Michel Dawans, Gordon Forbes and Jan Schreurs for assistance and support. Michael Poppelreiter is thanked for all his support throughout the project. PDO and the Ministry of Oil and Gas of the Sultanate of Oman is thanked for permission to publish the paper.

We are grateful to our Khuff team members Michael Zeller (now Statoil), Christoph Schneider (now Wintershall) and Daniel Bendias (University of Tuebingen) for help and useful ideas. Michael Obermaier (now Shell) is specifically thanked for his support in the field, for all the very helpful discussions and his support throughout the project. Special thanks to Holger Forke (Natural History Museum, Berlin) for his crucial microfossil analysis. The authors would also like to thank Per Jeisecke (University of Tuebingen) for the preparation of the thin sections. Shuram Oil and Gas (Muscat) is acknowledged for fieldwork logistics. We are also very grateful to ALT and Schlumberger for providing access to WellCAD and Petrel software.

The two anonymous reviewers are thanked for their helpful comments. GeoArabia’s Assistant Editor Kathy Breining is thanked for proofreading the manuscript, and GeoArabia’s Production Co-manager, Nestor “Nino” Buhay IV, for designing the paper for press. Moujahed Al-Husseini GeoArabia’s Editor-in-Chief is thanked for his help and useful comments throughout the entire publication process.
REFERENCES


ABOUT THE AUTHORS

Lisa Walz studied Geosciences at the University of Tuebingen (Germany) and the University of Oslo (Norway). Her diploma thesis (2011) at the University of Tuebingen focused on facies characterization, sequence-stratigraphic analysis and 3-D facies modeling of the Khuff Sequence KS5 in the Oman Mountains, Sultanate of Oman. The project was founded by Shell (Qatar) and Petroleum Development Oman. In 2011 she joined Shell International Exploration and Production as Exploration Geoscientist. Since then she has been working on regional exploration projects in New Ventures covering a wide range of geographic and geological settings. lisa.walz@shell.com

Thomas Aigner studied Geology and Paleontology at the Universities of Stuttgart, Tuebingen/Germany and Reading/UK. For his PhD dissertation on storm depositional systems (1985) he worked at the Senckenberg-Institute of Marine Geology in Wilhelmshaven (Germany) and spent one year at the University of Miami in Florida (USA). He then became an Exploration Geologist at Shell Research in Rijswijk/Holland and Houston/Texas focussing on basin analysis and modelling (1985–1990). Since 1991 Tom has been a Professor and Head of the Sedimentary Geology Group at the University of Tuebingen. In 1996 he was a “European Distinguished Lecturer” for the AAPG. His current projects focus is on sequence stratigraphy and reservoir characterisation/modelling in outcrop and subsurface. t.aigner@uni-tuebingen.de

Bastian Koehrer is a Development Geologist in Wintershall’s German business unit, working on mature oil field and tight gas sands development in the German North Sea and Lower Saxony. He has more than five years of E&P project experience in Germany, Oman, Qatar and the UAE with a professional track record in both carbonate and clastic reservoirs. Bastian obtained a PhD degree (2011) in Carbonate Sedimentology from the University of Tuebingen (Germany) in research collaboration with Shell (Qatar) and Petroleum Development Oman. For his PhD dissertation on the Khuff Formation, Bastian spent 18 months of outcrop mapping in the Sultanate of Oman. Bastian is a member of the EAGE, AAPG and DGMK and has published several papers on carbonate sequence stratigraphy and reservoir outcrop analogs. bastian.koehrer@wintershall.com

Manuscript submitted October 21, 2012
Revised April 23, 2013
Accepted May 15, 2013