High-resolution anatomy of a grainstone package in Khuff Sequence KS4, Oman Mountains, Sultanate of Oman

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ABSTRACT

This study is part of a large-scale outcrop analog study on Middle Permian to Lower Triassic Khuff-equivalent strata in the Oman Mountains, Al Jabal al-Akhdar, Sultanate of Oman. The Khuff outcrop equivalent can be divided into six sequences (Khuff sequences KS6 to KS1, from base to top). The main focus of this study is the description of the internal anatomy of the shoal grainstone bodies in the lower part of Sequence KS4 (“lower KS4”). High-resolution sedimentological logging of three outcrop sections in wadis Sahtan, Bani Awf and Mistal yielded eight lithofacies types that were grouped into five facies associations. Lower KS4 strata were mainly deposited within a “shoal complex” of an epeiric carbonate ramp, resulting in a thick pile of up to 70 m of grainstones that, on first sight, appear relatively homogeneous. However, detailed facies and microfacies analysis revealed their heterogeneous architecture on various scales: (1) Minor changes in depositional environments directly affected the type of carbonate grains (ooids versus peloids/cortoids versus bioclasts), leading potentially to highly variable pore systems (moldic versus interparticle versus intraparticle). (2) Vertically, detailed sequence-stratigraphic analysis revealed a higher-order of cyclicity (“mini-cycles”) on a decimeter- meter-scale. Four mini-cycle types were recognized. (3) Laterally, facies changes, the amalgamation of grainstone beds and mini-cycle pinch-outs were observed in 2-D correlations on a scale of a few kilometers. These different types of heterogeneities may contribute to varying production rates commonly observed in the subsurface KS4 reservoir.

INTRODUCTION

The Middle Permian to Lower Triassic Khuff Formation contains prolific hydrocarbon accumulations in several carbonate reservoirs throughout the Middle East (e.g. Al-Jallal, 1987, 1995; Konert et al., 2001; Sharland et al., 2001; Figure 1). In the Al-Jabal al-Akhdar, Sultanate of Oman, the Khuff outcrop analog can be divided into six sequences (Khuff sequences KS6 to KS1, from base to top; Figures 2 and 3). Khuff Sequence KS4 is especially noted for being one of the most prominent ever-recorded intervals of grainstones, and is the main reservoir in the world’s largest gas fields, the North Dome and South Pars in offshore Qatar and Iran (Figure 1). This analog study was carried out in the Khuff-equivalent outcrops in the Oman Mountains and focuses on the vertical anatomy of the deposits in the lower part of Sequence KS4 (“lower KS4”), and the investigation of the lateral continuity of the grainstone bodies on a scale of 10s of kilometers.

Previous investigations affirmed overall layer-cake geometries of the Middle and Upper Khuff (KS4 to KS1 sequences) strata with sequences and cycles sets that are traceable over 10s of kilometers (e.g. Aigner and Dott, 1990; Al-Jallal, 1995; Koehrer et al., 2011, 2012). Wide facies belts on this low topography and very gently inclined carbonate ramp (e.g. Alsharhan and Nairn, 1994; Sharland et al., 2001, 2004; Osterloff et al., 2004; Insalaco et al., 2006; Maurer et al., 2009) produced these extensive deposits, giving rise to further questions addressed in this study:

(1) Do microfacies change laterally within grainstone beds on a 10s of kilometers scale?

(2) What is the detailed vertical anatomy of the very extensive grainstone-dominated intervals?

This study of the lower KS4 is part of the outcrop analog study on Permian–Triassic deposits in the Al Jabal al-Akhdar region in the Sultanate of Oman (Figure 2). It builds on the initial stratigraphic
investigations presented in Koehrer et al. (2010, 2011, 2012), Pöppelreiter et al. (2011) and Zeller et al. (2011). Further detailed studies on individual Khuff sequences in the Oman Mountains cover sequences KS5 (Walz et al., 2013) and KS6 (Bendias et al., 2013).

**STRATIGRAPHIC FRAMEWORK**

The Khuff carbonates potentially represent one supersequence, which comprises six transgressive-regressive sequences (KS6–KS1) (Koehrer et al., 2010, 2012). Recent studies (Al-Husseini and Koehrer, 2013) 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). The stratigraphy is shown in Figure 3, and the interval of Sequence KS4 (lower KS4) studied in this paper is highlighted. The sections of Sequence KS4 surveyed in this study are placed chronostratigraphically in the early Wuchiapingian (Dzhulfian) Stage and stratigraphically in the middle part of the Upper Saiq Member (Glennie et al., 1974).

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), 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.
The base of KS4 (KS5/KS4 boundary; sequence boundary SB KS4) is correlated by Koehrer et al. (2010) to the transition from Capitanian to Wuchiapingian. The top of KS4 (SB KS3) is situated near the Wuchiapingian/Changhsingian transition, implying the depositional duration of KS4 is ca. 5 million years (Gradstein et al., 2012). It is interpreted as a third-order transgressive-regressive sequence that contains the Wuchiapingian maximum flooding surface MFS P30 defined by Sharland et al. (2001, 2004). The equivalent of Sequence KS4 in the subsurface is the important K4 reservoir (Koehrer et al., 2010), which is a major exploration target elsewhere in the Gulf region.

**METHODOLOGY**

Outcrop work was carried out in three wadis close to Ar Rustaq town, ca. 130 km southwest of Muscat, the capital of the Sultanate of Oman (Figures 1 and 2). From west to east, Wadi Sahtan, Wadi Bani Awf and Wadi Mistal (Figure 2) cut perpendicular into the northern flank of the Al Jabal al-Akhdar anticline, exposing accessible lower KS4 sections with only minor internal structural deformation (Searle, 2007).
The coordinates of the sections are taken from Koehrer et al. (2012): (1) Wadi Sahtan: 23°19'54.348”N, 57°18'42.613”E; (2) Wadi Bani Awf: 23°17'38.626”N, 57°27'50.183”E; and (3) Wadi Mistal: 23°17'9.388”N, 57°41'24.507”E.

The three lower KS4 sections, each on average 70 m thick, were logged with a scale of 1:50. This led to detailed stratigraphic descriptions, displaying beds with thicknesses of up to 5 cm. Lithology, Dunham texture, components and sedimentary structures were fundamental characteristics registered on the logging sheet. Lithofacies types (LFT), defined in the facies atlas developed by Koehrer et al. (2010) (Figure 4), were assigned to the logged units. Finally, outcrop gamma-ray measurements were conducted every 0.25 m (if possible as a vertical profile) with a measurement period of 15 seconds.

145 thin sections were produced and analyzed with a transmission light microscope. In all three wadis a cycle interval of approximately 10 m was sampled with a higher resolution (30 to 50 cm sampling steps), otherwise samples were taken every 1.5 m on average. During thin section analysis both the microfacies types (MFT) of the Saiq Formation developed by Forke (2010, Era
Period
Epoch
Stage
Group
Formation
Member
Subsurface Equivalent
Lithology
3rd-Order
MFS
Reservoir
(Onan)
Outcrop Marker Beds
Rift-stages (Neo-Tethys)
Pre-Permian Metamorphic Basement
Mesozoic
Triassic
Early
Olenekian
Kaihatu
Maha
Middle
Sudair
Tr20
K1
"Top Breccia"
"Saq/Mahil Boundary"
"Coral Marker"
"Microbial Marker 3"
Post-rift
P20
"Microbial Marker 2"
"Microbial Marker 2"
"Chert Marker"
"Microbial Marker 1"
"Muddy Marker"
Syn-rift
P30
KS1 to KS3
K2
"Microbial Marker 3"
"Coral Marker"
"Microbial Marker 3"
KS4
K3
KS5
P40
"Microbial Marker 1"
"Microbial Marker 2"
"Coral Marker"
"Microbial Marker 2"
KS6
P50
"Microbial Marker 2"
"Microbial Marker 1"
"Microbial Marker 2"
"Microbial Marker 3"
Pre-Permian Metamorphic Basement
Figure 3: Chronostratigraphic and sequence-stratigraphic framework of the studied interval (Koehrer et al., 2010). Age dates from Baud and Bernecker (2010). Geological time scale from Gradstein et al. (2012). Tentative correlation to MFS postulated by Sharland et al. (2004).
unpublished report) and lithofacies types (LFT) proposed by Koehrer et al. (2010) were considered.

When comparing the field observations of facies types with the refined analysis based on thin sections, a discrepancy rate of about 35% was noted. This rate was similar in all three wadis, indicating that dolomitization is the main factor influencing the error margin. In some outcrops it was extremely difficult to classify the facies types directly in the field, especially the component types (e.g. peloidal-/cortoidal-grainstone versus oolitic grainstone). Dunham textures were easier to assign, as weathering angles give good indications (see also Koehrer et al., 2012).

All logs were digitized with WellCAD. Lithofacies associations (LFA) were assigned to each interval, “mini-cycles” and fifth-order cycles, which were interpreted in the field and cross-checked with the microfacies analysis based on thin sections. Besides lithofacies types and their associations, sedimentary structures and bed thicknesses were used as indicators for picking sequence boundaries (SB) and maximum flooding surfaces (MFS). The 2-D correlations were interpreted by taking gamma-ray (GR) and lithofacies associations into account. Finally the logs were imported into Petrel 2010.1 to create a static 3-D facies model.

**SEDIMENTOLOGICAL CHARACTERIZATION**

**Lithofacies Analysis**

The facies atlas developed by Koehrer et al. (2010) was utilized to describe texture, sedimentary structures, sorting and composition of main facies types found in the Khuff outcrop analog (Figure 4). These attributes allow interpreting the depositional processes and environments of each lithofacies type (LFT). Lithofacies types with similar depositional environments are grouped into lithofacies associations (LFA), building the facies model. The lithofacies types found in this study represent the proximal shallow-ramp to back-bank setting of an epeiric carbonate platform. Occasionally, a shift towards distal shallow ramp settings was observed in the upper part of the lower KS4.

Five lithofacies associations dominate the lower KS4:

**Tidal Flat (LFA 3):** Microbial laminites (LFT 3a) are the most common facies type of LFA 3. They indicate low accommodation space, very shallow conditions and low energy. Evidence of temporary changes of depositional energy (e.g. storms) are preserved as mud- (sometimes imbricated) and armored clasts. Rooting and tepee-structures are associated with exposure. Microbial laminite “caps” or reworked microbial laminites at

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**Legend (Dunham Texture)**

- Mudstone
- Wackestone
- Packstone
- Pack- to grainstone
- Grainstone
- Boundstone

**Lithofacies Types**

- 2b (Burrowed/rooted mudstone wackestone)
- 3a (Microbial laminites)
- 5a1 (Graded mudstone wackestone)
- 5a2 (Graded wackestone packstone)
- 5b1 (Intraclastic packstone flakestone)
- 5c1 (Peloid-rich packstone grainstone)
- 5c2 (Bioclastic packstone grainstone)
- 5d1 (Cross-bedded oolitic grainstone)
- 5d2 (Cross-bedded peloidal grainstone)

**Lithofacies Associations**

- LFA 3 (Tidal mud flat)
- LFA 4A (Low-energy backshoal)
- LFA 4B (Moderate-energy backshoal)
- LFA 5 (Shoal)
- LFA 6 (Foreshoal)

**Potential Pore Types**

- Fenestral porosity
- Intraparticle porosity
- Oomoldic porosity
- Interparticle porosity
- Tight

**Sedimentary Structures**

- Trough cross-bedding
- Uniform grainstone
- Bioturbated top
- Remnants of microbial lamination
- Parallel wavy bedding
- Structureless due to rooting
- Mottled

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Figure 4 (Figure 1 old): Color codes and signatures used consistently in all WellCAD logs.
grainstone tops are interpreted as sequence boundaries at the top of shallowing-upward cycles (shoal to laminitic mini-cycle, see below).

**Low-energy Backshoal (LFA 4A):** Bioturbated packstones and pack- to grainstones (LFTs 5c1, 5a2 and 5c2) are characteristic for this setting in the lower KS4. They typically show low faunal diversity and mainly microfossils, which prefer a shallow and restrictive habitat. The majority of these deposits are storm deposits, including wave ripples, erosional bases and graded beds (LFT 5a2).

**Moderate-energy Backshoal (LFA 4B):** This lithofacies association can be interpreted as a shoal margin- to lagoonal, restricted setting, where occasionally the water energy is sufficiently high to form cross-bedded, peloidal-/cortoidal-rich grainstones. The closer the shoal complex, the better the sorting and the lower the percentage of cortoids and grapestones. Common sedimentary structures are bioturbated bed tops and cross-bedding.

**Shoal (LFA 5):** Oolitic cross-bedded grainstones (LFT 5d1) make up the largest part of all sections. Trough cross-bedding shows a high-energy, subtidal setting with bottom mobility. Generally staffelids (*Hemigordiellina*) are the only microfossils found in otherwise very homogeneous, purely oolitic grainstones. Muddy caps and thin microbial mats (at tops of LFT 5d1 and LFT 5d2 beds) indicate intervals of exposure.

**Moderate-energy Foreshoal (LFA 6):** Foreshoal facies (LFTs 5a2 and 5c1) occur rarely in all three sections and are only represented as cm- to dm-scale beds in higher stratigraphic positions of the logged sections. Sedimentary structures and the general appearance of foreshoal deposits are similar to those of LFA 4A. They are only differentiable through presence of macro- and microfossils indicating a foreshoal setting, such as open-marine fauna like corals, bryozoans and foraminifers (e.g. *Rectostipulina quadrata*).

Predominant sedimentary structures (wave ripples, post-event bioturbation) indicate that most beds of these facies associations are storm deposits.

**Backshoal versus Foreshoal Facies**

Macroscopically, backshoal and foreshoal deposits may look very similar in the field. The lack of macrofossil indicators requires a more detailed microfacies analysis (Figure 5). Key indicators for certain environments are provided by microfossils (Koehrer et al., 2012):

**Backshoal indicators:** Dasycladaceans (*Mizzia* sp., *Mizzia velebitana*), encrusting foraminifers (*Palaeonubecularia*), thin-shelled miliolids (*Hemigordius*). The presence of dasycladaceans and the high content of cortoids and coated grains indicate restricted, moderate- to low-energy settings typical of lagoonal and shoal margin environments. Lagenid foraminifers found in the lower KS4 are also indicators for backshoal conditions. Normally they are very small and thin-shelled in contrast to transported foreshoal-associated lagenids that are thick-shelled and larger. Lagenids are infauna that can be found in both offshoal mud- to wackestones, as well as in mud-dominated backshoal facies. The latter prevails in the lower KS4.

**Foreshoal indicators:** Corals, gymnocodiaceans, lagenids (*Rectostipulina quadrata*), bryozoans (rarely found in KS4 thin sections), echinoderms (crinoids). The stratigraphic positions of the foreshoal facies types are of high importance, as they are interpreted as maximum flooding surfaces (MFS) in the lower KS4.

**Potential Pore Types**

The grainstone packages in the lower KS4 display a heterogeneous internal anatomy, with very variable vertical and lateral microfacies changes, punctuated by mini-cycles (Figure 6). These cyclicities within grainstone complexes indicate minor changes in depositional environments. This has a direct effect on the dominant grain types, which in turn affects the potential pore
Figure 5: Since foreshoal and backshoal deposits can be very similar, thin sections with the same general lithofacies type can yield different microfacies types. Consequently their deposition took place within different depositional environments. On the left, microfossils typically found in restricted lagoonal depositional environments (backshoal) are demonstrated, on the right those of open-marine (foreshoal) conditions. The microfossils are arranged from most indicative to least from top to bottom.
Figure 6: See facing page for continuation.

Figure 6 (continued): Exemplary high-resolution log of a ca. 8.5 m-thick grainstone-dominated package (one cycle set) in the lower KS4 in Wadi Sahtan, illustrating highly differentiated internal anatomy, potential pore types (aragonitic ooids) and an additional, smaller scale of cycles (mini-cycles). To the right thin sections are shown. The sampled grainstone compositions range from cortoidal-, peloidal- and skeletal-rich to pure oolitic.

| Sample | Lithofacies | Lithofacies Type | Potential Pore Type | Sedimentary Structures | Depth (meters) |
|--------|-------------|-----------------|---------------------|------------------------|---------------|
| MS-27,8| MS-26       | MS-24,5         | MS-23,1             | MS-21,5                | MS-20,5       |
| Depth  | 4\(\text{m}) | 5\(\text{m})    | 6\(\text{m})       | 7\(\text{m})          | 8\(\text{m})  |
| 150    | 550         | 0               | 7                     | 4\(\text{m}) | 5\(\text{m}) |
| Gamma-Ray | Uranium | Uranium | Potassium | Thorium | 0 |
| 750    | 0           | 0               | 0                    | 0                      | 0             |
Oomoldic porosity is created when aragonitic ooids (a.o.) are leached. The isolated porosity type is primarily to be expected in oolitic grainstones (LFT 5d1). For ideal permeability and porosity values the oomoldic porosity should be connected by another type of secondary porosity/fractures.

Interparticle porosity is the primary porosity characteristic for peloidal-/cortoidal-rich grainstones (LFT 5d2); peloids and cortoids are only rarely leached.

Intraparticle porosity is only expected to occur in the skeletal components (e.g. gastropods, bivalves) contained in storm deposits (e.g. LFTs 5a2 and 5c2). Since these are pack- or pack-to grainstones porosity values would be low, resulting in beds that act as thin baffles within grainstone successions. Only skeletal-rich pack-to grainstones (LFT 5c2) could contain sufficient skeletal material to give these beds a slightly higher reservoir potential.

Fenestral porosity: The grainstone complexes are often separated by cm- to dm-thick microbial laminites (LFT 3a). These laterally persistent beds can act as baffles within the overall grainstone complexes. However, the microbial laminites may have fenestral porosity.

Mud-, wacke- and peloidal-rich packstones are mostly expected to not have any porosity in the subsurface, besides some potential microporosity. Although the shoal and moderate-energy backshoal facies (LFTs 5d1 and 5d2) have the best reservoir potential, internal heterogeneities and differing cementation or leaching can result in cm- to dm-thick grainstone beds that act either as baffles or good reservoir layers. Whether oolitic grainstones have a potential of being good reservoirs depends on several factors: (1) if interparticle pores (primary porosity) are not or only weakly cemented, the flow behavior would be enhanced; (2) dolomitization in the subsurface would increase interparticle pore volume further; and (3) fracturing increases reservoir permeability and porosity in many Khuff targets (Alsharhan and Nairn, 1994).
1-D SEQUENCE STRATIGRAPHIC ANALYSIS

High-resolution logging was crucial for sequence-stratigraphic analysis in the grainstone-dominated lower KS4. It revealed a smaller scale of cyclicity – termed “mini-cycles” – compared to those of previous studies (e.g. Koehrer et al., 2012). Four types of mini-cycles were recognized in all three studied sections (Figures 7–11). On average 43 mini-cycles occur in each section, and these form thirteen fifth-order cycles and five fourth-order cycle sets.

Interpreting mini-cycles and fifth-order cycles was a difficult task since all sections are dominated by grainstone facies (up to 80%) and are characterized by several m-thick grainstone complexes that show variability only in their microfacies. Therefore it was essential to subdivide shoal complexes, by differentiating the peloidal-/cortoidal-rich cross-bedded grainstones into shoal-to-shoal margin settings, an environment with high- to moderate-energy (LFA 4B). Very homogeneous, oolitic, cross-bedded grainstones, however, are indicators for high-energy depositional settings (high water turbulence, bottom mobility), hence representing the central shoal complex (LFA 5).

The presence of grapestones within oolitic grainstones suggests a slight decrease of water turbulence, bottom stability and non-deposition. They are proxies for periods of transgression, when oolite-producing depositional environments are subject to rising sea levels. The characteristic water turbulence magnitudes inhibit accumulation of mud yet are not high enough to prevent the ooids from coagulating to grapestones (Winland and Matthews, 1974).

The observation that grainstone packages are alternations of oolitic-, peloidal- and cortoidal-rich grainstones was the key point that made cycle interpretations within grainstone complexes possible ("shoal to backshoal mini-cycle").

Hierarchical cycle interpretations were based on field observations, thin section analysis and gamma-ray (GR) trends. The following list of key observational criteria was applied to consistently interpret cycles:

(1) Peloidal-/cortoidal-rich grainstones tend to be more proximal than oolitic grainstones.

(2) Coated grains, microbial laminations, roots and breccias are indices for backshoal environments.

(3) Packstones and pack- to grainstones (graded, peloidal-/skeletal-rich) indicate a shallowing trend. Only if their fossil assemblages contain foreshoal indicators the facies are interpreted as foreshoal deposits. Rooting is taken as evidence for times of maximum regression, even more prominent than microbial laminites.

(4) Thick grainstone beds formed as a result of larger accommodation space.

(5) Maximum flooding surfaces (MFS) are positioned within the top part of beds, sequence boundaries (SB) are interpreted at bed boundaries.

The following types of mini-cycles could be distinguished: (1) Shoal to Tidal Flat Mini-Cycle (Figure 7); (2) Shoal to Backshoal Mini-Cycle (Figure 8); (3) Shoal to Laminite Mini-Cycle (Figure 9); and (4) Shoal to Foreshoal Mini-Cycle (Figure 10). Figure 11 shows an exemplary stacking pattern of Mini-Cycles in Wadi Mistal.

Cycles and Cycle Sets

The fifth-order cycles and fourth-order cycle sets that are defined in this study have been described in detail by Koehrer et al. (2010, 2011, 2012), Zeller et al. (2011) and Bendias et al. (2013). Two to five mini-cycles are grouped into one fifth-order cycle. Exposure-capped cycles and intertidal facies deposits (e.g. laminite at the top of a shoal to laminite mini-cycle) show a decrease of accommodation space and can represent highly condensed intervals (“missed beats”). Amalgamation of grainstone layers accounts for cycles that might have been “erased” from the
Figure 7: Shoal to tidal flat mini-cycle shown in Wadi Sahtan, 33–38 m.
**SHOAL TO BACKSHOAL MINI-CYCLE**

**Identification of Lithofacies Types**

- **Dunham Texture**
  - C: Cortoidal-
  - P: Peloidal-rich grainstone
  - G: Well-sorted oolitic grainstone

**Legend**
- Transgressive hemicycle
- Regressive hemicycle
- Peloids
- Ooids
- Microbial influence
- Trough cross-bedding
- M: Mudstone
- W: Wackestone
- P: Packstone
- G: Grainstone

**Figure 8:** Shoal to backshoal mini-cycle shown in Wadi Bani Awf, 49–51 m.
Figure 9: Shoal to laminite mini-cycle shown in Wadi Mistal, 27.5–28 m.
Figure 10: Shoal to foreshoal mini-cycle shown in Wadi Bani Awf, 62–64 m.
Figure 11: Exemplary stacking pattern of mini-cycles shown in Wadi Mistal, 61–65 m. In general about 3 to 5 mini-cycles make up one fifth-order cycle.
sedimentary record by reworking. Furthermore it was observed that a lower ratio of mini-cycles per cycle commonly occur in successions of thick grainstone beds, such that some mini-cycles cannot always be recognized. The maximum number of mini-cycles within one cycle is five.

Two to four genetically related cycles are commonly stacked into one cycle set. The cycle set thicknesses vary between 12 m to nearly 20 m. The combination of significant stratal surfaces and GR trends was used to interpret their respective SBs and MFSs. SBs are mostly characterized by a GR peak originating from muddier regressive facies, such as microbial laminites and packstone sheets. Intervals of maximum flooding are mostly found within homogeneous grainstones, accompanied by lower GR values. These are the most distal deposits in the lower part of the sections. In the upper part of the logs a switch in the GR signal is noted. Intervals of maximum flooding are most likely to be foreshoal-influenced lithofacies types. The appearance of these packstone layers is characterized by relatively higher GR values compared to those of the SBs.

Generally speaking, the GR readings of the lower KS4 show subtle changes and mostly serrated patterns. Since these were not always indicative, field observations and results of thin section analysis were given higher significance for cycle interpretations.

**Previous Studies**

While Koehrer et al. (2010, 2012) commonly interpreted the mud-dominated facies as foreshoal deposits in the lower KS4 this was not confirmed by this study, which recorded more abundant microbial laminites and backshoal associated facies types. The GR logs of both studies shows partly similar trends yet differences are apparent. These differences can be explained by the high-resolution logging, which was carried out in this study with a scale of 1:50 and a sampling rate, which allowed a more in-depth investigation (samples were taken every ca. 1.5 m). Additionally, the smaller spacing of outcrop GR data points (0.25 m compared to 1.0 m in Koehrer et al., 2010, 2012) enabled the recognition of small-scale trends. Besides an additional cycle set, the present study showed that the grainstone complexes manifest a much higher degree of internal heterogeneity than previously recorded, both in terms of grain types and the occasional occurrence of facies types, which are normally found adjacent to the shoal complex.

**Vertical Facies Stacking Pattern Diagram**

In order to better illustrate changes in the depositional environment and to verify the interpreted sequences throughout the overall succession of grainstone packages, a facies stacking pattern diagram of the section Wadi Bani Awf was created (Figure 12). It shows the general facies association trends caused by the shifts in the depositional environment that were observed in all three logged sections. Whereas in the lower three cycle sets the most distal environment is the shoal complex, in the upper two cycle sets foreshoal deposits are the most distal deposits. Another observation is that in all but one cycle set the most regressive periods are indicated by tidal flat deposits. As mentioned above these deposits are interpreted to have formed on the shoal complex during times of relative sea-level falls.

**2-D CORRELATION**

Correlations were carried out between the three logged sections in Wadi Sahtan, Wadi Bani Awf and Wadi Mistal (Figure 13). Outcrop gamma-ray logs and the different cycle hierarchies were used as the basis to interpret timelines. A significant finding was that facies type changes occur within mini-cycles. These can occur for example within single shoal grainstone bodies on a 10s of km scale along the epeiric carbonate ramp. A common observation was the lateral change of peloidal-/cortoidal-rich grainstone facies into ooid-rich grainstones. This facies shift is interpreted as a change from a proximal shoal margin to a more central shoal setting.

Fourth- and fifth-order cycles as well as mini-cycles were correlated. Overall, the depositional environment is not characterized by drastic changes. It was dominated by the shoal complex and shoal margin of the carbonate ramp and the three sections were roughly parallel to the
Figure 12: Facies stacking pattern diagram of the reference section Wadi Bani Awf. The thick purple arrows coincide with the fourth-order transgression and regression periods that are caused by major changes of the relative sea-level. Arrows that point to the right suggest times of transgression, those pointed to the left, times of regression. The dashed purple lines illustrate these phases for the fifth-order cycles.
paleoshoreline (east-west). Wadi Mistal seems as though it was paleogeographically closer to the open-marine setting since it shows a higher content of allochthonous shallow-marine sediments (e.g. coral-fingers). This would imply a higher exposure to storms, currents and a higher degree of bed erosion.

**Base and Top of “lower KS4”**

The KS5/KS4 sequence boundary (SB KS4) is situated within a laterally continuous bed that shows rooting and burrows (“Microbial Marker 2” in Koehrer et al., 2010, 2012) (Figure 13, Base of CS-1). In both Wadi Sahtan and Wadi Bani Awf this is a thick microbial laminit. In Wadi Mistal on the other hand this sequence boundary was interpreted at the top of a rooted grainstone.

Logging was carried out down to where the “top lower KS4 microbial marker” was reached (Figure 13, Top of CS-5). This tidal flat deposit is a prominent white bed in all three logged locations. Whereas the top in Wadi Sahtan is a microbial laminit with distinct crinkly lamination, in Wadi Mistal it is a highly burrowed to vertically rooted wackestone. Wadi Bani Awf shows both lithofacies types, a thin microbial laminit overlying a burrowed mudstone. Nonetheless they all show signs of exposure and reworking, thus indicating similar depositional settings. Thick grainstone successions overly the tidal flat deposits.

**States of a Shoal Complex**

The correlations imply that the deposition of the lower KS4 was confined to the shoal and the marginal shoal depositional environments, thus a fairly limited portion of the epeiric carbonate ramp. Although there are facies that are grouped into the moderate-energy foreshoal facies association, this was done in order to highlight the occurrence of foreshoal indicators found in those beds. Changes of relative sea level had an impact on the type and supply of components transported onto the shoal complex from the adjacent depositional environments. The orientation of the sections are positioned approximately in strike direction of the carbonate ramp, therefore statements about the width of shoal anatomies cannot be made. Lateral continuities (west-east) of shoal bodies are within a range of 10s of km.

Based on the cyles recorded in the field, it is proposed here that three major “states” (Figure 14) may be distinguished during the evolution of a shoal complex:

**Healthy Shoal State:** The “healthy shoal state” (Figure 14a) involves shallow subtidal conditions, high-energy and bottom mobility with the deposition of trough cross-bedded grainstones. The proximal margin of the shoal is where energies diminish and only periodically induced events transport the sediment. This is where peloidal-/cortoidal-rich grainstones are deposited. High sedimentation rates can be expected. A migration of shoal bodies results in amalgamation of beds.

**Exposed Shoal State:** Once a drop in relative sea level takes place the shoal complex is covered by a shallower column of water and can ultimately be exposed (“exposed shoal state”) (Figure 14b). The production area of oolitic grainstones moves to more distal areas, where energies are high enough. Microbial laminites, packstones and intraclastic grainstones form amongst others. The latter develop when depositional energies rise (e.g. storm, transgressions) and the regressive facies are reworked. Higher microbial activities are characteristic and backshoal components (e.g. dasycladaceans) dominate the sedimentary record.

**Flooded Shoal State:** Towards the third-order MFS an increasing foreshoal influence is noted in the lower KS4 deposits. During times of transgression open-marine fauna is swept onto the shoal complex and overlies the grainstone beds. The “flooded shoal state” (Figure 14c) explains why foreshoal indicators are found in all three sections at similar stratigraphic positions. Pulses of relative sea-level rise seem to allow the transportation of open-marine fossils onto the shoal complex. Fully open-marine conditions are not likely to have existed in the investigated locations. This assumption is based on the fact that no thick foreshoal deposits were found, but rather thin sheets that indicate their storm related origin.
West-East Correlation

Besides a standard correlation of fifth- and fourth-order cycles, “exploded” sections were created (Figure 13). This is a correlation strategy in which cycle sets are separately illustrated and flattened on multiple stratigraphic datums. With this approach, thickness variations and changing sequence geometries are highlighted and easily identified. In the lower KS4 these are subtle differences, which mirror site-specific sedimentation and subsidence rates.

In all five cycle sets the upper sequence boundaries were chosen as datums. Although homogeneous m-thick grainstone beds are laterally traceable, the exact positions of maximum flooding surfaces were difficult to determine. In contrast, microbial laminites and bioturbated to rooted mudstones are clearer indicators for phases of regression and exposure. During these times similar environmental conditions must have prevailed and caused laterally continuous beds in the entire region.

**Cycle Set CS-1**

The thickest deposits of one cycle set are found in CS-1 (Figure 13). All three sections show different sediment thicknesses. The lowest cycle set marks the beginning of the third-order transgression of Khuff Sequence KS4, which can be seen in the transgression-dominated cycle symmetry in both the Wadi Sahtan and Wadi Bani Awf sections.

A variability in sediment thicknesses can be explained by higher sedimentation rates, especially on the main shoal complex, as well as different subsidence rates. Mini-cycles pinch-out from Wadi Sahtan and Wadi Mistal towards Wadi Bani Awf (Figure 13). The former sections are characterized by thick grainstone successions, whereas Wadi Bani Awf consists of facies of more restricted settings. Some mini-cycles that are not observed in Wadi Bani Awf may be contained as condensed cycles and thus hidden in the microbial laminites. These developed at the base of the lower KS4 in Wadi Bani Awf. A subtle paleohigh might explain these patterns, since moderate-energy backshoal deposits pinch out towards the adjacent wadis Sahtan and Mistal.

Towards the top of CS-1, Wadi Mistal shows a higher backshoal influence, which does not necessarily contradict the proposed proximal-distal trend. Slightest topography differences of shoal deposits can result in an irregular geometry when exposed. Consequently more restricted areas and “inlets” could have formed that are representative for calm depositional settings.

**Cycle Set CS-2**

The CS-2 shows fairly symmetrical cycles (Figure 13). Higher subsidence rates in Wadi Sahtan might have decreased as the section now shows the least sediment thickness. Thick microbial laminites alternate with typical backshoal mud-, pack- and pack-to grainstones. In both Wadi Bani Awf and Wadi Mistal general shallowing trends are observed (highly bioturbated grainstones, packstones) but are less distinctive than in Wadi Sahtan.

Wadi Bani Awf and Wadi Mistal show similar sediment thicknesses. At the lowest fifth-order SB a lateral facies change is observed. It is a good example of how changing lithofacies types reflect the paleolandscape. Intraclastic grainstones in Wadi Sahtan change laterally into microbial laminites towards Wadi Bani Awf and eventually into peloidal-rich grainstones in Wadi Mistal. This suggests that Wadi Bani Awf was most severely exposed and characterized by lowest energies. Wadi Sahtan on the other hand was subject to higher energies that consequently formed intraclastic grainstones. In line with the proximal-distal trend, Wadi Mistal shows the most distal lithofacies types characteristic of a shoal margin setting. Hence merely a shallowing trend and not a period of exposure can be assumed for the latter section.

**Cycle Set CS-3**

The CS-3 shows only small thickness variations between Wadi Sahtan and Wadi Bani Awf (Figure 13). Wadi Mistal, on the other hand, could have been influenced by a higher subsidence and sedimentation rate explaining the higher sediment thickness. During times of exposure, microbial laminites formed that represent the sequence boundary of all order of cyclicities (Figure 14b).
Figure 13 (continued): West-east correlation of mini-cycles CS-1 to CS-5. The cycles were colored to better show the lateral facies changes between the sections. Indicative trends are easier recognizable: e.g. back shoal influence in Wadi Sahtan in CS-2, foreshoal influence in Wadi Mistal in CS-4. Note the lithofacies changes within the mini-cycles.
Figure 13 (continued): West-east correlation of mini-cycles CS-1 to CS-5. The cycles were colored to better show the lateral facies changes between the sections. Indicative trends are easier recognizable: e.g. backshoal influence in Wadi Sahtan in CS-2, foreshoal influence in Wadi Mistal in CS-4. Note the lithofacies changes within the mini-cycles.
Two mini-cycles that are found in Wadi Sahtan and Wadi Mistal are thought to be condensed in the microbial laminites that mark the sequence boundary of the CS-3 in Wadi Bani Awf. A similar geometry as in CS-1 is detected, suggesting a paleohigh around that location. The cycle symmetry of all sections is rather regression-dominated, even though the superior third-order hemicycle is transgressive.

The sedimentary record of Wadi Mistal is dominated by grainstones, indicating that the main shoal complex was developed in that region (Figure 14a). Wadi Sahtan and Wadi Mistal were influenced by backshoal associated sediments.

**Cycle Set CS-4**
A distal trend towards Wadi Mistal is indicated by the first, sheet-like appearances of foreshoal component-rich beds in the CS-4 (Figure 13 and 14c). Their occurrence and thickness prevail in the most eastern location. The general impression is that the differential subsidence that might have caused thickness variations in lower cycle sets seems to cease in the two upper cycle sets. Thickness variations are minor and the depositional patterns are less complex. Another indicative factor could be that mini-cycles show only little pinch-outs. Wadi Bani Awf is again the most proximal section, while Wadi Sahtan's section shows facies that are associated to the main shoal complex (peloidal-/cortoidal or oolitic-rich grainstones).

**Cycle Set CS-5**
CS-5 is the cycle set with the highest percentage of foreshoal-associated lithofacies (Figures 13 and 14c). Wadi Bani Awf and Wadi Mistal seem to have a higher foreshoal influence than Wadi Sahtan. Here, tidal flat deposits develop around the sequence boundary. The increase in foreshoal facies toward the top of the lower KS4 strata indicates the proximity to the overall third-order MFS.

Three mini-cycles pinch-out towards the Wadi Sahtan section, a pattern that can be best explained with differential sedimentation rates and changing depositional environments. Cycle pinch-outs towards Wadi Mistal (e.g. in the lower fifth-order cycle) are most likely due to the amalgamation of grainstone beds.

**Discussion and Comparison to Previous Studies**
Very detailed logging and the high sampling rate of the lower KS4 lead to additional observations of the internal architecture of lower KS4 grainstone-dominated strata. The 2-D correlations show very pronounced internal heterogeneity of grainstone shoal complexes. An overall trend of increasing foreshoal influence can be distinguished and the overall “layer-cake” architecture suggested by Koehrer et al. (2012) was also reconfirmed by this study. However, the internal make-up of the general “layer-cake” in terms of carbonate grain types and microfacies types turned out to be rather complex. The Wadi Bani Awf sections represent a very gentle paleohigh with the highest percentage of shoal associated facies, also documented in Koehrer et al. (2012).

In this study, the introduction of the additional facies association “moderate-energy backshoal” allows a more detailed differentiation of the shoal deposits. It led to the understanding that a “healthy shoal state” (Figure 14a) comprises both oolitic and peloidal-/cortoidal-rich grainstones. Their alternating occurrence suggests a frequent, yet small-scale change in the depositional environment. Furthermore, Koehrer et al. (2012) implied a higher foreshoal influence in the lower KS4 than what was observed in this study.

**FACIES MODELING**
Collected data and cycle interpretations were integrated to build a stochastic 3-D facies model using Petrel 2010.1 (Figure 15). The first steps were the generation of “pseudo-wells” from the three sections (Wadi Sahtan, Wadi Bani Awf and Wadi Mistal). Lithofacies associations and outcrop GR logs were imported and correlated based on the 2-D correlations (Figure 13). A boundary was set outlining the three wells (X: 530,500.00, Y: 2,574,200.00, width: 41,000.00, length: 8,000.00).
Figure 14: The three states of a shoal complex were observed in the lower KS4. The black rectangle in the uppermost ramp outlines the depositional settings of the investigated KS4 section. Below, the three states of the shoal complex are outlined. The characteristic components are displayed adjacent to each state and highlighted in the respective lithofacies association color.
Two models were built which are based on different correlations. Model A is based on a mini-cycle correlation and Model B is based on a fifth-order cycle correlation. As discussed above, the correlations are flattened on the KS4/KS5 sequence boundary (SB KS4) and only the sequence boundaries are correlated (in Petrel referred to as “well tops”). 58 mini-cycle boundaries and 14 fifth-order cycle boundaries were correlated. The well tops were used to create surfaces. Since some mini-cycles pinch-out, surface intersections were merged. No faults were modelled.

The following steps were taken before modeling: (1) A 3-D grid was created. The grid increments were set to 500 m in x and y direction. (2) The surfaces generated during the correlations were used to create zones. (3) The zones were layered according to their thickness. Their amount of layering was a key point to prevent the loss of vertical resolution details. In both models the number of layers enabled a resolution that could display changes within a range of 5 cm. (4) Finally, the facies associations were upscaled (“most-of” mode) with a fine resolution to detect smallest changes in the depositional environment. The settings used for all zones in both models are listed in Table 1, final modeling outcomes are shown in Figure 15.

Different algorithms were used for the modeling runs. Considering the small amount of data points and their spatial distribution all algorithms provide similar statistics and outcomes. Yet they do not necessarily represent the observations in a geologically reasonable way. The TGS (Truncated Gaussian Simulation) algorithm was applied since it proved to illustrate the observed trends and geometries of geobodies (see also Koehrer et al., 2011 and Bendias et al., 2013). The algorithm

Figure 15: Final 3-D models both created with the TGS algorithm. The left model is based on the correlation of mini-cycles (Model A). See Figure 4 for LFA color coding. See facing page for continuation.
yielded suitinng lithofacies successions that resemble the expected facies changes of an epeiric carbonate ramp. A difficulty was the determination of variogram settings, as no recent analogues of these shoal-dimensions can be found presently. Therefore the studies of grainstone geometries carried out by Zeller et al. (2011) and Koehrer et al. (2011) helped to set variogram ranges (Variogram data: Major range 12 km; Minor range 10 km; Vertical range 1 m; Nugget 0.1; Azimuth -40). An azimuth of -40 was chosen to position the facies belts in a NW-SE strike position, perpendicular to the outer Arabian Platform margin, some tens of kilometers northeast of the present Omani coastline (Konert et al., 2001; Ziegler, 2001; Searle, 2007).

Discussion and Comparison to Previous Studies

When comparing models A and B no significant differences are noted (Figure 15). Model A with almost the triple amount of zones has a rather smooth appearance (vertical exaggeration of both models ca. 500x). The foreshoal-influenced deposits of Model A (light blue) for instance extend laterally between all three sections. They are interpreted to have formed when storms swept over the shoal complex. This sheet-like appearance seems more probable than the discontinuous shapes of foreshoal deposits in Model B. Otherwise the models show lateral facies changes and slight

Figure 15 (continued): The right model is based on the correlation of the fifth-order cycles (Model B). See Figure 4 for LFA color coding.

| Model Settings | Model A | Model B |
|----------------|---------|---------|
| Number of zones | 57      | 13      |
| Number of layers | 1,750  | 1,750   |
| Number of grid cells | 2,181,856 | 2,059,840 |
shingling of shoal associated facies towards the east. Both models show a limited area of the lower KS4. A 3-D model that extends over 10s of km in both x and y direction was not feasible considering the spacing and the amount of data points.

As the general sequence-stratigraphic framework of KS4 was already provided by Koehrer et al. (2012) these smaller, high-resolution models were built to understand the lateral facies and grain type variations of the highly heterogeneous grainstones in more detail. Facies changes and heterogeneous grainstone bodies in the lower KS4 make some units prone to have better reservoir quality than others. These are shoal deposits that extend laterally and do not show a facies change into more restricted shoal margin depositional environments. Thick shoal stacks are less likely to pinch out and extend further laterally. These are most frequently found in the transgressive hemicycles of the cycle sets.

This study’s emphasis on high-resolution logging and small cyclicities provided new findings that are listed below and compared with the overview studies of Koehrer et al. (2010, 2012):

1. The cross-section of lower KS4 facies associations in Koehrer et al. (2012) show very continuous, “layer-cake”-type shoal grainstone bodies that extend laterally and, in most cases, can be traced throughout the entire study area in the Al Jabal al-Akhdar region. This study revealed that the lower KS4 interval is more complex, and commonly characterized by lateral, internal changes when subdividing the shoal facies association into different microfacies and grain types.

2. The correlations established in this study illustrate that tidal flat settings developed in sheltered settings on the leeward sides of shoal topographies.

3. A similar observation to Koehrer et al. (2012) is the suspected paleohigh in Wadi Bani Awf. Figure 15 shows slightly inclined facies geometries that dip down in west and east direction from a higher situated location in Wadi Bani Awf.

4. The most striking finding is the heterogeneity of grainstone complexes resulting from the introduction of a “moderate energy backshoal” facies association in this study. The higher resolution logging of this study yielded new insights into the internal make-up of these grainstone bodies with lateral thickness changes and pinch-outs. Erosive bases of grainstone beds and amalgamated beds indicate that shoal facies accumulations shifted continuously. Therefore positions of the shoal margins and main shoal complex switched back and forth between different locations.

**CONCLUSIONS**

Three sections representing outcrop analogs of the lower part of the Upper Permian Khuff Sequence KS4 (“lower KS4”) were logged in wadis Sahtan, Mistal and Bani Awf, all situated on the northern flank of the Oman Mountains (Al Jabal al-Akhdar) in the Sultanate of Oman. The lower KS4 was deposited on an epeiric carbonate ramp. Eight lithofacies types (LFT) and five lithofacies associations (LFA) were differentiated. Microfossil indicators were used to distinguish between backshoal and foreshoal deposits, whereas the “shoal complex” represents the main depositional environment.

All outcrop sections consist of about 80% grainstones. Grainstones are variably composed of ooids, peloids and cortoids. The deposition of cortoidal/peloidal-rich grainstones is interpreted to have taken place within the moderate-energy backshoal, oolitic-rich grainstones within the shoal environment.

Detailed sequence-stratigraphic and biofacies analysis revealed a higher-, possibly sixth-order cyclicity on a decimeter to meter-scale, termed “mini-cycles”. Four different mini-cycle types were encountered. The mini-cycles form 13 fifth-order cycles, further grouped into five fourth-order cycles (CS-1 to CS-5).
2-D correlations, obtained through integration of all acquired data, revealed a general “layer cake”-type stratigraphic architecture on a 10s km scale. Within this overall “layer-cake”, however, the stratigraphic architecture was found to be rather complex with mini-cycles commonly showing lateral pinch-outs and internal facies changes. Mini-cycles and fifth-order cycles show that from west to east the sections were influenced by a higher amount of exposure, hence show slight changes in their allochthonous sediment content.

Detailed correlations revealed laterally changing carbonate particles and microfacies types within single grainstone units. The variety of particle types will lead to laterally changing pore types, and thus reservoir properties. Thickness variations of grainstone bodies are most likely the result of very subtle differential subsidence patterns and the movement of shoal bodies, e.g. caused by storm events.

Outcrop data was used to generate a static facies model using Petrel software. Applying a vertical exaggeration of 500, the model visualizes the geometry and architecture of highly heterogeneous grainstone bodies of the lower KS4. This underlines that apparently homogenous grainstone bodies show in fact a great variety of heterogeneities that have not been recorded before. A good understanding of the exact (moderate-energy shoal versus high-energy shoal) depositional environment (e.g. by detailed core analysis) of the K4-targets could therefore lead to a better prediction of reservoir quality and production rates.

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