Facies distribution, depositional environment, and reservoir geometries of clastic sandbodies in the Lower Jurassic Mafraq Member (Oman Mountains, Sultanate of Oman)

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Abstract

Jurassic mixed carbonate–siliciclastic systems form gas-bearing reservoir units in the subsurface of Oman. In this study, sandstone intervals were studied in two excellent outcrops in the lowermost 40 m of the Lower Mafraq Member in the Oman Mountains. This study focuses on documenting their complex geometry and internal architecture, as well as interpreting their depositional environment. One-dimensional sedimentological analyses were established in four outcrop sections in the Oman Mountains and combined with two-dimensional correlations and outcrop wall panels.

Stratigraphic cycles were identified on three scales, i.e., (i) small-scale cycles form (ii) medium-scale cycle sets, and these stack into (iii) large-scale high-frequency sequences. Cycle boundaries were interpreted at prominent surfaces, such as erosional surfaces, often related to the occurrence of sandstones and exposure surfaces with karst features or palaeosoils. The zone of maximum flooding is interpreted within carbonate deposits.

A reduced thickness of the most eastern section, as well as a higher number of erosional and exposure surfaces indicates a proximal-distal trend from east to west. Larger-scale high-frequency sequences and medium-scale cycle sets were interpreted to be formed by allocyclic mechanisms. Small-scale cycles often pinch out laterally, thus representing at least partly autocyclic changes.

The sandbody thicknesses reach up to 12 m and can be correlated in most cases over a distance of over 4 km. The depositional environment ranges from shallow marine deposits on the shelf to tidal flat, coastal bar sands, and an estuarine multistory channel system.

The reservoir quality of sandbodies varies significantly. While most of the sandbodies have a rather low reservoir potential, the estuarine deposits show the best reservoir potential with the highest thickness and probably the largest lateral extent.
Introduction

The Middle East is one of the regions with the worldwide largest hydrocarbon accumulations (e.g., Beydoun 1991; Nairn and Alsharhan 1997). In Mesozoic deposits throughout Oman, carbonates dominate and siliciclastics are rather scarce but occur, for example, in the Lower Jurassic Mafraq Formation. According to Mount (1984), mixtures of siliciclastics and carbonates can be found in many modern and ancient shelf deposits. Deposits of such a mixed system often record a complex relation between relative sea-level and climatic shifts. Lowstands in relative sea-level can often be indicated by subaerial exposure or fluvial incisions into subtidal sediments (Wilson 1967; Silver and Todd 1969; Rankey 1997). To get a better understanding of the siliciclastic intervals in the lower part of the Lower Jurassic Mafraq Formation in Oman and to understand their depositional environment, architecture, and potential reservoir net-to-gross ratios, the facies distribution and internal structures were studied in detail in two wadi outcrops along the northern flank of the Oman Mountains.

Stratigraphic setting

The sandbodies investigated in this study are Early Jurassic in age and belong to the lower part of the Mafraq Formation, which was deposited under a shallow sea throughout northwest Oman and became exposed during the uplift of the Oman Mountains. The Mafraq Formation is a part of the Sahtan Group as defined by Glennie et al. (1974) in outcrops of the Al Hajar Mountains. The Sahtan Group consists of five formations: Mafraq (Bendias and Aigner 2015), Dhruma (Schlaich and Aigner 2017), Tuwaiq Mountain, Hanifa, and Jubaila (Fig. 1A). The Tuwaiq Mountain and Hanifa/Jubaila Formations are missing in outcrops due to a Late Jurassic unconformity (Schlaich and Aigner 2017). The Mafraq Formation is the oldest member of the Sahtan Group and is subdivided into two parts: the Lower Mafraq Member and the Upper Mafraq Member, which represent the uppermost part of the AP6 megasequence and the base of the AP7 megasequence, respectively (Sharland et al. 2001). The base of the Upper Mafraq is marked by a Late Toarcian unconformity at 182 Ma (Ziegler 2001). The Oman subsurface stratigraphic chart in the work of Forbes, Jansen and Schreurs (2010) indicates a Pliensbachian to Toarcian age for the Lower Mafraq. New biostratigraphic data from outcrops in Wadi Sahtan suggest that the Lower Mafraq is older and ranges from the Hettangian to the Late Pliensbachian (Bendias and Aigner 2015; Fig. 1). A regional time-equivalent formation of the Mafraq Formation might be the Marrat Formation, which is present, e.g., in Saudi Arabia and Kuwait but not in outcrops of the Oman Mountains (Bendias and Aigner 2015). Its type section was first described near the town of Marat in Saudi Arabia (lat. 25°04’ N, long. 45°29’ E) by Powers (1968) and Powers et al. (1966) and consists mostly of limestone, shallow-water shale, and sandstone.

A detailed biostratigraphic zonation in the Jurassic and a correlation to the international chronostratigraphic chart (Cohen et al. 2016) are difficult in Oman. Jurassic stages are often defined by ammonites, which are rare or even absent in Oman. New biostratigraphic data from the Lower Mafraq in Wadi Sahtan by Bendias and Aigner (2015) help identify the boundaries of the Lower Mafraq Member.

The Mafraq Formation unconformably overlies a shoal-associated grainstone of the Upper Mahil Formation (Obermaier et al. 2012). The Lower Jurassic Lower Mafraq Member consists of siliciclastics at the base and grade upward into shallow-marine carbonates. These siliciclastics are exposed in Wadi Sahtan and Wadi Hail Bint and represent the first thick sandstones since Permian times. They represent an initial Early Jurassic phase of siliciclastic input during the early marine transgression, which eventually led to the deposition of fully marine Late Bajocian Dhruma carbonates (Schlaich and Aigner 2017) overlying the Mafraq Formation (Fig. 1A).
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Geological setting
During Permian times, the Arabian Peninsula was located 25° south of the equator and moved northward to 15° south during the Lower Triassic; it progressed further northward, approaching the equator during the Early Jurassic (Scotese 2001; Stampfli and Borel 2002). This gradual northward drift and the transition from a global icehouse to greenhouse climate resulted in a warm and humid to semi-arid climate during the deposition of the Lower Mafraq Formation (Al-Aswad and Al-Husseini 1994).

The opening of the Neo-Tethys began in the Permian with the creation of the Mozambique–Somali–Masirah rift system, which created a marine basin between Arabia and India/Madagascar (Hauser et al. 2001). During this time, a new passive margin, driven by rapid subsidence and the associated marine transgression of the Neo-Tethys, developed. A stable carbonate platform was established on the Arabian Peninsula, which resulted in the deposition of the Permian Khuff Formation (Forbes et al. 2010). Tectonics had only a minor influence on the depositional setting in the Lower Jurassic, resulting in a steady, continuous carbonate platform sedimentation (Mahil Formation). During Triassic to Middle

Figure 1: (A) Chronostratigraphy of the Sahtan Group was modified by Schlaich and Aigner (2017; based on the work of Forbes et al. (2010) and modified by Bendias and Aigner (2015)) to fit the new biostratigraphic data and the observations from outcrops. (B) Depositional environments during the Early Jurassic (after Ziegler 2001).
Jurassic times, the coastline of southeast Oman may have been an area with strike-slip tectonics (Shackleton and Ries 1990; Shackleton et al. 1990; Stampfli, Marcoux and Baud 1991, 1990; Shackleton et al., 1990; Stampfli et al., 1991). Due to the structural uplift of the Arabian Arch and a sea-level lowstand, parts of Oman became exposed at the end of the Triassic (Forbes et al. 2010). Mild subduction

**Figure 2:** (A) Location of the study area (yellow) in the Oman Mountains and outcrops of the Mafraq Formation studied by Bendias and Aigner (2015, grey; Google Earth V 7.1.8.30360, December 2015, Oman Mountains, Oman, 40Q 562380.70 m E 2566665.00 m N, 100-km eye altitude). (B) Outcrop image of Lower Mafraq outcrops in Wadi Sahtan. The yellow lines represent the sections logged in Wadi Sahtan: MS-1, MS-2, and MS-3; dark green lines mark minor faults. (C) Green areas mark the present sandbodies numbered from bottom to top from 1 to 5.
and back-arc rifting continued at the northern end of the plate. This led to a diachronous west–east Early Jurassic rifting that influenced the accommodation space (Loosveld, Bell and Terken 1996).

The studied area is located in the Oman Mountains (Fig. 2A), which are situated within the Tertiary convergence zone between the Arabian and the Eurasian Plate (Robertson and Searle 1990) interrupted by a pulse of crustal extension in Late Jurassic (Tithonian). They are the result of a collision of continental and oceanic crusts, which were deformed during this process. The Oman Mountains anticline provides a geological window into Earth’s history down to Precambrian strata.

Previous studies on the Mafraq Formation
Bendias and Aigner (2015) provided an extensive, detailed study of the Mafraq Formation in outcrops and subsurface of Oman. A new facies scheme was established for all outcrop sections and a sequence-stratigraphic framework. This paper is focused more specifically on the siliciclastic deposits of the Mafraq Formation. Forbes et al. (2010) described the Lower Mafraq as siliciclastic deposits that are followed by shallow-marine carbonates. It comprises offshore, shallow-marine, coastal plain, fluvial, and alluvial plain environments.

Rousseau et al. (2006) described the major depositional episodes of the Lower Mafraq Member as coastal encroachment in a southward direction during the Pliensbachian to Toarcian with the deposition of dominantly siliciclastics. Deposits of the Upper Mafraq Member, on the other hand, were described as carbonate-dominated deposits caused by a Late Bajocian marine flooding, which led to a diachronous overstepping of the Lower Mafraq. This is consistent with Ziegler (2001) who indicated a transgression in the Early Jurassic (Sinemurian to Aalenian) after a sea-level lowstand caused by the structural uplift of the Arabian Arc.

Study area
The studied sections are located in Wadi Sahtan and Wadi Hail Bint, at the northern flank of the Oman Mountains, approximately 130 km west of Muscat (Fig. 2A). Both wadis cut through the westward dipping Jabal Al Akhdar anticline and lie 4.4 km apart from each other. Both wadis were chosen, as the sandbodies are well exposed there and allow studying proximal and distal sections according to the reconstructed palaeo-coastline by Bendias and Aigner (2015). Three sections of the lowermost 40 m of the Lower Mafraq Member were logged with a lateral spacing of 200 m in Wadi Sahtan (Fig. 2B) and one section in Wadi Hail Bint.

The aims of this paper are as follows:
• detailed sedimentological description of the siliciclastic intervals in the lowermost 40–50 m of the Lower Mafraq Member.
• identification of the sandbodies present in the outcrops of Wadi Sahtan and Wadi Hail Bint.
• determination of the composition, thickness, and lateral extent of the sandbodies, their geometry, internal architecture, and facies types.
• interpretation of the sandbodies regarding their depositional environment.
• identification of potential reservoir geometries.

Methods
This study is based on four detailed sections of the basal 40 m of the Lower Mafraq Member in the Oman Mountains, Oman (Fig. 2B). One-dimensional sedimentological analyses in outcrops were used to establish a sequence stratigraphic framework, which finally resulted in 2D correlations.
Sedimentological logging
Carbonates were logged using the classification by Dunham (1962), and siliciclastic rocks were classified according to grain size (after Wentworth (1922)) and sorting. Physical and biogenic sedimentary structures, like ripples, trough cross-bedding, the orientation of components, or imbrications to identify the palaeo-current direction, facies types (after Bendias and Aigner 2015), lithology, colour, and spectral gamma-ray values were also logged along the vertical measured sections. In addition, the abundance of components, such as quartz grains, shells, shell debris, gastropods, foraminifera, peloids, ooids, etc., were logged using three classes: rare, common, and abundant. Measured sections were digitized using the WellCAD 4.3 software.

Gamma-ray logging
A portable gamma-ray device RS-125 Super-SPEC, manufactured by Radiation Solutions Inc., was used to measure the natural gamma radiation along the outcrops. The instrument uses a 2 × 2” (6.3 in³) sodium iodide detector with an energy response from 30 to 3000 keV, which allows a full assay capability with total gamma ray measured in cps, K in %, U in ppm, and Th in ppm. A measuring time of 30 seconds and a vertical spacing of 25 cm were chosen to obtain spectral gamma-ray log throughout the sections.

Thin section analysis
Fifty-nine thin sections from outcrop samples were analysed with the transmission light microscope Wild Leitz Aristoplan and an attached Olympus DP 25 camera. Thin sections were used to distinguish the mineralogical composition, grain size, rounding, sorting, and sedimentary features such as fining-up, coarsening-up, and cross-bedding in sandstones and to determine components, sedimentary structures, and Dunham texture in carbonates. Five categories were used to describe the sorting of sandstones: very well sorted, well sorted, sorted, poorly sorted, and very poorly sorted. The rounding of the quartz grains was differentiated from angular, subangular, subrounded, and rounded to well rounded (Wentworth 1922).

Lateral tracing of sandbodies
In total, 150 m of Lower Mafraq strata was logged in sections MS-1, MS-2, and HB. Individual sandbodies were walked out and studied laterally along the outcrop in Wadi Sahtan over a distance of 400 m to obtain detailed information about their geometry, architecture, and facies types. Vertical sections were logged every 6 to 20 m, depending on outcrop conditions. They display facies stacking patterns and enabled the identification of lateral thickness changes within the sandbodies.

Facies analysis
Facies types to describe the Mafraq Formation in Oman were established and described in detail by Bendias and Aigner (2015; Table 2). The same colour codes and lithofacies types were used in this study as in the study of Bendias and Aigner (2015).

Lithofacies types
Twenty-three lithofacies types were used by Bendias and Aigner (2015) to describe the whole Mafraq Formation, 19 of which were necessary to describe the lowermost 40 m of the Lower Mafraq Member. Their colour coding is shown in Fig. 3.
**Table 2a: Facies (LFT) described after Bendias and Aigner (2015): conglomerate; sandstone, massive, bioturbated, cross-bedded, laminated, and with soft-sediment deformation.**

<table>
<thead>
<tr>
<th>LFT</th>
<th>Key Attributes</th>
<th>Outcrop</th>
<th>Specimen</th>
<th>Thin Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>conglomerate</td>
<td>marine mass flow event</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>sandstone, massive</td>
<td>event deposition (mass flow) or massive appearance due to bioturbation</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>sandstone, bioturbated</td>
<td>marine bioturbation, possibly deltaic/estuarine environment; low energy conditions (compared to cross-beded sandstone) → potential reservoir</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>sandstone, cross-beded</td>
<td>constant high energy conditions, possibly channel facies (estuarine, fluvial) or tidal influence → potential reservoir</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>sandstone, laminated</td>
<td>constant energy conditions, low/upper flow regime (lower flat bed/upper plane bed)</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>sandstone, soft sediment deformed</td>
<td>Sandstone deposited at top of unconsolidated finer sediments and collapsed probably in a marine environment → potential reservoir</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
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</tbody>
</table>
Table 2b: Facies (LFT) described after Bendias and Aigner (2015): sandstone, rippled, and rooted; heterolithics; mudrock, mudstone, thinly bedded, and massive.

<table>
<thead>
<tr>
<th>LFT</th>
<th>Key Attributes</th>
<th>Outcrop</th>
<th>Specimen</th>
<th>Thin Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone, rippled</td>
<td>Sandstone deposited under the influence of currents or wave energy. Can be used to reconstruct paleo-currents or paleocoastlines</td>
<td><img src="image1.png" alt="Image" /> 5 cm</td>
<td><img src="image2.png" alt="Image" /> 20 cm</td>
<td><img src="image3.png" alt="Image" /> 5 mm</td>
</tr>
<tr>
<td>sandstone, rooted</td>
<td>paleosoil, representing most proximal facies of the Mafraq, often associated with unconformities</td>
<td><img src="image4.png" alt="Image" /> 5 cm</td>
<td><img src="image5.png" alt="Image" /> 1 cm</td>
<td><img src="image6.png" alt="Image" /> 1 cm</td>
</tr>
<tr>
<td>Heterolithics, sandstone/mudrock</td>
<td>deposition proximal to shoreline in a terrestrial to lagoonal environment → potential seal</td>
<td><img src="image7.png" alt="Image" /> 10 cm</td>
<td><img src="image8.png" alt="Image" /> 1 cm</td>
<td><img src="image9.png" alt="Image" /> 1 cm</td>
</tr>
<tr>
<td>Mudrock</td>
<td>deposition proximal to shoreline in a terrestrial to lagoonal environment → potential seal</td>
<td><img src="image10.png" alt="Image" /> 10 cm</td>
<td><img src="image11.png" alt="Image" /> 1 cm</td>
<td><img src="image12.png" alt="Image" /> 1 cm</td>
</tr>
<tr>
<td>Mudstone, thinly bedded</td>
<td>low energy conditions, possibly low energy lagoon → potential seal</td>
<td><img src="image13.png" alt="Image" /> 10 cm</td>
<td><img src="image14.png" alt="Image" /> 1 cm</td>
<td><img src="image15.png" alt="Image" /> 1 cm</td>
</tr>
<tr>
<td>Mudstone, massive</td>
<td>compacted peloidal mud, low energy conditions (possibly lagoonal environment) → potential seal</td>
<td><img src="image16.png" alt="Image" /> 50 cm</td>
<td><img src="image17.png" alt="Image" /> 15 cm</td>
<td><img src="image18.png" alt="Image" /> 1 cm</td>
</tr>
</tbody>
</table>
Table 2c: Facies (LFT) described after Bendias and Aigner (2015): dolo-mudstone; wackestone; wacke-stone to packstone; packstone to grainstone; and grainstone and iron ooids.

<table>
<thead>
<tr>
<th>LFT</th>
<th>Key Attributes</th>
<th>Outcrop</th>
<th>Specimen</th>
<th>Thin Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>dolo-mudstone</td>
<td>shallow marine deposits, possibly restricted conditions, if karstified one</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wackestone</td>
<td>Moderate to low energy deposits from a lagoonal or foreshoal environment.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wacke-to</td>
<td>possible tempestites (grading lost due to bioturbation) or other event like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>packstone</td>
<td>deposition; deposition in high energy lagoon or foreshoal environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pack-to</td>
<td>possible tempestites; deposition in high energy lagoon or foreshoal environment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grainstone</td>
<td>shoal deposits or deposits from a very proximal oolitic/peloidal shoal →</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iron ooids</td>
<td>potential reservoir</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ooids formed in a high energy environment within range of wave energy. Deposited in a lagoonal environment. Replacement by iron may indicate subaerial exposure.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3: Section MS-2 in Wadi Sahtan, with logged Dunham Texture, lithologies, lithofacies types (after Bendias and Aigner, 2015), gamma-ray values, and marked occurrence of sandbodies S1 to S5.
Sandbody analysis

The geometry, architecture, internal structures, and facies successions of the various sandbodies were studied, supported by a petrographic analysis. Next to the geometrical aspects, the orientation of palaeocurrent indicators, like trough and ripple cross-bedding and tool marks, was measured.

Sandbody 1 (S1)

Sandstones of S1 are located circa 1.5 m above the base of the Mafraq Formation and occur in Wadi Sahtan on top of iron ooids-bearing carbonates, which are overlain by a conglomerate. S1 shows a lateral extent of less than 100 m and cannot be found in all sections. It has an erosive base and is truncated at the top by a conglomerate, resulting in strong thickness variations from 115 to 200 cm at Wadi Sahtan. In section HB, S1 has a thickness of around 5 m.

S1 (Fig. 4) shows a weakly channelised geometry and passes laterally into rooted sandstones and mudrocks. Unfortunately, lateral facies trends are hard to identify in S1 due to several faults in the studied outcrops with an offset of up to 2 to 3 m.

The individual sandstone units of S1, which occur laterally from time to time, show internally large-scale cross-beds (Fig. 4) with a subtle fining-up trend, contain small clay intraclasts at its base, and are separated by several-millimetre-thick mud beds (Fig. 4). They show trough cross-bedding, indicating bidirectional flow to the west and to the east (Fig. 5).

Sandstones of S1 are medium to coarse arenites. Each epsilon cross-bed shows a fining-upward trend with angular to subrounded quartz grains. While most of the sandstones are bound by a siliceous cement, an increasing amount of calcite and sometimes of clay can be observed in the upper part of S1.

**Figure 4:** Photo of S1 in outcrops of Wadi Shatan; S1 is not present in section MS-2 on the right. (A)–(D) Trough cross-beded sandstones intercalated with up to 2-cm-thick clay-rich beds.
Figure 5: (A) Laterally spaced series of sedimentological logs showing facies types and their weathering profile. They were logged in several sections along S1 with a spacing of 5 to 10 m; individual beds were traced laterally. (B) Wall panel of S1 showing several sandstone units eroding into each other. Internally, they show lateral accretion. Laterally to trough cross-bedded sandstones, rooted sandstones, and mudrocks can be observed. (C) Wall panel without vertical exaggeration.
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**Basal conglomerate**
A several-metre-thick conglomerate follows S1 (if present) and directly underlies S2 (Fig. 6). It is a polymict, orthoconglomerate with a fine to medium crystalline dolomite matrix. It forms a ca. 6-m-thick massive unit where channel geometries with subtle fining-up trends are observed sometimes. It comprises limestone and sandstone components (Fig. 6A). Clast size ranges from centimetres up to 3 m, especially sandstone clasts seem to constitute the larger components (Fig. 6B): 85% limestone, 7.5% dolomite, and 7.5% sandstone.

The thickness of the conglomerate increases from 1.5 m in Wadi Hail Bint in the east to up to 5.7 m in Wadi Sahtan leading to thickness variations of about 20% over hundreds of metres. In some places, large sandstone clasts with an extent of up to 3 m are present (Fig. 6C).

**Sandbody 2 (S2)**
The conglomerate is topped by sandbody 2 (S2), which is present in all four sections and thins to the east. Vertically, it turns gradually into dolomitic mudstone (Figs. 7A and 7B). Laterally, it can be followed in outcrops of Wadi Sahtan for at least 400 m. Thickness varies from 45 cm in Wadi Hail Bint to a thickness of 105–390 cm in Wadi Sahtan.

S2 can be subdivided into a lower and an upper part (Fig. 7). The lower part shows an erosive contact with the underlying conglomerate. It consists of convex-down-shaped sandstone units with a width of several metres and thickness variations from 0 to up to 3.1 m (Figs. 8A–8C). Occasionally, thin clay layers are present between the conglomerate and S2. The upper part of S2 is present in all sections and can be followed between sections MS-1 and MS-3. It has a more or less constant thickness of around 80 cm, slightly decreasing toward Wadi Hail Bint.

Internal sedimentary structures include finely laminated sands, which show fining-up and a horizon-tal lamination in the upper part of S2, but follow the convex-down shape in the lower part with a fining trend toward the centre (Fig. 7C).

Additionally, a transition from horizontally laminated sandstones (Fig. 8D) to finer, rippled and sometimes hummocky cross-bedded sandstones (Fig. 8E) can be observed in the upper part of S2. They are topped by dolomitic mudstones. Soft sediment deformation (Figs. 8F and 8G), bioturbation of *Arenicolites* (Fig. 8H), and parting lineation can be observed within the laminated beds. The orientations of current ripples indicate flow from southwest to northeast and have thus an orientation more or less parallel to the palaeo-coastline.

The grain size mainly varies between a medium to very fine arenite. Coarse arenites are often biotur-bated. Within the lower part of S2, a fining-up trend from the convex-down base inward from rudite to fine arenite was observed. Overall, sandstones of S2 are well to very well sorted and grains are generally angular. In contrast to the other sandbodies, S2 has a dolomitic cement.

**Sandbody 3 (S3)**
S3 lies on top of a 15-m-thick carbonate interval, 27 m above the base of the Mafraq Formation. It is separated from S4 by another carbonate interval of about 1–2 m (Fig. 3). S3 is present in all four sections and thins toward the east. In Wadi Sahtan, S3 has a more or less constant thickness of 325–350 cm and a lateral extent of at least 400 m. In Wadi Hail Bint, it thins to 135 cm.

The vertical architecture of S3 is very similar in all sections in Wadi Sahtan. It can be divided into a lower part, which is dominated by sandstones and mudrocks, and an upper part with alternating layers of sandstone and limestone (Fig. 9).

The lower part of S3 (Fig. 10A) starts with a rooted sandstone in Wadi Sahtan and a rooted siltstone in Wadi Hail Bint. Above, thin sandstone beds show trough cross-bedding and sometimes wave ripples. They are interbedded with millimetre-thick mud beds and followed by bioturbated sandstones. Trough
Figure 6: (A) Limestone, dolomite, and sandstone clasts within the conglomerate. (B) and (C) 3-m sandstone clast/channel within the conglomerate.

Figure 7: (A) Photo of S2 in the outcrop of Wadi Sahtan. Lines mark the upper and the lower boundary of S2 and internal bed boundaries. (B) Architecture of S2: underlying conglomerate (brown), sandstones of S2 (yellow), and a vertical transition into carbonates (blue). (Arrow) In some places, a fault plane forms the contact between the sandstone and the conglomerate. (C) Bedding planes of S2; fining-up trends follow the base of load casts in the lower part and the horizontal bedding in the upper part of S2.
Figure 8: (Top) Two-dimensional wall panel of S2 and overlying carbonates; facies were mapped via vertical logs with a spacing of 10 m if accessible. (Top right) Rose chart illustrating the dip direction of current ripple foresets pointing dominantly toward the NE (blue) and tool marks (arrow) in S2. (A) Photo of S2 in Wadi Sahtan. (B) S2 is located above a conglomerate (orange) and can be subdivided into an upper and a lower part. (C) The upper part consists of horizontally laminated sandstones, whereas the lower part consists of soft sediment deformed sandstones. (D) Horizontally laminated sandstones. (E) Current ripples (northeastward direction; see the rose chart). (F) Soft sediment deformation. (G) Ball-and-pillow structure in sandstone. (H) Trace fossil of Arenicolites. The orientation of current ripples, as shown in the rose chart on the top right, indicates a flow direction toward the northeast.
cross-bedding in the lower part dips toward the east and the west with a dominance into an eastward direction (Fig. 9; rose chart).

The upper part of S3 shows alternating layers of sandy carbonates (limestone and dolo-limestone) and wave-rippled sandstones (Fig. 9). At its base, carbonates and sandstones are intercalated. Where carbonates dominate, sandstone intercalations show starved current ripples and wave ripples. Wave-ripple crests show an orientation from the northwest to the southeast, indicating wave oscillations in northeast and southwest directions. Toward the top of S3, sand bed thickness increases and fewer carbonates are present.

S3 sandstones consist of well-sorted, fine arenite with grain diameters between 88 and 250 μm. Occasionally, very few well-rounded grains with a diameter of 500–710 μm are present. The rounding of quartz grains varies between angular to subangular. The grain size is higher (> 710 μm) exclusively at the base of the cross-bedded layers. Fine sandstones often show bioturbation.

Sandbody 4 (S4)

S4 is located 1–2 m above S3, overlying karstified dolostones and limestones. It consists of sandstones, carbonates, and a mix of both (Fig. 11). S4 can be traced laterally in Wadi Sahtan over a distance of at least 400 m. It has a more or less constant thickness in Wadi Sahtan of 420–480 cm but thins toward the east to 195 cm in section HB.

In contrast to S3, S4 is quite heterogeneous in its vertical and lateral architecture. Lateral changes in lithology from carbonates to sandy carbonates and pure sandstones are common (Fig. 12). Pure sand units tend to have lens-like sigmoidal geometries with a height of several decimetres and a lateral extent of up to 100 m in an orientation from the northwest to the southeast.

S4 shows an upward decreasing clay content with mostly sandstone heterolithics in the lower part and an upward increasing carbonate content with sandy dolomite in the upper part. Sandstones are bioturbated and show trough cross-bedding, especially where they are thickest. Sometimes, wave ripples are present. Lateral transitions from pure carbonates to sandy dolomites can be observed on a hundreds

Figure 9: (A) and (B) Starved current ripples in the upper part of S3. (C) Lithofacies types (LFT), lithology, and grain size of S3. Rose diagram illustrating the dip orientation of trough cross-bedding foresets (blue) and the strikes of wave ripple crests (yellow) in S3.
Facies distribution, depositional environment, and reservoir geometries of clastic sandbodies in the Lower Jurassic Mafraq Member (Oman Mountains, Sultanate of Oman)

Figure 10: (A) General appearance of the lower part of S3. It has a homogeneous vertical facies succession over a distance of 400 m with rooted sandstones at the base, followed by mudrocks, trough cross-bedded, and burrowed sandstones. (B) Zoom-in illustrating complex bed configuration on a 2-m scale.
of metre scale (Fig. 12). Trough cross-bedding indicates an orientation to the east–northeast and to the west–southwest (Fig. 11).

Most sandstones of S4 are coarse arenites. In individual beds, a fining-up trend to fine arenite or silt can be observed. In general, sandstones are poorly sorted and rounding varies from angular to rounded. Sandstones are predominantly cemented by quartz, although some calcite cement is present throughout.

**Sandbody 5 (S5)**

S5 is the uppermost and thickest of all sandbodies. It is separated from S4 by 3–4 m of carbonates, is the last sandstone unit within the Lower Mafraq Member, and is also followed by carbonate deposits. In sections MS-3 and HB, a thickness of 10–12 m can be observed. Due to bad outcrop conditions in sections MS-1 and MS-2, it could not be logged completely. It has a thickness of 1170 cm in section MS-3 and 1065 cm in section HB.

S5 appears more homogeneous than sandbodies 3 and 4 as no lateral lithological changes can be observed. It can be subdivided vertically into two to three units with a thickness of 3–4 m each, showing a fining-up trend from coarse to fine arenite and clay toward the top.

In some parts of the outcrop, individual fining-up units, each several metre thick, can be subdivided into bundles of sigmoidal shaped beds that dip from the upper right (NE) to the lower left (SW; Fig. 13). Single sigmoidal units have an average thickness of approximately 20–30 cm, possess a coarse base, are trough cross-bedded in the middle part, and turn into rippled and bioturbated sandstones at the top. The trough cross-bedding indicates flow to the northwest.

Low-angle, sigmoidal beds, with a larger lateral extent of tens to hundreds of metres are observed in S5 in the W–E oriented outcrop of Wadi Hail Bint (Figs. 14A and 14B).

Thin section analyses revealed a mainly siliceous cement. Fining-up trends range from a fine rudite, with a grain diameter of 2–3 mm at the base of a sigmoidal bed, to a very fine arenite with a grain diameter of 88–125 μm at the top of the cross-bedded parts (Figs. 13A–13H). Bioturbated sandstones show variable grain sizes ranging from fine to coarse arenite. Sorting within the fining-up trends increases upward from poorly sorted to well sorted. The grains are angular to subrounded, without a recognizable connection to grain size or sedimentary structures. Sometimes, rectangular fractures within individual quartz grains of S5 can be detected.
Figure 12: (Top) Vertical facies logs with a distance of ~10 m. The thickness of each unit was traced laterally in between sections to generate a wall panel. (Middle) Wall panel of S4, showing internal geometries. Pure sandstones (yellow) with sigmoidal geometries pinch out laterally into sandy dolomites. The sandstones are bioturbated and show sometimes trough cross-bedding. The location of outcrop photos (A, B, and C) is marked by red boxes. (A) Vertical succession of bioturbated sandstones, sandy dolomite, and trough cross-bedded sandstones (50% carbonates in vertical succession). (B) Lateral decrease in the thickness of sandy dolomite layers (30% carbonates in vertical succession). (C) No carbonates in between sandstone layers (0% carbonates in vertical succession).
Discussion

The above described sandbody geometries, their internal architecture, and trends in facies or grain size distribution allow the interpretation of their respective depositional environment.

Sandbodies

Sandbody 1

With less than 100 m, S1 has the smallest lateral extent of all five sandbodies. The epsilon cross-bedded units with internal trough cross-bedding are interpreted as lateral accretion along channels (Fig. 15A). Bidirectional trough cross-beds, together with mud drapes between the sandstone beds, indicate a tidal influence. Consequently, S1 is interpreted as tidal channel deposits incising into a mudflat of the intertidal zone (Figs. 15B and 15C). Mudrocks and sandstones found laterally might represent lower energy intertidal deposits. Rootlets indicate periodic sub-aerial exposure. The bidirectional orientation of trough cross-bedding in a westward and an eastward direction are more or less perpendicular to the reconstructed palaeo-coastline as interpreted by Ziegler (2001) and Bendias and Aigner (2015). The lateral extent of S1 is limited, and no connectivity of individual tidal channels was observed in outcrops.

Basal conglomerate

Bendias and Aigner (2015) suggested that dolomites in the Mafraq Formation in Oman indicate a very shallow marine depositional environment. Since the matrix of the conglomerate mainly consists of fine-grained dolomite, it is assumed that the conglomerate was deposited in a shallow marine environment. An amount of approximately 85% of limestone components indicates that a considerable amount of limestone had to be present before the deposition of the conglomerate occurred (Fig. 16A).

Lens-shaped units within the conglomerate might represent single or multiple amalgamated channels. The conglomerate is thus interpreted as a stack of individual mass flows, some of which appear chan-
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**Figure 14:** Photo of the lower part of S5 with highlighted sigmoidal beds and sedimentary structures interpreted as lateral accretion along channels in the lower part of S5. Red dots labelled from I to VIII represent the position of samples. Thin sections from these positions are shown below. (I) Thin section from bioturbated sandstone at the base of S5 (sorted, angular grains). (II, III, IV, V, and VI) Thin sections from the sigmoidal bed, which was sampled from bottom to top, show a clear fining-up trend. (VII and VIII) Sandstones from the top of the channel sequence possess greater variations in grain size and sometimes show bioturbation (VIII). Rose chart illustrates the dip orientation of trough cross-bedding foresets in S5.
nelised. Unfortunately, no clear indicators for an erosive base can be observed. Furthermore, lack of internal structures does not allow a clear interpretation or the determination of a possible flow direction (Figs. 6B and 6C).

Thus, the deposition of the conglomerate might have been caused by tectonic events, like earthquakes, causing mass flows, which eroded the underlying carbonates and parts of S1 (Fig. 16B). Several observed lens-shaped conglomerate units might represent channel geometries. Thus, it is likely that the conglomerate was formed by several mass flow events. At least four to five events can be recognized in the outcrop of Wadi Sahtan. Due to the significant decrease in thickness over a relatively small distance, the lateral extent of the conglomerate is estimated as only a few kilometres. The smaller thickness in Wadi Hail Bint and larger thickness in Wadi Sahtan (Fig. 16C) may point to a westward-oriented flow. A biostratigraphic analysis of selected limestone clasts indicates an Early Jurassic age (Bendias and Aigner 2015), which marks it clearly as a time equivalent of the Lower Mafraq Member and not of the underlying Marrat Formation, which seems to be only present in the subsurface of Oman (Bendias and Aigner 2015).

Figure 15: Sedimentary structures in Fig. 4 show prominent lateral accretion surfaces, dipping with downlaps onto basal erosion surface in Wadi Sahtan and are interpreted as lateral accretion surfaces of a tidal channel. Bidirectional orientation of trough cross-bedding indicates tidal influence. (A) Interpreted depositional environment: mud flat with tidal channels. (B) Green box: alternating series of cross-bedded sandstones and mud drapes as observed in outcrops; orange box: schematic diagram of the tidal channel with lateral accretion.
Sandbody 2

S2 can be traced laterally over a distance of 400 m in Wadi Sahtan. Since S2 is present in Wadi Hail Bint at the same stratigraphic position, a lateral extent of at least 4–5 km can be assumed.

Parting lineation and current ripples indicate unidirectional flow to the northeast and thus flow parallel to the palaeo-coastline. As suspension feeders, *Arenicolites* are typical for environments where currents keep the detrital food in suspension (Seilacher 1978); their burrows can be used as indicators for coastal deposits like mudflats to sandflats (Brasier and Hewitt 1979). Fining-up trends, an increase in sorting, as well as the input of more and more carbonates toward the top of S2, is interpreted as a transition into a marine/lagoonal setting. S2 is interpreted as a longshore bar (Slatt 2006).

The convex-down shaped lower part of S2 is interpreted as metre scale load casts or, more, specifically as ball-and-pillow structures (Weaver and Jeffcoat 1978; Qiao and Li 2008). The formation of these

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**Figure 16:** Schematic illustration of the formation of the conglomerate: (A) Deposition of S1 on top of iron ooids-bearing carbonates, followed by limestone deposition. (B) Eventually tectonically induced event led to the destabilization of these layers and caused a mass flow into a westward direction, eroding the underlying carbonates and parts of S1. (C) Lithological succession, now present in the outcrop of Wadi Sahtan and Hail Bint indicate a stack of individual flows that potentially channelized.
structures is initiated, according to Qiao and Li (2008), by the drainage of water out of saturated sand layers, which forced the beds to fold as a result of an upward flow of the liquefied sand. Weaver and Jeffcoat (1978) did experiments on water-saturated deposits and concluded that ball-and-pillow structures may be produced by subjecting saturated sediments to seismic shocks.

This interpretation is supported by the presence of shales between S2 and the underlying conglomerate, which collapsed due to the load of the overlying sands of S2. It is therefore presumed that a rather uneven top surface of the conglomerate was overlain by mud and shale, above which the horizontally laminated sandstones of S2 were deposited (Fig. 17A). Possibly an external trigger, e.g., a tectonic event (like an earthquake, eventually connected to the rifting in the east) led to the destabilization of the underlying, unlithified muds and shales, as well as the sands above, causing the sand to form load casts and ball-and-pillow structures into the underlying mud (Fig. 17B).

Previously to the deposition of the upper part, erosion had to occur to create another plane surface for the deposition of the horizontally laminated upper part of S2 (Figs. 17C–17E). The predominating horizontal lamination of the fine sandstones, in combination with fining-up trends, followed by ripple cross-bedded sandstones and the transition into carbonates, indicates a reduction of depositional energy and might thus be interpreted as a transgressive trend.
**Sandbody 3**

Since S3 is present in all three sections in Wadi Sahtan and at the same stratigraphic position in Wadi Hail Bint, a lateral extent of at least 4–5 km is assumed. Bidirectional flow and mud interbeds indicate tidal influence. Most of the cross-bedding troughs dip in a landward direction (east); thus, a flood-dominated environment can be assumed. In the lower part the thinning-up trend of beds, as associated with a facies shift from trough cross-bedded to bioturbated sandstones, indicate a reduction in energy, most likely caused by a transgression. The lower part of S3 is interpreted as tidal flat deposits.

In the upper part, the environment favoured carbonate deposition in a low-energy, lagoonal environment, interrupted by higher-energy sand sheets. An upward increase of sandstones points to a landward shift of the depositional environment and a general increase in energy. Wave ripples are orientated approximately parallel to the palaeo-coastline. Sandstones of the upper part of S3 are interpreted as wave-induced deposits. In general, S3 can be placed in a sand flat of the intertidal zone (Fig. 18).

**Sandbody 4**

S4 has a lateral extent of at least 400 m. As similar sandstones are present at the same stratigraphic position in Wadi Hail Bint, an extent of at least 4–5 km is very likely. An increasing sand content toward the east in Wadi Hail Bint indicates a possible sand input from the east. The observed mix of carbonates and sandstones was most likely caused by bioturbation, mixing pre-existing carbonate and sandstone layers. The sigmoidal sandstone units of the lower part are interpreted as the lateral accretion along tidal channels of a distal sand flat environment (Fig. 18). The environment is thus more complex than in S3. The overall depositional environment shows lateral shifts between the sand-, mixed-, and mud-flat environment of the intertidal zone, which is occasionally interrupted by almost pure sandstone deposits of tidal channels.

**Sandbody 5**

In contrast to sandbodies 1 to 4, the thickness of S5 does not decrease toward the east. Thus, a lateral extent of more than 4–5 km is very likely. Sigmoid within S5 are interpreted as lateral accretion along channels and are steeper and with a shorter lateral extent in the outcrop of Wadi Sahtan (SW–NE orientation) than in Wadi Hail Bint (W–E orientation; Fig. 19). Trough cross-beds dip to the northwest, thus

![Figure 18: Block diagram of a siliciclastic tidal flat showing a decrease in tidal influence from distal sand flats to more and more proximal mixed flat to mud flats and salt marshes (modified after Walker and James 1992).](image)
indicating transport from SE more or less perpendicular to the palaeo-coastline. Sometimes, mud inter-beds can be observed, indicating intermittent deposition. *Arenicolithes* traces point to a sandflat environment (Brasier and Hewitt 1979) or fluvial channels (Kennedy and Droser 2011). This and a typical architecture of the multistory channel system, as well as the orientation of troughs within the sigmoidal beds, lead to the interpretation that S5 represents an estuarine multistory channel system (Fig. 19).

Note that the orientation of all outcrops is more or less perpendicular to the palaeo-coastline, as interpreted by Bendias and Aigner (2015). This explains the absence of thickness variations of S5 over 4–5 km from east to west and makes it difficult to predict the width of the estuarine system. Furthermore, no detailed information about the width of S5 is available. Nevertheless, the constant thickness of around 11 m over a distance of 4–5 km indicates the highest reservoir volume for all sandbodies and a good reservoir potential for S5.

Figure 19: (A) Outcrop picture of Wadi Hail Bint showing S5 (dark red). (B) Low-angle, sigmoidal beds within S5 over a distance of tens to hundreds of metres. In contrast to Wadi Sahtan, the orientation of the outcrop wall is east to west. (C) Estuarine depositional environment. (D, left) Photo of the lower part of S5 from the outcrop in Wadi Sahtan, showing lateral accretion; (right) cross section of an estuarine channel. (E) The difference in width of the sigmoidal beds might be related to the orientation of the outcrops: more extensive sigmoidal beds in flow direction than perpendicular to it.
Sequence stratigraphic analysis
The colourful outcrops of the Mafraq Formation with their alternation of carbonates and sandstones reveal conspicuous cyclicity within the studied interval. The deposits of the Lower Mafraq have a thickness of approximately 100 m and range in age from Hettangian to Late Pliensbachian (biostratigraphic data from Bendias and Aigner 2015). Thus, a rough time span of 13.1 Ma (Ogg, Ogg and Gradstein 2008) to 14.5 Ma (Gradstein et al. 2012) and the charts in this book present the most up-to-date, international standard, as ratified by the International Commission on Stratigraphy and the International Union of Geological Sciences. This 2012 geologic time scale is an enhanced, improved and expanded version of the GTS2004, including chapters on planetary scales, the Cryogenian-Ediacaran periods/systems, a prehistory scale of human development, a survey of sequence stratigraphy, and an extensive compilation of stable-isotope chemostratigraphy. This book is an essential reference for all geoscientists, including researchers, students, and petroleum and mining professionals. The presentation is non-technical and illustrated with numerous colour charts, maps and photographs. The book also includes a detachable wall chart of the complete time scale for use as a handy reference in the office, laboratory or field. The most detailed international geologic time scale available that contextualizes information in one single reference for quick desktop access. Gives insights in the construction, strengths, and limitations of the

Figure 20: (A)–(C) Karstified carbonates. (D) and (E) Rootlets in sandstone.
Chapter 7

geological time scale that greatly enhances its function and its utility. Aids understanding by combining with the mathematical and statistical methods to scaled composites of global succession of events. Meets the needs of a range of users at various points in the workflow (researchers extracting linear time from rock records, students recognizing the geologic stage by their content can be assumed. Analyses of vertical facies successions enable the identification of cycles on three different scales: cycles, cycle sets (CSs), and high-frequency sequences (HFSs; after Kerans and Tinker 1997). Two to six cycles form one CS, and two to three CSs form one HFS. A simple calculation dividing the age of the Lower Mafraq through the number of apparent cycles indicates a duration of ~2.2–2.4 Ma for HFSs of ~0.8–0.9 Ma for CSs and ~0.24–0.27 Ma for cycles.

**Cycle bounding surfaces**

Bounding surfaces are mainly defined by erosional surfaces, which can be found at the base of sandstone units and the conglomerate, or beds that show signs of subaerial exposure, e.g., karstification or rootlets (Figs. 20A–20E). An example is the base Jurassic unconformity separating the Upper Mahil Formation and the Lower Mafraq Member. Around sequence and CS boundaries, an increased clastic input can be observed. For CSs and cycles, less obvious indicators are also important: dolomite tends to appear in a more proximal environment than limestone (as described by Bendias and Aigner 2015). Furthermore, textural facies changes indicate a proximal–distal trend, with an increasing biodiversity into the most distal, lagoonal facies. Thus, the maximum flooding was defined where carbonates have the maximum grain content.

**Cycles**

Up to 24 cycles were interpreted within the studied interval (Fig. 21). With a thickness of 0.4–4.0 m, they each comprise a time span of approximately ~0.24–0.27 Ma and represent the smallest scale of cyclicity. They often cannot be correlated over distances higher than tens of metres.

A typical lithological succession in carbonate-dominated areas is shown in Fig. 22A: mudrocks and dolomudstones are followed by massive and thinly bedded lime mudstones, which are karstified at the top. In carbonate-dominated intervals, an increased clay and/or quartz content or karstification indicates cycle boundaries. Limestones probably represent the maximum flooding in the context of a depositional trend from proximal dolomites to more distal limestones.

An example for sandstone-dominated deposits is shown in Fig. 22B: rooted sandstones and mudrocks are topped by cross-bedded and bioturbated sandstones. They are overlain by an alternating series of dolomite and rippled sandstones with some rooted sandstones on top.

Sand-dominated cycles only show carbonates around maximum flooding intervals. Erosional surfaces and exposure surfaces that often show rootlets are characteristic for cycle boundaries.

Cycles often show an increased clastic input with higher gamma-ray values around cycle boundaries and limestones with lower gamma-ray values around the maximum flooding. Cycles represent small-scale shifts of the depositional environment, which are expressed not only by lithological variations between carbonates and clastics but also by the presence of karst horizons and erosional surfaces. In context of a limited accommodation space setting, it is very likely that not all cycles (thickness of 0.4–4 m) are preserved in the sedimentary record. This might explain why the number of cycles varies from section to section.

**Cycle sets**

Up to eight cycle sets (CSs) were interpreted in the lowermost 40 m of the Mafraq Formation (Fig. 21). They range in thickness from 1.2 to 7.3 m. Each CS comprises a calculated timespan of ~0.8 – 0.9 Ma years and contains up to 6 cycles. CS boundaries are often erosive surfaces, are karstified, or show rootlets. The zone of maximum flooding is mostly located in carbonates that are deposited in a
Figure 21: Facies stacking pattern of MS-2, illustrating the shifts of the depositional environment of CSs and HFSs. Cycle definers: karst (black), rooting (red), siltstones and sandstones (yellow), and carbonates (blue).
more distal environment than sandstones. The gamma-ray pattern is only slightly linked to the CS signal and shows marginally higher values around CS boundaries due to an increased clastic input. CSs express shifts of the depositional environment from a subtidal/lagoonal environment (mainly carbonates) to the tidal flat (mainly clastics, which often show signs of subaerial exposure).

High-frequency sequences
Four high-frequency sequences (HFSs) were interpreted in the lowermost 55 m of the Lower Mafraq Member. The uppermost HFS has not been part of this study since it is not exposed in some of the sections. HFSs range in thickness from 1.8 to 17.5 m and comprise a calculated timespan of ~2.2–2.4 Ma. Each HFS comprises two to three CSs. HFS1: The lowermost HFS is situated right above the base Jurassic unconformity (Fig. 21). HFS1 starts with bioturbated, dark red, iron ooids-bearing dolo-limestones, which pass into rooted siltstones and sandstones of S1. The top of HFS1 is interpreted at the erosive base of the overlying conglomerate (Fig. 21). In section HB, where the conglomerate is thinnest, carbonates are present between S1 and the conglomerate. This led to the delineation of an additional CS in section HB. Iron-rich intervals (iron oolites) and rooted horizons show highest gamma-ray values.

Interpretation: The maximum flooding zone of HFS1 is interpreted within the iron oolites at its base, resulting in a very thin transgressive hemicycle. The transition from carbonates to sandstones of S1 is interpreted as the regressive hemicycle. The depositional environment changes from carbonates of a lagoonal setting to sandstones of proximal tidal channels (mud flat area). The erosive surface at the top of HFS1 explains thickness variations and the presence of an additional CS in Wadi Hail Bint.

HFS2: HFS2 begins at the base of the conglomerate, followed by orange sandstones of S2. Above, a 12 m interval of beige dolo-mudstones with some bluish limestones in the centre can be observed. These
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The depositional environment changes after the deposition of the conglomerate from coastal sandstone deposits, such as a longshore bar, to carbonates of the backshoal area (Bendias and Aigner 2015) and back to a horizon of rooted siltstone and sandstone of the tidal area. The high number of karstified and rooted layers at the top of HFS2 in section HB indicates intense subaerial exposure and might be the reason for the thickness decrease toward the east.

HFS3: The lower part of HFS3 is dominated by orange, mostly bioturbated dolo-limestones, which are interbedded with several dark red sandstone layers. These are not connected and have a lateral extent of only tens of metres. Above, sandstones of S3 and S4 can be found, separated by a laterally continuous layer of carbonates. On top of S4, several metres of carbonates (wackestones and packstones) are topped by siltstones in MS-1 and MS-2 and karstified carbonates in section HB. The gamma-ray signal of HFS3 is rather serrate, although higher values can be observed in the clastic intervals and around the top.

Interpretation: The zone of maximum flooding is situated in the carbonates above S4 where components such as bivalve, gastropods, peloids, and shell debris are most abundant. The depositional environment changes from sandstone deposits of the intertidal zone to carbonates of a lagoonal setting and to siltstones of the tidal area. Most of the karstified and rooted layers in the Lower Mafraq Member are located in HFS3, which indicates frequent subaerial exposure, especially in section HB. Thus, an overall very shallow marine environment with only minor fluctuations in sea level can be assumed.

Most HFSs are rise dominated that highlights the overall transgressive trend of the Lower Mafraq (Bendias and Aigner 2015). The HFSs represent shifts from clastic-dominated coastal environments around sequence boundaries to carbonate-dominated more distal environments around their maximum flooding intervals. A general trend throughout all three HFSs is presented in Fig. 21. Sandstones occur mostly in transgressive hemi-sequences and illustrate a shift from deposits of the supratidal area to the tidal flat and to more and more marine deposits. Carbonates constitute the most distal deposits of a subtidal/lagoonal environment around maximum flooding intervals. Regressive hemi-sequences are generally smaller and show a fast change from lagoonal carbonates to supratidal deposits.

Two-dimensional correlation

Three logged sections in Wadi Sahtan, with a lateral spacing of 200 m, and one section in Wadi Hail Bint, 4.4 km to the east, were correlated (Fig. 23). Identified stratigraphic cycles on two different scales (CSs and HFSs) supported by continuous outcrop gamma-ray logs enabled a sequence stratigraphic correlation of all four sections.

Karstified and rooted horizons, present at the same stratigraphic position in all four sections, as well as the base of the sandbodies, represent cycle and sequence boundaries. The datum was chosen in the upper part of the section at the sequence boundary between HFS3 and HFS4 (base S5) to illustrate changes in subsidence and accommodation space.

Unfortunately, it was not possible to correlate the sequences described here to a global signal since the chronostratigraphic placement, mainly based on biostratigraphy, does not provide the necessary resolution.

Correlation of high-frequency sequences

In all four sections, HFSs can be easily correlated due to well-developed sequence boundaries (e.g., exposure and erosional surfaces) and maximum flooding intervals. A decrease in thickness of sequences can be observed in section HB in the east. This is consistent with the observation of an increased number of karstified and rooted horizons in section HB and supports the proximal–distal trend from east to west as proposed by Bendias and Aigner (2015). Locally, thickness increases from west to east (MS-1 to MS-3) in Wadi Sahtan. This trend is not consistent in all HFSs (Fig. 23).
deposits represent the thickest carbonate interval within the studied sections. The top of HFS2 is composed of red and green rooted siltstones and sandstones. In the most eastern section HB, more rooted and karstified layers can be found. The gamma-ray pattern shows high values in clastic parts at the base and top of HFS2 and lower values around carbonates.

**Interpretation:** The maximum flooding is located in the grainiest part of the carbonate interval in a thin layer of wackestones and packstones (Fig. 21). The sequence boundaries are assumed at the erosive
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A decrease in thickness of sequences, as well as an increased number of karstified and rooted horizons in section HB, implies less accommodation space to the east. Since an increase in thickness of HFSs from west to east is not consistent in all three HFSs in Wadi Sahtan (Fig. 23), small-scale changes in topography might be assumed, whereas more extensive variations in thickness between both wadis display the overall trend.

Correlation of cycle sets
The number of CSs is nearly identical in all four sections, and they are very well correlatable. In HFS 1 (HFS1), the conglomerate above cuts deeper into underlying strata in section MS-2, decreasing the number of CSs by one. In HFS3, one CS pinches out laterally between the two wadis (Fig. 23). Furthermore, an increase in karstified and rooted beds in section HB and a decreased thickness of sandbody 3 can be observed in this section. Where carbonates are present, an increased thickness of CSs was observed. This is nicely illustrated within sandbody 4 in section MS-2 (Fig. 23).

Local occurrences of carbonates within sandstone-dominated intervals can be explained by local lows in the seafloor relief. Thus, the correlation lines of CSs seem to trace palaeo-relief surfaces and indicate a locally complex and diverse landscape.

Reservoir potential
According to the analysis of the sandbodies, the reservoir potential, as well as the net-to-gross ratio, varies significantly between all five sandbodies.

A rather small net-to-gross ratio has to be expected for the tidal channel deposits of S1. Mud drapes between sandstone beds decrease the internal connectivity. Consequently, S1 has to be assigned a low reservoir potential.

In the coastal sand deposits of S2 (such as a longshore bar), a rather large net-to-gross ratio can be assumed, despite the strong variations in thickness. Due to the tight dolomite cementation in outcrops however, only a limited reservoir potential can be assigned to S2.

Figure 24: Schematic diagram of geometries, orders of magnitude of thickness, and lateral extent of the sandbodies (strike line of the outcrops, illustrated here, and the palaeo-coastline have an angle of approximately 60°).
S3 has a low net-to-gross ratio due to a highly heterogeneous architecture with abundant mud inter-beds and a high degree of carbonate cementation.

With a very complex architecture and pure sandstones pinching out laterally after tens to hundreds of metres, a rather small connectivity and thus a limited net-to-gross ratio have to be assumed for S4. Tight carbonates and sandy carbonates within S4 may act as internal baffles. Due to the small potential reservoir volume and an uncertain connectivity of the sandstone lenses, S4 has a very poor reservoir potential.

Most of the sandbodies of the Lower Mafraq Member possess only a low reservoir potential, due to small net-to-gross ratios and uncertain connectivity (Fig. 24). Exceptions are the estuarine sandstone deposits of sandbody 5. With the highest thickness and a composition of almost pure sandstones, S5 has the highest reservoir potential of all five sandbodies.

**Conclusion**

All studied sandbodies were deposited in a shallow marine to coastal environment. Sandbody 1 is interpreted as tidal channels in the mud flat area of a tidal flat (S1, Fig. 15). No connectivity of the single channels could be observed. Sandbody 2 (Fig. 17) probably represents a longshore bar and appears to have a large lateral extent and volume. Sandstones of sandbody 3 are interpreted as deposits of the tidal flat located in the sand flat area (Fig. 18). S3 has a heterogeneous architecture with abundant mud inter-beds forming internal baffles. Sandbody 4 is interpreted as slightly more distal deposits than S3 in the transitional area from the intertidal to subtidal zone (Fig. 18). It has a very complex architecture with a mix of different lithologies and an uncertain connectivity of pure sandstone intervals. Sandbody 5 is interpreted as a possibly estuarine multistory channel system (Fig. 19C). With a constant thickness of around 11 m over a distance of 4–5 km, a large potential reservoir volume can be assumed. With this observed vertical succession of depositional environments, an overall transgression can be interpreted for the lowermost 40 m of the Lower Mafraq Member.

Cycles on three different scales were identified in the studied sections: “cycles”, cycle sets (CSs), and high-frequency sequences (HFSs). Commonly, two to six of the “cycles” form one CS and two to three CSs form one high-frequency sequence. HFSs and CSs are correlatable over hundreds of metres in Wadi Sahtan and to section HB, 4.4 km to the east. They were probably formed by allocyclic mechanisms, most likely sea-level fluctuations. Cycles were observed to often pinch out laterally over a distance of hundreds of metres and thus seem to be at least partly due to autocyclic shifts and therefore cannot be used for correlations. Sequence boundaries of high-frequency sequences and sometimes CSs are marked by increased gamma-ray values. They are mostly located at the base of sandstone intervals where karst or rootlets mark times of subaerial exposure.

A correlation based on gamma-ray logs only is not advisable for the lowermost 40 m of the Mafraq Formation. In particular, rooted horizons lead to gamma-ray peaks that cannot be correlated over a distance of 200 m since they seem to represent a regionally very limited signal and were probably formed by autocyclic mechanisms.

A decrease in thickness, a pinch out of cycles and one CS, as well as an increased number of karstified and rooted horizons to the east indicate a proximal–distal trend from east to west as described by Bendias and Aigner (2015). This can be explained with a decrease in accommodation space toward the east, which indicates more proximal conditions in the east. Although the thickness decreases about 20% from Wadi Sahtan toward Hail Bint and more proximal facies are present in the east, the main vertical lithological trends are similar in all sections. This points to a very flat gently inclined shallow marine environment.

Most sandbodies of the Lower Mafraq Member possess a rather low reservoir potential. An exception is sandbody 5 with a thickness of up to 12 m and a lateral extent of at least 5 km, representing the highest reservoir potential.
The described outcrop sections from the Oman Mountains can be used as an excellent analogue for the Mafrak Formation in the subsurface of Oman, where very comparable geometries and depositional environments were observed (Bendias and Aigner, in prep.). The observations from the outcrops can be used (1) in field development for a rough estimate of potential net-to-gross ratios and reservoir characterization and (2) to develop future exploration strategies in the subsurface of Oman.

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