Facies, sequence stratigraphy and reservoir/seal potential of a Jilh Formation outcrop equivalent (Wadi Sahtan, Triassic, Upper Mahil Member, Sultanate of Oman)

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ABSTRACT

The investigated Middle to Upper Triassic Upper Mahil Member, representing a Jilh outcrop equivalent in the Northern Oman Mountains, illustrates the proximal portion of a flat epeiric carbonate ramp. A sedimentological study of well-exposed outcrops in Wadi Sahtan may serve as a reference section for a sequence-stratigraphic framework and detailed facies description of the Upper Mahil Member. It also provides an insight into the seal and reservoir potential of carbonates in a low-accommodation inner ramp setting.

Outcrop observations and thin section analyses yielded 14 different lithofacies types ranging from a supratidal marsh to high-energy subtidal shoal environment. Vertical facies stacking patterns show three basic small-scale cycle motifs (fifth-order). While mud-rich backshoal cycles with claystone intercalations and rooted/bioturbated mud-/wackestones illustrate potential baffles and seal units around the center of the Upper Mahil, potential reservoir units occur stratigraphically in the upper part of the formation. There, a few meter-thick trough cross-bedded oolitic-/peloidal-rich grainstone depicts maximum accommodation within backshoal to shoal cycle types below the erosional base-Jurassic unconformity.

The investigated outcrop section in Wadi Sahtan was subdivided into nine almost complete third-order sequences. Two to four of these sequences are further stacked into three second-order super-sequences which are well reflected in the gamma-ray pattern. The highest reservoir potential occurs around second-order maximum floodings. Internal seals can be observed at third-order sequence boundaries where shales and muddy carbonates are up to 20 m thick.

A regional correlation with subsurface data from Yibal and Lekhwair in Oman shows that the apparent thickness changes in the Upper Mahil (Jilh) are mainly determined by the Late Triassic/Early Jurassic erosional truncation. The occurrence of thick anhydrite units in the subsurface indicates a more proximal setting towards the southwest.

INTRODUCTION

Permian–Triassic carbonates on the Arabian Peninsula of the Khuff, Sudair, Jilh and equivalent formations constitute deposits of a vast and flat epeiric carbonate ramp. Covering most of the Arabian Platform they form important hydrocarbon systems in the Middle East. Recent research in the Oman Mountains (Al Jabal Al-Akhdar area) on autochthonous Permian and Lower Triassic Khuff and Sudair equivalents delivered facies and sequence-stratigraphic descriptions that form reference points for correlation purposes with the subsurface (Koehrer et al., 2010; Pöppelreiter et al., 2011). However, very little work has been carried out in the Middle to Upper Triassic Jilh Formation so far with only few data on facies and sequence stratigraphy. This study aims to: (1) characterize the predominating lithofacies types, (2) establish a stratigraphic framework for the Jilh Formation based on litho-, chemo- and biostratigraphy and (3) investigate potential reservoir and seal units in this formation.
In order to investigate Jilh outcrop equivalent strata, which is referred to as Upper Mahil Member in outcrops of Northern Oman (Glennie, 2005; Koehrer et al., 2010; Forbes et al., 2010), an outcrop study was initiated in the Al Jabal Al-Akhdar area of the Sultanate of Oman. Since the Upper Mahil Member in Wadi Sahtan appeared to form stratigraphically the most complete succession in the Oman Mountains, the Wadi Sahtan outcrops were chosen as a reference section for the Upper Mahil. Wadi Sahtan is located approximately 130 km west-southwest of Muscat and cuts through the northern flank of the Al Jabal Al-Akhdar anticline (Figure 1) and exposes strata from the Proterozoic to the Cretaceous.

Paleogeographic reconstructions place the study area during Mid-Triassic times some 150 km away from the interpreted Arabian Platform margin in a restricted shallow-marine carbonate environment (Figure 2). The gradual northward drift of the Arabian Plate during the Triassic moved the area of investigation to latitudes from 25°S to 10°S (Stampfli and Borel, 2002). A broad restricted shallow-marine carbonate shelf developed with evaporites, shallow-marine carbonates and fine-grained clastics (Alsharhan, 1993; Ziegler, 2001) indicating a hot and arid climate.

Tectonically the Arabian Platform remained relatively stable during the Mid- and Late Triassic. Although the break-up of the Baid Platform north of Oman into smaller platforms and basins caused a change in paleogeography in the Hawasina Basin, the sedimentation on the carbonate shelf was only marginally affected by the tectonic events (Béchennec et al., 1988; Robertson and Searle, 1990). Thus, vertical facies stacking patterns are likely to be mainly steered by the low-amplitude and high-frequency sea-level oscillations typical for transitional to greenhouse conditions.

A major regression in the Late Triassic due to epeirogenic movement and a westerly tilting of East Oman during Early Jurassic times led to sedimentary hiatuses between the Triassic and Jurassic (Alsharhan, 1993; Coy, 1997). A prominent angular unconformity regionally observable on seismic data (personal communication, Brandenburg, 2010) illustrates an erosional truncation of underlying Permian–Triassic sediments and an eastward onlap of the Jurassic Mafraq Formation (Mountain and Prell, 1990). This erosional truncation severely affects the thickness of the Jilh (Upper Mahil) Formation.

Economically the Jilh and time-equivalent formations are not only of interest because of their oil- and gas-prone source rocks in Saudi Arabia (Hakami et al., 2007), or offshore in the United Arab Emirates where high total organic carbon contents of up to 5% were discovered in the Ghasha Field (Hassan, 1989), but also for its hydrocarbon shows in Oman (personal communication, Lewandowski, 2010), Bahrain and UAE (Loutfi et al., 1987). In addition the Jilh forms an important aquifer (Saeed et al., 2001) and causes drilling hazards in the Ghawar field in Saudi Arabia or in Bahrain due to high pressure zones (Mohamed and Khalaf, 1991; Zhou et al., 2009).

**STRATIGRAPHIC FRAMEWORK**

The Mahil Formation was defined by Glennie et al. (1974) in outcrops of Al Jabal Al-Akhdar, which Koehrer et al. (2010) subdivided into the Lower, Middle and Upper Mahil members (Figure 3). It conformably overlies the Saq Formation, which constitutes together with the Mahil Formation the Akhdar Group. The Saq Formation and the Lower Mahil Member represent a time-equivalent of the Khuff Formation, and the Middle Mahil Member an outcrop equivalent of the Sudair Formation (Koehrer et al., 2010; Pöppelreiter et al., 2011). The Upper Mahil Member, the focus of this study, can be considered as time-equivalent to the Jilh Formation in the subsurface of Oman.

In the region around Al Jabal Al-Akhdar the Upper Mahil conformably overlies dolomites of the Middle Mahil with a distinctive reddish exposure-related paleo-karst horizon marking the base of the Upper Mahil, which probably indicates a major sequence boundary (second-order). The 365-m-thick succession consists mainly of beige-gray dolomites with occasional dm-thick reddish to purple shale intercalations. The top of the succession is marked by an erosional unconformity, which can be traced by a distinctive lithological change from brownish carbonates to reddish siliciclastics. It illustrates the upper boundary of the AP6 megasequence and indicates the beginning continental break-up of the Permian–Triassic carbonate platforms (Sharland et al., 2001).
Figure 1: (a) Geological map of Northern Oman showing location of study area (Wadi Sahtan) (from Béchennec et al., 1993).
(b) Satellite photograph showing Wadi Sahtan cutting through northern flank of Al Jabal Al-Akhdar anticline (Landsat 7, Geocover 2000, NASA World Wind).
The type section of the Middle to Upper Triassic Jilh Formation is located at the Jilh al ‘Ishan Escarpment in Saudi Arabia (Latitude 24°03’28''N, Longitude 45°46’00''E) (Powers et al., 1966). There, the 326-m-thick succession consists of cross-bedded marine sandstones with limestone and shale interbeds capped by sandy oolite (Powers et al., 1966; Alsharhan, 1993). From southern and central Saudi Arabia towards the north immature siliciclastics with limestone intercalations turn into carbonate rocks with exposure-related shales and calcareous mudstones (Sharief, 1982, 1986). In the central United Arab Emirates the Gulailah (Jilh) Formation reaches a maximum thickness of more than 530 m and decreases towards the SE (Oman) and towards the NE (offshore Iran) (Alsharhan, 1993).

Comparisons of various publications, which discuss the Jilh or equivalent formations yield significant age differences (Figure 3). Sharief (1982) and Alsharhan (1993) place the Jilh (Gulailah) in the Mid-Triassic, covering a time interval of approximately 11 My. Maurer et al. (2008) indicate an Anisian to Early Carnian age for the Ghail Formation. According to Sharland et al. (2004), Al-Husseini and Matthews (2005) and Forbes et al. (2010), the Jilh reaches up to the Norian comprising in total about ca. 30 My. Missing Anisian strata was reported by Sharland et al. (2004) and is interpreted as time of non-deposition/erosion in the Arabian region. The reason for the discrepancies may result either from the lack or misinterpretation of biostratigraphic/palynological data, and/or from the locally varying tectonic history and the locally variable early Jurassic erosional downcutting (Mafraq unconformity).
METHODS

The study in Wadi Sahtan (Al Jabal Al-Akhdar) is based on four overlapping sections providing in total one complete 365-m-thick sedimentary succession of the Upper Mahil Member. Bases and tops of the individual sections are given in Universal Transverse Mercator (WGS84, UTM Q40) grid data (Figure 9). Lithology, Dunham texture, components, sedimentary structures and rock color were recorded with a resolution of 10 centimeters. The lithofacies types were classified according to the slightly modified lithofacies scheme of Pöppelreiter et al. (2011). Numerous outcrop photographs were taken to document the rock character. Rock samples for biostratigraphic and carbon/oxygen stable isotope analyses were collected every 2 to 3 meters. 191 dolomitic samples were used for carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) stable isotope analyses. 1 mg of each sample was pulverized and reacted with $100\% \text{H}_3\text{PO}_4$ at $70\,^{\circ}\text{C}$ for 2 hours. Isotope ratio measurements were accomplished with a Finnigan Delta S gas mass spectrometer MAT 253 (manufactured by Fa. Thermo Scientific) linked with a Finnigan Gasbench II. Data is reported in $\delta$-notation in permille ($\text{‰}$) relative to the known isotope reference Vienna Peedee Belemnite Standard (V-PDB) (Coplen, 1994).

Figure 3: Stratigraphic chart showing Lower, Middle and Upper Mahil and time-equivalent formations. The correlation of the Middle and Upper Mahil members with the latest Triassic Time Scale (Mundil et al., 2010) is a “best guess”, compiling available data from biostratigraphy, cyclostratigraphy and isotope stratigraphy. Arrow bars indicate the large uncertainties in the biostratigraphy.
Natural gamma radiation was measured every 0.5 m for 15 seconds using a portable spectral GR tool (model GS-256, manufactured by GeoFyzika A.S. Brno, Czech Republic). The tool is equipped with a 3x3” Sodium-Iodide (NaI(Tl)) scintillation detector. The GR spectrometer produces separate logs for total bulk GR (counts per second, cps), Uranium (U in ppm), Potassium (K in %) and Thorium (Th in ppm).

Since this study does not focus on quantitative aspects of the spectral gamma-ray but rather to capture large-scale gamma-ray trends on a regional scale, which are mainly determined by recurring shale input in a carbonate setting, a measure time interval of 15 seconds was found to be sufficient. (cf. Figure 18: subsurface Jilh correlation). We are aware that small-scale vertical facies changes cannot be expected to be detectable.

Thin sections were studied with standard petrographic techniques and all data of the logged sections were integrated in WellCAD 4.3.

**FACIES ANALYSIS AND INTERPRETATION**

Since the facies types of Permian and Triassic sequences in the Oman Mountains show many similarities, Pöppelreiter et al. (2011) established a lithofacies scheme that is applicable for the entire Akhdar Group (Saïq and Mahil formations). Correspondingly facies of the Upper Mahil were classified according to this scheme. Outcrop observations and thin section analysis revealed 14 different lithofacies types (LFT) for the Upper Mahil Member (Figures 4 to 6, Plates 1−14). Lithofacies associations range from supratidal marsh to subtidal high-energy shoal settings (Table 1, Figure 7). Collapse breccias related to karstification and rooted mud-/wackestones occasionnally with leached gypsum/anhydrite crystals constitute the most proximal facies and potential seal units. Trough cross-bedded oolitic/peloidal grainstones represent the most distal facies. Those represent together with microbial laminites and a particular type of intraclastic grain-rudstones associated with a peritidal environment potential reservoir facies in the Upper Mahil Member.

This section provides a detailed documentation of Upper Mahil lithofacies based on observations from outcrops and thin sections.

**Lithofacies Associations and Depositional Model**

Based on fossil assemblage and sedimentary structures the 14 lithofacies types (LFT) were grouped into five lithofacies associations (LFA), arranged along a flat epeiric carbonate ramp (Figure 7, Table 1):

1. LFA 2: Supratidal marsh,
2. LFA 3: Peritidal,
3. LFA 4A: Low-energy backshoal,
4. LFA 4B: Moderate-energy backshoal (leeward shoal-margin),
5. LFA 5: High-energy shoal. Due to the lack of facies-indicating fossils in the Upper Mahil the analysis of sedimentary structures is essential to assign lithofacies types to specific lithofacies associations.

**Supratidal Marsh Environment (LFA 2)**

Lithofacies of the marsh environment show typically vertical rooting structures, in places with downward bifurcations. Subaerial exposure and related carbonate karstification often results in in-situ brecciation and a reddish mottled appearance of the rock. Lenticular crystal molds in mud-wackestones result probably from leached gypsum/anhydrite crystals and indicate a sabkha overprint. Occasionally thinly interbedded mud-wackestones (LFT 2a, Plate 1), but more often karst associated dissolution surfaces (LFT 6f, Plate 2) and root cast surfaces (LFT 6e, Plate 3) determine the facies of the supratidal marsh environment. This facies association is often accompanied by higher potassium (K) and thorium (Th) radiation due to claystone intercalations and contains potential seal/baffle units.
Table 1
Integrated lithofacies associations (LFA) scheme after Koehrer et al. (2010) and Pöppelreiter et al. (2011) summarizing macroscopic and microscopic observations for each environment. Note: only LFA 2 to LFA 5 occur in the Upper Mahil Member in outcrops of the Al Jabal Al-Akhdar area.

| Facies Association       | Facies Types                              | Macrofacies                                      | Microfacies                                      |
|--------------------------|-------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| LFA 1: Coastal sabkha/salina | Coastal sabkhas developed during more arid conditions that promoted evaporite precipitation in hypersaline waters and supratidal sediments. | Nodular "chicken-wire" anhydrites; Brecia-associated anhydrites; Cavity-associated anhydrites. | Coalescing nodular (chicken wire textures); isolated anhydrite nodules within mudstone/wackestone matrix, bedded/laminated anhydrite with intercalated mudstone laminae. | Not observed in thin sections. |
| LFA 2: Supratidal marsh    | Coastal marsh populated with mangrove-like plants developed during more humid phases which promoted ponds, paleosols and karst features. | Laminated to massive claystones; Thinly interbedded mud/wackestones; Massive calcrites; Root cast surfaces; Dissolution surfaces. | Irregular karst surfaces, in-situ precipitation textures, color mottling reducing zones, root cast horizons, incipient paleosols (root casts locally filled by anhydrite), massive calcite/dolomite, locally bioturbated. | Rootlets, circumgranular cracks. |
| LFA 3: Peritidal           | Low-energy tidal flats surrounded by higher energy channels building in places beach ridges. The peritidal can become locally evaporitic during more arid phases. | Fenestra/microbial laminites, intraclastic pack-grainstones with laminate flakes. | Structureless to laminated mudstones, discontinuity surfaces, mudcackts, tepees, microcalites, fenestrae, rare ostracods and gastropods. | Microbial bindstone, micritic to microporous matrix. Fossiliferous fabrics, vadose silt, circumgranular cracks. Low diversity smaller forams (biseriamediums, rare milolids and lagenosids). Presence of "Calciophyes". |
| LFA 4A: Low-energy backshoal | Low-energy, shallow water, with semirestricted circulation of marine waters associated with backshoal to intershoal lagoons rarely influenced by storm washovers. | Laminated to massive claystones; Thinly interbedded mud/wackestones; Burrowed/rooted mud/wackestones; Finely to wavy laminated mud/wackestones; Graded wacke (mudstones (tempestites)). | Moderate to poorly sorted mud/wackestone, heterolithic mudstones, peloids, strongly bioturbated, normal grading, clay drapes, mudstone intraclasts, common gastropods, thin-shelled bivalves, ostracods and foraminifers. | Dasycladacean wacke-packstone, low diversity forams (common milolids and staffellids). Common algae Mizia, Velella, rare gymnocodiaceans. |
| LFA 4B: Moderate-energy backshoal | Moderate-energy, shallow to intertidal inner ramp on the leeward side of the shoal complex, dominated by frequent storm washovers and sediment winnowing. | Graded pack/wackestones (tempestites); Intraclastic rudstones with grainstone-clasts; Pleoidal-rich pack/grainstones; Skeletal-rich pack/grainstones; Bioclastic wacke/packstones. | Moderately sorted pack/grainstone, aggregate grains, cortoids and oncoids, variably bioturbated, normal grading, clay drapes, intraclasts, common gastropods, thin-shelled bivalves and foraminifers. | Cortiobial/peloidal pack-grainstone, abundant microbial precipitation with cortoids, aggregate grains and oncoids (cyanoabacteria, encrusting forams); diverse smaller forams and algae. |
| LFA 5: High-energy shoal   | High hydrodynamic energies above SWB characterised by active shoals, barriers and tidal bars dominated by wave and wind activity. | Cross-bedded oolitic/peloidal grays; well developed through and planar cross stratified, high diversity fauna of gastropods, thick-shelled bivalves, Bryozoans, corals, shell debris highly abraded. | Moderately well sorted, peloidal and oolitic grainstones, well developed through and planar cross stratified, high diversity fauna of gastropods, thick-shelled bivalves, Bryozoans, corals, shell debris highly abraded. | Oolitic/peloidal grainstone with rare smaller forams. |
| LFA 6: Moderate-energy foreshoal | Moderately low to locally high-energy, deeper subtidal mid- to outer ramp between FWWB and SWB. Open circulation of fully marine waters, dominated by frequent storms. | Pack/grainstone (tempestites); Intraclastic rudstones with grainstone-clasts; Pleoidal-rich pack/grainstones; Skeletal-rich pack/grainstones. | Moderately to poorly sorted graded wackestones to packgrainstones, well developed low-angle lamination and HCS, normal grading, post event bioturbation, locally hardground development, abundant peloids, shells, intraclasts, foraminifers, coroids and algae. | Bioclastic pack/grainstone; diverse smaller and larger benthic forams, mixed algal assemblages. Gymnocodiacean (Pemocyclus) wacke/packstone; low diversity forams (staffellids and milolids). |
| LFA 7: Low-energy offshore  | Moderately low to low-energy, deep subtidal outer ramp below SWB with strongly varying oxidation, reduced circulation and low sedimentation rates. | Bioclastic pack/grainstones; Skeletal/coral floatstones. | Poorly sorted skeletal/floatstone/packstones and bioclastic mud/wackestones, strong bioturbation including a minor amount of preserved burrows and feeding structures, rare bivalves (foraminifers, corals, shell, peloids). | Bioclastic floatstones, coral/sponge/algal boundstones, diverse forams and algae. |

Peritidal Environment (LFA 3)
Cm- to dm-thick microbial laminites (LFT 3a, Plate 4) with tepees, fenestrae and in places mud cracks illustrate the most dominant lithofacies in a low-energy peritidal setting. Intraclastic packstones (flat-pebble conglomerates) (LFT 5b1, Plate 5) indicate short-term high-energy storm events or tidal channels reworking microbialites and mudstones. Trough cross-bedded intraclastic grain-rudstones (LFT 5b2, Plate 6) form peculiar, up to several meter-thick units that may be interpreted as high-energy beach ridge-like deposits. If present, fossils are rare and consist of ostracods and gastropods. The peritidal setting ranges from tidal flats to shallow subtidal lagoons (Wright, 1984). Fenestral porosity in microbial laminites and interparticle porosity in cross-bedded intraclastic grainstones highlight the peritidal setting as potential hydrocarbon reservoir. Onlap geometries common in peritidal sequences can additionally favor the development of stratigraphic traps (Wright, 1984).
| LFT | Description | Interpretation |
|-----|-------------|----------------|
| 1a. Laminated to massive claystone | Texture: mudstone | Low-energy backshoal (LFA 4A) or pond deposits with moderately to high organic content. |
|    | Mineralogy: claystone, shale (dolo-) marlstone |    |
|    | Color: reddish, purple, greenish-gray |    |
|    | Sedimentary Structures: thinly laminated, rare bioturbation traces, dissolution seams, form often mudcrack infillings |    |
|    | Components: absent |    |
|    | Grain size: lutite - siltite |    |
|    | Sorting: very well |    |
|    | Thickness: cm- to dm thin beds |    |
| 2a. Thinly interbedded mud/wackestone | Texture: mudstone, wackestone | Low-energy shallow subtidal deposits of a protected backshoal (LFA 4A) setting. |
|    | Mineralogy: dolomite, (dolo-) marlstone |    |
|    | Color: beige-brown to gray |    |
|    | Sedimentary Structures: mm- to cm-scale thinly bedded units, erosive bases, may show mudcracks on top, small-scale wave ripple common, bioturbation burrows rare |    |
|    | Components: peloids, skeletal debris, intraclasts |    |
|    | Grain size: siltite - fine arenite |    |
|    | Sorting: moderately sorted |    |
|    | Thickness: dm-thick beds |    |
| 3a. Burrowed mud/wackestone | Texture: mudstone, wackestone | Shallow subtidal low-energy backshoal (LFA 4A) setting. Reduced circulation and/or low sedimentation rates. |
|    | Mineralogy: dolomite |    |
|    | Color: light beige, gray (mottled appearance) |    |
|    | Sedimentary Structures: burrows often indicated by particle- and mud-rich patches, may form 'tubular tempestites', vugs common, geopetal fabrics (stromatolite-type), spreiten structures, rarely relict lamination |    |
|    | Components: skeletal debris, peloides, intraclasts |    |
|    | Grain size: siltite - fine arenite |    |
|    | Sorting: moderately sorted |    |
|    | Thickness: dm-thick beds |    |
| 4a. Fenestral/microbial laminites | Texture: boundstone | Low- to moderate-energy peritidal (LFA 3) deposits (may also be associated to shoal exposure). |
|    | Mineralogy: dolomite |    |
|    | Color: light gray-whitish |    |
|    | Sedimentary Structures: mm-thin crinkly to wavy bedded laminae, cm-scale tepee structures, 'birds-eyes', desiccation cracks, rarely bioturbated, interbeddings of reworked flat pebbles, stromatolite heads common |    |
|    | Components: peloids, flat pebbles (intraclasts), skeletal debris |    |
|    | Grain size: siltite |    |
|    | Sorting: moderately to poorly sorted |    |
|    | Thickness: cm- to dm-thick beds (rarely up to m-thick units) |    |
| 5a1. Graded wacke-to mudstone | Texture: wackestone - mudstone | Low- (LFA 4A) to moderate-energy (LFA 4B) distal storm deposits above storm wave base. |
|    | Mineralogy: dolomite |    |
|    | Color: brown-beige, light gray |    |
|    | Sedimentary Structures: thin normally graded interbedding of grainy and muddy beds, wavy lamination and scooped beds common, muddy topsets, escape structure and post-event bioturbation traces |    |
|    | Components: skeletal debris, intraclasts, peloids, cortoids, black pebbles |    |
|    | Grain size: siltite-medium arenite |    |
|    | Sorting: moderately sorted |    |
|    | Thickness: cm- to dm-thick beds |    |

Figure 4: Lithofacies description and interpretation – part 1.
### Figure 5: Lithofacies description and interpretation – part 2.

| LFT | Description | Interpretation |
|-----|-------------|----------------|
| 5a1 | Graded pack-to-wackestone | Moderate-energy (LFA 4B) proximal storm deposits above storm wave base. |
| 5a2 | Graded pack-to-wackestone | Moderate-energy shallow subtidal storm deposits, associated to muddy peritidal (LFA 3). |
| 5b1 | Intraclastic packstone with mud/laminite flakes | High-energy to moderate-energy peritidal deposits (channel fills, washover lobes, beach ridges) (LFA 3). |
| 5b2 | Intraclastic grain-/rudstone | Moderate- to high-energy shallow subtidal environment adjacent to shoais (LFA 4A, LFA 4B). |
| 5c1 | Peloidal-rich pack-/grainstone | Moderate- to high-energy shallow subtidal environment adjacent to shoais (LFA 4A, LFA 4B). |
| 5c2 | Skeletal-rich pack-/grainstone | Moderate- to high-energy shallow subtidal environment adjacent to shoais (LFA 4A, LFA 4B). |
| LFT | Description | Interpretation |
|-----|-------------|----------------|
| 5d1 | Cross-bedded oolitic grainstone | **Proximal incipient to fully developed shoal complexes within the high-energy mid-ramp environment (LFA 5).** |
| | Texture | grainstone |
| | Mineralogy | dolomite |
| | Color | brown-beige, brown-gray |
| | Sedimentary Structures | trough cross-bedding, erosive bases, in places normal grading, bioturbation rare, but intense |
| | Components | ooids (>50%), peloids, intraclasts |
| | Grain size | fine arenite (common) - coarse arenite (rare) |
| | Sorting | very well to well sorted |
| | Thickness | dm- to m-thick beds |
| 5d2 | Cross-bedded peloidal grainstone | **Proximal incipient to fully developed shoal complexes within the high-energy mid-ramp environment (LFA 5).** |
| | Texture | grainstone |
| | Mineralogy | dolomite |
| | Color | beige-brown, gray, brown-gray |
| | Sedimentary Structures | trough cross-bedding, erosive bases, in places normal grading, bioturbation common and intense |
| | Components | peloids (>50%), ooids, shells, cortoids, intraclasts |
| | Grain size | fine arenite (common) - coarse arenite (rare) |
| | Sorting | very well to well sorted |
| | Thickness | dm- to m-thick beds |
| 6e | Root cast surface | **Supratidal pond/incipient paleosoil deposits of a coastal marsh environment (LFA 2).** |
| | Texture | mudstone, wackestones |
| | Mineralogy | dolomite, (dolo-) marlstone |
| | Color | light beige, yellowish, pinkish-reddish |
| | Sedimentary Structures | densely rooted, roots may show bifurcation, circumgranular cracks, color mottling reducing zones, in-situ brecciation, bioturbation common, geopetal fabrics (stromatolites) |
| | Components | shell debris, intraclasts, black pebbles |
| | Grain size | siltite-arenite |
| | Sorting | poorly sorted |
| | Thickness | cm- to dm-thick beds |
| 6f | Dissolution surface | **Supratidal diagenetic overprint of pre-existing facies developed in a coastal marsh (LFA 2) environment (may also be associated to shoal exposure).** |
| | Texture | mudstone, wackestones |
| | Mineralogy | dolomite, (dolo-) marlstone |
| | Color | beige gray, whitish, pinkish-reddish |
| | Sedimentary Structures | in-situ brecciation, irregular karst surfaces, collapse structures, locally bioturbated, vugs (stromatolites), circumgranular cracks, shrinkage cracks |
| | Components | shell debris, intraclasts, peloids |
| | Grain size | siltite-arenite |
| | Sorting | poorly sorted |
| | Thickness | dm-thick beds |

*Figure 6: Lithofacies description and interpretation – part 3.*
Figure 7: Conceptual 3-D facies model for the Upper Mahil Member illustrating a flat epeiric carbonate ramp. Colors of facies associations are kept consistent throughout this paper.

Plate 1: LFT 2a – thinly laminated mud-/wackestone; (a) Outcrop photograph of a small mud crack (red arrow) within a thinly laminated dolo-mudstone; (b and c) thin sections of horizontally layered dolomites with rare burrows; (d) close-up of fine-grained mudstone (calcisiltite) showing small erosion marks at base of grainy laminae (green arrows).
Plate 2: LFT 6f – dissolution surface: (a) pinkish karst horizon; (b) collapse feature indicating an exposure event; (c and d) outcrop and detailed thin section photographs of mudstones with leached lenticular anhydrite/gypsum crystals; (e and f) thin sections showing diffuse dissolution phenomena and collapse features; (g and h) close-ups of circumgranular cracks (red arrow) suggesting a paleosol environment.
Plate 3: LFT 6e – root cast surface: (a) roots up to half a meter in length penetrate a thick wackestone unit from above; (b) rootlets on cm-scale within a pinkish mudstone exhibit bifurcations (red arrows); (c) thin section of a rooted mudstone; (d and e) thin section close-ups showing rootlets with bifurcations (red arrow); Note: rooted mudstones are often associated with stromatolites-like vugs.
Plate 4: LFT 3a – fenestral/microbial laminite: (a and b) crinkly lamination with tepee structures (green arrows) indicating intermittent subaerial exposure; (c) stromatolitic microbial head; (d) thin section with mud crack (red arrow); (e) reworked microbial laminite (yellow arrow) (flat-pebble conglomerate); (f and g) oncoid/stromatolite feature in thin section; (h) close-up of calcite-filled fenestral vugs and peloids.
Plate 5: LFT 5b1 – intraclastic packstone with mud/laminitite flakes: (a and b) flat-pebble conglomerate with imbricated mud clasts in outcrop; (c and d) thin section photographs of reworked microbial laminites with laminitite flakes; (e) close-up of microbially agglutinated peloids and cortoids. Red arrow points to an ostracod.

Low-energy Backshoal Environment (LFA 4A)
The low-energy backshoal environment is dominated by moderately to poorly sorted bioturbated lithofacies, which range from laminated to massive claystones (LFT 1, Plate 7) to thinly interbedded (LFT 2a, Plate 1) and burrowed mud-wackestones (LFT 2b, Plate 8). Occasional storm washovers in the low-energy lagoonal setting are reflected as normally graded wacke- to mudstones (LFT 5a1, Plate 9). Abiogenic components such as peloids and mud-intraclasts dominate. Macrofossils such as gastropods, thin-shelled bivalves and ostracods appear only sporadically. The low-energy backshoal environment occurs in a protected lagoonal setting behind shoal complexes.

Moderate-energy Backshoal (leeward shoal-margin) Environment (LFA 4B)
Frequent storm washovers from a shoal complex give rise to moderately sorted bioclastic-rich pack-grainstones (LFT 5c1, 5c2, Plates 10 and 11) shed into a leeward shoal-margin setting. Oncoids, cortoids and aggregate grains reflect periodic water agitation under the influence of microbial activity. Dm-thick normally graded pack- to wackestones (LFT 5a2, Plate 12) comprise gastropods, bivalves and intraclasts with occasionally wave ripples on top. These beds are interpreted as proximal tempestite sheets or spill-over lobes. Intraclastic rudstones/grainstones (LFT 5b2, Plate 6) with grainstone intraclasts indicate a moderate-energy shallow subtidal environment adjacent to high-energy shoals.
Plate 6: LFT 5b2 – intraclastic grain/-rudstone: (a) Cross-bedded intraclastic grainstones presumably deposited in a 'tidal flat shoal' environment; (b and c) outcrop photographs of mud-intraclastic grain/rudstones; (d) elongated oncoids (red arrows); (e) thin section with large (microbial-)intraclasts shows interparticle porosity; (f) thin fining upward laminae; (g) better sorted intraclastic grainstone.
Plate 7: LFT 1 – laminated to massive claystone: (a) Outcrop picture showing a reddish nodular claystone bed; (b) Thinly laminated pinkish claystone fills dm mud cracks (red arrows); (c) dm-thick claystone deposits trace former mud cracks on top of a rooted mudstone (d); (e) thin section photograph illustrates brecciation features and bioturbation traces (f) within a clay layer.
Plate 8: LFT 2b – burrowed mud-/wackestone: (a) Bioturbation features on bed surface; (b) outcrop photograph of a strongly bioturbated dolo-mud-wackestone; (c) spreiten structures within a highly dolomitized mudstone; (d) burrow filled with skeletal debris (tubular tempestite); (e) thin section photograph of spreiten structures.

High-energy Shoal Environment (LFA 5)

High-energy shoals are represented as trough cross-bedded peloidal-/oolitic-rich grainstones (LFT 5d1, 5d2, Plates 13 and 14). Half meter to several meters thick grainstone packages show amalgamation and cannibalism of previously deposited grain-dominated deposits. Although the grainstones consist mainly of abiogenic components (ooids, peloids and intraclasts), the occurrence of foraminifera in certain stratigraphic positions indicates occasionally more open-marine conditions. Grains range in size from fine to medium arenite and are well to very well sorted. Shoals occur typically above fair-weather wave base in a mid-ramp setting and represent potential reservoirs.

Although crinoids were found in a thin bed indicating more open-marine conditions, the foreshoal environment is not explicitly described since it is interpreted exclusively for this small unit.
Plate 9: LFT 5a1 – graded wacke- to mudstone: (a and b) outcrop pictures of thin graded laminae with wave ripples (red arrow) and erosive bases (green arrow); (c) thin section photograph of a mud-wackestone consisting mainly of cortoids and skeletal debris (distal tempestite); (d) thin section of a wackestone (tempestite) with peloids, ooids, cortoids and black pebbles. Components were presumably dispersed by post-event bioturbation.
Plate 10: LFT 5c1 – peloidal-rich pack-/grainstone: (a) bioturbated peloidal packstone; (b) close-up of a strongly dolomitized peloidal packstone with cortoids; (c) heavily bioturbated peloidal packstone in thin section; (d and f) very well sorted peloidal pack-grainstone with cortoids and occasionally ooids; (e) peloidal packstone with (g) circumgranular cracks (red arrow), and (h) stromatactis-like vugs. Microbial overprint and circumgranular cracks point to a paleosoil environment. Note: Dissolution features in lower part of thin section (e) point to karstification.
Plate 11: LFT 5c2 – skeletal-rich pack-/grainstone: (a) bivalve-rich packstone; (b and c) crinoids, skeletal debris and peloids within a packstone. Note: crinoids occur exclusively in a dm-thick layer at section meter 255; (d and e) thin section photographs of various skeletal-rich packstones with bivalve and gastropod shells; (f) close-up picture showing geopetal fabrics in gastropods and ostracods; (g) vertically oriented shells surrounded by peloids indicating wave influence during time of deposition.
Plate 12: LFT 5a2 – graded wacke- to packstone: (a) hummocky-cross stratification within dm-thick storm deposits; (b) post-event bioturbation at top of fine-grained graded beds; (c) alternation of cm-thick grainy storm beds with sharp bases and thinly laminated mud-wackestones; (d) wave ripples (red arrow) on top of graded packstone; (e and f) thin section photographs of graded pack- to wackestones showing in places post-event bioturbation features; (g) close-up of a geopetal fabric within a gastropod shell; (h) close-up of vertically oriented shells indicating the influence of waves during deposition.
Plate 13: LFT 5d1 – cross-bedded oolitic grainstone: (a) outcrop photograph of a meter thick cross-bedded oolitic grainstone; (b) close-up of trough cross-bedding; (c) close-up of ooids; (d) thin section of grainstone dominated by ooids, subordinate bivalve shells and well-rounded intraclasts; Close-ups of a tangential (concentric) ooid (e) and a radial ooid (f).
Plate 14: LFT 5d2 – cross-bedded peloidal grainstone: (a) brownish peloidal grainstone with sharp erosive base; (b) dm-thick trough cross-bedded strongly dolomitized peloidal grainstone in outcrop; (c) thin section photograph of a well-sorted peloidal grainstone with occasionally ooids, rounded mudclasts and skeletal debris; (d) close-up showing peloids, rounded intraclasts, undefined shell debris and few ooids.

VERTICAL FACIES STACKING PATTERN AND SEQUENCE STRATIGRAPHY

Already from the far distance, rocks of the Upper Mahil show a striking multi-scale cyclicity, which appears remarkably regular and systematic (Figure 8). Since the Mid-Triassic is characterized by relative tectonic quiescence in the studied region (Dercourt et al., 1993; Konert et al., 2001), vertical facies stacking patterns are most likely mainly controlled by sea-level changes.
Figure 8: The multi-fold cyclicity of the Upper Mahil Member is well reflected in the outcrop weathering profile. Yellow brackets: small-scale cycles, black brackets: cycle sets, red brackets: sequences.
Figure 9: See facing page for continuation.
The cyclic facies successions are grouped into the following orders:

(1) **Small-scale Cycles:** The smallest sets of genetically related facies which can be observed in outcrops are small-scale cycles, that are only several decimeters to a meter-scale; a rough calculation based on the total age data would suggest that these cycles comprise ca. 100,000 years falling into the fifth-order of cyclicity (cf. short eccentricity cycles of Szurlies, 2007). Three different types of small-scale cycles (fifth-order) could be observed in the Upper Mahil Member similar to the cycle types described from the underlying Middle Mahil Member (Pöppelreiter et al., 2011). Small-scale cycles in the Upper Mahil, however, are less thick (<1 to 4 m) and show more exposure-related features such as rootlets, mud cracks and tepees which were not or only rarely observed in the Saiq Formation or Lower and Middle Mahil members.

(2) **Cycle Sets:** Packages of 3 to 5 of the small-scale cycles build cycle sets, several meters to tens of meters in thickness. A lower number of cycles occur around higher-order (super)-sequence boundaries (second- and third-order) and may hint to missing cycles in the sedimentary record due to erosion or non-deposition. Cycle sets may be interpreted to represent 405,000 years Milankovitch cycles (fourth-order). Depending on their lateral position along a flat epeiric carbonate ramp, two different types of cycle sets are distinguished: (a) Marsh to Low-energy Backshoal Cycle Set and (b) Low-energy Backshoal to Shoal Cycle Set.

(3) **Sequences:** The Upper Mahil Member in Wadi Sahtan consists of 40 cycle sets, which may be grouped into 9 sequences, each some tens of meters in thickness. These sequences (third-order) can be correlated over tens of kilometers in the entire region around Al Jabal Al-Akhdar.

(4) **Super-sequences:** The entire studied section is made up of three second-order super-sequences, each with an average thickness of 100 m, and comprising two to four third-order sequences. The super-sequences are very well reflected in the gamma-ray pattern with low GR values around zones of maximum flooding and high gamma radiation around sequence boundaries.

Jilh super-sequences (JSS) are numbered from top to bottom with increasing numbers (JSS-1, JSS-2, JSS-3). Third-order sequences within JSS-1 are named JS-1.1, JS-1.2, etc. in descending order. Sequences within JSS-2 and JSS-3 are numbered accordingly (Figure 9).

### Small-scale Cycles (Fifth-order)

Depending on their stratigraphic position small-scale cycles in the Upper Mahil Member range in thickness from 0.6 to 6 m and can be grouped into three different cycle types: (1) Muddy Backshoal Cycle Type; (2) Grainy Backshoal Cycle Type, and (3) Shoal to Backshoal Cycle Type.

![Figure 9 diagram](http://pubs.geoscienceworld.org/geoarabia/article-pdf/17/3/5446132/obermaier.pdf)

Figure 9 (continued): Complete Upper Mahil section with stratigraphic subdivisions and corresponding sequence numbering. Left column presents GPS coordinates for bases and tops of the 4 overlapping sections. Foraminifera and tentative ages are given in the right columns.
**Muddy Backshoal Cycle Type**

The muddy backshoal cycle type (Figure 10) constitutes the most proximal facies stacking pattern in the Upper Mahil and ranges in thickness from 0.6 to 6 m. Purple to reddish shales (LFT 1) with typically no faunal content predominate in the early transgressive hemicycle which turn during further transgression into beige thinly laminated mud-wackestones (LFT 2a). The maximum flooding surface (mfs) is interpreted at the top of the thickest dolomite bed consisting of thin graded laminae of wacke-packstone texture (LFT 5a1/2). The predominantly skeletal debris-rich laminae with erosive bases are interpreted as thin storm deposits. During relative sea-level fall bed thickness decreases and bioturbation gets more intense (LFT 2b). The upper cycle boundary is often marked by a rooted mud-wackestone (LFT 6e) indicating a marsh environment. Mud cracks, sometimes filled with shales from the subsequent cycle indicate severe exposure.

**Grainy Backshoal Cycle Type**

This asymmetrical cycle (Figure 11) is typically 1–3 m thick. Bioturbated wackestones (LFT 2b) with occasional shale intercalations (LFT 1) characterize the early transgressive hemicycle. Graded wacke-packstones (LFT 5a1/2) with in places wave ripples indicate an increase of energy and
accommodation space. Decimeters-thick cross-bedded oolitic/peloidal grainstones (LFT 5d1/2) around maximum flooding are interpreted as spill-over lobes deposited in a leeward shoal-margin (moderate-energy backshoal) environment. Sedimentary structures such as microbial laminae with tepees (LFT 3a) or mud cracks in muddy bioturbated facies (LFT 2b) exhibit subaerial exposure at the top of the cycle.

**Shoal to Backshoal Cycle Type**

Brownish bioturbated wackestones (LFT 2b) occur within shoal to backshoal cycles (Figure 12) during early transgressive phases. Overlying dm-thick bioturbated pack-grainstones with gastropod and shell accumulations (LFT 5c2) turn upwards into meter-thick oolitic/peloidal grainstones, which are interpreted as the interval of maximum flooding (LFT 5d1/2). The well-sorted trough cross-bedded grainstones with sharp erosive bases are interpreted as high-energy shoal deposits, which gradually turn into bioclastic-rich packstones of a leeward shoal-margin environment during the regressive hemicycle. The top of the cycle is typically marked by a muddy facies type (LFT 2a/b). This commonly 2–6-m-thick cycle type has the highest reservoir potential.
Medium-scale Cycle Sets (Fourth-order)

Three to five of the small-scale cycles are commonly stacked into cycle sets. Coarsening/fining-up trends are well reflected in the gamma-ray pattern (Figure 13) and outcrop weathering profile (Figure 8). For the Upper Mahil Member two different cycle set types can be recognized:

**Marsh to Low-energy Backshoal Cycle Set Type**

This mud-dominated cycle set type (Figure 13a) ranges from 3–8 m in thickness. It typically consists of stacks of muddy backshoal cycles, occasionally with grainy backshoal cycles around the intervals of maximum flooding. Highest energy and maximum accommodation is interpreted where bioclastic packstones are thickest (LFT 5c2), often accompanied by low natural gamma radiation. Relative sea-level fall is marked by intense rooting, a rock color change from gray-beige to reddish and higher gamma-ray values. The interbedding of rooted mudstones (LFT 6e) and bioturbated
intraclastic/peloidal packstones (LFT 5b1/5c1) indicate a marsh to low-energy backshoal (lagoon) environment with intermittent reworking (storm) events. These cycle set types occur around third-order sequence boundaries (SB), especially around maximum regression in JS-1.2, JS-1.3, JS-1.4, JS-2.1 and JS-3.3 and might act as baffle and seal units for potential hydrocarbon accumulations.

**Low-energy Backshoal to Shoal Cycle Set Type**

The low-energy backshoal to shoal cycle set type (Figure 13b) is typically between 8–13 m thick. Grain-dominated facies make up high proportions of this cycle set type, and therefore show generally lower gamma radiation than marsh to low-energy backshoal cycle sets. In early transgressive and late regressive phases grainy backshoal cycles dominate, the intervals of maximum flooding are characterized by stacked thicker shoal- to backshoal cycles. Cycle set boundaries are often indicated by microbial boundstones (LFT 3a) with occasional tepee structures. The generally high organic content of the crinkly laminites results often in a pronounced positive peak in the GR log around cycle set boundaries. Microbial interlayers within grainstones, however,
are rather interpreted as short-term shoal exposure events than shifts in depositional environment from a shoal to a peritidal setting. Low-energy backshoal to shoal cycle sets develop around second-order maximum floodings in JSS-1 and JSS-3 and represent potential hydrocarbon reservoirs.

**Third-order Sequences and Second-order Super-sequences**

The entire Upper Mahil Member can be subdivided into three large-scale super-sequences (JSS-1, JSS-2, JSS-3), each comprising between 5–6 million years, depending on the interpreted time interval of the formation (see discussion below). The intervals of maximum flooding of these three super-sequences may correlate with MFS Tr50, Tr60 and Tr70 of Sharland et al. (2001).

**Jilh Super-sequence 3 (JSS-3)**

The lowermost Super-sequence JSS-3 (Figure 14) is approximately 126 m thick. It consists of three third-order sequences JS-3.3, JS-3.2 and JS-3.1 from bottom to top. The base of the super-sequence is above a prominent exposure-related dolomite bed with abundant rootlets and occasional karst collapse breccias. During third-order transgressions within JS-3.3 and JS-3.2 muddy lagoonal facies turn into intraclastic-rich grainstones interpreted as peritidal beach ridge deposits ('tidal flat shoal'). The zones of maximum flooding are interpreted within meters-thick peloidal/oolitic grainstones of low gamma radiation (Figure 16). Abundant microbial laminites accompanied by high GR values depict maximum regression of JS-3.3 and JS-3.2. The overall maximum flooding of JSS-3 occurs within crinoidal packstones in Jilh Sequence 3.1. Crinoids occur in the Upper Mahil Member exclusively within this stratigraphic interval and serve as biostratigraphic marker. The crinoidal packstone unit may be interpreted as the only foreshoal deposit in the entire succession. The low GR values increase again towards the second-order sequence boundary, which is marked by a severely rooted mudstone bed. The average natural gamma radiation below 250 cps indicates a high grainstone proportion. Interparticle porosities in intraclastic and peloidal grainstones characterizes the JSS-3 as potential reservoir interval.

**Jilh Super-sequence 2 (JSS-2)**

The 98-m-thick Jilh Super-sequence JSS-2 comprises the two sequences JS-2.2 and JS-2.1. The third-order sequence boundary of JS-2.2, and especially the upper sequence boundary of the Super-sequence JSS-2 have a good sealing potential: intercalation of mudstones and shales, tens of meters thick intervals of tight marsh/lagoon sediments (Figure 15). Minor reservoir units occur during third-order transgressions and the landward stepping of shoal associated grainstones. The maximum flooding zone of the symmetrical transgressive-regressive Jilh Sequence JS-2.2 is interpreted within an interval of meters-thick cross-bedded peloidal grainstones. An increasing abundance of microbial laminites and rooted mudstones in the regressive part of JS-2.2 indicates a shallowing trend and progradation of peritidal and marsh sediments. The frequent alternation of peloidal grainstones and microbial boundstones within JS-2.2 demonstrates high-frequency sea-level fluctuations in a low-accommodation setting. Associated changes in texture and components are recorded by the serrated gamma-ray pattern (Figure 16). Maximum regression is expressed by a meter-thick reddish rooted mudstone.

The transgressive hemisequence of upper Jilh Sequence JS-2.1 consists mostly of grainstones, pack- to grainstones and packstones, which are interpreted as deposits of a leeward shoal margin environment. Around maximum flooding at 172 meter cross-bedded peloidal grainstones occur again. Towards the second-order sequence boundary grainstones give way to a 30 m-thick interval of exposure-related breccias and rooted mudstones. The top of JSS-2 is picked at a surface where decimeter-size mud cracks penetrate a 50 centimeter thick severely rooted mudstone indicating major exposure. The zone of maximum regression at top JSS-2 is accompanied by a sudden increase of natural gamma radiation from ca. 400 cps to ca. 600 cps in average.

**Jilh Super-sequence 1 (JSS-1)**

The uppermost Jilh Super-sequence 1 (Figure 15) is 140 m thick and made up of three complete third-order sequences (JS-1.4, JS-1.3, JS-1.2) and the transgressive hemisequence of JS-1.1. This super-sequence is marked by abundant dm-thick purple to gray shale intercalations, which can
Figure 14: Jilh Super-sequence 3 (JSS-3) in Wadi Sahtan. Outcrop log shows texture, lithology, lithofacies associations (LFA), 3-fold cyclicity and total gamma-ray log.
Figure 15: Jilh Super-sequence 1 (JSS-1) and upper part of Jilh Super-sequence 2 (JSS-2) in Wadi Sahtan. Outcrop log shows texture, lithology, lithofacies associations (LFA), 3-fold cyclicity and total gamma-ray log.
Figure 16: Composite section of the Upper Mahil Member in Wadi Sahtan with spectral gamma-ray (total gamma-ray, uranium, potassium and thorium) and stable carbon/oxygen data.
be identified in the gamma-ray pattern by high Th/K readings (Figure 16). The overall deepening-shallowing trend of JSS-1 is reflected by the cleaning-dirtying trend in the gamma-ray pattern. Sequences JS-1.4 and JS-1.3 consist mainly of microbial laminites, lagoonal wacke- to packstones and occasionally of supratidal marsh mudstones. Thin grainstone layers appear almost exclusively around maximum flooding. Jilh Sequence 1.2 starts 56 m below top Upper Mahil. A distinctive drop in the gamma-ray pattern (Figure 16) caused by a sudden onset of cross-bedded oolitic grainstones marks the beginning zone of maximum flooding. The 20 m-thick interval of shoal-associated grainstones builds a conspicuous cliff in outcrops and has the best reservoir potential in the Upper Mahil. It can easily be picked on the gamma ray by its low values around 200 cps on average (Figure 16). During the subsequent regression, grainstones are replaced by bioturbated mud-wackestones and shales, marked by higher gamma radiation. A dark gray peloidal grainstone unit, some 6 m in thickness, indicates the third-order transgression of JS-1.1, before an erosional unconformity marks the top of the Upper Mahil Member (Jilh Formation). The overlying reddish Fe-oolites, iron crusts, and sandstones are ascribed to the overlying formation (Minjur/Mafraq).

**BIOSTRATIGRAPHY AND ISOTOPE STRATIGRAPHY**

The strong diagenetic alteration of Upper Mahil deposits, in particular the pervasive dolomitization, impedes taxonomic determination of microfossils in thin sections. Early diagenetic processes resulted in dissolution and subsequent recrystallization of most miliolid/involutinid shells. Most specimens have a moldic preservation and wall structures are generally not preserved. Species determinations of smaller foraminifera have to rely therefore on morphological characteristics like shape, size, and coiling.

Furthermore, due to the overall restricted, peritidal to shallow-marine environment, the faunal assemblages in the Upper Mahil Member show a low diversity with common mollusk (gastropods, bivalves) fragments, rare foraminifera and indeterminable algae (dasycladaceans, porostromate algae). Smaller foraminifera and algae are confined to intervals with backshoal to shoal environments. In the most open-marine environments, probably reflecting maximum flooding intervals on the platform, rare lagensids have been found (JS-3.1).

According to the stratigraphic occurrence in the sections, two Foraminiferal Assemblage Zones (FAZ 1 and FAZ 2) have been differentiated in the Upper Mahil Member: (1) Late Anisian–Ladinian FAZ 1 (Mid-Triassic), and (2) Ladinian–Carnian FAZ 2 (Mid- and Late Triassic).

_Hoyenella ex gr. sinensis_ (Figure 17/1–4), a widespread opportunistic form in Late Induan to Mid-Triassic deposits (Rettori et al., 1994; Márquez, 2005), occurs sometimes in great abundance in peloidal/oolitic grainstones in the upper part of the Middle Mahil Member (Sudair-equivalent), but rarely persists in the lower part of the Upper Mahil Member (MCS 1.3 – JS-3.3). Pöppelreiter et al. (2011) suggested a Late Olenekian age for the upper part of the Middle Mahil Member, based on the presence of rare _Tubiphytes_ (Payne et al., 2004), _Meandrospira_ sp. and _Gandinella silensis_ and the δ¹³C_carbon isotope data. This interpretation is also in accordance with Maurer et al. (2008), who described a similar assemblage from the Hagil Formation in the Musandam Mountains (UAE and Oman).

The FAZ 1 shows a slight increase in foraminiferal diversity but with a low abundance. Some miliolid? (cf. _Arenovidalina chialingchiangensis_), or early involutinid (cf. _Triadodiscus eomesozoicus_) forms (found in nearby Wadi Hedek, for location see Figure 1a), together with rare cf. _Turriglomina mesotriasica_, _Gaudryina triadica_, _Nodosaria cf. expolita_ and encrusting forms (”Tolypammina”) are present in the interval from JS-3.1 to JS-2.2 (Figure 17/7–10). _Arenovidalina chialingchiangensis_ and _Triadodiscus eomesozoicus_ first occur in the late Olenekian, but are more common in Anisian–Ladinian strata. _Turriglomina mesotriasica_ is described from Late Anisian to Ladinian strata, but the single oblique specimen is insufficient for accurate determination.

The FAZ 2 (JS-1.4 to JS-1.1, Figure 17) witnesses the appearance of common _Aulotortus friedli_ (morphotype praegaeschei; e.g. Ciarapica and Zaninetti, 1985), accompanied by rare _Glomospira_/ _Glomospirella ex gr. gemerica/kuthani_ and _Endoteba ex gr. controversa_ (found in nearby Wadi Bani...
Figure 17: Foraminifera of the Upper Mahil Member and their stratigraphic occurrence.
Aulotortus probably evolved in the Anisian, but becomes more common in Ladinian/Carnian deposits (Maurer et al., 2008), and extends into the Norian. Endoteba is originally described from the Permian in Tunisia (Vachard and Razgallah, 1988), but reappears during the Olenekian (Vachard et al., 1994) and ranges into the Norian.

The fauna from the Upper Mahil Member most probably corresponds to that from the Ghail Formation in Musandam (Maurer et al., 2008). Late Norian–Rhaetian deposits, characterized by megalodont wackestones, corals and the foraminifer Triasina hantkeni, have been reported from other parts of the Arabian Platform (Weidlich and Bernecker, 2003; Korngreen and Benjamini, 2006; Maurer et al., 2008) but seems to be truncated in the Al Jabal Al-Akhdar area by the Jurassic erosional unconformity.

Contrary to the Middle Mahil Member (Pöppelreiter et al., 2011), stable-isotope data do not display pronounced positive excursions in the Upper Mahil Member (Figure 16). Values range in average from 1–4‰, but show a general increase from 2–3‰ up-section, typical for Anisian–Carnian deposits in other regions (Korte et al., 2005; Preto et al., 2009). Higher values are generally recorded in the moderate-energy backshoal/shoal grainstones and some negative excursions are close to supposed sequence boundaries, which probably indicate the influence of meteoric diagenesis on the isotopic composition.

**REGIONAL CORRELATION WITH SUBSURFACE JILH FORMATION IN OMAN**

Similar to the Upper Mahil Member in outcrops, age determination of the subsurface Jilh Formation in Oman is problematic (Forbes et al., 2010). Two palynozones (Upper Jilh: 2255 Bartenia communis, Lower Jilh: 2370 Triadispora crassa) were found in subsurface wells, whose recorded forms allow age interpretations from the Middle to Late Triassic (Anisian–Norian) (Forbes et al., 2010). However, palynological analyses on outcrop samples yielded due to strong weathering and oxidation no results and make, together with the absence of micropaleontological zones in the subsurface (Forbes et al., 2010), biostratigraphic correlations difficult.

Comparing well logs from the subsurface of Northern Oman with the outcrop section exhibits significant changes in thickness and lithology (Figure 18). The Sudair/Jilh boundary lies 40–60 meters above the Middle Mahil/Upper Mahil boundary. This is because base Jilh was defined at the top of a distinctive shale (Forbes et al., 2010), thus is a litho-stratigraphic boundary. In contrast, the Middle Mahil/Upper Mahil boundary, defined in outcrops of Al Jabal Al-Akhdar at a severely brecciated exposure-related mudstone is a sequence-stratigraphic boundary (second-order cycle top).

Similar gamma-ray patterns in well logs, e.g. Lekhwair-70 (Forbes et al., 2010), and Wadi Sahtan indicate the correlatability of at least second-order large-scale sequences (JSS-1, JSS-2 and JSS-3) over hundreds of kilometers. A distinct low gamma-ray signal in Lekhwair (depth: 3,355–3,375 m) might correlate with the thick grainstone unit (section meter: 20–50 m) at top Upper Mahil in Wadi Sahtan, indicating a major transgression (maximum flooding of JSS-1).

The proximity of Lekhwair and Yibal to the Arabian Shield (Figure 2), the presumed clastic source in the west, is reflected by higher shale contents and more pronounced gamma-ray peaks than in outcrops of the Oman Mountains. The occurrence of anhydrite in Yibal and Lekhwair suggests a more proximal, intermittently restricted salina/sabkha environment. In Yibal, the Upper Mahil equivalent strata is approximately 90 m in thickness, in Lekhwair some 510 m. The considerable thickness changes are caused by the Late Triassic–Early Jurassic erosional truncation, which cuts down towards the southeast into older strata. The limited accommodation space, thus reduced cycle thickness due to the proximal setting may contribute to some extent to the reduced thickness of the Jilh Formation in Yibal.

A forthcoming paper will evaluate facies and thickness changes on production- (Al Jabal Al-Akhdar region) and exploration-scale (North Oman) in more detail.
Figure 18: Regional correlation of the Upper Mahil Member (Jilh Formation equivalent) between Yibal, Lekhwair (Forbes et al., 2010) and Wadi Sahtan (Overview picture in upper left corner from Osterloff et al., 2004).
DISCUSSION: PRESUMED AGE OF THE UPPER MAHIL MEMBER

Bio- and chemostratigraphic data in this study suggests a time interval roughly from the Anisian to Carnian for the deposition of the Upper Mahil Member.

Various publications (see above, Figure 3) which discuss the Jilh or equivalent formations suppose a time of non-deposition/erosion on the Arabian Platform during the Anisian and Late Carnian–Early Norian (Sharland et al., 2001) due to uplift and/or sea-level lowstand. The sediments tentatively interpreted as Anisian in this study coincide with the interpreted zone of the second-order sequence boundary between the Middle and Upper Mahil members (Figure 9). The proximal character of the facies (karst breccias, rooted surfaces) and the poorly constrained foraminiferal biostratigraphy (Late Olenekian–Anisian?) in the lowermost part of the Upper Mahil Member allows an interpretation with partly missing Anisian strata related to one or multiple unconformities at the boundary between the Middle and Upper Mahil members. Biostratigraphic data from the continental slope (Sumeini Group) and basin sediments (Hawasina Group) (Baud and Bernecker, 2010) further corroborate an exposed shelf during the Late Olenekian–Anisian with bypassed siliciclastic input (Robertson and Searle, 1990).

Transferring the biostratigraphic range data into the global chronostratigraphic scale, in order to estimate the duration of deposition in the Upper Mahil Member, is further complicated by the uncertainties of absolute ages of the stage boundaries. Recent works on radiometric ages, magnetostratigraphy and orbital tuning (Brack et al., 2005; Menning and Szurlies, 2005; Furin et al., 2006; Lehrmann et al., 2006; Ovtcharova et al., 2006; Galfetti et al., 2007; Kozur and Bachmann, 2008; Hüsing et al., 2011) have resulted in considerable changes of the Triassic time scale (Mundil et al., 2010). The integration of cyclostratigraphic results in this study can contribute additional information to unravel the time span represented by the Upper Mahil. As mentioned above, cycles (fifth-order), cycle sets (fourth-order) and sequences (third-order) in the Upper Mahil Member show remarkably regular bundling patterns. Three to five fifth-order cycles generally form fourth-order cycle sets and three to six fourth-order cycle sets build third-order sequences.

Multi-fold cyclicities in Triassic successions have been reported from numerous continental and marine deposits and are often related to Milankovitch-driven cyclicity. The 405 Ky eccentricity cycles are especially expected to be found since numerical calculations by Laskar et al. (2011) have proven their existence to be stable for at least the last 250 My.

Using a cyclostratigraphic approach, the following calculation options may be considered:

(1) As mostly four fifth-order cycles form one fourth-order cycle set, it may be assumed that they represent the 100 Ky and 405 Ky Milankovitch signals. With 168 fifth-order cycles recorded, the time span would be 16.8 My.

(2) The forty fourth-order cycle sets, which are assumed to represent Milankovitch eccentricity cycles (each comprising 405 Ky) result in approximately 16.2 My for the Upper Mahil.

(3) Furthermore, the common bundling of four fourth-order cycle sets forming a sequence would give a 1.75 My cyclicity for the third-order sequences. Olsen and Kent (1999) revealed the presence of long-term climatic cycles (“long modulation cycle”) in the continental, lacustrine sediments of the Newark Basin by tuning the depth rank and color records to the ca. 405 Ky eccentricity cycle. Their results likewise display a highly significant period of climatic precession modulations at periods of ca. 1.75 My. A similar large-scale cyclicity has been recently proposed by Hüsing et al. (2011) for the marine Pizzo Mondello section. Assigning 1.75 My for each third-order sequence, the whole succession consisting of 9 sequences would represent 15.75 My.

Unfortunately, neither radiometric ages, nor magnetostratigraphic studies are currently available from the Arabian Platform to confirm or discard the estimated duration of the Upper Mahil cycles. Similarly, the biostratigraphic data give only loose constraints for the age of the deposits.
The recent estimated ages (based on radiometric ages and orbital tuning) for the Olenekian are 3.5–4 My and ca. 20 My for the Anisian to Carnian interval (Galfetti et al., 2007; Menning and Szurlies, 2005; Kozur and Bachmann, 2008) (Figure 3). According to Pöppelreiter et al. (2011) the Middle Mahil Member supposedly ranges from the Late Dienerian up to the Late Olenekian.

Therefore the most likely estimate for the time span of the Upper Mahil Member, by the integration of bio-, chemo- and cyclostratigraphy, is between 15 and 20 My ranging from the Anisian?–Early Ladinian to the Late Carnian (Figure 9).

CONCLUSIONS

The study of the Middle to Upper Triassic Upper Mahil Member in the Oman Mountains revealed following results:

(1) The Upper Mahil Member in Wadi Sahtan can be considered as time-equivalent to the subsurface Jilh Formation in Oman.

(2) Facies in outcrops are dominated by supratidal marsh and lagoon deposits but also extend into a high-energy shoal environment. Distal foreshoal/offshoal-associated facies or evidence of open-marine conditions are not detected.

(3) Well-sorted cross-bedded oolitic/peloidal grainstones (about 10% of the succession), especially in the upper part (mfs JSS-1), and meters-thick microbial laminites (ca. 9%) with potential fenestral porosities highlight reservoir potential in the Upper Mahil Member.

(4) Muddy marsh/lagoon carbonates with shale interlayers around the center of the formation (upper SB JSS-2) might act as potential baffles and/or seals.

(5) The entire Upper Mahil Member can be subdivided into three large-scale super-sequences (second-order) and nine third-order sequences. The highest reservoir potential occurs around zones of second-order maximum floodings, potential seals occur as shale interbeds at third-order sequence boundaries.

(6) Regional correlations suggest large-scale sequences to be laterally very extensive and highlight regional trends in lithology. While the Jilh Formation provides better sealing potential in a landward (south-westward) direction where shales and evaporites make up an increasing proportion of the succession, potential reservoirs can be expected in a more seaward (north-eastward) platform margin setting.

(7) The thickness is strongly determined by the Late Triassic–Early Jurassic erosional truncation and is a crucial point for reservoir existence or absence in the upper part of the succession.

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