Facies, sequence stratigraphy, reservoir and seal potential of the Mafraq Formation, Sultanate of Oman: An integrated outcrop analogue study

Daniel Bendias and Thomas Aigner

ABSTRACT

The mixed carbonate-siliciclastic Lower to Middle Jurassic Mafraq Formation unconformably overlies the Triassic Mahil Formation in outcrops of the Oman Mountains (pre-Mafraq Unconformity, known as pre-Marrat unconformity in other regions of Arabia). Together with the overlying Dhurma Formation, it is part of the Sahtan Group. This study provides: (1) a detailed facies analysis based on sedimentological logging of 12 outcrops. Twenty-four facies types were established and grouped into five facies associations, which can also be recognized in subsurface core intervals; (2) a detailed sequence-stratigraphic framework of the Mafraq Formation. Facies stacking and log patterns reveal cycle hierarchies on four scales from m-scale cycles, to several m-thick cycle sets, to tens of m-thick, high-frequency sequences, to 100 m-thick composite sequences; and (3) a documentation of potential reservoir and seal units. The study follows an approach from 1-D (outcrop sections) to 2-D (correlations and potential reservoir dimensions). The Mafraq outcrop type section, located in Wadi Sahtan is documented in an integrated way (facies, litho-, bio-, chemo- and sequence stratigraphy), together with additional outcrops of the Mafraq Formation throughout North Oman.

2-D correlation of the Mafraq Formation throughout North Oman is essentially based on cycle sets and provides key information about the lateral paleogeographic development of the formation. A general proximal-distal trend, from south to north, has been proposed by Ziegler (2001); outcrop data from the Oman Mountains confirms this trend and adds an EW-deepening component. The mixed carbonate-clastic Lower Mafraq Member (Sequence) with a coastal/estuarine to shallow-marine environment forms onlaps onto the pre-Mafraq Unconformity below, and thins out completely after some 10s of kilometers towards the southeast. The Upper Mafraq Member (Sequence) seems to be continuous over 10s of kilometers with less thickness decrease. Instead, a transition from a more distal carbonate shoal - backshoal environment in the northwest to a proximal clastic coastal/estuarine/terrestrial environment in the southeast can be observed. On a 100s km-scale significant thinning and a change towards terrestrial clastic facies can be observed southeast of the Oman Mountains area. Combined results from lateral/vertical logging, paleoenvironmental interpretations and correlation provided 3-D information about the dimensions of potential reservoir and seal units.

Several potential reservoir/seal intervals and their dimensions in dip direction could be identified: (1) Lower Mafraq Sequence: various types of sandbodies, most of them with a lateral extent ca. 5 km, sealed by shales. (2) Upper Mafraq Sequence, northwestern part: oolitic grainstones, laterally correlative over 10–20 km, sealed by shales. (3) Upper Mafraq Sequence, southeastern part: channelized sandstones units, lateral extent up to km, sealed by shales.

INTRODUCTION

This paper focuses on facies, sequence- and bio-stratigraphy of the Mafraq Formation type section in Wadi Sahtan, the documentation of 11 Mafraq outcrops distributed over the Oman Mountains and North Oman and their correlation (Figure 1, Enclosures I and II). North Oman mixed
carbonate-siliciclastic deposits from the Minjur and Mafraq formations lie on top of km-thick Permian to Triassic carbonates from the Khuff, Sudair and Jilh formations. The complex Upper Triassic to Middle Jurassic systems of continental to shallow-marine deposits are of particular interest for present and future hydrocarbon exploration in Oman. So far only very little is known about the facies, depositional environment and reservoir potential of the Lower to Middle Jurassic in Oman as most publications concentrate on other areas of the Arabian Peninsula (Alsharhan et al., 1986).

Therefore, an outcrop analogue study, as a cooperation of the University of Tuebingen with Petroleum Development Oman (PDO), was initiated. Its aim was to capture the geology of the Lower to Middle Jurassic Mafraq and the Upper Triassic Minjur formations in Oman. The study uses a systematic approach from 1-D sedimentological observations to 2-D correlations and 3-D integration of collected data into facies models. It is a continuation of several studies covering older, Permian to Triassic strata by the sedimentary geology group at the University of Tuebingen (Koehrer et al., 2010; Koehrer et al., 2011; Pöppelreiter et al., 2011; Zeller et al., 2011; Obermaier et al., 2012; Bendias et al., 2013; Haase and Aigner, 2013; Walz et al., 2013). Combined, they provide detailed knowledge about the geology of North Oman from the Permian–Triassic Khuff Formation, Triassic Jilh and Sudair formations up to the Jurassic Mafraq Formation, and cover a period of about 100 Myr.

Between 2010 and 2014 this project investigated twelve outcrops and numerous subsurface wells in North Oman. Collected data from outcrops comprises sedimentological descriptions, gamma ray (GR), bio-, chemo- and sequence stratigraphy. In the subsurface the focus was on the analysis of cores, cuttings, logs, seismic data in the general framework of sequence stratigraphy. A detailed study of Lower Mafraq Member (Sequence) clastic intervals, and the 3-D subsurface integration will be presented in separate papers.

The aims of this paper are:

- Comprehensive sedimentological documentation of the Mafraq Formation type section in Wadi Sahtan, Oman.
- Establish a facies atlas: one catalogue usable for outcrop and subsurface.
- Generation of a conclusive sequence and bio-stratigraphic framework.
- Comprehensive documentation of 12 outcrops in North Oman.
- Outcrop correlation and discussion of vertical and lateral development of the Mafraq Formation through North Oman.
- Identification of potential reservoir/seal units and their lateral equivalents.

The main study area for outcrops is located in the Oman Mountains (Figure 1), about 130 km west of Muscat where Permian to Cretaceous strata are exposed in wadis, which cut through the flanks of a large anticline (Glennie et al., 1974; Rabu et al., 1990; Hanna, 1995). The Mafraq Formation type section in Oman is located in Wadi Sahtan in the northwest of the Oman Mountains. Including the type section in Wadi Sahtan, 10 outcrops of the Mafraq Formation have been logged in the Oman Mountains. Two additional outcrops have been logged at Jabal Madar some 100 km southeast of the Oman Mountains and in Al Huqf area in Central Oman (Figure 1).

PREVIOUS WORK

The type section of the Upper Triassic Minjur Formation has been defined by Powers (1968) in Saudi Arabia. In Oman the Minjur Formation has not been recognized as a separate unit in the subsurface for a long time since it was hard to be distinguished from the Lower Mafraq Sequence due to the absence of biostratigraphic evidence. The Triassic age of this interval, recognized by Kharusi (1986, 1989) and the work of Al-Aswad and Al-Harbi (2000), indicates that a correlation with the clastic Minjur Formation in adjacent United Arab Emirates (UAE) and Saudi Arabia is possible. A time gap at the top Minjur in Oman of approximately 13 Myr is indicated by palynological data (Forbes et al., 2010). Onlapping Lower Mafraq Sequence clastics on top support the interpretation of Forbes et al. (2010) that the Minjur Formation deposits are connected to a renewed uplift of the Neo-Tethys rift shoulder.
The Sahtan Group comprises the Mafraq Formation as the lowermost unit and has been defined by Glennie et al. (1974) in outcrops of the Al Hajar Mountains in Oman with the type section in Wadi Sahtan. Hughes Clarke defined the Mafraq-1 Well as a first subsurface reference type section for the Mafraq Formation (Hughes Clarke, 1988) before he replaced it by the more complete section in the Lekhwair area (Lekhwair-70 Well) where the Mafraq is thickest in Oman (Forbes et al., 2010). Rousseau et al. (2005, 2006) studied the Sahtan Group in several outcrops (Wadi Bani Awf, Wadi Bani Kharuz, Jabal Madar, Al Huqf) and in the subsurface of Oman, and was the first to publish sedimentological outcrop descriptions and outcrop/subsurface correlations. A detailed description of the Sahtan Group in the Oman Mountains has also been published by the BRGM mapping group in the explanatory notes provided with the geological maps, summarized in Rabu et al. (1990).

Hamad Al-Shuaily investigated the Mafraq Formation in North Oman in several subsurface and outcrop locations for his master thesis (Al-Shuaily, 2007; Al-Shuaily et al., 2008).

**GEOLOGICAL SETTING**

Starting at 15° south of the equator in the Early Triassic the Arabian Peninsula drifted northward and approached the equator during the Early Jurassic (Stampfli and Borel, 2002; Golonka, 2007). At the same time, the climate changed from ice- to greenhouse conditions creating a warm and
humid to semi-arid climate. Global plate tectonic reconstructions from Scotese (2001) and Blakey (2003, 2008) illustrate that a new ocean opened in between Arabia and India during Early Triassic and Late Jurassic (Figures 2 and 3). At the Triassic–Jurassic transition the beginning of this rift, in the southeast of the Arabian Peninsula, resulted in a northwestward tilting and the base Jurassic unconformity.

Stratigraphy

Upper Mahil Formation (equivalent to subsurface Jilh Formation): Middle to Upper Triassic dolomites and shales form a flat epeiric carbonate platform. In Oman, the thickness of the Mahil/Jilh Formation (up to ca. 500 m) depends strongly on the erosion of the unconformity above, which cuts down towards the southeast (Mountain and Prell, 1990; Coy, 1997). This might also explain the difference in the depositional time span of the Jilh Formation, which extends up to the Late Norian in the subsurface (Forbes et al., 2010; Figure 4) and to the Early Norian in outcrops (Obermaier, 2012; Figure 5).

Minjur Formation: The Upper Triassic mixed clastic-carbonate continental to shallow-marine deposits of the Minjur Formation reach a thickness of about 100 m in the subsurface of the Lekhwair area (Forbes et al., 2010; Figure 4). In the absence of biostratigraphic dating outside of the greater Lekhwair area, it is unclear whether the Minjur is present in other areas of Oman as the formation pinches out towards the southeast or is eroded by the Base Jurassic Unconformity at the top. In outcrops, biostratigraphic sampling yielded no evidence for Upper Triassic (Norian to Rhaetian) Minjur deposits (Figure 5).

Base Jurassic Unconformity (pre-Mafraq Unconformity): Erosional, angular unconformity that cuts regionally towards the southeast into older strata (Murris, 1980). It separates the Triassic Akhdar Group (Khuff, Sudair, Jilh and Minjur) from the Jurassic Mafraq Formation above.

Mafraq Formation: The Lower to Middle Jurassic Mafraq Formation is subdivided into the Lower and Upper Mafraq members corresponding to third-order sequences with an unconformity in between where parts or even the complete Toarcian is missing (depending on the location). The mixed carbonate-siliciclastic succession reaches a thickness of about 300 m in the subsurface Lekhwair area and 160 m in outcrops (Figure 6). Its facies ranges from terrestrial/fluvial deposits, marginal marine clastics and carbonates (estuarine/tidal/lagoonal) to fully marine, shoal-associated carbonates. The Mafraq Formation onlaps tilted and eroded Permian–Triassic strata from the Akhdar Group (Khuff, Sudair, Jilh and Minjur) below and is conformably covered by the Dhruma Formation.

Lower Mafraq Member: As it onlaps onto older strata below, it is only present in northwestern areas of Oman (Lekhwair, Oman Mountains) and thins out towards the southwest (Yibal, Jabal Madar). Terrestrial to shallow-marine clastics and carbonates with abundant paleosoils and other exposure related features characterize the Lower Mafraq Member in North Oman. According to Forbes et al. (2010), its age ranges from the Pliensbachian to the Early Toarcian (Figure 4) in the subsurface Lekhwair area. New palynological data from this study might indicate a longer time span from Late Hettangian to Late Pliensbachian. In outcrops, abundant biostratigraphic data from the type section in Wadi Sahtan documents a maximum range from Late Hettangian to Late Pliensbachian (Figure 5).

Toarcian Unconformity (AP6/AP7 megasequence boundary): In the subsurface Lekhwair area, parts of the Toarcian interval are missing between the Lower and Upper Mafraq members (Sharland et al., 2001; Forbes et al., 2010; Figure 4); in outcrops biostratigraphy indicates a larger unconformity with a missing interval from the Late Pliensbachian to Early Aalenian (Figure 5). Al-Husseini (2009) also mentions this Aalenian hiatus a regional hiatus on the Arabian Plate.

Upper Mafraq Member: The Upper Mafraq Member laterally extends to the southeast of North Oman where it eventually thins out (Al Huqf area). Clastic influence is most prominent around the top of the Mafraq Formation whereas other parts consist of shallow-marine carbonates from a lagoonal to shoal-associated environment with very few clastics. Most abundant distal facies (shoal)
can be observed around the Lekhwair area and in Wadi Sahtan. In a southeastward direction a transition to more proximal facies (lagoonal, peritidal) is noted. Further to the southeast (Al Huqf area) the Upper Mafraq Member consists only of few m-thick, condensed terrestrial deposits (paleosoils, calcretes) and few proximal carbonates. A Late Toarcian to Bajocian age for the Upper Mafraq Member has been recognized in the subsurface (Forbes et al., 2010; Figure 4). In outcrops biostratigraphy indicates a Late Aalenian to Bajocian age (Figure 5).

**Dhruama Formation:** Middle Jurassic (Bajocian to Bathonian–Callovian) carbonates lie conformably above the deposits of the Mafraq Formation (Figures 5 and 6). Dhruama facies range from peritidal and lagoonal deposits with some clastic influence to pure carbonates associated with a shoal environment. The Dhruama Formation reaches a thickness of up to 560 m in the subsurface around Lekhwair and 240 m in outcrops of Oman (Schlaich et al., in preparation).

Figure 2: Early Triassic plate tectonic setting with the position of the Arabian Plate shown in red (modified from Scotese, 2001; Blakey, 2003).

Figure 3: Late Jurassic plate tectonic setting with the position of Arabian Plate shown in red (modified from Scotese, 2001; Blakey, 2008). A new ocean opened in between Arabia and India.
**Figure 4:** Oman subsurface stratigraphy after Forbes et al. (2010) based on GTS 2008. Black dashed line marks extent of the Lower Mafraq Sequence according to new palynologic results from the Lekhwair area (this study) that indicate a longer timespan from late Hettangian to Pliensbachian.

**Figure 5:** Outcrop stratigraphy (based on detailed biostratigraphy from Wadi Sahtan, Oman Mountains) and GTS 2012. The Jilh Formation extends up to the Early Norian (Obermaier et al., 2012). The Late Triassic Minjur Formation is absent, the Lower Mafraq extends from the Hettangian to the Late Pliensbachian and the Upper Mafraq starts in the Aalenian creating a large unconformity in between that comprises the whole Toarcian.
Paleogeography

The Upper Triassic Minjur Formation is part of the Akhdar Group and has been deposited in northwest Oman with a depocenter around the Lekhwair area, where it reaches a thickness of up to 100 m. According to Forbes et al. (2010), the Minjur Formation represents a wedge of early syntectonic deposits, which are the result of renewed uplift along the Neo-Tethys rift shoulder in Oman. The Minjur shows a general proximal-distal trend from SE to NW (Loutfi et al., 1987; Issautier et al., 2012) with a transition from continental clastics to pure carbonates in the basin (UAE area). Despite extensive biostratigraphic sampling throughout northeast Oman this study could not find any evidence for the occurrence of Upper Triassic strata in outcrops. The paleogeographic reconstruction from Ziegler (2001) had to be slightly modified in order to accommodate the results from this study, which shows that the Minjur Formation cannot be found in the Oman Mountains and other parts of North Oman (Figure 7a).

At the Triassic–Jurassic transition the depositional system of the Minjur shifted northward due to a sea-level lowstand (Haq and Al-Qahtani, 2005) combined with a structural uplift in the southwest (onset of Mediterranean rifting and renewed uplift along the Neo-Tethys rift shoulder) leaving most of the Arabian Peninsula subaerially exposed (Figure 7b). Non-deposition and erosion during Rhaetian to Hettangian times resulted in the significant hiatus above the Minjur to the onlapping Mafraq Formation of the Sahtan Group. This prominent angular unconformity is regionally observable on seismic data and is referred to as “Base Jurassic Unconformity”, pre-Marrat or in this paper the “pre-Mafraq Unconformity” (Al-Shuaily, 2007; Al-Shuaily et al., 2008; Forbes et al., 2010).

After this time of northwestward tilting and erosion at the end of the Triassic, Early to Middle Jurassic times were characterized by a global sea-level rise (Haq and Al-Qahtani, 2005). Lower Jurassic deposits of the Mafraq Formation and time-equivalent formations (e.g. Marrat Formation) cover the northern part of the Arabian Peninsula with an extent of 2,500 km in NNE-SSW strike and up to 1,000 km in SW-NE dip direction (e.g. Sharland et al., 2001). In Oman the Mafraq
Figure 7: Modified paleogeographic reconstructions of the Arabian Plate (Ziegler, 2001). Small red rectangle: outcrops of the Oman Mountains; dashed red rectangle: complete study area; black star: subsurface Lekhwair area. Black dashed line in (a) represents the extent of Upper Triassic deposits according to the original interpretation from Ziegler. It has been modified because this study did not find any evidence for Triassic strata in the Oman Mountain area.
Figure 8: Paleogeographic reconstructions of the Arabian Plate (Ziegler, 2001). Small red rectangle: outcrops of the Oman Mountains; dashed red rectangle: complete study area; black star: subsurface Lekhwair area; blue arrow (Figure 8a): the SE-NW proximal-distal trend resulting from observations in this study.

Early Jurassic: Sinemurian to Aalenian (201.9–176.5 Ma)

Middle Jurassic: Bajocian to Bathonian (176.5–164.4 Ma)
Formation is thickest around the Lekhwair area (250 m) and thins-out landwards to the SSE around Al Huqf area (5–10 m). The paleogeographic reconstruction from Ziegler (2001) places the study area into an environment dominated by carbonates with some clastic influence from the south where the paleocoastline is located (Figure 8). This general deepening trend towards the north as observed by Ziegler (2001) was refined by outcrop observations that add an EW-deepening to his interpretation (Figure 8a, blue arrow).

In the Middle Jurassic, with ongoing global sea-level rise, an increasingly stable marine environment in North Oman was established despite continued regional continental margin uplift in the east. The Dhruma Formation conformably overlies the Mafraq Formation (Figure 8b) and is barely influenced by continental clastics as the paleocoastline shifted further to the south.

**METHODS**

This study focuses on the documentation of Mafraq outcrop sections at the type locality in Wadi Sahtan and in the northern Oman region (Figure 1). Twelve outcrop sections have been documented in detail. The following properties were recorded in the field with a vertical resolution of 5 cm and digitized with the software WellCAD 4.3: lithology, grain size, texture (Dunham, 1962), components, physical and biogenic sedimentary structures, stratigraphic cycles and spectral gamma-ray (GR). Numerous outcrop photographs were taken to document the rock character. All data from outcrops were used to define facies types, facies associations and cycle types. Facies types and associations were developed based on outcrop data and have been calibrated and modified with subsurface cores and cuttings in order to create a facies catalogue that can be used to describe both outcrop and subsurface facies.

Spectral gamma-ray measurements in outcrop sections produce vertical GR trends that help with stratigraphic correlations and sequence-stratigraphic interpretations (Aigner et al., 1995). Using a portable spectral GR device, a GR survey was run in all outcrops with a vertical spacing of 0.25 m and a measuring time of 30 seconds. Three different tools from different manufacturers have been used throughout the extensive field campaign: (1) Gamma Surveyor, manufactured by GF Instruments s.r.o., Brno, Czech Republic; (2) GS-256, manufactured by Geofyzica A.S. Brno, Czech Republic; and (3) RS-125 Super-SPEC, manufactured by Radiation Solutions Inc., Canada. All tools use a detector to record 4 separate values for: total bulk GR (CPS, tool 1; nGy/h, tools 2 and 3), Potassium (%), Uranium (ppm) and Thorium (ppm).

**Note:** The authors are aware that the use of different tools and a comparably small measuring time imply that absolute GR values are not suitable for quantitative analysis. As this study does not focus on quantitative aspects of the GR, a measuring time of 30 seconds was found to be sufficient after experimenting with different measuring intervals. GR trends can be reproduced and compared regardless of the tool that has been used to record it.

More than 500 outcrop samples were collected for microfacies analyses using a transmission light microscope on thin sections. Steve Packer from Millennia Stratigraphic Consultants Ltd. analyzed 65 fossil-rich carbonate samples from Wadi Sahtan to unravel the biostratigraphic framework of the Mafraq Formation in outcrops.

Stable-isotope analyses ($\delta^{13}C$, $\delta^{18}O$) were performed on 120 carbonate samples from Wadi Sahtan using a Finnigan MAT 252 gas source mass spectrometer combined with a ThermoFinnigan GasBench II / CTC Combi-Pal autosampler. About 0.1 mg dried sample powder is used and heated to a temperature of 72° C. After purging with pure He gas, 4–6 drops of 100% phosphoric acid are added. After a reaction time of about 90 minutes released CO2 is transferred (using a GC gas column to separate other components) to the mass spectrometer using a He carrier gas. The sample CO2 is measured relative to an internal laboratory tank gas standard which is calibrated against internal and international carbonate standards. All values are given in ‰ relative to V-PDB for carbon and VSMOW/VPDB for oxygen. The external precision calculated over 10–15 standards is typically in the range of 0.05–0.06‰ for $\delta^{13}C$ and 0.06–0.08‰ for $\delta^{18}O$ (Spötl and Vennemann, 2003).
FACIES ANALYSIS

Facies Code

In order to create a simple and comprehensive facies catalogue for a complex mix of carbonates and clastic rocks in the Mafraq Formation, a systematic approach was developed. All facies type codes were created using a minimum of one and a maximum of three criteria (Table 1, see Figures 9 to 20 for carbonate facies types, and Figures 21 to 31 for siliciclastics facies types). Nomenclature of clastic facies types is derived from the sandstone classification of Miall (1988), names of carbonate facies types comprise elements from the carbonate Dunham classification (Dunham, 1962), as follows:

Lithofacies type + sedimentary feature (optional) + main component (optional) = Facies code

Table 1

Scheme for the Creation of Facies Types for the Mafraq Facies Catalogue

| Lithofacies Type | Modifiers (if needed) | Components |
|------------------|-----------------------|------------|
| (1) Grain Size/Dunham | (2) Sedimentary Features | (3) Components |
| MR = Mudrock (Silt + Shale) | m = massive | s = skeletal |
| H = Heterolithic | b = laminated | p = peloidal |
| S = Sandstone | g = graded | o = oolithic |
| Cm = Conglomerate (matrix supported) | r = rippled | mi = microbial |
| CC = Conglomerate (clast supported) | d = deformed (soft sediment def.) | li = lithoidal |
| DM = Dolo-Mudstone | x = cross-bedded | fe = iron |
| M = Mudstone | b = bioturbated | on = oncoids |
| W = Wackestone | rt = rooted | |
| WP = Wacke-Packstone | tb = thinly bedded | |
| P = Packstone | |
| PG = Pack-Grainstone | |
| G = Grainstone | |
| B = Boundstone | |
| C = Coal | |

| Examples: WPg | Wacke-Packstone graded |
| Gx, o | Grainstone cross-bedded, oolitic |
| Sx | Sandstone cross-bedded |
| Srt | Sandstone rooted |

Mudstone, thinly bedded (Mt)

Components: clay-rich carbonate mud
Sedimentary structures: rare bioturbation
Bed thickness: 1 mm–10 cm
Interval thickness: 0.5 m–5 m
Continuity estimate: km

Interpretation: low-energy conditions, possibly low-energy lagoon

Potential seal!

Figure 9: (a, c and d) Thinly bedded mudstones interbedded with pink silt-rich layers; (b) thin section close-up.
Mudstone, massive (Mm)

Components: carbonates mud w/ peloids, skeletal debris
Sedimentary structures: abundant bioturbation (Thalassinoids)
Bed thickness: 10 cm–2 m
Interval thickness: up to 30 m
Continuity estimate: 10s of km
Interpretation: low-energy conditions, possibly low-energy lagoon
Potential seal!

Dolo-Mudstone (DM)

Dunham: mudstone/wackestone
Components: rare bioclasts
Sedimentary structures: bioturbation, sometimes karstification
Bed thickness: 5 cm–1 m
Interval thickness: up to 8 m
Continuity estimate: km
Interpretation: shallow-marine deposits, possibly restricted tidal flat, karstification indicative for subaerial exposure

Figure 10: (a and d) Massive mudstones with Thalassinoids bioturbation (red arrow); (b) thin section close-up; (c) meter-thick interval of intensively bioturbated massive mudstones.

Figure 11: (a, c and d) characteristic orange-brown dolomitic mudstones with stylolites (red arrow in photo a); (b) thin section close-up.
Jurassic Mafraq Formation, Oman

**Wackestone (W)**
- **Components**: various bioclasts, peloids, sometimes ooids, oncoids
- **Sedimentary structures**: bioturbation, sometimes grading
- **Bed thickness**: 5 cm–25 cm
- **Continuity estimate**: 100s of m
- **Interpretation**: moderate- to low-energy storm-influenced deposits from lagoonal or foreshoal environment

**Wacke- to Packstone graded (WPg)**
- **Components**: bioclasts, peloids, ooids, oncoids
- **Sedimentary structures**: grading, rare bioturbation
- **Bed thickness**: 5 cm–30 cm
- **Interval thickness**: up to 1 m
- **Continuity estimate**: 100s of m
- **Interpretation**: tempestites, deposition in storm-influenced lagoonal or foreshoal environment

Figure 12: (a, c and d) wackestones with bioclasts, red arrow marks coral finger; (b) thin section close-up.

Figure 13: (a, c and d) graded wacke- to packstones, erosive bases are common (red arrow); (b) thin section close-up.
**Components**: Lithiotis (bivalve) shells, bioclasts, peloids, oncoids, coral fingers
**Sedimentary structures**: rare bioturbation
**Bed thickness**: 30 cm–1 m
**Interval thickness**: up to 8 m, (Lithiotis mounds)
**Continuity estimate**: 10s to 100s of m (mounds), km (sheets)
**Interpretation**: lagoonal environment, extensive sheets (tempestites) or mounds (bioherm)

**Wacke- to Packstone massive (WPm)**

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**Components**: bioclasts, peloids, ooids, oncoids, coral fingers
**Sedimentary structures**: bioturbation
**Bed thickness**: 10 cm–1 m
**Interval thickness**: up to several meters
**Continuity estimate**: km
**Interpretation**: high-energy lagoonal or foreshoal environment, possibly storm influence (initial grading lost due to bioturbation or erosion)

**Lithiotis- Packstone (P, li)**

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**Figure 14**: (a) gastropods within massive packstone; (b) thin section close-up of massive packstone with geopedal fabric (red arrow); (c and d) massive wacke- to packstone with coral finger (red arrow).

**Figure 15**: (a, c and d) *Lithiotis* packstones, specimens reach a length of up to 40 cm, if imbricated they indicate paleocurrent directions (red arrow photo d); (b) thin section close-up.
Jurassic Mafraq Formation, Oman

**Pack- to Grainstone massive (PGm)**

Components: bioclasts, peloids, ooids, oncoids
Sedimentary structures: common bioturbation
Bed thickness: 10 cm - 1 m
Interval thickness: up to 6 m
Continuity estimate: 10s of km
Interpretation: possible tempestites (grading lost due to bioturbation) or other event like deposition, high-energy lagoon or foreshoal environment

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**Oolitic Pack- to Grainstone (PG, o)**

Components: ooids, peloids, bioclasts
Sorting: very well sorted
Sedimentary structures: gutter casts, ripples, hummocks
Bed thickness: 3 cm - 25 cm
Interval thickness: 0.5 m - 6 m
Continuity estimate: km
Interpretation: storm related spillover deposits from a proximal oolitic/peloidal shoal
Potential reservoir facies!

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Figure 16: (a) bioturbated massive pack to grainstones; (c and d) 5–20 cm thick sheets of massive pack- to grainstones form thick, laterally extensive units in outcrops; (b) thin section close-up.

Figure 17: (a, c and d) centimeter-thick oolitic pack- to grainstone sheets stack up to meter-thick, extensive intervals; (b) thin section close-up.
**Components**: few bioclasts
**Sorting**: very well sorted
**Sedimentary structures**: tepees, root traces, karstification, bioturbation
**Bed thickness**: 5 cm–50 cm
**Interval thickness**: 20 cm–2 m
**Continuity estimate**: 100s m

**Interpretation**: very shallow marine, algal mats, <10 cm water depth, tidal flat environment

**Potential reservoir facies!**

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**Figure 18**: (a and d) cross-bedded oolitic grainstone; (c) oolitic grainstone interval with oomoldic porosity from a subsurface core; (b) thin section close-up.

**Components**: ooids, peloids
**Sorting**: very well sorted
**Sedimentary structures**: cross-bedding
**Bed thickness**: 10 cm–40 cm
**Interval thickness**: 0.5 m–5 m
**Continuity estimate**: km

**Interpretation**: deposits from a shoal environment

**Potential reservoir facies!**

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**Figure 19**: (a, c and d) microbial boundstones, red arrow marks tepee structure; (b) thin section close-up.
Jurassic Mafraq Formation, Oman

### Iron Oolitic Packstone (P, fe-o)

**Components:** Iron ooids, ooids, bioclasts  
**Sedimentary structures:** common bioturbation  
**Bed thickness:** 5 cm–50 cm  
**Interval thickness:** ca. 1 m  
**Continuity estimate:** few km  

**Interpretation:** Ooids originate from a high-energy environment (shoal or peritidal). Oolitic packstones possibly formed in lagoonal environment with a shoal complex nearby. Diagenetic replacement by iron produced iron ooids.

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### Conglomerate (Cc/m)

**Components:** 85% carbonate-, 10% silt-5% sandstone-clasts  
**Grain size:** clay to boulder  
**Sorting:** very unsorted  
**Sedimentary structures:** massive, sometimes fining up in channels  
**Bed thickness:** 0.3 m–5 m  
**Interval thickness:** 2 m–8 m  
**Continuity estimate:** > 5 km  

**Interpretation:** Massive debris flow deposits, at some places subtle grading can indicate channelized flow.

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Figure 20: (a) iron oolitic packstone; (b) thin section close-up; (c) bioturbated iron oolitic wackestones; (d) one meter-thick interval of iron oolitic wacke- to packstones in Wadi Sahtan at the base of the Mafraq Formation.

Figure 21: (a and c) massive, clast supported conglomerate with carbonate, sandstone and siltstone clasts (Base Mafraq); (b) thin section close-up; (d) up to 8 meter-thick conglomerate unit around the base of the Mafraq Formation in Wadi Sahtan (red arrow/white dashed line).
Sandstone massive (Sm)

Components: silt, clay, bioclasts, carbonate matrix
Grain size: coarse to fine sand
Sorting: poor to well sorted
Sedimentary structures: rare bioturbation
Bed thickness: 5 cm–50 cm
Interval thickness: 1 m–2 m
Continuity estimate: > 100s of m
Interpretation: event deposition (mass flow) or massive appearance due to bioturbation

Figure 22: (a) massive sandstone; (b) thin section close-up with large quartz clasts in a finer quartz grain/carbonate mud matrix; (c and d) massive sandstones with carbonate matrix turn into carbonate mudstones.

Sandstone bioturbated (Sb)

Components: rare bioclasts
Grain size: fine to coarse arenite
Sorting: poor to well sorted
Sedimentary structures: bioturbation traces
Bed thickness: 5 cm–50 cm
Interval thickness: 0.5 m–2 m
Continuity estimate: km
Interpretation: possibly deltaic/estuarine/tidal environment (mainly marine bioturbation)
Potential reservoir facies!

Figure 23: (a) bioturbated sandstone with Arenicolites burrow; (b) thin section close-up; (c and d) heavily bioturbated sandstones.
Jurassic Mafraq Formation, Oman

**Sandstone cross-bedded (Sx)**

- **Components**: sometimes bioclasts
- **Grain size**: fine to coarse arenite
- **Sorting**: well to very well sorted
- **Sedimentary structures**: cross bedding
- **Bed thickness**: 20 cm–1 m
- **Interval thickness**: up to 5 m
- **Continuity estimate**: km
- **Interpretation**: constant high-energy conditions, channels of estuarine, tidal or fluvial environment
- **Potential reservoir facies!**

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**Sandstone laminated (Sl)**

- **Grain size**: fine to medium arenite
- **Sorting**: well to very well sorted
- **Sedimentary structures**: low angle to horizontally laminated, marine bioturbation
- **Bed thickness**: 20 cm–1 m
- **Interval thickness**: up to 5 m
- **Continuity estimate**: km
- **Interpretation**: constant energy conditions, lower/upper flow regime (lower flat bed/upper plane bed), possibly longshore current deposits

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Figure 24: (a and c) cross-bedded sandstones; (b) thin section close-up; (d) meter-thick interval of cross-bedded sandstone that shows lateral accretion which indicates point-bar deposition along a channel (marked with a red/white band, red arrow).

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Figure 25: (a, c and d) horizontally to low-angle laminated sandstones; (b) thin section close-up.
Grain size: fine to coarse arenite  
Sorting: poor to very well sorted  
Sedimentary structures: soft sediment deformation (e.g. ball and pillow structures, convolute bedding, fluid escape structures)  
Bed thickness: 5 cm–1 cm  
Interval thickness: up to 1 m  
Continuity estimate: km  

Interpretation: soft sediment deformation possibly triggered by an earthquake, marine environment

Figure 26: (a and c) Sandstone with soft sediment deformation (ball and pillow structures); (b) thin section close-up; (d) large-scale soft sediment deformation of sandstones (yellow line: base sandstone & top conglomerate, black dashed line: internal sandstone layering and red dashed line: base of overlying horizontally bedded sandstones).

Grain size: fine to coarse arenite  
Sorting: sorted to very well sorted  
Sedimentary structures: ripples  
Bed thickness: 1 cm–20 cm  
Interval thickness: up to 1 m  
Continuity estimate: 100s of m  

Interpretation: influence of currents or wave energy, direction of ripples indicative for paleocurrent direction or paleocoastline orientation. Tidal, estuarine, fluvial environments possible.

Figure 27: (a) thin section close-up of rippled sandstone; (b) sandstone with wave/current ripples in top view; (c) alternation of sandstones with current ripples and dolomitic mudstones.
Jurassic Mafraq Formation, Oman

### Sandstone rooted (Srt)

- **Grain size**: fine to coarse arenite
- **Sorting**: well to poorly sorted
- **Sedimentary structures**: intense rooting
- **Bed thickness**: up to 2 m
- **Continuity estimate**: 100s of m to km
- **Interpretation**: paleosol indicates subaerial exposure and thus a terrestrial, fluvial (floodplain) or deltaic environment. They often occur around unconformities or cycle boundaries (e.g., Toarcian unconformity, top Lower Mafraq).

### Mudrock (MR)

- **Grain size**: clay - silt
- **Sorting**: sorted to very well sorted
- **Sedimentary structures**: none
- **Bed thickness**: 1 cm - 50 cm
- **Interval thickness**: up to 2 m
- **Continuity estimate**: 100s of m
- **Interpretation**: very low-energy conditions (suspension settling), low-energy lagoon
- **Potential seal facies!**

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**Figure 28**: (a, c and d) Rooted sandstones in outcrops (“Oman Soil Facies”); (b) thin section close-up (red arrow marks root trace).

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**Figure 29**: (a, c and d) Red, grey or brown-red mudrock (mix of silt and shale) in outcrops; (b) close-up of a subsurface cutting sample.
**Coal (C)**

**Occurrence**: within clastic intervals of the Lower Mafraq in subsurface only

**Sedimentary structures**: none

**Bed thickness**: 0.5 cm–20 cm

**Continuity estimate**: n.a.

**Interpretation**: coal layers may represent a deltaic (interdistributary bay) or fluvial (floodplain) environment (a and b). Coal fragments are an indicator for a terrestrial origin of sandstone material (c and d).

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**Mudrock rooted (MRrt)**

**Grain size**: clay - silt

**Sorting**: well to very well sorted

**Sedimentary structures**: intense rooting, mud cracks, rare bioturbation

**Bed thickness**: 0.5 cm–20 cm

**Continuity estimate**: 100s of m to km

**Interpretation**: paleosoil indicates subareal exposure and thus a terrestrial environment. They occur around unconformities/cycle boundaries.

**Potential seal facies!**

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Figure 30: (a and c) Rooted mudrock in subsurface core slabs; “Oman Soil Facies”; (b) thin section close-up of outcrop sample (red arrow marks root trace); (d) grey-red rooted mudrock (red arrow) on top of karstified orange-brown dolomitic mudstone.

Figure 31: (a and b) Sandstone in subsurface cores with coal beds and fragments (red arrow); (c and d) coal pieces and coal-rich sandstones in subsurface cuttings. Note that this facies type is not present in outcrops.
Facies Associations

Facies types that are genetically related with respect to their depositional environment can be grouped into lithofacies associations. A schematic overview of the general depositional context of all facies associations and their specific sub-environment is illustrated in Figure 32. The 12 carbonate and 11 clastic Mafraq facies types were grouped into five facies associations.

The Fluvial/Terrestrial (LFA 1) association comprises fluvial facies such as cross-bedded sandstones from fluvial channels, conglomerates and clay-rich overbank/floodplain deposits. Rooted facies, coal-rich sandstones and mudrocks as well as condensed lateritic iron crusts characterize this most proximal Mafraq facies association, where carbonates are absent. Note that outcrops in the Oman Mountains do not cover this facies association. It is present in the subsurface Mafraq in south and Central Oman and in outcrops south of the Oman Mountains (Huqf, Jabal Madar) (Bendias et al., in preparation). The channel deposits (sandstones) are potential reservoirs, and floodplain deposits (mudrocks) potential seals. Possible facies types are Sx, Sr, Sm, Sl, Sb, Srt, MRm, MRrt, Cc/m, and C.

The Coastal Complex (supra- to intertidal) (LFA2) association contains a large variety of clastic and some carbonate facies types from a coastal environment. Deposits from a marsh environment (rooted sandstones/mudrocks, coal), deltaic/estuarine deposits (sandstones, coal) and tidal sediments (sandstones/mudrocks) characterize this clastic-dominated environment. Where clastic influence is low, marginal marine carbonates such as microbial boundstones and dolomitic mudstones take their place. Deltaic/estuarine/tidal sandstones can represent potential reservoirs and marsh/interdistributary bay mudrocks and mud-rich carbonates potential seals. Possible facies types are Sx, Sr, Sm, Sl, Sb, Sd, MRm, MRrt, Cc/m, C, B,mi, DM, MiB, P, and fe-o.

The Lagoonal/Backshoal (low- to medium-energy) (LFA 3) association is portrayed by mudstones, bioclastic wacke- and packstones (storm deposits) and Lithiotis mounds. Besides most carbonate facies types clastic influence can still be present and is expressed by fine-grained sandstones and mudrocks. This association bears no potential reservoirs, but mud-rich carbonates may form potential seals. Possible facies types are Sr, Sm, Sl, Sb, Sd, MRm, DM, MiB, Mn, W, WPg, WPm, Plt.

The High-energy Shoal/Shoal Fringe (LFA 4) association contains oolitic and peloidal pack- to grainstones and grainstones deposited on and around shoals. Thick, cross-bedded oolitic and peloidal grainstones deposit above fair-weather wave base and form shoals (massive shoal intervals exist only in the subsurface). Thinner, rippled/massive pack- to grainstones represent backshoal oriented spillover deposits and storm sheets that originate from a nearby shoal. Reservoir potential is expressed in oolitic and peloidal grainstones form potential reservoirs and interfingering lagoonal muddy carbonates and mudrocks potential seals. Possible facies types are PGm, PG,o, Gx,o.
The Foreshoal (LFA 5) association is not found in the study area. It most likely consists of storm influenced carbonate deposits and rare fine-grained clastics.

Depositional Model

A large variety of depositional sub-environments formed the sedimentary record of the Mafraq Formation (Figure 32). In Lower Mafraq times uplift of the Neo-Tethys rift shoulder resulted in a greater paleorelief with a dip towards the NW of Oman and an exposed landmass in the east. For outcrops in North Oman this results in a mix of coastal siliciclastic sediments that can be associated with some terrestrial facies and muddy carbonates (lagoon/backshoal to coastal complex environment). Subsequent flooding during Upper Mafraq times results in a southeastward shift of the paleocoastline. Thus carbonate-dominated sediments, with little siliciclastic influence, dominate the Upper Mafraq Sequence in the Oman Mountains (shoal/shoal fringe to lagoon/backshoal environment). Clear terrestrial siliciclastics can only be encountered southeast of the Oman Mountains (Jabal Madar and Al Huqf).

MAFRAQ TYPE SECTION IN WADI SAHTAN

This study documents a newly logged outcrop type section of the Mafraq Formation in the Oman Mountains in Wadi Sahtan (Figure 6, Enclosure I). There, the Mafraq directly overlies the Triassic Mahil Formation (equivalent to the subsurface Jilh Formation). As indicated by outcrop biostratigraphy the Upper Triassic Minjur Formation, which is present in the subsurface Lekhwair area (Forbes et al., 2010) cannot be found in outcrops of Oman. This enlarges the base Jurassic unconformity there to a time span from Norian to Hettangian (Figure 5).

The Lower Mafraq Sequence consists of about 50% clastics in the basal 50 m, passing upwards into more and more carbonates. A final siliciclastic bed at the top of the Lower Mafraq Sequence produces a last gamma-ray (GR) peak (Enclosure I). On top of this bed lies another unconformity that most likely represents the AP6/AP7 megasequence boundary (Sharland et al., 2001; Figure 5). The Upper Mafraq Sequence is composed of pure, clean limestones with clastic influence only at the top. This overall cleaning-dirtying trend is also well reflected by the GR (Enclosure I). Above the two to three prominent clastic intervals that produce high GR peaks, which are typical for the top of the Mafraq Formation, lies the Middle Jurassic Dhruma Formation. Enclosure I illustrates the development of the Mafraq Formation from bottom to top, and presents the color codes used for most figures.

Sedimentological Development

Dolomites of the Triassic Mahil Formation appear as a massive, grey grainstone unit below the Mafraq Formation (Enclosure I, Photo A). A mix of muddy carbonates (grey-blue lime mudstones and yellow, dolomitic mudstones) and clastic sediments such as conglomerates (brown) and sandstones (red) lies on top of the base Jurassic unconformity. Above the thick sandstone unit at ca. 120 m, clastic influence ceases and carbonates start to dominate. Yellow, muddy dolomites and grey limestones of varying Dunham texture alternate with few clastic, clay-rich intervals. The thick clastic bed at around 74 m marks the top of the Lower Mafraq Sequence.

Two ca. 25 m-thick, dark blue, pure limestone packages form the so called “massive limestone interval”. In the middle, it is interrupted by a small, recessive unit with clastic influence. This creates the typical GR pattern of the massive limestone interval: 50 m of very low GR values with a small peak in the center (Enclosure I). Limestones change gradually from wacke- to packstones in the lower part to more and more grainstones in the upper part. At the top of the massive limestone interval, grainstones alternate with some fine-grained sandstones and shales (yellow to red). The uppermost 10 meters of the Mafraq Formation are again dominated by clastics and muddy carbonates. Above the two to three clastic intervals with high GR values, which are characteristic for the top of the Mafraq Formation, lie the basal carbonates of the Dhruma Formation appear.
Sequence-Stratigraphic Approach

Field logging focused on sedimentological descriptions as well as the identification of criteria and trends that are critical for sequence-stratigraphic interpretations. High-frequency sequence and sequence boundaries were picked at the base of thick erosive sandstone units and conglomerates, or at the top of paleosoils and karst horizons. Maximum flooding zones/surfaces were interpreted in grain-rich carbonates. Consequently, relatively high GR values are common around sequence boundaries, low GR values around flooding zones (Enclosure I). As documented below, the Mafraq Formation can be subdivided into two major sequences. These are subdivided into high-frequency sequences (HFS) LM HFS-1 to LM HFS-6 in the Lower Mafraq Sequence, and UM HFS-1 and UM HFS-2 in the Upper Mafraq Sequences in outcrops. A more detailed account on sequence-stratigraphic hierarchy of the Mafraq Formation can be found in the next section.

Sand Bodies and Muddy Carbonates: Basal 50 m of the Mafraq Formation in Wadi Sahtan

Schlaich (2013) named the sandy units within this interval “sand body 1 to 5” and documented their depositional context, lateral continuity and reservoir potential. Some of the results of his study are presented here; more details will be published by Schlaich et al. (in preparation).

Description: The basal 50 m of the Mafraq Formation are characterized by abundant high GR clastic intervals that are sometimes intensively rooted and muddy carbonates that can show signs of karstification or erosion (Enclosure I, Photos a to i).

170–166 m: A m-thick interval of red, iron oolitic wacke- to packstones. The contact surface to the underlying dolomitic Mahil Formation shows signs of karstification and intense bioturbation (no borings) at some places (Enclosure I, Photo a).

166–164 m: Rooted sandstone interval that is partly eroded by a trough cross-bedded sandstone (bidirectional trough orientation SE-NW) with lateral accretion structures (sand body 1, Enclosure I, Photos b and c).

164–160 m: Up to 8 m-thick, massive and unsorted conglomerate with an erosive base. It shows a grain size distribution from silt to boulder size and a variety of different components such as dolomite, limestone, siltstone and sandstone clasts in a dolomitic mudstone matrix (Enclosure I, Photo d). The base of this conglomerate was picked as the boundary between the first and second high-frequency sequence (LM HFS-5 and LM HFS-6).

160–157 m: Sand body 2, a fine-grained, well-sorted sandstone with a dolomitic matrix and marine bioturbation (e.g. *Arenicolites*). It can be separated into two parts (Enclosure I, Photo e): The lower part shows sandstones with m-sized load casts. The upper portion consists of sandstones with current ripples (flow direction SW to NE), tool marks (bidirectional SW–SE), low-angle lamination and bioturbation.

157–149 m: Sand body 2 turns upwards into a m-thick interval of dolo- and lime-mudstones (Enclosure I, Photo f).

148 m: Intensively rooted sandstones were selected as the boundary between LM HFS-5 and LM HFS-4 high-frequency sequences.

148–132 m: Alternation of intensively rooted, fine-grained clastics, massive and rippled sandstones (e.g. sand body 3 and 4) and mud-dominated carbonates (Enclosure I, Photos g and h). Trough cross-bedding measurements in sand body 3 and 4 indicate bidirectional, east-west oriented flow directions.

132–120 m: The erosive base of sand body 5 (132 m) forms the upper boundary of LM HFS-4. Sand body 5 is up to 12 m thick and consists of several stories, each with a very characteristic pattern. Beds show a sigmoidal shape and pinch out laterally. Each dm-thick bed starts with an erosive coarse-grained base, which fines up into trough cross-bedded sandstones. At the top cross-bedded sandstones turn into rippled, bioturbated and sometimes into rooted sandstones (Enclosure I, Photo i) Trough cross-bedding measurements in sand body 5 indicate a flow direction from SE to NW.

Interpretation: Abundant rooted facies (paleosoils), erosive surfaces and karstified horizons indicate common sub-aerial exposure and thus a number of smaller and larger unconformities. Especially the
erosion at the base of the conglomerate in the lower part seems important as this surface probably represents a more significant unconformity. This thick, massive conglomerate most likely represents a mass-flow event (possibly triggered by an earthquake or a major rainfall leading to slope failure) that eroded into underlying sediments. One interpretation could be that such events occurred preferentially during peak regression as limited accommodation space, or local subaerial exposure led to erosion.

Muddy carbonates with some marine fossils and sandstones with marine bioturbation indicate a shallow-marine depositional environment. Sand bodies 1, 3 and 4 are placed, based on the interpretation of sedimentary structures, in a tidal flat environment. According to paleocurrent measurements sand body 2 possibly represents long-shore current deposits. The thickest sand body 5 is probably the result of an estuarine channel system as beds show a sigmoidal shape and pinch out laterally, which is typical for lateral accretion along channels.

The alternation and mix of carbonates and siliciclastics together with the sedimentological observations place the lowermost 50 m of the Mafraq Formation in a shallow-marine, tidal flat to lagoon/backshoal environment. Most parts of this interval are assigned to the coastal complex facies association.

**More Carbonates, Less Clastics: Upper part of the Lower Mafraq Sequence**

**Description:** Carbonates ranging from mudstone to grainstone dominate the upper 50 m of the Lower Mafraq Sequence (Enclosure I, Photos j–r). Clastics are generally less abundant, finer-grained and do not form thicker intervals as in the basal 50 m of the Mafraq Formation.

120–114 m: At and above the top of sand body 5 alternations of massive, bioturbated (Enclosure I, Photo k) or rippled (Enclosure I, Photos l and m) sandstones and sand-rich carbonates mark a change from clastic- to carbonate-dominated sediments.

114–112 m: The top of the LM HFS-3 is located above a rooted sandstone bed.

112–90 m: First fossil-rich wacke- and packstones (Enclosure I, Photos n and o), interrupted by few clastics and some dolomitic mudstones, portray an increasing percentage of carbonates and more biodiversity. Rooted facies and thick sandstone intervals are absent.

90–87 m: A small siltstone bed in the middle of a m-thick dolomitic mudstone interval (Enclosure I, Photo p) marks the top of LM HFS-2 with a high GR signal.

87–74 m: First *Lithiotis* (up to 40 cm large, Jurassic bivalves) beds (Enclosure I, Photo q) and other carbonates in the form of bioclastic wacke-, pack- and grainstones illustrate another upward increase in biodiversity. In contrast to the interval up to sand body 5, beds of this interval can contain peloids, ooids, oncoids or coral fingers.

74 m: The top of the Lower Mafraq Sequence (and the top of LM HFS-1) consists of a last, rooted, around 1 m-thick interval of very fine-grained, red, silt-rich sandstones (Enclosure I, Photo r). This sandstone also produces a last high GR peak that is interpreted to represent a sequence boundary below the massive limestone interval of the Upper Mafraq Sequence.

**Interpretation:** More carbonates, increasing biodiversity, decreasing clastic influence combined with very few paleosoils and exposure surfaces characterize the interval between top sand body 5 and top Lower Mafraq Sequence. This interval is interpreted to result from a lagoon/backshoal environment (LFA 3). This highlights an upward-deepening trend and places the maximum flooding surface of the Lower Mafraq Formation some 7 m below the top. The boundary between the Lower and the Upper Mafraq sequences (a rooted sandstone) is interpreted as non-angular unconformity, despite the absence of clear erosional features or karstification (see also biostratigraphy discussion below).

**Packstones, Grainstones and Clastics: Massive Limestone Interval and the Top of the Upper Mafraq Formation**

**Description:** Dark blue carbonates characterize the 50 m-thick, massive limestone interval in the lower part of the Upper Mafraq Sequence; it is capped by a 15 m alternation of multi-colored clastics and carbonates (Enclosure I).

73–48 m: The Upper Mafraq Sequence starts with 25 m of peloid-rich wacke- to packstones and a very low GR signature. They form intensively bioturbated (*Thalassinoides* traces), up to
Jurassic Mafraq Formation, Oman

several m-thick intervals (Enclosure I, Photos s and t). Besides abundant peloids, few other components, such as bioclasts like (e.g. Lithiotis, gastropods, bivalve shells or coral fingers), are present.

48–44 m: Recessive unit, very thin layers of bioturbated wackestones mixed with silt and shale (Enclosure I, Photo u) separates the massive limestone interval into a lower and an upper part. A GR peak at this location marks the top of the Upper Mafraq high-frequency sequence UM HFS-2.

44–23 m: Thick Lithiotis packstones and an upward increasing amount of thin peloidal and oolitic grainstones. Sometimes Lithiotis packstones form m-thick beds (Enclosure I, Photo v) with imbricated components indicating a transport direction from southeast to northwest. Biodiversity in this interval increases.

23–18 m: First clastic influence and higher GR values, a succession from clastics to a m-thick oolitic grainstone interval back to thick clastics (Enclosure I, Photo w). Clastics below the oolitic interval are mixed with peloidal carbonates, they are the reason for the small GR peak at meter 21. Oolitic grainstones above form thin 2–10 cm-thick beds with ripples and gutter casts (red arrow, Enclosure I, Photo x). The gutter casts are oriented in southeast-northwestward direction. Clastics on top are very fine-grained sandstones with small clay-rich seams (Enclosure I, Photo y). They produce a very prominent GR peak.

18–15 m: Carbonates in form of dolomitic mud and boundstones and few oolitic grainstone beds create low gamma-ray values.

15–10 m: Fine-grained, clay-rich sandstones with high GR values. In some places, these sandstones are rooted at the top where they lie right below a m-thick dolomitic mudstone that marks the top of the Mafraq Formation and the top of UM HFS-1 (Enclosure I, Photo z).

Interpretation: Thick peloidal wacke- to packstones with abundant bioturbation and some Lithiotis packstones indicate backshoal conditions for the lowermost 25 m of the Upper Mafraq Sequence. The recessive unit in the middle of the massive limestone interval probably represents a more proximal signal with a pulse of clastics that came probably from a landward direction. Above, biodiversity increases, peloidal and oolitic grainstones are more abundant indicating that this might be the most distal portion of the Mafraq in Wadi Sahtan. Thin oolitic grainstone beds, some 10–20 m below the top of the Mafraq are interpreted to mark the maximum flooding zone as they are likely to represent spillover deposits that originate from a nearby shoal. The clastic interval around the top represents again a more proximal tidal flat to marsh environment.

SEQUENCE STRATIGRAPHY

Lithofacies types show vertical stacking patterns that indicate a hierarchical cyclicity. The terminology for the detected cycle order was adopted from Kerans and Tinker (1997). Most cycles consist of a transgressive and a regressive hemicycle, although sometimes only the transgressive hemicycle may be present (erosion or non-deposition). The presence of cycles in the sedimentary record can be explained as follows (Enclosure I):

Creation of accommodation space (A) < sedimentation rate (S) = seaward environmental shift.
Creation of accommodation space > sedimentation rate = landward environmental shift.

Facies observations and interpreted environment shifts in outcrops lead to the interpretation of the A/S cycles (Enclosure I). Four cycle orders from small to large scale are detectable in the Mafraq: cycles, cycle sets, high-frequency sequences (HFS) and sequences.

Cycles

The smallest scale of cycles in the Mafraq has a thickness of 1-4 m (Enclosure I). Siliciclastic influence is common around cycle boundaries creating higher GR values, especially in the Lower Mafraq Sequence. Carbonates dominate around maximum flooding surfaces (MFS) producing lower GR values. This pattern makes cycles obvious and easy to detect in outcrops. A total of 83 cycles have been interpreted for the Mafraq Formation in Wadi Sahtan.
A rough calculation based on total age given by outcrop biostratigraphy using age dates after Gradstein et al. (2012) result in a time span for each cycle of ca. 100,000 years in the Upper Mafraq and ca. 250,000 years in the Lower Mafraq sequences. Supposing that many small-scale cycles are missing due to erosion or non-deposition, especially in the Lower Mafraq Sequence where small unconformities paleokarst surfaces and paleosoils are common, this could possibly generally indicate a ca. 100,000 year Milankovitch signal for cycles. As biostratigraphic resolution is rather poor and the lateral extent of these cycles is limited (see discussion below) assigning time spans to these cycles remains highly speculative.

Three basic cycle motifs can be distinguished in the field (Figures 32 to 35). Note that these idealized cycle types are meant to illustrate the range of possible cycles in the field. In reality, most cycles differ from these “ideal cycles” and can sometimes represent a mix of 2 cycle types.

**Cycle Type 1 (Clastic-Carbonate-Clastic Cycle)** is common in the Lower Mafraq Sequence where siliciclastic sediments and carbonates are mixed and interbedded (Figures 32 and 33). The cycle boundaries are characterized by sandstones and shales that are sometimes rooted (“Oman Soils”), karstified carbonate surfaces. Maximum flooding surfaces are formed by carbonates and carbonate-rich siliciclastic sediments.

**Cycle Type 2 (Carbonate Cycle)** is common in the upper part of the Lower Mafraq and in the lower part of the Upper Mafraq sequences where siliciclastic influence decreases and pure carbonates dominate (Figures 32 and 34). Cycle boundaries are characterized by mud-rich carbonates such as mudstones and wackestones sometimes with influence of shale. Maximum flooding surfaces are interpreted in the grain-rich carbonates such as pack- and grainstones.

**Cycle Type 3 (Clastic-Grainstone-Clastic Cycle)** is typical for the uppermost 20–30 m of the Mafraq Formation where intercalations of fine-grained siliciclastic sediments and carbonates are common (Figures 32 and 35). Cycle boundaries are characterized by fine-grained sandstones and shales, and maximum flooding surfaces by oolitic and peloidal grainstones.

**Discussion**: Despite the striking small-scale cyclicity in vertical outcrops, it is questionable whether these cycles can be correlated on a larger scale. Lower Mafraq correlations from Schlaich (2013, Schlaich et al., in preparation) showed that most of the cycles can be correlated on a 200 m-scale with only few pinching out laterally. On a kilometer scale, a consistent correlation of cycles is difficult. Therefore, cycles only seem to represent a correlative sequence-stratigraphic signal on a production scale (up to few kilometers). Thus it is debatable whether they have to be considered as auto- or allo-cycles.

**Cycle Sets**

Packages of 2–4 cycles form the up to 10 m-thick cycle sets (Figure 36). Cycle sets are very well reflected in the GR pattern and by clear lithological trends. In the lower 50 m of the formation cycle set boundaries are placed on top of major rooted sandstones and shales or karstified carbonate beds. Maximum flooding surfaces lie within mud-dominated carbonates. Above, sandstones, shales or shale-rich carbonates define cycle-set boundaries and grain-rich carbonates with more and more fossils were used to pick maximum flooding surfaces.

In Wadi Sahtan, a total of 15 cycle sets have been interpreted in the Lower and 8 in the Upper Mafraq sequences. The calculated time span for cycle sets results in ca. 850,000 years for the Lower and 480,000 years for the Upper Mafraq sequences. It can be assumed that some cycle sets are not complete in the sedimentary record or missing due to erosion or non-deposition in the Lower Mafraq Sequence. It may therefore be speculated that the stacking pattern of 2–4 cycles into one cycle set might indicate a 405,000 year Milankovitch signal for cycle sets.

Mafraq cycle sets can be correlated up to a distance of tens of kilometers in outcrops and clearly represent a sequence-stratigraphic signal that seems significant on a 50 km exploration scale.
CYCLE TYPE 1: CLASTIC - CARBONATE - CLASTIC CYCLE

- Shale-rich carbonates
- Carbonates
- Carbonate sandstone

Figure 33: Example of Cycle Type 1 (ca. 1.0 m thick) for intervals with mixed carbonates and siliciclastic sediments. Type 1 cycles commonly occur in the Lower Mafraq coastal complex (see Figure 32). Thin section (a) is a close-up of sandstone with carbonate matrix and some bioclastic components such as bivalve shells. Thin section (b) is a close-up of packstone with abundant peloids, some bioclasts and some quartz grains.

CYCLE TYPE 2: CARBONATE CYCLE

- Wacke- to packstones
- Pack-, pack- to grain and grainstones
- Wacke- to packstones

Figure 34: Example of Cycle Type 2 (ca. 2.0 m thick) for intervals where siliciclastic influence is scarce. Type 2 cycles commonly occur in the lagoon-backshoal setting (see Figure 32). Thin sections show: (a) bioturbated wackestones with some bioclasts and peloids (not shown); (b) close-up of packstone with abundant peloids and some bioclasts; (d) pack- to grainstone with abundant peloids, some bioclasts and few ooids; and (d) oolitic grainstone with some bioclasts.
High-frequency Sequences (HFS) and Sequences

Stacks of two to six cycle sets form up to 35 m-thick high-frequency sequences (HFS, Figure 36, Enclosure I). Six HFS form the Lower Mafraq Sequence (from top to bottom LM HFS-1 to LM HFS-6), two the Upper Mafraq Sequence (UM HFS-1 and UM HFS-2). Maximum regressive surfaces (sequence boundaries between HFSs) are placed at the most prominent erosive bases of sandstone units, on top of paleosoils or prominent siliciclastic beds in the Lower Mafraq Sequence. In the Upper Mafraq Sequence the boundary is placed within a shale-rich unit in the middle of the massive limestone interval. The exact position of each sequence boundary has also been described in the section on the Type Section of the Mafraq Formation (see above).

The logged components from the section in Wadi Sahtan, roughly arranged from proximal (left) to distal (right), illustrate how component composition and variety can be used for sequence-stratigraphic interpretations (Figure 36). Proximal components like quartz grains, glauconite and iron-rich layers can be associated with the coastal complex environment and mark sequence boundaries. Oncoids, peloids, ooids and corals mark maximum flooding surfaces as these components indicate more open-marine conditions and a backshoal to shoal environment. Especially in the Lower Mafraq Sequence the component diversity seem to roughly track the sequence-stratigraphic development. Mafraq HFS can be consistently correlated up to a distance of hundreds of kilometers throughout North Oman including subsurface locations (Bendias et al., in preparation).

BIOSTRATIGRAPHY

Sixty-five fossil-rich thin-section samples from Wadi Sahtan were analyzed by S. Packer (Millennia Stratigraphic Consultants Ltd.) to establish a biostratigraphic framework for the Mafraq Formation in outcrops (Figure 37). The thin-section slides were examined to record any fossil groups that might be present including foraminifera, ostracods, calcareous algae, charophytes, sponge spicules, macrofossil
debris (echinoderms, bivalves, crinoids etc). A count was made for each slide based on 10 FoV (field-of-view) at magnification of ten (x10) to provide a consistent database. The remainder of the slide was then scanned to capture the occurrence of any taxa occurring outside the count.

The age of the section is interpreted based on the unpublished PDO F Zonation for Oman (Sikkema, 1991), which provides the framework for chronostratigraphic interpretation. In general the subsurface Jurassic in Oman has not been extensively studied for calcareous micropaleontology as bigger rock samples for thin-section are rare. Therefore the zonation proposed by Sikkema (1991) is largely based on other published work. Subsurface interpretation of this interval in the past has largely relied on palynology. It may be speculated that some of the differences between outcrop and subsurface timeframe could be explained by the different sampling method of palynology (shale samples) and micropaleontology (carbonates).

Microfossil recovery in the Mafraq Formation thin sections comprises calcareous and agglutinating benthic foraminifera, ostracods, calcareous algae, calcispheres, bivalve, echinoid, bryozoan and crinoid debris, together with microgastropods, corals, and sponge spicules. Abundance and diversity of the faunas encountered varies through the sections. A high proportion of the samples contain only relatively low numbers of taxa, with distinct ‘floods’ of ostracods, calcareous algae, macrofossil debris and foraminifera concentrated at or within particular intervals. This pattern of distribution is influenced by the original depositional environment (e.g. foraminifera occur in shallow-marine sections), the sampling regime and the subsequent effects of post-depositional processes such as localized dolomitization or recrystallization.

Benthic foraminifera provide the primary age control, notably the last (extinction or ‘top’) and first (inception or ‘base’) occurrences of *Orbitopsella* spp., *Involutina* spp., *Haurania* spp., and *Redmondoides* spp. This is supplemented by the occurrences and relative abundance of calcareous algae, notably *Thumatoporella* spp., and *Salpingoporella* spp. These occurrences provided the framework for chronostratigraphic subdivision of the section. The count data and relative proportions of the various taxon groups provided the basis for interpreting the depositional environment based on biostratigraphy. This was subsequently integrated with the field observations of the first author to refine the paleoenvironmental and sequence interpretation. It could be speculated that some of the first and last appearances of the benthic foraminifera and their relative abundances are also facies controlled.

The main results of biostratigraphic analysis are: (1) Lower Mafraq Sequence is Hettangian–Late Pliensbachian (F30 Zone: F303-F307 Subzones). (2) Upper Mafraq Sequence is Late Aalenian–Late Bajocian (F45 Zone: F453-F457 Subzones). (3) Confirmation of the sequence-stratigraphic framework in outcrop on a HFS and sequence level. (4) Confirmation of a large unconformity between Lower and Upper Mafraq sequences that seems to comprise the complete Toarcian with about 10 Myr missing. (5) No Upper Triassic strata (Minjur Formation) is present in outcrops. It should be noted however that identification of the top Triassic based on foraminifera (e.g. *Trasina* spp.) relies on the presence of marine sequences. As first biostratigraphic samples locate ca. 2 m above the base of the Mafraq Formation the interval below could theoretically be part of the Upper Triassic Minjur Formation.

The results that are summarized above provide new constraints for several Arabian Plate maximum flooding surface (MFS) as defined by Sharland et al. (2001). They interpreted the oldest-Jurassic Middle Toarcian MFS J10, in what they considered the Lower Mafraq Member in Yibal-85 Well. Forbes et al. (2010) revised this interpretation by indicating that this position occurs in the Upper Mafraq Member. Our study indicates that the Toarcian Stage and therefore MFS J10 are not represented in the studied outcrops (Figure 5), which is surprising because MFS J10 is recognized as a widespread flooding event in most of the Arabian Plate (Sharland et al., 2001). Based on its Early Bajocian age, MFS J20 of Sharland et al. (2001) may correlate to the MFS of the Late Aalenian–Late Bajocian Upper Mafraq Sequence implying that Lower Bathonian MFS J30 occurs in the Dhurma Formation. The Upper Sinemurian–Upper Pliensbachian Lower Mafraq Sequence contains an MFS, which is not defined in the Arabian Plate; this is also surprising because these stages are reported as absent in most of the Arabian Plate (Sharland et al., 2001).
Figure 36: Facies, GR and components arranged from proximal to distal along the Mafraq type section in Wadi Sahtan are useful to determine sequence-stratigraphic trends from sequence to cycle set hierarchy. Red/black arrows at the right side mark a trend towards more distal components/more biodiversity when pointing to the right (and vice versa). Red arrows follow the trend along sequences, black arrows trace HFS. See Enclosure I for legend and Enclosure II for location.
Jurassic Mafraq Formation, Oman

Figure 36: Facies, GR and components arranged from proximal to distal along the Mafraq type section in Wadi Sahtan are useful to determine sequence-stratigraphic trends from sequence to cycle set hierarchy. Red/black arrows at the right side mark a trend towards more distal components/more biodiversity when pointing to the right (and vice versa). Red arrows follow the trend along sequences, black arrows trace HFS. See Enclosure I for legend and Enclosure II for location.

| Stratigraphy | Depth (m) | Dunham Texture | Biostratigraphic Samples |
|--------------|-----------|----------------|-------------------------|
| Dhruma        | 0-5       |                |                         |
| Formation     | 10-20     |                |                         |
| F 303 Subzone | 25-30     |                |                         |
| F 307 Subzone | 35-40     |                |                         |
| F 453 Subzone | 45-50     |                |                         |
| F 457 Subzone | 55-60     |                |                         |
| F 465 Subzone | 65-70     |                |                         |
| F 485 Subzone | 75-80     |                |                         |
| F 490 Subzone | 85-90     |                |                         |
| F 495 Subzone | 95-100    |                |                         |
| F 500 Subzone | 105-110   |                |                         |
| F 505 Subzone | 115-120   |                |                         |
| F 510 Subzone | 125-130   |                |                         |
| F 515 Subzone | 135-140   |                |                         |
| F 520 Subzone | 145-150   |                |                         |
| F 525 Subzone | 155-160   |                |                         |
| F 530 Subzone | 165-170   |                |                         |
| Mafraq        | 0-5       |                |                         |
| Formation     | 10-20     |                |                         |
| F 303 Subzone | 25-30     |                |                         |
| F 307 Subzone | 35-40     |                |                         |
| F 453 Subzone | 45-50     |                |                         |
| F 457 Subzone | 55-60     |                |                         |
| F 465 Subzone | 65-70     |                |                         |
| F 485 Subzone | 75-80     |                |                         |
| F 490 Subzone | 85-90     |                |                         |
| F 495 Subzone | 95-100    |                |                         |
| F 500 Subzone | 105-110   |                |                         |
| F 505 Subzone | 115-120   |                |                         |
| F 510 Subzone | 125-130   |                |                         |
| F 515 Subzone | 135-140   |                |                         |
| F 520 Subzone | 145-150   |                |                         |
| F 525 Subzone | 155-160   |                |                         |
| F 530 Subzone | 165-170   |                |                         |

Figure 37: Biostratigraphic sample distribution (red arrows), key taxa images and the resulting interpreted stratigraphic framework including the PDO zonation (after an internal PDO report from Sikkema, 1992) for the Mafraq Formation in Wadi Sahtan. Thin-section close-ups: (a) miliolids and microgastropods; (b) Involutina spp.; (c) Orbitopsella fragments, Textularia spp.; (d) O. praecursor; (e) R. lugoni; (f) sponge spicules; (g) T. parvovesiculifera; (h) bivalve assemblage; (i and j) microgastropods. See Enclosure I for legend and Enclosure II for location.
DESCRIPTION OF THE MAFRAQ FORMATION IN OUTCROPS OF OMAN

This section describes 11 additional outcrops of the Mafraq Formation in North Oman. Nine outcrops are located in the Oman Mountains; one is located in Jabal Madar and one in Al Huqf area in Central Oman (Figure 1, Enclosure II). Provided data includes outcrop coordinates (WGS 84 Zone 40N) for each logged section and where possible, illustrative outcrop overview and close-up pictures. Please note that outcrop pictures in Figures 38–69 can be rotated in order to better link outcrop and outcrop log data.

Wadi Hail Bint Section

The section in Hail Bint is located five kilometers to the east of the type section in Wadi Sahtan and has a thickness of 143 m (UTM coordinates 2583886N; 536000E; Figures 38 to 40). The Lower Mafraq Sequence has a thickness of around 80 m, and the Upper Mafraq Sequence ca. 63 m. The general facies and GR patterns are very similar to those in Wadi Sahtan.

The section starts with intercalations of partly rooted sandstones and muddy carbonates that are topped by a massive ca. one m-thick conglomerate (Figure 40a). After some 10 m of mud-rich carbonates the percentage of siliciclastics increases again. There sandstones and shales are commonly rooted and carbonates are sometimes heavily karstified (Figures 40b, c). Some 30 m above the base the thickest sand unit starts with some bioturbated sandstones (Figure 40d) before it turns into a ca. 6 m-thick interval of predominantly trough cross-bedded sandstones. This sand unit is most likely the lateral equivalent of the thickest sand unit in Wadi Sahtan, which has been termed sand-body 5 (Schlaich et al., in preparation). Above, siliciclastics are less abundant and carbonates start to dominate. A final sandstone interval ca. 70 m forms the boundary between Lower and Upper Mafraq sequences.

The so-called “Massive Limestone Interval” that lies above is around 55 m thick and shows the typical recessive unit in the middle where the GR signal shows higher values due to a small increase in clay content. Between meter 30 and 14 massive Lithiotis packstone beds (Figure 40f) turn upward into thin, rippled oolitic and peloidal grainstones (Figure 40g) that are sometimes interrupted by shale or sand-rich units. Siliciclastic intervals (sandstones and shales) with some carbonates in between result in high GR peaks in the uppermost 10 m. The top of the Mafraq Formation lies in a thick rooted mudrock interval (Figure 40h) right below a dolomitic mudstone unit. The outcrop condition in Wadi Hail Bint is excellent, a ca. 90-minute walk is required to reach the outcrop as the wadi has no road.

Figure 38: See facing page for continuation.
DESCRIPTION OF THE MAFRAQ FORMATION IN OUTCROPS OF OMAN

This section describes 11 additional outcrops of the Mafraq Formation in North Oman. Nine outcrops are located in the Oman Mountains; one is located in Jabal Madar and one in Al Huqf area in Central Oman (Figure 1, Enclosure II). Provided data includes outcrop coordinates (WGS 84 Zone 40N) for each logged section and where possible, illustrative outcrop overview and close-up pictures. Please note that outcrop pictures in Figures 38–69 can be rotated in order to better link outcrop and outcrop log data.

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The section starts with intercalations of partly rooted sandstones and muddy carbonates that are topped by a massive ca. one m-thick conglomerate (Figure 40a). After some 10 m of mud-rich carbonates the percentage of siliciclastics increases again. There sandstones and shales are commonly rooted and carbonates are sometimes heavily karstified (Figures 40b, c). Some 30 m above the base the thickest sand unit starts with some bioturbated sandstones (Figure 40d) before it turns into a ca. 6 m-thick interval of predominantly trough cross-bedded sandstones. This sand unit is most likely the lateral equivalent of the thickest sand unit in Wadi Sahtan, which has been termed sand-body 5 (Schlaich et al., in preparation). Above, siliciclastics are less abundant and carbonates start to dominate. A final sandstone interval ca. 70 m forms the boundary between Lower and Upper Mafraq sequences.

The so-called “Massive Limestone Interval” that lies above is around 55 m thick and shows the typical recessive unit in the middle where the GR signal shows higher values due to a small increase in clay content. Between meter 30 and 14 massive Lithiotis beds (Figure 40f) turn upward into thin, rippled oolitic and peloidal grainstones (Figure 40g) that are sometimes interrupted by shale or sand-rich units. Siliciclastic intervals (sandstones and shales) with some carbonates in between result in high GR peaks in the uppermost 10 m. The top of the Mafraq Formation lies in a thick rooted mudrock interval (Figure 40h) right below a dolomitic mudstone unit. The outcrop condition in Wadi Hail Bint is excellent, a ca. 90-minute walk is required to reach the outcrop as the wadi has no road.

Figure 38 (continued): Log of the Mafraq Formation in Wadi Hail Bint. See Enclosure I for legend and Enclosure II for location.
| Depth (m) | Grain Size | Total Gamma-Ray (nGy/h) |
|----------|------------|------------------------|
|          | Dunham Texture |             |
| 0        | B          | 0                      |
| 5        | G          | 20                     |
| 10       | P          | 30                     |
| 15       | W          | 40                     |
| 20       | M          | 50                     |
| 25       |             | 60                     |
| 30       |             | 70                     |
| 35       |             | 80                     |
| 40       |             | 90                     |
| 45       |             | 100                    |
| 50       |             | 110                    |
| 55       |             | 120                    |

Figure 40: Key outcrop pictures, Wadi Hail Bint. (a) meter-thick polymict conglomerate 8 meters above the base of the Mafraq Formation; (b) karstified dolomitic mudstone, blue arrow marks karst cavity filled with red shale; (c) rooted mudrock (MRrt) on top of dolomitic mudstone; (d) bioturbated sandstone (Sb); (e) bioturbated carbonate mudstone (Mm); (f) Lithiotis packstone (P,li) interval; (g) wave-rippled oolitic grainstone (PG,o) bed below the top of the Mafraq Formation; (h) rooted mudrock (MRrt) that forms the top of the Mafraq Formation.

Figure 39: Overview of the outcrop in Wadi Hail Bint. Letters a to h mark location of photos described in Figure 40. See Enclosure I for legend and Enclosure II for location.
Figure 40: Key outcrop pictures, Wadi Hail Bint. (a) meter-thick polymict conglomerate 8 meters above the base of the Mafraq Formation; (b) karstified dolomitic mudstone, blue arrow marks karst cavity filled with red shale; (c) rooted mudrock (MRrt) on top of dolomitic mudstone; (d) bioturbated sandstone (Sb); (e) bioturbated carbonate mudstone (Mm); (f) Lihkiolis packstone (P,li) interval; (g) wave-rippled oolitic grainstone (PG,o) bed below the top of the Mafraq Formation; (h) rooted mudrock (MRrt) that forms the top of the Mafraq Formation.
Wadi Bani Awf Section

The Mafraq Formation in Wadi Bani Awf is located some 18 kilometers to the east of Wadi Sahtan (UTM coordinates 2577978N; 548807E; Figures 41 to 43).

The formation has a thickness of 92 m. Whereas the thickness of the Lower Mafraq Sequence decreases from 86 m at the type section to 28 m in Wadi Bani Awf, the Upper Mafraq Sequence thickness stays constant at around 60–65 m.

The base of the section starts with an intensively brecciated and karstified unit around the top of the Triassic Mahil/Base Mafraq Formation and some intensively rooted sandstones (Figures 43a, b). A several m-thick sandstone unit is topped by intercalations of carbonate limestones, dolomites and siliciclastics (Figures 43c, d).

The percentage of carbonates increases towards the top of the Lower Mafraq Sequence around meter 77 where a last sandstone bed is located.

The Upper Mafraq Sequence is again characterized by thick, low GR carbonates (massive limestone interval), mud-dominated, bioturbated limestones (Figure 43e) and thick Lithiotis packstone beds (Figure 43f).

The 20 meter interval below the top of the Mafraq Formation consists of about 15 m of thinly bedded peloidal and oolitic grainstones (Figure 43g) that are capped by m-thick sand and shale intervals with some carbonates in between.

Like in Wadi Sahtan and Hail Bint, a final shale-rich sandstone bed right below a dolomitic mudstone forms the top of the Mafraq Formation (Figure 43h).

Outcrop condition and accessibility in Wadi Bani Awf are good, although the upper part of the outcrop was destroyed by newly built black top road.

Figure 41: See facing page for continuation.
### Components (Outcrop Observation)

| Component          | Depth (m) |
|--------------------|-----------|
| Quartz Grains      |           |
| Glauconite         |           |
| Iron Oods          |           |
| Iron Crystals      |           |
| Sandstone          |           |
| Brachiopods        |           |
| Muschelkalk        |           |
| Bryozoa            |           |
| Foraminifera       |           |
| Lithiotis          |           |
| Bryozoa            |           |
| Echinodermata      |           |
| Ooliths            |           |
| Pyroclastic        |           |
| Pink Sandstone     |           |
| Ooids              |           |
| Calciturbidites    |           |
| Carbonate          |           |
| Limestone          |           |
| Dolomite           |           |
| Total Gamma-Ray    |           |
| (nGy/h)            |           |

**Figure 41 (continued):** Log of the Mafraq Formation in Wadi Bani Awf. See Enclosure I for legend and Enclosure II for location.
Figure 42: Overview of the outcrop in Wadi Bani Awf. Letters a–h mark location of photos described in Figure 43. The outcrop picture in Figure 42 has been rotated. See Enclosure I for legend and Enclosure II for location.

Figure 43: Key outcrop pictures, Wadi Bani Awf. (a) karstified dolomitic mudstone (DM); (b) rooted sandstone (Srt); (c) bivalve-rich packstone (WPm); (d) small-scale intercalations of sandstones and carbonate wacke- to packstones; (e) massive, bioturbated (Thalassinoides) mudstone (Mm); (f) meter-thick Lithiotis packstone (P_{li}) interval; (g) thinly bedded oolitic (PG,o) and peloidal (PGm) grainstones form a meter-thick interval at the top of the "massive limestone interval"; (h) siliciclastic/carbonate intercalations below the top Mafraq (marked by the dashed yellow line).
Figure 43: Key outcrop pictures, Wadi Bani Awf. (a) karstified dolomitic mudstone (DM); (b) rooted sandstone (Srt); (c) bivalve-rich packstone (WPm); (d) small-scale intercalations of sandstones and carbonate wacke- to packstones; (e) massive, bioturbated (*Thalassinoides*) mudstone (Mm); (f) meter-thick *Lithiotis* packstone (P,li) interval; (g) thinly bedded oolitic (PG,o) and peloidal (PGm) grainstones form a meter-thick interval at the top of the “massive limestone interval”; (h) siliciclastic/carbonate intercalations below the top Mafraq (marked by the dashed yellow line).
Wadi Bani Kharus Section

The Mafraq Formation in Wadi Bani Kharus is about 88 m thick, a compound of 25 m Lower and 63 m Upper Mafraq sequences (UTM coordinates 2574153N; 553430E; Figures 44 to 46).

Like in other sections, the boundary between Triassic Mahil Formation and the Mafraq is intensively karstified (Figure 46a) and topped by a mix of siliciclastic and carbonate beds (Figure 46b).

Some 15 m above the base a m-thick dolomitic unit shows signs of karstification (Figures 46c, d) before lime mud- to packstones dominate.

A rooted mixed sand/shale unit marks the boundary between Lower and Upper Mafraq sequences.

Above, a 35 m interval of sometimes heavily bioturbated lime-mudstones (Figure 46e) is topped by 10 m of thin wacke-, pack- and grainstones forming the dark blue massive limestone interval.

The uppermost 10 m of the section are, like in other sections, characterized by thick clastic units with few carbonates, creating the GR peaks typical for the top Mafraq (Figure 46f).

Unlike other sections where grainstones are usually thin beds, the grainstone interval in Wadi Bani Kharus is 2–3 m-thick and consists of thick and massive beds (Figure 46g) that are overlain by a fine-grained, shale-rich, rooted sandstone, the top Mafraq (Figure 46h).

Wadi Bani Kharus has good outcrop condition and accessibility (by car).
Figure 44 (continued): Log of the Mafraq Formation in Wadi Bani Kharus. See Enclosure I for legend and Enclosure II for location.
Figure 45: Overview of the outcrop in Wadi Bani Kharus. Letters a to h mark location of photos described in Figure 46. See Enclosure I for legend and Enclosure II for location.

Figure 46: Key outcrop pictures, Wadi Bani Kharus: (a) karstified top of the Triassic Upper Mahil Fm. at the base of the Mafraq; (b) typical Lower Mafraq "clastic – carbonate - clastic" cycle; (c) meter-thick dolomitic mudstone (DM) interval with (d) karstified relief; (e) typical Upper Mafraq massive, bioturbated mudstone with "Thalassinoides" traces; (f) siliciclastic / carbonate interval below the top Mafraq; (g) oolitic grainstone (PG,o); (h) rooted mudrock (MRrt) that marks the top of the Mafraq Fm.
Figure 46: Key outcrop pictures, Wadi Bani Kharus: (a) karstified top of the Triassic Upper Mahil Fm. at the base of the Mafraq; (b) typical Lower Mafraq “clastic – carbonate - clastic” cycle; (c) meter-thick dolomitic mudstone (DM) interval with (d) karstified relief; (e) typical Upper Mafraq massive, bioturbated mudstone with “Thalassinoides” traces; (f) siliciclastic / carbonate interval below the top Mafraq; (g) oolitic grainstone (PG,o); (h) rooted mudrock (MRrt) that marks the top of the Mafraq Fm.
Wadi Mistal Section

Eighteen meters of Lower Mafraq Sequence and 46 m of Upper Mafraq sequences compose the 64 m-thick Mafraq Formation in Wadi Mistal (UTM coordinates 2577228N; 570870E; Figures 47 to 49).

Wadi Mistal represents one of the data points where Lower and Upper Mafraq sequences are thinner compared to other locations in the Oman Mountains. In addition, outcrop conditions in Wadi Mistal are quite difficult as folding and thrusting are common.

A 10 cm-thick iron-rich sandstone lies on top of the Triassic–Jurassic unconformity between the Mahil and Mafraq formations.

Apart from a few sandstone and shale beds siliciclastic influence is rare in the Lower Mafraq Sequence. Instead, heavily bioturbated wacke- and packstones (Figures 49a, c) and cross-bedded, oolitic grainstones (Figure 49b) are interbedded with muddy carbonates.

The top of the Lower Mafraq Sequence is represented by an interval of shale-rich, thinly bedded mudstones (Figure 49d).

The Upper Mafraq Sequence is, like in other wadis, characterized by massive, clean, mud-dominated limestones (Figure 49e) that are sometimes heavily bioturbated (Figure 49g) or thinly bedded (Figure 49f).

In comparison to wadis further to the west the Upper Mafraq Sequence contains only a very small percentage of grainstones in the uppermost 20 m of the section. Clastic influence that is typical for the top Mafraq Formation is expressed by a m-thick sandstone some 8 m below the top (Figure 49h) and a shale interval at the top.

Wadi Mistal has bad outcrop condition due to intense wadi tectonics; accessibility is good (by car).
Jurassic Mafraq Formation, Oman

Figure 47 (continued): Log of the Mafraq Formation in Wadi Mistal. See Enclosure I for legend and Enclosure II for location.
Figure 49: Key outcrop pictures, Wadi Mistal: (a) bioturbated wackestone (W); (b) cross-bedded oolitic grainstone (PGx,o) with some bioclasts; (c) bioturbated, bioclastic packstone; (d) thinly bedded shale-rich mudstone (Mtb) that marks the top of the Lower Mafraq; (e) massive, bioturbated mudstones (Mm); (f) thinly bedded mudstones with pink silt-rich seams (Mtb); (g) massively bioturbated mudstone (Mm) with "Thalassinoides" traces; (h) sandstone, few meters below the top Mafraq.

See facing page for continuation.
Figure 49 (continued): See facing page for caption.
Wadi Misin Section

With 15 m of Lower and 45 m of Upper Mafraq sequences, and a resulting thickness of 60 m, the section in Wadi Misin (UTM coordinates 2579704N; 581661E; Figures 50 to 52) is comparable to the section in Wadi Mistal, which is located some 12 km to the west.

Figure 50: Log of the Mafraq Formation in Wadi Misin. See Enclosure I for legend and Enclosure II for location.
The boundary between Triassic and Jurassic strata is heavily karstified. On top lie some 30 cm thick iron-rich sandstones (Figure 52a). The Lower Mafraq Sequence in Wadi Misin contains only few clastic beds. A rooted carbonate mudstone marks the sequence boundary between Lower and Upper Mafraq sequences (Figure 52b). The massive limestone interval above consists mainly of bioturbated mud-dominated limestones and some m-thick *Lithiotis* packstone beds (Figure 52c). Eight meters below the top, a 70 cm-thick sandstone marks the onset of siliciclastic influence (Figure 52d). The top Mafraq/base Dhruma is picked at a decimeter-thick shale interval. Outcrop conditions and accessibility are good.

Figure 52 (right column): Key outcrop pictures, Wadi Misin: (a) base Mafraq: iron-rich, red sandstones (Sm) on top of karstified dolomites from the Triassic Mahil Formation; (b) rooted carbonate mudstone (Mm) that marks the top of the Lower Mafraq Sequence; (c) *Lithiotis* packstone (P,li); (d) sandstone (Sm) near the top Mafraq Formation.
Wadi Hedek E Section

The Mafraq Formation in Wadi Hedek is 86 m thick (UTM coordinates 2587962N; 588330E; Figures 53 to 55). Lower (32 m) and Upper Mafraq (54 m) sequence thicknesses increase compared to the neighboring section in Wadi Misin that is located ca. 10 km to the south.

Above the karstified surface of the top Triassic Mahil Formation follow 17 meters that contain 2 thick cross-bedded/bioturbated sandstone intervals (Figure 55a) that may be rooted at some places.

Above and between these two prominent sand units lie thin shales, sandstones and carbonates. Especially in the upper part of the Lower Mafraq Sequence bioclastic packstones with increasing biodiversity are common (Figure 55b).

The top of the Lower Mafraq Sequence has been picked at a shale-rich mudstone. Above, thick beds of bioturbated mud- to wackestones (Figure 55c) and Lithiotis packstones (Figure 55d) form the “massive limestone interval”.

The uppermost 15 m of the Mafraq Formation contain only few grainstones. Instead Lithiotis packstones are common. Four meters below the top, a two m-thick and ten-meter wide, trough cross-bedded sand body with an erosive base is observed (Figure 55e).

The Mafraq/Dhruma boundary is placed at the last shale interval. Coral heads, only few meter above, witness the beginning of the Dhruma Formation (Figure 55f). Outcrop condition and accessibility are good (by car).
Figure 53 (continued): Log of the Mafraq Formation in Wadi Hedek. See Enclosure I for legend and Enclosure II for location.
Figure 54: Overview of the outcrop in Wadi Hedek. Letters a–f mark location of photos described in Figure 55. The outcrop pictures in Figure 54 have been rotated. See Enclosure I for legend and Enclosure II for location.

| Grain Size | Depth (m) |
|------------|-----------|
| Dunham Texture | 0 | 120 |
| B | G | P | V | M |

| Lithology | Total Gamma-Ray (nGy/h) |
|-----------|-------------------------|
| 0 | 120 |

Figure 55: Key outcrop pictures, Wadi Hedek: (a) bioturbated sandstone (Sb); (b) bioclastic packstone (WPm). (c) bioturbated mudstone (Mm); (d) Lithiotis packstone (P ,li). (e) coarse-grained sandstone channel (red dashed line) few meters below the top of the Mafraq; (f) wackestone containing coral heads above the top of the Mafraq Formation marks the beginning of the Dhruma Formation.
Figure 55: Key outcrop pictures, Wadi Hedek: (a) bioturbated sandstone (Sb); (b) bioclastic packstone (WPm).

Figure 55: (c) bioturbated mudstone (Mm); (d) *Lithiotis* packstone (P,li).

Figure 55: (e) coarse-grained sandstone channel (red dashed line) few meters below the top Mafraq; (f) wackestone containing coral heads above the top of the Mafraq Formation marks the beginning of the Dhruma Formation.
Figure 56: See facing page for continuation.

Saiq 2 Section

The Mafraq Formation at the “Saiq 2” section is 75 m thick (60 m Upper and 15 m Lower Mafraq sequences; UTM coordinates 2558653N; 561177E; Figures 56 to 58).

Like at most other locations where the Mafraq Formation is exposed the top of the underlying Triassic Mahil Formation appears karstified (Figure 58a).

The Lower Mafraq Sequence consists mainly of carbonates with textures ranging from mudstone to grainstone and few siliciclastics.

The greatest clastic interval is located at the top of the Lower Mafraq Sequence. There, bioturbated sand-rich carbonate mudstones (Figure 58b) turn upward into pure, massive sandstones.

Large parts of the Upper Mafraq Sequence are composed of mud-rich limestones with intense bioturbation (Figure 58c) and Lithiotis packstone intervals (Figure 58d).

The uppermost 20 m of the section contain siliciclastic intervals (Figure 58h) and some oolitic grainstones that appear partly cross-bedded (Figures 58e, f) but predominantly bioclastic carbonate wacke- and packstones (Figure 58g).

Outcrop conditions are difficult due to a big fault line in the center of the section, access is easy (by car).
Underlying Triassic Mahil Formation (Figure 58b) turn upward into pure, bioturbated sand-rich carbonate mudstones. The greatest clastic interval is located at the top of the Lower Mafraq Sequence. There, from mudstone to grainstone and few mainly of carbonates with textures ranging massiv sandstones. The uppermost 20 m of the section contain Lithiotis packstone intervals (Figure 58d).

Lithology

Jurassic Mafraq Formation, Oman

Components (Outcrop Observation)
Figure 58: Key outcrop pictures, Saiq 2: (a) karstified top of the Triassic (red dashed line) and the first clastics and dolomites of the Mafraq Formation; (b) sand-rich, bioturbated carbonate mudstone (Mm); (c) massive, bioturbated mudstone (Mm) from the Upper Mafraq; (d) Lithiotis packstone (P,l,i); (e) oolitic grainstone with some bioclasts (PG,o); (f) cross-bedded oolitic grainstone (PGx,o); (g) thin, graded wacke- to packstone beds (WPg); (h) sandstone located few meters below top Mafraq Formation. See facing page for continuation.
Figure 58 (continued): See facing page for caption.
**Saiq Section**

With 58 m (14 m Lower, 44 m Upper Mafraq) the Saiq section is the thinnest Mafraq section in the Oman Mountains (UTM coordinates 2550033N; 574721E; Figures 59 to 61).

Outcrop conditions are poor (faulted) so it cannot be ruled out that parts of the section might be missing. Access is easy (by car and a 10 minute walk).

On top of the karstified surface of the Upper Mahil/Mafraq boundary lie some 10 m of predominantly dolomitic mudstones, wacke- to packstones (Figure 61b) and cross-bedded, fine-grained grainstones (Figure 61c).

The top of the Lower Mafraq Sequence is formed by a sandstone (Figure 61d).

The lower portion of the Upper Mafraq Sequence is dolomitized, which makes it difficult to distinguish components and texture. Most of the lower 20 m (meter 30–50) are probably dolomitic mudstones with a 3–4 m interval of grainstone and some Lithiotis packstones in between.

Above, wackestones, Lithiotis packstones (Figure 61e) and some grainstones form the second half of the “massive limestone interval”.

A m-thick, cross-bedded sandstone (Figure 61f) and several shale intervals (Figure 61h) are the cause for high GR peaks in the top 10 meters of the Mafraq Formation. The carbonates in between are mud-dominated and often intensively bioturbated (Figure 61g).

The top Mafraq has been placed at a shale-rich mudstone interval that produces a final GR peak.

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**Figure 59:** See facing page for continuation.
Figure 59 (continued): Log of the Mafraq Formation in the south of the Saiq Plateau, “Saiq”. See Enclosure I for legend and Enclosure II for location.
Figure 60: Overview of the outcrop “Saiq” on the Saiq Plateau, Oman Mountains. Letters b–h mark location of photos described in Figure 61. The outcrop picture in Figure 60 has been rotated. See Enclosure I for legend and Enclosure II for location.

Figure 61: Key outcrop pictures, Saiq: (a) overview picture over the first meters of the Mafraq Formation, red line marks the karstified top of Triassic strata below; (b) bioclastic packstone (WPm) with bivalve shells, gastropods and coral fingers; (c) cross-beded grainstones (PGx,o); (d) carbonate sandstone (Sm/Sb); (e) Lithiotis packstone (P,li); (f) thick sandstone interval, few meters below top Mafraq; (g) intensively bioturbated carbonate mudstone (Mm); (h) typical shale interval (MR) that occurs around the top Mafraq Formation.

See facing page for continuation.
Figure 61 (continued): See facing page for caption.
Wadi Mu‘aidin Section

The Mafraq Formation in Wadi Mu‘aidin (UTM coordinates 2542343N; 568692E) is 75 m thick with 20 m Lower and 55 m of Upper Mafraq sequences (Figures 62 to 64).

Intensive karstification at the base of the Mafraq cuts up to 2 m deep into the underlying dolomites of the Triassic Mahil Formation. The karst cavities are filled with iron-rich high-GR sandstones (Figures 64a, b).

The Lower Mafraq Sequence in Wadi Mu‘aidin contains few siliciclastic beds. Instead, dolomites and limestones are abundant. At some places transitions from limestone to dolomite within one single bed can be observed (Figure 64c).

Some beds are intensively bioturbated (*Thalassinoides*) (Figure 64d).

A thin sandstone bed marks the top of the Lower Mafraq Sequence.

Up to a recessive unit (Figure 64e) in the middle of the “massive limestone interval”, the muddy carbonates of the Upper Mafraq Sequence are entirely dolomitized.

Above the recessive unit grain-rich bioclastic carbonate facies dominate. *Lithiotis* packstones are abundant; they form large m-thick and tens of meters wide mounds in between meter 14 and 18 of the section (Figure 64f).

The onset of siliciclastic influence between meter 4 and 13 produces the typical top Mafraq GR peaks. In the middle of the first GR peak (meter 11) lies a lime-mudstone with large root traces (Figure 64g). It is overlain by the most prominent siliciclastic unit, a m-thick cross-bedded/bioturbated sandstone (Figure 64h). The top of the Mafraq Formation is located on top of the last prominent shale interval.

Outcrop condition is very good and access by car is easy.

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**Figure 62:** See facing page for continuation.
Jurassic Mafraq Formation, Oman

Figure 62 (continued): Log of the Mafraq Formation in Wadi Mu'aidin. See Enclosure I for legend and Enclosure II for location.

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Figure 63: Overview of the outcrop in Wadi Mu’aidin. Letters a–h mark location of photos described in Figure 64. See Enclosure I for legend and Enclosure II for location.

Figure 64: Key outcrop pictures, Wadi Mu’aidin: (a and b) intensively karstified top of the Triassic Mahil Formation. Karst cavities are filled with iron and shale-rich sandstones (Sm); (c) lateral limestone - dolomite transition within wackestone (W); (d) Thalassinoides traces at the top of a mudstone (Mm); (e) recessive unit in the center of the massive limestone interval of the Upper Mafraq; (f) top surface of a meter-thick and tens of meters wide Lithiotis mound, that is typical for the Lower to Middle Jurassic (Nauss and Smith, 1988); (g) potential root trace in a carbonate mudstone (Mm); (h) cross-bedded sandstone (Sx) a few meters below the top Mafraq Formation. See facing page for continuation.
Figure 64: See facing page for caption.
Jabal Madar Section

The Mafraq Formation at Jabal Madar (UTM coordinates 2476766N; 617477E), located ca. 80 km southeast of Wadi Mu’aidin has a thickness of 36 m (Figures 65 to 67). Rousseau et al. (2006) published the first description of this section. The complete succession is most likely equivalent to the Upper Mafraq Sequence in the Oman Mountains; the Lower Mafraq Sequence is not present (see Enclosure II). The karstified base Mafraq surface (Figure 67a) is overlain by 8 meters of coarse-grained, trough cross-bedded sandstones (Figure 67b). The trough orientation has been measured at 3 different locations and indicates a flow direction towards NE/NNE (perpendicular to the presumed paleocoastline). On top of this sand unit lies a 6–8 meter interval of Lithiotis-rich wacke- to packstones (Figure 67c). The interval is heavily karstified/rooted (Figure 67d) and partly eroded by overlying sandstones (Figure 67e). The sandstones reach a thickness of up to 16 m; they are trough cross-bedded, rooted (meter 10) or bioturbated. Trough orientation indicates a general flow direction towards NW/NNW (three measurements). The top of the sandstone interval is intensively bioturbated around meter 6 (Figure 67f). Above lies a succession of high GR shales (Figure 67h), sandstones and some meters of mud-dominated carbonates. A last decimeter-thick, massive sandstone forms the top of the Mafraq Formation. Outcrop condition is very good but access is difficult (3 hour walk).

Figure 65: Log of the Mafraq Formation at Jabal Madar. See Enclosure I for legend and Enclosure II for location.

Figure 66: (center left photo on facing page): Overview of the outcrop at Jabal Madar. Letters a–h mark location photos described in Figure 67.

Figure 67: Key outcrop pictures, Jabal Madar: (a) karstified Base Mafraq surface; (b) thick, cross-bedded sandstone (Sx); (c) Lithiotis packstone (Pli); (d) rooted/karstified top of the underlying Lithiotis packstones; (e) trough cross-bedded sandstone on top of carbonates in the center of the section, yellow dashed line marks an erosive surface below a sandstone channel; (f) Trough cross-bedded sandstones (Sx); (g) top surface of a bioturbated sandstone (Sb); (h) typical top Mafraq shale interval (MR). See facing page for continuation.
The Mafraq Formation at Jabal Madar (UTM coordinates 2476766N; 617477E), located ca. 80 km southeast of Wadi Mu’aidin has a thickness of 36 m (Figures 65 to 67). Rousseau et al. (2006) published the first description of this section. The complete succession is most likely equivalent to the Upper Mafraq Sequence in the Oman Mountains; the Lower Mafraq Sequence is not present (see Enclosure II). The karstified base Mafraq surface (Figure 67a) is overlain by 8 meters of coarse-grained, trough cross-bedded sandstones (Figure 67b). The trough orientation has been measured at 3 different locations and indicates a flow direction towards NE/NNE (perpendicular to the presumed paleocoastline). On top of this sand unit lies a 6–8 meter interval of Lithiotis-rich wacke- to packstones (Figure 67c). The interval is heavily karstified/rooted (Figure 67d) and partly eroded by overlying sandstones (Figure 67e). The sandstones reach a thickness of up to 16 m; they are trough cross-bedded, rooted (meter 10) or bioturbated. Trough orientation indicates a general flow direction towards NW/NNW (three measurements). The top of the sandstone interval is intensively bioturbated around meter 6 (Figure 67f). Above lies a succession of high GR shales (Figure 67h), sandstones and some meters of mud-dominated carbonates. A last decimeter-thick, massive sandstone forms the top of the Mafraq Formation. Outcrop condition is very good but access is difficult (3 hour walk).

Figures 66 and 67: See facing page for captions.
Al Huqf Section

The Al Huqf outcrop (UTM Coordinates 2299991N; 564313E) probably represents the southernmost studied outcrop of the Mafraq Formation in Oman. The thickness sums up to just about 12 m (Figures 68 and 69). As discussed in the correlation section (below), the Al Huqf section is probably equivalent to the uppermost 20 m of the Upper Mafraq Sequence in the Oman Mountains. Outcrop conditions are poor, and a ca. 2 m interval in the middle of the section is not exposed.

The base of the Mafraq Formation is not exposed. The section starts with about 2 meters of massive, sandstones with small white gypsum layers (Figure 69a). Above lies a 3 m-thick carbonate interval with mud-dominated limestones and bivalve-rich packstones (Figure 69b).

The upper part of the section is characterized by several meters of rooted, iron-rich, and bioturbated (*Thalassinoides*) sandstones (Figures 69c, d). At the top of the section, sandstones with fossil wood fragments (tree trunk fragments and leaves) are common (Figure 69e).

Some kilometers away from the outcrop position lies a complete fossil palm tree that is oriented along an SSE-NNW axis. (Figures 69f, g). This could indicate a general flow direction of the top Mafraq sandstones towards the NNE. Outcrop condition is good but access is difficult (by car, long desert off-road drive).

![Diagram](Figure 68: Log of the Mafraq Formation in the Huqf area. Letters a–g mark location of photos described in Figure 69. See Enclosure I for legend and Enclosure II for location.)

**OUTCROP CORRELATION**

This chapter discusses how the Mafraq Formation develops laterally in North Oman (Enclosure II). Detailed one-dimensional descriptions, facies and sequence-stratigraphic interpretations, in combination with the paleogeographic context are used as keys for robust two-dimensional correlations. The correlation strategy for the Mafraq Formation follows possible paleolandscape surfaces at sequence and cycle set boundaries to trace lateral facies changes throughout North Oman. The best possible vertical resolution is reached when correlating on a cycle set level. The smaller scale "cycles" cannot be correlated consistently at a 10 km scale. Based on these considerations, the lateral extent of potential reservoir/seal facies and a reservoir/seal distribution can be estimated for the covered areas in Oman.
Figure 68: Log of the Mafraq Formation in the Huqf area. Letters a–g mark location of photos described in Figure 69. See Enclosure I for legend and Enclosure II for location.

Figure 69: Key outcrop pictures, Huqf: (a) gypsum layers in massive sandstone (Sm); (b) bivalve-rich packstone (WPm); (c) iron-rich, lateritic sandstone with basal root traces; (d) bioturbated sandstone (Sb); (e) sandstone with fossil plant fragments; (f and g) fossil tree found at the top of the Mafraq Formation.

Al Huqf Section
The Al Huqf outcrop (UTM Coordinates 2299591N; 564313E) probably represents the southernmost studied outcrop of the Mafraq Formation in Oman. The thickness sums up to just about 12 m (Figures 68 and 69). As discussed in the correlation section (below), the Al Huqf section is probably equivalent to the uppermost 20 m of the Upper Mafraq Sequence in the Oman Mountains. Outcrop conditions are poor, and a ca. 2 m interval in the middle of the section is not exposed.

The base of the Mafraq Formation is not exposed. The section starts with about 2 meters of massive, sandstones with small white gypsum layers (Figure 69a). Above lies a 3 m-thick carbonate interval with mud-dominated limestones and bivalve-rich packstones (Figure 69b).

The upper part of the section is characterized by several meters of rooted, iron-rich, and bioturbated (Thalassinoides) sandstones (Figures 69c, d). At the top of the section, sandstones with fossil wood fragments (tree trunk fragments and leaves) are common (Figure 69e).

Some kilometers away from the outcrop position lies a complete fossil palm tree that is oriented along an SSE-NNW axis. (Figures 69f, g). This could indicate a general flow direction of the top Mafraq sandstones towards the NNE. Outcrop condition is good but access is difficult (by car, long desert off-road drive).
Top Mafraq Datum

Conventionally the top Mafraq is picked at the uppermost prominent GR peak in the subsurface of Oman (Forbes et al., 2010). In outcrops and in the subsurface of Oman the top of the Mafraq Formation shows prominent GR peaks that are associated with siliciclastic intervals. In some outcrops (e.g. Wadi Mu’aidin), the exact position of the sequence-stratigraphic boundary at the top of the Mafraq Formation could also lie within a siliciclastic unit some meters below the picked top.

For pragmatic reasons, the top of the Mafraq in outcrops has been placed at the uppermost prominent siliciclastic interval. This pragmatic definition of the top Mafraq enables the correlation of outcrops with subsurface wells. The transition from the clastic Mafraq Formation into the carbonate Dhruma Formation could be diachronous. This question might be answered by ongoing work about the Dhruma Formation in Oman by M. Schlaich and T. Aigner from the University of Tuebingen.

Dip of Correlation Lines

As correlation lines are interpreted to follow paleolandscape surfaces their dip angles and dip directions can hold information about proximal-distal trends and the paleorelief at times of deposition. The highest observed dip angle is about 0.1°; most angles especially in the Upper Mafraq Sequence are between 0.01° and 0.05° (Enclosure II). The dip direction of correlation lines tends to trace the paleorelief and follows the general deepening trend. Especially in the Lower Mafraq Sequence NW-oriented dips can be observed.

In the Upper Mafraq Sequence, where thick carbonate intervals cover the complete study area, correlation lines seem to be influenced by the initial NW-deepening paleotopography and a potential local paleohigh around Wadi Misin and Mistal. Local tectonics around Wadi Hedek could explain the inversed dip direction of the correlation lines, together with the thickening of the Mafraq Formation, which is in contrast to the observed general eastward thinning. This interpretation is supported by Obermaier et al. (2012), who reported a thickening of Triassic strata around Wadi Hedek, and a potential paleohigh around Wadi Mistal and Wadi Misin. A major lineament east of Al Jabal al-Akhdar influencing the Mesozoic sequence has also been mentioned in Pratt and Smewing (1990).

Correlation Traverses (Enclosure II)

Correlation Traverse A starts at the type section in Wadi Sahtan in the northwest of the Oman Mountains and continues eastwards toward Wadi Bani Kharus (Enclosure II). It ends with a section in Jabal Madar some 80 km southeast of the Oman Mountains. The traverse connects seven sections and is oriented more-or-less perpendicular to the paleocoastline as postulated by Ziegler (2001) and by this study.

Traverse B ties Traverse A in Wadi Bani Kharus and continues eastwards towards Wadi Mistal, Wadi Misin and Wadi Hedek (Enclosure II). The line has an orientation of 45° in respect to the postulated paleocoastline in the southeast.

Traverse C connects four sections in a line that is oriented approximately parallel to the postulated paleocoastline of the Mafraq Formation (Enclosure II). It starts in Wadi Mu’aidin in the southern Oman Mountains and ends some 50 km to the north-northeast in Wadi Hedek.

Lateral Development of the Lower Mafraq Sequence

The thickness of the Lower Mafraq Sequence decreases significantly in the southeastward direction and completely vanishes between the Oman Mountains and Jabal Madar (Traverse A, Enclosure II). The Lower Mafraq Sequence contains a maximum of 6 high-frequency sequences (HFS). Due to
south-eastward thinning with onlaps onto underlying Permian–Triassic strata, only the uppermost LM HFS-1 to LM HFS-3 can be correlated throughout all sections in the Oman Mountains.

From Wadi Sahtan to Hail Bint the Lower Mafraq Sequence thins by 16 m, while the number of cycle sets and HFS stays constant. Lower Mafraq sand bodies and carbonate intervals occur at the same stratigraphic position at both locations and seem therefore correlative over a distance of 4.5 km. In Wadi Bani Awf, 14 km to the east of Wadi Hail Bint, the Lower Mafraq Sequence thins by another ca. 50 m. Nine cycle sets and nearly four HFS, together with most sand bodies pinch out against the base Jurassic unconformity (pre-Mafraq Unconformity) forming onlaps. Between Wadi Bani Awf and Bani Kharus the number of cycle sets and HFSs stays constant, although slight thinning and a facies change from sandstones in Bani Awf to carbonates in Bani Kharus can be observed in the basal cycle set (Enclosure II).

In the central and southern area of the Oman Mountains (Wadi Mistal, Wadi Misin, Wadi Mu‘aidin, Saq and Saq 2, Enclosure II), 15 m of the Lower Mafraq Sequence (3 cycle sets and one HFS) disappear, potentially forming onlaps onto the initial paleotopography. The remaining Upper Mafraq Sequence (UM HFS-1, 3 cycle sets) has a thickness of about 15–20 m. Towards Jabal Madar, 80 km southeast of the Oman Mountains, the Lower Mafraq Sequence pinches out completely.

The general eastward thinning of the Lower Mafraq Sequence observable throughout the study area is interrupted in Wadi Hedek, where 32 m of Lower Mafraq Sequence (> 2 HFS; 6 cycle sets) are present. Two sandstone units, each several meters thick can be observed in the lowermost 15 m.

The major unconformity between the Upper and Lower Mafraq sequences, which is suggested by outcrop observations and biostratigraphy, appears conformable throughout all outcrops where the Lower Mafraq Sequence is present. Onlapping features or truncation could not be detected.

**Lateral Development of the Upper Mafraq Sequence**

The thickness of the Upper Mafraq Sequence decreases slightly in southeastward direction from around 65 m in Wadi Sahtan to a minimum of 45 m around Wadi Mistal. The first more significant thickness changes are observed outside of the Oman Mountain area at Jabal Madar (Traverse A, Enclosure II) where only 32 m are present. An exception to the overall southeastward thinning of the Upper Mafraq Sequence is represented in Wadi Hedek (as discussed above). The Upper Mafraq Sequence contains two high-frequency sequences (HFS) and 8 cycle sets that can be correlated throughout the Oman Mountains. The first five cycle sets of the Upper Mafraq UM HFS-2 are dominated by mud-rich carbonates such as massive, bioturbated mudstones, *Lithiotis* packstones and bioclastic wacke- to packstones at most locations. Only in Wadi Sahtan grain-rich carbonates (peloidal packstones) are slightly more abundant. At most places a m-thick, shale-rich carbonate interval, the so called “recessive unit”, is present in the middle of the massive limestone interval of the Upper Mafraq Sequence.

Significant lateral facies changes can be observed in the top 10–20 m (top 3 cycle sets) of the Upper Mafraq Sequence. Intercalations of oolitic and peloidal grainstones and thick shale-rich siliciclastic units are abundant in the northwest of the Oman Mountains from Wadi Sahtan to Wadi Bani Kharus. Thinner but coarser-grained siliciclastics and more mud-rich carbonates (e.g. *Lithiotis* packstones mounds in Wadi Mu‘aidin) dominate the same interval at the locations east and southeast of Wadi Bani Kharus (Enclosure II). In Wadi Hedek, sandstone channels at the top Mafraq highlight the facies changes laterally to coarser-grained siliciclastics in the top Mafraq interval towards the east.

Eighty kilometers southeast of the Oman Mountains the Upper Mafraq facies changes significantly. The 32 m-thick succession consists almost entirely of coarse-grained channel sandstones. Upper Mafraq carbonates are present in the form of a few m-thick intervals of *Lithiotis* packstones. The section in Jabal Madar probably correlates with the UM HFS-1 of the Upper Mafraq Sequence in the Oman Mountains.
An additional outcrop in Al Huqf area ca. 200 km to the south of Jabal Madar, in Central Oman (Enclosure II) has not been included in the correlations. The very condensed Al Huqf section contains lateritic iron-rich facies that is for the most part clearly terrestrial and only very few potentially marine carbonates. The 12 m of Mafraq there probably correlate with the Upper Mafraq Sequence in northern Oman as they probably formed during a time of maximum flooding in an area that was presumably exposed at times of sea-level lowstand.

**RESERVOIR AND SEAL POTENTIAL OF THE MAFRAQ FORMATION**

Sandstones form the most important potential reservoirs in the Lower Mafraq Sequence. In outcrops the presence of sandstones is confined to sections in the northwest of the Oman Mountains and Wadi Hedek, where the Lower Mafraq Sequence is thickest (Sahtan, Hail Bint and Bani Awf). The correlativity of up to 12-m-thick sand bodies from Wadi Sahtan to Wadi Hail Bint over 4.5 km indicates a lateral extent of at least several kilometers in dip direction (perpendicular to the paleocoastline).

Up to one m-thick shale intervals (“Oman Soils”) that often lie on top of sand intervals represent the facies with the best seal potential. Their lateral extent can only be estimated to reach a distance of several kilometers. Another potential seal facies are carbonate mudstones although their sealing quality seems questionable due to common fracturing of carbonates in the subsurface. They are abundant, up to several meters thick and correlative over kilometers to tens of kilometers in all outcrops where the Lower Mafraq Sequence is present.

Two types of potential reservoirs are present in the Upper Mafraq Sequence. Oolitic and peloidal grainstones that are common in the uppermost Mafraq in the northwest of the Oman Mountains from Wadi Sahtan to Wadi Bani Kharus. They are present at the same stratigraphic position at all four locations and have a lateral extent of at least several kilometers. Some of the m-thick oolitic intervals potentially extend to 10s of kilometers. The second type of potential reservoirs is formed by sandstone intervals that are present around the top of the Mafraq Formation in the east of the Oman Mountains (Wadi Hedek, Saiq, Wadi Mu‘aidin) and further to the southeast (Jabal Madar, Al Huqf). In the Oman Mountains they form thin intervals (< 2 m) or small channels (Hedek) and are thus considered to not be laterally very extensive. Southeast of the Oman Mountains, in Jabal Madar, channel sand intervals reach a thickness of 15 m and are thus considered to form promising potential reservoirs although their lateral extent is again uncertain.

Thick, shale-rich siliciclastic intervals, correlative over 10s of kilometers, form potential seals at the top of the Mafraq Formation. They are concentrated in the northwest of the Oman Mountains from Wadi Sahtan to Wadi Bani Kharus, where they lie commonly on top or below oolitic grainstone intervals. At other places they appear thinner (< 1 m) and are less abundant. Like in the Lower Mafraq Sequence, mud-rich carbonates could form potential seals since they are abundant in the Upper Mafraq Sequence and the overlying Dhruma Formation.

**CONCLUSIONS**

Twelve outcrops of the Mafraq Formation in North and Central Oman were investigated. All outcrops are documented in detail and now represent outcrop data points that are accessible for further research or field trips.

**Mafraq Type Section, Wadi Sahtan**

The Mafraq Formation unconformably overlies the Triassic Upper Mahil Formation (equivalent to Jilh Formation). No Upper Triassic Minjur Formation is present in outcrops, resulting in an unconformity of more than 10 million years duration (pre-Mafraq unconformity). The Mafraq Formation can be subdivided into the Lower and Upper Mafraq sequences. According to outcrop biostratigraphy the Lower Mafraq Sequence extends from Hettangian to the Late Pliensbachian and the Upper Mafraq Sequence starts in the Aalenian and ranges up to the Bajocian or younger.
Contrary to regional Toarcian stratigraphy of the Arabian Plate (Sharland et al., 2001), the complete Toarcian is apparently missing between Lower and Upper Mafraq sequences. The complex, mixed carbonate-siliciclastic Mafraq Formation in Wadi Sahtan is 160 m and includes 23 facies types grouped into 5 facies associations. The Lower Mafraq Sequence contains a mix of siliciclastics and an upward-increasing amount of carbonates. The Upper Mafraq Sequence comprises 45 m of massive, clean limestones, which are topped by some 20 m-thick alterations of grainstones and fine-grained siliciclastics. Interpreted depositional environments range from fluvial/terrestrial and coastal to lagoonal/backshoal, shoal and foreshoal.

A multi-fold cyclicity is apparent in outcrops. Four cycle orders from small to large scale are detected in the Mafraq Formation: cycles, cycle sets, high-frequency sequences (HFS) and sequences. The Lower Mafraq Member forms one sequence, subdivided into six HFS. The Upper Mafraq Member forms one sequence and two HFS.

**Lateral Development**

The Lower Mafraq Sequence shows significant thinning (ca. 80%) on a 50 km scale (Oman Mountains) towards the southeast and forms onlaps onto the initial paleotopography that is probably the result of the Early Jurassic plate tectonism (rifting in the southeast). On a larger 100 km scale, the Lower Mafraq Sequence pinches out completely and is thus not present in outcrops southeast of the Oman Mountains. Significant lateral facies changes in the Lower Mafraq Sequence are rare and do not follow systematic trends. The Lower Mafraq Sequence consists of lagoon/backshoal to coastal complex deposits.

The thickness of the Upper Mafraq Sequence decreases gradually in the Oman Mountains from northwest to southeast before it thins significantly towards Jabal Madar and Al Huqf. Upper Mafraq facies change from grainstones and fine-grained siliciclastics in the northwest (shoal fringe-lagoon/backshoal environment) to mud-dominated carbonates and thin, coarse-grained siliciclastic sediments (lagoon/backshoal-coastal complex environment) in the southeast of the Oman Mountains. At Jabal Madar and in Al Huqf area the same interval consists mainly of coarse-grained channel sandstones and few carbonates (fluvial/terrestrial to coastal-complex environment) highlighting the general southeastward oriented proximal trend.

**Reservoir and Seal Potential**

The Mafraq is a proven hydrocarbon-bearing interval in subsurface Oman with producible gas in Lekhwair Field and producible oil in the Yibal, Al Huwaisah and Saih Rawl fields (Al-Shuaily, 2007). This study revealed potential reservoir and seal units in the Lower and the Upper Mafraq sequences. In the Lower Mafraq Sequence laterally extensive sand units are concentrated in the northwest of the Oman Mountains, where the Mafraq Formation is thickest. These units represent promising potential reservoirs. Intra-formational seals are present as shale intervals and mud-rich carbonates in the Upper Mafraq Sequence. Oolitic grainstones in the northwest of the Oman Mountains and thick sandstones in Jabal Madar (southeast) represent good potential reservoirs in the Upper Mafraq Sequence. Shale intervals could form excellent intra-formational seals in the northwest of the Oman Mountains. In other areas of Oman mud-rich carbonates and some thin shale intervals could act as Upper Mafraq seals.

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ABOUT THE AUTHORS

Daniel Bendias studied Geosciences at the University of Tuebingen (Germany). His diploma thesis (2010) at the University of Tuebingen was on the Palorelief-influenced facies and sequence patterns in the Lower Khuff time equivalent strata (Sultanate of Oman). His PhD thesis, funded by Petroleum Development Oman (PDO), focuses on sequence stratigraphy, reservoir and seal potential of the Jurassic Mafraq Formation, a mixed carbonate siliciclastic system in outcrops and subsurface of Oman. In 2014 Daniel started working as a Sedimentologist for Eni International Resources Limited (EIRL) in England.

daniel.bendias@gmail.com

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

t.aigner@uni-tuebingen.de

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