Facies and integrated sequence stratigraphy of an Epeiric Carbonate Ramp Succession: Dhruma Formation, Sultanate of Oman

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ABSTRACT

As an example of an epeiric carbonate ramp depositional system, the world-class outcrops of the Middle Jurassic Dhruma Formation were studied in the Oman Mountains (Sultanate of Oman). An integrated approach was followed: facies analyses were combined with quantitative sequence-stratigraphic methods as well as bio- and chemostratigraphy. Depositional environments range from peritidal to lagoonal and ‘shoal-like’ environments. A conspicuous four-level hierarchy of cyclicity was identified. This is substantiated by facies trends and specific cycle indicators such as various types of discontinuity surfaces, biofacies changes, and a suite of quantitative- and semi-quantitative-sequence-stratigraphic methods like facies stacking pattern plots, facies percentage, bed-thickness and bio-component diversity plots, as well as diagrams representing the environmental range and facies belt width per high-frequency sequence. Potential reservoir facies are present in the form of peloidal and oolitic grainstones; potential baffle/seal facies as vastly extensive mudstones and marls. A transition from peritidal to low-energy lagoonal deposits to increasingly high-energy deposits can be observed towards the top of the Dhruma Formation representing a landward shift of the depositional environment. This study may be useful as outcrop analogue for the hydrocarbon-bearing parts of the Dhruma in the subsurface of the Arabian Plate and for similar epeiric carbonates elsewhere.

INTRODUCTION

The hydrocarbon reserves on the Arabian Plate are mostly contained in carbonate rocks (Beydoun, 1991; Nairn & Alsharhan, 1997). Among the wide variety of depositional systems, epeiric carbonate ramps are widespread yet still relatively little understood in relation to facies distribution and present geometries and their small scale complexity (Ahr, 1973; Petrovic & Aigner, 2017). As a spectacular example of an epeiric carbonate ramp succession, this paper documents the facies, sequence-, bio- and chemostratigraphy of the Middle Jurassic Dhruma Formation in the type section in Wadi Sahtan on the northern flank of the Oman Mountains. From 2013 to 2016, nine outcrop sections were investigated in North Oman as well as 20 subsurface wells in North and Central Oman. Collected data from outcrops comprise sedimentological descriptions like lithology, texture classification for carbonates (Dunham, 1962), sedimentary structures, occurrence and abundance of components, bio-, chemo- and sequence stratigraphy as well as gamma-ray (GR). Subsurface investigations were based on cuttings and cores. The rest of the outcrop sections next to the type section in Wadi Sahtan, as well as the 2D sequence stratigraphy of the Dhruma and the overlying Middle Jurassic Tuwaiq Mountain and Upper Jurassic Hanifa/Jubaila Formations will be documented in separate papers.

The aims of this paper are:
• Sedimentological documentation of the Dhruma Formation focusing on the type section in Wadi Sahtan, Sultanate of Oman.
• To establish a facies atlas applicable for outcrops and subsurface.
• Generation of a robust sequence- and bio-stratigraphic framework.
• Semi-quantitative sequence-stratigraphic analysis of the succession.

The study area (Fig. 1), which consists of a large anticline that enables detailed investigation of Permian to Cretaceous strata (Glennie et al., 1974), is located ca 100 km to the west-southwest of Muscat in the Oman Mountains. Eight outcrop sections were logged along the northern flank of the Oman Mountains, where the type section of the Dhruma Formation represents the westernmost section. Towards the southeast another section was logged at the southern flank in Wadi Muaidin together with another in Jabal Madar.

To this date, the Dhruma Formation has not been described in detail in outcrops of the Oman Mountains (Fig. 2) and only roughly in the subsurface of Oman (Forbes et al., 2010), where descriptions are mainly based on cuttings since only short cored intervals are available. This paper thus aims to get a better and more detailed understanding of the Dhruma Formation by establishing a facies atlas, identifying palaeoenvironmental conditions and generating a conclusive sequence- and bio-stratigraphic framework for Oman.

GEOLoGICAL SETTING

In Permian times, the Arabian Plate was located 25° south of the equator moving northward to 15° south in the Triassic (Scotese, 2001; Ziegler, 2001). During the Early Jurassic, the Arabian Plate drifted even farther north to the equator and remained there throughout the Jurassic (Scotese, 2001). From the Early Permian onwards, the Arabian Peninsula formed a stable epicontinental area which was periodically covered by epeiric seas (Clarke, 1988). A stable carbonate platform, established on the Arabian Peninsula from the Late Permian to Triassic, was then exposed at the end of the Triassic. In the Early Jurassic, the break-up of Pangea led to rifting events and subsidence in the north resulting in a northward tilt of the Arabian Plate and a rift shoulder uplift in the south (Grabowski & Norton, 1994). In the Middle and Upper Jurassic, the depositional system in Oman evolved to a low-angle, epeiric ramp dipping in a northwestward direction. Murray (1981) and de Matos & Hulstrand (1995) suggest a low-angle sediment ramp setting in the Toarcian to the Bathonian, which turned into a slightly steepened ramp from the Callovian to the end of the Jurassic for the rest of the Arabian Plate.

In outcrops of the Oman Mountains, shallow marine dolomites of the Triassic Mahil Formation are followed by shallow marine siliciclastic deposits of the Early Jurassic Mafraq Formation. These are overlain by marine carbonates of the Dhruma Formation, which is truncated by a Tithonian unconformity followed by Cretaceous limestones and marls of the Kahmah Group (Clarke, 1988; Fig. 3). Palaeogeographic reconstructions place the study area during the Middle and Upper Jurassic in a transition zone between a shallow marine and open marine, limestone dominated environment (Ziegler, 2001).

In the Late Jurassic, thermal uplift and rifting marked the opening of the Proto-Owen Ocean (early Indian Ocean) in the southeast. With the Tethys Ocean closing,
oceanic lithosphere was pushed on top of the northeastern edge of the Arabian continent in the Late Cretaceous, giving rise to the obduction of the Semail Ophiolite, an area of almost 100,000 km². Subsequently, a broad flexural bulge developed in the central part of the Arabian shelf, folding Precambrian to Cretaceous rocks and
forming a westward dipping anticlinal structure, the Oman Mountains. These are framed on the northern and southern flanks by the Semail Ophiolite.

**Sea-level**

According to the sea-level curve from Haq & Al-Qahtani (2005; Fig. 4) a general sea-level rise is present during deposition of the Jurassic Mafraq, Dhruma, Tuwaiq Mountain and Hanifa/Jubaila Formations. This is reflected in a change from mixed carbonate-siliciclastic deposits in the Lower Jurassic to shallow marine carbonates in the Middle to Upper Jurassic, which can be found over most of the Arabian Plate (Sharland et al., 2001). Three sea-level highstands are shown for the Dhruma and Tuwaiq Mountain Formations and several short ones of lower magnitude, probably representing a higher cycle hierarchy, for the Hanifa/Jubaila Fm (Fig. 4). No depositional record exists between the Mafraq and Dhruma Formation, which are the likely result of a continental-margin uplift in the east.

**Climate**

The Permian and Triassic were times of global warming probably caused by runaway greenhouse conditions driven by elevated atmospheric CO₂ levels (Twitchett, 2007). Furthermore, the Pangean Mega-Monsoon was established at this time causing very hot and arid conditions in the interior of Pangea (Sharland et al., 2001). In Jurassic times, the supercontinent Pangea split apart, leading to an increase in sea floor spreading and consequently a rise in sea-level (Fig. 4). The Jurassic climate was rather equable with tropical-subtropical conditions extending into present day polar regions (Hallam, 1982), hence towards the continental-margin of Pangea, like in the southern part of the Arabian Plate, more humid conditions were present (Al-Aswad & Al-Husseini, 1994), leading to the deposition of carbonates on extensive carbonate ramps in southeast plate areas which were exhibiting limited accommodation space (Clarke, 1988).

**PREVIOUS WORK – STRATIGRAPHY**

The Dhruma together with the overlying Tuwaiq Mountain, Hanifa/Jubaila and the underlying Mafraq Formations form the Sahtan Group (Fig. 3), which was originally defined by Glennie et al. (1974) in the Al Hajar Mountains outcrops. The Sahtan Group reflects a second order transgressive and regressive hemicycle according to Haq et al. (1987). The Sahtan Group, without the Lower Mafraq, builds the AP7 Tectonostratigraphic Mega-sequence (TMS) of Sharland et al. (2001), which ends at the Late Jurassic (Tithonian) unconformity (de Matos & Hulstrand, 1995). In contrast to the Permo-Triassic Mega-sequence AP6, which is characterized by carbonate-evaporite platform sediments (Obermaier et al., 2012), the AP7 Mega-sequence is dominated by carbonate deposits on a differentiated platform, containing intra shelf basins. This is the result of increased subsidence causing widespread open marine conditions. In contrast to the rest of the Arabian Plate, formations of the Sahtan Group in Oman were influenced by a tectonic uplift in the southeast, causing shallower depositional conditions in this area.

In the UAE, the Dhruma Formation is described as a condensed and strongly regressive sequence, which indicates a continued continental-margin uplift (Rousseau et al., 2006). In Oman, the Dhruma Formation consists of shallow-marine deposits. Its lower part is dominated by argillaceous limestone containing mollusc and echinoid debris as well as bivalves. Its upper part is grainier, resulting from deposition in a shallow marine shoal to intertidal setting (Forbes et al., 2010). The Dhruma Formation shows a substantial and regular thickening to the northwest. Together with the underlying Mafraq Formation and the lower part of the Tuwaiq Mountain Formation, the Dhruma Formation belongs to Biozone F45.
(Pfenderina salernitana and Pfenderina trochoidea) after an unpublished scheme from Sikkema (1992).

The influence of sea-level fluctuations and tectonics led to the development of several maximum flooding surfaces (MFS), which were described by Sharland et al. (2001; Fig. 5). The MFS J10 is located in the Lower Mafraq Formation in Oman. It is followed by a progressive fall in sea-level which caused a hiatus in central plate areas. A following sea-level rise into the Middle Jurassic lead to the deposition of shallow marine carbonates (Sharland et al., 2001). The J20 MFS is represented by shales near its base in the lower part of the Dhruma Formation in Oman (Clarke, 1988; Fig. 5), by open marine shales containing the ammonite Shirbuirna fastigata in Saudi Arabia (Enay et al., 1987; Enay & Mangold, 1994) and shales of Bajocian age at the base of the Marrat Formation in Qatar and the UAE (de Matos, 1997). The J30 MFS is of Bathonian age and is located in Saudi Arabia in Unit D5 of the Dhruma Formation (Fig. 5) and can be correlated across the Arabian Plate. At this time, stable carbonate shelf platform conditions existed across the southern half of the Arabian Plate (Sharland et al., 2001) and a weak clastic influx derived from the ‘southern Arabian Uplift’ (Hadhramaut Arch area of Al-Aswad & Al-Husseini, 1994) towards the south-west, south and southeast of the carbonate shelf (Murris, 1981).

Since the Dhruma Formation in Oman was deposited in a more proximal setting, ranging from a peritidal, to lagoonal and shoal-associated environment, the zones of maximum flooding in the studied outcrops are located in the most distal deposits: cross-bedded, shoal-associated grainstones. Thus, the argillaceous mudstone intervals in Oman which represent lagoonal deposits are not where the MFSs of Sharland et al. (2001) are located, but rather in or on top of high-energy, grainstone dominated intervals. In Kuwait, the upper part of the Dhruma Formation shows porous intervals, which are probably continuous with the ‘Uwainat’ reservoir unit in Qatar and the Emirates (Sugden et al., 1975) and the ‘Lower Fadhili’ reservoir unit in Saudi Arabia (Powers, 1968).

**METHODS**

Where possible, sedimentary structures like ripples, trough cross-bedding, the orientation of components or imbrications were used to identify the palaeo-current direction and were plotted in rose-diagrams (Schlaich, 2016). The raw data were digitalized using the software WellCAD 4.3. To establish a general consistency for Jurassic studies in Oman, the lithofacies types (LFT) employed were based on the LFTs of Bendias & Aigner (2015) used to describe the Mafraq Formation.

**Gamma-ray logging**

The portable gamma-ray device RS-125 Super-SPEC, manufactured by Radiation Solutions Inc., was used to measure the natural gamma radiation in outcrops. It uses...
a 2 × 2" (6.3 cu ins) sodium-iodide detector with an energy response from 30 to 3000 keV, which allows a full assay capability with total gamma-ray measured in cps, K in %, U in ppm and Th in ppm. Since gamma-ray trends are sufficient for correlation and no precise values are needed, a measuring time of 30 sec and a vertical spacing of 25 cm were chosen to obtain spectral gamma-ray trends throughout the sections.

**Thin section analysis**

A total of 388 thin sections were created from field samples from all nine wadi outcrop sections. They were analysed using the transmission light microscope Wild Leitz Aristoplan and an attached Olympus DP 25 camera to record the mineralogical composition, sedimentary features like fining- and coarsening-up, etc. and the component composition.

**Isotope analysis**

The Type-Section of the Dhruma Formation in Wadi Sahtan was sampled with a vertical spacing of ca 1-5 m. For each sample the $\delta^{18}$O and $\delta^{13}$C values were measured on crushed whole rock samples. The delta values are measured relative to the V-PDB (Vienna Pee Dee Belemnite) standard for oxygen and carbon. Isotope ratios were calibrated with NBS18 ($\delta^{13}$C = -5.00‰; $\delta^{18}$O = -22.96‰) and NBS19 ($\delta^{13}$C = 1.95‰; $\delta^{18}$O = -2.20‰) relative to V-PDB. Both oxygen and carbon isotopes were measured with a ‘Gasbench II’ in an automated procedure with a ‘Finnigan Mat 252’ mass spectrometer.

**Palynological analysis**

Since low-energy facies in the Dhruma Formation of Oman are key to understanding the range of palaeoenvironments and thus the present cyclicity, mudstones were sampled at several locations (Wadi Sahtan, Wadi Bani Awf and Wadi Bani Kharus; Fig. 1) to identify if they were deposited in a fore- or backshoal environment. About 100 g of each of the nine samples obtained were processed for palynology at Petroleum Development Oman using standardized methods.

**BIO-, CHEMO-, CHRONOSTRATIGRAPHY**

The time span of the Jurassic System covers ca 56 Myr and is divided into 11 stages consisting of 14 ammonite and nautiloid based biozones and subzones (Cox, 1990). However, no ammonites are present in outcrops of the Dhruma Formation in Oman. Thus, the chronostratigraphic framework for this study is based on the use of biostratigraphy (foraminifera) and isotope-stratigraphy in the type section of Wadi Sahtan.

**Biostratigraphy**

As foraminifera were used for dating purposes in previous studies in Oman (Forbes et al., 2010; Sikkema, 1992) they were selected for a biostratigraphic analysis here. While their occurrence is not abundant it is consistent throughout the sections. Age interpretations are based on an unpublished PDO-Zonation for Oman after Sikkema (1992) and Forbes et al. (2010) and thus refer to biozones and their assigned ages which are still in need of comprehensive revision. According to Forbes et al. (2010) the Upper Mafraq Member as well as the Dhruma Formation and the lower part of the Tuwaiq Mountain Formation belong to biozone F45 (Pfenderina salernitana, P. trochoidea; Table 1).

Samples from outcrops of Wadi Sahtan were analysed by Dr. Stephen Packer from the Millennia Stratigraphic Consultants Limited Company. Foraminifera such as Haurania spp., Pseudocyclamina spp., Textularia spp. or Trochamijiella golleshstanehi (Fig. 6) are found to be more abundant in the lower part of the Dhruma Formation, especially around 210 m and again at 105 m (Fig. 2). Consequently, the lower part of the Dhruma Formation up to 146 m (Fig. 2) was interpreted as subzone F455 (lower). Foraminifera like Trocholina elongata, Trocholina palasinensis and Pfenderina salernitana (Fig. 6) are rare in the Dhruma Formation and occur preferentially in the upper part of the formation in Wadi Sahtan. Thus, the upper part of the formation was interpreted as subzone F455 (upper) to F457. Due to this differentiation in foraminiferal sub-biozones, a Late Aalenian to Bajocian age is suggested for the lower composite sequence and a Bathonian to Middle Callovian age for most of the upper composite sequence (Fig. 7).

**Chemostratigraphy**

The type section of the Dhruma Formation in Wadi Sahtan was sampled with a vertical spacing of ca 1-5 m. For each sample the $\delta^{18}$O and $\delta^{13}$C values were measured on whole rock samples.

| Formation | Micropal. Zone | Palyno. Zone | Relative age |
|-----------|----------------|--------------|--------------|
| Dhruma    | F45            | (40097) 4191-2262 | L. Bajocian  |
|           | F457-F455      |              | – Bathonian  |

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The $\delta^{18}O$ values in the Dhruma Formation

The $\delta^{18}O$ value of a mineral is dependent on temperature during precipitation and the $\delta^{18}O$ value and salinity of the solution from which the mineral is precipitated (Epstein et al., 1953). Since whole rock samples were measured and the contribution from photosynthetic organisms was negligible, any influence attributable to vital effects was not considered. Positive values indicate a colder climate than today and negative a warmer climate.

While the $\delta^{18}O_{\text{sample}}$ can be measured, the $\delta^{18}O_{\text{H}_2\text{O}}$ value for sea water during the time of deposition has to be estimated. It depends on latitude ($0^\circ_\text{C}$ around the equator and decreasing towards the poles), altitude ($0^\circ_\text{C}$ at sea-level and decreasing with elevation) and the amount of ice in the world (modern world: $0^\circ_\text{C}$, glacial

![Image of foraminifera](image)

**Fig. 6.** Most abundant foraminifera of the Dhruma Fm. in outcrops of Wadi Sahtan: (A) Pfenderina salernitana?, (B) Pfenderina trochoidea, (C) Haurania spp., (D) Pseudocyammina spp., (E) Textularia spp., (F) Trochomijiella golleshstanehi, (G) Trocholina elongata.
world: $+1\%_o$, non-glacial world: $-1\%_o$ V-SMOW; Vienna Standard Mean Ocean Water).

In the Middle Jurassic, the study area (Oman Mountains) was located at the equator (Scotese, 2001) and deposition took place in a shallow marine environment in a non-glacial world (Price, 1999; Price et al., 2009). Thus, only the ice-effect changes the $\delta^{18}O_{H_2O}$ value for sea water to ca $-1\%_o$. Calculated $\delta^{18}O_{carb}$ values indicate a decrease in sea water temperature during deposition of the Dhruma Formation (Fig. 7). Brigaud et al. (2009) also suggest a cooling from the latest Early Bajocian to the Late Bajocian, which seems to be in agreement with this study.

The accuracy of the calculated palaeo-temperatures is debatable, as whole rock samples were analysed rather than phylogenetic or species specific components, as well as possible kinetic isotope fractionation caused, for example, by diagenesis. Due to the limited amount of samples available for isotope analysis, no changes related to facies could be observed.

The $\delta^{13}C$ values in the Dhruma Formation

The $\delta^{13}C$ value of a mineral is (almost) independent of temperature during deposition. Positive $\delta^{13}C$ values are indicative of an increase in organic productivity in the photic zone or the removal of carbon, for example, by burial (Holser, 1997). Negative values can be associated with a significant decrease in organic productivity or a significant release of methane, for example, from methane hydrates (Holser, 1997; Thomas et al., 2002).

The $\delta^{13}C$ values from Wadi Sahtan show strong variations between $-2\%_o$ and $2-2\%_o$ (Fig. 7) which may result from whole rock measurements or diagenetic alteration. Thus, a moving average was calculated to mitigate these effects and to create a $\delta^{13}C$-graph with similar resolution to comparable data from Italy (Morettini et al., 2002) and Spain (O’Dogherty et al., 2006; Fig. 8).

In the lowermost 10s of metres of the Dhruma Formation $\delta^{13}C$-values are rather low at ca $0\%_o$. Values show an overall increase towards the top of the formation to ca $2\%_o$. According to O’Dogherty et al. (2006), increasing $\delta^{13}C$-values are often associated with transgressive sea-level rise, which is consistent with the transgressive dominated Dhruma Formation in Oman. Data from central Italy and southern France (Bartolini et al., 1996; Bartolini & Cecca, 1999) and Scotland (Jenkyns et al., 2002) show a positive $\delta^{13}C$-excursion in the Lower Aalenian and Lower Bajocian, and a negative $\delta^{13}C$-excursion around the Aalenian-Bajocian boundary. Thus, the low of $-0.8\%_o$
in the lower part of the Dhruma Formation in Wadi Sahtan might be associated with the Aalenian-Bajocian boundary, matching the biostratigraphic dating. The low values are succeeded upwards by a pronounced positive δ13C-excursion of up to 2.1‰ in Wadi Sahtan. This effect was also recorded by data from Italy, Spain and England, where it is associated with the Early to Middle (Morettini et al., 2002) and Late Bajocian (O’Dogherty et al., 2006). Thus, a global signal can be assumed for the positive δ13C-excursion (Hesselbo et al., 2003), which has been correlated with a ‘carbonate production crisis’ in the southern margin of western Tethys (Bartolini et al., 1996) and may be related to greater oceanic fertilization as shown by radiolarian assemblages (Bartolini & Cecca, 1999). This might also be partly responsible for the low biodiversity in the lower part of the Dhruma Formation. Throughout the Bathonian rather constant δ13C-values are reported with an increase in the Upper Bathonian. A slight increase to 2.2‰ can also be observed in the uppermmost part of the section from Wadi Sahtan. This is consistent with Forbes et al. (2010), Dubreuilh et al. (1992) and Rousseau et al. (2006), who suggest that the Dhruma-Tuwaïq Mountain boundary roughly approximates to the Bathonian-Callovian boundary. The correlation of δ13C-data from Wadi Sahtan, Oman Mountains to data from Italy and Spain suggests a depositional period for the Dhruma Formation from Late Aalenian to Late Bathonian. This is consistent with biostratigraphic dating. As already mentioned for oxygen isotopes, a diagenetic overprint cannot be excluded for δ13C-values. No facies dependencies of δ13C-values were observed (Fig. 7), which might be due to the limited number of measured samples.

**Chronostratigraphy**

Biostratigraphic analyses and chemostratigraphic correlations of data from Wadi Sahtan reveal a Late Aalenian to...
Late Bathonian age. Referring to the ‘International Chronostratigraphic Chart’ from 2016 after Cohen et al. (2016) this results in a time span of ca 6.5 Myr (172.0 to 165.5 Ma). Different studies on the Middle and Upper Jurassic of the Arabian Peninsula use different time scales for Jurassic stages in outcrops and subsurface of Oman (Forbes et al., 2010), central Saudi Arabia (Enay et al., 1987), Qatar (Droste, 1990), Kuwait (Yousif & Nouman, 1997) and Yemen (Howarth & Morris, 1998), compared to the ‘International Chronostratigraphic Chart’ from 2015 (Cohen et al., 2016; Fig. 9).

This problem arises as relative ages in Oman are based on foraminiferal assemblages (Hughes, 2004), in Saudi Arabia on ammonite faunas (Enay et al., 1987), in Kuwait on lithostratigraphic correlations to the better dated sections of Iraq and Saudi Arabia (Yousif & Nouman, 1997) and in Yemen on ammonite faunas (Howarth & Morris, 1998). Droste (1990) and Sharland et al. (2001) did not state that used for age determinations in Qatar.

Even within Oman, the depositional timeframe for the Dhruma Formation varies from study to study. Considering that deposition of the Dhruma Formation initially

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**Fig. 9.** Timeframe for Middle and Upper Jurassic Stages from outcrop data from Wadi Sahtan in Oman, subsurface of Oman (Sikkema, 1992; Forbes et al., 2010), central Saudi Arabia (Enay et al., 1987), Qatar (Droste, 1990), Kuwait (Yousif & Nouman, 1997) and Yemen (Howarth & Morris, 1998), compared to the ‘International Chronostratigraphic Chart, v2016/04’ (Cohen et al., 2016) (http://www.stratigraphy.org/ICSchart/ChronostratChart2015-01.jpg, effective 04/29/2016).
commenced in the northwest of Oman and began later in the southeast, it is important to consider the location of outcrops and wells used for dating. In Central Oman, a timeframe from Late Bajocian to Bathonian (168 to 165.5 Ma) is suggested for the Dhruma Formation (Forbes et al., 2010). A Bathonian to Callovian age was suggested by Dubreuilh et al. (1992) based on foraminifera in the Haushi area, east Central Oman. Rousseau et al. (2006) put the Dhruma and Tuwaiq Mountain formations within a general Bathonian to Callovian age, based on the faunal assemblage described by Dubreuilh et al. (1992). Sharland et al. (2001) on the other hand suggest an Early Bajocian to Callovian age based on his interpretation of maximum flooding surfaces (MFS J20, J30 and J40). Unfortunately some chronological discrepancies exist, for example, the MFS J20 is put near the base of the Dhruma Formation in Oman and described as Early Bajocian in age and dated to 175 Ma. Depending on reference literature, an age of 175 Ma is associated with the Toarcian in the ‘International Chronostratigraphic Chart’, the Aalenian in Oman and Kuwait and the Bajocian in central Saudi Arabia and Qatar (Fig. 9).

Thus, it is important to clearly state the age of the deposits described and if the measured dates derive from isotope dating, isotope correlations, faunal assemblage or other sources. To give an overview of some literature describing Middle and Upper Jurassic formations on the Arabian Peninsula, stages and formations were illustrated in Fig. 9. Ages in this study are based on foraminiferal assemblages from the section in Wadi Sahtan and isotope correlations to other sections around the Tethys Ocean.

**FACIES ANALYSIS**

All formations of the Jurassic Sahtan Group were deposited in similar carbonate ramp environments. Lithofacies types (LFTs) thus follow largely the LFTs of Bendias & Aigner (2015) of the Lower Jurassic Mafrak Formation. However as the Dhruma to Hanifa/Jubaila formations are carbonate dominated, whereas the Mafrak Formation is a mixed carbonate-siliciclastic system, some of the LFTs of Bendias & Aigner (2015) were modified and facies types added to include all observed components and environmental settings of the low-angle carbonate ramp present in the Middle and Upper Jurassic.

The studied formations consist dominantly of limestones. Dolomites, sandstones and shales play only a minor role. Twelve lithofacies types were used to describe the Dhruma Formation in outcrops and subsurface of Oman. They are based on a combination of Dunham texture, sedimentary features and components (Table 2). Depositional environments range from peritidal to low-energy lagoon and high-energy, shoal-like. Generally, sandstones, mudrocks and microbial laminites represent the most proximal facies, whereas massive and thinly bedded mudstones and marls were deposited in a low-energy, lagoonal environment and might act as baffles or seals. Cross-bedded peloidal and oolitic grainstones represent the most distal environment and constitute potential reservoir rocks.

**Lithofacies types**

**Facies associations – depositional model**

The 12 described lithofacies types of the Dhruma Formation (Figs 10 to 21) were grouped into four lithofacies associations (Table 2), based on lithological composition, biogenic and abiogenic component assemblages, as well as sedimentary features. Due to rather homogeneous biogenic component assemblages throughout the section, a detailed analysis of the occurrence of biogenic components along with sedimentary structures is essential to assign a lithofacies type to the proper depositional environment and thus the appropriate lithofacies association.

The proposed depositional model for the Dhruma Formation (Fig. 22) is an epeiric carbonate ramp with a very small slope as described by Irwin (1965). He suggested three zones representing a distal low-energy Zone X, a high-energy Zone Y and a proximal low-energy Zone Z (Fig. 22). The three zones were subdivided in this study into six LFAs, allowing a more detailed differentiation of the depositional environments on the epeiric ramp: LFA 1: Peritidal, LFA 2: low-energy Zone Z (lagoonal), LFA 3: moderate-energy Zone Y to Z, LFA 4: high-energy Zone Y, LFA 5: moderate-energy Zone X to Y and LFA 6: low-energy Zone X (offshore). However, moderate-energy Zone X to Y and low-energy Zone X are not present in outcrops of the Dhruma Formation in the Oman Mountains, but are mentioned here for a comprehensible modification and description of the Irwin Model.

The peritidal lithofacies association (LFA 1) comprises carbonates, which show dominantly micritic textures and a minor quartz content. They are sometimes interbedded with thin, several centimetres thick sandstone sheets (Fig. 10) with a lateral consistent thickness of at least hundreds of metres to kilometres. Peritidal facies were deposited in a wide spectrum of energy conditions, leading to a diverse sedimentary record ranging from low-energy mudrocks (Fig. 11), to medium-energy microbial laminites and stromatolites (Fig. 12), as well as rippled wacke- to packstones, to high-energy events which show scour fills and occasionally cross-bedding. Peritidal facies of the Dhruma Formation show a rather low biodiversity comprising gastropods, bivalves, undefined shell debris, foraminifera and peloids. Individual facies are
**Table 2.** Scheme for the nomenclature of lithofacies types for the Dhruma, Tuwaq Mountain and Hanifa/Jubaila formations in Oman, modified after Bendias & Aigner (2015). Lithofacies associations (LFA) present in the Dhruma Formation outcrops of the Oman Mountains and their assigned lithofacies types.

| Lithofacies types (LFT) | Modifiers | Example |
|-------------------------|-----------|---------|
| S: Sandstone | m: massive | mi: microbial |
| MR: Mudrock | tb: thinly bedded | o: oolitic |
| B: Boundstone | x: cross-bedded | on: oncoidal |
| M: Mudstone | p: peloidal | s: skeletal |
| DM: Dolo-Mudstone | |
| W: Wackestone | |
| WP: Wacke- to Packstone | Mtb: Mudstone, thinly bedded |
| P: Packstone | WP,s: Wacke-to Packstone |
| PG: Pack- to Grainstone | WP: Wackestone, skeletal |
| G: Grainstone | Gx,o: Grainstone, cross-bedded, oolitic |

Lithofacies associations (LFA) | Facies types
---|---
LFA 1 Peritidal | sandstone (LFT: S), mudrock (LFT: MR), microbial boundstone (LFT: B; mi)
LFA 2 Low-Energy Zone Z | mud- and wackestones (LFT: Mm; Bb; DM)
LFA 3 Moderate-Energy Zone Y to Z | wacke- and packstones (LFT: W; WP; s; WP; on)
LFA 4 High-Energy Zone Y | pack- and grainstones (LFT: PGm; Gx,p; Gx,o)

Generally homogeneous in composition and are locally bioturbated.

Since supratidal indicators such as evaporites, desiccation cracks, tepee structures, rootlets of mangroves or saltwater grasses are absent, the peritidal environment of the Dhruma Formation can be described as a storm influenced, intertidal setting without significant preserved pore spaces.

The Low-Energy Zone Z lithofacies association (LFA 2) extends over 10s of kilometres and is dominated by lime- and dolo-mudstones (Figs 13 and 14), occasionally with a minor clay content. In some places, thin (less than 10 cm thick) packstone sheets with a lateral extent of hundreds of metres to kilometres can be observed. Associated facies types are exclusively micritic. Bioturbation is common in Zone Z with abundant *Thalassinoides* trace fossils suggesting a marine shelf environment (Seilacher, 2007). Mud- and wackestones are often bioturbated and contain gastropods, bivalves, echinoderms or undefined shell debris (Figs 15 and 16) as well as abiotic components such as peloids and coated grains.

Restricted, low-energy conditions in combination with a very low carbonate productivity, probably due to clastic input from the hinterland, lead to the formation of mudstones with a minor clay content (facies type: Mt). These beds tend to be thinly bedded (Mt, Fig. 14) and show only a low biodiversity and no bioturbation. The clay content is often reflected in a slight increase in the gamma-ray signal. Thin packstone sheets can probably be interpreted as storm deposits.

The Moderate-Energy Zone Y to Z lithofacies association (LFA 3) extends over 10s of kilometres and represents the transition between high-energy Zone Y and low-energy Zone Z. It comprises the point where wave and tidal actions are largely dissipated by friction. Deposits are defined by textures ranging from wacke- to packstones which are often bioturbated, for example, by *Thalassinoides*, and are of a lagoonal to shoal-margin setting. Centimetres to decimetres thick, graded layers occasionally containing mud clasts at the base, are interpreted as storm deposits which were able to reach low-energy Zone Z. Wacke- to packstones are either dominated by bivalves, peloids and shell hash with subordinate brachiopods and gastropods (Fig. 17) or oncoids (Fig. 18). As oncoids of the Dhruma Formation are usually equidimensional, they were probably formed by continuous rolling above the wave base (Ratcliffe, 1988).

The High-Energy Zone Y lithofacies association (LFA 4) extends over 10s of kilometres and contains deposits of a high-energy, shoal-like setting, which is created by waves striking the bottom and tidal action. The energy decreases landward towards moderate-energy Zone Y to Z due to friction. The main lithofacies types are massive to cross-bedded, peloidal and oolitic pack- and grainstones which are occasionally storm influenced (Figs 19, 20 and 21). In contrast to typical shoal deposits, the observed pack-and grainstones of high-energy Zone Y rarely possess erosional bases but display consistently uniform bedthickness over several kilometres. Furthermore, low-angle cross-bedding is more common than high-angle cross-bedding. Thus it is likely, that deposits in Zone Y are rather sheet-like, as described in the depositional model by Irwin (1965), and do not show high-relief shoal geometries. Since no pore spaces can be observed in outcrops of the Dhruma Formation in LFA Zone Y, only deposits of Zone Y of the Dhruma Formation can be described as potential reservoir facies.

**TYPE SECTION IN WADI SAHTAN**

The Middle Jurassic Dhruma Formation unconformably overlies the Mafraq Formation and is truncated by the Tithonian unconformity which marks the AP7/AP8 Mega-Sequence boundary (Sharland et al., 2001) in...
outcrops, followed by the Early Cretaceous Rayda Formation. Its lower boundary lies on top of siliciclastic beds marked by a distinct gamma-ray peak at the top of the Mafraq Formation, while at the Tithonian unconformity only a minor gamma-ray peak can be observed (Fig. 2). The Rayda Formation is marked by the abrupt occurrence of thin, up to 15 cm thick, light grey mudstone beds which are intercalated with chert layers and sometimes contain belemnites.

**Cycle indicators**

In contrast to the cyclicity of the Dhruma Formation in other countries like the UAE, Qatar, Kuwait and Saudi Arabia, where a regression dominated cyclicity is considered (Sharland et al., 2001), several aspects point to a transgression dominated cyclicity for the Dhruma Formation in Oman. The following indicators for delineating and interpreting cycles were used:

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**Fig. 10.** (A) Thin section of massive sandstone: quartz grains in a carbonate mud matrix and (B) cross-bedded sandstone; (C) 60 cm thick, massive sandstone interval with a typical dark red colour; (D) with increasing carbonate content colour changes to orange-brown.

**Fig. 11.** (A) Thin section of quartz grains in a matrix of silt and clay; (B, C) orange-brown mudrock with thin horizontal bedding, interbedded with shales; (D) occasionally small ripples are present.
Discontinuity surfaces

Several discontinuity surfaces are present throughout all outcrop sections, representing breaks in sedimentation in the Dhruma Formation. They are best explained in the context of relative sea-level fall (Osleger, 1991; Schlager, 1993; Tucker & Wright, 2009), particularly maximum regression phases. In a shallow epeiric sea, currents or wave action can prevent the deposition of sediments (Voigt, 1959; Immuenhauser, 2009) causing an early sub-marine cementation of the sea floor (Bathurst, 1974). In this study, discontinuity surfaces were classified into three categories as suggested by Christ et al. (2012): condensed surfaces, firmgrounds and hardgrounds.

Condensed surfaces within the Dhruma Formation show increasing Thalassinoides burrowing towards the
upper bedding plane (Fig. 23E and F). Often many condensed surfaces can be observed over a thickness of several metres in an outcrop section (Fig. 23C). In contrast to the surrounding bluish grey limestone, the Thalassinoideas burrow infillings are mainly brown-yellow in colour (Fig. 23), which is related to burrow-selective dolomitization (Gingras et al., 2004; Rameil, 2008). The burrows mainly possess blurry to sharp boundaries and their width ranges from several millimetres up to 2 cm (Fig. 23D). Thalassinoideas burrows are commonly formed below the oxic pore water zone within the sediment column (Coimbra et al., 2009) and are essentially related to dewatered, uncemented firm sediments (Bromley, 1975a; Ekdale & Bromley, 1984; MacEachern & Burton, 2000) or soft sediments (Bromley & Frey, 1974; Savrda et al., 2001). As described by Christ et al. (2012), they mainly

Fig. 14. (A) Thin sections of thinly bedded mudstones; wavy bedding (B) might indicate a slight microbial influence; (C) typical thickening-up cycle for the Dhruwa Fm. in Oman with thinly bedded mudstones at the base.

Fig. 15. (A, B) Thin sections of massive mudstone; grey mudstone intervals can be up to 4 m thick in outcrops and are either massive (C) or are bioturbated by Thalassinoideas (D: section view, E: top view).
occur at the top of mud- and wackestone facies, but can also be observed at the top of packstones. They laterally extend over hundreds of metres or maybe even kilometres, although there is no unequivocal clear correlation between the studied outcrop sections over kilometres. Condensed surfaces without an accompanying facies change were not considered to be cycle-boundaries.

Firmgrounds show minor degrees of lithification with a diffuse boundary to the underlying beds and a sharp boundary to younger, post-firmground sediments. Sometimes bioclasts can be observed on their surface. In contrast to condensed surfaces, they have a dark grey to reddish colour and sharp bioturbation boundaries.

Hardgrounds show a characteristic dark grey to dark red colour (Fig. 24B and C) which is caused by secondary iron mineralizations (Christ et al., 2012) or this might be a result of sub-recent to recent fluid flow (Gómez &
Fernández-López, 1994). Boring traces with a diameter of 2 to 12 mm (Fig. 24B and C) are clear indications of a lithified sediment (Goldring & Kazmierczak, 1974; Baird & Fürsich, 1975; Bromley, 1975b; Palmer & Palmer, 1977) as is colonization by sessile benthos in the form of oyster shells (Fig. 24C). Oysters commonly form small bioherms/biostromes tens of centimetres in extent. Hardgrounds always mark a clear change in facies with predominately peloidal pack- and grainstones containing bivalves and brachiopods as the synsedimentary fauna followed by a post-hardground facies mostly consisting of a mud dominated, thinly bedded limestone with a distinct decrease in biodiversity (Fig. 24A). Therefore, hardgrounds play an essential role, delineating a typical cycle set of the Dhruma Formation: the transgressive hemicycle shows a slow increase in grain content towards the zone of maximum flooding (Fig. 24A) and a rapid change back to a low-energy setting in the regressive hemicycle. The regressive hemicycle, if present, is topped by a hardground which represents the cycle set boundary and was
most likely developed in a low-energy, lagoonal environment. Most of the hardgrounds and some of the firmgrounds can be correlated throughout all outcrop sections. Thus, it is likely, that hardgrounds are isochronous surfaces and influenced by variations in sea-level, while firmgrounds may be diachronous and thus influenced by, for example, variations in sediment supply (Burgess & Prince, 2015).

**Lithological indicators**

Sandstones and quartz are rare in the Dhruma Formation. After an initial quartz input at the base of the formation, another quartz containing interval can be observed just below the highest gamma-ray values 55 m above the base (CoSe1-CoSe2 boundary, Fig. 2). In addition, microbial laminites and stromatolites occur in the lowermost 20 m

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Fig. 20. (A, B) Thin sections of cross-bedded peloidal grainstones; (C) tens of centimetre-thick beds of grainstones stack up to several metres, deposited in a high-energy environment; (D) cross-bedding is sometimes hard to recognize and if present mainly of low angle-type; sheets of tens of centimetres occasionally display erosive bases overlain by mudclast-rich deposits (E) and are likely storm influenced.

Fig. 21. (A) Thin section of oolitic grainstone; beds are generally 10s of centimetres thick and cross-bedding is hard to recognize (B); oolitic grainstones often contain no other components but ooids (C, D).
Fig. 22. Schematic 2D illustration of an epeiric carbonate ramp after Irwin (1965): black bars represent the distribution of lithofacies types (left) along the epeiric carbonate ramp (after Irwin, 1965) proposed for the Dhruma Fm. and the related lithofacies associations.

Fig. 23. (A) Discontinuity surface, heavily bioturbated by Thalassinoides; (B) close-up of Thalassinoides burrows; (C) part of the outcrop of the Dhruma Fm. in Wadi Sahtan, showing bioturbated discontinuity surface (orange to brown); (D) top view of Thalassinoides burrows; (E) discontinuity showing dolomitized burrows in lime mudstone. Often increasingly more intense burrowing can be observed towards the upper bedding plane. Sometimes no trend in bioturbation intensity can be observed (F).
of the formation. Furthermore, the lower part of the formation (CoSe1) shows condensed cycles and sequences when compared to more distal sections towards the northwest. The reduced cycle thickness coincides with both the quartz input and the occurrence of dolomite. Dolomitization in the Dhruma Formation seems to be stratigraphically bound and thus might be caused by limited circulation in Zone Z, which led to an increased landward Mg$^{2+}$ concentration. Consequently, quartz input and the occurrence of dolomite can be interpreted as indicating a shallow marine depositional environment for the Dhruma Formation in Oman. This is consistent with the interpretation of dolomite in the underlying Lower Jurassic Mafraq Formation, where dolomite seems to indicate very shallow marine deposits, possibly a restricted tidal flat environment (Bendias & Aigner, 2015). Sidewall samples of the Dhruma Formation from a well in the northwest of Oman comprise skeletal wackestones and lime mudstones, which both possess skeletal assemblages consistent with deposition in a shallow water, protected inner platform setting (Goodall & Coy, 2000). Thus, mudstones of the Dhruma Formation can be considered as ‘lagoonal’, even in the most distal sections.

**Biofacies indicators**

Some organisms living during deposition of the Dhruma Formation occupied a wide range of environmental conditions, ranging from restricted, shallow waters to open marine and sometimes even deep marine conditions. Bivalves, echinoderms and calcareous large benthic foraminifera, as well as components like peloids can be found throughout the formation. Other components show a specific distribution pattern. In the lower part of the Dhruma Formation gastropods occur in most of the beds with their abundance decreasing towards the top of the formation. Other components show a specific distribution pattern. In the lower part of the Dhruma Formation gastropods occur in most of the beds with their abundance decreasing towards the top of the formation. In contrast, brachiopods as well as coral heads and coral fingers are rare in the lower part but appear more and more frequently towards the top. This might point to increasing open marine condition towards the top of the formation.

**Corals**

Different coral shapes can be observed in the Dhruma Formation. Since coral morphology is an indicator of habitat, inferences concerning the energy conditions are possible (Lough & Barnes, 1997). Branching corals (Fig. 25A and C) prefer a low-energy environment since they are rather fragile. In contrast, interconnected, bulky corals (Fig. 25B) occur under medium- to high-energy conditions, since their design can withstand a stronger water movement (Lough & Barnes, 1997). The predominant shapes observed within the Dhruma Formation are branching corals. However, bulky corals occur more frequently towards the top of the formation which might indicate an overall increase in depositional energy.

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Fig. 24. (A) Cycle set in Wadi Bani Awf: hardground at the bottom is followed by a typical cycle set for the Dhruma Fm. with increasing grain content towards the top; (B) topview of a hardground with dark grey to dark red colour, bioturbation and drillings; (C) close-up of the hardground surface with indicative drillings and oyster colonisations.
A palynological study revealed leiospheres with accessory pollen, spores and some phytoclasts in mudstone dominated intervals of the formation, but no dinoflagellates. Consequently, the analysed mudstones have to be put in a proximal marine environment under restricted and not open marine conditions. However, the palynological recovery was very poor and the possibility that dinoflagellates were initially present and selectively destroyed during burial cannot be fully discarded.

**Megalodonts**

Megalodonts (Fig. 25D) are bivalves which appear in all studied sections in CoSe2 of the Dhruma Formation (Fig. 2). They can be found in wackestones, packstones and sometimes even grainstones. Megalodonts are considered to represent the earliest record of algal symbiosis in bivalvia, housing microalgal endosymbionts (Yancey & Boyd, 1983; Benini, 1985). According to De Freitas et al. (1993), megalodonts occupied different environments tending to prefer protected, lime-mud rich settings in

![Fig. 25. (A, C) Branching corals indicating low- to medium-energy conditions; (B) bulky corals indicating medium- to high-energy conditions; (D) accumulation of bivalves (megalodonts) in peloidal pack- to grainstones; (E, F) large gastropods with a length of at least 20 cm and a diameter of up to 14 cm form a gastropod macrofauna near the top of the Dhruma Fm. in outcrops of the Oman Mountains.](image-url)
shallow water. With their large and thick shell, they are considered to have been epifaunal suspension feeders and tended to be most abundant in and adjacent to high-energy conditions in subtidal lime muds and microbial influenced lime muds above storm wave base on an open marine ramp (De Freitas et al., 1993), where they would rest slightly inclined (Seilacher, 1984, 1990). Thus, the occurrence of megalodonts in the upper part of the formation indicates a shallow marine depositional setting and medium- to high-energy conditions within the formation.

**Upper Dhruma – Gastropod Macrofauna**

In an interval some metres below the Tithonian unconformity, several pack- and grainstone beds can be found which contain a gastropod macrofauna with abundant corals, bivalves (megalodonts), some brachiopods and conspicuous large gastropods with a diameter of up to 14 cm and a length of at least 20 cm (Fig. 25E and F).

It is unclear why gastropod macrofauna occurs near the top of the Dhruma Formation. According to Wernberg et al. (2008), there is a positive relationship for some gastropods between the rate of consumption and size, which might indicate abundant food for gastropods at that time. A concurrent abundance of corals may have created a sheltered habitat for gastropods, which allowed the formation of larger shells. Other factors, like the absence of predators or low predation rates might be responsible. It is also possible that ecological opportunities and selective pressures led to the origination of new species or genera with larger shells as in the Phanerozoic or as described by Payne (2005) for the Middle Triassic. Finally, it might represent a late recovery from the Lilliput-effect (Brayard et al., 2010), which states, that after the Permian-Triassic mass extinction event only very small gastropods not larger than 2-6 cm occurred in the Early Triassic, in contrast to lengths of 5 to 10 cm in the Middle Triassic (Payne, 2005).

**SEQUENCE STRATIGRAPHY**

‘Cycles’

Biostratigraphic analyses from the section in Wadi Sahtan combined with chemostratigraphic data point to a Late Aalenian to Late Bathonian age for the Dhruma Formation. Referring to the ‘International Chronostratigraphic Chart’ from 2016 after Cohen et al. (2016) this results in an interval of ca 6-5 Myr (172.0 to 165.5 Ma). In contrast, Forbes et al. (2010) and Clarke (1988) suggest a Late Bajocian to Bathonian age (168 to 165.5 Ma) for the Dhruma Formation in Oman and thus, a time span of ca 2.5 Myr. Four cycle hierarchies are observable in outcrops (‘cycles’, cycle sets, high-frequency sequences and composite sequences), all of which can be correlated over kilometres with the exception of some ‘cycles’, which represent the highest hierarchy. Cycle stacking patterns in combination with a rough calculation for the duration of a Dhruma Formation ‘cycle’ (6-5 Ma/57 cycles = 114 000 years/cycle) suggests that one ‘cycle’ extends over ca 114 000 years, which might be related to the 100 000 years Milanković signal (eccentricity of earth’s orbit). Four different types of ‘cycles’ can be observed in Oman Mountain outcrops.

- Mixed cycle type (Fig. 26)
- Low-energy cycle type (Figs 27 and 28)
- Medium-energy cycle type (Figs 29 and 31)
- High-energy cycle type (Figs 32 and 33)

**Mixed cycles**

Mices cycles (clastic-carbonate) only occur in CoSe1 (Fig. 2). They range in thickness from 1.0 to 3.3 m. Alternating orange to dark-red sandstones with an erosive base (Fig. 26) and grey, rippled or cross-bedded wacke- and packstones, containing shell debris, intraclasts and peloids, predominate in the early transgressive hemicycle. They turn to light grey, bivalve and shell debris rich pack- to grainstones at the zone of maximum flooding. The regressive hemicycle mirrors the transgressive one and bioturbation increases towards the cycle-boundaries. The gamma-ray signal nicely reflects the clastic input in the form of higher values and a lower signal at the zone of maximum flooding. For mixed cycles, a proximal periti- dal setting of Zone Z is assumed. Massive and rippled sandstones with erosive bases are interpreted as intertidal or subtidal deposits, dependent on the occurrence of sedimentary structures such as ripples. Limited bed-thickness in intervals with alternations of sandstones and carbonates and sediment reworking point to sea-level fluctuations in a limited accommodation space setting. Facies changes to thicker beds of shell and shell hash-rich cross-bedded, peloidal pack- to grainstones reflect an increase in energy that might be associated with a relative rise in sea-level. Intense bioturbation may have destroyed further evidence of tidal influence in the lower part of the formation.

**Low-energy cycles**

Low-energy cycles: Muddy cycles dominate CoSe1 of the Dhruma Formation (Fig. 2). They range in thickness from 2.0 to 3.8 m and are light grey to grey in colour. Transgressive and regressive hemicycles show only little
compositional variation. Cycle-boundaries are often marked by lithological changes with clay input or dolomite (Fig. 27). Shell debris, gastropods, bivalves and brachiopods are the dominant components and form mud- to wackestones or wackestones at the zone of maximum flooding. The gamma-ray signal is rather clean with low values which may increase towards the cycle-boundaries due to clastic input. Bioturbation is ubiquitous, but increases towards the cycle-boundaries, especially when condensed surfaces or firmgrounds, bioturbated by *Thalassinoides*, are present. These muddy cycles are interpreted as deposits of the low-energy, lagoonal environment of Zone Z.

Low-energy cycles are occasionally dominated by thinly bedded mudstones (Fig. 28) which are sometimes argillaceous and occur often near or rather above sequence boundaries of high-frequency sequences. They range in thickness from 2·0 to 6·0 m and stack into intervals with a thickness of up to 6 m. Dominant components are shell debris and gastropods and sometimes sponge spicules with increasing numbers of peloids and bivalves towards the zone of maximum flooding. In contrast to clay free cycles, bioturbation is rare in thinly bedded mudstones close to the cycle-boundaries but increases towards the zone of maximum flooding.

Cycles dominated by thinly bedded, often argillaceous mudstones are interpreted as very low-energy lagoonal deposits in Zone Z with low sedimentation rates. If they occur at high-frequency sequence boundaries and follow high-energy deposits, this succession might indicate a fast change in the depositional environment from high-energy deposits of Zone Y to low-energy Zone Z and thus represent a fast regression.

**Medium-energy cycles**

Medium-energy cycles are the most common cycle type of the Dhruma Formation. They range from mudstones...
to pack- and grainstones and are sometimes highly transgressive in nature (Fig. 29). They occur throughout the formation and dominate HFS2-HFS4 (Fig. 2), ranging in thickness from 1.8 to 7.6 m. The transgressive hemicycle shows a slow shift from mud- to wacke-, pack- and grainstones which is reflected in decreasing gamma-ray values. They are sometimes topped by a hard- or firmground and are often followed by massive or thinly bedded mudstones. Mudstones are dominated by shell debris, bivalves and peloids. In wacke-, pack- and grainstones peloids become the main component. In some cases cross-bedded grainstones constitute the zone of maximum flooding and are composed of peloids and in rare cases ooids. Beds are light grey to dark grey in colour. Wacke- and packstones, as well as the top part of the regressive hemicycle, are often bioturbated by *Thalassinoides* traces, beige-brown in colour due to dolomitization (Fig. 30).

Strong variations in the thickness of medium-energy cycles are caused by limited accommodation space in CoSe1 (Fig. 2), discussed further in a forthcoming paper covering correlations between 29 outcrop sections and the subsurface of Oman. Low-energy textures vary between mud- and wackestones and high-energy texture between pack- and grainstones (Fig. 31). Medium-energy cycles are not always dominated by transgressive features but are sometimes symmetrical (Fig. 31, upper cycle).

The succession is interpreted as a slow shift of the depositional environment from the low-energy, lagoonal setting of Zone Z to medium- and in some cases high-energy conditions of Zone Y. The frequently fast change from cross-bedded grainstones to massive or thinly bedded mudstones might indicate a fast regression after a continuous transgression.

**High-energy cycles**

High-energy cycles (Fig. 32) are, like medium-energy cycles, strongly transgressive and mainly present in HFS5 and HFS6 (Fig. 2) of the formation. In contrast to medium-cycles, the transition from mud- to wacke-, pack- and grainstones is faster, the amount and thickness of grainstones is higher and they are often cross-bedded and
contain ooids, which represent the most distal facies within the formation. The transgressive hemicycle is defined by continuous changes from mud- to wacke-, pack- and grainstones which is accompanied by a decrease in gamma-ray values. Carbonates are grey to dark grey in colour and variations in Dunham texture are often not that obvious in the field without closer investigation (Fig. 32). Mud- and wackestones are dominated by shell debris, gastropods and bivalves. Packstones are composed of peloids, shell debris, brachiopods and coral fingers. Grainstones at the maximum flooding zone are often cross-bedded and contain peloids and coral heads. Beds show only minor variations in thickness and extend laterally for kilometres to tens of kilometres.

These cycles are interpreted as a transition from a low- to medium-energy, lagoonal setting to high-energy shoal-associated deposits. Due to little variations in bed-thickness over kilometres to tens of kilometres a shift of vastly extensive facies belts is likely.

High-energy cycles also vary considerably in thickness from 3.5 to 11.5 m due to limited accommodation space in CoSe1 (especially HFS3, Fig. 2). Lower gamma-ray values in pack- and grainstones and higher values in mudstones is not seen in the upper part of the formation due to a lack of clastic material in the mud- or wackestones (Fig. 33). Medium and high-energy cycles are often easy to recognize due to preferential weathering of mudstones at the cycle boundary.
Cycle sets

All cycle sets can be correlated throughout all outcrop sections. Their thickness varies between 5 and 22.3 m, which is again due to the limited accommodation space in the lower part of the Dhruma Formation. Cycle stacking patterns combined with a rough calculation for the time span of the Dhruma Formation (6.5 Myr/18 cycle sets = 361 000 years/cycle set) suggests that cycle sets persisted for ca 361 000 years. Thus, a connection to the 400 000 years Milanković signal (superimposed peaks of eccentricity) is possible assuming that some cycle sets might be missing in outcrops due to non-deposition, erosion or might be explained by uncertainty in the actual timeframe for the Dhruma Formation. Three different types of cycle sets can be observed in outcrops of the Oman Mountains.

Low-energy cycle sets

Low-energy cycle sets (Fig. 34) occur only in CoSe1 of the Dhruma Formation (Fig. 2). Their thickness varies between 5 and 14 m and typically comprise stacks of two to three peritidal or low-energy cycles. Mudstones dominate in low-energy cycle sets. The zone of maximum flooding is defined where wacke- or packstones are most abundant and thickest. Cycle set boundaries are defined at the base of orange to beige microbial laminites, which are always dolomitized, beds which experienced clastic input, sandstones or grey to orange dolo-mudstones.
Bioturbation is common and dominant components are gastropods, shells and shell hash. Higher gamma-ray values can be observed in intervals with clastic input. Massive mudstones and microbial boundstones show a low gamma-ray signal.

Microbial boundstones and the presence of beds containing quartz and sedimentary structures that suggest the influence of wave-action (Fig. 26) around cycle set boundaries are interpreted as peritidal deposits. Mud- and wackestones are interpreted as lagoonal deposits of Zone Z. Packstones indicate moderate-energy Zone Y to Z, or if graded storm deposits are present, reaching low-energy Zone Z. Low-energy cycle sets are thus dominated by deposits of Zone Z.

**Medium-energy cycle sets**

Medium-energy cycle sets (Fig. 35) are most abundant in HFS2 to HFS5 of the Dhruma Formation (Fig. 2). Their thickness varies from about 7 to 22 m and they are commonly built of packages of three to four cycles (Fig. 35). Medium-energy cycle sets are primarily composed of limestones. The cycle set boundary is defined at the base of thinly bedded mudstone intervals which may be argillaceous or where dolo-mudstone is present. Bioturbation is especially high in mud- and wackestones. Gamma-ray values are normally below 30 cps, but a low can still be observed at the zone of maximum flooding, which is defined where pack- or grainstones are most abundant and thickest.

Mud- and wackestones at medium-energy cycle set boundaries are interpreted as low-energy, lagoonal deposits of Zone Z, packstones as moderate-energy deposits of Zone Y to Z and pack-to grainstones and grainstones, if present, as high-energy deposits of Zone Y. In contrast to low-energy cycle sets, deposits of low-energy Zone Z and moderate-energy Zone Y to Z are preset in the same ratio in medium-energy cycle sets.

**High-energy cycle sets**

High-energy cycle sets (Fig. 36) occur more frequently in the upper part of the Dhruma Formation. They range in

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*Fig. 30. Appearance of low- (bottom) and medium-energy cycles (top) in CoSe2 of the Dhruma Fm. in outcrops of Wadi Bani Kharus. Bioturbation of Thalassinoides appears orange due to burrow-selective dolomitization. The colour code for LFTs and LFA's is shown in Fig. 22 and lithology in Fig. 3.*
thickness from about 11 to 28 m and are commonly built of three to four cycles (Fig. 36). High-energy cycle sets consist of pure limestone, only around cycle set boundaries do thinly bedded mudstones appear which may possess a slight clay content. Cycle set boundaries are defined at the base of mudstone intervals. The zone of maximum flooding is defined where grainstones contain ooids or where peloidal grainstones are cross-bedded and thickest. Bioturbation is predominantly present in mud- and wackestones and rare in pack- and grainstones.

Mud- and wackestones are interpreted as low-energy, lagoonal deposits of Zone Z which turn rapidly to wacke- to pack- and packstones of moderate-energy Zone Y to Z and pack- to grain- and grainstones of high-energy Zone Y. In contrast to medium-energy cycles, the thickness of pack- and grainstones is higher. Thus, high-energy cycle sets are dominated by deposits of Zone Y.

**High-frequency sequences and composite sequences**

A bundling of two to three cycle sets commonly build one high-frequency sequence. CoSe1 is dominated by per-itidal deposits and deposits of Zone Z, a reduction in HFS thickness seems to be caused by limited accommodation space. All HFSs can be correlated throughout all outcrop sections over 10s of kilometres. Their thickness varies between 6 and 61 m due to the limited accommodation space. A rough calculation for the time span of the Dhruma Formation (6.5 Myr/7 HFSs = 929 000 years/
HFS) suggests a duration of high-frequency sequences of ca 929 000 years. Such HFSs are easy to recognize, especially in cutting sections since they nicely reflect major changes in depositional environment between Zone Z, dominated by mudstones, and Zone Y, dominated by grainstones. Thus, HFSs seem to be the controlling influence on levels of cyclicity affecting the alternation of reservoir and seal intervals in the Dhruma Formation (Fig. 2).

When not influenced by an unconformity such as that occurring at the base of the Dhruma Formation three to four HFSs constitute one composite sequence (CoSe) in the Dhruma Formation. They range in thickness in Wadi Sahtan from 68 to 170 m. The low thickness is caused by limited accommodation space in CoSe1, while the high value is limited by the Tithonian unconformity in outcrop sections. A rough calculation for the time span of the Dhruma Formation suggests that composite sequences extended over ca 3.25 Myr.

**High-frequency sequence 1**

High-Frequency Sequence 1 (HFS1; Fig. 2) unconformably overlies mudrocks and sandstones of the Mafrak Formation in outcrops of the Oman Mountains. Whether a conformable succession from the Mafrak to Dhruma Formation is present in wells in the northwest of Oman is not clear. HFS1 has a thickness of 18 m in Wadi Sahtan and comprises two cycle sets and four ‘cycles’. Sequence boundaries were defined at the basal unconformity and at the base of a 60 cm thick bed of microbial boundstone which extend over kilometres in outcrops. The zone of maximum flooding was defined at the occurrence of wackestones which contain gastropods, bivalve...
shells and shell debris. Gamma-ray values are low at the zone of maximum flooding and higher towards the sequence boundaries.

The whole sequence is interpreted as deposits of a peri-tidal mudflat environment of low-energy Zone Z. Harsh conditions with times of exposure probably cause the low biodiversity in HFS1.

**High-frequency sequence 2**

High-Frequency Sequence 2 (HFS2; Fig. 2) has a thickness of 36 m in Wadi Sahtan and comprises three cycle sets and nine ‘cycles’. The thickness of cycle sets decreases from bottom to top. This might indicate a reduction in accommodation space. A bed of peloidal pack- to grainstones, over 1 m thick and containing oncoids, shows noticeably lower gamma-ray values than the surrounding beds, and is interpreted as the zone of maximum flooding. Towards the upper sequence boundary, argillaceous mudstones possess a slight quartz content. The sequence boundary is then marked by a firmground. Gamma-ray values are rather high in HFS2 and range from 8 to 30 cps. Except for the above mentioned low at the zone of maximum flooding, a continuous decrease can be observed throughout HFS2.

Deposits of this sequence are interpreted as storm-influenced which range from peritidal at the bottom to moderate-energy Zone Y to Z at the zone of maximum flooding.
flooding and return to the lagoonal deposits with quartz of low-energy Zone Z at the upper sequence boundary. The zone of maximum flooding of HFS2 also constitutes the zone of maximum flooding of the lowermost composite sequence (CoSe1), which might correlate to the maximum flooding surface J20 of Sharland et al. (2001).

High-frequency sequence 3

High-Frequency Sequence 3 (HFS3) of CoSe1 (Fig. 2) has a thickness of 15 m in Wadi Sahtan and comprises two cycle sets and eight ‘cycles’. The thickness of the ‘cycles’ decreases again from bottom to top which might indicate a reduction in accommodation space. Cross-bedded peloidal grainstones at 184 m in Fig. 2 contain shell debris, bivalve shells and gastropods and constitute the zone of maximum flooding. Towards the upper sequence boundary several beds contain quartz grains up to the sequence boundary which is defined at a hardground located on shell debris-rich mudstones. Several quartz containing intervals represent cycle set boundaries. The gamma-ray signal resembles HFS2 with a continuous upwardly decreasing trend, although several peaks mark clastic input.

The depositional environment of HFS3 varies from low-energy deposits of Zone Z to moderate-energy Zone Y to Z and occasionally even high-energy Zone Y. The strong decrease in cycle thickness combined with the occurrence of firm- and hardgrounds and quartz input points to a very shallow environment with less accommodation space towards the upper boundary of HFS3, which coincides with the upper sequence boundary of CoSe1.

High-frequency sequence 4

High-Frequency Sequence 4 (HFS4) is the lowermost HFS of CoSe2 (Fig. 2). It has a thickness of 56-5 m in Wadi Sahtan and comprises three cycle sets and 11 ‘cycles’. Firmgrounds often mark the boundary of cycle sets. Deposits with quartz input near the lower sequence boundary show the highest gamma-ray values within the Dhruma Formation of up to 43 cps. Pack- to grainstones are sometimes cross-bedded and occur around the zone of maximum flooding. The upper sequence boundary was picked at a hardground followed by several metres of thinly bedded mudstones at the base of HFS5. Except for the lower part of HFS4, the gamma-ray signal is more or less constant and ranges between 7 and 20 cps.

The depositional environments change from the lagoonal setting of low-energy Zone Z to moderate-energy Zone Y to Z and high-energy Zone Y and back again.

High-frequency sequence 5

High-Frequency Sequence 5 (HFS5) has a thickness of 61 m in Wadi Sahtan and comprises three cycle sets and ten ‘cycles’ (Fig. 2). A 15 m thick interval with cross-bedded peloidal grainstones and several decimetre-
thick beds of oolitic grainstones contains the zone of maximum flooding. The upper sequence boundary is defined at an extensive hardground again followed by several metres of argillaceous, thinly bedded mudstones at the base of HFS6. Gamma-ray values are rather low and range from 6 to 24 cps with slightly higher values in mud- and wackestones than pack- and grainstones.

The range of the depositional environment is the same as in HFS4 (low-, moderate- and high-energy Zone Y to Z), except that there is a greater contribution from the high-energy facies (Fig. 37).

High-frequency sequence 6

High-Frequency Sequence 6 (HFS6, Fig. 2) has a thickness of 52 m in Wadi Sahtan but is erosively truncated by the Tithonian unconformity. It comprises three cycle sets and at least seven ‘cycles’. Over 50% of HFS6 consists of peloidal and oolitic grainstones (Fig. 37) which are mainly massive and frequently cross-bedded. They contain bivalve and brachiopod shells, shell hash, echinoids and are rich in coral fingers and coral heads. The zone of maximum flooding of HFS6 was defined in the lower part of the grainstone interval, where cross-bedded grainstones are thickest and contain ooids, coral heads and some crinoid stem fragments.

As already shown in Fig. 37 the amount of high-energy deposits of Zone Y increases and low-energy deposits of Zone Z decreases towards the top of the Dhruma Formation in CoSe2, while the amount of moderate-energy deposits stays more or less the same. Considering this and the description of all high-frequency sequences, where mudstones occur near sequence boundaries and grainstones at the zone of maximum flooding, a shift of the range of all LFAs present in each HFS to more and more distal environments (transgression) is likely (Fig. 37).


**SEMI-QUANTITATIVE ANALYSES: KEYS FOR SEQUENCE-STRATIGRAPHY**

Semi-quantitative approaches were applied in this study to substantiate and verify the sequence-stratigraphic interpretations based on facies analysis.

**Facies stacking pattern**

A facies stacking pattern diagram was created for the type section in Wadi Sahtan to illustrate shifts in the depositional environment through time (Fig. 38). In a facies stacking diagram, lithofacies associations are arranged from proximal (left) to distal (right). In combination with the vertical log from Wadi Sahtan (including lithology, Dunham texture and gamma-ray), changes in relative sea-level can be identified.

Throughout the 240 m thick section (Fig. 38) five cyclic shifts from a peritidal environment or low-energy Zone Z to the distal high-energy Zone Y can be observed and are interpreted as high-frequency sequences (Fig. 38: black line). Peloids, ooids and especially corals seem to be most abundant around the zone of maximum flooding of high-frequency sequences. All six HFSs can be subdivided into 15 cycle sets (Fig. 38: grey line). Even smaller environmental shifts can be observed and are interpreted as cycles. Cross-bedded peloidal and oolitic grainstones represent potential reservoir facies and occur only in LFA high-energy Zone Y. Potential seal or baffling facies are massive and thinly bedded mudstones which only occur in LFA low-energy Zone Z. Thus, facies stacking diagrams help to identify potential reservoir and seal units within the Dhruma Formation.

*Fig. 36.* Appearance of high-energy cycle sets in the upper third of the Dhruma Fm. in outcrops of Wadi Bani Awt. The colour code for LFTs and LFA is shown in Fig. 22 and lithology in Fig. 3.
Fig. 37. Environmental range for each high-frequency sequence at Wadi Sahtan.

Fig. 38. Facies stacking pattern of the section in Wadi Sahtan showing an increase in distal facies towards the top of the formation. The plot on the right shows the occurrence and abundance of components as recorded in outcrop for each bed. Ooids and corals seem to be present around the zone of maximum flooding of high-frequency sequences. Black line represents the high-frequency sequences.
Grainstone-abundance and thickness

Throughout all outcrop sections of the Dhruma Formation, the grainstone contribution increases towards the top of the formation (Fig. 39) and within each high-frequency sequence. This indicates an overall increase in depositional energy and a shift of the depositional environment from Zone Z to Zone Y towards the top of the Dhruma Formation. Furthermore, the thickness of grainstones beds increases from the lowermost high-frequency sequence to the uppermost. While all grainstone beds have a thickness of less than 25 cm in HFS2 and HFS3, their thickness increases to up to 50 cm in HFS4 and up to 75 cm in HFS5. In HFS6 grainstones are also the most abundant textural facies and show a bed-thickness of more than 1 m (Fig. 40). This indicates an increase in accommodation space towards the top of the Dhruma Formation.

Biodiversity

Most parts of the Dhruma Formation display a low biodiversity. Common components are gastropods, bivalves and peloids. Subordinate brachiopods, echinoids, foraminifera, oncoids, ooids, corals, sponge spicule and very rarely bryozoans and crinoids can be observed. Peritidal deposits like microbial laminites and stromatolites are only present in CoSe1 (Fig. 2), where

![Fig. 39. Section of the Dhruma Fm. in Wadi Sahtan: pie charts illustrating the increasing amount of grainstones (left) and high-energy deposits (right) for each high-frequency sequence and the decreasing amount of mudstones (left) and low-energy facies (right).](image-url)
also gastropods are abundant. While below the CoSe1-CoSe2 boundary an influx of quartz can be observed, above, sponge spicules and bivalves can be found. Low-energy facies containing sponge spicules are interpreted, as in a study from Saudi Arabia, as lagoonal deposits, where spicule-secreting sponges lived, often surrounded by stromatoporoids (Hughes, 2004). Ooids, bulky corals and some rare crinoid fragments occur exclusively in the high-energy environment of Zone Y. Crinoid fragments can exclusively be observed near the top of the formation and probably derive from moderate-energy Zone X to Y (Fig. 22) which is located towards the northwest of the study area. As crinoids are an indicator of more open marine conditions, their occurrence suggests that these are the most distal deposits within the Dhruma Formation and thus are a candidate to define the position of the zone of maximum flooding of the upper composite sequence. The bio-component diversity is variable throughout the section and appears to correspond to high-frequency sequences. As shown in Fig. 41, the diversity increases towards the zone of maximum flooding of each high-frequency sequence and decreases towards their boundary. Furthermore, an overall increase in biodiversity can be observed towards the top of the formation, most likely due to increasing open marine conditions, while rather restricted marine conditions in the lower composite sequence led to a milieu which was only habitable for a limited range of organisms.

The new semi-quantitative methods for sequence-stratigraphic interpretations were shown to be quite useful in...
identifying vertical and lateral changes in the depositional environment in relation to energy conditions, accommodation space, bio-component diversity and the identification of cycles on different levels. Thus, the combination of these parameters provides a good basis for the interpretation of the depositional environment.

SUMMARY

A detailed study of epeiric ramp carbonates of the Middle Jurassic Dhruma Formation in a spectacular outcrop of Wadi Sahtan in the Oman Mountains is presented. A rigorous facies analysis as well as bio- and chemostratigraphic methods were applied with the aim of establishing a robust sequence-stratigraphic framework.

Facies analysis

Twelve lithofacies types were differentiated in outcrops of the Oman Mountains to describe the Dhruma Formation. Lithofacies types were grouped into four lithofacies associations reflecting the various subenvironments across the carbonate ramp setting. The correlation of cycles throughout North and Central Oman (which will be discussed in a forthcoming paper), indicates deposition of the Dhruma Formation on a vastly extensive, epeiric carbonate ramp with a
very gentle slope. Such a setting does not correspond to standard carbonate ramp models, but follows the Irwin (1965) model with three zones: X (low-energy, distal environment), Y (high-energy environment) and Z (proximal, low-energy environment). Deposits from outcrops of the Oman Mountains range from a peritidal environment to a ‘lagoonal’ setting of low-energy Zone Z to a ‘shoal-like’ setting of high-energy Zone Y. Lithofacies, supported by biofacies data suggest that predominantly restricted, lagoonal conditions in the lower parts of the Dhruma Formation give way to increasingly open marine conditions towards the top of the formation. Outcrop data reveal two unconformities within the studies succession:

• Mafrac-Dhruma boundary, probably of Bajocian age.
• Jurassic-Cretaceous boundary of Tithonian age.

High-energy peloidal and oolitic grainstones form potential reservoir facies. However, the Dhruma Formation grainstone outcrops do not show preserved pore spaces.

1D sequence stratigraphy

Since only deposits of Zone Y and Z are present in outcrops of the Oman Mountains, high-energy deposits (often grainstones) represent the most distal facies and thus are interpreted as zones of maximum flooding, while low-energy deposits of Zone Z contain cycle-boundaries.

To identify different levels of cyclicity, several cycle indicators were utilized.

Several semi-quantitative sequence-stratigraphic methods were used to unravel the multifold cyclicity of the Dhruma Formation (e.g. facies stacking pattern plots, facies percentage, bed-thickness and bio-component diversity plots). The quantitative analysis of grainstone-thickness indicates an increase in accommodation space towards the top of the formation. Trends in bio-component diversity show increasing biodiversity towards the maximum flooding of each high-frequency sequence, also an overall increase towards the top of the formation, indicating increasing open marine conditions.

Consequently, the Dhruma Formation shows a distinct transgressive dominated cyclicity. It is possible that for two levels of cyclicity orbital forcing (Milanković signal) might be the controlling factor, based on age constraints provided by bio- and chronostratigraphy:

• Cycles – metre-scale: Four types of cycles were identified, ranging from peritidal, to low-energy, medium-energy and high-energy cycles; each covering a time span of ca 100 000 years.
• Cycle sets – metre to decametre-scale: Typically three to four cycles stack into one cycle set. They are subdivided according to depositional energy in low-, medium- and high-energy cycle sets. Each covers a time span of ca 400 000 years.
• High-frequency sequences – several decametre-scale: Typically three cycle sets form one high-frequency sequence. They cover a time span of ca 1 000 000 years and appear to be the controlling factor for alternation of deposits of Zone Y and Z.
• Composite Sequences – decametre to hectometre-scale: Three high-frequency sequences form one composite sequence which covers a time span of ca 3-25 Myr.

The outcrop data presented here form excellent analogues for the subsurface portions of the Dhruma Formation in North and Central Oman, as will be documented in a separate paper. Moreover, the general patterns found (i) in overall facies distribution, (ii) in the highly systematic hierarchy of cyclicity, as well as the partly newly developed semi-quantitative methods of analysis may be useful in better understanding epeiric carbonate ramp depositional systems elsewhere on the Arabian Plate and beyond.

ACKNOWLEDGEMENTS

As part of an extra-mural research project of the University of Tübingen and Petroleum Development Oman (PDO) we would like to thank PDO for their financial support and D. Sim, C. de Oliveira Neves, J.-M. Dawans, G. de Al-Aswad, A. Al-Farqani, H. Jansen, J. Moss and G. Machado for their assistance. PDO and the Ministry of Oil and Gas of Oman are thanked for permission to publish the paper and we are grateful to our SedGeo members of the University of Tübingen: D. Bendias (now ENI), M. Obermaier (now Shell), J. Schonwald and I. Reckinger are thanked for an exceptional time in the field. A. Petrovic, M. Warnecke for an exceptional time in the office. P. Jeisecke is thanked for the preparation of thin sections and S. Packer for biostratigraphic analyses of the thin sections. Shuram Oil and Gas is acknowledged for fieldwork logistics. We are very grateful to ALT Luxembourg for providing access to WellCAD software packages.

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