Article

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**The geology of Khuff outcrop analogues in the United Arab Emirates**

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## ABSTRACT

A revision of the stratigraphy of late Paleozoic and early Mesozoic carbonates (Bih Formation) in the Musandam Mountains near Ras Al Khaimah, United Arab Emirates (UAE), clarifies the presence of deposits that are age-equivalent to the Late Permian and Early Triassic Khuff Formation. Biostratigraphic markers including benthic foraminifera and calcareous algae indicate a Permian age for the stratigraphically oldest outcrops ranging from late Wuchiapingian to late Changhsingian (K4 and K3 reservoir units in the subsurface). A late Induan – early Olenekian (Early Triassic) age is documented for the stratigraphically youngest outcrops. Sedimentological features, stacking patterns and microfacies of the Permian outcrops show strong affinity to the KS3 and KS2 Khuff sequences, dominated by high-energy bioclastic pack- and grainstone. The depositional environment of the Bih Formation is further characterised by a palynological evaluation of claystones and by XRD analysis of clay minerals. Spectral gamma-ray data from the outcrop, which indicate Uranium depletion following the extinction of Permian foraminifera, help to pinpoint the position of the Permian – Triassic boundary and to correlate the measured section with the subsurface. Some stratigraphic intervals in outcrop are affected by strong secondary dolomitisation and do not reflect the same diagenetic patterns as their subsurface counterparts. Patterns of secondary dolomitisation, however, indicate the flow of formation water and thus mimic pore-fluid flow in the subsurface reservoirs. The depositional facies show clear resemblances to the reservoir facies, and the studied outcrops most likely represent the best analogue to the Khuff reservoirs in the UAE and in the North Dome / South Pars field area offshore Qatar and Iran.

## INTRODUCTION

The Permian – Lower Triassic Khuff Formation in the Middle East contains some of the World's largest gas accumulations. In these predominantly carbonate and evaporite deposits exploration has been difficult due to the sub-seismic resolution of reservoir-prone intervals, while gas production is challenged by heterogeneity due to facies variations, dolomitisation, cementation and fracturing (Konert et al., 2001). To better predict the heterogeneities in the various Khuff reservoirs several studies have been carried out using cores from subsurface gas fields as well as outcrop analogues (Figure 1). Published reservoir studies include the South Pars area in Iran (Insalaco et al., 2006), the Ghawar field in Saudi Arabia (Dasgupta et al., 2001) and the subsurface of Interior Oman

(Osterloff et al., 2004). Outcrop studies include the classical sections near Khuff town in Saudi Arabia (Figure 1, locations 1–3: Vaslet et al., 2005), interior Oman (4: Angiolini et al., 2003, 2004), northern Oman (5: Richoz 2006; 6–8: Montenat et al., 1976; Weidlich and Bernecker, 2003) and the Zagros Mountains (9–11: Szabo and Kheradpir, 1978; Insalaco et al., 2006).

Despite current advances in the study of facies associations in the Khuff Formation there is still a lack of understanding in the overall distribution of facies belts, biostratigraphy, diagenetic patterns and log response (Al-Jallal, 1994). In part this is due to the limited number of reservoir studies compared to Jurassic and Cretaceous reservoirs of the region. Furthermore, outcrops of formations, which are age-equivalent to the Khuff reservoirs do not necessarily reflect the subsurface facies and composition. The classical outcrops near Khuff in Saudi Arabia, for instance, are more proximal to the shoreline with an increased clastic input (Vaslet et al., 2005). The outcrops of interior Oman show progressive truncation southwards and increased hiatuses (Angiolini et al., 2004; Osterloff et al., 2004), while those onshore Iran comprise more open-marine facies compared to the shelf facies associated with Khuff reservoirs in the North Field area (Insalaco et al., 2006).

In an attempt to find a better outcrop equivalent to Khuff reservoirs, the Upper Permian – Lower Triassic outcrops of the Musandam Peninsula (orange rectangle in Figure 1) have been studied, and the results are presented in this paper. A Permian age for the carbonates carbonates in this area (Bih and Hagil Formations) was originally proposed by Lees (1928) and later confirmed by Hudson (1960) on the basis of foraminifera. Despite being possible age-equivalents to the Khuff Formation, these outcrops have so far attracted little interest among petroleum geologists. Recently, the age of Permian and Triassic formations of the Musandam Peninsula has been reviewed, and the Bih Formation was found to be partly time-equivalent to the Upper Khuff Formation (Maurer et al., 2008).

In this study the main outcrop locations of Permian carbonates in Musandam are introduced. This is followed by a detailed foraminiferal biostratigraphy and a description of the dominant facies encountered in outcrop and confirmed in thin-sections. Furthermore, results on spectral gamma ray measurements are presented and compared with clay mineralogy quantified by XRD. A correlation of the outcrop with subsurface equivalents is then proposed. We anticipate that the studied section represents one of the best available outcrop analogues to the Upper Khuff reservoirs. In addition to the geological similarity, these outcrops near Ras Al Khaimah are easily accessible.

## DATA AND METHODS

A lithological log with scale 1:100 has been compiled for the entire Bih Formation in Wadi Shahha including lithology, carbonate textures, macrofossils and sedimentary structures. The line of section is indicated in Figure 3, the log itself is illustrated in Figure 4. Along the logged section a sample for microfacies and biostratigraphic analysis has been taken every 2–3 m. In total, 210 thin sections have been produced of which approximately one third derives from the Permian and two thirds come from the presumed Early Triassic interval of the studied section.

Selected clay layers were sampled for X-ray diffraction analysis. Fresh samples from 10 cm below the surface were obtained in order to avoid surface contamination. Samples were powdered and the clay fraction (< 4 µm) was subsequently analysed using a Philips PW1730 Generator with copper anode tube and a Philips PW1050 Goniometer with graphite monochromator. The samples were measured between 2° and 60° 2Θ (theta) with a step size of 0.05°/sec using X-ray radiation from the copper anode at 35 kV and 30 mA. Mineral compositions were interpreted from diffractograms by X-ray Mineral Services (UK).

Gamma-ray radiation was measured in the lower part of the outcrop using a hand-held gamma ray spectrometer (model GRS 2000 by GF Instruments, Czech Republic). This device is equipped with a 3x3" NaI(Tl) detector that collects natural gamma radiation at the rock surface with a sampling depth ranging between 30 to 60 cm depending on the density of the formation. The radiation was measured in one-meter intervals, producing separate logs for emitted Uranium (U), Thorium (Th) and Potassium (K), as well as a bulk gamma ray log. Each measurement was performed for a duration of three minutes which is necessary to obtain a statistically reproducible result with a standard deviation of < 0.4 for U, < 0.4 for Th and < 0.08 for K spectra (e.g. Lüning et al., 2004). The concentrations of the various elements are calculated automatically by the spectrometer and are given in % units for K and in ppm for Th and U. To convert the data to API units, and to get an approximation to standard API gamma ray measurements in the subsurface, the following formula is used:

$$\text{API value} = K \times 13.078 + U \times 5.675 + Th \times 2.494$$

The preparation of palynomorph samples was carried out using a combination of several standard procedures (Faegri & Iversen, 1975; Doher, 1980; Heusser & Stock, 1984; Wood et al., 1996). Samples were crushed, and the power was treated in both hydrochloric acid (37%) and in hydrofluoric acid (50 %) to remove carbonate and siliciclastic sediment, respectively. After the neutralisation of the acid solution, a heavy liquid (saturated zinc chloride – $ZnCl_2$) was added to separate organic matter from heavy minerals. The residue was sieved in a 10 micron mesh sieve, mounted by strewing onto cover slips, dried and then glued onto a slide. The palynological slides were analysed by transmitted light microscopy, commonly with 40x dry and 100x oil immersion magnification. The thermal alteration index of the organic material has been estimated through the visual comparison of sporomorph colours to Munsell colour standards, using a five point scale ranging from 1 to 5 (Dow, 1977; Staplin, 1982; Utting et al., 1989).

## GEOLOGICAL SETTING AND STUDIED OUTCROPS

The Musandam Mountains (Ru'us Al Jibal) form the northern extension of the Oman Mountains and occupy the entire Musandam Peninsula. They comprise Permo-Mesozoic shallow-water carbonates that were deposited on the northeastern margin of the Arabian Plate. The approximately 3,000 m thick sedimentary succession was detached from the basement during the emplacement of the Semail ophiolites in the Cretaceous (Glennie et al., 1974). Culmination of thrusting in the Musandam area occurred during the mid-Tertiary and resulted in the present-day arrangement of thrust sheets that build up the peninsula (Searle, 1988).

Outcrops of the Upper Permian to Lower Triassic carbonates (Bih Formation) occur in both, the western and eastern part of the Musandam Peninsula. In Omani Musandam steep-dipping beds of the Bih Formation are present along the rocky coastline of the Gulf of Oman at Ras Haffah 15 km north of Dibba. More accessible outcrops are found on the western side of Musandam in the Emirate of Ras Al Khaimah. Hudson et al. (1954) first described the structural geology of this area and recognised that the Permian formations are located at the center of two N-S striking anticlines in the Wadi Bih area: the Jebel Hagab and Jebel Yabana anticlines (Figures 2, 3a-b).

Although the Bih Formation is outcropping in both anticlines, tectonic overprint and stratigraphic range vary between the two locations. Along the Jebel Hagab anticline, which extends from the entry of Wadi Bih to the eastern side of Wadi Hagil, steeply dipping grey dolostone of the Bih Formation shows frequent shearing parallel and subparallel to the bedding planes. In contrast, beds of the same formation exposed on the eastern limb of the Yabana anticline along the east side of Wadi Shahha suggest minor tectonic deformation. The difference in the stratigraphic range between the two locations can be assessed by correlation of an ubiquitous white marker horizon within the Bih Formation (Figure 3). This horizon is composed of a porcelaneous weathering, dolomitic mudstone, which frequently changes laterally into an intraformational tectonic breccia (hence called “mid-Bih breccia horizon” in Maurer et al., 2008, and “Bih Formation white marker bed” in Ellison et al., 2006; Figure 3e-f). In Wadi Hagil this marker bed occurs just a few tens of meters above the stratigraphically oldest outcropping beds. In contrast, the stratigraphic thickness below the breccia reaches 200 m in Wadi Shahha (compare Figure 3c and 3d, stratigraphic range on Figure 5).

Due to the larger stratigraphic range and smaller tectonic deformation the outcrops in Wadi Shahha were selected for this study. The described outcrops are located in a small side-valley east of Wadi Shahha where the beds are dipping approximately 15º towards east (Figure 3b). The stratigraphically lowermost 35 m of the formation were logged starting at GPS point 25º 50' 59.1" N / 56º 6' 36.2" E, and the measured section was then continued further south at 25º 50' 45.5" N / 56º 6' 35.6" E (line of section indicated on Figure 3b). The logging ended at the top of the Bih Formation at point 25º 50' 43.3" N / 56º 7' 4.9" E on the crest that separates Wadi Shahha from Wadi Ghabbas. The Bih Formation reaches a total thickness of 560 m in the study area of which the lower 450 m are illustrated in Figure 4.

In the lower part of the measured section dark-grey intervals in outcrop are composed of meter-bedded dolomitic pack- and grainstone that occasionally show internal low-angle cross bedding (e.g. 60-88 m interval in Figure 4). Higher up in the section (from 168 m onwards) the same lithology is characterised by a brownish weathering in the field. Light grey to porcelaneous weathering dolostones are commonly cm-dm bedded wacke- and mudstones with occasional laminations. The mid-Bih marker horizon, present from 218 to 226 m in the studied section, is a brecciated interval that contains clasts from both types of lithology (Figure 3e). From this breccia level to the top of the Bih Formation, lithologies similar to the lower part of the section are present. The interval from 432 to 448 m is richer in clay compared to the rest of the formation (Figure 4c) and represents the uppermost interval of the "Bih Formation thin bedded member" of Ellison et al (2006). Different types of facies have been identified in the Bih Formation based on microfacies analysis (color-coded in the texture column on the left of the measured section in Figure 4) and are described below.

In the measured section indicated on Figure 4, the mid-Bih marker horizon above the 220 m level is not representing the true stratigraphic thickness. The porcelaneous weathering portion of the breccia interval, visible as white marker bed from afar, is around 6 m thick, and breccias even occur as far as 9 meters further down in the section as well as in a smaller breccia layer from 206 to 208 m. In contrast, on the east slope of Wadi Hagil the breccia in the marker bed reaches a maximum of 10 m in thickness and the lower breccia layer is not present. In one outcrop in Wadi Hagil the marker horizon can be observed in its original stratigraphic thickness, where it is composed of a 4 m thick interval of cm-bedded porcelaneous dolomudstone (Figure 3f). This interval conformably overlies dark grey, entirely recrystallised dolostone, which according to our correlation is equivalent to the 208-211 m interval in Wadi Shahha. The changing thickness of the mid-Bih marker breccia and its absence in some outcrops points at a tectonic origin of the breccias. The degree of deformation of this stratigraphic interval does not seem to be related to the proximity of nearby thrusts. In Wadi Hagil, for instance, where the main thrust horizon above the Hagil window is just an estimated 50-100 m below the mid-Bih marker horizon, there are still outcrops with undisturbed stratigraphy (i.e. lack of breccia) present across the marker horizon.

## BIOSTRATIGRAPHY

### Stratigraphic Range of the Khuff Formation

In order to better compare the age of the studied outcrops with the main reservoir units in the subsurface, previous work on biostratigraphy and stratigraphic subdivision of the Khuff Formation is briefly summarised in this chapter.

Sedimentation of the Khuff carbonates and clastics started diachronuously across the Arabian Plate with onset of sedimentation onto the pre-Khuff unconformity ranging from the Murgabian (= Wordian; Angiolini et al., 1998) to the late Midian (= Capitanian; Vachard et al., 2005). A widespread flooding of the entire area is assumed for the Wordian, which led to the deposition of the Lower Khuff Formation holding the K7-K5 Khuff reservoir units (Sharland et al., 2001). After a widespread regression and evaporation in the late Midian ('Middle Anhydrite' interval), sedimentation resumed in the Djulfian (= Wuchapingian) with the deposition of the Upper Khuff Formation throughout the Late Permian (= Lopingian; K4 and K3 reservoirs) and Induan (Early Triassic K2 and K1 reservoir units; Insalaco et al., 2006).

The Triassic part of the Upper Khuff Formation (sequences KS2 and KS1) is biostratigraphically not well constrained due to poor biodiversity following the Permian mass extinction. As a result, the stratigraphic top of the formation interpreted either to be late Induan in age (Sharland et al., 2001) or to be approximately equivalent to the Induan-Olenekian boundary (Insalaco et al., 2006). In this study the stratigraphic scheme proposed by Insalaco et al (2006) is used to compare the stratigraphic range of the Bih Formation with that of the Khuff Formation in the subsurface (Figure 5).

### Foraminifera

Species of both Permian and Triassic age have been encountered in the studied section. The Upper Permian interval, reaching from the base until the 170-180 m interval, is characterised by an abundant and diversified foraminiferal assemblage (Figure 4). All along the succession, the foraminifera are generally well preserved even if the miliolids can sometimes be highly recrystallised.

The microfauna is mainly represented by the orders Milioida and Fusulinida. The former mostly corresponds to the family Hemigordiopsidae with taxa referable to the genera *Neodiscopsis*, *Hemigordius*, *Midiella* as well the large *Glomomidiellopsis*. The following species have been identified: *Neodiscopsis* specialis (Plates 1.1, 1.2, 1.11, 1.12, 1.20, 1.25, 1.26 and 2.10), Hemigordius cf. longus (Plates 1.4, 1.13 and 1.14), Midiella sp. (Plates 1.5, 1.16 and 1.22) and Glomomidiellopsis uenoi (Plates 2.12 and 2.13). A few representatives of the family Cornuspiridae are identified such as Agathammina cf. rosella (Plate 1.7) and Hemigordiellina cf. regularis (Plate 1.8 left). Miliolids are porcelaneous foraminifers, which had flourished in the Tethyan Realm in the Middle and Late Permian (= Guadalupian and Lopingian; Altiner et al., 2003). The hemigordiopsids, generally considered as generalist/opportunist taxa, are very abundant in the studied material. Their palaeobiogeographic distribution is confined to the western Tethyan area, including Italy, Hungary, former-Yugoslavia, Bulgaria, Austria, Turkey and Iran (Rettori, 1995).

The fusulinid foraminifers in the Bih Formation are especially represented by the family Biseriamminidae, a group of non-fusulinoidean fusulinids. However, few genera of true fusulinoidean fusulinids also occur. They belong to the family Staffellidae and are Sphaerulina and Nankinella. The Fusulinida, more abundant and diversified comparing to the Miliolida, are characterised by Globivalvulinidae and subordinate Staffellidae. Among the Globivalvulinidae we identified Paradagmarita zaninettiae (Plate 1.8 right), P. monodi (Plate 1.29), Paraglobivalvulina mira (Plate 1.15), Paremiratella robusta (Plates 2.1 and 2.5), Paradagmacrusta callosa (Plates 2.2 and 2.3), Globivalvulina vonderschmitti (Plates 2.4 and 2.14), G. parascaphoidea (Plate 2.11), Septoglobivalvulina distensa (Plate 1.3), Siphoglobivalvulina fortis (Plates 2.6 and 2.7 right), S. cf. baudi (Plate 2.19), Louisettita elegantissima (Plates 2.22 and 2.23), L. ultima (Plate 2.24 centre) and Retroseptellina decrouezae (Plate 2.20). The only species referable to Staffellidae are Sphaerulina croatica (Plates 1.9, 1.18 and 1.27), Nankinella minor (Plates 1.10 and 1.28) and Staffella sp. (Plate 2.7 left). A few representatives of Earlandia ex gr. minor (Earlandiidae) also occur (Plate 1.6).

The lagenid foraminifers are relatively rare in the Bih Formation, with a low number of species and individuals. Nevertheless, Pachyphloia schwageri (Plate 2.8), Ichthyolaria sp., Rectostipulina pentacamerata (Plate 1.17) and Nodosinelloides cf. caucasica (Plate 2.21) have been recorded while primitive Colaniella are absent. The lagenids are diverse and usually abundant in inner to middle neritic environments throughout the Tethyan region as well as at the northern higher palaeolatitudes in the Late Permian (Groves et al., 2003).

Among the foraminifera, biostratigraphic markers have been recognised that allow assigning the Permian portion of the Bih Formation to the Lopingian (Wuchiapingian-Changhsingian) time interval. The continuous presence, in addition to the diversification and the abundance, of the representatives of the sub-family Paradagmaritinae (Gaillot and Vachard 2007) in the Permian part of the stratigraphic section allows us to refer this interval to the Paradagmarita Zone, considered to be uppermost Djulfian to Dorashamian (= Wuchiapingian-Changhsingian) in age (Altiner and Özgül, 2001; Ünal et al., 2003). This time interval is also in agreement with the compiled biostratigraphic and chronostratigraphic table proposed by Vachard et al. (2002) for the Middle-Late Permian.

The absence of large and morphologically complex keriothecal fusulinids attributed to Schwagerinids and Neoschwagerinids is also emphasised along this interval, confirming its Lopingian age. The initial decline of these families matches with the end-Guadalupian extinction event which gets rid of all their representatives (Sheng, 1992). Insalaco et al. (2006) refer the occurrence of the "*Paradagmarita* bloom", during the Lopingian, just above the Wuchapingian-Changhsingian boundary. This boundary corresponds to the sequence boundary between KS4 and KS3 cycles from Insalaco et al. (2006; see Figure 5). Therefore the studied Permian outcrops of the Bih Formation are equivalent to the KS3 and lower part of KS2 sequence and thus time-equivalent to the K3 Khuff reservoir interval (= Khuff B in Saudi Arabia).

The last occurrence of Permian fauna was recorded at the 168 m-level. After this level age-diagnostic foraminifera are absent and only reappear at the 403 m-level, more than 200 m higher in the section. At this level an association of *Hoyenella sinensis* and *Meandrospira pusilla* has been found (Figure 4). Morphotypes and association of these foraminifera indicate a Late Induan to Olenekian age. Typical Early Induan disaster species such as "*Cornuspira*" *mahajeri* and *Rectocornuspira kahlori* have not been found in the section probably due to the invasive dolomitisation in this stratigraphic interval. In general, foraminifera are much more abundant in the Permian interval with their presence in over 60% of the thin sections. In contrast, only 5% of thin sections studied from the Triassic interval yield foraminifera.

The encountered foraminifera allow to characterise the depositional environment s where the Permian interval of the Bih Formation was deposited. Shallow water biota of reduced diversity, but commonly with high number of individuals, such as miliolid and other ubiquitous foraminifers, are indicative of flat platform top within the euphotic zone. In our context, it was probably an inner ramp s.s. or a lagoon, less connected with the open ocean, on which large variation in salinity and temperature occurred. By contrast, biseriaminid as well as staffellid foraminifers point to a well-oxygenated tidal sandwave complex. Low-diverse assemblages with *Paraglobivalvulina*, *Paradagmarita* and *Louisettita* for instance, denote possible connection with more distal environments. Similar depositional settings for the encountered species have been described by Insalaco et al. (2006) and Gaillot and Vachard (2007).

## Calcareous Algae

Calcareous algae are quite frequent and diversified throughout the Bih Formation. Although often recrystallised, some specimens principally of Gymnocodiaceae and Dasycladaceae could be identified, such as *Gymnocodium* *bellerophontis* (Plate 1.21), *Mizzia cornuta* (Plate 1.19), *M. yabei* (Plates 2.15 and 2.16), *Permocalculus plumosus* (Plate 2.9), *P. digitatus* (Plates 2.24 and 2.25) and *Eogoniolina*? sp. (Plates 1.23 and 1.24). They are particularly abundant in the lower part of the Bih Formation in the 120–160 m level, corroborating the Permian age of this interval along with the foraminiferal associations.

Calcareous algae are frequently present in quiet, well oxygenated shallow meadows, and often transported and slightly reworked into the transgressive deposits. They are rare in the mud-dominates facies of a lagoon belt, behind a shoal. In the studied succession *Mizzia* and *Permocalculus* are particularly abundant in the transgressive sands. They are found from the tidal, mixed flats to the inner shoal including the lagoon and the tidal channels. *Gymnocodium* preferentially occur in the open shoal.

We remark that the algal association of the Bih Formation is very different from that of the Late Permian, Djulfian (= Wuchapingian) from the Batain Plain (East Oman; Vachard et al., 2001). This supports the hypothesis of these authors and Pillevuit (1993) that, during the Midian (= Wordian *p.p.*–Capitanian) and subsequent periods, the palaeogeography of Oman consisted of different provinces. They are, from south to north: Huqf-Haushi, Batain Plain and Oman Mountains. The algal association of the Bih Formation of the Musandam Peninsula seems to belong to the Huqf-Haushi province, which is, however, limited to outcrops of Wordian age (Angiolini et al., 2004).

## Palynomorphs and Palynofacies

Six samples were collected for palynological analysis from claystones and clay-rich carbonate levels along the section (Table 1). Due to scarcity and poor preservation of organic matter, only three claystone samples (P30, P31 and P34) were palynologically productive, while the others contain variable amounts of finely dispersed organic debris and woody fragments with rare sporomorphs ~5%). Preservation of palynomorphs is fair to poor with corrosion attributed to oxidation processes and to biological degradation.

Table 1: Palynosamples and their content

| Sample nr. | Level (m) | Palynomorphs and associated organic matter |
|---|---|---|
| P30 | 93.5 | *Leiotriletes ulutus, Leiotriletes blairatholensis*, *Lophotriletes novicus*, *Cycadopites follicularis, Cycadopites* sp.; undetermined bisaccates. Palynofacies: fungal hyphae (55%); equidimensional inertinite (15%): sporomorphs (15%); vitrinite (15%) |
| P31 | 140.0 | *Leiotriletes ulutus, Lophotriletes novicus, Dictyotriletes* sp., undetermined bisaccates. Palynofacies: fungal hyphae |

| | | |
|---|---|---|
| | | (60%); equidimensional inertinite (20%); sporomorphs (10%); vitrinite (10%) |
| P33 | 200.6 | Lophotriletes novicus, Dictyotriletes sp.. Palynofacies: fungal hyphae (60%); equidimensional inertinite (20%); sporomorphs (5%); vitrinite (15%) |
| P34 | 305.5 | Dictyotriletes sp., Calamospora brunneola, Svedrupollenites sp., Laevigatisporites sp., Leiotriletes ulutus, undetermined bisaccates. Palynofacies: algal spores and fungal hyphae (40%), sporomorphs (10%), amorphised phytoclasts (30%), vitrinite (10%), equidimensional inertinite (10%). |
| P35 | 355.0 | Broken and stronghly damaged sporomorphs, mostly represented by smooth small spores of possible algal origin. Palynofacies: groumous–peloidal organic amorphous matter (60%), fungal hyphae (20%), inertinite (18%), sporomorphs (2%). |
| P37 | 435.0 | Dictyotriletes sp., Cycadopites follicularis, *Crinalites sabinensis.* Palynofacies: fungal hyphae (60%); equidimensional inertinite (30%); sporomorphs (5%); vitrinite (10%) |

The palynomorph content is quite similar for all the productive samples dominated by trilete spores and subordinate pollens. The first group is mostly composed of acavatitrilete spores both laevigati such as Calamospora brunneola, Leiotriletes blairatholensis, Leiotriletes ulutus and verrucati such as Lophotriletes novicus. Minor components are murornate as Dictyotriletes sp., and monolete as Laevigatisporites sp.. Pollen are represented by praecolpate as Svedrupollenites sp., monocolpati as the long ranging Cycadopites follicularis and Cycadopites sp., and alete as Crinalites sabinensis. Bisaccate are occasionally present, but frequently broken, corroded and strongly damaged by oxidation processes. Algal spores and filamentous fungal hyphae are commonly present.

The scarcity of the recovered sporomorphs and the absence of good chronostratigraphic markers prevent a detailed subdivision into the substage level. However, the recovered microfloral assemblage indicates a Permian to early Triassic age and thus supports the biostratigraphic interpretation based on foraminifera and calcareous algae. Leiotriletes blairatholensis is known as a Permian spore (Foster, 1975; Raine et al., 2008). So is the trilete spore L. ulutus, which was firstly described by Utting (1994) in the Permian formations of the Sverdrup Basin in assemblage with C. brunneola and C. sabienensis, and later also recorded in the Permian of the southern Kitakami Mountains (NE Japan) in association with C. sabienensis (Yang and Tazawa, 2000). Calamospora brunneola has also been found in Artinskian-Kazanian beds of the Pechora Basin (Virbitskas, 1983). The genus Svedrupollenites and the species C. sabinensis have been firstly described by Utting (1994) from the Permian of the Sverdrup Basin in the Canadian Arctic Archipelago. Lophotriletes novicus has been cited as a

Permian to Triassic trilete spore (Singh, 1964; Zhu et al., 2002; Raine et al., 2008). It is common in the Permian of New Zealand (Crosbie 1985), South Africa (Retallack et al. 2006) and Antarctica (Farabee et al., 1991). Morever, spores of the genera *Calamospora*, *Laevigatosporites* and *Leiotriletes* have been described from the Changhsingian Midhnab Member of the Khuff Formation in Saudi Arabia (Berthelin et al., 2006).

The dominance in the present microflora assemblage of trilete spores with a botanical affinity to ferns (e.g. *Leiotriletes*, *Lophotriletes*, *Laevigatisporites*) could indicate that the parent flora grew on moist soils and possibly developed in a marginal marine setting. A humid, lagoonal palaeoenvironment has also been proposed for fern spores found in the Midhnab Member, where the associated macroflora was found in claystone deposits (Berthelin et al., 2006). In such an environment, the strong degradation and the scarcity of palynomorphs could be attributed to periodic exposure of the sediments during deposition, resulting in oxidation of the organic matter as visible in the studied material.

The palynological assemblage of the Upper Khuff formation and Bih Formation shows marked differences to that described from the clastic sequence of the basal Khuff formation in Saudi Arabia (Stephenson and Filatoff, 2000; Stephenson, 2006). The Lower Permian floras are abundant in taeniate and striate bisaccate pollens and grew in marginal continental areas under arid to semiarid conditions dominated by high plants producing bisaccate pollen. This difference in assemblage and depositional environment between Lower and Upper Khuff palynofloras is most likely attributed to the Permian northward movement of the Arabian Plate towards the equator and its associated change in climate (Al-Fares et al., 1998).

## FACIES AND DEPOSITIONAL SETTING

### Carbonate Facies

The hereafter described facies are listed according to their first occurrence in the section. The description is somewhat biased towards the Permian facies associations because the Triassic interval is more affected by secondary dolomitisation, which makes distinct recognition of microfacies difficult. Along the section a shift in biological composition from algae and foraminifera to a bivalve- and gastropod-dominated fauna is observed. This change occurs rather abruptly at the Permian-Triassic transition and is interpreted as a result of the end-Permian mass extinction.

***Bioturbated Dolomudstone to -Packstone***

**Description:** Throughout the formation this facies is present as cm- to dm-thick, grey weathering dolostone. The gentle dolomitisation preserved the original microfacies, which commonly comprises dolowackestone to -packstone with varying abundance of peloids, dasycladacean algae, miliolid foraminifera and gastropods (Figures 6c, d). Apart from bioturbation bedding features are absent.

**Interpretation:** The microfacies indicates that these sediments were deposited in a moderate to low-energy environment of an open lagoon. This facies is represented in the facies F5 of Insalaco et al. (2006).

***Laminated to Massive Dolomudstone and –Wackestone***

**Description:** Light grey to porcelaneous weathering, cm-thick beds are characteristic for this facies in outcrop. Lamination occurs occasionally, a massive appearance without internal bedding or bioturbation is commonly observed (Figure 6a). In the 433–448 m interval this facies is enriched in clay, accentuating the lamination. This mud-rich microfacies is mostly lacking fossils, and only rarely a poor biota assemblage limited to gastropods is present. Among other intervals in the section, the mid-Bih marker horizon is made up of this facies (Figure 3f). In the middle to upper part of the studied section laminae occasionally show a slight relief similar to layered stromatolites.

**Interpretation:** These dolomudstone and -wackestone were deposited in restricted, low-energy settings of the lagoon and nearshore mudflats (shallow subtidal to intertidal). The occasional stromatolitic appearance suggests that at least part of the lamination is due to the presence of microbial mats. This facies includes facies F6 of Insalaco et al (2006).

***Pisolitic Dolopackstone***

**Description:** This facies was encountered near the base of the section (30.8 m) as a 1–5 cm-thick, reddish bed overlying an irregular bedding plane. Its microscopic fabric is made up of pisoids in a packstone matrix (Figure 6b).

**Interpretation:** The combination of pisoids and reddish weathering of this facies suggests that it is related to subaerial exposure. It therefore represents the shallowest depositional environment among all studied facies. A similar facies was described by Insalaco et al. (2006) for the base of the Upper Dalan Member and interpreted as part of a palaeosoil level.

***Dolopackstone to -Grainstone with Staffelids***

**Description:** Grey to dark brown weathering, dm- to m-thick beds mark this faices in the field. Low-angle cross stratification is commonly arranged as trough cross bedding (Figure 6e). The microfacies is characterised by fusulinid foraminifera belonging to the family Staffellidae (mostly *Nankinella*) associated with peloids and micritised grains (Figure 6f). The degree of dolomitisation ranges from dolomite cement growth in inter- and intraparticle pore space to pervasive dolomitisation with dolomite rhombs entirely replacing the original rock fabric. This facies is most abundant in the 63–86 m interval of the logged section, and represents the darkest weathering color in the field.

**Interpretation**: Bedding characteristics and rock texture point to a high-energy depositional environment for this facies, most likely sand shoals. This interpretation is in agreement with the palaeoecological model of Insalaco et al. (2006), which proposes the highest occurrence of staffellids in shoal deposits. This facies is interpreted to have developed during a major flooding, when wave energy was high enough to remove most mud from the shelf.

***Bioclastic Dolopackstone-Grainstone***

**Description:** This facies is particularly abundant in the 120–150 m interval and is macroscopically easily identifiable in the field due to its coarse-grained character. Single beds are dm- to m-thick and often erode into the underlying sediment (Figure 6g). The microfacies shows the highest biodiversity among all studied facies, reflected by the richness of various types of foraminifera and calcareous algae (Figure 6h). Among the foraminifera fusulinids belonging to the family Globivalvulinidae are most frequent. Peloids and skeletal cyanobacteria (i.e. *Cayeuxia*) are subordinately present.

**Interpretation:** The coarse-grained texture and biodiversity of this facies indicate that these sediments were deposited in moderate to high-energy settings, most likely in leeward shoals of an open lagoon, as storm deposits and perhaps channelised tidal flat deposits. This facies resembles facies F8 of Insalaco et al. (2006).

***Oolitic Dolograinstone***

**Description:** This dolograinstone dominates the 170–200 m interval, forming dm- to m-thick cross-bedded dolostone beds (Figure 7a). This facies is identified from afar as a brownish weathering, massive-appearing interval in the section. Intensive dolomitisation largely obliterated the microfacies. Where the original texture is preserved, ooids are recognised as round grains with relics of internal layering, and are associated with broken and well-rounded gastropod and bivalve shell fragments (Figure 7b). Bedding and sedimentological features are very similar in the entirely dolomitised interval 0–20 m of the studied section, and that interval might therefore bear the same facies.

**Interpretation:** High-energy sand shoals facing the outer shelf are the most likely depositional environment of this facies. In seismic these shoals sometimes show progradational geometries (e.g. Yibal Field, Masaferro et al. 2004). Facies F9 and possibly F16 of Insalaco et al. (2006) are similar to this facies.

***Thrombolitic Doloboundstone***

**Description:** This facies is limited to a single stratigraphic occurrence of a 5–20 cm-thick boundstone interval which is observed in both Wadi Hagil and Wadi Shahha. In the latter location it occurs at the 181.7 m level in the logged section and is identified by its thrombolitic fabric (Figures 7c, d). In thin section, the originally microbial framework is replaced by coarse dolomite crystals, whereas the sediment trapped in the bindstone is preserved as mudstone with rare bivalve and gastropod shells.

**Interpretation:** Macroscopically the thrombolitic texture resembles the F12T facies in Insalaco et al. (2006), which is ubiquitously present in the subsurface at the Permian-Triassic boundary. The origin of this facies is microbial activity that was prolific at the Permian-Triassic boundary and in the lowermost Triassic on Peri-tethyan shelves (Baud et al., 2007; Kershaw et al., 2007).

***Lithoclastic Dolograinstone-Packstone***

**Description:** This facies becomes dominant in coarse-grained carbonates above the 200 m level. Lithoclasts are the primary component and are associated with bivalves and gastropods in varying percentages (Figure 7e). In the field this facies is found in dm-m bedded, often strongly dolomitised beds with grey to brown weathering. Sometimes flat pebbles occur (Figure 7g). Occasionally beds of this facies develop into m-thick layers with internal cross bedding.

**Interpretation:** A high-energy setting with frequent erosion and reworking of sediment is envisaged as depositional environment of this facies. Larger accumulations of this facies have probably taken place in sand shoals. The abundance of lithoclasts in this stratigraphic interval has also been reported from other Lower Triassic formations, and might point at rapid submarine lithification and suppression of bioturbation (Wignall and Twitchett, 1999). This facies is partly comparable to Facies F7 of Insalaco et al. (2006).

***Mollusk Dolorudstone***

**Description:** This facies is limited to cm- to dm-thick beds from 235 m upsection primarily composed of bivalves and sometimes associated with gastropods. Frequently this rudstone forms lumachelle layers within lithoclastic grainstones, or they occur in association with peloids and carbonate mud dispersed between the shell accumulations (Figure 7f). Bivalve shells are often replaced by cement, but the shell shape is preserved due to micritic envelopes.

**Interpretation:** These thin-bedded shell accumulations are interpreted as storm deposits. The micritic envelopes suggest prolonged abidance of shell material at the see floor prior to burial. Partial reworking of sediment is indicated by the presence of early-cemented carbonate mud around some of the shells. Storm lags of bioclastic material have also been described in facies F7 of Insalaco et al. (2006).

## Clay Mineralogy

The occurrence of clays is limited to around a dozen intervals along the studied section. Where observed, they are associated with or bracketed by low-energy mud-and wackestones. They can be followed along the outcrop and they laterally retain a constant thickness. Pie charts of the composition of six clay samples in the Bih Formation are illustrated in Figure 8. X-ray diffraction reveals the presence of various clay minerals and other components in the sediment fraction <4 microns. The minerals quartz, chlorite, kaolinite, illite and mixed-layer clays are considered as detrital components of weathered rocks and soils from the Arabian hinterland. They are common clay minerals in platform carbonates and their distribution may reflect distance to the shore and resedimentation patterns on the platform (Adatte and Rumley, 1984). The presence of chlorite in most samples indicates weathering in hot climate conditions (Chamley, 1989), which is in agreement with previous interpretations of the Late Permian / Early Triassic climate in this region. The horizons with samples dominated by these minerals (from levels 140, 200.6 and 365.5 m) are therefore interpreted as detrital clay layers.

Palygorskite and sepiolite are interpreted as authigenic minerals. These fibrous clays are common constituents of restricted carbonate and evaporite deposits in pre-Miocene successions and form under strong evaporitic conditions in brines dominated by different alkaline elements (Callen, 1984). The samples rich in palygorskite (from levels 93.5, 435 and 550 m) could therefore have been deposited in environments with increased evaporation and salinity. According to Trauth (1977), sepiolite forms by precipitation from Mg-rich sea water in a purely chemical environment and is frequently found in argillaceous carbonates; this lithology is in fact present in the sepiolite-bearing sample from the 435 m level in the section. Palygorskite is more frequent in the transitional zone between purely chemical and detrital clay formation. The interaction between detrital minerals and ionic solutions favours the formation of Al-Mg smectite and palygorskite (Trauth 1977).

Taking the thickness of the Triassic to Cretaceous sedimentary column of Musandam into consideration, the burial depth of the Bih Formation is estimated at 2500–3000 m, which roughly corresponds to the current depth of the gas-bearing Kangan (Khuff) formation along the Qatar Arch (Bashari, 2005) and an associated burial temperature of 60-100° C. Although burial clay alteration (i.e. illitisation) starts at temperatures above 100° C, we cannot rule out that at least part of the illite found in the Bih Formation is of diagenetic origin. Considering the high variability of clay spectra in the analysed samples, we conclude that most of the clay fraction reflects the original mineralogical spectrum at the time of deposition. In our interpretation, the clay mineral assemblage of the Bih Formation thus reflects the hot climate, Mg-rich sea water and restricted evaporitic environment during the deposition of the Khuff carbonates and evaporites.

## Depositional Environments

Based on the distribution of facies and its associated microfauna a conceptual depositional model for the Permian interval of the Bih Formation is proposed (Figure 9). It combines the depositional environments developed during the KS3a and KS3b Khuff sequences, which are as follows:

**Windward shoals:** The over 20 m thick package of dolopackstone-grainstone with staffellids (63–86 m interval) indicates a period of significant shoal development, most likely located on the windward side of an extensive inner shelf. A similar environment is envisaged for the oolithic dolograinstone (from 170 m upsection), and for the dolostone in the lowermost 20 m of the section.

**Open lagoon:** The common presence of bioturbated dolomudstone to -packstone suggests the presence of a large open lagoon behind the windward shoals. This environment was the habitat of dasycladacean algae, miliolids, bivalves and gastropods.

**Restricted lagoon and mudflats:** The scarcity of fauna is indicative for a restricted environment during the deposition of laminated to massive dolomustone. Occasional mudcracks point at intermittent exposure and thus at a more shallow subtidal setting compared to the open lagoon. Intertidal mudflats with microbial mats are at least in part the environment of deposition of the laminated dolomudstone. The influx of clay in this facies suggests proximity to land, and thus places this depositional environment to the innermost part of the shelf, close to a supratidal sabkha. The presence of the clay minerals palygorskite and sepiolite indicates hypersaline conditions within this environment.

**Leeward shoals:** The bioclastic dolopackstone/grainstone facies is commonly interfingering with both open lagoon and restricted lagoonal facies. These sediments are therefore thought to have been deposited in leeward shoals that reach their highest accumulation in a zone roughly between those environments. These shoals hold the highest biodiversity, and yield the biostratigraphically most viable taxa.

The general facies distribution also shows a distribution pattern of the studied foraminifera. The microfaunal assemblage dominated by *Nankinella*, staffelids in association with large representatives of the porcelaneous family Hemigordiopsidae can be referred, as already stated by Insalaco et al. (2006), to the sand-wave shoals and oolithic shoals while the association of Biseriaminidae, large Hemigordiopsidae and the disappearance of staffelids can be referred to the leeward shoals *sensu* Insalaco et al. (2006).

The encountered facies range from shallow subtidal to intertidal settings, while deeper water shelf facies such as in the South Zagros was not recorded in the studied section. It is therefore interpreted that the Musandam area was palaeogeographically situated on a mid- to inner-shelf position, similar to the North Field area offshore Qatar.

## SPECTRAL GAMMA RAY

Gamma-ray radiation is notoriously low in carbonates and thus not as representative for mineralogy as in their siliciclastic counterparts. In the Khuff Formation, standard API gamma-ray logs have been successfully used for correlation of the Permian-Triassic boundary interval, which is characterised by a marked drop in radiation (El-Bishlawy, 1985). As seen in spectral gamma ray data the decrease in radiation from the uppermost Permian to lowermost Triassic strata is caused by loss of Uranium, which in turn is attributed to the reduction of organic matter in the sediment, most likely due to the end-Permian mass extinction (Insalaco et al., 2006; Ehrenberg et al., 2008).

To test the decrease in gamma radiation, spectral gamma ray data were acquired in the 35–190 m level of the studied section in Wadi Shahha (Figure 10). Uranium (U) in carbonates is commonly associated with marine deposits formed under reducing conditions, and thus reflects the amount of organic matter preserved in the sediment. Uranium levels in carbonates also increase with the presence of terrigenous clays. The Uranium log reveals the continuous presence of this element along the section, and illustrates the increased Uranium radiation from facies associated with lagoonal environments, in particular from the laminated to massive dolomudstones. Over most of the measured section the U-content fluctuates between 1 and 6 ppm, while it drops to values consistently at or below 1 ppm from 168 m upsection (Figure 10). This drop coincides with the last occurrence of Permian foraminifera and calcareous algae, and thus points at the extinction event at the Permian-Triassic boundary.

Thorium (Th) is not found in pure lime- and dolostones, and thus any thorium radiation found in carbonates originates from clay mineral impurities. As a result, Thorium peaks are associated with clay layers and nearshore facies in the log, while the high-energy facies (from 62 to 78 m and from 170 m to 180 m) lack Thorium completely (Figure 10). Although the latter intervals are also affected by pervasive dolomitisation, the lack of Thorium is not interpreted as a result of leaching during diagenesis because Thorium represents the least soluble of all radioactive elements.

Potassium (K) is commonly observed in detrital clays and certain evaporites. In the illustrated log the K-concentrations are given in percentages, and therefore seem to have a small contribution to the overall radioactivity (Figure 10). Marked peaks in potassium concentration are associated with levels rich in clay, namely the clay minerals illite and mixed layer illite/smectite identified in the XRD analysis. Some potassium might also derive from remnant traces of dissolved or altered potassium evaporites.

For a better comparison between the collected spectral gamma ray data and published gamma-ray logs from the Khuff Formation in the subsurface, a composite API log was created using the formula given in the section 'Data and Methods'. This log shows that Uranium is the main contributor to the radiation shown on standard API gamma ray logs (Figure 10). The tentative correlation of this API-equivalent log from outcrop with Nasr-7 well from offshore Abu Dhabi indicates similar order of decrease in gamma radiation near the top of the Permian interval. As seen in the spectral gamma ray dataset this decrease goes along with the drop in Uranium, and thus suggests the position of the Permian-Triassic boundary somewhere between levels 166 m and 185 m of the measured section.

## THE PERMIAN–TRIASSIC BOUNDARY INTERVAL

The Permian – Triassic boundary (PTB) marks the most severe marine mass extinction in Earth history, and is often readily identifiable by the disappearance of Palaeozoic fossils in many marine sedimentary rocks straddling this boundary. In the Khuff reservoirs the PTB can be recognised by (1) a sharp shift of Uranium in spectral gamma-ray logs towards lower concentrations as outlined above, (2) the appearance of microbial, commonly thrombolitic carbonate facies, (3) the extinction of Permian fusulinids and miliolids, (4) a positive shift in sulphur isotopes in the Lower Triassic anhydrites, and (5) a shift in carbon isotopes to more negative values above the boundary (Insalaco et al., 2006; Richoz, 2006). Previously, Osterloff et al. (2004) placed the PTB at the first downhole occurrence of Permian microfauna, and thus below the drop-off in radioactivity.

Since evaporites are absent in outcrop, only the first three criteria were used to locate the PTB in Wadi Shahha. Rather than an exact boundary bed we propose a transition interval located between levels 169 m and 186 m in the logged section (Figure 11). The criteria for selecting this interval are as follows:

1. At around 169 m a marked decrease in the bulk-rock uranium content to >1 ppm is observed. From 169 m to the last measured station at 190 m the concentration stays consistently below 1 ppm, while further downsection values between 1 and 6 ppm are common. In the subsurface this uranium drop occurs 3-5 m below the first thrombolites, while in the measured section

this decrease is observed approximately 10 m below a microbial boundstone layer.

2. The only microbial facies with thrombolitic fabric in the entire section is represented by a thrombolitic boundstone at the 181.7 m-level. This facies is bracketed by oolitic grainstones, and thus this interval resembles the facies succession present in the subsurface at the PTB (see Masaferro et al., 2004; Insalaco et al., 2006).
3. Biseriaminidae and Hemigordiopsidae are important and abundant constituents of the bioclastic pack- and grainstone facies in the 100–160 m level. The last sample with representatives of these families occurs at 166.5 m, and no foraminifera are observed further upsection for more than 200 meters. The extinction of foraminifera goes along with the last appearance of Permian calcareous algae.

In contrast to the disappearance of foraminifera and calcareous algae, both gastropods and bivalves are present throughout the transition zone, and the latter are also frequent in the grainstones above the thrombolite layer. The occurrence of these faunas across the PTB is also observed in the subsurface reservoirs, and can be explained by the presence of opportunistic species less sensitive to environmental change.

The identified PTB interval is ubiquitously present in the study area (Wadi Shahha and Wadi Hagil). It has a uniform thickness of around 15 m, does not indicate intraformational erosion and can be discriminated in the field by its brownish weathering (Figure 11). The thrombolite facies is commonly associated with the Permian-Triassic transition, and microbial boundstones at this stratigraphic interval are present in shelf deposits around the Tethys such as Turkey, Iran, Oman and China (Heydari et al., 2000; Angiolini et al., 2007; Baud et al., 2007; Kershaw et al., 2007, and references therein).

## STACKING PATTERNS AND OUTCROP–SUBSURFACE CORRELATION

The limited number of undisturbed outcrops of the Bih Formation in the Musandam Peninsula limits all observation regarding stacking patterns and sequence stratigraphy to the studied section in Wadi Shahha. With this limitation in mind we propose a subdivision of the Permian part of the section in 3rd and 4th order sequences (Figure 12).

The lowermost 30 m are interpreted as equivalent to the KS4c sequence, and thus to the topmost interval of the K4 Khuff reservoir. According to this interpretation the first 20 m of the section are the dolomitised analogue to the uppermost grainstones in the K4 reservoir (see figure 9 in Insalaco et al., 2006) which developed during major flooding of the shelf. Interval 20–30 m is considered as the regressive part of the sequence composed of restricted low-energy mud- and wackestones. The sequence boundary at the top is represented by the pisolitic packstone facies indicating exposure.

The KS3a sequence ranges from the emersion horizon at 30.8 m to the claystone layer at 93.5 m, which again indicates the most proximal environment relative to the shoreline. Lagoonal sediments of the early transgression (31–50 m) are replaced by packstones and grainstones that indicate the most open-marine conditions during maximum accommodation (60–88 m). This sequence' facies composition differs from KS3a in Insalaco et al. (2006, figure 9) in that there are only small packstone and grainstone levels at the zone of maximum accommodation in the subsurface. The thickness of the sequence in outcrop is 63 m against 50 m in South Pars, and thus indicates a higher accommodation rate in Musandam.

Interval 93.5–157 m brackets sequence KS3b of late Changhsingian age, which displays a characteristic alternation of lagoonal sediments and higher-energy bioclastic grainstones (Figure 12). This alternation is arranged in 1–5 m thick, shallowing-upward high-frequency depositional units, whose base is commonly erosional and composed of coarse sands (Figure 6g). The facies distribution and small-scale stacking pattern observed in outcrop is similar to this sequence in the subsurface, and indicative for frequent reworking of sediment as seen in the upper K3 Khuff reservoir (figure 9 in Insalaco et al., 2006). With 63 m thickness this sequence is again thicker than its subsurface counterpart (~52 m), and thus has a similarly higher sedimentation rate as the underlying sequence. The variations in accommodation in sequences KS3a and KS3b are, however, still in the range of thickness variations observed between intrashelf highs and lows in the South Pars field (see figures 46 to 49 in Insalaco et al. 2006).

Sequence KS2 straddles across the Permian-Triassic transition and yields, as already stated in the previous section, high-energy grainstones documenting major flooding of the shelf. The regressive part of the sequence ends with the mudstones forming the mid-Bih white marker bed (Figure 3f; 222-226 m interval in Figure 12). The upper part of the sequence is present as tectonic breccia, and this is probably the reason why the thickness of this sequence (69 m) is so different from the KS2 in the subsurface (42 m; Figure 5; figure 9 of Insalaco et al., 2006). Taking the undisturbed section of Wadi Hagil into account, the thickness of the KS2 in outcrop is 10 to 15 m less than in Wadi Shahha, and thus closer to the sequence thickness in the subsurface.

The sequences KS3a, KS3b and the lower part of KS2 make up the K3 Khuff reservoir in the subsurface. With the upper boundary of the K3 equivalent set at 178 m, and thus a couple of meters below the thrombolite, the whole thickness of this reservoir unit amounts to 147 m. This is an increase of 20% compared to the K3 reservoir thickness of 120 m in the South Pars subsurface (Insalaco et al. 2006), but is within the range of equivalent sections in Interior Oman (Osterloff et al., 2004).

The correlation of the Triassic part of the section with the subsurface proves far more challenging due to the lack of age-diagnostic marker fossils. As illustrated in Figure 13 the interval from 226 m to 385 m might be equivalent to the KS1 sequence. It is subdivided into three 4$^{th}$ order sequences KS1a to KS1c. The lowermost sequence KS1a ends in a poorly outcropping mudstone interval, while both KS1b and KS1c terminate with a claystone layer, pointing at a nearshore depositional settings. Compared to the Permian part of the outcrop the prevalence of lithoclastic and mollusk-rich facies is observed. This facies change is also observed in the North Field area where coarse grainstones rich in flat pebbles are abundant in the upper part of KS2 and in KS1 (Insalaco et al., 2006).

With a range of 160 m the proposed K1 reservoir equivalent is 60% thicker than in the South Pars subsurface. The development of a greater accommodation space compared to the North Dome field area is observed in Abu Dhabi, and would thus support the current interpretation. The future availability of biostratigraphic data for the studied interval could, however, revise the top of the K1 equivalent to a stratigraphically lower level.

The succession above the 385 m level (Bih Formation thin-bedded member *sensu* Ellison et al., 2006) is most likely equivalent to the Sudair in the subsurface. It is characterised by sequences developed during reduced increase in accommodation and yields a foraminiferal assemblage indicative for Late Induan/Early Olenekian age. The overlying Hagil Formation in the study area might in part also be equivalent to the Sudair, as sketched in Figure 5.

Figure 14 illustrates the correlation between the Upper Khuff model section of offshore Fars (figure 9 of Insalaco et al. 2006) and the measured section in Wadi Shahha. For the KS3a, KS3b and KS2 sequences a similar thickness and facies association can be observed between the two locations. Lagoonal facies dominate in the lower KS3a, mixed lagoonal and shoal facies make up sequence KS3b and oolithic grainstones are frequent in KS2. The biodiversity shows similar trends as well, with a higher diversification of faunas in the KS3b compared to KS3a. The correlation of sequences KS1a–KS1c accentuates the difference in thickness between the two locations, as mentioned above. Depositional facies, however, characterised by storm deposits and lithoclastic grainstones, are present in both sections.

Overall the gathered data clarify that the Bih Formation represents a more suitable outcrop analogue to the gas-bearing Khuff formation of the North Dome area and Abu Dhabi compared to previously studied outcrops in Saudi Arabia (Vaslet et al., 2005), the Haushi-Huqf area (Angiolini et al., 2004) and probably also the Saiq Plateau in Oman (Coy, 1997).

## DIAGENETIC OVERPRINT

In contrast to the subsurface, where both lime- and dolostones are present, the Bih Formation is entirely dolomitised. The following observations on dolomitisation are based on the study of thin sections only, and do not have the support of geochemical data. Two principal stages of dolomitisation are identified:

(a) A primary dolomitisation affected the entire sedimentary succession independent from the facies, and is considered as syn- to early post-depositional in nature. Magnesium was most likely enriched in the seawater due to increased evaporation, and led to dolomitisation similarly as observed in modern hot and arid nearshore environments. This interpretation is in agreement with the occurrence of sepiolite which preferentially precipitates from Mg-rich brines (Trauth, 1977). This first stage of dolomitisation was mild in that it preserved the original rock texture and most of the initial porosity.

(b) A secondary dolomitisation occurred during burial diagenesis and affected only packstones and grainstones that had preserved a high intergranular permeability after the first phase of dolomitisation. Sediments belonging to other facies were commonly cemented and compacted before the occurrence of burial dolomitisation. During that process Mg-rich formation waters percolated the permeable sedimentary bodies and led to a partial to complete recrystallisation of the original rock texture. As a result, large dolomite rhombs replace the original sediments and cause the dark weathering of affected beds in outcrop. Larger intervals (> 3 m thickness) affected by this pervasive dolomitisation are indicated in the column 'dolomitisation' on Figures 12 and 13. Only rarely the original texture or fossils can still be identified in these intervals (Figures 7b, h).

The distribution of this later stage of dolomitisation might give insights into the stratigraphic position and geometry of hydrocarbon flow units in the subsurface. In fact, the intervals with pervasive secondary dolomitisation in outcrop are potentially also the most porous and/or permeable units in subsurface reservoirs, because effective permeability is necessary for sufficient percolation of magnesium-rich fluids and subsequent dolomitisation. According to this hypothesis, the most intensively dolomitised intervals (as outlined in Figures 12 and 13) are corresponding to the units with highest potential of storage and/or flow of hydrocarbons in the subsurface. As seen in outcrop, these intervals are the grainstones and packstones in the upper K4, lower K3, uppermost K3, upper part of K2 and smaller intervals in the higher portion of K1 reservoir equivalent.

Next to dolomitisation, rapid early-marine cementation appears widespread in the lower Triassic part of the Bih Formation, and is partly responsible for the abundance of lithoclasts and flat pebbles in this stratigraphic interval also outside of the Khuff depositional realm (Wignall and Twitchett, 1999).

## CONCLUSIONS

The evaluation of the outcrops in the western part of the Musandam Peninsula leads to the following conclusions:

(a) The studied section represents the first illustrated field example, which shows facies and stacking patterns similar to the K3 to K1 reservoirs in the North Dome/South Pars field area. The outcrops are suitable for further work, in particular to study smaller-scale stratigraphic stacking patterns and geobody geometries, a task which is hard to achieve with limited core data from the subsurface.

(b) Diagenetic patterns of secondary dolomitisation follow paths of high porosity and permeability preserved after early diagenesis. This demonstrates the potential that further studies in outcrop may help in understanding diagenetic patterns and the 3D–distribution of storage and flow units in the subsurface on a field to sub-field scale.

(c) Clay mineralogy and palynofacies from the Bih Formation confirm the hot arid environment envisaged for the deposition of the Khuff Formation. The presence of abundant algal and fern spores should be indicative of marginal environments and/or proximity to coastal swamps and ponds where parent plants grew on permanent humid soils.

(d) The Uranium depletion at the PTB coincides with the disappearance of Permian foraminifers and dasyclads at the end-Permian mass extinction. This suggests a direct correlation between Uranium signature and organic matter content in the sediment. Spectral gamma ray might therefore be a useful tool to detect extinction events in carbonate successions straddling the PTB or other geological periods.

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## FIGURE CAPTIONS

**Figure 1:**
Palaeogeography and distribution of main lithofacies across the Arabian Plate during the deposition of the Khuff KS3b sequence of Late Permian (Changhsingian) age. Outcrops of the Khuff Formation and its age-equivalents are known from Saudi Arabia (1-3), Oman (4-8), Iran (9-11) and now from the United Arab Emirates (orange rectangle). This map was compiled using information from Szabo and Kheradpir (1978), Ziegler (2001), Weidlich and Bernecker (2003), Angiolini et al. (2004), Osterloff et al. (2004), Vaslet et al. (2005), Insalaco et al. (2006) , Richoz (2006) and the present study.

**Figure 2:**
Geological map of the study area in the western part of the Musandam Peninsula, Emirate of Ras Al Khaimah (slightly modified from Maurer et al., 2008). Names of major valleys (W. = Wadi) and mountains (J. = Jebel) are indicated. The Permian - Lower Triassic Bih Formation is outcropping along the north-south trending Jebel Hagab and Jebel Yabana anticlines.

**Figure 3:**
Outcrop photographs of the Bih Formation. All white arrows point at the same mid-Bih marker horizon. - **(a)** East side of Wadi Hagil: Bih Formation overlain by Lower to Middle Triassic Hagil and Ghail Formations; **(b)** Study area in a small side wadi east of Wadi Shahha. Dotted lines indicate line of section from the base until the top of the Bih Formation, while numbers are m-levels relative to the bottom. The boundary to the overlying Hagil Formation runs along the crest at the top of the section; **(c)**, **(d)** Comparison between the two outcrop locations: in Wadi Shahha (c) the outcrops cover a larger stratigraphic interval with 200 m of sediment outcropping below the marker bed, whereas in Wadi Hagil (d) the outcrop ends around 30 m below the same marker horizon; **(e)** Close-up view of marker horizon in Wadi Shahha occurring as a tectonic breccia composed of white mudstone and grey crystalline dolomite clasts; **(f)** Same marker bed in Wadi Hagil originally preserved as a 4 m thick interval of porcelaneous mudstone located 50 m east of GPS point 25º 49' 26.7" N / 56º 04' 08.2" E (on the far left of Figure 3a).

**Figure 4:**
(a)–(c) Lithological log of the Bih Formation in Wadi Shahha with carbonate textures on the left of the meter scale and weathering profile, sample numbers and fossils displayed on the right side. Numbers in brackets and italics show meter levels given in figure 5 of Maurer et al. (2008). (d) Key for symbols and facies color code.

**Figure 5:**
Chronostratigraphic framework and sequence stratigraphy of the Khuff Formation in the subsurface on the right compared to the stratigraphic range of the studied Bih Formation of Musandam on the left. Formation and sequence thicknesses in subsurface after Insalaco et al. (2006, figures 3 and 9; for Upper Khuff) and Johannessen et al. (2006; for Sudair). Meter scale for outcrop and feet scale for subsurface are not proportional to each other.

**Plate 1:**
Foraminifers and algae of the Upper Permian (Lopingian) interval of the Bih Formation (the stratigraphic order is respected from 1 to 29). Position of samples (10 digit- numbers) is indicated on Figure 4.
**1-2, 11-12, 20, 25-26** Neodiscopsis specialis (1-2: smp. 0611020900; 11-12: smp. 0611161240; 20: smp. 0611161602; 25-26: smp. 0611170957).
**3** Septoglobivalvulina distensa (smp. 0611020900).
**4, 13-14** Hemigordius cf. longus (4: smp. 0611020900; 13-14: smp. 0611161240).
**5, 16, 22** Midiella sp. (5: smp. 0611020900; 16: smp. 0611161240: 22: smp. 0611161602).
**6** Earlandia ex gr. minor (smp. 0611021514).
**7** Agathammina cf. rosella (smp. 0611021514).
**8 left** Hemigordiellina cf. regularis (smp. 0611021514). **8 right** Paradagmarita

zaninettiae (smp. 0611021514).
**9, 18, 27** Sphaerulina croatica (9: smp. 0611160717; 18: smp. 0611161602; 27: smp. 0611170957).
**10, 28** Nankinella minor (10: smp. 0611021514; 28: smp. 0611170957).
**15** Paraglobivalvulina mira (smp. 0611161240).
**17** Rectostipulina pentacamerata (smp. 0611161240).
**19** Mizzia cornuta (smp. 0611161602).
**21** Gymnocodium bellerophontis (smp. 0611161602).
**23-24** Eogoniolina? sp. (smp. 0611161602).
**29** Paradagmarita cf. monodi (smp. 0611170957).

**Plate 2:**
Foraminifers and algae of the Upper Permian (Lopingian) interval of the Bih Formation
(the stratigraphic order is respected from 1 to 25). Position of samples (10 digit-numbers) is indicated on Figure 4.
**1, 5** Paremiratella robusta (smp. 0611170957).
**2-3** Paradagmacrusta callosa (smp. 0611170957).
**4, 14** Globivalvulina vonderschmitti (4: smp. 0611170957; 14: smp. 0611171255).
**6-7 right** Siphoglobivalvulina fortis (smp. 0611170957).
**7 left** Staffella sp. (smp. 0611170957).
**8** Pachyphloia schwageri (smp. 0611170957).
**9** Permocalculus plumosus (smp. 0611170957).
**10** Neodiscopsis specialis (two individuals; smp. 0611171255).
**11** Globivalvulina parascaphoidea (smp. 0611171255).
**12-13** Glomomidiellopsis uenoi (smp. 0611171255).
**15-16** Mizzia yabei (smp. 0611171255).
**17-18, 26** Undetermined Gymnocodiaceae (17-18: smp. 0611171255; 26: smp. 0611171439).
**19** Siphoglobivalvulina cf. baudi (smp. 0611171439).
**20** Retroseptellina decrouezae (smp. 0611171439).
**21** Nodosinelloides cf. caucasica (smp. 0611171439).
**22-23** Louisettita elegantissima (smp. 0611171439).
**24** Louisettita ultima (centre; smp. 0611171439).
**24-25** Permocalculus digitatus (smp. 0611171439; 24: around L. ultima)

**Figure 6:**
Facies of the Bih Formation – **(a)** laminated mudstone, 392 m level; **(b)** pisolitic packstone, 30.8 m level (smp. 0612211657); **(c)** dasycladacean wackestone, 165.5 m level (smp. 0611171551); **(d)** peloidal foraminiferal packstone with Neodiscopsis, 40.7 m level (smp. 0611020900); **(e)** dolomitised pack-grainstone with through cross–bedding, 53 m level; **(f)** dolomitised grainstone with staffelids and peloids, 66.5 m level (smp. 0611160717); **(g)** coarse bioclastic grainstone eroding into underlying sediment, 123 m level; **(h)** bioclastic grainstone illustrating diversity in Permian foraminifera, 137.9 m level (smp. 0611170957). Scale bar is 2 mm in all photomicrographs.

**Figure 7:**
Facies of the Bih Formation – **(a)** dolomitised oolitic grainstone with bi–directional cross–bedding, 195 m level; **(b)** grainstone with ghosts of ooids, gastropods and bivalve fragments, 170.7 m level (smp. 0611181243); **(c)** 8 cm thick thrombolitic boundstone in outcrop, 181.7 m level; **(d)** polished slab of boundstone showing microbial–thrombolitic texture, 181.7 m level (illustrated area is 5 cm wide) ; **(e)** lithoclastic grainstone with minor percentage of bivalve shells, 247 m level (smp. 0611301725); **(f)** mollusk rudstone with micritised bivalve shells and peloids, 303 m level (0612011340); **(g)** lithoclastic rudstone with flat pebbles, 336.7 m level; **(h)** recrystallised dolostones with Lower Triassic foraminifer *Hoyenella sinensis*, 496 m level (0604031227); note that original carbonate texture is entirely destroyed by dolomitisation while tests of foraminifera are still preserved. Scale bar is 2 mm in all photomicrographs.

**Figure 8:**
Pie charts showing the composition of the clay fraction of claystones from the following levels in the studied section: **(a)** 93.5 m; **(b)** 140 m; **(c)** 200.6 m; **(d)** 385.5 m; **(e)** 435 m; **(f)** Bih/Hagil contact at 550 m.

**Figure 9:**
Conceptual facies model for the Late Permian shelf in the Musandam area (sequences KS3a and KS3b). Colors correspond to the facies color code outlined in Figure 4d.

**Figure 10:**
Spectral gamma ray logs for U, Th, K from the 35–190 m level of the studied section (on the left). Its composite signal, given in API equivalents, is tentatively correlated with Nasr-7 well in the subsurface of Abu Dhabi (on the right). Note the drop in radioactivity in both datasets, occurring at the Permian-Triassic boundary in the subsurface. Log data and lithology of Nasr-7 well after El-Bishlawy (1985), sequence stratigraphy after Sharland et al. (2001). The location of the Nasr field is given in Figure 1.

**Figure 11:**
Facies, fossil occurrence and Uranium concentrations across the Permian-Triassic boundary interval.

**Figure 12:**
Interpretation on sequence stratigraphy and Khuff reservoir equivalents for the Permian interval of the Bih Formation in Wadi Shahha. Intervals affected by secondary dolomitisation and over 3 m thickness are indicated, along with an API-standardised gamma ray log from outcrop.

**Figure 13:**

Stacking patterns and Khuff reservoir equivalents for the Triassic interval of the Bih Formation in Wadi Shahha illustrated along with patterns of secondary dolomitisation.

**Figure 14:**
Correlation of Upper Khuff reservoirs of offshore Fars with the Bih Formation of Musandam. Facies, stacking patterns and biodiversity in the Permian part of the sections are shown. See Figure 4d for facies legend of outcrop section.

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