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A geological view into Permo-Triassic Khuff reservoirs from outcrop analogues in the United Arab Emirates

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Introduction

The availability of outcrops to study reservoir-scale geobodies is key for a successful exploration and exploitation of subsurface hydrocarbon accumulations. The increased development of giant gas fields in the Permian Khuff Formation in the Persian Gulf calls for more geological work in such outcrop equivalents. Next to the known outcrop analogues in Saudi Arabia (Vaslet et al., 2005) and Iran (Insalaco et al., 2006) we present outcrops from the Musandam Peninsula (Ras Al Khaimah, UAE) with close affinity to the reservoir geology of Khuff gas fields.

Data and methods

A lithological log with scale 1:100 including lithology, carbonate textures, macrofossils and sedimentary structures and covering the 500 m thick stratigraphic interval of interest has been compiled in the field (Figure 1). Along the logged section a sample for microfacies and biostratigraphic analysis has been taken every 2–3 m. Selected clay layers were sampled for X-ray diffraction and palynological analyses. Gamma ray radiation was measured at 1m-intervals in the lower part of the outcrop using a hand-held gamma ray spectrometer which produced separate logs for emitted Uranium (U), Thorium (Th) and Potassium (K), as well as a bulk gamma ray log converted to standard API gamma ray units.

Results

Biostratigraphy – Biostratigraphic markers of both Permian and Triassic age have been encountered in the studied section. The upper Permian interval is characterised by an abundant and diversified foraminiferal assemblage. Representatives of the order Miliolida mostly corresponds to the family Hemigordiidae (*Neodiscopsis*, *Hemigordius*, *Midiella*, *Glomomidiellopsis*) and Cornuspiridae (*Agathammina*, *Hemigordiellina*). Fusulinid foraminifers are represented by the family Biseriamminidae/Globivalvulinidae (*Paradagmarita*, *Paraglobivalvulina*, *Paremiratella*, *Paradagmacrusta*, *Globivalvulina*, *Septoglobivalvulina*, *Siphoglobivalvulina*, *Louisettita*, *Retroseptellina*) and the family Staffellidae (*Sphaerulina*, *Nankinella*). This association allows assigning the Permian portion of the studied section to the Lopingian (Wuchiapingian-Changhsingian) time interval (*Paradagmarita* Zone *sensu* Altiner and Özgül, 2001). The Late Permian age identified by foraminifera is further corroborated by the

occurrence of Permian calcareous algae (*Gymnocodium bellerophontis*, *Mizzia cornuta*, *M. yabei*, *Permocalculus plumosus*, *P. digitatus*). After a 200 m long section without stratigraphic markers, foraminifera reappear in the uppermost part of the section with the Late Induan to Olenekian species *Hoyenella sinensis* and *Meandrospira pusilla*. The few recovered palynological samples contain spores (*Calamospora brunneola*, *Dictyotriletes* sp., *Laevigatisporites* sp., *Leiotriletes blairatholensis*, *L. ulutus*, *Lophotriletes novicus*) and pollen (*Crinalites sabinensis*, *Cycadopites follicularis*, *Svedrupollenites* sp.) of Late Permian to Early Triassic age.

Clay mineralogy – The occurrence of clays is limited to around a dozen intervals along the studied section. The composition of six clay samples was analysed using X-ray diffraction of minerals 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. The presence of chlorite in most samples indicates weathering in hot climate conditions, which is in agreement with previous interpretations of the Late Permian / Early Triassic climate in this region. Palygorskite and sepiolite are interpreted as authigenic minerals. These fibrous clays are common constituents of restricted carbonate and evaporite deposits and form under strong evaporitic conditions in brines dominated by different alkaline elements. The encountered clay minerals thus reflect the hot climate, Mg-rich sea water and restricted evaporitic environment during the deposition of the Khuff carbonates and evaporites.

Carbonate facies and depositional environments – Nine carbonate facies are identified by combining microfacies from thin sections and sedimentological features observed in outcrop. These can be grouped into four depositional environments:

- Windward shoals: The highest-energy facies include pack-grainstones with staffellids and oolitic grainstones; these form up to 20 m thick intervals of m-bedded dolostones with frequent cross bedding and are interpreted to have been formed in windward shoals.
- Open lagoon: The common occurrence of bioturbated mud- 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. Mollusc rudstone, deposited as storm layers, is commonly intercalated in the Triassic part of the section.
- Restricted lagoon and mudflats: The scarcity of fauna is indicative for a restricted environment during the deposition of laminated to massive dolomustones. Occasional mudcracks point at intermittent exposure and thus at a more shallow subtidal setting compared to the open lagoon. Intertidal mudflats with algal mats are at least in part the environment of deposition of the laminated mudstones. 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.
- Leeward shoals: The bioclastic packstone/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.

A very peculiar facies is the thrombolitic boundstone, which is limited to a 5–20 cm thick interval and resembles microbialites typical for the Permian/Triassic boundary (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 – 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 Uranium radiation (Insalaco et al., 2006). To test the presence of this drop in gamma radiation, spectral gamma ray data were acquired in the 35–190 m level of the studied section in Wadi Shahha (Figure 1). 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, and points at the position of the Permian-Triassic boundary somewhere between levels 166 m and 185 m in the measured section.

Stacking patterns and outcrop-subsurface correlation – We propose a subdivision of the Permian to lowermost Triassic part of the studied section into 3rd and 4th order sequences (Figure 10) following the scheme used by Insalaco et al. (2006) in the South Pars area. In our interpretation emersion horizons and clay layers are corresponding to sea-level lowstands, and thus mark sequence boundaries. In contrast, high-energy grainstones are envisaged as deposits during maximum flooding. Both sequences KS3a and KS3b are around 20% thicker than in the subsurface, indicating a higher sedimentation rate in the Musandam area. 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).

Diagenetic overprint – In contrast to the subsurface, where both lime- and dolostones are present, the outcrops are entirely dolomitised. The evaluation of thin sections points at two principal stages of dolomitisation: (i) a primary dolomitisation affected the entire sedimentary succession independent from the facies, and is considered as syn- to early post-depositional in nature, preserving the original rock texture and most of the initial porosity; (ii) 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. The distribution of this later stage of dolomitisation might give insights into the stratigraphic position and geometry of hydrocarbon flow units in the subsurface. According to this hypothesis, the most intensively dolomitised intervals, such as the upper K4, lower K3 and uppermost K3 (marked in grey in the dolomitisation column on Figure 1) might correspond to the units with highest potential of storage and/or flow of hydrocarbons in the subsurface.

Conclusions

The studied outcrops show strong affinity to facies and stacking patterns in the K3 reservoir 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, which are hard to characterise using limited core data from the subsurface. 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.

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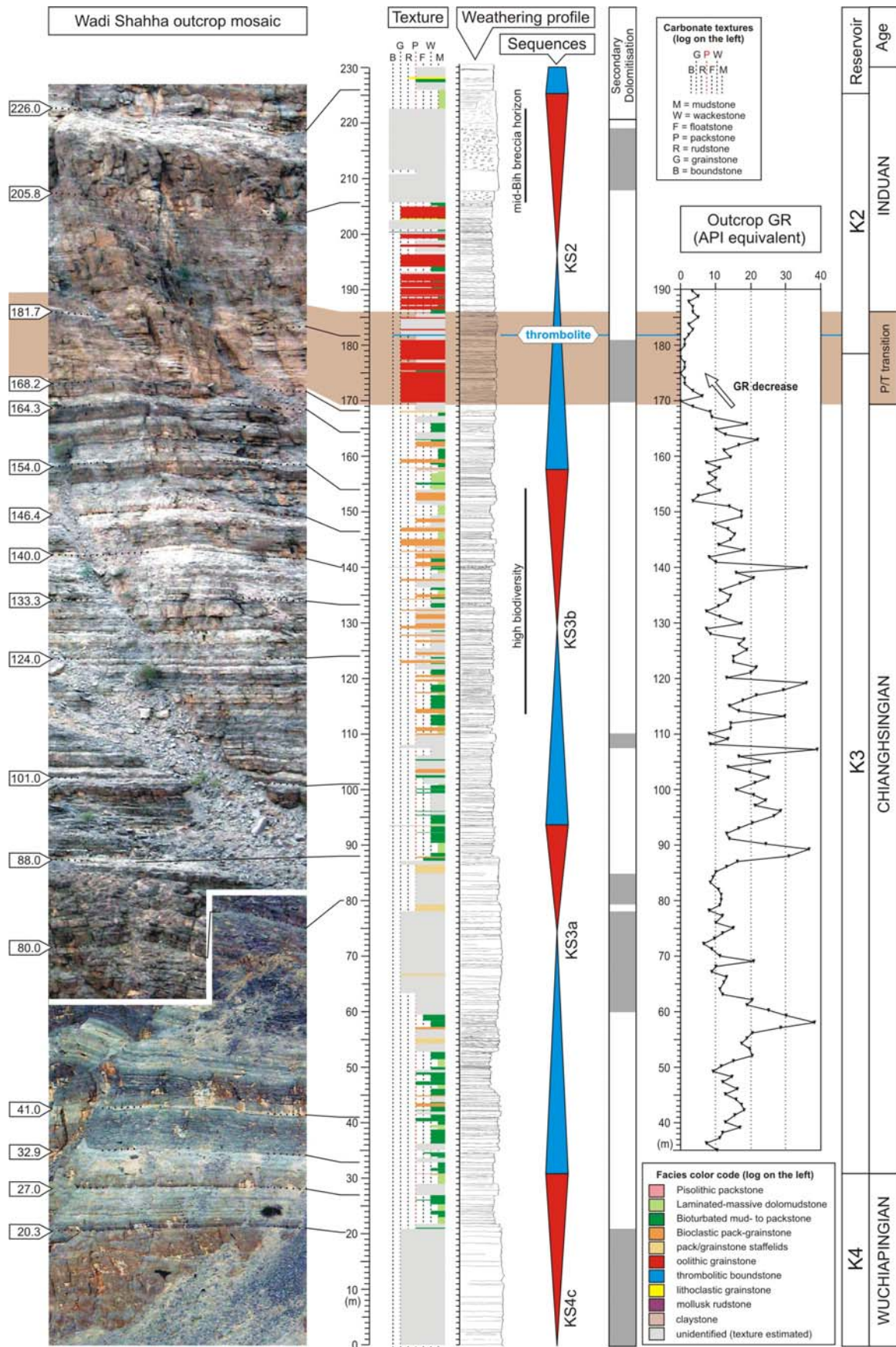


Figure 1: Upper Permian to lowermost Triassic outcrops in Wadi Shahha (Ras Al Khaimah, UAE) with interpretation of Khuff reservoir range (far right) based on facies, stacking patterns and outcrop gamma ray.