The Permo–Triassic Sequence of the Arabian Plate
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11828 Hydrocarbon potential of the Upper Permian
Chia Zairi Formation in northwest Iraq

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In Iraq the Upper Permian Chia Zairi Formation, together with the overlying Lower Triassic Mirga
Mir Formation, forms the chronostratigraphic equivalent of the Khuff Formation of eastern Arabia
and the Dalan and Kangan formations of Iran. The Chia Zairi Formation extends from the northern
Ora outcrops near the Turkish border to southern Iraq (wells West Kifil-1 and Diwan-1), thus covering
the central and eastern parts of the country. It is absent in the far western deserts at the Jordanian
border and some areas near the Syrian border (i.e. Khelsia High region and south of Jabal Sinjar)
due either to non-deposition or erosion. Lithologically, the Chia Zairi Formation is composed of
both carbonates and siliciclastics, and the carbonate proportion increases northward and eastward.
However, the formation is deeply buried in most regions except in the northwestern and potentially
the southwestern region, where based on seismic, it is estimated to be around 3–5 km deep.

This study of the Chia Zairi Formation in northwest Iraq used data collected from both outcrops (in
Ora region of Kurdistan) and deep wells (Atshan-1, Jabal Kand-1 and Mityaha-1). The formation
is subdivided into four units: CH1 to CH4 units downwards. The upper Darriri Member or CH1
carbonates contain regional MFS P30 and P40, which can be correlated with the Khuff C (and possibly
the Khuff B) of Saudi Arabia, the Khuff cycles P30 to P40 of Oman, and the Upper Dalan Member of
Iran. While the middle Satina Evaporite Member (i.e. CH2 unit of subsurface) may be correlated with
the Khuff D anhydrites of Saudi Arabia, the Nar Member of Iran, and the middle Khuff anhydrite
of Oman and the United Arab Emirates. The lower Zinnar Member (probably CH3 of subsurface)
contains carbonates deposited during the Middle Permian transgression and consists of the regional
MFS P20 that can be correlated with the Khuff D Member of Saudi Arabia, the Lower Dalan Member
of Iran, and the Khuff cycles P17–P27 of Oman. This Khuff equivalent, a thick dolomitic limestone,
has the potential to form an important gas reservoir in Iraq, particularly in the northwest region.
However, the Chia Zairi appears to be characterized by lower porosities compared to the Khuff in the
Gulf region.

The main source rocks for the entire Paleozoic plays in Iraq are the proven Lower Silurian Akkas
hot shale, in addition to the potential organic-rich shales of the Ordovician Khabour and the Lower
Carboniferous Ora formations. The Chia Zairi Formation also has source rock potential in its lower
shaly parts (ca. 20 m thick). This lower shaly part of the formation may also act as a seal for the
underlying older reservoir units.

11703 Khuff Sequence KS4: High-resolution anatomy of a Middle Khuff
grainstone package, Oman Mountains, Sultanate of Oman

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This outcrop study is part of a larger-scale project on the Saiq Formation in the Oman Mountains
(outcrop analog of Khuff Formation), and focussed on the small-scale heterogeneities of the lower part
of Khuff Sequence 4 (KS4). This interval is dominated by massive grainstones that at first glance seem
extremely homogenous with distinct trough cross-bedding detectable in spite of strong dolomitization. Serrated gamma-ray patterns made small-scale cycle interpretations difficult. Therefore a very detailed facies and sequence analysis was necessary to decipher the vertical microfacies make-up of the grainstones and link it with potential pore types.

Methods

Three KS4 sections of around 70 m were logged with a high-resolution scale of 1:50. Lithology, Dunham texture, components and sedimentary structures were logged. Extensive microfacies analyses of 145 thin-sections sampled every 1.5 m on average throughout the lower part of the KS4 was carried out. Gamma-ray measurements were conducted every 0.25 m with a measurement period of 15 seconds. The detailed one-dimensional data analysis reflected here will be followed by two-dimensional correlations. Finally a three-dimensional exploration-scale model will be constructed.

Sedimentological Analysis

The detailed logging enabled the interpretation of a smaller scale of cyclicity compared to those of previous studies. These are termed “small-scale cycles”. Small-scale cycles are stacked into fifth- and fourth-order cycles. These are nested within the overall third-order transgressive-regressive cycle of the KS4. As minor microfacies changes were difficult to make out in the outcrop due to strong and multiple dolomitization processes, thin-section analysis was crucial.

Biofacies

To fully understand small-scale depositional environment changes biofacies criteria in the thin-section were recorded. To differentiate between back or foreshoal deposition, foraminifera, algae and metazoan species were grouped into the environmental settings they are characteristic of. For instance: increased occurrence of the dasycladacean algae *Mizziia* indicates restrictive, intraplatform deposition. Predominant gymnocodiacean algae such as *Gymnocodium* or *Permacalculus* represent foreshoal deposits.

Conclusions

The grainstone package in Khuff Sequence 4 (KS4) displays a highly differentiated internal anatomy. Mini-cycles and variable microfacies type changes result in a heterogeneous build-up of grainstones. The cyclicities within grainstone complexes indicate minor changes in depositional environments. This has a direct effect on the dominant grain types, which in turn affects the potential pore types. Pore types in the KS4 are therefore likely to vary: oomoldic versus interparticle versus intraparticle; this has a profound influence on permeability. Vertical microfacies variance could therefore account for differing production rates in KS4 grainstones.

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Figure 1: Example high-resolution log of a ca. 10 m thick grainstone-dominated package (one cycle set) in the lower KS4 in Wadi Sahtan, illustrating highly differentiated internal anatomy and an additional, smaller scale of cycles. To the right thin-sections are shown. The sampled grainstone composition ranges from cortoidal-, peloidal- and skeletal-rich to pure oolitic.
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### 11793 Microfacies, diagenesis and reservoir quality of Early Triassic Kangan Formation in offshore Zagros: A case study

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Significant amounts of hydrocarbon resources are hosted by the Lower Triassic Kangan Formation (Upper Khuff equivalent) in the southern part of the Gulf. This carbonate gas reservoir is known to be a complex carbonate system with a high degree of heterogeneity, which has a direct impact on the reservoir quality. The formation consists mainly of limestone, dolomitic limestone, dolomite

| STRATIGRAPHY | DT (us/f) | RHOZ (g/cc) | TNPH (v/v) | Grain Size & Structures | Lithology | Grain Size | LITHOLOGY | ENVIRONMENT | PORE TYPES | Porosity (%) | Permeability (mD) |
|--------------|----------|-------------|------------|-------------------------|-----------|------------|-----------|-------------|------------|--------------|-----------------|
| K1           |          |             |            |                         |           |            |           |             |            |              |                 |
| K2           |          |             |            |                         |           |            |           |             |            |              |                 |
| EARLY TRASSIC|          |             |            |                         |           |            |           |             |            |              |                 |

**Figure 1:** Sedimentological logs showing facies belts and poroperm values of the Kangan Formation in Well A.
Figure 2: Cathodo-luminescence (CL) image of marine fibrous cements (1), meteoric bladed (2) and coarse burial bulky cements (3). Zoomed picture shows zonation in calcite cements due to change of chemistry of diagenetic fluids.

Figure 3: CL zonation of coarse inclusion rich dolomite cements occluding oomolds in shoal facies.

and evaporites. Combined core examinations and detailed thin-section studies are used for facies analysis. Accordingly, 10 major facies were recognized in the Kangan reservoir. They are grouped as five facies assemblages deposited in supratidal, intertidal, lagoonal, shoal and off-shoal environments. These facies associations reflect an ideal shallowing-upward sequence. These facies are genetically related and indicate a gentle depositional gradient and morphology during deposition. Thus, they represent the shallow part of a homoclinal carbonate ramp (Figure 1). This interpretation is based on the characteristics of the constituent facies, lateral and vertical relations between sedimentary facies
and the presence of thick succession of shallow-water deposits (high relative proportion of peritidal and lagoon versus open-marine facies).

Reservoir properties are greatly affected by diagenetic events such as dolomitization, cementation, micritization, compaction and dissolution. Cementation is the main diagenetic process that reduces reservoir quality by occluding pore spaces in some parts. Cathodo-luminescence petrography revealed the following three calcite cement types, which are generated during early to burial diagenesis:

(1) non-ferroan fibrous cement consists of thin fibrous fringes (10–15 μm) and exhibits light brown luminescence. This cement was formed in eogenetic diagenetic stages under influence of marine conditions.

(2) Ferroan bladed calcite cement that exhibits bladed texture with about 30–70 μm long. It is non-luminescent and formed in eogenetic diagenetic stages with possible origin of meteoric and mixing-zone waters.

(3) Ferroan blocky calcite cement which is characterized by coarse crystalline (200–350 μm) texture, displaying a dull-dark luminescence (Figure 2). It was generated in burial diagenesis setting with no recharge of surface waters.

Three types of dolomitic cements are recognized in the Kangan reservoir in general. They include limpid dolomite, coarse inclusion rich dolomite and saddle dolomite. Limpid cements, probably formed in mixing-zone environments, are not common in reservoir rocks. The most abundant dolomite cements, coarse dolomitic ones are characterized by having several zones, under CL microscopic studies. These zones are: (1) ferroan, non-luminescent zone, (2) dark brown zone, (3) light brown to orange zone and (4) dull zone (Figure 3). Saddle dolomite cement is scarce, and formed in deep-burial diagenesis conditions. Therefore, paragenetic sequence reconstructed based on petrographic observations suggest that diagenetic carbonate cements have been formed in early, burial and deep-burial diagenesis stages which cause a significant reduction of porosity in the Kangan Formation (Figure 4).
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11737 Khuff Formation in Kuwait: An Overview

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The Khuff Formation represents a Permian transgression over a varied topography in Kuwait. The formation occurs at greater depth in comparison to adjoining regions and is fully penetrated only in the wells located over the Kuwait Arch. The formation comprises mainly dolomudstone, foraminiferal and algal dolowackestone, peloidal and algal dolopackstone, peloidal and oolitic dolograinstone, anhydrite and minor limestone deposited in evaporitic low energy inner to middle ramp setting. Dominantly supratidal to subtidal, restricted setting and hypersaline conditions were prevailing during the deposition. Dolomitization has caused rare development of intercrystalline porosity, however mostly over dolomitization coupled with anhydrite cementation has deteriorated the porosity. Biostratigraphic and strontium-isotope analyses are indicative of a Wordian to Capitanian (Middle Permian) for the Lower Khuff while the Upper Khuff ranges in age from Wuchiapingian (Late Permian) at its base to Induan (Early Triassic) at its top.

Sequence Stratigraphy

The formation represents a second-order transgressive-regressive sequence composed of six third-order depositional sequences (Khuff sequences KS1 through KS6; Figure 1). Composite sequences KS6, KS5 and transgressive systems tract of KS4 are characterized by relatively thick anhydrite intercalations and represent the lower Khuff transgression, while the highstand systems tract of sequence KS4 and composite sequences KS3, KS2 and KS1 are more carbonate-dominated with thinner and less common anhydrite intercalations and represent a regressive phase marked by progradation back towards the east. The top of the Median Anhydrite, a persistent anhydritic bed identified regionally, which lies immediately below the maximum flooding surface of the Khuff, represents the point of maximum transgression for the second-order sequence.

Controls on Thickness and Diagenesis

The Khuff isochore map from seismic interpretation and well log correlation shows less thickness of the formation over the Kuwait Arch and greater thicknesses in western Kuwait. The thickness variations suggest that the Kuwait Arch subsided at a lower rate than western Kuwait. Also extensive dolomitization characterize the formation over the Kuwait Arch. In contrast, a greater abundance of grainy facies and a much more limestone-rich mineralogy in western Kuwait combine to yield the better porosities in areas away from the Kuwait Arch. These observations lead to conclude the existence of the Kuwait Arch during the deposition of Khuff.

Qusaiba-Khuff Petroleum System

A speculative petroleum system, namely the Qusaiba-Khuff (?) Petroleum System, is envisaged based on available exploration data. The source rock is believed to be Silurian Qusaiba Formation, which is speculated to be preserved off the flanks of the Kuwait Arch. Peak oil generation probably occurred in Late Triassic or Early Jurassic time. The porous grainy intervals in the Upper Khuff in western Kuwait and fractured dolomites within the Lower Khuff in the areas over the Kuwait Arch are envisaged to be the reservoirs. The shallow-marine to sabkha shales of the Sudair Formation are expected to act as the top seal for the petroleum system. Additionally the Median Anhydrite and intra-formational anhydrites and tight dolomites can provide local seals. The basin was flooded with hydrocarbon that is evidenced by direct as well as indirect events. Gas indications have been observed in many wells drilled over and in the flank of the Kuwait Arch. The presence of bituminous material in varying quantity in the entire Khuff section, more predominantly in the Upper Khuff section, is direct evidence whereas presence of H2S and late stage calcite crystallization are indirect evidence of presence of hydrocarbon.
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Figure 1: Sequence-stratigraphic framework of the Khuff Formation.
The major challenges for exploration of the Khuff in Kuwait are timing of hydrocarbon generation and expulsion relative to trap formation in western Kuwait and predictability of reservoir quality due to diagenetic heterogeneity variation in eastern Kuwait. Detailed studies on structural evolution of western Kuwait and depositional and diagenetic modeling for reservoir quality predictability are keys to exploration success.

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11771 The Khuff impact on Unayzah seismic response: Umm Jurf Field

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The combined effects of variations in thickness and impedance in the Khuff Formation are significant and are sources of noise in the seismic image of the Unayzah Formation in the Umm Jurf Field. They obscure important reservoir signals and degrade the accuracy of the depth and thickness maps. The influence of these variations is readily seen on seismic time and horizon slices.

The upper part of the Khuff is mainly a high-impedance carbonate unit divided by a thin calcareous shale layer. The top Khuff amplitude represents a sharp contrast with the low-impedance Sudair shale, but lateral variations in thickness and acoustic properties of the shale layer below the top Khuff introduced significant variations in the composite seismic response of the top Khuff, which in turn affected the subsequent signals.

The basal part of the Khuff includes a stable and uniform anhydrite layer and stack of carbonates and siliciclastic layers. There are very distinctive channel networks in the basal Khuff with a very strong impedance contrast, which makes these channels prominent features on the seismic data. Overprints from the Khuff channels into Unayzah Formation are evident on seismic slices that were cut through the reservoir. The overprint problem is a limiting factor on the interpretation of the seismic data in Umm Jurf Field.

The trend of variation oscillates in the basal Khuff because of the interaction between two depositional mechanisms of almost perpendicular strikes. The clastic sediments that were deposited during sea-level drops at the base Khuff cut into the carbonate in their movement towards the east and southeast. This process leaves isolated patches of carbonates and siliciclastics, producing lateral lithofacies heterogeneity. These variations are a significant cause of the geological noise in the reservoir interval.

11723 Depositional sequences of the Lower Triassic Kangan Formation, southwest Iran

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The Lower Triassic Kangan Formation is a major gas reservoir in southwest Iran. It is composed mainly of limestone and dolostone with evaporite interbeds. The lower and upper contacts with the Permian Dalan Formation and the Lower–Middle Triassic Dashtak Formation are discontinuous but conformable. To study the facies and depositional environments of the Lower Triassic Kangan Formation, eight wells and the Surmeh outcrop section were studied. Field and petrographic studies combined with wire-line well logs analyses resulted in the recognition of facies related to tidal flat, lagoon, shelf margin, basinal facies tracts, which were deposited on a carbonate ramp.
Hardgrounds, flooding and discontinuity surfaces, vertical and lateral facies tracts changes, combined with diagenetic overprints such as dissolution features, led to the recognition of three third-order depositional sequences. This study shows that relative sea-level changes had the main role in the creation of Lower Triassic depositional sequences. The overall facies and thickness variation and sequence boundaries are in phase with the climatic changes. Relative sea-level changes of the Lower Triassic deposits are compatible with global trend.

Introduction

The Middle Permian–Lower Triassic Deh Ram Group hosts giant gas reservoirs, especially in the Fars region of Iran. The Upper Permian carbonates of the Dalan and Lower Triassic Kangan formations have reservoir continuity, which are capped by Lower–Middle Triassic evaporites of the Dashtak Formation. The Kangan Formation consists of carbonates and evaporites and in the type section in Well Kuh-e Siah-1 it has a total thickness of 178 meters. At the Surmeh outcrop reference section, the formation thickness decreases to 140 meters (Szabo and Kheradpir, 1978). The Lower Triassic Kangan Formation can be subdivided into three lithostratigraphic units. Presence of Claria spp. from the basal argillaceous and shaly beds of the Kangan Formation, suggest an Early Triassic (Scythian) age for the lowermost part of the formation (Szabo and Kheradpir, 1978).

Since gas exploration from Permian–Triassic sediments (the Khuff Formation equivalent) in late 1975, no comprehensive studies have been carried out yet regarding depositional sequences of the mentioned interval. As sequence stratigraphy integrates time and relative sea-level changes to track facies migration (Handford and Loucks, 1993), so it helps us to follow reservoir facies.

The base of the Kangan Formation is picked at the base of a shaly unit, which is expressed by a high gamma-ray reading. A key aspect of this study is to re-evaluate the contact of the Dalan and Kangan formations. Detailed field surveys carried out at the Surmeh outcrop section show the presence of strong iron-staining at the top of the Dalan Formation, which is overlain by thrombolite boundstone facies. This suggests that the base of the Kangan Formation starts with the thrombolite boundstone facies. The iron-stained surface that is overlain by thrombolite boundstone provides evidence for a relative sea-level fall, subaerial exposure and then a sudden sea-level rise.

The objective of this study is to report on the depositional sequences of the Lower Triassic Kangan Formation by means of detailed field surveys, microscope-based microfacies, and wireline log analyses, diagenetic overprints, discontinuity surfaces and limited seismic images along a transect that comprises the Surmeh outcrop section and the Day, Nar, Assaluyeh, Varavi, Tabnak, Khalfani, Lavan and Kish wells.

Microfacies and Facies Tracts

Vertical changes in facies types enable us to interpret lateral shifts in the depositional environments and facies. These, in turn, are controlled by sedimentary processes that operate in particular areas of the depositional environments (Catuneanu, 2006). Detailed field, core, facies and wire-line well-log analyses of the Kangan Formation along the above-mentioned transect resulted in the recognition of several genetically linked facies, which were deposited on a carbonate ramp. Facies analysis is based on both macroscopic and microscopic observations. The environmental interpretation is based on the sediment texture, skeletal and non-skeletal grains, faunal composition, sedimentary structures and comparison with modern and ancient sedimentary environments.

Outer-ramp facies tract: This facies tract is comprised of lime mudstone, bioturbated bioclastic wackestone and claria wackestone-packstone. Bioclasts included siliceous sponge spicules, filaments, crinoids/echinoids and claria, which indicate outer-ramp depositional environment.

Mid-ramp facies tract: Bioclastic peloid packstone, laminated lime mudstone, laminated peloid grainstone and intraclastic wackestone-packstone with basal erosional surfaces and graded bedding are other facies that were deposited on this facies tract. Presence of gutter casts, flat pebble conglomerate/intraclasts, graded bedding, indicates that mentioned facies were deposited by storm deposits, which their stratigraphic position is consistent with outer ramp.
**Inner-ramp facies tract:** Inner-ramp facies tract comprises of shoal, lagoon and tidal facies tracts. Shoal facies are characterized by bioclastic peloid grainstone/packstone, peloid grainstone, bioclastic peloid grainstone and ooid grainstone. Lagoonal facies are characterized by bioclastic wackestone and packstone. Bioclast included gastropods and ostracods. Tidal flat facies are composed of lime mudstone, dolomitized lime mudstone, peloid intraclast grainstone, ooid grainstone and gypsum/anhydrite, and stromatolite boundstone. Lime mudstone display fenestral/birds-eye fabrics and microbial filaments.

**Sequence Stratigraphy**

Sequence stratigraphy has become an increasingly widespread method in the hydrocarbon industry to help understand the sediment geometries and controls of basin-fills and also to predict the location of reservoir facies (Booler and Tucker, 2002). The Lower Triassic deposits of the study area can be divided into three third-order depositional sequences (Figure 1), following the sequence-stratigraphic concepts of van Wagoner et al. (1988, 1990) and Vail et al. (1991). Indicative surfaces such as hardgrounds, flooding surfaces and discontinuity surfaces have been considered in defining depositional sequences at the Surmeh outcrop section and in the studied wells. Stratigraphic surfaces mark shifts through time in depositional regimes and are created by the interplay of base level and sedimentation changes (Catuneanu, 2006).

Depositional Sequence 1 (DS1), which comprises of Scythian stage (Szabo and Kheradpir, 1978) was deposited after mass extinction during Late Permian. Its lower and upper sequence boundaries are type 1 (SB1), which are indicated by strong iron-staining and sharp shift in depositional environments. The transgressive systems tract (TST) starts with thrombolite boundstone and then consists of *Claria* wackestone to packstone. This systems tract reflects an open-marine setting. It is marked by considerable retrogradation of facies and a higher rate of relative sea-level rise as evidenced by a deepening-upward trend and parasequence stacking pattern. There was a major rise at the beginning of the Triassic, which led to widespread flooding of the continental margin (Hallam, 1992).

The maximum flooding surface (MFS) is marked by a condensed surface, which is suggested by glauconitic bioclastic wackestone at the Surmeh outcrop section. The MFS also corresponds to the maximum gamma-ray readings and hardgrounds, which are evidenced by sharp shifts in gamma-ray, neutron and sonic logs in the wells. The highstand systems tract (HST) consists mainly of bioturbated bioclastic wackestone and packstone with shale interbeds rich in *Claria*. These *Claria*-rich facies are replaced by storm deposits. The top of the HST marks the base of the forced regressive systems tract, which is characterized by a significant shift of facies tracts. This is coincident with microbialites and evaporitic deposits that correspond to an abrupt fall in relative sea level. In some wells which have lower paleogeography position (e.g. Khalafani), calcite pseudomorphs after anhydrite, nodular and chicken-wire anhydrites appear at the top of the depositional sequence.

Depositional Sequence 2 (DS2) is characterized by carbonate deposits, which correspond to the middle part of the Lower Triassic succession. The upper sequence boundary is type 1 and indicated by iron-staining, limonitic grains, mouldic and vuggy porosity and half-moon ooids. The transgressive systems tract consists of microbialite boundstone and bioclastic wackestone to packstone and ooid grainstone. This systems tract consists of open-marine, shallowing-upward, aggradational and retrogradational parasequences, which mark the catch-up phase. The MFS is characterized by *Claria* filaments/sponge spicules facies of outer-ramp facies tract. The early highstand systems tract consists of bioclastic wackestone, bioclastic peloid wackestone that show thickening-upward parasequence sets. The late HST includes high-energy shoal deposits, shallowing-upward aggradational and finally progradational parasequences (Figure 2). It is striking that the HST of DS2 is characterized with progressive shallowing- and thickening-upward parasequences. The thickening-upward trend indicates the presence of sufficient accommodation space implying that progradation appears to have ended due to climatic changes. This interpretation is supported by several lines of evidence such as half-moon ooids, mouldic and vuggy porosity, and dissolution of marine cements in the wells that are situated above the Gavbandi and Kish paleohighs. This could be related to the combined effect of paleohighs and orbitally controlled cyclicity, which played a main role in reservoir creation.
Considerable facies tracts aggradation and progradation could have been due to a higher paleogeography position (Gavbandi High or salt dome like Kish Well). These findings are in agreement with the results from petrographic studies, wire-line well logs, seismic images and depositional sequences correlation in the studied areas.

Depositional Sequence 3 (DS3) consists of a TST and HST. Its sequence boundaries are type 1 (SB1) and indicated by iron-staining, as well as sudden shifts of facies tracts, lithology and depositional systems. The TST is composed of intraclastic and peloid grainstone facies of lagoonal and tidal flat environments, shallowing-upward progradational parasequences. TST parasequences show a thickening-upward trend. The MFS is recognized by a hardground (Figure 2) that is encrusted by bivalves at the Surmeh outcrop section and strong electrical log peaks in most of the studied wells. The early HST is characterized by aggradational and progradational mid-ramp facies tract, which is followed by late highstand shallowing- and thinning-upward parasequences of lagoonal and tidal flat deposits. Progressive shallowing- and thinning-upward is characteristic of progressive loss of accommodation space and tidal flat facies tract progradation.

In the late HST of DS3, sedimentary structures such as lower erosional surfaces, gutter and pot, graded bedding with basal sharp and gradational upper contacts are observed both in field survey and microscopic investigations, which is attributed to tempestites. It seems that this condition was
favored for tempestite generation by storm-generated density currents during HSTs in the shallow and wide carbonate platform (Kavoosi et al., 2009).

This study shows that relative sea-level changes and climate had a main role in creation of depositional sequences of Lower Triassic deposits along the studied transect. The overall facies changes along the study areas and sequence boundaries are in phase with the climatic changes observed during this time that is compatible with sea-level changes proposed by Hallam (1996).

Conclusions

The Lower Triassic deposits of the study areas can be divided into three third-order depositional sequences. This study shows that relative sea-level and climate changes had a main role in the creation of the Lower Triassic depositional sequences along the studied transect. The overall lateral facies and thickness changes in the study areas and sequence boundaries are in phase with the climatic changes observed during this time.

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11724 Reservoir facies controlling factors in the Permian Dalan Formation, southwest Iran

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Summary

The Permian Dalan Formation is an economically significant gas and condensate reservoir in the Fars region of southwest Iran. It is composed mainly of limestone and dolostone. Facies analyses, depositional environments and diagenetic processes of the Dalan Formation in eight wells and the reference section at the Surmeh Anticline were studied. Field and petrographic studies combined
with wire-line well-logs analyses and available seismic images resulted in recognition of various carbonate facies related to tidal flat, lagoon, shoal, basinal facies tracts, siliciclastic and evaporitic facies deposited on a carbonate ramp.

Petrographic investigations and facies analyses of the Dalan Formation, led to the recognition of aragonite mineralogy and diagenetic environments of the Dalan Formation, which resulted in recognition of controlling factors of reservoir facies. Grainstone facies deposited on paleohighs have marine cements with isopachous and fibrous fabrics, where leaching of grains created porous intervals. On the other hand, grainstone facies deposited in places with lower palaeogeographic positions, not only show limited distribution but also have been affected much more by deep burial cements and diagenetic processes, which resulted in a loss of reservoir properties. This study suggests that paleohighs had played a main role in the diagenetic sequences and reservoir facies distribution.

Introduction

The Deh Ram Group (Middle Permian–Lower Triassic) is an economically significant gas and condensate reservoir in the Fars region and the Gulf region. The petroleum system of the Deh Ram Group are: (1) the Lower Silurian hot shale as source rock, (2) Middle Permian–Lower Triassic carbonates of Dalan and Kangan formations are the reservoirs, and (3) the Lower–Middle Triassic evaporites of the Dashtak Formation provide a significant cap rock. The Dalan Formation is comprised of carbonates and evaporites, and has been subdivided into one formal and two informal members. The lower carbonates (informal), Nar Member (formal) and upper carbonates (Szabo and Kheradpir, 1978). In the Zagros fold-and-thrust belt, the upper carbonates of the Dalan Formation are producing gas except in a few wells where gas has been tested from the Nar Member and lower carbonates.

After gas exploration from Permian–Triassic sediments (Khuff Formation equivalent) in late 1975, increasing exploration and drilling activities have been conducted. In spite of more than thirty-five years of exploration and production activities, no comprehensive studies have been carried out regarding factors that control reservoir facies creation and distribution.

The quantification of diagenetic processes such as dissolution, cementation, dolomitization and pressure solution and their impact on the reservoir facies are very important from a hydrocarbon activities perspective. Some authors (e.g. Ehrenberg, 2006; Ehrenberg et al., 2007; Moradpour et al., 2008) believe that depositional facies and original mineralogy have an effective role on reservoir, while Esrafili-Dizaji et al. (2008) believe that late diagenetic process could reduce or enhance reservoir properties via chemical compaction and fracturing, respectively. However, bear in mind that the Permian carbonates of the Dalan Formation are composed mainly of dolostone with intercrystalline porosity, which form a good pay zone in the upper carbonate unit. Regarding dolomitization processes, some workers proposed dolomitization formed in evaporitic sabkha and shallow reflux setting (e.g. Talu and Abu-Ghabin, 1989; Ehrenberg, 2006); however, dolomite recrystallization and cementation in deep burial diagenetic environments cannot be ruled out (e.g. Alsharhan, 2006).

The main objective of this study is to report on factors that control reservoir facies of the Permian Dalan Formation by means of detailed field surveys, microscope-based microfacies and wireline well-log analyses and limited seismic images along a transect that comprises the Kuh-e Surmeh outcrop section and Day, Nar, Assaluyeh, Varavi, Tabnak, Khalfani, Lavan and Kish wells.

Microfacies and Facies Tracts

Detailed field, core, facies and wireline well logs analyses of the Upper Dalan Formation in the drilled wells, resulted in recognition of several genetically linked facies that assign deeper marine (outer ramp), shoal, lagoonal and tidal flat facies tracts, which were deposited on a carbonate ramp.

Basinal facies tract is comprised of lime mudstone, crinoid wackestone and bioclastic packstone. Bioclasts include crinoids, bryozoan, and fusulinid.

Shoal facies tract is characterized by ooid grainstone, bioclastic peloid grainstone/packstone and bioclastic grainstone/packstone, which separate the shoal and restricted lagoon facies. Shoal facies
occur in thick to massive beds with lamination and cross bedding. Ooids may show diagenetic modification such as dolomitization, dissolution, distortion (Spastolith ooids) and micritization. Cross-bedding, large- to medium-scale parallel laminations, planar cross-bedding, chevron and trough cross bedding were observed.

Lagoonal facies tract is characterized by dasyclad wackestone/packstone, bioclastic wackestone/packstone, bioclastic peloid packstone and oncoid packstone.

Tidal flat facies tract is composed of lime mudstone, dolomudstone/dolomitized lime mudstone, gypsum/anhydrite nodules/layers, flat laminated stromatolite boundstones and peloid grainstone. Lime mudstone display fenestral/birds-eye fabrics and sparse microbial filaments.

**Diagenesis**

The Dalan Formation ooids with leached nuclei have completely been dolomitized, while ghosts of spherical shapes characterize ooid grains (Figures 1b–d). This can be attributed to their aragonitic primary mineralogy. Early marine cementation of ooid grainstone is evidenced by weak compaction and remaining large interagranular spaces (Figures 1c–d), whilst at some succession of studied wells, pore spaces were filled with blocky, drusy mosaic and poikilotopic cements. Early cementation phase of grainstone facies especially ooids in the marine diagenetic environment is indicated by the presence of isopachous and fibrous cements (Figures 1a, 1c–d) and polygonal fabrics. Fibrous and isopachous cements are characteristic of aragonitic mineralogy and early marine diagenetic environment (Inden and Moore, 1983; Tucker and Wright, 1990; El-Saiy and Jordan, 2007; Kavoosi et al., 2009). Aragonitic cements can form under most environmental conditions, but generally aragonite is favored under higher-energy conditions (Morse, 2005), which indicate cementation in permeable deposits during low sedimentation rate under arid conditions (Tucker, 1993).

![Figure 1](http://pubs.geoscienceworld.org/geoarabia/article-pdf/17/2/189/5445944/eage_2012.pdf)

Figure 1: (a) Bioclastic grainstone with isopachous cement and dissolution porosity, Varavi Well, PPL. (b) Dolomitized ooid grainstone with dissolution and intercrystalline porosity, PPL. (c) Ooid grainstone with vuggy porosity resulted from fresh-water percolation, Nar Well, XPL. (d) Porous ooid grainstone with equant calcite cement, PPL. Blue dye shows porosity in Figures b and d.
The Late Permian was generally a period of icehouse climate and a time of aragonite seas. The presence of leached ooids (as evidenced by half-moon ooids, vadose silt, meniscus cement and dissolute metastable aragonitic cements) is consistent with subaerial exposure of ooid and bioclastic shoals (Figure 1) during relative sea-level fall. Our study indicates that the Upper Dalan carbonates, which are located on the basement paleohighs and salt domes, exhibit aggradation of ooid and bioclastic grainstone facies with marine cements. These facies are dominated by mouldic porosity. Seismic images indicate that the salt domes had a pulse of growth during the early Paleozoic, as exemplified by Kish Salt Dome. In contrast, carbonates deposited in lower paleogeographic areas have a lesser amount of marine cements. This pattern is apparent in spite of the similarity of facies and tectonic setting and is characterized by the Khalfani Well. In these areas cementation followed due to deep burial. These patterns are supported by considerable and widespread pressure solution, stylolites and poikilotopic anhydritic cements that sealed thin reservoir zones in the Khalfani and Day wells. In these wells, thin grain-supported facies are underlain by keystone peloid ooid grainstone/packstone and dolomitized lime mudstone and anhydrite. The peloid and grainstone texture with keystone fabric and its vertical association with lagoonal and upper intertidal/supratidal facies indicate deposition in a lower intertidal sub-environment.

The progradation of the tidal-flat-facies tract provides a vertical and lateral seal for the reservoir facies. This interpretation is supported by several lines of evidence: (1) the widespread distribution of dolomitized mudstone with birds-eye, and (2) discontinuous laminae with calcite pseudomorphs after gypsum/anhydrite. These occur above the carbonate cycles in the Khalfani and Day wells. This pattern signifies deposition in upper intertidal to supratidal environments (e.g. Shinn, 1983a, b).

Considerable aggradation and progradation/migration of high-porosity facies tracts was probably due to a combination of a higher paleogeographic position and orbitally controlled cyclicity. Depositional facies play a main role in the creation of reservoir zones, determining their lateral distribution and subsequent diagenetic processes, such as dolomitization, dissolution and fracturing (Kavoosi, 2007; Kavoosi et al., 2009). These findings are in agreement with the results from petrographic investigations, namely that dolomitized facies such as sucrosic dolomites resulted from packstone and grainstone facies tracts. Taking into account that the Late Permian was a time of high-frequency sea-level fluctuations, the reservoir facies tracts with considerable thickness and intergranular, vuggy and intercrystalline porosity had higher distribution on paleohighs in comparison with wells that had a lower paleogeographic position.

Conclusions

Petrographic investigations and facies analyses led to the recognition of diagenetic environments and reservoir facies of the Permian Dalan Formation. This study suggests that paleohighs played a main role in diagenesis and the distribution of reservoir facies by the creation of porous zones. Ooid and bioclastic grainstone/packstone facies tracts exhibit intergranular, vuggy and intercrystalline porosity, which may have been controlled by high-frequency sea-level fluctuations during the Late Permian. These facies show greater lateral continuity and higher development over paleohighs in comparison with wells drilled in lower paleogeographic positions.

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11891 Stratigraphic controls on carbonate evaporite stratigraphy - importance to hydrocarbon exploration: Examples from Middle Eastern oil fields and their response to plate tectonic cycle, climate, basin position and sea level

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Paleozoic, Mesozoic through Cenozoic sedimentary fill of the Tethys southern margin is subdivided stratigraphically by the beat of second- and third-order changes in eustasy, tectonic movement, sediment supply and Wilsonian cycles of plate movement. This northeastern flank of Gondwanaland extends from the Arabian Plate through the Zagros and Taurus Mountains, Levant and North Africa. Regional chronostratigraphic charts and cross-sections detail products of these processes and major petroleum production from carbonates and evaporites interbedded with clastic sequences; with flatter-lying horizons in Arabia, folded in the Zagros and Taurus Mountains of Iran and Turkey, wrenched margin through the Levant and disrupted block-faulted terrains in North Africa from Egypt through Libya.

In Arabia, during late Paleozoic and Mesozoic time, deposition was in tropical settings and on an extensional passive Tethyan margin, which by the late Cretaceous to Tertiary was a foreland basin flanking the Zagros and Taurus uplift. Contrasting deposition on the North African plate also occurred in tropical settings, but followed an extensional passive margin through late Paleozoic, to Mesozoic, and Tertiary.

Recent advances in sequence stratigraphy provide a detailed and flexible framework to track and predict the distribution of evolving sedimentary facies on smaller spatial and temporal scales to determine future plays and define existing reservoirs. Tectonic mega-sequence events governed low-frequency accommodation of sedimentary fill interrupted by surfaces formed by periods of non-deposition, and/or unconformities. Maximum flooding surfaces (mfs) express the maximum regional transgressions of fluctuations in eustasy. Both surfaces provide chronostratigraphic order to sedimentary fill dated by radiometric and biologic markers.
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11848 Improving the mapping of Permian–Triassic layers using inversion with inter-bed multiple method: A case study of Mutriba Field, Kuwait

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The onshore Mutriba Field, located in northwest Kuwait, shows some potential gas targets in the Lower Triassic to Permian formations. These levels are well known in the Middle East for being severely contaminated by coherent inter-bed multiple reflection events in the seismic data. These multiples have the same velocities as the primaries and cannot be adequately attenuated during processing. As a result, the acoustic impedance (AI) predicted from such seismic data is significantly affected. We present here an inversion study, which incorporates an Inter-Bed Multiple Modeling (IBMM), into the generation of synthetic seismograms, which are involved into the seismic inversion workflow.

The current study was carried out in Mutriba Field covering an area of about 1,000 square km. Only one well was drilled to the Khuff Formation. At the well position, these levels are found between 2.5 and 3.0 seconds two-way time (TWT) in the seismic data. The seismic interpretation for these levels is difficult because of the presence of inter-bed multiples. We propose here the application of a recent acoustic inversion methodology, which provides an IBMM, in addition to the primaries, into the generation of synthetic seismograms and use these synthetics during the seismic inversion process. The use of the IBMM allows dealing with two issues concerning the multiples: (1) evaluate the impact of inter-bed multiples on the quality of the well-to-seismic calibration, and (2) minimize the impact of

![Figure 1](image-url)
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the inter-bed multiple contamination on the acoustic inversion results, targeting Triassic and deeper levels of the Mutriba Field.

Method

The model-based inversion with IBMM based on the 1-D elasto-dynamic equations assumes that the 1-D medium is made of a series of homogeneous layers. The AI log at the well has been computed starting from the very shallow part (above top Dammam Formation) to the deep target levels (top Khuff C). Well-to-seismic calibration was conducted with and without using inter-bed multiple modeling. Tests were carried out for the IBMM using different starting tops for the generation of the inter-bed multiples. The selection of the starting point of the generation of the IBMM mainly influences the wavelet phase rotation and the synthetic seismic trace shape. The best result, in terms of well-to-seismic calibration in the target, was obtained when using the top Dammam. After the well-to-seismic calibration, an initial impedance model is built. It can be defined as the initial geological modeling. It integrates the seismic interpretation and associated stratigraphy with the calibrated impedance well log. Using the initial impedance model, a model-based inversion is considered. During the inversion a 3-D synthetic volume is computed at each iteration of the inversion process. At this stage some inversion tests were performed: (1) standard inversion without IBMM; (2) inversion using IBMM from the top Hith, and (3) inversion using IBMM from the top Dammam.

Conclusions

This methodology has been successfully applied on the Mutriba Field. The evaluation of the inversion results confirms the presence of significant inter-bed multiples within the Kra-Al-Maru and the Khuff intervals. The use of the inter-bed multiple modeling led to a better match between inversion results and the AI log at the well location. Moreover, the results show that the use of the IBMM in the inversion helps to get a more accurate vertical impedance contrast, associated to a better lateral homogeneity and is expected to allow a more reliable seismic reservoir characterization.

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11781 Khuff Formation in Kuwait: Depositional facies and diagenetic control on reservoir characterization

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The Permian–Triassic Khuff Formation holds huge oil and gas reserves in the Arabian Gulf region and is an important exploration target. The formation is poorly explored in Kuwait due to its occurrence at greater depths and hostile drilling environment. The Khuff Formation in Kuwait is divisible into A, B, C and D members. The Upper Khuff comprises A, B and C members and is separated from the Lower Khuff D Member by the Median Anhydrite.

The formation is comprised of dolomudstone, foraminiferal and algal dolowackestone, peloidal and algal dolopackstone, peloidal and oolitic dolograinsandstone, anhydrite and minor limestone (mudstone-wackestone with rare packstone and grainstone). The representative microfacies are grouped into four facies associations: (1) dolomudstone-dolowackestone; (2) dolopackstone-dolograinstone; (3) anhydrite; and (4) limestone. The formation was deposited under restricted setting in a subtidal to supratidal environment with minor variations in water depths (Figure 1). Syn-depositional tectonics played an important role on thickness variations and diagenetic history.

The diagenetic history is complex and sediments have undergone multiple diagenetic events from syn-depositional to post-depositional stages. Diagenetic events in the Khuff Formation have taken place in marine phreatic, mixed phreatic, meteoric phreatic and burial stages of diagenesis. The early diagenetic processes in marine phreatic environment are indicated by micritization and isopachous cements. However micritization is mostly obliterated by later diagenetic processes (Figure 2a). Mixed phreatic diagenesis has played a major role in Khuff diagenesis and is represented by dolomitization, anhydrite nodule formation and rare neomorphism. Dolomitization has generated intergranular porosity. However, at places over dolomitization has resulted in deterioration of porosity. Both mimetic and non-mimetic dolomite with varying crystal sizes is present. Meteoric phreatic stage of diagenesis has caused leaching and syntactical overgrowths.

Leaching has caused porosity generation in the areas away from the Kuwait Arch in the west where well-developed oomoldic porosity is preserved. Syntactical overgrowths on echinoderm grains have been dolomitized with mimic texture. Late stage diagenetic processes like stylolitization, saddle

Figure 1: Schematic diagram showing the depositional model of the Khuff Formation in Kuwait.

![Diagram](http://pubs.geoscienceworld.org/geoarabia/article-pdf/17/2/189/5445944/eage_2012.pdf)
The dolomitizing fluid percolates through the sediments flowing to west and east, away from the Kuwait Arch.

Less dolomitized and higher porosity Khuff preserved in western Kuwait.

dolomite, dedolomitization, poikilotopic anhydrite and late-stage fracturing are well-preserved. Stylolites are mostly low amplitude with black insoluble residue along stylolitic seams. At least two stages of fracturing are evident: the first-generation fracture fillings are mostly dolomitized, while later-stage fractures are filled with anhydrite and rare calcite. Scattered calcite crystals are present in selected intervals that might have been derived from fracture fills as well as by thermochemical sulphate reduction. The activation of the Kuwait Arch in successive pulses has also played a role, to some extent, in modifying the diagenetic patterns (Figure 2a).

These events have modified reservoir quality, to a certain extent, and have resulted in both the generation as well as destruction of porosity. Dolomitization, leaching and anhydrite cementation are the dominant control on porosity modification and its distribution. Variations in intensity of diagenesis have been observed vertically as well as laterally.

Most of the pores are occluded by anhydrite in the Khuff A Member, however, occasional intercrystalline porosity is seen. The poorly developed porosity in the Khuff B Member is mostly intercrystalline and rarely intergranular. The porosity in the Khuff C Member is mainly intercrystalline to rarely interparticle and locally moldic. The Khuff D Member has poor porosity development. Spatially, dolomitization is more pervasive over the Kuwait Arch where over-dolomitization and anhydrite cementation has mostly destroyed the porosity. The better porosity development is seen in the western part away from the Kuwait Arch where leaching has played an important role in porosity generation in the form of moldic porosity.
11460 Importance of trace fossils and bioturbation in carbonate reservoir characterization and reservoir quality: Examples from the Khuff Formation

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Several aspects of the study of trace fossils (ichnology) are relevant for the characterization of carbonate reservoirs, of which the following are most important: (1) facies interpretation by utilizing the ecological information of trace fossils and ichnocoenoses; (2) reservoir zonation by identifying sequence boundaries and flooding surfaces for correlation; and (3) reservoir quality and connectivity, which is directly affected by bioturbation. The vast shallow-marine carbonate platform of the Middle Permian to Lower Triassic Khuff Formation in the Middle East comprises broad facies belts with little significant changes in the lithofacies. However, trace fossil assemblages and ichnofabrics, in combination with sedimentological observations, serve in subdividing this platform and in distinguishing sub-environments. From proximal to distal, these are sabkha and salina, tidal flat, restricted lagoon, open lagoon, platform margin, shoreface/inner ramp, slope/outer ramp and basin/deeper intra-shelf. In this way, changes in relative sea level can be better reconstructed and guide the sequence-stratigraphic interpretation.

Meter-scale shallowing-upward cycles dominate the succession and, in addition to conventional methods, bioturbation, trace fossil assemblages and tiering patterns aid in interpreting subtidal, lower and upper intertidal and supratidal portions of these peritidal cycles. Bioturbation (and cryptobioturbation) have an impact on the primary reservoir quality before diagenetic processes overprint the deposits. For instance, deposit-feeders (such as vermiform organisms) introduce a certain amount of mud and decrease porosity and permeability considerably, whereas others like the Zoophycos-producers fill their dwellings with ooid grains and turn a mudstone from a barrier to a flow unit. This novel study demonstrates the value of ichnological information in carbonate reservoir characterization and the significance of trace fossil analysis in facies interpretation, reservoir zonation and the impact of bioturbation on the reservoir quality. Finally, a semi-quantitative analysis of the endobenthic activity across the Permian/Triassic boundary (PTB) enables for the first time the evaluation of recovery of endobenthic organisms after the end-Permian mass extinction by direct comparison of post-extinction (Lower Triassic) with pre-extinction (Upper Permian) units.

11711 Khuff sequences KS1 to KS4: Grainstone geobodies in the Middle and Upper Khuff of the Oman Mountains, Sultanate of Oman

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Summary

This study is part of a research project on Khuff grainstone bodies carried out in the Al Jabal al-Akhdar area (Oman Mountains) in the Sultanate of Oman (Figure 1) and focusses on Khuff sequences KS1 to KS4. Its aim was to unravel the Khuff stratigraphic architecture on hierarchical scales to understand geometries and textural variation of grainstones as potential reservoir bodies. Hierarchical static 3-D geological models were generated that visualise the sedimentary architecture of primary reservoir bodies using industry standard 3-D geomodelling software.

Methods

Outcrop data has been acquired in wadis on the northern flank of the Oman Mountains as well as on the Saq Plateau in the south (Figure 1). Each of the outcrop sections was worked from 1-D to 3-D analysis.
The 1-D analysis included detailed sedimentological and outcrop gamma-ray logging. Rock samples for detailed microfacies-, bio- and chemostratigraphic analyses were collected every few metres. In total, 575 rock samples were collected and 558 thin sections were prepared. Facies types were analysed and interpreted in terms of vertical stacking patterns on multiple scales (second- to fifth-order). One second-order supersequence made up of four third-order sequences (KS1 to KS4) was defined and interpreted to be time-equivalent with the Upper to Middle Khuff Formation (Koehrer et al., 2010). All 1-D data was recorded in WellCAD format.

In the 2-D analysis, outcrop sections were correlated by integrating all available bio-, chemo-, litho- and sequence-stratigraphic information. The stratigraphic architecture was visualised by the construction of facies cross-sections on various scales. On the Saiq Plateau, the 2-D analysis also included mapping of major stratigraphic surfaces and facies bodies along the outcrop wall with high-resolution Global Positioning System (GPS) technology (Zeller et al., 2011).

In the 3-D analysis, all generated data was used to build hierarchical static 3-D facies models (Petrel) from near-well-scale (2 x 1 km) to field-scale (8 x 8 km) to subregional-scale (60 x 40 km) (Figure 1). For the near-well-scale model of the Saiq Plateau outcrop, a digital elevation model (Quickbird) was used to drape the outcrop data.

**Near-well-scale Grainstone Architecture (100s of m-scale)**
A well-exposed outcrop section on the Saiq Plateau, 1,800 m wide, 1,000 m long and 100 m high, was studied to capture lateral and vertical depositional heterogeneities within sequences KS3 to KS1 Middle to Upper Khuff time-equivalent strata.
The highest net-to-gross values (53%) of grainstone reservoir facies can be found in the KS1 Sequence (Zeller et al., 2011). No significant lateral facies changes were observed in ten logged KS3 to KS1 sections over a lateral distance of 1,800 m. This suggests “layer-cake-type” geometries at the scale of 100s of metres. Individual grainstone bodies have some lateral thickness variations of 13% on average. This is most likely due to syn-sedimentary erosive amalgamation, truncation and “cannibalism” by repeated reworking in a high-energy environment.

Field-scale Grainstone Architecture (1,000s of m-scale)
Correlation of fifth-order cycles between five sections of KS3 to KS1 in an 8 x 8 km outcrop window on the Saiq Plateau revealed the importance of the sequence-stratigraphic hierarchy strongly controlling grainstone volumes and geometries (Koehrer et al., 2011).

The thickest and laterally most persistent shoal bodies occur during peak regression within each order of the hierarchical stratigraphic cyclicity. During transgression, shoal bodies systematically decrease in size and already pinch out after a few kilometres laterally. A clear correlation (Ro = 0.82) between maximum shoal body thickness and lateral extent was observed. Generally, the thicker a grainstone body, the longer it will be. Shingles or clinoforms of grainstone bodies were explicitly searched for along the outcrop wall but were not observed in the studied area.

Subregional-scale Grainstone Architecture (10s of km-scale)
Fourth-order cycle sets together with bio- and lithostratigraphic markers were used as time lines for stratigraphic correlation of the KS1 to KS4 portion of the Khuff-equivalent on a subregional-scale (60 x 40 km). Constructed cross-sections show high lateral continuity of facies, indicating the absence of any significant tectonic deformation of the area during the Late Permian and Early Triassic.

Presence, architecture and thickness of grainstones are largely governed by large-scale (second-order) stratigraphic trends. Thicker and more abundant grainstones are present during the early transgressive (KS4) and late regressive (KS1) portions of the second-order supersequence. Thinner and less abundant grainstones are present during the late transgression (KS3 and lower KS2) and early regression (upper KS2). Shoal-associated grainstone bodies are completely absent around the second-order zone of maximum flooding.

Conclusions

(1) A facies atlas has been established for the Khuff-equivalent deposits. 23 lithofacies types can be grouped into eight lithofacies associations.

(2) A depositional model could be established for the Khuff outcrops, representing a wide epeiric carbonate ramp, subdivided into seven sub-environments and lithofacies associations.

(3) Facies types occur in a number of re-occurring types and motifs of cycles and cycle sets.

(4) The stacking patterns of cycles, cycle sets and sequences led to the establishment of a sequence-stratigraphic framework for the Khuff in Oman.

(5) Based on integration of the sequence-stratigraphic framework, the depositional model and biostratigraphic data, nested 3-D models of the grainstone architecture of Khuff time-equivalent deposits in the Oman Mountains has been established on three different scales.

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11748 Uncertainties on Basal Khuff Clastics in outcrop in Saudi Arabia

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Introduction

Various types of clastic and mixed clastic-carbonate deposits represent the transition from the pre-Hercynian and Hercynian Palaeozoic formations and the marine Khuff carbonate in Saudi Arabia. Due to sedimentary and erosional hiatuses, the complexity of this sedimentation is particularly reinforced near the outcrop and on top of the Central Arabian Arch or of the Rayn Plate. Therefore, age and lithostratigraphic assignments of the litho-units resting underneath the Khuff carbonate are often uncertain or questionable. In order to avoid unconsidered assignments to a particular formation of these sediments prior to any critical analysis of the retained criteria, this study proposes a review of typical uncertainties and proposals of clarification.

D. Vaslet and Y.-M. Le Nindre in Delfour et al. (1982) subdivided the Khuff Formation in outcrop into five litho-sequential members: Unayzah, Huqayl, Duhaysan, Midhnab and Khartam, from type localities in Central Arabia near the type section at Khuff. To avoid confusion with the “Unayzah Formation” (A, B, C members) previously defined in subsurface, this interval, also named “Basal Khuff Clastics” or “Khuff E” (Al-Jallal, 1995) was renamed Ash-Shiqqah Member by Senalp (Senalp and Duaiji, 1995).

In the framework of the geological mapping of the cover-rock at a scale 1:250,000 (BRGM-DMMR, Figure 1), a set of lithostratigraphic sections along the outcrop belt from latitudes 20°N to 28°N show various modalities of contact between the marine Huqayl Member and the basement, or lower Palaeozoic formations through:

• A Lateritic paleosoil,
• The Ash-Shiqqah Member (former ‘Unayzah Member’),
• Khuff D and Mid Anhydrite,
• The Unayzah Formation,
• Other formations, tentatively assigned to Saq Sandstone, to other Palaeozoic sandstones.

In fact, uncertainties affect these assignments in several points. Not all is known in outcrop about the transition between the Pre-Unayzah Unconformity (PUU), and the Pre-Khuf Unconformity (PKU) or the ‘Pre-Wasia’ unconformity (= Pre-Majmah Unconformity PMU, Le Nindre et al., 2008) where it rests directly on the Palaeozoic, in particular about existence of the Unayzah Formation.

Lateritic Paleosoil

It was described by D. Vaslet in Delfour et al. (1982) in the Ad-Dawadimi Quadrangle, then generalised by Vaslet et al. (2005) with a certain extent between latitudes 23°45’N (Al-Mizal) and 27°10’N (Jal al-Khuffiyat). As it has been mapped, the lateritic paleosoil, although at the base of the Khuff Formation was in fact observed on pre-Unayzah formations as parent rocks (Figure 1). Therefore, there is no certainty regarding its age, and, as it is, it reflects more a pedogenesis on the pre-Unayzah unconformity surface than the pre-Khuff unconformity.

Ash Shiqqah Member

The Ash Shiqqah Member (cf. Basal Khuff Clastics/E Member) has to be differentiated from the Unayzah Formation in outcrop. First of all, users are easily confused by the dual nomenclature “Unayzah Member” (now obsolete) defined in outcrop near the town Unayzah, and the underlying “Unayzah Formation”, defined in subsurface (e.g. Al-Laboun, 1987). The main point is that, the Unayzah Formation, rarely found or characterized, was not definitely identified in outcrop in spite of the assignment of the lower portion of the Unayzah section (bearing flora) to the Unayzah Formation sensu subsurface by Vaslet et al. (2005). This question needs a discussion based on field evidence, biostratigraphic results, and regional correlation.
Figure 1: Pre-Khuff unconformity in Central Saudi Arabia with an index map of the BRGM-DMMM1 1:250,000 mapping programme (Vaslet et al., 2005, reprinted by permission of GeoArabia).
Khuff D and Mid Anhydrite

It is remarkable to observe the difference of facies between the former ‘Unayzah Member’ in the north and in the south of the Central Arabian Arch as shown by the mapping of the 1:250,000 quadrangles at the periphery of the shield. In the north (Ad-Dawadimi, Al-Faydah and Buraydah quadrangles), the basal member of the formation consists of red shale, pink/brown Mn dolomite and small-scale sandstone channels of marsh environments, similar to the definition of the Khuff E/Basal Khuff Clastics. In the south (Ar-Rayn and Al-Mulayh quadrangles), it consists of green shale and light grey dolomite with abundant gypsum, of playa/sabkha environment, similar to the description of the Khuff D/Mid Anhydrite, interpreted as on-lapping the shield (Vaslet et al., 2005).

Unayzah Formation

A map of the extent of the Unayzah Formation was published by Konert et al. (2001). Its correlation with the outcrop suggests very few exposed occurrences including the Unayzah type locality, already discussed, in the Qasim area. Based on several arguments, geometric, biostratigraphic, sedimentologic, geophysical, or on heavy minerals (Knox et al., 2010) new occurrences of this formation in outcrop could be demonstrated in scattered places all along the outcrop belt; in particular in the case of sandstone on sandstone contacts, so-far undifferentiated by accurate sedimentologic studies.

Basement Paleo-topography

Detailed surveys by Le Nindre et al. (1983) of the cover-rock basement contact in Central Saudi Arabia have shown various modalities of transition between the Upper Proterozoic basement and the Khuff.

Figure 2: Infra Khuff sandstones (brown) filling paleo-reliefs of volcanic rocks (black) of the Upper Proterozoic basement. Ar-Rayn quadrangle (Vaslet et al., 1983). Photo Le Nindre (2010).
carbonate. In particular, underlying the Mn dolomite of the Ash Shiqqah Member, sandstone bodies fill the paleo-topographies. On the Darma’ Quadrangle (Manivit et al., 1985) they were assigned by default to the Saq Sandstone, assuming a continuous extent of the formation from the north up to the paleorelief (Figure 2). In fact, from Cambrian–Ordovician to Late Permian, several scenarios are theoretically possible.

Conclusions

Modes of contact between the Proterozoic basement in central Arabia, or pre-Unayzah Palaeozoic formation, and the transgressive Khuff formation are various, and complex in outcrop. This is due to multiple unconformities, hiatuses, paleo-topographies, and stacking of mostly undated clastic deposits. Detailed sedimentologic studies, biostratigraphic analysis and accurate comparisons all along the outcrop belt, would be very fruitful to develop the knowledge of this interval, reduce uncertainties, and aid correlation for reservoir exploration and characterisation.

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11712 Post-stack seismic processing refinement facilitating Khuff and pre-Khuff exploration: Case study from shallow-marine offshore Abu Dhabi

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Three 3-D ocean-bottom cable (OBC) seismic surveys acquired in offshore Abu Dhabi have been subjected to ADNOC’s in-house post-stack seismic refinement routine. The objectives were to resolve the tuning effects caused by various stratigraphic features and enhance fault imaging at the deep Khuff and pre-Khuff targets. There were some remaining persistent issues, such as: (1) noise; (2) strong short-wavelength jitters of the acquisition footprint, which degraded the stack continuity even at depth; (3) multiples; and (4) the relatively low-frequency bandwidth of the final data. These issues hampered the interpretation of the data after the imaging stage.

A post-stack seismic data reprocessing flow was used, which includes 3-D FKK dip filter, notch filter, deconvolution-after-stack, time-variant spectral whitening and 3-D spatial filtering. Post-stack P-Z summation of the dual-sensor components was investigated and assessed on one of those surveys. The in-house reprocessing resulted not only in the significant reduction of the residual, random and linear noise, but also in the significant attenuation of the severe acquisition footprints. Time-variant spectral whitening resulted in wide usable frequency bandwidth without either magnifying the noise level or distorting the phase and/or amplitude of the input dataset. Deconvolution-after-stack significantly minimized the residual shallow-water reverberation multiples that were detrimentally interfering with the primaries in the dataset.

ADNOC’s in-house post-stack processing flow reduced the uncertainties in the interpretation stage. The horizon tracking at the Khuff and pre-Khuff levels turned out to be much easier compared to the interpretation of the previous processing vintages of those surveys. Seismic attributes such as curvature and coherency cubes have been extracted from the data after the completion of the in-house reprocessing. Some geological features, such as subtle structure undulations with faults lineaments, became easily delineated on the reprocessed dataset with this tailor-made post-stack reprocessing route, which were hardly easy to be achieved on the original dataset because of the various noise problems.

11772 Carbon- and oxygen-isotope stratigraphy: A tool for confirming sequence stratigraphy in the Early Triassic Kangan Formation, northern part of the Arabian Plate

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Summary

The Early Triassic Kangan Formation, which is equivalent to the Upper Khuff Formation, is the main reservoir for natural gas in southwest Iran and the northern Gulf. Investigations of this formation in offshore “Field A” indicate that it is composed of 14 facies deposited in tidal flat, lagoon and oolitic barrier settings in the inner part of a carbonate ramp or platform. Vertical variations of microfacies and gamma-ray, log profiles show that the formation consists of three depositional sequences (KG1 to KG3), each consisting of transgressive and highstand systems tracts and each bounded above by a Type-2 unconformity. Carbon- and oxygen-isotope profiles from a well-dated carbonate section were compared to sedimentological data and the results from a sequence-stratigraphic study. The profiles showed negative and positive peaks coinciding with sequence boundaries and maximum flooding surfaces, respectively.
Abstracts of Khuff Sequence Workshop, Part II

Introduction

The Early Triassic Kangan Formation comprises one of the most important carbonate reservoir rocks in southwest Iran. The Kangan and underlying Dalan formations form the Deh Ram Group (Stratigraphic Committee of Iran, 1976). The two formations were discussed in detail in a regional-scale account by Insalaco et al. (2006). Rahimpour-Bonab et al. (2010) investigated the reservoir quality of the formations in the South Pars gas field based on petrography, stable-isotope measurements, scanning electron microscope (SEM) analyses, and X-ray and CT scans of core samples. Peyravi et al. (2010) investigated the sedimentary environments, and sequence stratigraphy of the Kangan Formation in the northern part of the Gulf, emphasizing the implications for reservoir characterization based on petrography, gamma-ray log, Cyclolog® software and Gunter’s Technique. This present contribution shows that carbon- and oxygen-isotope signals can be used as a tool for confirmation of the sequence-stratigraphic surfaces.

Geological Setting

The Kangan Formation is the main reservoir in the offshore Field A, located 140 km south of Lavan Island offshore southern Iran (Figure 1). The formation is correlative with the upper part of the Khuff Formation to the south (Alsharhan, 1993; Al-Jallal, 1995; Kashfi, 2000, Fontana et al., 2010). In the study area, the Kangan Formation is composed of dolomites, evaporites, limestones and shales with an overall thickness of 390 m. At its type section, the Kangan rests conformably on the Dalan Formation (Motiei, 1993) and is conformably overlain by the Aghar Shale, part of the Dashtak Formation (Szabo and Kheradpir, 1978). Several authors have suggested that Early Silurian organic-rich shales, known in Iran as the Sarchahan Formation and in Saudi Arabia as the Qusaiiba “hot shales”, represent the source rock for the hydrocarbons in Permian and Lower Triassic reservoirs (e.g. Bordenave, 2008; Ameen et al., 2010; Rahimpour et al., 2010). In Iran, the Kangan Formation is sealed by the thick, massive anhydrites of the Middle to Late Triassic Dashtak Formation (Bordenave, 2008; Rahimpour et al., 2010).

Material and Methods

This research is based on petrographic studies of 270 thin sections obtained from cores from Field A, as well as sedimentological interpretations of gamma-ray logs. Thin sections were treated with Alizarin Red-S following Dickson (1966). Carbonate rocks were classified following Dunham (1962). Facies analysis and vertical and lateral changes were recorded following Carrozzi (1989) and Flügel (2004). Sequence-stratigraphic interpretations followed Van Wagoner (1988), Tucker (1999), Emery
Figure 2: Lithological column, facies, sequence stratigraphy, gamma-ray log, and carbon- and oxygen-isotope profiles from the studied area.
and Myers (1996), Miall (1997, 2000) and Catuneanu (2002). 44 samples were selected for carbon and oxygen stable-isotope analyses ($\delta^{13}C$ and $\delta^{18}O$).

Considering the sequence-stratigraphic surfaces and framework, and homogeneity, 41 samples from well core slabs were microdrilled while four samples were obtained by computer-automated micromill (IFP Energies nouvelles – Petrography Laboratory). The analyses was carried out at the Department of Geology, University of Erlangen, Germany. Carbonate powders were reacted with 100% phosphoric acid at 75°C using a Kiel III carbonate preparation line connected online to a Thermo Finnigan 252 mass spectrometer. All values are reported in permil relative to V-PDB by assuming a $\delta^{13}C$ value of +1.95‰ and $\delta^{18}O$ of -2.20‰ to NSB19. Oxygen-isotope values of dolomite were corrected using the phosphoric acid fractionation factor given by Rosenbaum and Sheppard (1986) and Kim et al (2007).

Results and Discussion

From petrographic observations of the Kangan Formation and gamma-ray logs, 14 microfacies were identified and were grouped into three facies associations: (1) tidal flat, (2) lagoonal, and (3) barrier. Equivalent facies were recognized by Insalaco et al. (2006) and Moradpour et al. (2008). These facies were deposited in the inner part of the carbonate ramp platform (Insalaco et al., 2006; Rahimpour et al., 2010; Peyravi et al., 2010).

(1) The tidal flat facies association consists of facies interpreted as originating in the intertidal and supratidal zone. It includes facies (A1), layered anhydrites with chickenwire texture; (A2) fenestral dolomudstones and stromatolite-thrombolite boundstones; and (A3) dolomudstones with evaporate casts and peloid grainstones with keystone vugs.

(2) The lagoonal facies association contains facies (B1): peloid grainstones and bioclast peloid packstone-grainstones; (B2) bioclast wackestones and bioturbated dolomitized lime mudstone/mudstones; and (B3) shale.

(3) The barrier facies association includes: (C1) ooid peloid grainstones and dolomitized ooid packstone/grainstones; (C2) dolomitized bioclastic oolitic intraclast packstone/grainstones; and (C3) dolomitized intraclastic/oolitic bioclastgrainstones.

Vertical facies variations in the Kangan Formation in Field A led to the recognition of three unconformity-bound sequences (KG3, KG2 and KG1). These sequences are comparable to the Lower Triassic part of the Permian–Triassic Ashk Supersquence of Heydari (2008).

Carbon- and oxygen-isotope profiles from a well-dated carbonate section from the Kangan Formation were compared to the sedimentological data and the results from sequence-stratigraphic analysis, in order to discuss the origin of isotopic variations in a shallow-marine carbonate succession. Our study led to the recognition of three third-order cycles whose boundaries correspond to distinct $\delta^{13}C$ and $\delta^{18}O$ negative peaks (Figure 2).

Conclusions

A study of lateral and vertical facies changes of the Kangan Formation in offshore southern Iran indicates that the formation was deposited in the inner part of a carbonate ramp/platform. The Kangan Formation comprises three depositional sequences, from oldest to youngest: KG3, KG2 and KG1. The lower boundary of KG3 forms a correlative conformity rather than an unconformity due to its palaeo-depositional setting. Isotopic data validated the sequence stratigraphy based on facies analysis; boundaries of the third-order cycles correspond with depleted isotopic compositions; and maximum flooding surfaces are marked by enriched isotopic compositions which is validated.

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11731 Using gravity and magnetic data to delineate deep basin geometry and faulting: Implications for Paleozoic sourcing for Permian–Triassic reservoirs in the Partitioned Zone/Divided Zone of Saudi Arabia and Kuwait

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Within the Partitioned Zone/Divided Zone (PZ/DZ) of the Kingdom of Saudi Arabia and the State of Kuwait, Wafra Joint Operations (WJO) utilizes non-seismic geophysical technologies as a means of complementing and leveraging the value returned by seismic exploration efforts – this in order to optimize development of the PZ/DZ asset. Legacy gravity data available in the area (dating back to 1949) were confirmed and supplemented by a ground gravity program acquired in 2010. Future plans initiated by WJO include the execution of an airborne gravity gradiometry and magnetic survey using latest technologies.

In this presentation we discuss the present and future use of gravity and magnetic data for delineating deep basin geometry and faulting manifested within the pre-Khuff Paleozoic intervals for which seismic imaging is typically problematic and poor. Based on currently available gravity data, the western Partitioned Zone/Divided Zone is high-graded as having a seemingly thick Paleozoic sedimentary section, which may contain Silurian Qusaiba source rock with the potential to charge the Khuff and the Permian–Triassic reservoirs as a whole. In contrast, other areas of the PZ/DZ are downgraded due to the apparent thinness of the Paleozoic section. Building on these positive gravity results, it is expected that the new airborne gravity gradiometry and magnetic survey data will further refine the understanding of deep basin geometry and hydrocarbon sourcing of the Permian–Triassic reservoirs.

11774 The Khuff multi-dimensional: Results from outcrop analogue studies in Oman

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The Permian–Triassic Khuff platform is a classical epeiric sequence with limited seismic-scale reservoir geometries. It is referred to by some as the thickest “pile of grainstones on Earth” and shows significant variations in productivity. To better understand these, grainstone dimensions and distributions were investigated in outcrops to:

• Establish a regional tie point for the Khuff stratigraphic framework.
• Describe grainstone architecture on different scales.
• Correlate reservoir bodies on sub-seismic scale (architecture of epeiric deposits).

The study area is the Al Jabal al-Akhdar in the Sultanate of Oman. Six outcrop sections of Lower to Upper Khuff time-equivalent strata (each about 1,000 m thick) were investigated. The study was designed:

• Multi-scale: from near-well bore to regional scale (‘Russian-doll’ approach).
• Multi-disciplinary: sedimentology-bio-chemo-sequence stratigraphy-petrophysics.
• Multi-dimensional: from 1-D sections to 3-D digital models.
Abstracts of Khuff Sequence Workshop, Part II

Results

(1) Khuff analogues in the Oman Mountains constitute the seaward margin of the Permian–Triassic platform.
(2) Study established the first complete Permian–Triassic outcrop section in the Middle East (biostratigraphy, chemostratigraphy and sequence stratigraphy).
(3) Two second-order supersequences were interpreted in the Khuff equivalent strata with maximum flooding in the KS6 and KS2 sequences.
(4) Interpreted time-lines allowed a regional correlation of six Khuff sequences.
(5) The presence of several important regional biostratigraphic markers (benthic foraminifera) has been reported for the first time in the Al Jabal al-Akhdar region.
(6) Nested 3-D models (‘Russian-doll’ approach) were created and predictive rules and trends established that describe grainstone architecture and geometries from 10s to > 10,000s meters.
(7) Geological concepts suggest potential for stratigraphic traps in the KS6 and KS5 sequences: (onlap and bypass channels) and potential source rock intervals around the KS6 to KS2 mfs.
(8) Grainstone attributes (e.g. aspect ratio, grain types, texture) are controlled by stratigraphic and paleotectonic position.

11826 Integrated formation evaluation and production potential of pre-Jurassic formations in Kuwait

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The Permian–Triassic Khuff Formation is an important hydrocarbon exploratory target in view of its proven potential in countries adjoining Kuwait. The formation, divisible into A, B, C and D units, is comprised of dolomite and limestone (mudstone-wackestone with rare packstone and grainstone) with subordinate shale and anhydrite. The formation is interpreted to be deposited in sub-tidal to supra-tidal environment with development of shoal and lagoon under hyper-saline conditions in a restricted setting. Diagenetic history is complex and sediments have undergone multiple diagenetic events that include micritization, dolomitization, anhydrite cementation, leaching, stylolitization, fracturing and fracture filling. In the north, the formation is over-dolomitized and can be categorized as tight non-conventional reservoir. In the west the formation has shown development of grainstone in the Khuff C with significant porosity preservation. Here, the formation has shown hydrocarbon potential on logs but the testing results did not match the conventional log interpretation. This has adversely impacted the hydrocarbon assessment of this formation. To analyze the inconsistency, petrophysical and testing data were re-evaluated.

A clear-cut workflow involving synergistic interpretation of different datasets has been evolved and lithological and flow properties and saturation models were prepared. The re-evaluation has been carried out integrating all the relevant data particularly well logs, core reports, well testing, mud log and drilling reports. The a, m, and n parameters generated afresh from the core plugs along with thin section petrography and the sigma measurements from the Accelerator Porosity Sonde (APS) were used to refine the model. Also SPAN analysis showed that the perforation reached to the virgin zones of the formation. The productivity index analysis suggests that the flow capacity is in agreement with the flow rates indicating that the test-produced water is coming from the formation itself. It is recommended to run LWD in exploratory wells, introduce Dielectric Scanner for continuous measurement of cementation factor, carry out core analysis at formation net confining stress and temperature and longer test durations to enable flow stabilization and removal of formation skin damage.
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11849 Prospectivity of Khuff reservoir in southwest Kuwait

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The Permian–Triassic Khuff Formation is an extensive gas reservoir in the Arabian Gulf area. The formation houses the world’s largest gas accumulation: the combined North Field (Qatar) and South Pars (Iran) dome, contain approximately 1,500 TCF of gas (Halbouty, 2003). The formation was deposited during a regional transgression over a stable shelf of very low relief, which had minor clastic supply on the margin of Arabian Peninsula. The porosity and permeability of the Khuff carbonate reservoirs are generally very low in the entire Middle East. Ehrenberg et al. (2007) showed that porosity in the Middle East varies from 2–14%, where the depth of reservoir varies from 2–5.5 km. To explore the Khuff reservoir prospectivity, post–stack seismic inversion and porosity modeling was carried out using recently acquired 3-D Q-Land seismic data. The study area consists of two major fields, Minagish and Umm Gudair, which are located over major structural highs. In the southwestern part of Kuwait only one well was drilled to the Khuff-C reservoir over the structural high of West Umm Gudair Field. Here the Khuff-C reservoir occurs at greater depth and is around 350 feet thick. The observed porosity of the unit is around 2.0%. The testing of the unit could not be carried due to mechanical problem.

The principal objective of seismic inversion is to transform seismic reflection data into a quantitative rock property and is being used in the industry for better understanding of the reservoir properties and realistic assessment of oil-in-place. In the present study geological, geophysical and petrophysical data are combined through the Constrained Sparse Spike Inversion (CSSI) technique to generate an Acoustic Impedance (AI) volume. The interpreted seismic horizons and AI logs are used to create a low-frequency component of seismic inversion, whereas the band-limited information is taken from seismic data. The AI volume is generated through CSSI process. As AI is closely related to lithology, porosity and pore fluid saturation of reservoir rock, it is possible to find an empirical relationship between AI and rock properties. Within the Khuff-C reservoir the cross-plot between AI and porosity at the well indicates an inverse relationship that is utilized in transforming AI to porosity volume.

A modeling study shows that porosity for Khuff-C layer varies from 2–3% in the study area. Porosity development corresponding to the Khuff-C reservoir shows overall better porosity development over the East Umm Gudair anticline compared to West Umm Gudair and Minagish fields. But porosity is...
poorly developed at the structurally highest part of the area. Careful analysis of seismic data shows some anomalous feature over the East Umm Gudair anticline. The character of seismic data is quite different from the rest of the area around the Khuff level. The data looks noisy and disturbed in this part and this anomaly does not continue in shallower level. It is interpreted that the anomaly might be associated with faulting and intense fracturing.

In view of the seismic anomaly associated with the Khuff level and observed better porosity development over East Umm Gudair Field, the area is recommended to be explored for Khuff-C prospectively.

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11722: Upper Permian to Lower Triassic carbon-isotope record in the Oman and Zagros Mountains: An overview from the shallow platform to the basin

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The Oman Mountains as well as the Zagros Mountains expose a segment of Neo-Tethyan southern margin. We will review the $\delta^{13}C$ and $\delta^{18}O$ isotope curves in various sections from shallow- to deep-water facies zones for the Upper Permian-Lower Triassic carbonate sequences from Oman and show some preliminary results from Zagros. The shallow-water environment was measured in the Al Jabal al-Akhdar Mountains (Wadi Sathan section), the Saih Hatat (Wadi Sawat) and the Musandam (Wadi Shahha), and the slope carbonates of the platform margin in the Sumeini area (Wadi Maqam). Deep-water deposits from the basinal sector of the margin were studied in the Hawasina Nappes (Wadi Wasit South, Wadi Musjah and Buday‘ah) and the Bata‘in complex (Sal). Drowned carbonate platform (Oman Exotics) and tilted blocks of the platform have also been studied (Ba‘id and Wadi Wasit block).

Not all the sections span the Upper Permian until the Spathian without gap and/or sufficient biostratigraphic constraints but we could reconstruct a well-founded curve for the three paleo-settings and we can use it as an efficient correlation tool for the Khuff and Sudair formations or equivalent.

Wordian to Wuchiapingian carbonates have high $\delta^{13}C$ values between +3‰ and +6.6‰. The Changhsingian is missing or not proven in many sections except at Maqam and Wadi Sahtan, where the main negative carbon-isotope excursion typical for the Permian/Triassic Boundary interval is present. The Griesbachian sediments display negative values, constantly increasing upwards. In the Wadi Wasit block, this increase is simultaneous with the increase in biodiversity. In many other sections worldwide the upper Griesbachian units show a negative excursion, which is here present only in Wadi Sahtan. In the Wadi Wasit block this period is probably absent or condensed. In other sections a Dienerian megabreccia evidences erosion of upper Griesbachian sediments.
The Dienerian sediments, where present, are thin and show increasing carbon-isotope values. The upper Dienerian (N. cristigalli Zone) shows a very short distinct negative excursion of 1.5‰ to 4‰, more pronounced in the basinal sediments. This short excursion is followed by a strong double-positive peak of 1.9‰ to 7.5‰ amplitude. These peaks are again stronger in basinal sediments and less marked on the platform. Above, very negative δ13C values continue for most of the Smithian with values between 0.9‰ and -2.5‰ in all the different paleo-settings, indicating increased ocean circulation. The Smithian/Spathian boundary, present in Wadi Sahtan, Wadi Maqam and Sa is marked by a short strong positive peak with amplitude up to 7.2‰ and, again, more pronounced in the basinal sediments.

In summary, the Wordian and Wuchiapingian give a consistent dataset, the Changhsingian and Griesbachian are poorly preserved, whereas during Dienerian to Spathian time, platform and basin are showing divergent amplitude in the carbon-isotope signal.
Arid region carbonate platforms: Middle East reservoirs

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Calcitic grainstones and some dolomitic packstones are amongst the most common Middle East reservoir lithologies and they host some of the best hydrocarbon reservoirs in the world. They are well-sorted, winnowed carbonate deposits with little or no carbonate mud, normally formed in moderate to warm shallow-water, high-energy settings. Substantial accumulations of this facies may form in relatively shallow, subsiding basins so that deposition and subsidence remain in balance thus permitting continuous deposition. Where these sediments remain only partially cemented, fairly open porosity is maintained and upon burial there is only moderate compaction and such sediments can act as excellent hydrocarbon reservoirs. The packstones accumulated both downslope from the grainshoals and updip to their lee-side. Their porosity is in part depositional and in part diagenetic.

Evaporites form excellent seals for the grainstone and packstone porosity. In the same basinal settings, small worldwide sea-level fluctuations produce more restricted marine circulation, and evaporite formation may result. While shallow-water carbonate accumulation takes place at 1–3 cm/1,000 years (for non-reefal carbonates) and 1–3 m/1,000 years (reefal carbonates), the shallow-water evaporites (in the same settings) may form at 1–40 m/1,000 years for sulphates and 10–100 m/1,000 years for halite. While carbonate deposition commonly just keeps up with developing basinal accommodation (at about the same rate), evaporites completely fill all available basinal capacity within a very short time period, perhaps a few thousand years, vastly exceeding subsidence.

Evaporites can also tell you something about the geological history of a basin. For open-water marine carbonates, small changes in sea level merely result in lateral depositional shifts, as the products of biotic carbonate formation and deposition are redistributed by migrating wave action and associated currents. However evaporites fill almost any basin nearly up to sea level, within a few thousand years. This creates almost perfect depositional time lines. These depositional fill-surfaces may also become truncated wherever sea level actually drops below the regional sediment top and become karstified down to the levels of regional drawdown. The next marine sea-level rise that overtops the regional barriers permits re-establishment of open-marine deposition, a much slower process, thus new accommodation can develop. In this way regional correlation is relatively easy and the evaporites represent a useful time line.

Delineation of Khuff reservoir in Kra Al Maru Area of Kuwait using seismic inversion and lithology modeling: A case study

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A seismic reservoir characterization study was carried out over the Kra Al Maru structural trend in Kuwait to model the lithology of the Permian–Triassic Khuff reservoir. The dominant lithologies of the Khuff Formation are dolomites and dolomitic limestone with thin inter-beds of anhydrite and shale. The Khuff Formation has been divided into three units based on the lithological characters observed from one well. All three units contain dolomites, limestone, anhydrite and shale. The seismic data used was processed in 2005 with 25 meter bin spacing. Only one well was available for this study with the required log suite. The technique used was the Constraint Sparse Spike Inversion (CSSI) to produce the Acoustic Impedance (AI) volume. The principle objective of seismic inversion is to transform seismic reflection data into a quantitative Khuff rock property. A relationship between the acoustic impedance (AI) log and porosity log was established using the available well data to transform the AI volume to lithology volume.

Methodology

In this study, one available well was considered for well-to-seismic correlation. At the well location an acoustic impedance log was generated using the sonic and density logs. As part of the well-to-seismic
Figure 1: Relative and absolute acoustic impedance.
calibration process a synthetic Ricker wavelet was generated and scaled to seismic amplitudes. The synthetic seismogram was computed using the synthetic Ricker wavelet and the acoustic impedance log. The match between the synthetic seismogram and the seismic trace was reasonable from the Jilh Dolomite to the bottom of Khuff, which allowed a reasonable estimation of the wavelet. A 3-D acoustic impedance model was built using an interpolation technique that is guided by the interpreted horizons and the stratigraphic framework provided by the interpreters. This model was used to provide the low-frequency component for the seismic inversion. The CSSI technique was used to generate the relative acoustic impedance volume with band-pass frequency of 10–40 Hz. Figure 1 shows the relative acoustic impedance and absolute impedance volumes. The relative acoustic impedance 3-D model was then merged with the low-frequency component of the well acoustic impedance 3-D model to produce the final absolute acoustic impedance (full bandwidth). Quality control steps were carried out to check the validity of seismic inversion volume. The relationship between AI and porosity was established from the well logs through cross plots for the reservoir layer from top to base of the Khuff Formation. This relationship was applied on the final absolute AI volume to transform into a lithology volume.

Results and Conclusions

This study identified a low-impedance layer in the final absolute AI volume within the Khuff. It also showed a high porosity layer in the lithology volume within the Khuff, which may be related to the shale content. The high acoustic impedance values are related to dolomite content but no clear evidence of prospective matrix porosity was observed. The log characters also indicate poor reservoir potential. The study has allowed reconsidering the future drilling plan targeting the Khuff Formation in Kra Al Maru and has helped the geophysicists to reinterpret the deep horizons with a good level of confidence by using the relative AI volume (seismic band pass inversion).

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11773 Basement configuration and its impact on Permian–Triassic prospectivity in Kuwait

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Summary

Petroleum exploration efforts to date have been primarily focused on the Cretaceous and Jurassic targets and very little effort has been made for exploring deeper prospects in Kuwait. The seismic data quality due to its infestation with multiples does not allow for mapping the deeper prospects with confidence. For meeting this objective, an integrated modelling of seismic, gravity, magnetic and borehole data was carried out for generating a basement configuration map to evaluate the likely preservation of the Lower Silurian Qusaiba hot shale. The Qusaiba hot shale is the source for some
Introduction

The broad structural architecture of Kuwait is defined by the NNW-trending Kuwait Arch flanked by the Dibdibba Trough to its west and offshore Kuwait to its east. Considerable flow of high-pressure, high-temperature (HPHT) gas in the Kra-Al Maru Member of the Lower Jilh (Middle Triassic) in deep wells at Mutriba and Kra-Al Maru structures has enhanced the hydrocarbon prospectivity of the Dibdibba Trough for the deeper prospects. In view of the possible potential at deeper levels of the Triassic–Paleozoic system, the salt-triggered structures of Kra-Al Maru and Mutriba in the Dibdibba Graben (Singh et al., 2009, 2010) assume greater importance for future deeper exploration. So far only a few wells located on the Kuwait Arch have penetrated the pre-Khuff sequences.

The Silurian sedimentary package comprising the most prolific source rock, the Qusaiba hot shale, is missing in these wells. No well penetrated the entire Khuff section in the Dibdibba Trough. The deeper anomalous structures and basement faults are mainly obscured on the seismic data due to the presence of multiple events and limited impedance contrast between the Devonian-Silurian and Cambrian-Ordovician sediments (economical basement). To enhance the geological understanding of the trough, integrated modeling has been carried out with the objective to envisage the possible preservation of the Lower Silurian Qusaiba Member in the deepest part of the basin. This unit is

Figure 1: Basement configuration map of onland Kuwait generated from integrated modelling of seismic, gravity, magnetic and borehole data. Black dotted lines are faults mapped from combined modelling of seismic, gravity and magnetic data. Parrot dotted lines are the faults mapped from uplifted basement blocks from bandpass filtered magnetic data.
the main source of low-sulfur light oil and gas, and one of the most prolific petroleum-generating systems of Khuff and Pre-Khuff in the Middle East region (McGillivray and Husseini, 1992).

Methodology

In order to meet the objective of estimating basement depth, integrated modelling along sixteen regional seismic lines has been carried out using seismic, gravity, magnetic and well data. The estimated depth to the Khuff using available well and regional velocity model is fairly acceptable. The density values of each formation are picked from density logs and averaged for the similar lithological suites with a weighted average method. The depth-converted seismic sections are used as a bit map for 2½-D modeling to guide the geometry of the density polygons. The density polygon at the economic basement level and top of Hormuz Salt are exported to OpenWorks along the seismic lines. Horizon correlation at these levels is carried out with additional 25 depth-converted dip and strike seismic sections (grid 5 x 5 km) for better control for generating a regional basement configuration map (Figure 1). The major faults are also mapped from integrated models (black dotted lines). The faults in light blue colour dotted lines are mapped from the bandpass filtered magnetic map.

Analysis

A maximum sedimentary thickness of nearly 28,000 feet in the Dibdibba Trough is estimated (Figure 1). The basement depth near Mutriba and Kra-Al Maru in the Dibdibba Trough is the maximum. The Qusaiba hot shale is inferred to be preserved in the Dibdibba Trough in western Kuwait and enhances the deeper prospectivity. Underlying Phanerozoic strata in Kuwait, there is a faulted Precambrian basement, with alternating horsts and grabens directed along the dominant N-S Arabian trend. The faults mapped from filtered magnetic data and represented by light blue dotted lines are deep-seated and affect Precambrian crystalline basement and might have been reactivated during various tectonic movements of the Arabian Plate. These faults may act as a conduit for the migration of hydrocarbons sourced by the Qusaiba hot shale for the Permian–Triassic structural traps. The basement configuration map has important implications for Permian–Triassic prospectivity of Kuwait.

Conclusions

The integrated modeling using seismic, gravity, magnetic and well data helped in understanding the basement configuration, Khuff and pre-Khuff sedimentary fill and basement faults. These elements are envisaged to have influenced the Permian–Triassic petroleum system.

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Diagenetic trends in arid carbonates: What makes the Khuff dolostone reservoirs?

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Numerous studies and publications have shown that the Khuff reservoirs in the Middle East consist of carbonates that were deposited on shallow, hypersaline epeiric platforms. Hypersaline deposits are represented by evaporites, whilst carbonates correspond to the more open-marine conditions. Thus, a significant percentage of the Khuff Formation contains dolostones, which were formed during early diagenetic stages (sabkha and/or reflux dolomitization) and during burial (burial dolomitization and fault/fracture-related dolomitization).

The prediction of the distribution of dolostones and their rock properties is of relevance to optimally produce Khuff hydrocarbon accumulations and to explore for Khuff reservoirs at significant depths (< 4,000 m). Seismic information is of limited use in this case, as dolostones are commonly too thin to be detected. Genetic models are required to help establishing areas with porous dolostones. This contribution will discuss the dolomitization processes (with associated by-products) that have been proposed/recorded in the Khuff Formation, as well as their impact on the lateral extension and the reservoir properties of the dolomitized reservoir units.

Dolostone Types in Khuff Formation

Genetically, the dolostone types observed in the Khuff Formation include: (1) early, mud- and anhydrite-rich, fine-grained dolostones that formed in sabkha or lagoonal environments, with poor reservoir quality; (2) early, mud-lean and anhydrite-poor, dolomitized shoal grainstones of good reservoir quality; and (3) iron-rich burial (to fault-related dolostones), of variable reservoir quality, which have mostly excellent properties if associated to late leaching. Each dolomite type has different characteristics such as stratigraphic position, textural and cathodo-luminescence patterns, isotopic compositions and well-log signatures.

Diagenetic Environments and Impact on Reservoir Quality

The depositional and early diagenetic characteristics of the Khuff Formation, and the presence of early dolomites at parasequence level, support a depositional template resulting from the stacking of salinity increase parasequences. This is evidenced in the vertical rock record as follows: subaerial exposure followed by peloidal-oolitic limestones at the bottom, followed by early diagenetic dolomites and ending in evaporites (originally subaqueous selenitic gypsum and sabkha anhydrites).

These parasequences show early diagenetic products that record the oscillations of free and interstitial waters, from marine to hypersaline conditions, with fresh water inflows. The distribution of the early diagenetic products mostly followed the depositional template. Late diagenesis (burial and fault/fracture-related) modified the depositional/early diagenetic template of porosity/permeability distribution, increasing the lateral and vertical heterogeneity as a result of (1) burial and/or fault/fracture-related dolomitization, (2) leaching, and (3) dissolution-reprecipitation of anhydrite.

The early dolomitized intervals are mostly non-reservoir in the region, whilst the ooid grainstones commonly exhibit good reservoir quality. Net increase and/or redistribution of porosity of Khuff reservoirs at burial stages are mostly related to dolomitization (including fault- and fracture-related dolomitization) and late leaching. Associated to these processes, late calcite and late anhydrite precipitation locally degraded reservoir properties of ooid grainstones and burial dolomites. Understanding the successive diagenetic stages and their impact on the rock properties has been proven of relevance for the prediction and distribution of rock types away from the well bore.
Learnings from Diagenetic and Geochemical Studies

This paper will present an overview of: (1) overall diagenetic changes in hypersaline carbonate settings, their impact on reservoir properties and the applicability to the Khuff reservoirs; (2) the diagenetic trends recorded in Khuff reservoirs in the region; (3) the use of isotopic composition and fluid inclusions to unravel the fluid evolution during diagenesis and its impact on reservoir properties; (4) the role of residual hypersaline brines derived from evaporite precipitation in both, early and burial diagenetic patterns observed in Khuff reservoirs; and (5) the modification of reservoir properties due to the inflow of deep-seated brines, associated fault-related dolomitization and dissolution/re-preservation of anhydrite.

The overall diagenetic evolution and the different scenarios of diagenetic changes occurring in open versus closed systems are of relevance for the property distribution and dimensions of dolostone reservoirs (Figure 1). The source of Mg$^{2+}$ will impact the volumes of dolomitized rock, the export of solutes from the reservoir units will favour porosity (and most likely permeability enhancement), and the inflow of external fluids (e.g. deep seated hydrothermal fluids) may cause leaching fronts, overdolomitization close to faults and fractures, and dissolution-reprecipitation of anhydrite. All these products contribute to the increase of the reservoir heterogeneity with local improvement or deterioration of the rock properties.

Dolostones, both early or burial in origin, follow a primary depositional-stratigraphic-structural template. Mapping of grainstone belts of third-order sequences and basement-rooted faults are key strategies to predict the distribution of the dolostone reservoirs.

| Diagenetic Environments | Fluid source (open/closed system) | Mg$^{2+}$ Source | Diagenetic Products | Reservoir Quality | Porosity Trend | Permeability Trend | Template/Dimensions |
|-------------------------|----------------------------------|------------------|--------------------|------------------|---------------|-------------------|-------------------|
| Sabkha                  | Open    | Seawater         | Dolomite. Early anhydrite | Very poor        |               |                   | Depositional. Constrained by extension of evaporites and flow/density gradients. |
| Reflux                  | Open    | Seawater         | Dolomite. Early anhydrite | Poor to good     |               |                   | Depositional. Constrained by extension of evaporites and flow/density gradients. |
| Burial                  | Closed  | Residual evaporitic brines | Dolomite. Minor anhydrite | Good/Very good  |               |                   | Depositional. Follow depositional units with originally good reservoir properties. |
| Fault-related           | Open    | Basal clastics? Evaporites? | Dolomite. Late anhydrite. Late calcite | Poor to very good (if leaching) - Heterogeneity increases |               |                   | Mixed: Depositional and structural. Unknown dimensions |

Figure 1: Summary table compiling the recognized dolomitization processes and their impact on the reservoir properties.

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11721 Pre-Permian extensional deformation and uplift in the central High Zagros, Iran

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Throughout the Arabian Plate (Figure 1), a more-or-less prominent sedimentary hiatus separates the late Carboniferous (?)–Permian sequence from the older sedimentary formations. This hiatus and corresponding unconformity is generally named the “Hercynian unconformity” suggesting a relationship with the Hercynian (Variscan) Orogeny, which affected Western Europe and westernmost Africa during the Carboniferous. In the High Zagros Belt (HZB), which belongs to the Zagros Fold-and-Thrust belt (ZFTB), this pre-Permian unconformity exists everywhere. However, this unconformity seals truncated Lower Paleozoic strata and normal faults by the new mapping and field evidences (Figure 2).

Figure 1: The Zagros Fold-Thrust Belt in the frame of the Arabian Plate with location of the Central High Zagros and Ghawar Field area.
In Central High Zagros (CHZ, Figure 1) the only structures that can be related to the pre-Permian events are normal faults and tilted blocks. Further work is required to constrain both the timing and amount of uplift. However, examination of existing data in the Arabian Plate already suggests some hypotheses. The Ghawar area (one of the largest hydrocarbon fields in the world) is located in eastern Saudi Arabia about 300 km south of the study area. A cross-section (Figure 3) in this field shows a set of normal faults delineating horst blocks, where Cambrian–Ordovician rocks rest directly below the unconformity (Wender et al., 1998).

Further to the west in the Arabian Plate, Kohn et al. (1992) define a “major Late Devonian–Early Carboniferous thermo-tectonic event” responsible for uplift and huge erosion. Using Zircon fission track of Precambrian samples from deep boreholes and outcrops, these authors obtained 330–370 Ma ages (Late Devonian–Early Carboniferous). These ages indicate that: (1) there was a total resetting of Zircon fission tracks clocks (temperature required: 225 ± 50°C); (2) the timing of exhumation (and related erosion) is Late Devonian–Early Carboniferous; (3) the thermal gradient was probably high (about 50°C/km) before the exhumation.

Interestingly, in the Central High Zagros, Gavillot et al. (2010) noticed that a sample from the Mila Formation (deposited ca. 500 Ma ago) was reset and then exhumed at 350 Ma, which is the same age found by Kohn et al. (1992). Further thermo-chronologic work is required to reinforce this preliminary result. However, numerous indications suggest that the pre-Permian geological history results from thermal uplift accompanying normal faulting and not from a far effect of the Variscan Orogeny as classically assumed. The age of the uplift is not yet well-constrained but seems to occur during the
Late Devonian–Early Carboniferous. The subsequent cooling of the lithosphere should be responsible for thermal subsidence and deposition of the Faraghan-Unayzah and Dalan-Khuff formations by the Late Carboniferous.

Our results raise the question regarding the effects of the Variscan Orogeny in the Arabian domain. Thermo-chronologic data obtained by Kohn et al. (1992) in the northwestern end of Arabia as well as the preliminary results by Gavillot et al. (2010) in the study area show that the uplift of the whole Arabia as early as the Late Devonian is most probably due to thermal origin. Moreover, the great wavelength (ca. 1,000 km) suggests a relationship with aesthenosphere dynamics rather than a far compressive field. Quantification of these processes requires more data and more modelling.

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11745 Multi-scale assessment of the Middle Eastern Permian–Triassic Khuff carbonate: Structural evolution and its impact on reservoir properties

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The Khuff Petroleum System Study is a multi-scale, multi-disciplinary analysis that integrates subsurface and outcrop, rock and fluid samples, and static and dynamic data in order to characterize the Permian–Triassic Khuff carbonate, one of the major petroleum reservoirs in the Middle East region. At regional scale, the Khuff carbonate shows a variety of depositional environments (with facies ranging from coastal plain anhydritic claystone, tidal flat/low-to-high energy lagoonal deposits to open-marine dolostones alternating with grainy limestones and high-energy shoal-dominated dolostone/thick grainy limestones). The thickness varies from near zero at the pinch-out of siliciclastic facies in Central Saudi Arabia, to more than 400 m (1,300 ft) in Ghawar Field in northern Saudi Arabia, expanding to 800 m (2,600 ft) in the North Field, Qatar and to nearly 1,000 m (3,300 ft) in the eastern United Arab Emirates.

Local seismic data calibrated to regional well correlations indicate that Khuff thickness, lithology and facies distributions are strongly controlled by the inherited structural relief and also by the reactivation of the basement structural fabric related to Permian–Triassic tectonic events. Therefore according to the tectonic setting, the study area could be subdivided in four mega-structural provinces: (1) the Arabian Peninsula, (2) Oman, (3) the Zagros region, and the (4) the salt provinces.
In the Arabian Peninsula, pre-Khuff basement-related anisotropies are interpreted to have formed as early as late Neoproterozoic to Ediacarian time and to follow several main trends: (1) N-S (Nabitah), (2) NW-SE to WNW-ESE (Najd), (3) NNW-SSE to NW-SE (Mesopotamian).

At the regional-scale the Lower Khuff thickness shows a step-wise increase from fault block to fault block towards the northeast. This trend is consistent with an extensional/transtensional reactivation of the NW-SE to WNW-ESE pre-existing basement anisotropies. During the Middle to Late Permian, the break-up of the Cimmerian terranes was associated with an azimuth of extension oriented around NNE-SSW implying the Lower Khuff to represent a syn-rift sequence. During the Early–Middle Triassic, the Cimmerian blocks made a relatively rapid separation from the Arabian margin, opening the Neo-Tethys behind. Its evolving active spreading centre exerted a ridge-push progressively stabilizing the passive margins of the opening oceanic basin. Accordingly, the stress field was re-oriented with a NE-trending maximum horizontal stress direction allowing reactivation of the N-S and the NNW-/NW-trending basement fabrics. The resulting pattern of fault-interferences is interpreted to be responsible for the irregular thickness distribution observed in the Upper Khuff Member.

Within the salt mega-structural province, the producing fields and discoveries in the Southern Gulf Salt Basin show a surprising variability in depth, thickness, bulk lithology, average porosity, reservoir fluids and productivity. At regional scale, the variability in reservoir properties identified in this study is interpreted to be controlled by different tectonic structuration and activity such as fault reactivations, by salt diapir-specific growth history coupled with large-scale burial alteration, deep burial in-situ modification of hydrocarbons in-place and displacement of hydrocarbons by late non-hydrocarbon charge. Therefore, understanding the interaction between regional tectonic events, basin trunk lineaments and sedimentation is a crucial and critical step in order to map paleogeography, thickness distributions, facies patterns and play fairways across the entire Arabian Plate.

11714 Khuff Sequence 5 (KS5), Oman Mountains:
Lateral facies and sequence variability – a record of differential subsidence?
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This study focuses on the sequence stratigraphy and 3-D modelling of the Khuff Sequence 5 (KS5) in the Oman Mountains (Al Jabal al-Akhdar), Sultanate of Oman. The Lower Khuff sequences (KS5 and KS6) are at this stage poorly understood, since most of the reservoir units are located in the Upper and Middle Khuff sequences (KS1 to KS4). Previous studies (Koehrer et al., 2010, 2011) revealed layer-cake geometries of grainstone bodies in the Middle and Upper Khuff sequences (KS1 to KS4) on outcrop to exploration scales. The key question of this study was if the layer-cake geometries continue to be present or are different in the KS5.

Database and Workflow

Five outcrop sections in the Oman Mountains form the basis for this project. The sections were logged sedimentologically on a 1:100 scale. In total 1,080 m of KS5 strata was investigated. Data on lithology, sedimentary structures and textures, facies types, components and rock colour were noted. For the determination of facies types an established Khuff facies atlas (Koehrer et al., 2010) was applied. A total of 227 thin sections were analysed for detailed interpretation of depositional environments. Furthermore the natural gamma-radiation of the outcrop strata was measured with a spacing of every half a metre.

The concept of dynamic stratigraphy (Aigner, 1985; Kerans and Tinker, 1997; Aigner et al., 1998) was applied as workflow for this project. Based on the 1-D analysis of sequences and their stacking patterns, 2-dimensional correlations were constructed, that built the framework for the final 3-dimensional models.
Sedimentological Analysis

Based on the detailed sedimentological analysis and thin-section investigations 11 different lithofacies types could be identified in KS5. These were grouped into six lithofacies associations, which were 3-dimensionally modelled: (1) tidal flat, (2) low-energy backshoal, (3) moderate-energy backshoal, (4) high-energy shoal, (5) moderate-energy fore-shoal, and (6) low-energy off-shoal. Since several facies types can either represent fore-shoal or back-shoal deposits, it was crucial to find indicators that allow the differentiation between fore-shoal and back-shoal. Several skeletal as well as non-skeletal particles were found to provide indicator criteria.

One-dimensional sequence stratigraphy: The 1-D sequence-stratigraphic analysis revealed several orders of cyclicity. The smallest scale of cycles was identified directly in the outcrops. A maximum of 66 small-scale cycles were recorded. Taking the 6.8 million years of KS5 into account the resulting average time span of a cycle comprises 103,000 years and can be assigned to the fifth-order Milankovitch cycles. The small-scale cycles could be grouped into genetically related medium-scale cycle sets. With a maximum of 21 medium-scale cycle sets an average cycle set duration of about 324,000 years results. They probably represent the fourth-order Milankovitch signals. Furthermore four high-frequency sequences (HFS) could be identified, marked by very characteristic gamma-ray patterns. It was possible to correlate these HFSs with subsurface well data. The whole Khuff Sequence KS5 represents one third-order composite sequence.

Two-dimensional correlations: Two different correlation strategies were applied: the first one is based on the appearance of the four HFSs; the second one does not take the HFSs into account. Due to thickness variations between the different sections, lateral facies changes (Figure 1) as well as differential subsidence, complex correlation geometries, such as apparent downlaps, resulted. Thus, the KS5 differs markedly from the relatively simple layer-cake pattern of the Middle and Upper Khuff.

Three-dimensional models: Different 3-D models (based on the different correlation versions as well as different algorithms) clearly display the lateral facies changes, thickness differences and depositional geometries (Figure 2). The appearance of shoal facies, representing possible reservoirs, is governed by palaeogeography and stratigraphic position. The proximal sections in the northwest

Figure 1: Correlation example of the lowermost high-frequency sequence HFS 4. The maximum flooding of the HFS is used as datum. A clear deepening trend from west to east can be seen in the regressive phase.
Figure 2: Example of a 3-D model run with the SIS algorithm. It shows the lower part of the smoothed model resulting from 12 realizations. This realization is based on the HFS correlation. Important horizons are displayed to point out the downlapping or onlapping geometries of cycle sets (indicated by the arrows). The colour code is the same as in Figure 1. View is from the northeast.

show a high percentage of shoal facies throughout the KS5 whereas in the more distal sections in the southeast the shoal facies appears mainly around sequence boundaries of the HFSs. Due to dynamic lateral facies changes throughout the KS5, the lateral extent of reservoir bodies is limited.

Conclusions

In contrast to the Middle and Upper Khuff sequences (KS1 to K4) the Khuff Sequence 5 shows marked facies and thickness variability, which makes sequence-stratigraphic correlations challenging. The overall layer-cake appearance of the Khuff sequences 1 to 4 is not observed in the KS5. There, probably due to proceeding rifting accompanied by differential subsidence a more complex pattern resulted. The overall high percentage of backshoal environment with intercalated grainy shoal intervals suggests that the KS5 could be a good facies analogue to the subsurface North Field and South Pars area.

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11743 Earthquake-triggered post-depositional deformation at the rim of the Arabian Platform (Permian–Triassic, Oman Mountains)

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Introduction

The carbonate sequence of the Middle Permian to Early Triassic Saiq Formation is situated at the eastern rim of the Arabian Platform. It represents a lateral equivalent of the Khuff Formation, a major hydrocarbon reservoir in the Middle East. Late Permian to Early Triassic deposits comprise the following sequence of lithofacies associations in Wadi Aday, located in Saih Hatat, in the eastern Oman Mountains (Weidlich and Bernecker, 2011, Figure 1).

Permian: Middle Permian (Guadalupian) photozoan facies association. Late Permian (Lopingian) heterozoan facies association – wackestones with bryozoans, crinoids and brachiopods, mudstones;

Early Triassic: Facies association A – mixed carbonate-siliciclastic sediments with upwards increase of lime mudstone. Facies association B – bioclastic carbonate with grain- and mud-support fabrics. Facies association C – bedded dolomitized mud- to wackestone with microbialites and trace fossil horizons. Facies association D – intercalations of thinly bedded yellowish siltstone, silty dolomite and black calcite.

Close to the rim of the Arabian Platform, in the Saih Hatat, the Lopingian–Early Triassic was a phase of intense tectonic activity during rifting of the Neo-Tethys Ocean, as indicated by syn-sedimentary deformation.

Figure 1: Chronostratigraphy (for details, see Weidlich and Bernecker, 2011) and simplified palaeogeographic reconstruction of the SE Arabian Plate in the Late Permian (after Golonka et al., 1994) showing facies distribution patterns during the deposition of the Khuff Formation (after Ziegler, 2001). Important gas fields are marked in red, oil fields in green.
Late Permian heterozoan facies association

Figure 2: (a) Panorama illustrating block-faulting of carbonates of the Late Permian Saiq Formation, Wadi Aday. Close-up images exhibit details of non-stratiform (b) and stratiform tectonic breccias (c and d); for reference, see Weidlich and Bernecker (2011).
Figure 3: (a) Panorama illustrating dark lime mudstones with intrusions of fluidized brownish sediment. (b) to (d) Close-up images show details of mudstone intrusion.
faults, laterally rapid facies changes, breccias with a high fitting of the clasts and slumping structures. Depending on the degree of lithification, deposits of the afore-mentioned facies associations were affected by post-depositional sediment deformation in a different way.

**Field Observations**

The field observations presented in Figures 2 and 3 represent the lateral variation of the Saiq Formation over a distance of about 1 km.

Figure 2 represents a panorama illustrating rotated blocks of Upper Permian platform carbonates overlain by Lower Triassic facies associations (coordinates of the lower left corner of the panorama are $23^\circ34'03"$N and $58^\circ31'37"$E). Close-ups exhibit details of non-stratiform and stratiform breccias. They are polymict; the size of the clasts varies between a few centimeters and decimeter and the groundmass is dolomitized lime mudstone (cement was observed subordinately). Imbrication is the only observed sediment structure. The deposits fulfil all the criteria of non-depositional breccias and are typical of autochthonous deposits, which formed during syn-depositional tectonic activity.

Figure 3 illustrates a panorama highlighting dark lime mudstones (Early Triassic facies association C) with intrusions of clast-rich, fine-grained mud- and/or siltstone (panorama is situated southeast of Figure 2). Black colors represent lithified lime mudstone, whereas brownish colors indicate fluidized mudstone and/or siliclastic siltstone, which dolomitized after injection. The pattern of fluidized brownish muds resembles intrusive mud-/sandstone intrusion complexes known from deep-marine clastics of hydrocarbon-bearing sediment basins (e.g. North Sea, see Huuse et al., 2010) for reference.

**Discussion**

- Data are presented which shed more light on post depositional deformation processes of so-called “Khuff” carbonates.
- The described post depositional features are related to extensional tectonism during rifting of the Neo-Tethys and were triggered by earthquakes. It is unlikely that the observed features were caused during Cretaceous nappe emplacement or Paleogene uplift of the Oman Mountains.
- Differential (rock-mechanical) response of lithofacies associations might have controlled post-depositional deformation process: (1) *in-situ* brecciation is more typical for well-cemented medium-bedded carbonates, notably Lopingian (Late Permian) heterozoan facies and Early Triassic facies association B. (2) Poorly lithified muds with varying carbonate content suffered from fluidization. (3) Thin-bedded carbonates were probably more affected by sediment intrusion.
- Subsurface sediment remobilization is a well-known phenomenon of many sedimentary basins (e.g., North Sea). Mud- or sand intrusions have not been reported from the Arabian platform so far.
- Post-depositional sediment mobilization triggered migration of formation waters and controlled further diagenetic processes (e.g. burial dolomitization)
- Much further work is required to answer questions, which result from this study (abundance of phenomenon, stress regime during intrusion, pore fluid pressure etc).

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