*GeoArabia*, v. 16, no. 1, 2011, p. 151-203
Gulf PetroLink, Bahrain

# GEO 2010 Abstracts Part I

The following abstracts are a selection from those accepted for presentation at GEO 2010, the Ninth Middle East Geosciences Exhibition and Conference that was held in Bahrain on March 7-10, 2010. GEO 2010 was organized by Arabian Exhibition Management (AEM), the American Association of Petroleum Geologists (AAPG) in collaboration with the European Association of Geoscientists and Engineers (EAGE), and was supported by the Society of Exploration Geophysicists (SEG), Dhahran Geoscience Society (DGS), Bahrain Geoscience Society (BGS), Geological Society of Oman (GSO) and Emirates Society of Geoscience (ESG).

The abstracts that are published here by permission of the organizers represent the first group that primarily cover the stratigraphy of the Middle East. The abstracts have been slightly edited and/or reworded so as to conform to a more common style and format; for example, capitalization of formal names for formations, geological periods and stages, etc. Some abstracts required rewording to clarify the scientific content or were submitted as short papers. Every effort was made to present these as concisely and accurately as possible. GeoArabia sent the pre-press version of all the abstracts to the primary authors for their approval, but regretably some could not be reached or did not respond.

In the next issues of GeoArabia, additional groups of GEO 2010 abstracts will be published so that a permanent record of these important studies is available to GeoArabia's readers and the international geoscience community.

## 681069 An approach to identify sink-holes through seismic imaging: A case study from a West Kuwait Field

*J.A. Abdul, D.S. Ray and W. Al-Khamees*

A sink-hole is a closed depression (karst feature), which drains fluid underground. The Lower Cretaecous Shu'aiba Formation is known to have karstic topography with ubiquitous sink-holes throughout West Kuwait area. They formed at the intersection of joints or fault planes and solution of limestone, underlying superficial fluvial deposits resulting in gradual subsidence, forming a sink-hole/doline feature. Drilling in one of the wells of Dharif Field in West Kuwait, through one of these shallow sink-holes (unknown before drilling) to reach the targeted Jurassic reservoir, was a very difficult experience. It immediately started with severe, unprecedented and uncontrollable lost circulation (40,000 barrels of mud) in a 22-inch open-hole section, causing a great loss of man days/rig days and cost. Altogether 13 cement plugs were placed. Ultimately the well was controlled, and the target was reached. Geophysical analysis of a nearby released well in the same field was conducted. The result confirmed the presence of a sink-hole/doline feature which was encountered by the well, and on the basis of the study, the surface location and well trajectory was shifted.

This presentation provides an overview of methods in imaging sink-holes in the Shu'aiba Formation using seismic attribute analysis. It discusses how to plan wells to bypass Shu'aiba sinkhole features in order to enhance the safety of the well, efficiency and cost effectiveness. After evaluating different seismic attributes, the ESP (Event Similarity Prediction) and Curvature technique were found suitable and most appropriate. These attributes identify discontinuities and dissimilarities observed in the seismic and were used to identify the sink-hole features. Dissimilarity measurements visually identify features such as faults, facies changes and other geological patterns. Sink-holes have been identified in all fields in West Kuwait (i.e. Minagish, Umm Gudair, Abduliya and Dharif) and are discussed in this presentation. Another utility of these attributes is to identify the locale of water-disposable wells. In the Minagish Field some water-disposable wells also have been planned and drilled on the basis of this analysis.

## 705312 Lower Cretaceous dense rock bodies in East Abu Dhabi, United Arab Emirates

*A.A. Abdul Ghani*

Areas with a weak seismic reflection (low amplitude) and a circular shape have been observed in the Lower Cretaceous Lekhwair Formation in East Abu Dhabi. They are imaged in seismic sections and can be mapped using seismic attributes. A well drilled in one of these features shows that the Upper Valanginian rock section is highly cemented (dense), with extensive stylolitization and reduction in formation thickness, compared with typical thickness and rock characteristics in the nearby wells (outside the features). This phenomenon is limited to that stratigraphic section, and does not affect the overlying Hauterivian section. These features are most likely caused by either meteorite impact occuring in the Late Valanginian time, or by upward forces. Further investigation is required.

## 705300 Microfacies of Abu Dhabi Lower Cretaceous Section, United Arab Emirates

*A.A. Abdul Ghani and A.E. Al Mansoori*

The Lower Cretaceous subsurface section of Abu Dhabi (K_10 to K_90) is composed of a carbonate sequence reaching 2,900 ft in thickness, deposited over a time span of nearly 30 million years. Sixty lithofacies types have been recognized, and these represent environments ranging from restricted supratidal to deep basinal settings. The Thamama Group consists of four formations: in ascending order Habshan, Lekhwair, Kharaib and Shu'aiba. The Habshan Formation was deposited up-dip on a wide and gentle carbonate ramp developed during the initial Cretaceous flooding of the stable cratonal platform. It embodies the progradation over, and subsequent filling of the old Middle to Upper Jurassic cratonal margin depression. The Habshan Formation consists mainly of grainy, peloidal, sometimes intra-clastic, and less commonly, oolitic limestone, with some lime packstone-wackestone and is highly dolomitic in the lower part. During deposition of the Lekhwair Formation, minor tectonic pulses created a series of minor transgression and regression. Cyclic sedimentation took place in the area with the lower part consisting mainly of wackestone-mudstone, which grades upwards into skeletal, peloidal packstone-grainstone.

The Kharaib Formation is composed of four sedimentary cycles. The porous, grain-supported limestones represent regressive phases, whereas the dense limestone units represent restricted platform. The Shu'aiba Formation is the terminal event in the deposition of Thamama Group, and records the differentiation of the stable craton in Early Aptian time into an intra-shelf basin surrounded by shallow-water carbonate shelf facies. The Shu'aiba basinal facies have been termed the Bab Member, which consists mainly of dark grey, dense argillaceous lime mudstone-wackestone and shales. On the shelf margin of this basin, calcareous algae and foraminifera with biohermal rudists accumulated bioclastic peloidal, grainstone and floatstone-rudstone sediments.

## 681333 Characterizing rock-type variation with outcrop-based Lidar mapping of Permian – Triassic carbonate strata, Al Jabal al-Akhdar, Sultanate of Oman

*E.W. Adams and J.A. Bellian*

A Permian – Triassic (Wordian – Induan) succession more than 700 m thick is exposed on the Saiq Plateau in Al-Jabal al-Akhdar, Oman. The outcrops provide an ideal opportunity to investigate the evolution of a carbonate depositional system equivalent to important reservoirs in the Arabian Platform, such as the Khuff Formation. On a field scale, Permian – Triassic carbonate strata in the Middle East are strongly layered and correlatable over long distances (more than 10 km), comprising uniform stratigraphic thicknesses and similar facies associations. Nevertheless, sedimentologic and diagenetic heterogeneity within the layers is complex creating significant lateral reservoir property variations. The diagenetic overprint, including cementation, leaching, and dolomitization can be strongly linked to the original sedimentary texture and fabric governing distinct cement and pore types that define rock types. Most of the succession exposed on Al-Jabal al-Akhdar, except for the lower 120 m, is completely dolomitized. Nevertheless, well-preserved precursor fabrics can be recognized in these dolostones.

To help delineate rock-type partitioning, ground-based Lidar and high-resolution GPS were used to record geological observations in 3-D from the cm to km scale. The data were assimilated, visualized, and modeled to create a digital outcrop model (DOM). A new method of supervised-automated feature extraction using Lidar was developed and tested to identify outcrop-based rock types on the basis of geometrically corrected surface reflectivity (laser intensity) and roughness (weathering). These parameters were used to classify outcrop-based

rock types and subsequently populate the DOM. Laser intensity can be used to discriminate fine- from coarse-crystalline dolostones correlative with mud *versus* grain-rich textures. The link between intensity and outcrop-based rock types using grain size enables us to constrain the geocellular outcrop models. These models can be used to reduce uncertainties in static reservoir models and to test the effect of heterogeneity on dynamic behavior. In addition, the data and technology can also be used to establish a virtual training dataset.

## 681340 Rule-based static modeling of shoal-dominated carbonate reservoirs

*E.W. Adams and C. Hasler*

Several important carbonate reservoirs in the Arabian Platform, such as the Khuff Formation, are comprised of carbonate shoal geobodies. While it has been demonstrated that individual carbonate sand geobodies are correlatable over large distances (more than 10 km) and can have uniform stratigraphic thicknesses, the internal sedimentologic partitioning of texture and fabric is intricate. In addition, diagenetic processes, which can either follow or cross cut the depositional architecture, introduce another level of complexity by altering primary porosity and permeability. To better predict the significant lateral reservoir property variations associated with carbonate shoal deposition and early diagenetic overprints, a forward modeling approach is adopted. We choose to use cell-based forward modeling aiming to reproduce both sedimentary and early diagenetic processes, since these processes feedback and interlink through time during the development of the initial porosity and permeability architecture.

The cell-based rules that have been postulated are efficient in simplifying the interaction of complex processes while creating emergent carbonate geometries. The model grid of the approach can be defined at the scale of the relevant heterogeneities within a subsurface reservoir. The cell-based forward modeling approach is supported with process-oriented input data from analogs to constrain modeling parameters and by geometry-oriented studies to constrain fundamental geometries associated with shoal deposition and early diagenesis. The analogs used are modern-day carbonate banks, which display diverse external landscape geometries as well internal partitioning of sedimentological properties. In addition, digital outcrop modeling is used to quantitatively validate the emergent geometries produced by the cell-based forward models. The outcrop we studied is the Permian Saiq Formation of the Akhdar Group exposed on the Saiq Plateau in Oman. This outcrop provides an ideal opportunity to investigate and quantify relevant geometries such as height and spacing of shoal crests and grain size distributions. Preliminary results are promising as model geometries are mimicking observations made on these modern-day and outcrop analogs. The combined forward modeling and quantitative analog approach tries to achieve a significant reduction in the present uncertainties of spatial prediction of properties in shoal-dominated carbonate reservoirs.

## 678381 Cambrian Miqrat Formation: A challenging, tight gas play in prograding sheetflood sands, Sultanate of Oman

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The Miqrat Formation (middle Cambrian, Haima Supergroup) of North Oman is an identified deep, tight (low permeability) gas reservoir that was deposited in an arid to semi-arid continental setting, consequently it is biostratigraphically barren. It is dominated by finely interbedded, red-brown shales intercalated with argillaceous and feldspathic/micaceous very fine- to fine-grained sandstones and siltstones. These were deposited in alluvial and playa/lacustrine to sabkha environments with minor aeolian intervals. The formation offers a variety of geological and well engineering challenges, largely related to its depositional setting and age.

Facies relationships were controlled by a spectrum of sedimentary processes operating at different scales. Important constraints, at a basin scale, are wet/dry climate cycles within a framework of varying sedimentation rates and accommodation space. Developing accurate subsurface depositional models is hampered by poor seismic resolution and a lack of reliable correlation events to constrain palaeogeographic reconstructions and tie these to field-scale depositional models. With limited well control, absence of biostratigraphic markers and non-unique wireline log characteristics, correlation of similar-appearing sheetflood sands may be erroneous as these may correlate with time equivalent flood margin or muddy playa deposits. The identification of correlatable markers is, therefore, significant. Pilot studies applying chemostratigraphy suggest that this technique may prove to be a useful tool for subdividing the Miqrat Formation.

Regional and in-field Miqrat well data, integrated with outcrop studies, provide the main input into geological models and the basis for play maps and static reservoir modelling. However, many challenges exist, especially for early appraisal activities. These include reservoir productivity identification and "sweet-spotting", assessment of gas mobility during drilling, and petrophysical evaluation (saturation/mobile phase identification). Additionally, the role of fractures needs to be understood in achieving commercial rates, whilst fraccing and testing require innovative solutions to provide optimal stimulation and reservoir assessment, respectively. Project attractiveness may rely on improvements in seismic imaging, improved play models, better prediction of reservoir quality/fracture networks, together with a better understanding of charge history and improved offtake rates.

## 681099 Late Cretaceous seismic stratigraphy, offshore Batinah Coast

*M.A. Al Balushi and L.B. Collins*

Seismic interpretations of the Late Cretaceous unit (sediments) from the deep-water area south of Block-18, in the Gulf of Oman, show interesting seismic facies for frontier exploration. Despite the absence of well control in the deep-water area, it is still valid to interpret seismic facies using the shallow well B from the near top Upper Cretaceous unconformity, which was interpreted from down-lapping of Lower Tertiary reflectors on it. These facies could represent the deep-water end of the onshore fluvial origin Al Khawd Formation, from North Oman. The Late Cretaceous unit is more than three seconds two-way time in the block and occupies intra graben-faulted basement. It consists of six seismic facies as shown in the proposed seismic stratigraphic log. The seismic stratigraphy first started with sub-marine slope fan deposits in the basin followed by intervals of seismic facies 2 to 6, exhibited by original sedimentary structures and high and low amplitude acoustic facies. It is expected to show better reservoir facies development from the well B equivalent shale-rich section. Moreover, channels show axes trending NE-SW with minor presence of soft-sediment diapirism interpreted at seismic reflection times greater than six seconds. Generally, structural developments during Late Cretaceous were influenced by the start of the Oman Mountains uplift and its continuous subsequent erosion. In contrast the study area remained under structural quiescence, which provided potential source rock developments especially within the deeper sections beside potential reservoir facies represented by prospective channel sands. All these are sealed with intra Late Cretaceous seals.

## 681984 Facies mapping within the late Permian Khuff-C high-resolution sequence-stratigraphic framework in Hawiyah, Ghawar Field: Implications for reservoir predictions

*G.A. Al Eid and A. Al Tawil*

Over 7,000 feet of core in 24 wells in the Hawiyah, South Uthmaniyah and North Haradh areas in Ghawar Field were utilized in a study to generate a high-resolution sequence-stratigraphic and facies distribution framework for the Khuff-C reservoirs. Four high-frequency sequences make up the late Permian Khuff-C in Ghawar, where each is bounded by well-defined sequence boundaries. Each sequence is made up of a transgressive systems tract (TST) and a high stand systems tract (HST), separated by a mappable maximum flooding surface (MFS). Systems tracts are made up of mappable meter-scale shallowing-upward cycles, for a total of 32 cycles within the entire studied interval.

Two facies maps have been created for each of the 32 cycles across the entire studied area. Each cycle has a facies mosaic map at the surface of maximum retrogradation and another at the surface of maximum progradation. The accumulated result of all maps provides the spatial and temporal facies distribution for the four high-frequency sequences that make up the long-term Khuff C composite sequence.

These are not interval maps but rather they are time-facies maps that represent the facies evolution, position and facies migration (vertical and lateral) through time. The advantage of this mapping technique is that it places facies within the context of their times of deposition during a particular event of sea-level rise and fall, allowing better prediction of reservoir facies occurrences. One key control on reservoir quality is anhydrite cementation, which works to destroy pore networks. Petrographic studies suggest that such cementation is likely to have occurred at, or very shortly after, the time of deposition of reservoir (grainstone) facies. This is demonstrated through the preservation of original grains encased within tight anhydrite cement networks; all preserved porosity is otherwise moldic. The high-resolution surface mapping suggests, through superposition of facies maps, that anhydrite cementation is sourced through brine reflux processes from stacked, cycle-capping,

tidal-flat facies lying directly above. In a down-dip direction, the same stacked tidal flats sourced lighter, magnesium-rich, brines that laterally dolomitized time-equivalent subtidal calci-silt facies.

## 683694 High-resolution sequence stratigraphy of the late Permian Khuff-C in Hawiyah, Ghawar Field

*G.A. Al Eid and A. Al Tawil*

Four high-frequency sequences make up the late Permian Khuff-C in Ghawar, where each is bounded by well-defined sequence boundaries on core and logs. Each sequence is made up of a transgressive systems tract (TST) and a high stand systems tract (HST), separated by a mappable maximum flooding surface (MFS). Systems tracts are made up of mappable, meter-scale shallowing-upward cycles, for a total of 32 cycles within the entire studied interval.

Khuff-C1 (KC1) is made up of 10 mappable cycles, where the TST of each cycle starts with flooding storm beds and restricted dolomudstones that shallow-up to a regional tidal-flat cap. The MFS is totally dolomitized distal lime-mudstone, passing into cross-bedded grainstones. The HST is made up of prograding grainstone overlain by restricted lagoon and tidal-flat mudstones.

Khuff-C Sequence 2 (KC2) consists of seven cycles and is defined by an initial transgressive set of restricted cycles with storm-influenced facies deposited over the thick, extensive tidal-flat sediments of KC1, which extend field-wide across Ghawar. The middle cycles are made up of storm beds and intensely burrowed shallow subtidal pellet packstones, deepening to dominantly open marine lime-mudstone (MFS), and shallowing-up to sand-flat low-angle cross-bedded to burrowed peloid packstones. The upper cycle is made up of shallow subtidal embayment lime-mudstone shallowing-up to brecciated paleosol, which is the sequence boundary of KC3.

Khuff-C Sequence 3 (KC3) is made up of 10 cycles with four initial transgressive peri-tidal cycles of lagoonal dolomudstone capped by crinkly laminated to mud-cracked dolomudstone tidal-flat facies. This is overlain by a back-stepping cycle-set of grainstone with their distal bryozoan lime-mudstone equivalent (MFS). The HST of KC3 is marked by shallow subtidal sand flat facies prograding over distal open-marine lime-mudstone. KC3 is marked at the top by a paleosol, which also extends across Ghawar.

Finally, Khuff-C Sequence 4 (KC4) consists of five mud-dominated cycles. The base of this sequence is bounded by a field-wide exposure surface of KC3. The TST is represented by transgressive peri-tidal to shallow subtidal cycles while the prograding grainstones and the anhydrite behind define the HST.

## 706304 "Intra-Al Bashair Boundary" (late Cambrian, Sultanate of Oman): Is it a maximum flooding surface or a sequence boundary?

*S.A. Al Marjibi, C.P. North and J.E. Neilson*

The late Cambrian age Al Bashair Formation of the Andam Group (Haima Supergroup) of the north-central part of Oman consists mainly of thin (< 0.5 m) layers of sandstone, siltstone and mudstone that are occasionally interbedded with various types of thin (< 1 m) carbonate layers. Carbonate rocks are absent in the upper half of the succession of the Al Bashair Formation and the interval becomes much muddier than the underlying unit. These features allow the division of the Al Bashair Formation stratigraphically into two units, the lower unit and the upper unit.

Previously it has been thought the mudstone intervals in the Al Bashair succession were deposited in a deeper water setting than the carbonate and sandstone strata. Consequently, the increased proportion of this mudstone in the upper unit of the Al Bashair Formation was interpreted as representing a significant relative sea-level rise. Thus the contact between the lower and upper units, the "Intra-Al Bashair Boundary", was thought to represent a maximum flooding surface.

However, recent detailed study of the succession at outcrop shows that these mudstone intervals are always associated with terrestrial sedimentary structures including pedogenic slickensides, blocky ped structure and occasionally desiccation mudcracks, indicating they were subaerially exposed for sufficient time for soils to form soon after their deposition. This indicates that the succession of the upper unit of the Al Bashair Formation generally was deposited in an overall shallower water setting than the underlying unit, and the "Intra-Al Bashair Boundary" cannot be interpreted as a maximum flooding surface. Alternative interpretations of the nature of this boundary are considered, including the possibility that it represents a sequence boundary. What is certain is that the "Intra-Al Bashair Boundary" should not be correlated regionally

with other maximum flooding surfaces across the Arabian Plate.

## 701330 Integrated diagenesis and sequence-stratigraphic study of tidal sandstones: The Adedia Formation (Cambrian – Ordovician), Sinai, Egypt

*K. Al Ramadan, S. Morad and E. El-Khoriby*

This work examines the effects of meteoric *versus* marine diagenesis on Cambrian – Ordovician tidal sandstones owing to fluctuation of relative sea level (RSL). The distribution of diagenetic alterations is thus constrained within the sequence-stratigraphic framework of the succession. Initially, a rise in RSL resulted in the deposition of transgressive systems tract (TST) sands directly onto crystalline basement. These sandstones display evidence of limited cementation by marine, grain-fringing dogtooth-like and fibrous calcite. A fall in RSL resulted in the progradation of a tidal-flat complex and deposition of highstand systems tract (HST) and lowstand systems tract (braided fluvial) sandstones. Contemporaneous meteoric-water flux into sands of all the systems tracts resulted in the dissolution and kaolinitization of feldspars, micas and mud intra-clasts in all systems tracts. Sequence boundaries (SB) are marked by fluvial incision of tidal sands and by the development of palaeosols. Mesogenetic alterations include partial transformation of kaolinite into dickite, intergranular pressure dissolution, and formation of variable amounts of syntaxial quartz overgrowths in all systems tracts. Telogenetic alteration (i.e. weathering) in the sandstones includes the formation of goethite and calcite. Thus, the integration of diagenesis with sequence stratigraphy provides a useful tool with which to understand reservoir quality distribution in sand-dominated, tidal sediments.

## 681071 Sequence stratigraphy and reservoir compartmentalization in the lower Wasia Formation, Saudi Arabia

*A.A. Al-Duaiji, M.J. Al-Mahmoud, M.H. Khalil and H.R. Al Anzi*

High-resolution sequence-stratigraphic analysis was applied at the lower part of the Wasia Formation (Khafji, Safaniya and Mauddud members) of Albian age in offshore Saudi Arabia. Core analysis, wire-line logs, biostratigraphy and fluid data were used in the analysis. Two third-order sequences were identified within the lower part of the Wasia Formation. The Wasia Formation (Albian – Turonian) in Saudi Arabia is represented by seven members; from bottom to top: Khafji, Safaniya, Mauddud, Wara, Ahmadi, Rumaila and Mishrif. The Wasia Formation is bounded by two pronounced regional unconformities related to major tectonic events: the pre-Wasia (Albian – Aptian) and pre-Aruma (Campanian – Turonian).

The lower sequence starts at the base of the Khafji Member with the lowstand Khafji Main Sand followed by transgressive Khafji sand stringers with a maximum flooding limestone marker named the Dair Limestone. This sequence was terminated with the highstand Khafji stray sands; a very thin continuous sand overlying the Dair Limestone. The upper sequence starts with the lowstand Safaniya reservoir sandstone followed by the transgressive and maximum flooding surface of the Mauddud Limestone. The sequence ends with the highstand thin carbonates and shales of the upper Mauddud. Outcrop data has been correlated with the subsurface to establish the regional framework.

Detailed tectono-stratigraphic analysis of the lower Wasia in the offshore fields indicates that the lower Khafji Main Sand was deposited as fluvial filling of the tectonically-controlled irregular basin topography. The deposition of the remaining section of the two sequences was primarily controlled by the sea-level eustacy with weak tectonic imprints. Tertiary reactivation of the faults cutting the pre-Wasia has resulted in compartmentalization of the lower Wasia reservoirs.

## 680787 Devonian spore assemblages from the Jubah, Jauf and Tawil formations, south of Ghawar Field, Eastern Saudi Arabia

*A.M. Al-Ghazi, M. Al-Ruwaili and M. Miller*

An exploration well located south of Ghawar Field contains one of the most complete ?early Upper and Lower Devonian successions in the area. The palynological control from this well provides a Devonian reference section for this area that will help refine regional correlations. An apparently complete succession of operational palynological zones from the ?Frasnian – Givetian/Eifelian D2 Palynozone to the Lochkovian D4B Palynozone was identified in this well. The upper part of the Jubah Formation, typically represented by the D0 to D1 Palynozones, was truncated by the Hercynian erosion. D2 Palynozone was recognized from 15,000–15,350 ft and is indicative of the presence of ?Frasnian – late Eifelian age sediments. This interval is dominated by terrestrial palynofloras. D3A Palynozone spans the Jubah/Jauf formational

boundary and occurs from the 15,350–15,690 ft interval. D3B Palynosubzone, which caps the Jauf reservoir, occurs in the 15,690–15,710 ft sample (D3A and D3B are late Emsian in age). The D3B event is the only acritarch (leiosphere) dominated palynological event recognized in the succession. The D3/D4–D4A palynozones of Emsian – Pragian age are present in the 15,710–15,890 ft interval and span the Jauf/Tawil formational boundary. Lochkovian D4B was recognized from 15,890–16,090 ft and suggests the presence of the Tawil Formation. The section below the D3B Palynozone is dominated by terrestrial palynomorph assemblages.

## 696519 Facies and high-frequency sequence stratigraphy of the Lower Fadhili carbonate reservoir, Khurais Field, Saudi Arabia

*A.S. Al-Mojel and L. Smith*

The Middle Jurassic Lower Fadhili reservoir of the Dhruma Formation in Khurais Field is composed of three high-frequency sequences, with numerous small-scale fining-upward cycles that vertically partition the reservoir. The Lower Fadhili was deposited in a shallow-marine intra-shelf basin. The reservoir is overlain and underlain by marls. The reservoir consists mainly of wackestones and packstones with several thin layers of grainstones capped by hardgrounds/firmgrounds.

The first sequence consists of argillaceous mudstone, beach intra-clast-ooid grainstone and shoreface coated-grain, ooid grainstone. Chondrities burrows occur only in argillaceous mudstone facies. Gastropods are common in the beach intra-clast, ooid grainstone facies. The sequence is capped by an exposure surface (hardground). The beach intra-clast, ooid grainstone facies is cemented by early ferroan calcite cement beneath the unconformity, with some reddened strata. Dissolution features include partially/totally dissolved grains, with meteoric calcite cement common.

Fining-upward small-scale cycles of the second sequence onlap the unconformity. These are dominated by open-marine *Pfenderina trochoidea* wackestone facies and stromatoporoid packstone/wackestone facies. The maximum flooding surface can be traced across the field. Grain-rich lithofacies are common in the highstand systems tract.

The third-sequence highstand is dominated by fining-upward cycles of stromatoporoid packstone/wackestone facies, shallow-marine lagoonal wackestone and shoreface coated-grain grainstone. *Thaumatoporella* and *Cladocoropsis* are abundant in the lagoonal wackestones. These are capped by thin cycles of shoreface coated-grain grainstone, beach grainstone and marginal marine green marl/argillaceous mudstone. Progradational and retrogradational stacking patterns of these lithofacies reflect a low-relief carbonate ramp that dipped gently to the north.

High-resolution sequence stratigraphy of the Lower Fadhili reservoir has been beneficial to reservoir characterization and geological modeling.

## 680611 Regional geological modeling of Marrat Formation in West Kuwait with special reference to Jurassic petroleum system

*R. Al-Muraikhi and N. Verma*

The Marrat Formation is considered to be one of the most important carbonate oil reservoirs in West Kuwait oil fields area. This work focuses on the regional geology of Marrat based on deep wells in conjunction with 3-D seismic data. The paper documents the construction of a regional 3-D geo-model to understand the geology of Marrat and its bearing on the petroleum system. Wells and 3-D seismic data have been used to identify the main structural elements of West Kuwait and their tectonic evolution, particularly since the Jurassic Period, to determine their influence on the architecture and depositional fabric of the Marrat Basin. Tectono-stratigraphic analysis of the Gotnia Formation has also been carried out to understand the Jurassic Basin evolution through time. The area has four main anticlinal structures with known multiple Jurassic oil entrapments: Abduliya, Dharif, Minagish and Umm Gudair. These structures were found to be affected by three main compressional events during the pre-Jurassic, Jurassic and Cretaceous times.

The Marrat Formation was divided into three main parasequences: upper, middle and lower. The upper part of the Middle Marrat was further subdivided into 13 sub-layers. The lithology is derived from electro-logs calibrated with cores. Detailed rock typing was accomplished using neural network technique that resulted in identification of eight carbonate/evaporite rock types grouped into five litho-facies.

The geological layering based on sequence stratigraphy combined with 3-D seismic data provided the framework for a structural model, while the lithofacies were propagated in a property

model honoring well control. This high-resolution 3-D modeling and visualization proved valuable in interpretating the primary depositional and secondary diagenetic processes that left their imprints on Marrat rocks. The porous and permeable aggradational and progradational carbonate parasequences of Middle Marrat constitute the main oil accumulations where reservoir quality is strongly controlled by structure, primary depositional fabrics, as well as extensive dolomitisation.

## 680392 Reservoir facies and sequence stratigraphy of the Khasib Formation in selected fields from Central Iraq

*B.J. Al-Qayim*

The bioturbated chalky limestones of the Khasib Formation (Upper Turonian – Lower Coniacian) furnish an extensive reservoir rock in several oil fields in Central Iraq including the Tikrit, Balad, Samarah, and East Baghdad fields. Investigation of these rocks by means of microfacies analysis and electrofacies correlation, as well as sequence-stratigraphic analysis, indicate that they were deposited in a ramp setting sloping east-southeastwards forming part of the Arabian Plate's passive margin.

The inner ramp is characterized by a bioclastic packstone of a carbonate bank with green shale intercalations of peri-bank sediments. The middle ramp, which dominates the Khasib Formation section, consists of white-beige, porous, bioturbated, chalky and dolomitic bioclastic wackestone. Bioclasts include shelf faunal debris with a variable mixture of benthic and planktonic forams. Intensive *Thalasionodes* and *Palaeophycus* bioturbations significantly contributed to the high porosity of this part. The outer ramp consists of intercalations of bioturbated bioclastic chalky limestone and basinal argillaceous limestone. The latter is characterized by the occurrence of planktonic forams, calcispheres, dwarf rotalids and sponge spicules.

The Khasib section represents a third-order cycle with a lower sequence boundary of type one separating Khasib Sequence from the underlying lowstand systems tract of the Kifl Formation. The transgressive systems tract consists of thin and basinal facies. The highstand systems tract is the thickest and is represented by the bioturbated chalky limestone of the middle ramp facies. The maximum flooding surface is indicated by a thin horizon dominated by *Paleophycus* bioturbation and calcispheric marly limestone within the middle ramp facies. The boundary with the overlying Tanuma Formation is of type two and is represented by the transition to the lowstand systems tract of the next cycle.

## 680829 Ara Group depositional architecture and controls from reservoir development, Sultanate of Oman

*Z. Al-Rawahi, J. Grotzinger, J. Rodrigues, S. Vaddey and H. Jansen*

An integrated subsurface approach to understand reservoir development of a unique Neoproterozoic – early Cambrian hydrocarbon system in the South Oman Salt Basin (SOSB) is presented here. New well data and recently re-processed PreSDM data were used to improve the basement fault and overburden tectonic models. Existing depositional models have been refined to identify reservoir fairways and aid in play segment risking.

The Neoproterozoic – early Cambrian Ara Group comprises six (A1–A6C) carbonate-evaporite cycles, most of which are totally encased in salt. Hydrocarbons are produced from the overpressured to hydrostatically-pressured dolomite "stringer" intervals, which define the focus of the study. Some of the complexities in predicting reservoir sweetspots for exploration of the Ara carbonate stringers are: (1) slabs encased in salt can only be jump-correlated seismically to another slab hence palaeogeographic reconstruction is hampered by salt halokinesis; (2) primary reservoir quality is complicated by diagenesis and charge timing; (3) post-charge reactivation of structures affects hydrocarbon column, -phase, and distribution of pressures.

Each stringer records a third-order sequence. Facies show substantial lateral continuity, within and between the slabs, and are dominated by thrombolitic build-ups, microbial laminites and carbonate calcarenites of the ensuing highstand phase. Subsequent lowstand evaporites are anhydrite and thick halite facies that onlap and overlap highstand reservoir carbonates indicating a tectonic control on sequence development.

Palaeogeographic maps show that A1C and A2C stringers have facies distributions that differ between the Harweel and Birba areas due to the influence of antecedent topography, syndepositional salt withdrawal and basement-involved faulting. A major platform of A1C age is developed in the Birba area. This platform continued to aggrade along its edge during A2C times, forming a barrier shoal and development of isolated carbonates in restricted environments in the Birba area. In contrast, platforms and reservoirs of A2C age are best developed in the

Harweel area. A3C platforms are developed atop A2C platforms. A4C reservoirs are restricted to the Birba area, where it was localized above the major platform that initiated during A1C time. A refined risk assessment of the different stringer intervals in the SOSB could therefore be constructed in distinctive geographic areas, leading to improved ranking of future exploration targets.

## 683414 Early and Middle Jurassic Marrat Formation, Onshore Kuwait: A depositional sequence-stratigraphic framework

*G.A. Alsahlan, A. Youssef, A.P. Kadar, J.P.G. Fenton and P. Marshall*

A high-resolution investigation, comprising stratigraphy (biostratigraphy and Strontium-isotope analyses) and sedimentology, of 19 onshore wells in Kuwait has been undertaken. Data from ca. 500 core and cutting samples have been integrated with electric wireline log data to establish a biostratigraphically constrained depositional sequence-stratigraphic framework for the tripartite Marrat Formation of Kuwait. The Marrat Formation rests unconformably on the Minjur Formation, which is no younger than Hettangian in age. A further hiatus is identified at the base of the overlying Dhruma Formation, with the probability of some Bajocian strata missing.

A locally applicable microfaunal biozonation has been established for the Marrat Formation, comprising three zones. The *Pseudocyclammina maynci* Zone of Aalenian age, characterises the Upper Marrat. The *Siphovalvulina* spp. Zone of Early – Middle Toarcian age characterises the bulk of the Middle Marrat, while the basal part of the Middle Marrat and the upper part of the Lower Marrat is characterised by the *Amijiella amiji* Zone (Early – Middle Toarcian to Pliensbachian – Sinemurian). The latter zone is tentatively divided into the *A. amiji* and *Haurania deserta* subzones. Palynofloral, nannofloral data and Strontium-isotope analyses have assisted in age determinations with varying success.

A wide range of shallow, neritic to supratidal facies are identified. Eleven depositional sequences have been recognized, most of which are considered to be of third-order hierarchical status and calibrated where possible to those of the Geological Time Scale 2004. The Lower Marrat essentially comprises informal sequences Si-Pl1 to Si-Pl3 and Sequence Pl8. The uppermost part of Sequence Si-Pl3 and Pl8 are well constrained using biostratigraphy and Strontium-isotope results, being dated as earliest Late Pliensbachian and earliest Toarcian, respectively. The uppermost part of the Lower Marrat and the Middle Marrat comprise at least four third-order sequences (Toa1 to Toa4), with an Early – Middle Toarcian age range. An intra-Marrat Formation unconformity occurs at the base of the Upper Marrat, with the latter comprising three third-order sequences (Aa1, Aa2 and Bj1-Bj2). While the lower two sequences are confidently dated as Aalenian, the youngest sequence is poorly age-constrained.

## 703330 Cretaceous sequence stratigraphy of western Zagros outcrops from Kurdistan Region, North Iraq

*F.A. Ameen and H. Gahrib*

The exposed Cretaceous sequence in the Kurdistan region was studied from four outcrops sections (Qamchuqa, Dokan, Smaqwly and Safin), and correlated with oil wells (Taq-Taq and Chemchemal). The sequence consists of the Qamchuqa, Dokan, Gulneri, Kometan, Shiranish and Tanjero formations, which were deposited in a pre-foreland and foreland basin between the Barremian to the Late Maastrichtian. In this work the Cretaceous sequence is subdivided into four third-order sequences, bounded by five sequence boundaries of type 1 or 2, and occasionally type 3: (1) intra-Barremian (SB type 1), (2) late Early to Middle Cenomanian (SB type 2), (3) latest Cenomanian (SB type 2), (4) Middle Campanian (SB type 2) and (5) Late Maastrichtian (SB type 1). The nature and duration of each sequence and its boundaries are estimated by planktonic foraminifera zonations. The oldest sequence (intra-Barremian to earliest Cenomanian) is represented by the Qamchuqa Formation, which consists of aggradational to progradational rudist-bearing carbonate ramp facies associations (600 m thick). This sequence was terminated either by drowning or by subaerial erosion indicated by the Cenomanian unconformity and coincides with the global Cenomanian – Turonian euxinic event (OAE2). The second Late Cenomanian sequence consists of Oligosteginal carbonates, which are related to the Dokan Formation, and terminated with submarine erosion. The third sequence is represented by the Gulneri Formation (Turonian to Early Campanian) and consists of a condensed section of black shale. The fourth and youngest sequence is represented by the Kometan Formation. It consists of a shallowing upwards succession from deep outer to middle and inner shelf settings. It is capped by a hardground surface within the Middle Campanian unconformity surface. Late Campanian to Late Maastrichtian third-order sequences consist of outer shelf, turbidite facies and reef build-up (Aqra Formation), which are occasionally

intercalated with oceanic red beds (ORB). Within the Zagros foreland basin, these sequences act as the best productive reservoir in the Upper Cretaceous of the Kurdistan region.

## 680432 Characterisation of the mid-Cretaceous Mishrif reservoir of the southern Mesopotamian Basin, Iraq

*A.A. Aqrawi, T.A. Mahdi, G.H. Sherwani and A.D. Horbury*

The Cenomanian – Early Turonian Mishrif Formation reservoir of the Mesopotamian Basin accommodates more than one third of the proven Iraqi oil reserves within rudist-bearing stratigraphic units. Difficulty in predicting the presence of reservoir units is due to the complex palaeogeography. Extensive accumulation of rudist banks occurred along an exterior shelf margin of the basin along an axis that runs from Hamrin to Badra and southeast of that, with interior margins around an intra-shelf basin. Buildups were stacked or sometimes shingled as thicker shallowing-up cycles of several smaller-scale accommodation cycles. As a result, each field shows different combinations of pay zones, barriers and seal geometries.

The sequence-stratigraphic analysis led to three complete third-order sequences being distinguished. Eustatic sea-level changes controlled development of the sequence stratigraphy. Tectonism primarily defined the sites of platform development that complicated the architectural heterogeneity of the depositional sequences.

A porosity-predictive model, employing sequence-stratigraphic concepts, shows porosity increasing beneath sequence boundaries due to meteoric dissolution and karstification, whilst rising sea level induces dolomitization on the platform, causing porosity enhancement at early transgressive systems tract. Porous rudist facies usually coincide with the crestal areas of many fields in the region, particularly in those anticlines which show evidence of synsedimentary structural growth. However, other structures have also proven to be non-productive along their crests because of the presence of tight or microporous offshore facies instead of rudist-bearing reservoir facies. Presences of interconnected vug pores of grain-dominated fabric in the grainy facies make them the best reservoir units. Dissolution of the aragonitic components of rudist shells was the most important diagenetic process that enhanced reservoir characteristics. Presence of rudist-bearing facies with their diagenetic effects within highstand systems tracts is considered the primary factor in effective porosity development and distribution.

Predicted facies relationships indicate prograding and pinch out of rudist-bearing facies, including lowstand shelf systems, into shallow open facies that can form stratigraphic traps. However, exploring such trap types will require 3-D seismic to resolve the positions of the external and internal shelf margins via application of high-resolution sequence analysis.

## 743156 The Ratawi reservoir of the Partitioned Neutral Zone (PNZ), Saudi Arabia and Kuwait

*B. Archuleta, A. Saller and S. Bachtel*

The Lower Cretaceous Ratawi Formation is a target for increased production and ongoing exploration within the Partitioned Neutral Zone (PNZ). The Ratawi Formation consists of three members: Ratawi Oolite (base), Ratawi Limestone and Ratawi Shale (top). Deposition of the Ratawi Oolite and Ratawi Limestone occurred on a low-angle carbonate ramp roughly dipping to the east to northeast. Oil from the Ratawi reservoir is currently being produced from the South Umm Gudair, Wafra, and South Fuwaris fields. The purpose of this study is to better understand the reservoir heterogeneity of the Ratawi at both the regional and field scale to provide inputs for future development and exploration activities.

Based on seven cores and wireline log correlations, the Ratawi Oolite and Ratawi Limestone consist of four transgressive-regressive depositional sequences representing an overall progradational trend. Sequences 1 and 2, within the Ratawi Oolite, are dominated by lithofacies deposited in a high-energy grainstone shoal to open-marine environment. These lithofacies include: argillaceous wackestone/packstone, fine-grained peloidal, skeletal grainstone/packstone, oolitic grainstone, coarse-grained skeletal grainstone and skeletal wackestone. Sequences 3 and 4 of the Ratawi Limestone, consist of lithofacies deposited in a low-energy, restricted inner ramp environment. Common lithofacies include: argillaceous lime mudstone and peloidal, skeletal wackestone/packstone.

Reservoir quality within the Ratawi Oolite varies from field to field and is a function of pore type. In the Wafra Field, the producing interval within the Ratawi Oolite is dominated by well-connected, primary intergranular porosity. From a single Wafra well, core porosity ranges from 3 to 35% and core permeability ranges from 0.1 to 1000 mD. In South Fuwaris, the Ratawi Oolite consists of very poorly connected micro-porosity, as a result of equant calcite cement occluding primary porosity. Core

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porosity from a single South Fuwaris well ranges from 5 to 25% and core permeability ranges from 0.01 to 10 mD.

## 705388 Late Campanian to Paleocene planktic foraminiferal biozonation for Izeh, Zagros Basin, Iran

*B. Beiranvand and E. Ghasemi Nejad*

Planktonic foraminiferal biostratigraphic study of the Gurpi Formation at Danial section in northeast Izeh, Zagros Basin, Iran, provides improved age resolution and good biostratigraphic control for Late Cretaceous to Paleocene strata. Late Cretaceous to Paleocene assemblages are open marine faunas, and most of the standard tropical/subtropical planktonic foraminiferal zones are represented in the section. The Late Cretaceous proposed biostratigraphic zones include one Late Campanian zone, *Radotruncana calcarata*, and five Maastrichtian zones, *Globotruncanella havanensis*, *Globotruncana aegyptiaca*, *Gansserina gansseri*, *Contusotruncana contusa* and *Abathomphalus mayaroensis* (four subzones; CF1, CF2, CF3, and CF4). On the other hand, eight Paleocene proposed biostratigraphic zones and subzones are P0-P (*P. eugubina-G. cretacea*), P1a (*P. eugubina*), P1b (*S. trilocolinoides*), P1c (*G. compressa/P. inconstans*), P2 (*P. uncinata/P. praeangulata*), P3a (*M. angulata*), P3b (*M. velascoensis*), and P4a (*P. pseudomenardii*).

The turning point of the study is relatively complete succession across the Cretaceous/Tertiary (K/T) transition, which is presented by four subzones (*R. fructicosa*, *P. hariaensis*, *P. palpebra* and *P. hantkeninoides*) within the Late Maastrichtian and eight zone and subzones within the Paleocene. The K/T boundary is marked continuously by using the zones CF1 and P0-P at the latest part of the Maastrichtian and Early Danian, respectively. This considerably higher resolution in biostratigraphic zonation is a result of good foraminiferal preservation that may reflect larger, more rapid sea-level changes, consistent with increasing ice volume during the time interval.

## 705924 Sea-level changes and depositional environments of the Late Cretaceous to Paleocene sedimentary succession, Izeh, Zagros Basin, Iran

*B. Beiranvand, E. Ghasemi Nejad, A.H. Amini and M. Kamali*

Integration of micro-biostratigraphy and palynofacies analysis of the Gurpi Formation at the Danial section, northeast Izeh, Zagros Basin, Iran, provide improved age resolution and information on the reconstruction of depositional environments. The section is a key succession to investigate the Late Cretaceous to Paleocene sea-level history. Relatively deep-marine dark bluish-gray calcareous shale, marl and argillaceous lime mudstone of the Gurpi Formation, which marks the Late Cretaceous – Paleocene sequence, exposes the interval between the Santonian Ilam Formation and the overlying Upper Paleocene – Oligocene Pabdeh Formation. The age of the Gurpi Formation in the section is estimated to span from Late Campanian (*Radotruncana calcarata* planktonic foraminifera Biozone) to Late Paleocene (*Globanomalina pseudomenardii* planktonic foraminifera Zone). The Cretaceous/Tertiary boundary within the upper part of the formation marks continuously by using the zones CF1 (*P. hantkeninoides*; latest Maastrichtian, 65.3–65.0 Ma) and P0-P (*P. eugubina-G. cretacea*; base of Danian age, 65.0–64.97 Ma) respectively.

Results from a sea-level change analysis, based on palynofacies analysis and additional proxies (percent planktic foraminifera, planktic foraminifera morphogroups, total organic carbon content (TOC), and geophysical (gamma-ray log) show a general deepening trend for the investigated sections. As a result, the sedimentary succession reflects deposition in outer neritic environment and not any tectonic activities during the Maastrichtian – Paleocene in the basin but more rapid sea-level changes, consistent with increasing ice volume in the world during the time interval. The area was located near the palaeoequator and provides tropical to subtropical paleoenvironmental conditions. Finally, six Type-III sequences were distinguished in the section during the study. Microfacies analysis of the marls and argillaceous lime mudstones (Emam Hassan Member) at the middle part of the sediment succession provides three main microfacies, corresponding to two, three, and four facies belts. These show a relatively deep-marine environment at the end of a continental slope during sea-level highstand in outer to inner neritic environments. On the other hand, fossiliferous marly shales and marls at the lower and upper parts of the succession during sea-level rising are characterized by dysaerobic or low oxygen conditions in outer neritic environments.

## 680500 Devonian miospore stratigraphy and palaeogeography of the northern margin of western Gondwana

*P. Breuer, P. Steemans and M. Miller*

Well-preserved Devonian miospore assemblages from Saudi Arabia and North Africa allow a good correlation of the studied sections and the

establishment of a biozonation for the northern margin of western Gondwana. More than 200 miospore species, including many new species endemic to western Gondwana, have been identified in 16 sections. Although the standard Devonian miospore zonations established in Euramerica are commonly used in most palynological studies, they are not always easily applicable to western Gondwanan localities because of the endemic nature of the assemblages. Therefore, a new regional biozonation based on Gondwanan miospore species has been established. It consists of nine assemblage zones, eight interval zones and two acme zones, from the Late Pragian to the Early Frasnian. A biozonation based on the first downhole occurrence of species is also developed for oil exploration. This provisional downward biozonation consists of eight interval zones. Although it seems relatively reliable by comparison with the previously defined upward biozonation, it needs to be further tested. The review of the miospore assemblages from the literature has allowed evaluation of the provincialism of assemblages on a worldwide scale for the Emsian – Givetian interval. Coefficient of similarity has been calculated between palynofloras from northern and southern Euramerica and eastern, southwestern and northwestern Gondwana. The resulting low values correspond to low to moderate similarity of miospore assemblages. The provincialism may be explained by a latitudinal climatic gradient as no significant palaeogeographic barrier is known during this time. Despite a certain degree of provincialism, floristic interchanges existed. Saudi Arabia and North Africa constituted an intermediate warm temperate region and shared taxa mainly from more arid Euramerican localities in the north, and cooler southwestern Gondwanan localities in higher latitudes. It seems that a progressive homogenization of the vegetation took place in Middle Devonian as the standard Euramerican biozones are more easily recognized in Givetian than in Eifelian and Emsian. This transition from provincialism to cosmopolitanism during the Devonian is not only shown by palynofloras but also by the palaeogeographic distribution of many other fossil groups. It is likely due to a decrease of the latitudinal climatic gradient in Middle Devonian.

## 688766 Carbonate-evaporite sequence stratigraphy of the subsurface Late Jurassic Arab-C Member, Khursaniyah Field, eastern Saudi Arabia

*E.A. Busbait, I. Ishak, L. Smith and K. Al Ramadan*

This study defines the cycles and sequence-stratigraphic framework of the Arab-C Member of the Khursaniyah Field to enhance the understanding of both sedimentological and depositional models of the Arab-C reservoir. The sediments of the Arab Formation in the Arabian Peninsula are typically composed of shallow-water limestones and dolomites interbedded with restricted facies of anhydrites. Each reservoir layer corresponds to retrogradational-progradational cycles. The reservoir-bearing Arab-C carbonate in Khursaniyah Field (150 ft thick) is an overall shallowing-upward composite sequence that can be subdivided into five high-frequency sequences. Each of these high-frequency sequences can be subdivided into multiple fining-upward small-scale cycles. The lower part of the Arab-C Member is made up of cycles that fine upward from intra-clastic/oolitic rudstone into skeletal wackestone and lime mudstone. These are overlain by 9 to 20 ft thick cycles that consist of ooid grainstones capped by anhydrite. The overall evolution is that the basal sequence consists of ooid grainstones and rudstones capped by an anhydrite. The second sequence consists of cyclic ooid grainstones and dolomitized mudstones. The third sequence consists of thick cross-bedded grainstones (which mark the maximum flooding) capped by thrombolite facies. The fourth sequence consists of peloidal grainstones capped by thin evaporites and then there is a thin fifth sequence that has a carbonate stringer in the base that is capped by the regional anhydrite that extends upward to the base of the Arab-C. Grainstones are mostly in the transgressive portions of the sequences and cycles while anhydrite, tidal-flat facies and thrombolites mostly occur in the highstand parts of the sequences and cycles. The middle evaporite package thins toward the northeast of the field. Dolomite increases in the southeast of the field and the thromoblites decrease on the crest of the field. This core/log based-work leads to a better correlation framework for the Arab-C Reservoir where the wire line logs alone are often difficult to correlate. Moreover, the sedimentological work helps to break out facies with differing porosity and permeability relationships that can be imported into geocellular models for matching production history and field optimization planning.

## 680858 Prediction of Unayzah reservoir quality ahead-of-the-bit

*D.L. Cantrell, C.M. Griffiths, S.G. Franks and M.R. Al-Khadhrawi*

Recent research at Saudi Aramco has examined the feasibility of predicting areas of good reservoir quality - "sweet spots" - in the Permian-Carboniferous Unayzah reservoir away from areas of well control using stratigraphic forward modeling. The Unayzah Group reservoir interval was

deposited above the Hercynian Unconformity over a 56 million year period during the late Carboniferous to early Permian in central and eastern Saudi Arabia. The Unayzah Group consists of a succession of sandstones and siltstones that reflect changing climatic conditions, from glacial, peri-glacial, and lacustrine conditions in the lower Unayzah (Unayzah-C, or Ghazal Formation, and Unayzah B, or Jaub Formation), to fluvial and ultimately eolian conditions in the upper Unayzah (Unayzah A, or Nuayyim Formation). Stratigraphic forward modeling has been applied to predict the distribution of facies, grain size, porosity, and reservoir architecture in this diverse suite of rocks. Initial conditions and paleotopography were established above the Hercynian Unconformity, with sediment erosion, transport, and deposition modeled along this surface; lower Unayzah (especially the Unayzah-C) sediments were modeled as the products of fluvial depositional systems intercalated with repeated glacial advances and retreats. Modern analogues for this interval include glacial outwash plains in front of retreating glaciers in Iceland and Argentina. Middle Unayzah sediments were modeled as predominantly fluvial and lacustrine systems that arose during glacial retreat and collapse, while upper Unayzah sediments were modeled as the result of primarily eolian deposition. Analogues for upper Unayzah eolian sedimentation occur in modern-day Saudi Arabia. Model results correspond to observed sedimentary facies and initial reservoir quality in cores and logs, and with stratal geometries defined to the limit of seismic resolution. Results from this research will be used in conjunction with diagenetic modeling in Saudi Aramco's on-going reservoir quality prediction effort to develop better pre-drill risk estimates for exploration efforts in this interval.

## 680924 Biogenic silica particles in Permian – Carboniferous rocks and their significance as biostratigraphic indicators

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Late Carboniferous to early Permian clastic rocks of the Unayzah resting on the Hercynian Unconformity in Saudi Arabia, are of great economic significance, bearing significant quantities of gas and oil. The Unayzah reservoir sequences are often barren of fauna and flora, which limits independent biostratigraphic control and well correlation. The presence of newly discovered siliceous microfossils may provide a tool for subdividing and correlating these rock successions. These siliceous microfossils may constitute phytoliths, microscopic silica bodies of various shape and size that form in the cells of roots, stems and leaves of plants. As major plant groups like gymnosperms, lycopods and ferns already existed by the end of the Devonian, one might expect that these early land plants also formed phytoliths in their tissues. Following decay of the plant, the silica bodies may become part of the sedimentary record. In order to test this hypothesis Permian – Carboniferous rocks from 12 wells, distributed over a large geographic area in Saudi Arabia, were studied. Biogenic silica particles (BSPs) were found in all studied wells and lithostratigraphic units. A total of 14 BSPs with some significant morphological differences were identified and described. BSP assemblages are currently being studied to determine whether they can provide information on facies, paleoclimate or stratigraphy. The fact that almost all BSP species were found in all lithostratigraphic units studied suggests that subdivision of the sedimentary sequences based on conventional first and last occurrence datums of BSPs, is not promising. On the other hand, BSPs show distinct abundance patterns that may be of stratigraphic importance. The sample collection from the Unayzah succession has recently been extended in order to enlarge the areal and stratigraphic coverage. If the outlined studies are successful, BSPs may provide a new tool for subdividing and correlating terrestrial rock sequences that are often barren of microfossils, including palynomorphs.

## 694825 Meteoric diagenesis of microporous carbonates: Example of the Mishrif Formation (Cenomanian – Early Turonian) of Qatar

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Shallow-marine carbonate sediments of the Mishrif Formation (Mid-Cenomanian to Early Turonian) were deposited on a low-energy ramp, before a Mid-Turonian relative sea-level fall. Depositional environments vary from inner-ramp to open mid-ramp, with very shallow rudist biostromes. In the predominant mud-supported sediments (mudstones, wackestones, etc.), the heterogeneity of reservoir properties (e.g. porosity, permeability, pore access radii distribution) is closely related to micro-textures of the micritic matrix. Microporosity is relatively constant, high (up to 35%), and represents up to 98% of the total porosity. Permeability is low (below 1 mD) to moderate (up to 100 mD).

Using cathodoluminescence (CL), scanning electron microscopy and isotopic analyses, 240 samples coming from seven cored wells of a Mishrif oil Field have been studied to characterize the sedimentary and diagenetic factors that have controlled reservoir properties.

Micritic facies with the best permeability (up to 100 mD) and the higher pore threshold radius (PTR - up than 0.5 µm) generally show coarse, badly sorted and poorly luminescent micrites. These micrites are spatially and chronologically associated with eogenetic phases, indicating the development of an important oxidizing vadose interval (up to 30 m thick) below the Mid-Turonian exposure surface. These eogenitic phases are: (1) endokarstic cavities; (2) rare poorly luminescent sparry low magnesium calcite (LMC) with low $\delta^{18}O$ and low $\delta^{13}C$; (3) corrosion gulfs on early spars. In this vadose zone, the development of coarse (crystallometry > 2 µm), poorly luminescent micrites with similar geochemical signature is explained by the early dissolution of fine aragonite and HMC particles leading to a simultaneous overgrowth of LMC particles.

Below the vadose zone most of the micritic facies are associated with low permeability and PTR (less than 10 mD and 0.5 µm, respectively). Micrites are finer (crystallometry less than 2 µm), well sorted and luminescent under CL. This micritic pole is explained by a mineralogical stabilization of micritic particles that ends later, in poorly oxygenated waters, probably after the deposition of the Laffan shales that seal the Mishrif reservoir.

## 680557 3-D seismic evidence of Tertiary - Cretaceous karsts and Cretaceous marine channels from an offshore oil field in Abu Dhabi and outcrop analogs from United Arab Emirates

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Tertiary to Cretaceous age karsts and Cretaceous marine channels were observed from recent 3-D seismic interpretation of an offshore Abu Dhabi oil field. The seismic evidence of karst features was investigated using full-stack, spectral whitened, and discontinuity volumes. In addition, circular features were detected at specific sequence boundaries after examining curvature maps, disturbed amplitudes, velocity effects, and attenuation attributes. Several karsts and collapse disturbances tend to be associated with anhydrite beds overlying thick carbonate intervals and seem to be limited to the Tertiary stratigraphic column. Other karsts were observed to be limited to Cretaceous dolomite and limestone reservoir intervals. The Tertiary age karsts were observed to cause seismic reflectors and amplitude disturbance at various depths, whereas the Cretaceous age karsts tend to be limited in radius and depth and have more limited effect on seismic response. The Cretaceous marine channels were also observed to cause seismic reflectors and amplitude disturbance at various depths but with opposite velocity response of both karst systems.

In an attempt to better understand the limit of some karsts and marine channels, well data (wireline log, conventional core, and thin-section) were investigated within the karst areas and integrated with 3-D seismic data. 3-D seismic based geometries and attributes were analyzed to evaluate the possibility of detecting the karsts' damage-zone and marine channels limit *versus* velocity effect with depth due to fill material. Another effect investigated is that of fracture-fault zone distribution relative to karst localization and the possible deep fault relationship to each marine-channel cut.

Analogue karst features of a similar age-range (Tertiary and younger) to the seismic examples occur within Jabal Hafeet in the onshore UAE, where solution effects, debris fill, mineralization, and collapse effects can be observed and compared with the offshore examples. Here, structural discontinuities also enhance the karstic features. Cretaceous marine-channel outcrop analogs additionally were investigated in northern Emirates.

## 657130 Deposition of retrogradational carbonate grainstone shoals and subsequent basal barrier (sole seal) development by deposition and diagenesis in the Lower Cretaceous Ratawi Oolite Reservoir (Minagish Formation) Wafra Field, PNZ-Kuwait

*O.M. El-Gendi, J. Weston and B. Al-Otaibi*

The Wafra Field is located in the Partitioned Neutral Zone (PNZ) between Kuwait and Saudi Arabia and has been producing medium gravity oil from the Ratawi Oolite Limestone Reservoir since 1956. The Ratawi in Wafra is an example of a detached rimmed shelf carbonate shoal depositional system deposited on a paleo-high in the Late Cretaceous. The depositional architecture was analyzed for major depositional controls and to explain the

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existence of a sole seal (basal barrier) that restricted early water encroachment and contributed greatly to the productivity of the reservoir.

The carbonate platform is made up of allochem oolitic limestone shoals (grainstones) during relative sea level stagnation in an overall transgressive retrogradation shoal system with shallowing-upward sequences. The reservoir is structurally trapped on three sides and stratigraphically trapped on one side where tighter, off-shoal deeper marine carbonate wackestones and mudstones provide the necessary reservoir seal.

As the leeward and windward carbonate grainstone shoals developed, a tighter carbonate mudstone was deposited by reduced circulation of nutrients and aeration, and increased excessive heat, resulting in a lowstand system tract (LST) lagoonal facies. The retrogradation of these grainstone shoals with intervening lagoonal facies resulted in a continuous development of a tighter facies across the field, enhancing a substantially facies-driven sole-seal to the reservoir called the basal barrier. Diagenetic cementation of the basal barrier (possibly due to neomorphism or re-crystallization of pre-existing carbonate fines) further reduced the sole seal permeability restricting bottom aquifer support, resulting in lower water production for much of the production life.

As transgression continued, the grainstone-forming carbonate factory was overwhelmed and drowned by a rapid rise in sea level during the transgressive system tract (TST), and tighter, deeper marine carbonates capped the main reservoir grainstone shoals. Complete entrapment came with continued transgression during the highstand system tract (HST) and deposition of tight, deeper marine argillaceous carbonates, which grade upwards to calcareous shales, forming the cap rock to the reservoir.

## 684527 Chemostratigraphic differentiation between fluvial and shore-face sands as a real-time geosteering tool in the Albian Upper Burgan Formation, Minagish Field, West Kuwait

*T. EL-Gezeery, C. Scheibe and R. Zereik*

The Albian Upper Burgan Formation of Minagish Field consists of siliciclastic sediments, which were deposited in fluvial and tide-influenced deltaic to shore-face environments. The uppermost unit of the formation (U1) is characterised by bioturbated, glauconitic shore-face sands, which are mostly argillaceous and of poorer reservoir quality. The sands (U2 to U4), consist of: (1) channel fill sand-bodies with good to excellent reservoir qualities; (2) sandbar complexes with fair to good reservoir qualities.

Both of the latter facies are influenced by tidal processes that reworked the sediments at the time of deposition. This complexity of the channel geometry makes targeting and drilling of the best reservoir facies a serious challenge. Elemental chemostratigraphy uses whole-rock inorganic geochemistry to characterise and differentiate sedimentary units. This team managed to identify "geochemical proxies" that distinguish fluvial from tidal shore-face sands of the Burgan reservoir. Furthermore, the geochemical proxies also differentiated the apparently monotonous sandstone packages into distinct sub-units that are linked to the underlying mineralogy, e.g. glauconite and dolomite, as described in petrographic studies.

Chemostratigraphy has advanced into a proven real-time application that can be utilized for: (1) improved borehole positioning while drilling; (2) geochemical data produced from near real-time analyses of cuttings samples (LIBS and ED-XRF), which are successfully used for monitoring and optimizing the wellbore in highly deviated wells through Wara and Burgan reservoirs drilled in the field; (3) application in slim-hole wells, for which no 'gamma-ray at bit' or 'resistivity at bit' tools are available.

In a recent 4¾ inch borehole, chemostratigraphic data were used for geosteering and correcting the well path within the Upper Burgan unit U3.

## 705324 Distribution of carbonate cements within depositional facies and sequence-stratigraphic framework of shoreface and deltaic sandstones: Evidence from Lower Miocene succession, Gulf of Suez Rift, Egypt

*M.A. El-Ghali, E. El-Khoriby, S. Morad and H. Mansurbeg*

In the Gulf of Suez, Egypt, the shoreface-offshore (transgressive systems tract TST and highstand systems tract HST) and coarse-grained deltaic (lowstand systems tract LST) calcarenite and hybrid arenites of the Mheiherrat Member of the Early Miocene Rudeis Formation were pervasively cemented by carbonate cements and lesser amounts of zeolite, palygorskite, pyrite and iron oxides.

The spatial and temporal distribution of carbonate cements were constrained within a sequence-stratigraphic framework. The shoreface-offshore TST and HST calcarenite and hybrid arenites, particularly below parasequence boundaries (BPs), transgressive surfaces (TS) and maximum flooding surfaces (MFS) were pervasively cemented. These cements include: (i) grain-coating and inter- and intra-granular pore-filling microcrystalline calcite (e.g. circumgranular isopacheous acicular, and columnar and small amounts of circumgranular equant) and inter- and intra-granular pore-filling coarse-crystalline calcite (e.g. poikilotopic and overgrowths) with $\delta^{18}$O VPDB = -3.6 to -0.3‰ and $\delta^{13}$C VPDB = -2.3 to -0.7‰ and (ii) non-ferroan rhombic dolomite ($\delta^{18}$O VPDB = -3.9 to +0.9‰; $\delta^{13}$C VPDB = -2.5‰ to -0.7 ‰). The coarse-grained deltaic LST calcarenite and hybrid arenites were pervasively cemented by (iv) grain-coating calcite (e.g. columnar and circumgranular equant) and inter- and intra-granular pore-filling coarse-crystalline calcite (e.g. poikilotopic and overgrowths) with $\delta^{18}$O VPDB = -4.4 to -2.3‰; $\delta^{13}$C VPDB = -2.8 to -1.3‰, and (v) small amounts of non-ferroan rhombic dolomite ($\delta^{18}$O VPDB = -4.8 to -2.5‰; $\delta^{13}$C VPDB = -3.3 to -1.5‰). Such extensive cementations by carbonates (i.e. calcite and dolomite), particularly below BPs, TS s and MFSs, were being facilitated by the presence of detrital carbonates and bioclasts. This study demonstrates that the spatial and temporal distribution of diagenetic alterations in deltaic and shallow-marine calcarenite to hybrid arenites can be better predicted when linked to depositional facies and sequence stratigraphy.

## 726611 Study of microfacies and sequence stratigraphy of the Fahliyan Formation in the Marun Oil Field, northern Dezful Embayment, southwestern Iran

*A. Feghhi, B. Habibnia, H. Amiri Bakhtiar and S. Avarjani*

Considering all the different formations in the Zagros Basin, the Cretaceous column has a remarkable position. The Fahliyan carbonate formation with the age of Neocomian (Early Cretaceous) is a main reservoir of the Khami Group and extends throughout the Zagros depositional basin. The Fahliyan Formation is equivalent to the Yamama Formation in Saudi Arabia, Bahrain and Qatar and (from earlier to later) the Makhul, Minaghish and Ratawi formations in Kuwait. According to characteristics of the Fahliyan's equivalent formation in Saudi Arabia and Qatar (Yamama Formation), it appears that their depositional conditions were similar. In the past, several geological studies had been done on this formation mostly using lithostratigraphic and biostratigraphic analysis. However, considering its performance as a high-quality reservoir, and since the Marun Field is one of the largest oil fields in Dezful Embayment and in Iran, there is a critical need for more detailed studies to help hydrocarbon exploitation from the Khami Group in this field. This research was mainly an effort to this aim.

This research has been done using petrographic analysis and methodology and principles of sequence stratigraphy. Moreover, well logs have been used as a subsidiary tool to assess the sequence-stratigraphical studies. The "Wilson" (1975) and "Flüge" (2004) methods were applied to describe microfacies and to determine their depositional environment. The nomenclature for carbonate rocks follows "Dunham" (1962). After recognition of microfacies and evaluation of lateral and vertical variations (using Walter's law) a depositional model for the Fahliyan Formation was proposed. Then, sequences of the Fahliyan Formation and their systems tracts were identified. Finally, compartments with more reservoir potential were recognized.

The main tasks completed during this study are as follows: (1) study of microfossils (benthic foraminifera and algae); (2) relative age determination of the Fahliyan Formation (based on age of microfossils); (3) study of different kinds of microfacies; (4) study of the depositional environment and sedimentary cycles; (5) sequence stratigraphy of the Fahliyan Formation in well section; (6) evaluation of the Fahliyan reservoir characteristics in the Marun Field; and (7) assessment of the relationship between microfacies with reservoir potential and sedimentary cycles of the Fahliyan Formation, using thin sections and well logs.

## 680830 Tertiary petroleum geology of the southern Mediterranean: A regional correlation from northern Tunisia to the Levantine Basin

*C. Fildes, A. Godet, M. Simmons, O. Sutcliffe and D. MacGregor*

The Tertiary petroleum system of the southern Mediterranean has resulted in major discoveries that can be placed in the context of the sequence-stratigraphic scheme developed by Sharland et al. (2001) for the Arabian Plate and further updated by Simmons et al. (2007) (with some further modifications). Throughout Tertiary times significant falls in sea level, driven by eustacy, have been identified. These falls in sea level have

associated lowstand deposits that can be correlated regionally.

The Nile Delta is proving to be a world class hydrocarbon province with an abundance of potential source rocks within the Lower Miocene, Oligocene and possibly the Mesozoic. The most prolific plays to date are associated with Pliocene reservoirs, which can be linked to a latest Messinian sea-level fall. In the adjacent Levantine Basin, the Mari B Field gas discoveries have been made in Pliocene sediments that also correspond to the same lowstand described in offshore Egypt. Another important play is within the Miocene, constituted by submarine sandy fans related to a sea-level fall recorded in the Langhian and Messinian of the Nile Delta (Ng 30 and Ng 40 SB).

Other potential plays have been postulated, especially those associated with Oligocene lowstand and transgressive sediments that display good reservoir quality within the Satis Oil Field. Elsewhere in North Africa this play is of interest, especially offshore northern Tunisia where the deepwater turbidites of the Numidian Flysch (Late Oligocene to Early Miocene; Pg 50 and Ng 10 SB) exhibit excellent reservoir potential and are a proven play in Sicily.

Finally, the offshore Sirt Basin is a promising frontier basin, and as with the Nile Delta, the Messinian lowstand is an important time for reservoir and seal formation. The palaeo-Sahabi river system drained from Lake Chad into the offshore Sirt Basin during the Zeit Wet Phase. This river system has left a significant erosional imprint on the east flank of the Tibesti and near the coast of the Gulf of Sirt, which indicates a large sediment supply during this time, creating large lowstand fans and delta deposits in the offshore Sirt Basin.

## 680053 Improved understanding of the Athel silicilyte through the Fara Formation: A coeval Neoproterozoic analogue in the Sultanate of Oman

*C. Fonseca-Rivera, O. Shoufi, J. Irvine-Fortescue, T. Johnson and J. Schreurs*

The Athel silicilyte represents a unique type of reservoir in the Sultanate of Oman with only two fields currently on production in the South Oman Salt Basin under pressure depletion schemes. The next development for one of these fields will incorporate miscible gas injection where sweep efficiency, injectivity and rapid gas breakthrough are key uncertainties. Since the development of the field, the lack of an identified depositional analogue has limited the understanding of rock property distribution, the prediction of facies and potential reservoir extent that all impact these key uncertainties. However, examination of the Neoproterozoic – early Cambrian Fara Formation in Wadi Bani Awf provides a potential analogue for sediments with similar lithologies and age of deposition. Characterization of the Fara Formation and the extent to which it can be directly applied to the subsurface is the focus of our current research.

The screening of the Fara Formation as an analogue has involved detailed measuring of stratigraphic sections, acquisition of spectral gamma ray, petrography, bulk mineralogy and stable isotope analysis. Initial results indicate the Fara Formation and the Athel silicilyte were both deposited in an enclosed basin, starved of clastic input, under reducing conditions and below storm wave base. Both formations display laminated silicified sediments that indicate seasonality, deposition by traction and suspension and occurrence of microbial mats. Slumping and fine-grained turbidites are common and reflect margin instability likely associated with ongoing tectonism. Petrographic and field examinations indicate dolomite cementation predated silicification, and at least two phases of silicification have taken place in the Fara Formation. This has implications for the silica precipitation model. The large component of volcaniclastic material in the Fara Formation suggests that volcanic activity and basin configuration were key factors in the development of the Athel silicilyte during the Neoproterozoic – early Cambrian of the Sultanate of Oman. Unlike the Athel however, the Fara Formation also shows a large proportion of carbonate and a diversity of lithofacies including fore-reef talus deposits, debris flows, turbidites, and redeposited laminated microbial boundstones that has not been recognized to date in the subsurface. This paper presents early results and potential implications for exploration and production of the Athel silicilyte.

## 724921 Stratigraphy of the Albian to Santonian sediments of Bangestan palaeo-high, southwest Iran

*A. Ghabeishavi, H. Vaziri-Moghaddam, A. Taheri and F. Taati*

The Bangestan palaeo-high is one of the well-exposed Cretaceous palaeo-highs, which crops out in the Bangestan Anticline (southwest Iran, about

150 km west of Ahwaz). Eight outcrop sections and one subsurface section (Pr#35) from Parsi Oil Field (10 km southwest of Bangestan Anticline) were studied. More than 2,000 thin sections were analyzed. Biostratigraphy, microfacies, sedimentary environment and sequence-stratigraphic techniques were used for better understanding of palaeogeography of Bangestan palaeo-high. The foraminifers biostratigraphic study led to recognition of 10 biozones.

The sedimentary environment of the lower Sarvak Formation is interpreted as a carbonate shelf without an effective barrier separating the platform from the open–marine environment. The inner shelf environment was dominated by benthic foraminifers such as miliolids, *Nezzazata* spp. and alveolinids. The rudist community was well developed in the middle shelf environment. The outer shelf was dominated by oligosteginids and fine-grained, platform-derived material. The intra-shelf basin is identified by planktonic foraminifers, radiolarians and oligosteginids.

The grainstone-dominated upper Sarvak sediments are subdivided into six microfacies belonging to a high-energy fringing carbonate platform around the emerged area. The proximal to distal positions are identified by variations in facies dominated by intra-clasts to benthic foraminifers, followed by rudists and finally oligosteginids, respectively.

The Coniacian – Santonian sediments (Surgah and Ilam formations), which were deposited on the flanks of Bangestan palaeo-high, are subdivided into nine microfacies types. Various sedimentary environments, ranging from continental lacustrine to very shallow and relatively deep-water (hemiplegic to pelagic) marine environments are recognized.

The sequence-stratigraphic analyses led to identification of five (A-E) sedimentary sequences. The sequence-stratigraphic correlation shows that in the Cenomanian time, Bangestan Anticline was located at the margin of an intra-shelf basin, while in this time Parsi Field was in the intra-shelf basin. During the Late Cenomanian, the lower Sarvak sediments were differentially uplifted along pre-existing basement faults. Deposition of the Cenomanian – Turonian limestones (upper Sarvak) and Coniacian – Santonian (Surgah and Ilam) sediments took place on the flanks of Bangestan Palaeo-high and beyond. The center of this palaeo-high emerged and was exposed to erosion until Late Campanian.

## 696107 Halite in the Upper Jurassic of the Marib-Jawf Basin, Yemen

*G.J. Grabowski, G.K. Edgerton, A.M. Noman, J. Ottmann and C.R. Beeman*

The Marib-Jawf Basin is a Kimmeridgian northwest-trending extensional graben in western Yemen. There are 36 discoveries in the basin, with an original expected ultimate recovery (EUR) of almost 1.7 billion barrels of oil and condensate and 18 trillion cubic feet of gas. These occur in sandstone reservoirs with halite seal, in traps formed in part by salt structuring. Evaporite deposits and decolling salt movements are the critical elements in the development of trap, top seal, and foot seal.

Halite occurs in thick beds in the Safer Formation (Upper Tithonian), up to 750 meters net thickness. Meter-scale anhydrite beds occur at the top and base of halite beds. The halite is sub-aqueous salt deposited in restricted-marine basins. Thinner halite deposits occur in the Alif Formation (Lower Tithonian) in the downdip southeast end of the basin, mostly in the lower Yah Member, but also in the middle Sean Member and the upper Alif Member. The Safer and Alif formations merge to form the Sabatayn Formation in the Shabwah Basin southeast of the Marib-Jawf.

Intervals of shale, siltstone, sandstone, and thin limestone beds divide the Safer Formation into five members. These fluvial-alluvial to paralic- and shelfal-marine deposits formed when the evaporitic basin was desiccated. The fluvial sandstones in the Safer Formation contain some oil and gas. Fluvial to deltaic-marine sandstones of the Alif Formation are the major reservoirs, with halite of the Safer Formation forming the topseal. Some shale in the Safer Formation is organic-rich (< 16% TOC, HI < 955 mg HC/gC). They generated oil in deeply buried portions of the basin, and the oil occurs in sandstone reservoirs of the Safer Formation. The oils are low gravity (14–27° API) and 3–6% sulfur, with biomarkers typical of anoxic hypersaline source rocks (Pr/Ph < 1.0, abundant gammacerane, C35 pentacyclic hopanes, and C27 cholestanes).

Halite deformed by gravity sliding on listric faults detached in the basal salt and uppermost Lam Formation, forming rafts that enclose the Alif Formation. This created gaps in the Alif Formation, where salt is grounded on the underlying Lam Formation. Salt flowed into the lowside of normal faults that moved during the Cretaceous. Salt diapirs are present mainly in the SE end of the basin

and the adjacent Shabwah Basin. Most fields are structural closures formed by salt movement. Halite cementation in Alif sandstone reservoirs on the downdip side of structural closures in the southeast end of the basin form stratigraphic traps, as in Al-Raja Field.

## 696123 Strontium-isotope age dating and correlation of Phanerozoic anhydrites and unfossiliferous limestones of Arabia

*G.J. Grabowski and C. Liu*

We are dating anhydrites and limestones that lack age-diagnostic faunas using $^{87}Sr/^{86}Sr$ ratios. It has enhanced our correlation of the Miocene and Oligocene, Jurassic, and Triassic – Permian. Deposits in Iraq that have been considered Middle Miocene are actually older. Sr-isotope ages of anhydrites from the Fatha Formation from many wells give consistent ages of Late to Middle Burdigalian (15.6–18.5 Ma). Platform carbonates of the Jeribe Formation are Middle to Early Burdigalian in age (18.5–19.6 Ma). The basin-filling evaporites of the Dhiban Formation were deposited from earliest Burdigalian through Late Aquitanian (19.6–21.3 Ma). The Euphrates and Serikagni formations are older still, deposited in the Early Aquitanian to Late Chattian (21.8–24.3 Ma).

The Kirkuk Group is composed of shelfal, shelf-margin and basinal limestones divided into many lithostratigraphic units which are not easily correlated without an age framework. The youngest units are Middle to Early Chattian (24.4–33.9 Ma), with the Bajawan, Baba and Tarjil formations being Late to Middle Rupelian (28.5–32 Ma), and the Shurau, Sheikh Alas and Palani formations are Early Rupelian (32.2–33.9 Ma).

The Hith Formation is Middle to Early Tithonian (147.5–150.7 Ma). Anhydrites of the underlying Arab Formation on the Southern Arabian Platform (SAP) are Late to Middle Kimmeridgian (150.7–153.5 Ma). Strontium ages of the basinal evaporites of the Gotnia Formation in the Gotnia Basin give the same ages.

Thick shelfal limestones below the Arab Formation on the SAP are Early Kimmeridgian to as old as Bajocian (168–171 Ma) in the Lower Araej Formation. Thin basinal Najmah and Naokelekan formations in the Gotnia Basin are Early Kimmeridgian to Middle Bathonian (153.5–166.5 Ma). The underlying Sargelu Formation is Early Bathonian to Bajocian (167–168.5 Ma), equivalent to the Upper Araej and Uwainat formations of the SAP.

Anhydrites in the Alan and Adaiyah formations are Middle to Early Toarcian (178–183 Ma) and Late to Middle Pliensbachian (183–187 Ma), respectively. The Butmah Formation is Late Sinemurian to Late Rhaetian (187–200 Ma). The Lower Araej of the SAP is Early Toarcian – Late Pliensbachian.

The Kurra Chine Formation in Iraq has yielded a Rhaetian Sr age, and the underlying Geli Khana is dated Ladinian. Anhydrites of the Jilh Formation on the SAP give older ages (Carnian to Anisian), equivalent to the lower part of the Gulailah Formation (Rhaetian – Norian to Ladinian – Anisian).

## 680864 High-resolution sequence stratigraphy and reservoir development of the Kurra Chine Dolomite, Ash Shaer Field, Palmyra, Syria

*P. Gutteridge, J. Hall and L. Hamdoun*

The Triassic Kurra Chine Dolomite Formation of the Ash Shaer Field, Palmyra, Syria, comprises repeated cycles of shale, dolomitised carbonate mudstone and wackestone, peritidal limestone and subaqueous anhydrite deposited in a restricted intra-shelf basin, sometimes connected to the Neo-Tethys Ocean. The aim of this study is to demonstrate a high-resolution sequence-stratigraphic model for the Kurra Chine Dolomite that may explain and predict the distribution of porosity throughout the reservoir. Cycles observed and described in core were used to validate the field stratigraphy, such that Fischer plot analyses could be extended to uncored logged intervals for each well. The corresponding correlations of cycle number *versus* net deviation of cycle thickness from average cycle thickness demonstrates the influence and control of high and low order sea-level variations on porosity development and preservation.

High-frequency sequence stratigraphy has aided the identification and characterisation of correlatable productive intervals in the Triassic upper and middle Kurra Chine of the Ash Shaer Field, Palmyra Province. This has enhanced our understanding of reservoir connectivity and stacking, providing a valuable tool for improved development and well planning. The following cycle types were defined: (1) Subtidal cycles are argillaceous laminated and bioturbated carbonate mudstone and shales. Cycle boundaries are non-emergent. Maximum flooding events are bioclast-rich shales that may form field-scale correlative layers. These cycles are mainly limestone with little dolomitisation. (2) Subtidal cycles with anhydrite contain anhydrite beds, which occur in the subtidal cycles that formed

during draw-down events and may form field-scale correlative layers. Dolomitisation is much more prevalent in these cycles than the subtidal cycles. (3) Peritidal cycles are subtidal cycles capped by peritidal facies. Occasional anhydrite beds were deposited in local hypersaline lagoons and are not useful for correlation.

The sequence architecture of the Kurra Chine Dolomite reservoir is controlled by the interplay of lower and higher orders of sea-level variations: (1) Low-order regressions cause basinward stacking of high order peritidal and subtidal-with-anhydrite cycles because of reducing accommodation space. (2) Low-order transgressions cause higher order subtidal cycles to back-step towards the basin margin. (3) Low-order highstands cause higher-order subtidal cycles to stack progressively basinward.

## 670129 Jurassic and Cretaceous carbonate geology and stratigraphic plays in the Rub' al-Khali Basin, Kingdom of Saudi Arabia

*C. Harvey, A. Azzouni and H. Droste*

The South Rub' al-Khali Company Limited (SRAK) is an Incorporated Joint Venture between Shell Saudi Ventures Limited (50%) and Saudi Arabian Oil Company (50%) and was set up in order to explore for non-associated gas in the South Rub' al-Khali Basin as part of the Natural Gas Initiative in the Kingdom of Saudi Arabia.

Building on its Paleozoic play mapping in Contract Area 1, SRAK has also been developing and inventorizing Jurassic and Cretaceous stratigraphic play opportunities, driven in part by the successful exploration at similar stratigraphic levels in neighboring countries. This study presents a comprehensive evaluation of this play potential. We will outline our ground-up approach moving from well-based work, to conceptual geological models, to integration with seismic, in order to delineate potential reservoir seal pairs and stratigraphic plays that help to build a risked portfolio of leads and prospects.

Key to our understanding has been the integration of published and in-house regional knowledge. The Upper Jurassic and Cretaceous stratigraphy has been assessed in over 30 offset wells using a sequence-stratigraphic approach combining available biostratigraphy, sedimentology, structural and well log data. Correlation of wells and basic seismic screening have enabled the development of conceptual geological models and gross depositional environment time slice maps for the Jurassic Tuwaiq Mountain Formation through to the Upper Cretaceous Aruma Formation.

Major breakthroughs included the identification of Middle Jurassic progradation directions, location of the Upper Jurassic platform margin, subsequent Lower Cretaceous prograding clinoform system and later interior platform conditions. These depositional patterns have been linked to major tectonic events. Depositional features including reservoir and source rock distributions in the Lower Cretaceous Shu'aiba to Upper Cretaceous Aruma package have also been delineated. In total 15 potential stratigraphic play types have been identified in Contract Area 1 of which many have been high graded or down graded dependent on seismic quality. The regional geological work presented here forms the basis for both regional and prospect scale seismic interpretation work.

## 680843 The Dhruma Formation of Saudi Arabia: Bajocian to Bathonian micropalaeontology and sedimentology

*G.W. Hughes, R. Lindsay, N. Naji, P.D. Jenden, N. Hooker, F.O. Meyer and C. Toland*

The Faridah, Sharar and Lower Fadhili hydrocarbon reservoirs of Saudi Arabia represent grain-dominated terminations of a succession of shoaling-upwards depositional cycles. They are hosted within the Dhruma Formation and a recent study of outcrops and shallow cores drilled in the outcrop belt has revealed the palaeoenvironmental and lithostratigraphic locations of the reservoir facies as well as a regionally significant seismic reflector known as the Dhruma Shale. The age of the Dhruma Formation is based primarily on ammonites and nautiloids but supplemented by micropalaeontological and palynological evidence. Carbon and oxygen isotope determinations complement the biostratigraphic evidence. The Dhruma lies unconformably on the Lower Jurassic (Middle to Upper Toarcian) Marrat Formation and is unconformably overlain by the Middle Jurassic (Middle to Upper Callovian) Tuwaiq Formation. An allostratigraphic, sequence-based reinterpretation of the originally defined Dhruma now assigns the Atash and Hisyan members, previously of the uppermost Dhruma Formation, to the overlying Tuwaiq Mountain Formation.

The Dhruma Formation at outcrop consists sedimentologically of a thick succession of shoaling-upwards depositional cycles, each of which commences with calcareous mudstones (marls) that contain moderately deep marine foraminifera with

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pelagic bivalves, and terminate with clean, locally cross-bedded to hummocky cross-bedded and ooid-bearing carbonates that contain very shallow marine foraminifera and associated microfossils.

The study concludes that the Dhruma Formation was deposited as a succession of high-frequency depositional cycles. The outcrop has provided new information on the palaeoenvironment and lithostratigraphy of the Dhruma Shale, Faridah, Sharar and Lower Fadhili reservoirs and will have significant impact on further exploration activities to identify these reservoirs in the subsurface.

## 680861 The palaeoenvironmental and microstratigraphic significance of microcoprolites in Saudi Arabian Upper Jurassic carbonates

*G.W. Hughes*

Reservoir carbonates of the Arab Formation B and A units and Hith Formation contain beds in which microcoprolites are well preserved. Species of the tubule-bearing, rod-like *Favreina* are attributed to *F. salevensis* and *F. fontana* and represent derivation from a decapod crustacean source. Contorted ribbon-like microcoproliths of *Prethecoprolithus centripetalus* represent derivation from a mollusc source. Their association with cyanobacterial microgranules, often in stromatolitic layers, and monospecific unornamented cyprid ostracods, *Terebella lapilloides* and absence of foraminifera suggests a bacterial grazing mode of life within a stressed, marine environment that may have experienced elevated salinity and temperature. The ascending succession from: (a) microfaunally-barren anhydrite lithofacies; (b) microfossil-barren, granular cyanobacterial microbialite - *Decastronema* / *Aeolisaccus* biofacies; (c) ostracod biofacies; (d) *Favreina-Prethocoprolithus* - ostracod - cerithid gastropod biofacies; (e) *Trocholina* - *Redmondoides* - *Palaeopfenderina* - *Mangashtia* - *Clypeina-Salpingoporella* - *Thaumatoporella* biofacies; to (f) concentric ooid biofacies. These facies are considered to represent a parasequence within a shallow-marine palaeoenvironment. The alternation of such stressed carbonate units and evaporitic sediments is considered to represent episodic flooding of a playa-like evaporitic basin, in which the foraminiferal biofacies probably represents the maximum flooding event and best circulation of marine water. Microcoproliths provide intra-reservoir stratigraphic events to complement micropalaeontologically sparse carbonates and would be expected to provide valuable micro-biocomponents to assist coiled-tube biosteering of Upper Jurassic carbonate reservoirs.

## 680859 Biofacies and palaeoenvironments of the Khuff carbonates in southern Ghawar Field, Saudi Arabia

*G.W. Hughes*

Semi-quantitative micropalaeontological analysis of closely-spaced core samples from the upper Permian Khuff C carbonates in the Haradh area of southern Ghawar Field has revealed rich and diverse foraminiferal assemblages and associated microfossils, including bryozoa, calcareous algae, brachiopods, echinoids, ostracods, rare sponge spicules and cyanobacterial sheaths. The foraminifera are typically very small and include agglutinated, microgranular, miliolid and calcareous hyaline forms that display a variety of morphotypes that assist to refine the depositional environment. In addition to the considerable biofacies variations in ascending stratigraphic order within individual wells, lateral variations are present that together reveal regional and temporal palaeoenvironmental changes. These changes can be related to successive transgressive-regressive depositional cycles that compare readily with the distribution of porosity. Rock fabrics range from dense mudstones through wackestones, peloidal packstones to ooid grainstones. Porosity types encountered within the Khuff C reservoir include interparticle, mouldic and intercrystal. Diagenetic alteration of the primary fabrics includes cementation by calcite, dolomite and anhydrite, of which pervasive dolomitization is responsible for creating porosity within otherwise non-porous carbonates. The close association between biofacies and reservoir porosity distribution has led to the recent application of rigsite micropalaeontological analysis to biosteer under-balanced coiled-tube development drilling of the Khuff C reservoirs.

## 680217 Controls from the hydrocarbon entrapment in Burgan and Wara formations in Offshore Kuwait

*F. Hussain, R. Husain, A.H. Sajer and A. Al-Kandary*

Offshore Kuwait lies to the east of Kuwait with an aerial extent of about 10,000 sq km. It is not comprehensively explored and only a few wells have been drilled to explore Cretaceous structural prospects. The objective of the study is to bring out the depositional environments, distribution of lithofacies and their control on hydrocarbon entrapment for Burgan and Wara formations.

The Lower to Middle Albian Burgan Formation is a thick clastic sequence, which was deposited in a fluvial to marginal marine environment. The formation is broadly divided into two major sand packages separated by a major shale unit. The lower sand package corresponds to lowstand systems tract while the upper package corresponds to the highstand systems tract as well as lowstand clastics of the overlying sequence. In the Upper Burgan, the fluvial and tidal sands that filled incised valleys are prolific oil producers onshore. Reservoir quality deteriorates in the seaward direction as the valley systems thin and become mud prone. The Cenomanian Wara Formation is also a clastic sequence comprised of sandstone with interbedded shales deposited in an inner to middle shelf environment. The formation corresponds to highstand systems tract of the sequence initiated in Upper Burgan. The thin sandstone beds in the Wara Formation are also known commercial producers in onshore.

Prospectivity analysis of the Burgan and Wara formations in Offshore Kuwait has indicated that hydrocarbon occurrences are controlled by temporal and spatial variations of lithofacies. The study has indicated that the Kuwait Bay appears to be the most prospective for exploration of these reservoirs in terms of development of favourable lithofacies associations occurring in a favourable structural setting. High-resolution sequence stratigraphy and depositional modeling is key to the exploration of these formations.

## 680335 Minjur Sandstone revisited: New advances in sequence stratigraphy and modeling in the Khashm-Al-Khalta reference area, Central Saudi Arabia

*B.H. Issautier, Y.M. Le Nindre, A. Memesh and S. Dini*

In connection with the issues of $CO_2$ geological storage in complex reservoirs, the Minjur Sandstone, in outcrop in Central Saudi Arabia, was selected as a case study for modeling and simulating the spatial distribution of sand bodies in a fluvial-deltaic system. As a first step, detailed sedimentologic mapping, sequence stratigraphy and 3-D geological modeling were performed in the area of inlet/outlet maximum activity of the deltaic system.

Compared to the reference studies by Vaslet et al. (1983) and Le Nindre et al. (1987, 1990), the vertical and lateral variations around the type section were studied in detail, and interpreted with greater accuracy in terms of depositional features and sequence stratigraphy. This new survey was specifically designed to collect 3-D information for numerical modeling.

High-resolution sequence stratigraphy demonstrates nine third-order sequences, involving four environments: sabkha, tidal, estuarine and fluvial-continental. The general trend at the formation scale is a thickening-coarsening upward trend related to increasing clastic influx and development of fluvial systems. As originally described, a maximum flooding occurs near the middle of the formation with a development of tidal mud flats and carbonate facies. The lower member is dominated by subtidal, brackish and scattered fluvial environments, while the upper member is fluvial dominated with amalgamated sand bars.

The facies variations were analyzed on the field by vertical sedimentological measured sections, spectral gamma-ray logs, and a network of georeferenced scattered observation points. These data were mapped by using high-resolution IKONOS satellite imagery and an enhanced DTM. These investigations demonstrated that the more distal deposits of the lower Minjur include disconnected, scattered and narrow sand bars. Wide meandering point bars appear upward. Above the MFS, massive and very wide sand bars resulting from an important sediment supply exhibit a maximum vertical and horizontal connectivity with a continuity of several hundred of meters.

Using mapping, logs and field observation points, a deterministic numerical model of the sand/mud distribution was built. This outcrop analogue is currently used to build conceptual numerical models respecting the Minjur architecture but with varying connectivity between the sand bodies in order to quantify how the connectivity evolves in fluvial style reservoirs. Further $CO_2$ flow simulations are expected to provide conclusions on response of $CO_2$ injection to fluvial heterogeneities in each case.

## 680489 Modern lessons for the interpretation of ancient sabkhas: Examples from the Holocene of Qatar

*J. Jameson, M.G. Kozar and D.D. Puls*

Holocene coastal and sabkha deposits of Qatar illustrate depositional and diagenetic trends that aid in interpretation of ancient, evaporite-carbonate reservoir sequences. Recent data from offshore and on land provide new insights into evaporite distribution, facies and stacking patterns of sediments deposited during the Holocene sea-level

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rise. Comparison of coastal deposits from different regions of Qatar formed during the Holocene sea-level rise reveals new insights into characterization of ancient rocks.

Coastal Holocene sediments form a predictable profile from offshore to onshore, varying with sediment supply, circulation, and bathymetry. Windward-facing coasts are characterized by narrow, coarse-grained facies belts dominated initially by fringing coral reefs, followed by formation of mobile sand belts and islands with algal flats, mangroves, and sheets of aeolian sands. Oblique and protected coasts are characterized by finer grain sizes, mixed carbonate and quartz sands formed in a mosaic of subtidal, beach intertidal and aeolian settings. The leeward coasts are marked by quartz sands and extremely high rates of coastline progradation.

Most coastlines are marked by low relief, with the result that high-frequency oscillations in sea level are responsible for major offsets in facies tracts. Age dating reveals that inland sabkhas are relicts of a high stand in sea level ca. 4,000–6,000 years ago. These areas are presently eroding. Extensive pedogenic modification of original marine sediments (by burrowing, infiltration, micrite precipitation) creates characteristic textures. Groundwater modification includes extensive precipitation of $CaSO_4$ (nearly all gypsum), minor halite, micrite, and dolomite. Gypsum precipitation near the water table may reach 20–40% of sediment volume and extend over several square kilometers.

Modern Qatar sabkhas are characterized by facies offsets at cycle breaks, laterally extensive erosional surfaces and associated gypsum precipitation. Documentation of these features aids in recognition of ancient sabkhas. Neither the sedimentary structures nor the biota are distinctive. Recognition of a sabkha relies on understanding styles of diagenesis that modify sediment texture and interparticle porosity. This process approach helps aid in sabkha recognition and to explain styles of diagenesis that control reservoir properties.

## 678393 Exploration for hydrocarbons in a half-billion-year-old chert: The Athel story continues

*T. Johnson, A. Brandenburg, C. Fonseca, S.G. Fryberger, Y. Hajri, S. Kindy, J. Schreurs, O. Shoufi and W. Wilks*

In 1989 and 1995, two oil fields were discovered in South Oman in Athel 'Silicilyte' reservoirs, comprising Neoproterozoic to early Cambrian chert slabs encased in Ara salt. The reservoir units have good porosity but very low permeability and only flow light oil if massively fracc'ed. When discovered it was thought that the chert layers might be present throughout the region, but with limited drilling success in the 1990s, it became clear that the reservoir was more restricted in occurrence. A plethora of possible models exists for the origin of the chert and, therefore, its distribution.

The play requires that a porous slab of laminated chert be encased in salt, charged with light oil and that overpressure is maintained. The permeability must be sufficient to maintain long-term flow after fracc'ing. These constraints together with the reservoir, seal and charge distribution maps help define the play sweet spot. In order to identify and evaluate likely prospects, high quality 3-D seismic is needed and an extensive seismic acquisition, reprocessing and analysis program is in progress in PDO's Block 6. Re-mapping and prospect analysis is being used to update the lead and prospect portfolio and help de-risk the play. The play-based approach provides a balanced geological and geophysical de-risking scheme with the intent of providing drill worthy opportunities by 2011. This paper presents a new reservoir distribution model based on integration of previous work, regional well and seismic data analysis, study of global chert analogues and outcrops in Oman.

## 678389 The Upper Triassic Minjur Formation: A new bio- and sequence-stratigraphic framework and its implications for hydrocarbon prospectivity

*N.S. Jones and N.P. Hooker*

The Upper Triassic (Norian to Rhaetian) Minjur Formation is a siliciclastic succession present at the surface and also in the subsurface across large parts of central and southern Saudi Arabia. Until recently its stratigraphy and sedimentology have been poorly understood and it has largely been ignored as a target for hydrocarbon exploration. A recent study by the Area Exploration Department of Saudi Aramco built a regional bio- and sequence-stratigraphic framework to support regional exploration efforts in Central Saudi Arabia and better understand its prospectivity. This study utilizes core and cuttings data from 26 wells, combined with wireline logs from an additional 100 wells. It should be noted that all 600 ft of available Minjur Formation core in Saudi Arabia was studied.

The core-based sedimentology, together with palynology from core and cuttings samples, indicates palaeoenvironments that include extensive coastal alluvial plain, with fluvial channels and adjacent floodplain environments, passing basinwards into shoreline facies, typically marked by tidal, deltaic and marine settings. Routine core analysis data indicates that the best potential reservoirs are the fluvial channel facies, with porosities of 15 to 25% and wide permeability range from 100 md up to 10 darcies.

Wireline log correlations were integrated with new biostratigraphic data to establish five depositional sequences, from the base of the Minjur up to the unconformity at the base of the overlying Marrat Formation (the Pre-Marrat Unconformity). Lowstand, transgressive and highstand systems tracts have been identified from gamma log character and show distinctive proximal to distal changes. Only one palynofloral unit of a non-marine character (T1 Palynozone) was previously recognized within the Minjur Formation, but new palynological data and interpretations have established a four-fold biostratigraphic subdivision. Palynofacies provide evidence of marine to non-marine palaeoenvironmental variations within each log-defined sequence.

The new stratigraphic framework is important because it predicts the position and systems tract of the main reservoir and source rock facies. It further allows better risk assessment of various existing play types, and has helped identify new play concepts in the previously under explored Minjur Formation.

## 705374 Calcareous nannofossils from Middle to Upper Jurassic sediments of North Kuwait Onshore

*A.P. Kadar, K. Karam and M. Al-Baghli*

Biostratigraphic analysis of Jurassic nannofossil assemblages were performed on a total of 188 core samples, collected at 4 ft intervals, from MU-A, MU-C and RA-A wells, North Kuwait Onshore. Ninety-one samples from MU-A well represent the Middle Marrat, upper Dhruma, Sargelu, Najmah and lower Jubaila formations, 61 samples from MU-C correspond to the upper Dhruma, Sargelu, Najmah and lower Jubaila formations. The other 36 samples are from RA-A well represent the upper Dhruma, Sargelu and Najmah formations. The rocks consist of argillaceous limestone, grainstone, packstone, bituminous packstone, wackestone dolomite, anhydrite, laminated bituminous calcareous mudstone and calcareous shale.

Samples from the Middle Marrat Formation are barren, whereas most of the samples from other formations contain nannofossils with the total abundance fluctuating from rare to abundant, allowing the identification of maximum flooding surface candidates. Preservation of the nannoflora is poor to moderate. The diversity of nannofossil assemblages is relatively low, dominated by the most dissolution resistant species *Watznaueria barnesae*.

An index species *Cyclagelosphaera margerelii* is present in the samples of upper Dhruma, Sargelu and lower Jubaila sediments. The first occurrence (FO) of *C. margerelii* was reported to occur in Late Bajocian. The laminated bituminous mudstone of the Najmah Formation contains common to abundant nannofossils, but most of the specimens are poorly preserved because most of the inner part of the coccoliths are covered by oil stains. Strong dissolution-resistant species, *Watznaueria barnesae*, and highly birefringent, *Watznaueria manivitae* can still be identified. The *W. barnesae* occurs abundantly whereas *W. manivitae* presents sporadically. Nannofossil assemblage in the Jubaila shale is characterized by the association of *Watznaueria barnesae*, *Watznaueria britannica*, *Watznaueria communis* and *Watznaueria manivitae*. Those fossils' record suggests that the interval of the upper Dhruma to Najmah formations falls within Middle Jurassic Upper Bajocian to Upper Jurassic Oxfordian stages and the lower Jubaila shale is Upper Jurassic Kimmeridgian stage. There is a strong possibility of stratigraphic discontinuity between the Najmah and Jubaila formations and the time gap is not as great as that suggested by some previous workers.

## 695192 Biostratigraphy of Dashtak and Khaneh Kat formations in Zagros Basin

*M. Khoshnoodkia, H. Mohseni, M. Hajian, M. Fallah Kheyrkhah, K. Khosro Tehrani and M. Khaleghi*

The Dashtak Formation is composed of dolomite, anhydrite and limestone whereas the Khaneh Kat Formation is composed of dolomite, shale and limestone excluding evaporites. Both formations were deposited in a homocline carbonate ramp with a widespread depositional facies including supratidal, tidal-flat, lagoon, shoal and lower mid ramp. These formations were evaluated in a basin-wide cross section including eight wells (Aghar-1, West Aghar-1, Naura-1, Dashtak-1, Dalan-1, Kuh Siah-1, Sartal-1, and Huleylan-1) and three outcrop sections (Kuh-e-Surmeh, Kuh-e-Manghasht, Oshteran Kuh). Data were gathered from field observations, thin sections of borehole

cuttings, geophysical data (gamma-ray, sonic and neutron logs) and geochemical analysis was performed (strontium isotope only from Sartal-1). This study revealed that the Dashtak Formation comprises four sequences (Middle to Late Triassic) and the Khaneh Kat Formation is composed of five sequences (Middle to Late Triassic). Due to lack of considerable biota content, a comprehensive biostratigraphy for these formations can not be carried out. Unfortunately subsequent pervasive dolomitization obliterated the rare biotas scattered throughout the limestone beds. In some cases the preserved biota represents a wide range (from the base to the top of the formation) and hence can not be used for biostratigraphic purposes, but remain useful in the recognition of maximum flooding surfaces (MFS). MFS Tr 40 is only restricted to the Khaneh Kat Formation, which contains *Agathammina sp.*, *Valvanids*, and *Endothyramidae*. MFS Tr 50 terminates in an ooid grainstone (shoal environment) rich in bioclasts including pelecypods, *Agathammina* sp., *Trocholina cross*, *Involutina* sp., and *Hemigordius* sp. MFS Tr 60 was determinate in limestone beds containing *Agathammina*, *Involutina*, *Ophthalmidium*, *Pragsoconulus*, *Frondiculina* sp., ostracods, echinoids, *Faverina* sp., *Iriondic* and *Glomospira*. This surface in the Khaneh Kat Formation is located in a limestone bed containing sponge spicules, pelecypods, echinoids, gastropods and algae. MFS Tr 70 was introduced in the Sefidar Dolomite Member, but we shift this surface downward into a fossiliferous limestone bed, containing *Agathammina*, *Trocholina*, *Lituosepta*, echinoids, gastropods, ostracods, *Aulotorus*, *Glomospira*, and *Irandia*. In the Khaneh Kat Formation this MFS contains algae, gastropods, *Involutina*, *Aulotorus* and echinoids.

## 680608 Outcrop characterization of the Khuff Formation from production- to exploration-scale, Oman Mountains, Sultanate of Oman

*B. Koehrer, T. Aigner, M. Poppelreiter, P. Bizarro and S. Kindy*

We present complete sedimentological-stratigraphic outcrop descriptions of Khuff time-equivalent strata (Saiq and Mahil formations) from the Oman Mountains. These were used to: (1) establish conceptual depositional models of the Khuff Formation highlighting nature and dimensions of reservoir geobodies, and (2) contribute to a regional Khuff stratigraphic framework by integrating bio-, chemo-, litho- and sequence stratigraphy.

Primary textural heterogeneities within these outcrops were mapped-out from near well (2 x 1 km) - to exploration-scale (60 x 40 km). Digital field geology was combined with traditional sedimentological investigations to place all observations in a 3-D framework for geological modeling purposes. Based on 1-D and 2-D outcrop data, hierarchical 3-D static facies models were generated.

On a 2 x 1 km near well-scale, walked-out reservoir bodies show general layer-cake geometries of grainstone bodies. Reservoir bodies tend to have a standard deviation of 13% in thickness. This variability may influence volume calculations in producing Khuff reservoirs.

The 8 x 8 km field-scale model revealed the importance of cyclicity on reservoir geometries. Considerable differences regarding percentage, thickness and lateral extend of individual grainstone geobodies within different stratigraphic intervals of the Khuff were observed in the outcrop. Reservoir facies developed preferentially in the regressive parts of cycles of multiple hierarchies. Finally, an exploration-scale model of the Khuff Formation showed systematic lateral facies changes in a 60 x 40 km area. Reservoir body distribution and stratigraphic architecture appear to be influenced by the Pre-Khuff topography, local paleohighs and paleogeographic position. The results of the study are applicable to Khuff reservoir characterization and correlation from production- to exploration-scale.

## 680509 Ichnology of the Early Devonian Jauf Formation in northern Saudi Arabia

*S. Leszczynski, P. Breuer and M. Miller*

The Jauf Formation in northern Saudi Arabia embraces a several hundred meters thick succession of mixed siliclastic-carbonate marginal marine and shallow marine deposits dated as Late Pragian to Late Emsian. Sedimentological logging of two pairs of core holes (JNDL-3, JNDL-4 and BAQA-1, BAQA-2), located about 350 km apart, has supplied original data on bioturbation structures recorded in the Jauf Formation. In northern Saudi Arabia, the formation is divided into five members differing in lithofacies. Combined cores form a 270 m thick composite section of the Jauf Formation. This study aims primarily to show the most distinct types of bioturbation structures recorded in the examined cores, their distribution in the succession and relationship to lithofacies, palynofacies, and depositional environments.

The investigated deposits display highly variable, lithofacies controlled bioturbation style and

intensity. The most intense burrowing occurs in deposits dominated by fine-grained sand and green mud. A tendency toward an increase of bioturbation intensity in heteroliths consisting of interbedded very thin sandstone, siltstone and mudstone layers suggests that the totally burrowed beds were also originally heteroliths. Their total burrowing results from slow sedimentation rate, rather high fertility, low salinity and satisfactory aeration of the depositional setting. The ichnofossils most distinct in succession divisions dominated with fine-grained sand and mud, which in vertical sections show patterns corresponding to *Spirophyton-Zoophycos*, *Rhizocorallium* and *Phycodes flabellum*, were produced by opportunistic organisms adapted for areas strongly influenced by fresh water and land (in brackish water). Their distribution in the succession corresponds with the distribution of *Spirophyton*, *Rhizocorallium* and *Phycodes flabellum* in other areas. The absence or subordinate occurrence of burrows in mudstone to grainstone type limestones results in part from their mass deposition by storm processes. Common interbedding of non-burrowed black mudstones and restriction of bioturbation structures to faint sediment mottling, indicate sedimentation in areas hostile for macrobenthos, and particularly for the deep sediment penetration. The boundary between the Jauf and the underlying Tawil formations is distinctively marked by plant root structures.

## 680516 Buried evaporite paleokarsts in the Arab evaporites and the Hith Formation, Saudi Arabia

*K. Leyrer and F.O. Meyer*

Evaporites represent a major lithology in the hydrocarbon-rich Upper Jurassic section of Saudi Arabia. In many places these evaporites form competent seals and provide a framework for potential stratigraphic traps. Despite this obvious importance, little is published about the internal architecture of Arab and Hith formations' evaporite sections. In-depth study of the anhydrite sections and their relationship to interbedded carbonate stringers and reservoirs help clarify interpretation issues concerning evaporite fabric patterns, internal organization and their sequence-stratigraphic position in the Upper Jurassic.

Recently conducted high-resolution core studies identified several phases of evaporite karstification that punctuate Arab and Hith depositional successions. Available core material includes examples of evaporite karst solution pipes filled with transgressive and regressive or lowstand sediment. The observed karst phenomena are small-scale features up to 12 feet deep. All solution pipes studied penetrate anhydrite sequences and document that a loss of accommodation space across the up-dip limits of the carbonate platform leads to the cessation of groundwater Arab and Hith anhydrite formation. Transgressive carbonate deposits fill and define most of these evaporite karst phenomena. Typical fill sequences display a consistent facies evolution. Complex-depositional fill sequences begin with an intra-clast packstone facies that passes gradationally upward through a peloid packstone into a capping thrombolite boundstone facies. Locally some of the facies types may be absent.

Closer to the continental limits of the platform, karst features display a combination of transgressive carbonate deposits and siliciclastics or only siliciclastics. Transgressive carbonates filling solution pipes are mainly a polymictic breccia. In addition, greenish shale may occupy centrally located space in solution pipes that exhibit only partial infilling by transgressive carbonate accumulations. The green shale also forms beds overlying such solution pipe fill features and may occur as a solitary fill in some solution pipes. These unconformities appear widespread and as such document unconformities at the top of the Arab B and C evaporite members as well as the middle of the Hith Formation. The unconformities mark unequivocal sequence boundaries that terminate highstand deposition across the Arabian Platform during Arab and Hith deposition.

## 650722 Quantitative characterisation of intertidal to supratidal sediments of the Abu Dhabi coastline

*S. Lokier, A. Knaf and T. Steuber*

The Abu Dhabi coastline provides an ideal setting for the study of sedimentary systems inferred to be directly analogous to those deposited in many of the region's Mesozoic petroleum reservoirs. Improved understanding of these complex depositional environments, supported by quantitative sedimentological data, is essential to the development of accurate depositional models and reliable simulations for carbonate reservoirs.

The arid southern shore of the Arabian Gulf has an extremely low-angle ramp geometry. The coast is locally protected from open-marine conditions by a number of peninsulas and offshore shoals and islands. Sedimentary processes in the supratidal zone are dominated by the precipitation of evaporite minerals in the shallow subsurface. A broad

carbonate-evaporite intertidal setting, characterised by complex depositional facies geometries, passes off-shore, into a subtidal carbonate depositional environment.

The coastline of the United Arab Emirates is currently undergoing massive infrastructure development at an unprecedented scale, with huge dredging and island-building projects, changing the sedimentary dynamics of the coast beyond recognition. The impending loss of many of the natural coastal systems gives further impetus to the need for accurately recording these sedimentary environments before they are eradicated by the anthropogenic overprint.

This study employs a range of analytical techniques to investigate and characterise the surface sediments of the supratidal and intertidal zones of the Abu Dhabi coastline. Multiple transects were established between the lower intertidal and supratidal zones to the southwest of Abu Dhabi Island. Sampling stations were identified at regular intervals and the surface sediments were described and sampled. Samples were returned to the laboratory for detailed analysis.

The results of this study exhibit clear trends in the composition, grain size and maturity of sediments within the current depositional architecture of the Abu Dhabi coastline. High-energy lower intertidal zone facies are dominated by coarse grained ooidal and bioclastic sediments that grade into very fine carbonate and gypsiferous sands in the supratidal zone. Analysis of facies distribution allows us to establish quantitatively-constrained facies geometries that can be applied as a recent analogue in the development of our understanding of sub-surface facies distribution and its control on reservoir development.

## 680935 Sequence-stratigraphic analysis of carbonate and evaporite of Sachun Formation (Paleogene) from type locality, Fars region, Zagros Basin

*A. Mahboubi, R. Moussavi-Harami and R. Shabafrooz*

The Paleocene – Lower Eocene Sachun Formation in the southern Zagros Basin consists of carbonate, evaporite and siliciclastic rocks. It is conformably overlain by the Jahrum Formation and conformably underlain by the Tarbur Formation. Field and laboratory studies led to identification of 13 carbonate-evaporite and two siliciclastic lithofacies. These lithofacies at type locality of the Sachun Formation were deposited in tidal-flat, lagoon, barrier and open-marine environments in a ramp-type carbonate platform. Sequence-stratigraphic analysis of Sachun Formation at type locality led to the recognition of four large-scale depositional sequences. The upper and lower boundaries of these depositional sequences are type 1. The interpreted sea-level curve during deposition of this interval is relatively similar to world sea-level curve but there are some differences that can be related to tectonic effects of the study area. We hope these data can be used in reconstruction of paleogeography of the petroliferous Fars region during the Paleogene time.

## 680609 Paradigm change: Seal turns into reservoir: An outcrop and modeling study of a Sudair Formation equivalent in the Oman Mountains (Al Jabal al-Akhdar Area)

*M. Obermaier, C. Schneider, T. Aigner, M. Claps and C. von Winterfeld*

The deposition of evaporites and shales over most of the Arabian platform during the Lower Triassic provides seals for hydrocarbon accumulations in the underlying Khuff Formation. Our work on well-exposed outcrops of the Mahil Formation in the Oman Mountains (a time-equivalent unit to the Sudair Formation in the subsurface) reveals abundant potential reservoir units. A major aim of the ongoing study is to find relationships between shoal thickness and lateral extent as well as to unravel the overall geometries of shoal reservoir bodies in low-accommodation settings.

Sedimentological analyses of several sections in the region of Al Jabal al-Akhdar yielded 3 facies associations with a total of 12 facies types of a mostly backshoal to shoal setting. Except for exposure-related layers (each a few meters thick) at the top of one of the investigated sections, no occurrences of any sabkha-associates were detected. An integration of facies types in stacking patterns revealed three basic cycle motifs.

Potential seal units only occur in the detrital-rich backshoal cycle type in the lowest middle Mahil Formation and consist of laminated claystones and bioturbated mud-/wackestones. The remaining major part of the ca. 260-m-thick formation is mainly built by dolomitic backshoal to shoal cycles with a high reservoir potential. Shoal deposits consist either of oolitic- or peloidal-rich grainstones that strongly determine reservoir quality.

Sequence-stratigraphic correlations based on litho, chemo-, and biostratigraphy show subtle pinch-outs and facies changes on the scale of tens of kilometers. Thicker grainstone bodies are laterally more extensive and are correlatable within fifth-order cycles on a field scale.

A field-scale static reservoir model was created using the outcrop sections as pseudo-well logs. Correlating the sections on a north-south transect indicated a deepening trend to the north by a shift from a mainly backshoal-associated setting around the center of the Al Jabal al-Akhdar anticline to more shoal-associated facies types at the northern flank of the anticline. This proximal-distal trend and the overall cyclicity could be well reproduced with stratigraphic forward modeling using the software Dionisos, suggesting that relative sea-level changes form major controls on the depositional architecture.

## 706064 Multiple incision levels in Al Shaheen Field, offshore Qatar

*R. Pedersen-Tatalovic, M. Wendorff, F.S. van Buchem, M. Emang and N. Bounoua*

Recent acquisition of a large high-resolution 3-D seismic data over Al Shaheen Field in offshore Qatar revealed the presence of several levels of channel incisions, which provide important information about the geological evolution of this part of the Arabian Plate. The acquisition parameters and subsequent processing flow were selected for best resolution of shallow targets at some 2,000–4,000 ft. Data quality was hampered by the shallow water and present-day reefs, small-scale erosional features and interchanging lithology in the overburden. Ongoing efforts to improve data quality are designed to further eliminate multiples and to resolve imaging problems caused by the shallow erosional and deep collapse features and gas chimneys. Further data processing notwithstanding, the analysis of the data has already allowed us to recognise a number of significant stratigraphic features.

There are four levels of channels, starting as shallow as 100–160 milliseconds at Dammam level. Second, the Umm3 channelised drainage features with steep edges are recognised as one of the major causes of energy scattering, which deteriorates imaging and overall data quality. These are short erosional channel-like features oriented radially around a topographic paleo-low. Third, top Halul channels also cause significant imaging problems due to a large velocity contrast between the infill and the surrounding sediments. These channels are long, relatively straight, and have dimensions that allow them to be easily recognised both on stratigraphic time slices as well as on seismic cross-sections. Fourth, incision at the top of the Shu'aiba Platform during sub-areal exposure, which has previously been established and described, has been confirmed for the whole block. Several levels and dimensions of channels are evident, with smaller channel systems towards the highest point of Shu'aiba Platform in the north and a larger meandering channel system in the south.

Each of these channel levels requires different tools and attributes for their delineation. The geological significance of these incised channel levels for the Arabian Plate geological evolution is discussed.

## 670168 Where is my sand wedge? Part 1: Exploring for stratigraphic trapping potential in the Unayzah Group, South Rubʻ al-Khali Basin

*G. Pike, C. Harvey, M. Hulver, A. Khalil and P. van Mastrigt*

The South Rubʻ al-Khali Company Ltd is an Incorporated Joint Venture between Shell Saudi Ventures Limited (50%) and Saudi Arabian Oil Company (50%) and was set up in order to explore for non-associated gas in the South Rubʻ al-Khali Basin as part of the Natural Gas Initiative in the Kingdom of Saudi Arabia.

To date, exploration for a working Palaeozoic petroleum system has proven reservoir in 4-way structural dip closure and the presence of mature source rock. The search for gas is focused on the subtle, off-structure stratigraphic potential of the Unayzah Group, and in particular the Nuayyim Formation and/or Jawb Member sandstones.

The Unayzah Group is subdivided into the Juwayl and overlying Nuayyim formations. The Juwayl Formation comprises a lower Ghazal Member, equivalent to the Al Khlata Formation in Oman, and an upper Jawb Member. Respectively, these contain the Unayzah C and B reservoir units. The Ghazal Member infilled palaeo-topography with glacio-fluvial outwash braidplain, cold aeolian dune, lacustrine, and braid delta facies. The Jawb Member is coeval to the upper Al Khlata Formation and to the Rahab Shales of Oman and begins with ice advance deposits (diamictites) that grade upward into glacio-lacustrine sediments characterized by debris flow diamictites, lake shoreface sandstones,

turbidites, and finally by laminated mudrocks with dropstones. The early – middle Permian Nuayyim Formation (containing the Unayzah A reservoir unit) is coeval with the Lower Gharif and Haushi Limestone of Oman and comprises the Wudayhi and overlying Tinat members. The Tinat Member comprises ephemeral/playa lakes, alluvial plain, and aeolian (dune, interdune, and sheet sand facies) deposits with time-equivalent fluvial (wadi) deposits along the basin margin. The depositional model is a dryland basin model, characterized by seasonal river flow and flood-drought cycles.

Prospectivity within the southern Rub' al-Khali Basin comprises conventional four-way structural dip closures as well as stratigraphic traps on the flanks of Permian structures. These stratigraphic traps may be very common and are under-explored. This presentation will combine geological models with seismic evidence to define the exploration potential of the Unayzah Group in the South Rub' al-Khali Basin.

## 670174 Where is my sand wedge? Part 2: Lessons from SRAK'S first stratigraphic trap test in the South Rub' al-Khali Basin

*G. Pike, C. Harvey, M. Hulver, A. Khalil and P. van Mastrigt*

The South Rub' al-Khali Company Ltd is an Incorporated Joint Venture between Shell Saudi Ventures Limited (50%) and Saudi Arabian Oil Company (50%) and was set up in order to explore for non-associated gas in the South Rub' al-Khali Basin as part of the Natural Gas Initiative in the Kingdom of Saudi Arabia.

SRAK's Unayzah Stratigraphic Play exploration has resulted in the identification, de-risking and drilling of a number of stratigraphic traps in the South Rub' al-Khali Basin. Such traps rely on Nuayyim Formation (Unayzah A reservoir unit) and Jawb Member (Unayzah B reservoir unit) targets that developed preferentially off-structure. Exploration for these stratigraphic traps is generally difficult as even good quality 3-D seismic data cannot resolve subtle facies changes and faults that may be fundamental trapping components. On 2-D seismic, such problems are enhanced and exploration therefore relies much more heavily on good geological models coupled with geophysical or geochemical direct hydrocarbon indicators (DHIs). SRAK tested the largest known stratigraphic trap in its acreage with its sixth well. Critical to the evaluation and de-risking were a sound geological model from analogues in the Saudi Aramco Reserved Area, an up-dip calibration well and a world class, 600 km low-frequency seismic (LF) dataset to de-risk the trap.

The presentation will discuss the lessons from the current drilling campaign including an update to the geological model for the Unayzah Group for the southern Rub' al-Khali Basin. The application of low-frequency seismic techniques to de-risking has been tested by the drill-bit for both conventional and unconventional traps, and this new technology will be discussed.

## 743150 Strategies for modeling depositional heterogeneity of carbonate ramps using outcrop analogs and multiple point statistics

*T. Playton, J. Kenter, M. Levy, A. Pierre, G.D. Jones and P.M. Harris*

Outcrop exposures offer continuity, correlation, and resolution of geological data well beyond that of the subsurface, and serve as 'idealized' analogs for reservoirs. In this study, measured sections, photomosaic mapping, DGPS, and Lidar data were collected along a 38 km dip exposure of Lower Jurassic carbonate ramp strata in the High Atlas of Morocco, and converted into a static model using multiple point statistics (MPS). The goal was to generate new modeling strategies through simulation of ramp depositional heterogeneity during both transgressive systems tract (TST) and highstand systems tract (HST) conditions, and for each of the facies belts observed (inner, middle, outer, and basinal ramp settings).

The MPS approach uses combinations of hard data constraints (i.e. well data) and soft geologic concepts (i.e. depositional models) to populate 3-D grid space. Outcrop Lidar and GPS data were integral for the model stratigraphic framework and representation of complex stratal patterns. Soft constraints entailed Training Images and a Facies Probability Cube, which together capture juxtaposition relationships and spatial proportions and likelihoods of the facies belts while honoring the hard measured section and traced outcrop surface data. Using this approach, ramp depositional heterogeneity was successfully simulated within the sequence-stratigraphic architecture, including stratigraphic partitioning of facies belts, ramp progradation and retrogradation, and changes in facies belt width.

This outcrop-based modeling effort provides strategies that can be incorporated into subsurface modeling workflows. For example, only two systems tract-specific (TST and HST) Training

Images were required to capture stratigraphic facies belt partitioning. This enabled simulation of muddier, peloid-dominated settings in the TST and grainier, ooid-dominated settings in the HST for all mapped sequences. Another outcome involved high degrees of facies belt interfingering in the Training Images to replicate facies belt contraction, expansion, and migration while preserving juxtaposition rules. This study also addresses the effects of: (1) data configuration (i.e. well spacing); (2) facies delineation schemes (i.e. rock types *versus* cycle types) and (3) modeling targets on the preservation of geological heterogeneity that impacts subsurface flow and reservoir quality distribution.

## 689613 Borehole-image log interpretation in the Wara and Burgan palaeotransport system, Greater Burgan Fields, Kuwait

*M.A. Rashaid, K.J. Burman, A.A. Aviantara, V.G. Soneji, M. Al-Khabbaz and A. Prabantara*

The Wara and Burgan sandstones are major oil producers in Kuwait. In our study, the formations have been characterized using cores, borehole images and open-hole log data from 16 wells. Five lithofacies were determined: (1) massive, cross-bedded and low-angle sandstone units; (2) structureless, cross-bedded and low-angle argillaceous units; (3) interbedded sand and shale heterolithic units; (4) structureless and laminated shale units, and (5) undefined carbonate units.

The palaeotransport direction was analyzed separately for the Wara Sandstone and four members of the Burgan Sandstone, which are the Third Sand Upper (3SU), Third Sand Middle (3SM), Third Sand Lower (3SL) and Fourth Sand (4S). Results showed bi-modal and tri-modal distribution of palaeocurrents for some intervals, in agreement with previous interpretations for this field. For the first time, we have identified a main source of sediment from 135° (40% of the footage) and 250° (32% of the footage) with a high variation (standard deviation = 120° ) for the Wara Sandstone.

In the 3SU member of the Burgan Formation, 15° was the dominant palaeocurrent direction (45% of the footage), whereas in member 3SM, the palaeocurrent direction is toward the 45° (50% of the footage). In member 3SL, palaeocurrents show a tri-modal distribution, with the main trends towards 60° and 10° (40% of the footage) and a minor trend towards 280° (29% of the footage). Finally in member 4S, the main palaeocurrent direction is towards 65° (49% of the footage).

Eighteen faults were identified with strike azimuths that range from 310° to 345° and dip azimuths that range from 220° to 255° (72% of the footage). The NW-SE strike azimuth fits well with the structural trend of the Greater Burgan fields, which consist of three giants: Burgan, Magwa and Ahmadi fields. The combination of fault (NW-SE trend) and palaeocurrent distribution (mostly with a NE trend) has helped in characterizing the Wara and Burgan reservoirs.

## 741669 Hydrocarbon potential of Devonian Jauf Formation: A case study from Awali Field

*C.B. Reddy and Y. Al-Ansari*

The Jauf Formation is of Early to Middle Devonian age. It underlies the Jubah Formation and overlies the Tawil Formation with conformable contacts. After deposition of the Tawil Formation, the shallow-marine sands of the Jauf Formation were deposited over a broad shelf. It consists of thick sandstone with thin shale intercalations. The Jauf reservoir is relatively the cleanest and most porous of all pre-Unayzah reservoirs. It is a continuous zone with sand thickness varying from 250 to 400 ft. The Jauf reservoir is penetrated in a few wells in the Awali Field area. The top of the reservoir is encountered at a depth of 11,000 ft on the structural crest and reaches depths of over 15,000 ft in the flanks of the field. Individual porous layers are 5–15 ft thick and alternate with tight well-cemented sandstones or shales. The zone proved to be gas bearing in a test conducted in two of the crestal wells of Awali Field. Gas shows were also reported in a few drilled wells, but production testing was not carried out in these wells.

Three-dimensional seismic interpretation has been carried out by using 3-D re-processed PSDM volume. The relevant well data of the area has been duly incorporated into the study. Integration of 3-D seismic data and geological information resulted in preparation of detailed subsurface structural and attribute maps at selected levels. Seismic attributes such as frequency and amplitude maps show some anomaly on the Jauf level. These indirectly indicate that the development of Jauf reservoir as validated by the available test results from wells. A few potential stratigraphic and fault-closure traps have also been identified in the flank of the Awali Field. Besides supporting the ongoing exploration efforts in the surrounding offshore areas for similar gas prospects, the study resulted in identifying potential areas of better reservoir development.

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## 706236 The surface-piercing salt domes in the Ghaba Salt Basin (Oman): A comparison to the intra-salt hydrocarbon play of the Ara Group

*L. Reuning, J. Schoenherr, A. Heimann, J.L. Urai, R. Littke, P.A. Kukla and Z. Rawahi*

In the South Oman Salt Basin the Ara carbonates form an extensively cored, deeply buried intra-salt hydrocarbon play. Six surface-piercing salt domes in the Ghaba Salt Basin (North Oman) provide the only outcrop equivalents for carbonates and evaporites of the Ediacaran – early Cambrian Ara Group (uppermost Huqf Supergroup). Based on fieldwork, satellite imaging and isotope analysis it is concluded that most of the carbonate bodies (so-called stringers) in the Ghaba Salt domes are time equivalent to the stratigraphically uppermost stringer intervals in the South Oman Salt Basin (A5-A6). Maturity analyses demonstrate that the carbonate stringers in the salt domes were transported with the rising Ara Salt from burial depths of 6 to 10 km to the surface. Petrographic and stable-isotope data show that their diagenetic evolution during shallow and deep burial was very similar to the Ara carbonate stringer play in the South Oman Salt Basin. However, during the retrograde pathway of salt diapir evolution, the carbonate stringers were exposed to strong deformation in the diapir stem and diagenetic alterations related to dedolomitisation. As the salt domes contain facies that are in all aspects identical to the deeply buried Ara play in the South Oman Salt Basin, this study provides substantial additional information for hydrocarbon exploration in South Oman. In addition, our work has implications for the hydrocarbon prospectivity of the Ghaba Salt Basin and possibly of other Ediacaran – early Cambrian evaporite basins in the Middle East such as for the time-equivalent Hormuz Salt basins.

## 655008 Depositional environment and sequence stratigraphy of the Neocomian Fahliyan Formation in the north Dezful Embayment, southwest Iran

*M. Sabouhi, D. Jahani, F. Taati Qurayem and A. Aminzadeh*

The Neocomian (Early Cretaceous) Fahliyan Formation is one of the important hydrocarbon reservoirs of the Khami Group in southwest Iran. This formation is 332 m thick in type section and mainly consists of carbonates. In this study, the formation was investigated in the AZN-B well in the north Dezful Embayment (281 m thick). The lower boundary of the Fahliyan Formation with the Garau Formation is continuous. The upper contact of the Fahliyan Formation with the Gadvan Formation is conformable. In this study 13 carbonate microfacies and one shaly facies were recognized and grouped into four facies associations (microfacies group). These facies associations are interpreted in a platform to basin depositional setting as follows: tidal-flat, lagoon, bar and open marine.

Based on the available dataset (cutting samples, thin sections and well log analysis) the Fahliyan Formation was deposited in a carbonate shelf setting, and the studied profile occurs in the shallowest part of the platform. The vertical succession of microfacies and relative depth changes of the Fahliyan Formation led to the identification of two third-order depositional sequences. The first sequence straddles the Garau and Fahliyan formations; the transgressive systems tract (TST) is in the Garau Formation and the highstand systems tract (HST) occurs in the lower part of the Fahliyan Formation. The upper boundary of this older sequence is type 2. The second younger sequence occurs in the Fahliyan Formation; the upper boundary is type 1 and corresponds to the base of the Gadvan Formation.

## 666093 Challenges associated with exploring the Cretaceous rudist basin-margin buildups of the Arabian Basin

*F. Sadooni*

Rudist buildups were described from many horizons within the Cretaceous strata of the Arabian Basin. The most prominent among these were described from the Aptian Shu'aiba Formation in the major oil fields of the Arabian Gulf region. They were also documented from the Albian Mauddud Formation in the eastern offshore areas of Saudi Arabia and southeast Iraq and from the Albian – Cenomanian Mishrif Formation in the southern Arabian Gulf and southern Iraq (e.g. Majnoon Field). More varied buildups were found in the Upper Cretaceous carbonates of the Maastrichtian Simsima Formation in Oman and the UAE, the Campanian Hartha Formation in central and west Iraq and from the Turonian Wadi Sir Formation in Jordan.

The buildups were found to occupy either: (1) paleotopographic highs resulting from severe erosion as is the case with the Simsima Formation in Oman and the UAE, or (2) on horst structures resulted from basement block faulting such as the

Aqra Formation in northern Iraq, or (3) occupying the crests of growing structures as is the case with the Mishrif Formation in Dubai and southern Iraq. There are several problems associated with the exploration of these bodies resulting from their special nature and geometry. They lack a definite geometry that can be detected in seismic sections or logs. They are relatively narrow and located on the inflection point of the slope and could be easily missed by exploration drilling. They could be extensively altered by diagenesis, removed by erosion or simply overlooked by geologists.

Since rudists do not build "real" wave-resistant reefs, they would be reduced by the action of water and wind into bioclastic grainstone and packstone that may be scattered over areas of tens of kilometers around the original location of the buildups as is the case with the Mishrif Formation in Abu Dhabi and southern Iraq. In such cases, this breakdown and distribution of the original components increases the surface area of the potential reservoir rocks. Available data suggest that these rocks have higher porosity and permeability values than the actual reefal suites, and hence exploration should be expanded to include all these porous bodies of bioclastic materials. Furthermore, recent investigation of the rudist buildups in the Dujaila Field, southern Iraq suggested that these buildups may act as stratigraphic traps, and they may have significant oil accumulation beyond the conventional structural traps of the formation.

## 680215 Arabian Plate sequence stratigraphy: 10 years on

*M. Simmons, S. Cain, D. Casey, R. Davies, A. Godet, P. Sharland and O. Sutcliffe*

Almost 10 years have passed since Sharland et al. (2001) published Arabian Plate Sequence Stratigraphy. This work correlated 63 maximum flooding surfaces across Arabia and, for the first time, placed the complex lithostratigraphy of the Middle East into a sequence-stratigraphic framework. Since its publication we have developed the sequence-stratigraphic model by further investigations in the Middle East coupled with an analysis of the validity of the sequence-stratigraphic model worldwide. We now know that with some minor modifications, the Arabian Plate Sequences can be seen globally and are thus eustatically driven. We have also been able to further develop the model with additional surfaces.

It is interesting to speculate on the causes of this eustasy throughout the Phanerozoic. The pace and amplitude of the changes points strongly to a glacio-eustatic origin for our sequences. This is supported by a growing body of direct and proxy evidence that points to a coincidence of climatic fluctuation and eustasy, suggesting that melting and creation of ephemeral polar ice may be a causal mechanism, even in what is commonly regarded as a "greenhouse" times.

A robust third-order sequence-stratigraphic model for the Arabian Plate is a valuable tool for regional correlation and mapping, and the recognition of exploration analogues, as well as placing existing reservoirs and source rocks in a regional context.

## 707502 Sedimentology and exploration potential of the Haima Supergroup from the eastern flank of the Ghaba Salt Basin in Central Oman

*J.D. Smewing, J. Vargo, H. Miller, E. Price, C.K. Hunter and M. Amin*

In Central Oman the lower Palaeozoic Haima Supergroup contains important clastic reservoirs charged by hydrocarbons from the underlying Huqf Supergroup. CCED (Oman) and partners are exploring on the eastern flank of the Ghaba Salt Basin. The Amin, Miqrat, Al Bashair and Barik formations in the lower part of the Haima Supergroup form part of their exploration portfolio. Recent heavy oil discoveries have been made in the Amin and Miqrat clastics as well as newly discovered light oil in the underlying Huqf carbonates. We report on new data on the Amin to Barik formations which have emerged as a result of the recent drilling and on a linked outcrop-based program in the nearby Huqf inlier.

The Huqf inlier is a 10,000 sq km area of outcropping Cretaceous to Neoproterozoic sediments. Here, the Amin Formation at the base of the Haima Supergroup comprises coarse lithic sandstones and chert conglomerates that were deposited in channel bars on a west-facing continental braid plain. A marine flooding surface in the upper part of the Amin Formation terminates continental sedimentation. Thereafter all Haima sediments were deposited in marginal marine to fully marine settings.

Contrary to previous suggestions no evidence for primary aeolian sand deposition has been found. Instead marine incursion during upper Amin times resulted in flooding of the continental braid plain and a shore-fringing mixed clastic-carbonate tidal flat developed upon which the fine clastics

of the Miqrat Formation were deposited. The tidal flat interpretation is based on the occurrence of channelling, convolute bedding and starved wave ripples, on the overall fine grained nature of the sediment and on the ubiquitous presence of dewatering structures and carbonate mud. Highly porous large-scale cross-bedded sandstones occur within the Miqrat Formation in the outcrop belt. Based on the evidence for marine deposition these sandstones are believed to represent subtidal straight-crested dunes. Marine influence increases upwards into the Al Bashair Formation with oolitic limestones interbedded with the fine clastics. The Barik Formation represents progradation of deltaic sands out over this marine basin.

These revisions to the stratigraphy and palaeoenvironmental interpretations of the Haima Supergroup have provided a better framework for east flank exploration in Central Oman and for prediction of the geometry of potential clastic reservoirs in the target formations.

## 680534 Stratigraphic framework and exploration potential of Early Jurassic Marrat Formation, northern Saudi Arabia

*D.Z. Tang, P. Lawrence, A.E. Gregory, A.M. Bakhiet, A.G. Bhullar, A. Ahmed and B. Macurda*

The Marrat carbonate reservoir produces a significant volume of hydrocarbons in the Partitioned Neutral Zone (PNZ) and Kuwait. This play has emerged as an increasingly important Jurassic exploration target in Saudi Arabia, the PNZ and Kuwait. The Marrat Formation is unconformably underlain by Upper Triassic Minjur Formation clastics and overlain unconformably by Middle Jurassic "Dhruma Shale". It comprises a composite third-order sequence with the Lower, Middle and Upper Marrat each comprising a fourth-order sequence.

The Lower Marrat consists of mixed clastics and carbonates with anhydritic interbeds. It is the earliest basin-fill in response to Early Jurassic marine transgression that flooded the platform from the northeast, progressively onlapping onto the Qatar Arch and the Arabian Shield. The Lower Marrat was deposited in a very shallow, and relatively low-energy environment with limited accommodation space. The cleaner, grainy carbonates are confined predominantly to the northern onshore and offshore areas. Overlying the Lower Marrat carbonates is the "Lower Marrat Shale", which thickens to the southwest and thins substantially to the northeast, suggesting a possible siliciclastic influx from the Arabian Shield. The top of the Lower Marrat was locally eroded and marks a fourth-order sequence boundary. Renewed flooding and moderately increased accommodation space during the Middle Marrat resulted in the major transgression and maximum flooding onto the platform with widespread carbonate deposition. An extensive shoaling complex and backshoal flats, with mixed skeletal and oolitic grainstones-packstones, were developed as aggrading and generally northeasterly prograding highstand systems in the northeast onshore and offshore areas. Latest Middle Marrat sediments are mostly anhydrites, which provide an excellent marker and top seal for the Middle Marrat across the region. The Upper Marrat consists of shaley carbonates and thinly intercalated evaporites, particularly in southerly and westerly, more restricted areas. The post-Marrat subaerial unconformity has been identified in the subsurface through well-log correlations and is evident in a recently cored shallow well in an outcrop south of Riyadh.

Exploration opportunities for the Marrat play have been identified by integrating the reservoir fairways, source rocks and seals through 3-D basin modeling. Potential stratigraphic traps within Marrat carbonate reservoirs may add additional hydrocarbon resources.

## 670187 Sequence-stratigraphic analysis of the Ratawi Shale Formation: Implications for reservoir distribution and exploration potential in Kuwait

*S.K. Tanoli, M.D. Al-Ajmi, S.M. Behbehani, R. Prasad and S.R. Mushnuri*

The Ratawi Shale Formation is the first Cretaceous, dominantly clastic unit, which overlies a thick carbonate succession in Kuwait. The formation is divisible into three informal zones. The lower zone consists mainly of shale with limestone interbeds. This part was deposited under transgressive conditions in shallow-marine to offshore environments. A maximum flooding surface (MFS) is recognized near the top of this zone, which follows a highstand interval of variable thickness (usually thin) due to incision during the overlying lowstand. The middle zone of the formation consists of a better sandstone facies. It was deposited in fluvial to estuarine environments representing sedimentation in incised valleys, in the western part, and in nearshore to shallow-marine environments, eastward. This zone makes the lowstand deposition and completes one third-order cycle of deposition. The overlying upper zone consists of shale with

locally thin sandstone, siltstone and limestone interbeds and is interpreted to have been deposited under transgressive conditions with or without a recognizable highstand before its termination by the overlying Pre-Zubair Late Valanginian unconformity.

High-frequency sequences and important related surfaces such as regressive surface of marine erosion, subaerial unconformity or subaerial exposure surface, subaerial erosion surface, shoreline ravinement or transgressive surface, flooding surface and possible existence of basal surface of forced regression were identified and described from the cores. The regressive surface of marine erosion is usually sharp and wavy, separating the underlying offshore muddier facies from the overlying shoreface sandier facies. The sequence boundary is marked by an exposed surface, locally represented by rooted interfluves and, in other areas, by the weathered horizons and, still in others, by an incised fluvial surface. The transgressive surface or shoreline ravinement in one case lies at the base of a tidally influenced channel but usually makes a thin burrowed horizon with a fining- and deepening-upward trend. The reservoir facies are variably associated with the falling stage systems tract (e.g. shoreface sandstone above the regressive surface of marine erosion), with the lowstand systems tract (e.g. fluvial to estuarine sandstones) and locally with the transgressive systems tract (e.g. tidal channel above shoreline ravinement). An understanding of the sequence-stratigraphic set up along with paleoenvironmental regime is crucial for identification and distribution of reservoir facies in this formation.

## 680438 Application of a sequence-stratigraphic framework for the Wasia Formation: A basis for mapping lithofacies variability and petroleum systems in the Rub' al-Khali Basin of Saudi Arabia

*D.P. Taylor, D.L. Ternes and W. Hughes*

The Albian – Turonian age Wasia Formation in the Rub' al-Khali Basin of Saudi Arabia represents a time of shallow-water carbonate progradation directed northeasterly into an intra-shelf basin. Up to 150 kilometres of lateral progradation is observed on the windward western side of the intra-shelf basin, terminating with a rimmed carbonate shoal platform with up to 900 feet of relief. New biostratigraphic interpretations have provided a basis for identifying third-order and fourth-order cycles within the Wasia Formation, and can be tied to log and seismic data, allowing construction of chronostratigraphic lithofacies maps. Higher-frequency depositional cyclicity is observed and it is possible to interpret individual depositional assemblages comprising bioclastic shoals and rudist-bank facies, in areas with 3-D seismic coverage and well control.

Based on new micropaleontological data, the Mishrif Member of the Wasia Formation, consists of up to four fourth-order depositional sequences. Each sequence commences with a planktonic foraminiferal dominated biofacies that represents deep-marine conditions of the transgressive system tract (TST). Highstand system tract (HST) associated foraminiferal and rudist biofacies are represented by shallow-marine carbonates typically deposited in shoal and localised rudist-banks. These deepening and shallowing cycles have been correlated across the eastern Rub' al-Khali, and designated Mishrif TST1-HST1, TST2-HST2, TST3-HST3 and TST4-HST4 in ascending order. Mishrif source rocks correspond to the Mishrif TST1 sequence, and the overlying Mishrif HST1 reservoir sequence is sealed by the next transgressive cycle, Mishrif TST2. This reservoir-seal cyclicity continues in some places up to TST4-HST4, which is ultimately sealed by regionally extensive shales of the Aruma Formation.

There are two proven petroleum systems within the Wasia Formation, the Safaniya-Mauddud and the self-sourcing Mishrif petroleum system. New 3-D seismic data provides the opportunity to apply a sequence-stratigraphic framework that constrains these petroleum systems. Third-order scale geometries are clearly imaged for the Wasia Formation and fourth-order sequences can be identified locally. Internal seismic reflection geometries have been characterised into lithofacies associations. Horizon and time slices through the seismic volume are effective tools for mapping the distribution of these lithofacies. Automatic voxel tracking delineates discrete depositional assemblages.

## 743158 Stratigraphy and depositional history of the First Eocene reservoir from Wafra Field, Partitioned Neutral Zone (PNZ), Saudi Arabia and Kuwait

*N. Toomey, P. Montgomery and W.S. Meddaugh*

The Paleocene – Eocene aged First Eocene reservoir at Wafra Field in the PNZ (Saudi Arabia and Kuwait) is a dolomitized, heavy oil (18–22°API) carbonate reservoir. The 40 acre Large Scale Pilot (LSP) is located in the southern portion of the field and

contains 56 producers, injectors, and temperature observation wells. Additionally, four cores were taken from the LSP area. The high well density and variety of data types (core, borehole image logs, wireline logs) provides a unique opportunity to examine the stratigraphy and depositional history of this complex carbonate system. This study focuses on the EOC500 to EOC700 interval, which is the zone targeted for initial enhanced oil recovery.

The carbonates of the First Eocene were deposited in shallow subtidal to supratidal environments on a low to moderate energy inner shelf or ramp. Based on core observations, facies are dominantly dolomitized peloidal wackestone to packstone, dolomitized algal wackestone, dolomitized mudstone and carbonate mudstone. Based on a combination of core, wireline (especially gamma ray), at least 11 shallowing-upward cycles were identified in the study interval and correlated across the LSP area. A typical cycle consists of subtidal dolomitized peloidal wackestone/packstone overlain by algal wackestone or mudstone. These shallowing-upward cycles form the basis of paloegeographic maps, which when combined with modern analogs can be used to estimate facies distribution across the LSP area. Detailed paleogeographic maps and 3-D models can also be used to help understand the impact of stratigraphy and paleo-topography on production. In this case, it appears that higher production occurs closer to subtidal/intertidal facies and lower production occurs in wells located closer to supratidal facies.

## 681073 The sedimentary architecture of a prograding platform margin and its impact from production behavior: An example from Giant Field "A", Abu Dhabi

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Giant Field "A" in Abu Dhabi produces from limestones of the Aptian Shu'aiba Formation with a complex platform margin architecture. Earlier analysis has revealed that after an initial stage of aggradation, the platform prograded into the Bab Basin with a prominent set of clinoforms. A southern platform interior area of aggradation was separated from the well-defined northern clinoforms by a central platform margin belt with a less distinct seismic signature but a distinct production behavior.

Detailed seismic and core analysis has revealed that this margin actually represents another prograding clinoform belt of a third-order depositional sequence. The clinoform belt originated during the late highstand systems tract (HST) of the aggradational late Early Aptian platform phase (Apt 3). There is a distinct difference in composition and reservoir character between the sediments of the transgressive systems tract (TST) and the HST. Property differences resulting from cementation at clinoform boundaries allow the detailed delineation of sedimentary features on depth-converted seismic horizon slices. Clinoform packages are relatively steeply dipping with a depositional slope of up to 3 degrees. A distinct triangular feature along the progradation front is interpreted to represent a sediment point source such as a tidal delta draining sand flats on the platform top. The location of the platform margin and possibly subsequent diagenetic alteration is profoundly influenced by a deep rooted fault system that became periodically reactivated.

Recognition of the architecture has had a profound impact on understanding production behavior in the field. Peripheral injected water advances more rapidly in heterogeneous platform interior sediments forming a locally restricted water finger. The localized water advance is likely aided by fault planes. Its spread into the crestal parts of the field is retarded by a dense layer associated with a third-order maximum flooding surface and cementation along fault planes. The flood front in the central area is less advanced, and more even. Individual lower order clinoforms introduce a preferred directional flow behavior parallel to the platform margin further reducing the influx of water from the platform area.

## 680600 The Late Aptian Early Albian carbonate crisis: Evidence for glacio-eustacy and environmental change from the Arabian Plate, offshore Qatar

*F.S. van Buchem, R. Pedersen-Tatalovic, E. Hoch, M. Emang and N. Bounoua*

The mid-Cretaceous carbonate succession of the Arabian Plate is interrupted by a phase of exposure and condensed siliciclastic sedimentation spanning the Late Aptian and Early Albian. This dramatic change in sedimentation pattern is attributed to a glacio-eustatic sea-level fall, dramatically documented with incised valleys in offshore Qatar, and was followed by a phase of condensed, iron-rich siliciclastic sedimentation at the end of the subsequent sea-level rise. This anomalous facies pattern produced a unique, thin, but high-pay siliciclastic reservoir.

Based on 25 cored wells, a high-resolution seismic dataset, and extensive palynological analyses, a high-resolution, sequence-stratigraphic model has been built. The lower sequence boundary is the incised valley floor that penetrates approximately 25 meters into the underlying Shu'aiba Formation with a maximum valley width of 8 kilometers. A cored well in the middle of this channel shows that the fill sediment consists of plant-material-rich, bi-directional cross-bedded, medium-grained sandstones changing upward to bioturbated sandstones. This succession is interpreted, based on sedimentary facies and palynofacies, as an estuarine environment, displaying a deepening-upward trend of a transgressive back-fill succession. The overlying highstand deposits are thin (approximately 6 to 7 meters) and consist mainly of oolitic ironstone, locally admixed with glauconite and sandstones. This succession has been dated as Late Aptian and ?Early Albian age. The top sequence boundary is placed at the base of a thin, but regionally extensive sandstone bed, rich in glauconite, that has been dated as Middle Albian, and forms the beginning of the next sequence.

The offshore Qatar dataset provides detailed insight in this little known, but geologically and economically significant part of the Arabian Plate stratigraphy. It provides a conceptual depositional model, and unequivocal evidence for Late Aptian sea-level fluctuations and sedimentation that will have affected other petroleum systems on this Plate.

## 702100 An outcrop analog of the Kharaib and Shu'aiba reservoirs: Example of the Urgonian Platform (Lussanenque Area, Gard, southeast France)

*A. Virgone, G. Massonnat and C. Pabian*

Urgonian limestone (Lower Cretaceous) of southeastern France is a coeval analogue of the Shu'aiba and Kharaib formations of the Middle East and can constitute a good reference proxy to illustrate and understand the internal geometries of these reservoirs. It is also a relevant database for reservoir modeling and/or enhanced oil recovery (EOR) studies. Total Company has proposed an R&D program focused on the comprehension of geometric and petrophysical heterogeneities of the Barremmian – Aptian carbonate reservoirs, located in Lussanenque area (Gard, southeast France). The present paper allows us to: (1) present internal geometry of high-resolution sequences (vertical and horizontal variations at the fourth- and fifth-order scales) of outcropping sections. This analysis can be used to comprehend the internal reservoir architecture of the Kharaib and Shu'aiba formations in different paleogeographic domains of carbonate platform (from internal to the slope); (2) discuss the relationship between sedimentary discontinuities and early acquisition of porosity; (3) identify palaeogeographic trends for the main environmental belts in relationship to the structural framework; and (4) discuss the impact of the facies distribution around the Bab Basin in the southeastern Arabian Plate.

To achieve these objectives, an integrated workflow using a mixed static and dynamic approach was used in order to constrain the reservoir architecture. A substantial database was studied, including several key sections and more than 60 vertical wells drilled in the Urgonian aquifer. Some wells were logged (gamma-ray, resistivity, borehole images). This "rock" database was completed by several dynamical data including 40 well tests and the surveying of 8 springs for one year. A biostratigraphic framework was updated in order to discuss correlations between the different studied areas, in agreement with the regional background knowledge (Vercors and Provence areas). A reliable faciological model and an integrated sequential framework were built based on a detailed thin section analysis. A fracturing study at different scales was also achieved (outcrops, aerial photogeology) in order to support the geological model. The dynamic dataset is in phase with the presence of east/west structural highs and the hypothesis of a dislocated platform during the Early Aptian age. As a conclusion, an integrated geological model for the Urgonian platform for Lussanenque area will be exhibited and the impact of the structural framework on the facies belts will be discussed.

## 678391 Geology meets petrophysics: Example of a process-based rock type methodology for a Khuff Reservoir, North Oman

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Carbonate reservoirs are inherently heterogeneous as a result of being deposited in laterally variable settings with subsequent overprint of complex and substantial diagenetic processes. The upper Khuff carbonate reservoir, deposited on a large carbonate/evaporitic ramp (late Permian – Early Triassic), is a prime example for such reservoir quality variability dictated by its intrinsic carbonate nature.

A Rock Type (RT) "process-based" geological-petrophysical approach has been applied to an upper Khuff reservoir in North Oman in order to improve the reservoir characterization and the understanding of its heterogeneity, and ultimately to derive representative static and dynamic models. This approach is based on the integration of sedimentological/petrographic core observations and the analysis of petrophysical properties in wells.

A core-based Rock Type scheme was defined based on porosity/permeability from CCA, pore type identification and sedimentological observation on thin sections. Each RT was linked to the original depositional facies and the subsequent diagenetic processes (cementation, dissolution, dolomitization, anhydrite precipitation). Pore throat distribution and capillary pressure curves were also used to calibrate the classification scheme. RTs with enhanced properties correspond to two classes: dolomitized oolitic-skeletal grainstones and thrombolites (with intercrystalline, interparticle/mouldic and vuggy porosity) and oolitic/peloidal/skeletal grainstones and packstones (with mouldic, interparticle and vuggy porosity).

A neural network approach was used to implement this RT scheme to all wells, and its results were calibrated to cores. An electro-facies log was obtained by combining gamma-ray, porosity and BVSxo logs. This results in a 'depositional facies' log, comprising: bioconstructed facies, grainstones (well- and poorly-sorted), packstones to mudstones and argillaceous mudstone. The 'lithology' log was generated from the gamma-ray, neutron/density and PE logs to distinguish amongst limestone, dolostone, anhydrite and argillaceous mudstone. The final RT log was generated by merging 'depositional facies' and 'lithology' logs.

'Depositional facies' and 'lithology' logs were used to build 3-D facies properties (depositional facies and lithology). The latter were directly merged to generate RT models. Porosity and permeability were modelled conditioned to RTs which resulted in more realistic distributions.

## 692203 Evaporites across deep time: Tectonic, climatic and eustatic controls in marine and nonmarine deposits

*J. Warren*

Plots of the world's Phanerozoic and Neoproterozoic evaporite deposits, using a GIS base, shows that Quaternary evaporite deposits are poor counterparts to the greater portion of the world's Phanerozoic evaporite deposits. They are only directly relevant to same-scale continental hydrologies of the past and, as such, can be used to better understand what is needed to create beds rich in salt-cake, soda-ash, borate and lithium salts. These deposits are typically Neogene and mostly occur in supra-sea-level hydrographically-isolated (endorheic) continental intermontane and desert margin settings that are subject to the pluvial-interpluvial oscillations of today's ice-house climate. When compared to ancient marine evaporites, today's marine-fed sub-sea-level deposits tend to be small sea-edge deposits, their distribution and extent is limited by the current ice-house driven eustacy and a lack of appropriate hydrographically isolated sub-sea-level tectonic depressions.

For the past forty years, Quaternary continental lacustrine deposit models have been applied to the interpretation of ancient marine evaporite basins without recognition of the time-limited nature of this comparison. Ancient mega-evaporite deposits (platform and/or basinwide deposits) require conditions such as epeiric seaways (greenhouse climate) and/or continent-continent proximity. Basinwide evaporite deposition is facilitated by continent-continent proximity at tectonic plate margins (late stage E through stage B in the Wilson cycle). This creates an isostatic response where, in an appropriate arid climate belt, large portions of the collision suture belt or the incipient opening rift can be sub-sea-level, hydrographically isolated (a marine evaporite drawdown basin) and yet fed seawater by a combination of ongoing seepage and occasional marine overflow. Basinwide evaporite deposits can be classified by tectonic setting into: convergent (collision basin), divergent (rift basin; pre-rift, syn-rift and post-rift) and intra-cratonic settings.

Ancient platform evaporites can be a subset of basinwide deposits, especially in intra-cratonic sag basins, or part of a widespread epeiric marine platform fill. The latter tend to be mega-sulphates and are associated with hydrographically-isolated, marine-fed, saltern and evaporitic mudflat systems in a greenhouse climatic setting. The lower amplitude fourth- and fifth-order marine eustatic cycles and the greater magnitude of marine freeboard during greenhouse climatic periods encourages deposition of marine platform mega-sulphates. Platform mega-evaporites in intra-cratonic settings are typically combinations of halite and sulphate beds. Potash evaporates tend to show a dichotomy of occurrence with Quaternary deposits formed in

small-scale endorheic basins, while ancient potash deposits formed in basinwide settings in situations that, like all basinwides, have no same-scale Quaternary counterparts.

Distribution of the world's major halite-rich salt basins can be classified according to plate tectonic association at the time of salt accumulation. Many of these basins experienced subsequent polyphase tectonic deformation histories.

## 688039 A Permian/Triassic boundary (PTB) in the Middle East: A review

*O. Weidlich, A. Baud, M. Bernecker, L. Krystyn and S. Richoz*

The middle Permian – Early Triassic Khuff Formation occurs throughout the subsurface in the Middle East and is believed to contain the largest gas reserves in the region. Along the epeiric Arabian platform shallow-water carbonates and evaporites prevail in the northern and central part and pass southward into argillaceous carbonates and siliciclastics. Eastward, shallow-water carbonates pass into deep marine deposits of the Neo-Tethys. Outcrops in Saudi Arabia, Iran, UAE and Oman provide important analogue data for subsurface geologic models.

The Permian/Triassic boundary (PTB) event, about 251 million years ago, was the time of the most severe mass extinction during the Phanerozoic that heavily affected marine and terrestrial ecosystems. Sedimentary rocks of the Khuff Formation and equivalent formations in the Middle East yield abrupt litho- and biofacies changes which are believed to be the result of events associated with the Permian/Triassic boundary (also called end-Permian mass extinction in the literature) and the Early Triassic recovery interval.

During the last decade numerous data of Permian – Triassic rocks in the Middle East have been published which make a compilation of the state-of-the-art knowledge of the PTB necessary. Possible phenomena associated with PTB and the Early Triassic recovery are: (1) hardground ontop Permian strata, (2) clay and high gamma-ray readings at the PTB, (3) negative Uranium excursion, (4) negative stable carbon isotope shift(s), (5) microbialite horizon(s), (6) anoxic oceanic conditions and so-called anachronistic sediments, (7) seafloor cements, (8) organisms with small body size.

Generally, the PTB data collected by numerous researches in the Middle East are in good correspondence with observations from locations around the world. A more detailed comparison of Middle East data suggests that duration and severity changed across the Arabian platform. Depending on the depositional setting and ecosystem, recovery was either rapid or could encompass as much as the Lower and Middle Triassic. Possible scenarios explaining the differential response of carbonate-producing organisms to environmental changes will be discussed in more detail.

The following key observations have been made:

| | Saudi Arabia outcrops | Subsurface Saudi, Qatar, UAE | N Oman subsurface | S Oman subsurface | Oman Mts Arab PF | Oman Mts Tethys | Iran Zagros | Iran Subsurface |
|---|---|---|---|---|---|---|---|---|
| Seafloor cement | not observed | not observed | not observed | not observed | observed | observed | not observed | not observed |
| Anoxic conditions | not observed | not observed | not observed | not observed | observed | observed | observed | observed |
| Microbialites | observed | not observed | not observed | not observed | observed | observed | observed | observed |
| Negative $\delta^{13}C$ excurs. | not observed | not observed | not observed | not observed | observed | observed | observed | observed |
| Negative U excurs. | not observed | not observed | not observed | not observed | not observed | observed | observed | observed |
| PTB clay and GR peak | not observed | not observed | observed | observed | not observed | observed | not observed | not observed |
| PTB hardground | not observed | not observed | not observed | not observed | observed | observed | not observed | not observed |

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## 680575 Seismic geomorphology of Paleozoic reservoirs in the South Ghawar area, Saudi Arabia

*S.R. Wharton and T. Loretto*

The evaluation of Paleozoic depositional megasequences in the South Ghawar area is complex, as the area has been influenced by periods of early Paleozoic glaciation, marine transgression, and tectonism. Late Ordovician glacial advance and retreat generated distinct elongated paleovalleys within which subsequent megasequence deposition occurred. The Hercynian orogeny influenced the paleotopography, upon which Carboniferous and Permian sequences have distinct onlapping relationships to the north and west of the Hercynian depocenter. A seismic/geomorphological analysis was applied in the basin in order to elucidate depositional styles of Paleozoic sequences, onlap relationships, unconformities, and tectonic styles associated with hydrocarbon migration.

Using post-stack time migrated data, seismic attribute volumes were generated for multi-volume, multi-attribute analysis. The geomorphological extent of the depositional sequences was analyzed, in order to reflect the infilling stages of sequences within and beyond a major paleovalley near the base of the Silurian Qusaiba Member. Key mapped horizons in Paleozoic megasequences from Permian to near Base Qusaiba enabled assessment of isochores, which indicate thinning trends towards the flanks of the depocenter. Both the Wudayhi and Ghazal structures are major Hercynian-eroded features that controlled Carboniferous Unayzah deposition. Well data and palynological picks were used to constrain key paleosurfaces, and seismic facies analysis calibrated to wells helped define gross depositional environments that have variable progradational directions through time. The multi-volume, multi-attribute data analyses assisted with evaluation of the depositional sequences. The steeper flanks of the basin, however, have varying sequence relationships and complexities related to pinchouts and drapes onto Hercynian-related structure.



Structural analysis using automatic fault mapping routines on coherency data enabled quick assessment of complex subregional structural styles that are dominated by strike-slip tectonics.

The seismic geomorphology approach enabled the definition of the morphology of the sequences and depositional styles within the basin. Although unconformity traps on basin flanks were more difficult to define, they present significant exploration opportunities. This approach enables the targeting of key areas for exploration, with focus on unconventional traps.

## 677660 New insights from hydrocarbon prospectivity: Moroccan and Nova Scotian conjugate margins

*H. Wilson and M. Luheshi*

Emerging plays in Brazil, Ghana and Morocco have triggered interest in searching for analogue plays in conjugate margins. Using paired margins is a powerful way to evaluate basins in search of overlooked plays. Interest in Morocco and Nova Scotia has been triggered by licence activity. Using data and maps across the margin is vital in understanding the critical syn-rift and early post-rift play systems. The paper is based on work undertaken for OETR in Halifax and studies completed on the Moroccan margin. Both margins show that when integrated into play analyses there is potential for significant volumes of hydrocarbons. The use of conjugate margin analysis is critical in developing models for de-risking hydrocarbon prospectivity.

Jurassic and Cretaceous delta systems with associated slope turbidites can be postulated and de-risked using high quality seismic data. Reservoir deposition and salt movements are inter-related and numeric models backed by seismic data show that reservoir-quality facies exist. The Jurassic carbonate bank is a proven play system in Nova Scotia and Morocco. Proving a world-class source system is vital to the hydrocarbon prospectivity of both margins. Extensive shows, commercial discoveries, and evidence of by-passed oil demonstrate source systems that produce hydrocarbons. The paper will show forensic geochemical work being used to type the shows and link the fluids to specific source bed sequences. Traditional sourcing models rely on Jurassic and Cretaceous delta systems, but may not be supported by the geochemical data. We postulate there must be a deeper source. The location of

the break-up unconformity and the relationship between evaporite deposition and lacustrine environments will be explained. The models are based on plate-scale tectonic modelling combined with fault mapping using high quality deep seismic on both margins.

We will show the development of Jurassic and Cretaceous models. Several plays exist, including Jurassic carbonates, delta and deep marine reservoir systems, sourced locally or from deeper syn-rift lacustrine sediments. Extensive large-scale salt related structures show potential for a high-value petroleum province on both sides of the Atlantic Ocean. The play evaluations are based on a rigorous understanding of sequence stratigraphy built on existing and new biostratigraphic and seismic stratigraphic studies.

## 680445 Sequence-stratigraphic study of the Albian succession and evaluation of the source and reservoir rocks in the north Fars Province, Zagros Mountains, Iran

*M. Yavari, A.A. Julapoor and E. Tarhandeh*

The Albian sedimentary interval (Kazhdoumi Formation) was measured in six outcrop sections in the northern part of the Fars area. Based on field and microfacies results, the interval is dominantly composed of limestone attributed to inner ramp and mid ramp environments. The Albian successions in this area form one-third of the sedimentary sequence. The lower sequence boundary (SB) is characterized by an erosional surface, which probably was caused by tectonism (between Aptian and Albian time). The top of the sequence boundary (SB2) resulted from tectonism at the end of Aptian, when Zagros was affected by the Austrian phase (orogeny phase), creating a high by epirogenic movements.

In order to determine conditions of source and reservoir rocks in this area, 48 samples from the Kazhdoumi Formation in 12 stratigraphic surface sections and drilled wells were examined geochemically including Rock Eval., Ro%, and gas chromatography (GC).

According to geochemical studies, most of the Albian deposits in this area are not suitable as source rocks, but, rather, show reservoir characteristics. Also, regarding sedimentology studies, the presence of grainstone to packstone facies, porosity and shallow-water depositional environments suggest characteristics attributable to reservoir rocks.

Intercalations of shale and marl in some parts of the succession are immature geochemically and take place early in the window for oil generation. Towards the main Zagros fault, maturity of shales increases and the quantity in synclines for hydrocarbon production is considerable.

## 681098 Biostratigraphy and palaeoenvironments of the Early to Middle Miocene Lower Fars Formation, North Kuwait

*A. Youssef and H. Al-Owihan*

Full biostratigraphical and palaeoenvironmental analyses have been applied to 220 core samples taken from 14 cored intervals in the Lower Fars Formation, North Kuwait area. The Lower Fars Formation (200 ft thick on average) is mainly composed of channel deposits interbedded with shallow-marine to lagoonal deposits, unconformably underlain and overlain by the Ghar and Dibdibba formations respectively.

The analyses of the foraminifera, ostracoda, palynology and nannopaleontology have identified four regional marine flooding events in the studied sections. These four marine flooding events have been found to coincide with those maximum flooding surfaces of the short term eustatic curve identified by Haq et al. (2005). Four depositional sequences have been defined based on those flooding events and bounded by erosional unconformities. Age dating of these flooding events is tentative due to the absence of planktic foraminifera and nannofossils. The Langhian palynological species exist along with the long range Early to Middle Miocene species in the studied intervals. Most of analyzed samples are barren of nannofossils, except for a single sample, indicating a barrier separating these marine-influenced enclosed environments from the open marine environment on the eastern part of the study area. The palaeoenvironmental analysis has revealed that diverse palaeoenvironments have been established during the deposition of the Lower Fars Formation; shallow marginal marine with intermittent fluvial channeling; coastal marine to estuarine environments, with a lagoonal environment formed in the interdistributary areas.

## 681043 Multi-scale assessment of the Middle Eastern Permian – Triassic Khuff carbonate: Structural evolution and its impact from reservoir properties

*V. Zampetti, R. Borkhataria and M. Vroon*

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) and thicknesses (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 the thickness, lithology and facies distributions of the Khuff Formation are strongly controlled by the inherited structural relief e.g. by the reactivation of the basement structural fabric related to Permian – Triassic tectonic events. Following the regional tectonic setting, the study area can be subdivided in four mega-structural provinces: (1) the Arabian Peninsula, (2) Oman, (3) the Zagros region and (4) the salt provinces.

At the location of the Arabian Peninsula, Pre-Khuff basement-related anisotropies are interpreted to have formed as early as late Neoproterozoic to Ediacarian time and to follow three 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 NE. 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 and Middle Triassic, the Cimmerian blocks moved rapidly away from the Arabian margin, opening up the Neo-Tethys Ocean behind them. The 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 NS- and the NNW-and 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 mega-structural salt 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 a regional scale, the variability in reservoir properties identified in this study can be partially explained by different tectonic events such as fault reactivations. Also salt diapir-specific growth history coupled with large-scale burial alteration has played a role, combined with deep burial *in-situ* modification of hydrocarbons in-place and displacement of hydrocarbons by late non-hydrocarbon charge.

In conclusion understanding the interaction between regional tectonic events, basement 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.

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