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GEO 2006 SELECTED GEOLOGICAL ABSTRACTS

The following abstracts were accepted for presentation at GEO 2006, the Seventh Middle East Geosciences Exhibition and Conference that was held in Bahrain on March 27–29, 2006. GEO 2006 was organized by Arabian Exhibition Management (AEM), the American Association of Petroleum Geologists (AAPG), the European Association of Geoscientists and Engineers (EAGE), and was supported by the Society of Exploration Geophysicists (SEG) and the Dhahran Geoscience Society (DGS). The abstracts that are published here represent subjects dealing primarily with the structural geology, tectonic evolution and stratigraphy of the Middle East. In the forthcoming issue of GeoArabia, the final group of abstracts describes exploration and reservoir characterization case studies.

MIDDLE EAST STRUCTURAL GEOLOGY AND TECTONICS

Structural evolution and fracture patterns in the front range of northern Oman Mountains

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The front range of northern Oman Mountains (Salakh Arch) consists of five doubly-plunging anticlines that collectively extend for 75 km. It forms an excellent structural and stratigraphical analog for hydrocarbon fields and the area can be a host for hydrocarbon accumulations. Comprehensive fieldwork and seismic interpretation were conducted to evaluate the structural style and fracture patterns in the arch. Measurements from seismic data show detaching folds along the salt. The results from fracture mapping show variable orientations through the arch. Fractures mainly trend parallel and perpendicular to fold axes indicating that they are genetically related to the folding process. Static 3-D geometrical analyses of Jabal Qusaibah, the western anticline of the arch, were compared to robust fracture field data from the Natih-A member in the Jabal to evaluate their significance to fracture orientation, density and aperture. Finite-dip, simple and Gaussian curvature analyses show a strong relation to fracture density and cylindricity deviation influences the main fracture orientations, particularly in the southeast corner of the anticline. 3-D restoration of the fold and bounding faults show strain concentration in the back-limb and eastern plunge respectively, and are considered responsible for the E-W and NE-trending shear fractures in these areas. The fracture patterns are generally explored using a faulted detachment-fold model. Analytical solutions and numerical methods indicate that the fold developed with a wide wavelength, and as the shortening proceeded, the hinge narrowed and limbs' length and dip increased by the inward propagation and rotation of the inner axial surfaces. Generally, the results show that fractures are mainly induced by layer-parallel shortening and outer-arc extension. However, local fold-related strains at different stages of fold evolution formed various fracture sets and commonly altered the type and orientation of dominant sets.

Evidences on the Caledonian tectonic movements in Central Arabia

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Periods of structural movements and diastrophism synchronous with the Acadian uplift phase of the Caledonian tectonic movements are well documented in North Africa. The Late Ordovician to Late Silurian deposits in Central Arabian Peninsula were severely affected by contemporaneous tectonic movements. Influence of the Acadian tectonic movements is indicated by a recognizable Late Silurian regional hiatus preceded the deposition of the Early Devonian Tawil Formation.

The Early Silurian Sharawra Formation shows a progressive thinning from the Tabuk area in the west to Qusayba area in the east. The formation in the Tabuk area is about 510 meters thick and it decreases in thickness eastward to about 42 meters in the Jal Qusayba, and is completely missing in the northern part of the Qusayba depression. This depression is an excellent outcrops window documenting the effect of such movements. The Silurian Sharawra, Qusaiba and Uqlah formations and Hawban member, the upper member of the Ordovician Sarah Formation are truncated and are unconformably overlain by Devonian Tawil sandstones. The influence of the Acadian uplift is also indicated in the subsurface. However, the influence of these movements is masked by later tectonic movements mainly the Hercynian tectonic movements in other parts of Arabia.

Tilt-derivative filtered potential fields data unravel the Paleozoic structure image in Tinat field, Saudi Arabia

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The 3-D seismic structure image of the Paleozoic reservoir in Tinat gas field, located southeast of the Ghawar field, was enhanced to match with the shape of the basement map. The map was derived from the tilt filtered gravity data (mathematical derivative). The objective of this study is to enhance the Paleozoic reservoir structure image to guide future delineation and development of the Tinat field. The study depended on integrating new seismic structure maps with the tilt-filtered gravity data and the well data. The tilt-filter technique enhances subtle magnetic and gravity anomalies, and maximizes the geometrical contrast of the basement structure. Results indicated a strong basement structural fabric at the Paleozoic reservoir level that may cause future compartmentalization in the field. The structural setting of the field indicates a set of NS-oriented, push-up fault closures over a series of basement micro-blocks. Several EW-oriented stress-partitioning faults dissect the field into different domains with a strike-slip transpressional sense of motion. The shape of the basement map derived from the filtered tilt-gravity data mimics, to a great extent, the seismic structure image at the top of the Upper Paleozoic Unayzah reservoir.

Differential exhumation and the structural evolution of the northern Oman Mountains

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The Late Cretaceous orogeny that formed the Oman Mountains provides an ideal site to investigate this tectonic process as there are nearly continuous outcrops throughout the different structural levels. In the northeast, the Saih Hatat culmination preserves eclogite and the blue schists. In contrast the southern flank of the Al Jabal al Akhdar culmination was buried to only a few kilometers. Although these culminations are the surface manifestation of a thickened Arabian continental crust they all show extensional tectonics at outcrop. Extension and contraction were broadly coeval and both were influenced by pre-existing NNE-trending basement structures.

In Saih Hatat, syn-exhumation shears were directed top NNE, accompanied by lineation-parallel folding on all scales. Rather than simply interpret these as sheath folds we propose that they represent a component of constrictional strain, the product of transtension. In contrast the northern flank of the Al Jabal al Akhdar culmination contains a few such folds, so we suggest the extension there was largely plane-strain. The intervening eastern edge of the Al Jabal al Akhdar culmination (Jabal Nakhal) forms a km-scale NNE-trending anticline. We infer that the constriction was the result of laterally varying crustal extension (differential exhumation) whereby top NNE extension was locally combined with left-lateral shearing. The imbalance between net extension and possible contraction within the Arabian Plate suggest that the crustal extension continued after the end of convergent tectonics in the region.

In summary, although all parts of the culminations of Arabian continental crust show NNE-directed extension, different areas manifest this strain in different ways, with varying degree of apparent constriction. The degree of constriction, and presumably therefore the role of non-plane strain in the extension of the northern margin of the Oman Orogen, varies with crustal level and proximity of the pre-existing basement faults.

Tectonics of Afghan-India collision zone, Kuram-Waziristan region, North Pakistan

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The northwest India-Afghanistan collision zone exposed in the Kurram-Waziristan area of northern Pakistan comprises a stack of thrust sheets derived from various parts of a continental shelf-ocean floor transition, formerly located at the northwest margin of the Indian Plate. From southwest to northeast, these thrust sheets include the Waziristan Ophiolite (oceanic mantle-crust sequence), the Khaisora-Kurram Group (distal/outer shelf-slope sequence), the Shahur Tangi-Kahi Group (oceanic fore-deep/olistostrome) and the Isha Group (proximal/inner continental shelf). Late Paleocene and younger shallow-marine limestone and terrestrial foreland molasse sediments unconformably overly this thrust stack, suggesting middle Paleocene as the minimum age of thrust stacking. The absence of this unconformity in the shelf sequences in the north (e.g. Kalachitta, Margala) suggests that this tectonic event was local, probably related with an event of ophiolite obduction rather than to the India-Eurasia collision. An earlier event of ophiolite obduction is indicated by the middle Cretaceous Shahur Tangi-Kahi melange/olistostrome. The northwest India-Afghanistan continent-continent collision in this region is indicated by middle Eocene oblitration of marine sedimentation and continued transpression as late as 2 Ma or less.

Integrated geological and geophysical methods to map subsurface contact between ultramafic and carbonate sequences in Al Wadiyein, Buraimi, Oman

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An integrated geological and geophysical investigation

is being carried out in Al Wadiyein, five kilometers east of Buraimi, at the western edge of the northern Oman Mountains. The area studied to date includes ultramafic rocks (Semail Ophiolite) exposed on the east side of the wadi and allocthonous recrystallized carbonate exposed on the west side. The aim of the investigation was to detect and map the subsurface contact between the ultramafic and carbonate rocks and to establish the geometry and orientation of the contact. The investigation included geological mapping, gravity, and magnetic and seismic survey. In addition, rock samples were collected and analyzed to obtain densities for the gravity modeling. Preliminary results indicate that the geophysical methods have proven to be valuable tools in evaluating the geological setting of the area. The gravity anomalies gradually decrease towards the northwest from a high near the outcrops of the ultramafic rocks to low over the carbonate rocks. The magnetic anomalies reveal lineations that are oriented northeast-southwest, perpendicular to the dip direction of the gravity trend. This data is interpreted to represent NE-trending faults along the northwestward dipping contact between the ultramafic rocks and the carbonates. Seismic reflection and refraction data have imaged the top layer of the ultramafic sequence and constrained the gravity models. Based on this, we deduce that the model that best explains both geological and geophysical data is one in which the ophiolite has a wedge-shaped structure that thins to the northwest as it dips under the carbonates.

The MEBE Tectonic Maps: evolution of the Middle East since Mesozoic

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A set of 14 palinspastic tectonic maps is developed for the Middle East, including the South Caspian, Caucasian and Black Sea domains. These reconstructions are produced by the Middle East Basins Evolution Program (MEBE). Our objective is establishing a model of tectonic evolution of the Middle East since the Triassic times. The palinspastic maps are based on up-to-date kinematics of the Tethyan domain. These maps integrate the original results of the MEBE scientific teams working on tectonics, sedimentology, stratigraphy, and basin modeling. In our reconstruction we estimate the age and the main characteristics of the major tectonic events (rifting, marginal basin opening, basin subsidence, basin inversion, major collisions and orogenies, main transcurrent faults, etc.) that occurred in the Middle East since the Triassic Cimmerian Orogeny. We distinguish two major periods: one before and the one during the collision of Africa-Arabia with the Eurasian margin. The first period lasted from Middle Triassic to Paleogene during which an active and a passive margin developed north and south of the Tethyan Ocean, respectively. Mesozoic extensional tectonics mainly developed on the active Eurasian margin and on the Arabian Platform, and was only interrupted by minor inversion and the Late Cretaceous obduction. The early stage of the Arabia-Eurasia collision started during the Eocene and extended from Bulgaria to the west, to Zagros and the Caspian-Caucasus domain to the east. After the complete closure of the remnant Tethyan oceanic domain, the orogenies related to the continent-continent collision mainly developed during Neogene times. They constitute the almost continuous orogenic belt that extends from central Mediterranean to Iran through Turkey and the Caucasus.

Role of precursor faults in the growth of anticlinal reservoirs in the Middle East

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Anticlinal reservoirs in the Middle East (Oman and Zagros Mountains) are related to faults and fractures. While outer parts of most of these anticlines are relatively well known and understood through either 2-D or 3-D seismic data, and recent analogue studies, their internal architecture remains poorly studied and understood despite their hydrocarbon potential. On one hand, seismological studies in the Zagros Mountains suggest that deep and relatively steep master faults underlie many giant Zagros folds and are somehow linked to them. On the other hand, many models of these folds still favor thin-skinned interpretations and exclude the contribution from deep-seated faults in fold growth. Seismological data is unfortunately at best patchy and confined to the parts of active orogens such as the Zagros Mountains and it does not provide a complete dataset on the deeper fault geometries underneath all folds. More data is needed to better constrain balanced and restored cross sections and also to construct realistic reservoir models of the deep targets in anticlinal structures. Our field investigations focus on large, dissected, anticlines in the Iranian Zagros, the Iraqi Zagros/Taurus Mountains and in the Oman foothills for which the contribution of underlying deep-seated faults in folding cannot be ruled out. Our studies focus on the role played by pre- and syn-folding faulting on fold seeding, inception and growth. Our observations suggest that in some cases pre-folding basement faulting, as well as mechanical stratigraphy, largely controls the ways syn- and post-fold faults develop and link. This has key implications for the possible internal geometries of less accessible, neighboring buried Middle East carbonate anticlinal reservoirs, either prospective or already producing hydrocarbons.

Polygonal faults/fractures pattern within Abu Dhabi onshore Lower Cretaceous Platform carbonates

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Recent improvements in seismic interpretation tools highlight a polygonal subseismic pattern in the entire geological section in onshore fields in Abu Dhabi, United Arab Emirates. Does this new image result from real geological event or/and seismic noise? Persistence of this geometry, through different seismic acquisitions, processing methods and interpretation tools suggests a geological origin. Analyses of specific seismic attributes suggest the following three conclusions. (1) The pattern is characterized by "honeycomb shape" geometries as compared with polygonal fault patterns observed within clastic sediments or chalk. Each body (3-D polygonal cell) is made of facets at different scale. Such a pattern has never been previously observed in platform carbonates. (2) Their vertical distribution is linked to mechanical strata units. It is lithological and burial dependant, although the relationship is not yet clear. (3) Horizontally, a relation between the expression of polygons and the topography of the studied sequence is observed.

The polygonal pattern is enhanced in deformed areas, while facets are less expressed within quiet areas. Focused analysis within the main fault zones reveals that fault segments are made of previously identified polygonal facets. Geological and seismic observations support an early origin of the polygons. Later, during the Late Cretaceous deformation event, some polygon facets evolved from a random orientation away from the faults with a slight readjustment, eventually to the fault plane itself. Fault segments are likely to re-activate former polygonal facets; these facets being re-organized as straighter fault planes. Locally, dynamic data support the polygonal faults/fractures pattern as being flow barriers and /or vertical conduits for flow.

Joint study, high Central Zagros: Part 2 – structural geology - new insights

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After a primary evaluation in 2000 of the Central Zagros area and the existing structural and petroleum play concepts, a joint study project between NIOC and RWE Dea was established and successfully accomplished in the years 2001 to 2004 (Bosold et al., The structural geology of the High Central Zagros revisited (Iran), Petroleum Geoscience, 2005, vol. 11, p. 225-238). The area of interest was situated near the townships of Lordegan and Yasuj at the Dinar Mountain range in the Central Zagros Mountains. The main purpose of the study was to investigate the nature of the High Zagros Fault and the structural styles in the adjacent foreland and hinterland. A second task was to investigate whether the prolific petroleum plays of the Zagros Foreland extended into the study area and new petroleum plays could be recognized. The investigation is not only based on the existing surface and subsurface datasets, but essentially on the unique set of newly acquired geophysical data (see Henke et al., Part 1 (this issue) and Henke et al., Exploring the High Zagros (Iran): a challenge for geophysical integration, First Break, November 2005, vol. 23, p. 32) of dense regional gravity and regional profiles of magnetotelluric (MT), wide-angle reflection refraction profiling (WARRP) seismic and conventional 2-D reflection seismic. The results complement existing research and publications and give new insights in this still poorly understood mountain range. In the foreland, direct evidence was found for the existence of multiple detachment levels above the ubiquitous deep Hormuz Salt level, separating the section into structural units that are not directly related to the structuring observed on surface. These decoupled units give potential for a deep structural play, already tested by the Mokhtar-1 well. The High Zagros Fault and conjugate thrust faults could be imaged by WARRP seismic and MT as real overthrusts that give local potential for a subthrust play. Additionally, the hinterland structure directly following the High Zagros Fault could be imaged with great detail by conventional 2-D seismic showing the thick-skinned nature of the overthrust zone and gives evidence for basement involved tectonics.

Episodic growth history of onshore Kuwait

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A comprehensive study was undertaken to determine and document the structural growth history of Kuwait. This effort attempts to apply the regional tectonic setting of the Arabian Plate to the petroleum system of Kuwait in order to mitigate specific risk factors involving the Cretaceous, Jurassic, and Paleozoic exploration portfolios. The work incorporated all regional 2-D and field-specific 3-D seismic data, well control, and gravity/magnetic data. The effort is meant to address the entirety of the stratigraphic section from Proterozoic to Recent. Approximately 20 isopach maps and reconstructed sections were generated, extending from the Permian-Early Triassic Khuff Formation to the Neogene Lower Fars Formation. Structural episodes were interpreted using the isopach maps and reconstructed sections. Gravity and magnetic data was most beneficial in the interpretation of the pre-Khuff section. Nine episodes of structural adjustments affected onshore Kuwait, resulting in a complex structural architecture. This structural history reflects the regional structural movements that have affected the Arabian Plate.

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The purpose of this study is to: (1) establish a linkage between specific episodes of movement experienced by the Arabian Plate and resultant structural fabrics, through time, as observed in onshore Kuwait; and (2) determine the effects of structural development on deposition, reservoir development, fracture density/orientation, and hydrocarbon maturation and migration.

Interplay between folding, fracturing and diagenesis in the Zagros Foredeep

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Fractures are known to play a key role in the production of the carbonate Asmari reservoir in the foredeep of the Zagros Mountain. Outcrop and subsurface data in this area provide key constraints on the relative timing of fracturing and folding. This study demonstrates that fracturing began at the inception of folding and that most of the present-day characteristics of the fracture pattern are strongly related to the progressive evolution of folds and to the genetic relationship between folding and basement faults. The outcrop data presented here are used to define the fracturing style in various Asmari units at several key structural positions: fold hinge, limbs and tips, along large-scale and well-known transverse lineaments and nearby major topographic steps. Particular attention was placed on the interplay between diagenesis and fracturing because it has a significant impact on the fracture dynamic behavior at depth. From a structural geology point of view, this provided key information on the timing of fracturing and the identification of fracture sets. These are generally mixed together leading to an erroneous interpretation of the relationship between fold geometry and fracture growth. The synthesis of the various types of fracture patterns in regards to the main structural elements at the scale of the Dezful Embayment and is used to challenge the various models of fold/fracture genetic relationships. We also predict the impact of fracturing on the productivity of fractured carbonates in the Zagros Foredeep.

Constraining *in-situ* stress in north and south Oman with implications for exploration and drilling

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Electrical and acoustic wellbore image data from numerous exploration wells in north and south Oman were analyzed to detect and orient stress-induced wellbore failures. Complementary data including leak-off tests, minifrac, pore pressure and rock strength measurements were integrated to constrain the complete *in-situ* stress tensor. The results imply that the stress state in Oman is characterized by strike-slip faulting, where the maximum horizontal stress is greater than the vertical stress, which in turn is greater than the minimum horizontal stress (SHmax > Sv > Shmin). The maximum horizontal stress is generally oriented NE-SW except near major fault zones (e.g. Maradi Fault Zone) and within carbonate floaters of the infra-Cambrian Ara Salt. The substantial difference between the minimum and maximum stresses appears sufficient to bring optimally oriented faults close to incipient shear failure (i.e. frictional equilibrium). The results have been applied to assess fault slip, wellbore stability and fracture initiation in North Oman.

Uplift and subsidence of the southeastern portion of the Arabian Plate from Triassic to Early Cretaceous

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We interpret the tectono-stratigraphic responses of the Arabian Plate to Triassic through earliest Cretaceous events, based on areal extent and the amount of erosion at three unconformities: (1) intra-Hettangian, 202 Ma; (2) intra-Toarcian, 186 Ma; and (3) intra-Tithonian, 148 Ma). We also use Triassic to Cretaceous isopachs and depositional environments. The depositional thickness of the Middle and Upper Triassic succession varied little in southern Arabia. Hettangian erosion removed less than 200 m of section in most areas to the northwest of the Qatar Arch. That event removed even greater amounts from the arch southeastward, but in a broad, undulating pattern. It preferentially removed more from the arch (600–800 m) and most of Oman and Yemen (700–800 m) than from the intervening Rub' Al-Khali (300–500 m). Toarcian erosion also removed more section (300–400 m) from southeast Arabia than elsewhere, but preferential erosion of the Qatar Arch and Oman-Yemen, relative to the Rub' Al-Khali, was reduced. Thus, uplift of southeast Arabia became more uniform from Hettangian to Toarcian times.

The Middle to Upper Jurassic south of Kuwait comprises 800–1,500 m of mainly platform carbonates and evaporites, consistent with slow and areally nearly-uniform subsidence. The Gotnia Basin (Kuwait and most of Iraq) also subsided, although the section there is thinner owing to sediment-starvation until the Kimmeridgian (ca. 152 Ma). Areal coincidence of Toarcian erosion with subsequent subsidence suggests mantle-induced thermal uplift and relaxation. Deep intra-Tithonian erosion characterized all areas east of a NNE-trending limit close to the Saudi Arabian-Omani border and Musandam Peninsula. Late Tithonian-early Valanginian subsidence exceeded 500 m only in two areas (Gotnia Basin and

northern Oman). The absence of areal coincidence of greatest intra-Tithonian erosion with greatest late Tithonian to early Valanginian subsidence suggests that local tectonics, not regional thermal processes, drove the subsidence.

Magnetotelluric (MT) profiling of Oman deep crustal structure as a test for geodynamic models

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A new 130 km long magnetotelluric (MT) resistivity profile across the Oman Mountains near Muscat suggests that the crustal scale architecture of this part of the former Arabian Plate margin is dominated by a SW-dipping to sub-vertical shear system transitional into a zone of deformed mantle recording passage of a craton- or SW-directed, descending subducted oceanic slab and/or ascending high-P metamorphosed microcontinental fragment. Characteristics of this resistivity anomaly match those shown by descending slabs of modern subduction systems, suggesting that the lithosphere-asthenosphere beneath the Oman Mountains preserves a memory of craton-directed subduction. The MT image is dominated by a broad, gently (approximately 10°), SW-dipping conductive zone that steepens to subvertical at the depth of the Moho (approximately 40 km), appearing to extend for another 80 km into the mantle but becoming less conductive with depth. At shallow levels the most conductive part (greater than 15 ohm-m) coincides with strongly deformed schistose rocks (Hatat Schist) in the core of the Saih Hatat fold-nappe, intensely deformed rocks of the upper plate-lower plate (UP-LP) shear zone, and strongly to intensely deformed, schistose rocks of the Hul'w lower plate window. There is no compelling evidence in the resistivity data for any NE-dipping shear system, as required by popular Oman-type supra-subduction models involving subduction of the margin beneath the Neo-Tethys Ocean followed by overthrusting (obduction) of the oceanic lithosphere. The presence of such a major conductive landwards-dipping structure beneath the Semail Ophiolite suggests that major underthrusting of the continental margin has to be part of the geodynamics of the Semail Ophiolite obduction.

Revised structure of the Oman Mountains based on new structural mapping and geophysical data

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The classic structural model of the Oman Mountains consists of three aspects: (1) a stacked series of thrust-nappes including the Semail Ophiolite and Hawasina nappes overlying a para-autochthonous platform carbonate succession, (2) a series of domal culminations including the Hawasina, Al Jabal al Akhdar and Saih Hatat windows related to inferred subsurface ramps, and (3) a series of frontal folds and thrusts that affect the Tertiary units. Implicit in this geometry was a NE-dipping shear system required by popular Oman-type supra-subduction models involving subduction of the margin beneath the Neo-Tethys Ocean, followed by overthrusting (obduction) of the oceanic lithosphere. New structural and geophysical data from the Oman Mountains presented as four new structural profiles necessitate revision of the general structural relationships and the crustal architecture of this part of the Arabian margin. The revised profiles cross Saih Hatat, Al Jabal al Akhdar, the Hawasina window and Bani Hamid to the Musandam Peninsula. Major changes in the Saih Hatat profile relate to the presence of a major NE-vergent fold-nappe in the Paleozoic platform sequence and a SW-dipping shear zone that dips beneath the mountains as inferred from a new geophysical magnetotelluric resistivity image. The new geometry requires, firstly major underthrusting of the continental margin, and secondly post-ophiolite emplacement backthrusting and oceanwards vergent fold-nappe development, that have to be part of Semail Ophiolite obduction geodynamics. Major changes in the Al Jabal al Akhdar profile relate to the presence of a crustal root and the NE-directed asymmetry of the anticline. No NE-dipping, ramp-flat systems have been identified in the subsurface beneath the Oman Mountains.

Geodynamics of the northeast Arabian Plate revisited

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Magnetotelluric (MT) data across the Oman Mountains and geochronological data on As Sifah High-P rocks suggest there is a possibility that much of the Neo-Tethys oceanic crust could have been subducted underneath Arabia with apparently little surface expression. High-P metamorphism, and therefore subduction, must have been occurring at about 110 Ma. Possible effects on the over-riding plate, the Arabian margin of the Neo-Tethys Ocean, may have included subsidence related to lithospheric extension, as well as that induced by down-pulling related to mantle flow above the subducting slab. Interpretation of the Arabian Plate sedimentology and sequence stratigraphy for Oman and the interior has previously been done within the context of the current suprasubduction paradigm of northwards subduction beneath the Neo-Tethys Ocean. Subduction of oceanic lithosphere beneath the Arabian margin however, would have different interpreted consequences in a "soft" type of subduction scenario that does not produce an Andean-type arc. The lithosphere of the over-riding plate, the

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Arabian margin of the Neo-Tethys Ocean, should exhibit changes in sea-level due to regional tilting of the margin on length scales of 1,000–1,500 km as a response to down-pulling by mantle flow, coupled to the margin-directed subduction zone. Uplift in this scenario relates to termination of subduction, or to change in the angle of subduction. Re-examination of the first-order stratigraphic relationships suggests that: (1) the sedimentation interval between the Tithonian unconformity and the Aptian-Albian unconformity may reflect subduction-related subsidence, suggesting that subduction beneath Arabia could have been occurring between 150 and 110 Ma; and (2) lithospheric extension may be responsible for the deepening of the Rub' Al-Khali Basin with implications for hydrocarbon generation.

Joint study, High Central Zagros: Part 1 – a challenge for geophysical integration

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The purpose of a combined geological and geophysical study in the High Central Zagros area near the townships of Lordegan and Yasuj was to find answers to the following main questions: (1) Is the High Zagros Fault an overthrust fault? (2) Are there vertically separated structural/tectonic units in the "Complex" Foreland of the Zagros? (3) Are there chances for hydrocarbon exploration targets beyond the High Zagros Fault? A joint study program between NIOC and RWE Dea was conducted in the years 2001 to 2004 (Bosold et al., The structural geology of the High Central Zagros revisited (Iran), Petroleum Geoscience, 2005, vol. 11, p. 225-238). The study area exceeds 11,000 sq km in size and is characterized by a highly complex geological and tectonic setting. The topography is extremely rugged with elevations ranging from 900 to 4,450 m. The main and most difficult task was to acquire geophysical data that would be of sufficiently good quality to allow a reasonable interpretation and validate the structural concepts (Henke et al., Exploring the High Zagros (Iran): a challenge for geophysical integration, First Break, November 2005, vol. 23, p. 32). A combination of seismic and potential field geophysical methods was felt to be capable of focusing on the different depth levels and changes in the structural geology. Key sections were selected for repeated acquisition of magnetotelluric (MT), wide-angle reflection refraction profiling (WARRP) seismic and reflection seismic data, accompanied by detailed surface geological analysis, dense area-wide gravity measurements and modern satellite image analyses including construction of a DEM. MT and WARRP were found to complement each other ideally, the first for the shallow parts and the latter for the deeper parts of a section. The combination of both methods worked well in the complex tectonic terrain such as across the High Zagros Front Thrust, where surface geology was integrated in the modeling. Integration of all geological and geophysical results led to a structural 3-D model of the study area, satisfying the measured gravity.

Neogene salt southwest Iran and interaction with Zagros

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Two Neogene salt accumulations exist in southwestern Iran. The first one (Fars salt), with early to middle Miocene age, is located in the southern part of the Iranian offshore region in a tectonically quiet domain between the Zagros and Oman Mountains. The second one (Gachsaran Formation), with middle Miocene age, was deposited in a flexural basin related to the Miocene-Pliocene Zagros Orogeny with rapid subsidence in the Dezful Embayment and was folded during the onset of Zagros deformation. Towards the extreme southwest of the Zagros Foreland, the Gachsaran Formation extends beyond the folded zone and experienced pre-Zagros tectonism related to basement fault reactivation. Local thickness variations of seismic reflectors, above the salt, show very early salt movements despite having thin overburden. Salt pillow, asymmetric ridges, rim synclines and turtle-back structures are common features in the Fars salt domain. Salt structures form two large circular patterns with diameters in the order of 10 to 15 km.

The Gachsaran evaporite contains a salt layer at its base, and intercalation of anhydrite, marl and carbonate in the upper part. These mobile basal deposits appear to have had a depositional thickness in the order of 1,200 m towards the southwest and 1,800 m towards the northeast. Seismic images show that in the Zagros Foreland, beyond the present folded zone, tectonic movements along basement faults triggered the movement of the Gachsaran salt. In contrast, in the folded zone, it is invariably thin or absent over the major anticlines culmination, and could be up to 4,500 m thick along their southwestern flanks. The aim of this study is to describe the salt structures in order to improve the velocity model and seismic processing for sub-salt imagery, in addition to discussing the salt movement mechanism in different tectonic contexts.

Upper Cretaceous fault trends in the Bahra area, North Kuwait

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Located in the northern extension of the Burgan Arch in Kuwait, the Bahra area is recognized as a northwards plunging anticline. It hosted the first exploration well to be drilled in the country. The structural axis orientation in the Bahra area is north-south, whereas the predominant fault trend along the anticline is northwest-southeast. An

intersecting zone of dislocations trending approximately east-west occurs in the southern parts of the area. Dislocation is uncommonly severe for this trend, which often is visible only on horizontal data displays. Faults with a northwest-southeast trend are typically of a dilatational nature, sub-vertical, laterally extensive and very straight. Fault throw is moderate, about 20–40 milliseconds two-way seismic time. The age of the tectonic pulse is Late Cretaceous Cenomanian as indicated by the dislocation of the Mishrif Formation. East-west faulting has occurred in a structurally constrained zone where intense dislocation has obliterated traces of individual faults on seismic. The zone is interpreted as a Cenomanian age, faulted uplift, followed by subsequent pulses of uplift and collapse extending into the latest Cretaceous Maastrichtian times. Notably the deposition of the Mishrif-Tayarat formations was severely disrupted along the zone. Renewed subsidence post-dates the Eocene Rus Formation, which was deposited during a period of tectonic quiescence. Anomalous seismic velocities are noted in the east-west fault zone. The carbonate section of the Maastrichtian-Campanian Tayarat-Hartha formations appears to be the most severely affected rock unit, where an interval velocity increase over undisturbed areas has been noted.

Structural evolution of the Wajid area, western Rub' Al-Khali basin, Saudi Arabia

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A several-hundred-kilometer-long, NW-trending half-graben-like structure exists at a depth of approximately six kilometers below the western Rub' Al-Khali desert in southwest Saudi Arabia. Ediacaran and Cambrian strata are interpreted to be vertically offset by more than 600 m along faults overlying a basement terrane boundary, whereas the shallower expression of the structure is a series of relatively low-relief flexures at middle and upper Paleozoic and Mesozoic levels. This structure is informally referred to as the "Wajid Graben". It is of petroleum geological importance since it disrupts the homoclinal dip of Phanerozoic strata onlaping onto the Arabian Shield in the west, thereby creating the potential for structural and stratigraphic hydrocarbon traps. Stratigraphic correlations of regional seismic lines to outcrops in the Wajid area and to adjacent wellbore data, in conjunction with the regional interpretation of gravity and magnetic data, allow the modeling and reconstruction of the complex multi-phase re-activation history of the Wajid Graben. The interpretation of reprocessed 1990–2000 vintage and recently acquired 2-D seismic data provide evidence for at least five major structural events: two events prior to 520 Ma, a Middle-Late Cambrian event, an earliest Devonian event, a Carboniferous event, and several tectonic pulses in the Mesozoic and Cenozoic eras. Along strike the graben edge changes its character. At the Ediacaran to Cambrian stratigraphic level open folds with shallow dipping detachment-like structures underly the northwestern part. Steeply dipping en-echelon faults form the central part of the half-graben and in the southeast the Wajid Graben ends in an en-echelon arrangement of widely-spaced northwest trending faults with relay ramps back-stepping to the east.

Geometry and chronology of basement faulting in the Fars Arc: a view from structural and morphological analysis

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In the Zagros Fold Thrust Belt (ZFTB) of Iran it is firmly established that the basement is involved in the deformation. The strongest line of evidence for this assertion comes from the relatively intense mid-crustal seismic activity. Previous studies have shown that in the Eastern Zagros Mountains basement control on surface structures only occurred at a late stage of the tectonic evolution. In other words, the current thick-skinned style of Zagros deformation succeeded a more general thin-skinned phase of orogeny. This chronology is particularly well illustrated by spectacular interference patterns, in which early detachment folds are cut by late oblique basement faults. This led to the formation of sigmoid structures on the surface. Systematic morphological analysis (large-scale topography and river networks) combined with structural analysis were used to construct a general map of basement faulting in the Fars Arc. The basement trends identified in this study show similarities with the ones drawn in earlier studies, however, more faults are depicted. These are shown to be mainly reverse faults and not, as had been previously suggested, strike-slip trends. The faults show an increase in segmentation in the eastern limb of the Fars Arc. This change in geometry may be related to the influence of inherited transverse structures within the Arabian basement, related to the Oman Line transform fault system, which developed during Permian-Triassic Neo-Tethys rifting.

Tectonic controls of fracturing in the Gulf region

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This presentation shows the age relationships and tectonic causes of filled and unfilled fractures in the Mesozoic and Tertiary carbonates of the Gulf Region. Well and field data are used to determine the orientations and ages of different fracture sets, and to make inferences about the controlling stress systems. We make the case for examining fracture systems in their regional tectonic context. An early set

of carbonate and anhydrite veins is commonly related to diagenesis of the reservoir rocks. These have a wide range of orientations and are cut by all the later fracture sets. Steeply dipping carbonate and anhydrite veins strike approximately NW-SE, tend to be clustered around normal faults, and are related to Mesozoic NE-SW extension. These veins pre-date hydrocarbon migration, formed when carbonate-rich fluids were circulating, and tend to act as baffles to fluid flow. Open fractures are related to Late Cretaceous development of the Oman Mountains (commonly E-W striking fractures) and to the Tertiary Zagros orogenic event (commonly NE-SW striking fractures). Earthquake and borehole breakout data show that the dominant orientation of the present-day maximum compressive stress is approximately NE-SW. Local variability occurs, however, including around salt diapirs, adjacent to faults, and along the Batinah Coast of Oman, where gravity-induced sliding has created open fractures that strike approximately NW-SE. Open fractures are synchronous with and post-date hydrocarbon migration, as indicated by the absence of mineral fill. Open fractures improve hydrocarbon mobility, so understanding their age, geometry and distribution has particular significance for reservoir modeling.

A structural model for typical hydrocarbon traps in Saudi Arabia

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The typical hydrocarbon trap in Saudi Arabia comprises a broad, low-relief, asymmetric anticline formed above a moderate to high angle (45–70° degree) master reverse fault. The fault-fold geometry of one typical trap, the Khurais field, can be quantitatively modeled by basement-involved block rotation along a listric, circular arc fault that flattens to a mid-crustal lower detachment approximately 20 km below ground level. The majority of anticline-forming compressional deformation occurred during Late Cretaceous (Turonian) time. The structural model proposed here, which is readily applicable to several other hydrocarbon-bearing anticlines in Saudi Arabia, provides a quantitative relationship between the shape of the master fault, the geometry of the hanging wall, the depth to fault detachment and the kinematic history of the structure.

Monitoring oil field-induced subsidence using satellite-based radarinterferometry

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In 2003 a consortium around the company Deutsche Montan Technologie (DMT) and several industrial partners from the mining and oil industry launched a project "Earth Observation Market Development for the Mining Sector (EOMD Mining)". This project is funded by the European Space Agency (ESA) within a program "Earth Observation Market Development (EOMD)". The goal of the project is the development of a new integrated service for monitoring mining and oil exploitation induced surface movements. This service includes the application of the latest remote sensing monitoring technique of radar-interferometry and the use of a Geographic Information System (GIS) for analysis and interpretation of the monitoring results. The integrated service has been established and applied to several "Pre-Commercial Projects (PCP)" provided by industrial partners. The PCP "Kuwait Oil Field Subsidence Monitoring" is on the way in co-operation with Kuwait Institute for Scientific Research (KISR). This PCP serves as a base for this contribution.

In a preliminary project a small Synthetic Aperture Radar (SAR) dataset from ERS-1/2 sensors has been purchased and processed. Problems arose due to strong atmospherical artefacts in the resulting interferograms. Nevertheless the general capability of the technique has been shown due to a sufficient coherence in the area of interest encouraging further work. New SAR data from Envisat's ASAR sensor acquired between 2003 and the end of 2005 have been purchased by KISR and processed at DMT. Surface movements have been determined using SAR data by the application of the Differential Interferometric SAR (DInSAR) and the Interferometric Point Target Analysis (IPTA) approach. The results have been integrated into a GIS for further analysis and interpretation in combination with information about the reservoir.

A tale of two basins: Hercynian structural evolution of the Permian and Arabian basins

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The Permian basin in west Texas and the "Arabian" basin between Kuwait and the Yemen-Oman borders are Paleozoic foreland basins that were both affected by the Carboniferous Hercynian tectonic event. The basins were located inboard of the subduction-related fold-and-thrust belt and developed similar forced folds as a result of the Hercynian event. Both basins were relatively unmodified by later tectonism and thus are the home of major hydrocarbon accumulations. Basement-involved faults from the Hercynian event partitioned earlier large basins into several sub-basins, and considerable thicknesses of pre-tectonic section were removed from the crests of the forced folds. After the Hercynian event, a post-tectonic clastic section filled in the relict topography of both basins and was in turn covered by an extensive carbonate section. Both basins were affected by Mesozoic tectonic

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events while relatively proximal Cenozoic tectonism had a greater effect on the basins. The Arabian basin is today again in the foreland of the Zagros convergence zone. The structural style of the Hercynian in both basins is similar. Structures in both basins originated as forced folds over high-angle basement faults. Because of seismic acquisition challenges, it has been very difficult to image the basement faults in both basins. Structures in the Arabian basin have been reactivated at least three times since the Hercynian, but there is little evidence of later reactivation in the Permian basin. Plays include structural closure at the crests of forced folds and pinchouts of pre-Hercynian section along the flanks of the folds. Sub-thrust plays on the flanks of uplifts that are seen in the Permian basin may also be important in the Arabian basin.

Basement control on structure and evolution of the salt basins of Oman

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The basement of Oman comprises a NE-trending collage of accretionary wedge, ophiolitic, magmatic arc and microcontinental terranes that accreted onto the southeast margin of the East Arabian Terrane during the Pan African Orogeny (about 850–520 Ma). The character of the basement, its composition and structural grain, and the terrane boundaries have significantly and repeatedly influenced infra-Cambrian and Phanerozoic basin evolution and sedimentation. The amalgamation of Oman's basement was completed at about 730 Ma, accompanied by the development of major, regional approximately NS-trending fracture-fault zones that were reactivated during accretion, cutting across and offsetting the accreted terranes. These faults were reactivated during extension and deposition of the Neoproterozoic Abu Mahara Group, and during compression when the Oman microcontinent collided with the Arabian Shield. Subsequent reactivation during the infra-Cambrian resulted in compartmentalization of the developing salt basins. The Ghaba and South Oman Salt basins are relatively narrow and deep, and are underlain by a basement formed by the NE-trending belt of accreted terranes. The Fahud Salt basin developed on basement similar to the East Arabian Terrane, a more stable, probably microcontinental terrane ("Fahud Terrane"). During the development of the salt basins and later during post-salt sedimentation and salt movement, subsidence and accommodation was much greater in the Ghaba and South Oman Salt basins than in the Fahud Salt Basin. During transpression associated with terminal Pan African orogenic activity along the Eastern margin of Africa-Arabia (Angudan event), the terrane boundary between the accreted terranes and the Fahud/East Arabian Terrane reactivated and became the focus of thrusting and inversion. The intensity of this deformation was partitioned by reactivation of the plate-scale NS-trending fracture/fault zones.

Structural evolution of the eastern Arabian Terrane: basement to more than 20% of the world's petroleum

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Integrated interpretation of potential field, seismic and geological data from the Arabian Plate shows a collage of basement terranes assembled in the Neoproterozoic Pan African Orogeny. The Eastern Arabian Terrane (EAT) spans more than 1.5 million sq km through Yemen, Oman, Saudi Arabia and the Gulf, and underlies much of the Zagros Fold Belt. According to USGS estimates, more than 20% of the World's total petroleum endowment occurs in basins overlying the EAT. The EAT is interpreted as a Paleo-Mesoproterozoic continental fragment that amalgamated with adjacent terranes in Oman at about 760–720 Ma. Extension and subsidence occurred from about 720–680 Ma, with widespread deposition of the Abu Mahara Group of Oman and age equivalent rocks. At about 680–630 Ma the collision of the EAT with the Arabian Shield terranes caused deformation at the terrane margins and subtle folding, and very low-grade metamorphism of older sediments in the terrane's interior. Further sedimentation and plutonism occurred from about 630–540 Ma, which culminated in the Early Cambrian Angudan Event at about 540–520 Ma at which time the terranes of the Arabian Plate underwent structural reactivation, widespread erosion and peneplanation. We suggest that pre-Angudan sediments in the Eastern Arabian Terrane are probably sufficiently deformed and metamorphosed to be considered economic basement and form a Neoproterozoic-Early Cambrian fold belt overlying extended Paleo-Mesoproterozoic continental crust. From the Middle Cambrian to Recent, the EAT formed part of a remarkably stable platform. Tectonic events at the margins of Gondwana exerted a subtle influence on the plate interior, forming sequence boundaries and regional unconformities and subtly influencing subsidence rates. Minor compressional and/or transpressional reactivation of deep-seated Proterozoic basement structures occurred during several of these events, including the late Silurian (Caledonian), middle Carboniferous (Hercynian), Late Cretaceous, and Tertiary-Recent. Reactivation of deep-seated basement structures caused very subtle, long-wavelength folding of Paleozoic-Tertiary strata, forming most of the major hydrocarbon traps in the Middle East.

Structural styles in central and eastern Saudi Arabia

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Located on opposite margins of the western Rub' Al-Khali Basin, two structural trends of the Central

Arabia and Eastern Arabia share a general north-south orientation and similar transpressional styles during the Carboniferous Hercynian Orogeny. Multiple seismic profile and map geometry criteria are used to identify the magnitude and direction of strike-slip faulting for the two trends. Transpressional structures in Central Arabia have been interpreted by recent 3-D seismic surveys. The long, linear NS-trending master faults of infra-Cambrian age form an integral part of a right-lateral transpressional fault system with many distinctive coeval, en-echelon flanking folds. Many oil fields are associated with these structures. Right-lateral slip of a minimum of 0.5 km along individual fault is observed based on offsets of pre-existing faults. Recent 3-D seismic interpretation of the structural trend on the eastern basin margin indicates a left-lateral transpressional system, with a much smaller strike-slip component. Most fault planes are sub-parallel but discontinuous along the strike, as opposed to their through-going and solitary counterparts in Central Arabia to the west. However, some amount of strike-slip movement can be inferred, based on the following evidence: (1) relatively linear fault traces and steeply dipping fault planes offsetting the top of basement; (2) relatively symmetrical shape of a few folds; (3) acute angular relationship of a few coeval, flanking folds to the causative fault trace; and (4) change of fault-dip direction with depth.

MIDDLE EAST STRATIGRAPHY

High-resolution sequence stratigraphy and reservoir characterization of a Lekhwair reservoir unit (Lower Cretaceous, United Arab Emirates)

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Significant hydrocarbon accumulations have been found in the lower part of the Lekhwair Formation (lower part of the Thamama Group, Valanginian). The succession studied is interpreted to correspond to the transgressive sequence set (TSS) of a second-order supersequence that ranges from the top Habshan Formations (lower Valanginian) to the base of the so-called "Lower Dense Zone" of the Kharaib Formation (Barremian). The TSS is built by a third-order sequence (Valanginian) that is composed by three fourth-order, high-frequency sequences, comprising three reservoir units and three non-reservoir (dense) zones. The uppermost reservoir unit, the focus of the study, can further be subdivided into four fifth-order parasequences, corresponding to four reservoir sub-units. Third- and fourth-order sequence boundaries, fourth-order maximum flooding surfaces, as well as fifth-order flooding surfaces were identified in core material from wells of Abu Dhabi and tied to well logs.

Based on texture, grain types, sedimentary structures, faunal content, and lithologic composition, seven reservoir lithofacies and three non-reservoir (dense) lithofacies have been identified. The reservoir unit is composed of limestone, mainly deposited in an open platform, upper to middle ramp to restricted platform subtidal to intertidal environment. Good reservoir quality is developed within *Bacinella/lithocodium* packstone to floatstone, floatstone to rudstone, and boundstone. Intensively bioturbated, siliciclastic- and organic-rich wackestone and packstone characterize the dense zones. Using geological (lithofacies) and petrophysical (porosity/permeability and mercury injection) data, five facies associations and ten reservoir rock types (RRT) have been defined for the reservoir unit. The observed heterogeneity of the reservoir is mainly due to depositional facies. Diagenesis (cementation and compaction) is interpreted to play only a minor role in reservoir quality distribution. The established high-frequency sequence stratigraphic framework allows a better prediction of the vertical and horizontal distribution of reservoir lithofacies and reservoir quality throughout the field.

Subregional high-resolution sequence stratigraphy and reservoir characterization of Upper Thamama (Lower Cretaceous) reservoirs of onshore and offshore Abu Dhabi, United Arab Emirates

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Important hydrocarbon accumulations occur in Upper Thamama platform carbonates of the Kharaib (Barremian and early Aptian) and Shu'aiba (Aptian) formations of Abu Dhabi. These formations contain three reservoir units bounded by low porosity/permeability dense zones. Core descriptions of 25 wells were used to establish a sequence-stratigraphic framework of the Upper Thamama applicable to reservoir units and dense zones alike. Thirteen reservoir and eight non-reservoir (dense) lithofacies are identified from texture, grain type, sedimentary structure, and lithology. Depositional environments of reservoir units range from lower ramp to shoal crest to near-back-shoal. Dense zones (locally with features indicative of very shallow-water deposition and exposure) were deposited in a restricted shallow-lagoonal setting.

The Kharaib Formation is a second-order, late transgressive sequence set, built by several third-order composite sequences. The Lower Shu'aiba is one third-order composite sequence, deposited during a second-order transgression. These third-order composite

sequences consist of fourth-order parasequence sets. This framework provides insight into the distribution of "higher" and "lower" quality reservoir. In the middle Kharaib reservoir, mud-dominated, low to moderate porosity/permeability rocks were deposited during a third-order transgression. Higher porosity/permeability grain-dominated rocks occur in a third-order highstand. Thickness and facies changes are minor within one field and only become obvious with a regional view. The lower Kharaib reservoir unit thins by nearly one-half from west to east, most likely due to lap-out. A facies change follows this trend: orbitolinid-rich skeletal wackestone/packstone (west) becomes bioturbated wackestone/packstone (east). The stratigraphic framework established in this study gives insight on distribution of reservoir rocks within the ADCO concession. Further, a more "regional" view of these formations reveals facies, stratigraphic geometries, and thickness variations not obvious within one field.

Sag-interior Oligocene basin of north-central Iraq: sequence stratigraphy and basin overview

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The Oligocene sequence of north-central Iraq is oil-rich carbonate rock and referred to as the "Kirkuk Group". It developed in a relatively narrow, downwarping sag-interior basin following a period of uplift and widespread regression. This study attempts the sequence stratigraphic analysis of these sediments using subsurface data from thirty boreholes from Kirkuk oil field to elaborate on basin architecture and evolution. Marginal reef-controlled ramp complexes along coastal areas and basinal marlstone dominate basin sequence and represent a second-order sequence as it is bounded by unconformity surfaces of SB1 type. The cyclic nature of these sediments is well differentiated at the marginal ramps and considered to represent a three-fold third order cycles of fairly consistent facies architecture.

The lower cycle (Lower Oligocene) is developed after a long period of subaerial exposure and erosion with an unconformable lower contact. The early stage of reef nucleation and ramp zonation into the associated facies represent the transgressive system tract (TST). The maximum flooding surface of this cycle is recognized by the occurrence of a glauconitic horizon within the basinal facies. The highstand system tract (HST) is represented by the extensive progradation of the reef and back reef facies over its fore reef facies. The lowstand system tract (LST) is less developed due to its short duration. It is represented by the seaward downshift of the ramp facies belt, which is accompanied by subsequent local erosion of the upper reefal part. The second (Middle Oligocene) cycle is similarly developed with relatively extensive reef development that indicates a longer highstand interval as compared to the lower cycle. The uniform thickness of the reef and back-reef facies indicates deposition in a uniformly furnished accommodation space during most of the cycle period, which reflects relatively stable environmental conditions over a tectonically stable ramp development. The third Upper Oligocene Cycle is missing in the study area either due to poor development or erosion by the subsequent rapid fall of post-Oligocene sea level. The carbonate-dominated, and narrow and elongated extension of Oligocene Series and its position within the foreland Tertiary succession of north-central Iraq indicate its deposition as a part of an intra-collision sagging of the under-riding Arabian Plate.

Seismic stratigraphy of the Cretaceous and Tertiary of the Mesopotamian Basin, Central Iraq

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The Mesopotamian Basin is a prolific hydrocarbon system with reserves of more than 100 billion barrels of oil. Large areas of the basin still have significant exploration potential. An understanding of the spatial and temporal distribution of reservoir, source rocks and seals in these areas can reduce exploration risk. We have constructed a sequence-stratigraphic framework from the uppermost Jurassic to the Miocene based on regional seismic-stratigraphic interpretation of 2-D lines in central Iraq, integrated with biostratigraphy. Two prograding wedges are observed during the Early Cretaceous and Paleogene. These prograding packages are formed by aggrading to prograding depositional sequences (Highstand Sequence Sets - HSSs). The Lower Cretaceous HSS was deposited during the Berriasian and early Valanginian. This HSS prograded over a lower-order Tithonian (latest Jurassic) maximum flooding surface associated with the Makhul Formation source rocks. Reservoirs associated with this HSS are shelf-margin carbonate buildups and shoals, and incised-valley fills. Downlapping sequence boundaries of the HSS can act as stratigraphic migration pathways linking the HSS reservoirs to the Tithonian source. This HSS is followed by a pronounced downward shift in coastal onlap, resulting in a mid-Valanginian unconformity. Upper Valanginian to Hauterivian depositional sequences lap onto this unconformity, producing a prograding to aggrading wedge (Lowstand Sequence Set). The mid-Valanginian unconformity is associated with a marked change in the configuration of the Neo-Tethys Ocean in this area, from shallow and widespread in the Berriasian to narrow and deep in the Hauterivian, restricted to the northeastern portion of the basin. This trough (Mesopotamian Basin) broadens in the Late Cretaceous and narrows again in the Paleogene, becoming the foredeep basin to the Zagros Foldbelt in the Miocene.

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From ice to salt: stratigraphic synopsis of the Huqf Supergroup of Oman

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The Huqf Supergroup is the oldest sedimentary sequence overlying crystalline basement in the Sultanate of Oman, and spans approximately 200 My of Earth history from the Late Neoproterozoic (Cryogenian and Ediacaran) to the earliest Cambrian. It crops out in the core of the Al Jabal al Akhdar and in the Saih Hatat mountain regions of north Oman, in the Huqf area of east-central Oman and near Mirbat in the south of Oman. Refinement of the Huqf Supergroup stratigraphy has mostly been triggered by the continued drilling by Petroleum Development Oman (PDO) of exploration wells targeting this sequence. To-date more than 300 wells penetrate Huqf Supergroup strata. In support of these exploration activities, PDO has sponsored and supported a number of research projects that have addressed the Huqf Supergroup in outcrops and in the subsurface. In addition to commercial interests, the Huqf Supergroup has become the focus of the worldwide scientific debate on the "Snowball Earth hypothesis". Oman has now emerged as one of the localities in the world that provides direct constraints on both the Sturtian (740–700 Ma) and Marinoan (665–635 Ma) glacial episodes. This is underpinned by a combination of precise radiometric ages and detailed carbon isotopic data covering the full terminal Neoproterozoic of Oman and providing an important component of the global composite carbon isotopic record. This paper summarizes the efforts and advances made over the last six years in both the subsurface and surface rocks. The available stratigraphic, isotopic and radiometric data of the Neoproterozoic of Oman are reviewed, and a composite Oman reference section is proposed as an important update for the Arabian Plate Sequence Stratigraphy.

Correlation of the Lower Permian surface Saiwan Formation and subsurface Haushi Limestone, Central Oman

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The paleontology of the Lower Permian Saiwan Formation of the Al-Huqf outcrop, central Oman, has been the subject of significant study. In contrast, the approximately equivalent beds in the subsurface (the Haushi limestone and 'basal sandstones' of the lower Gharif member) have, until now, received less attention, preventing precise surface-subsurface comparison. A recent brachiopod study of cored Petroleum Development Oman wells has allowed a four-fold biozonation correlating the Haushi limestone and the Saiwan Formation, implying that previous direct correlation of the Saiwan Formation with the lower Gharif member is incorrect. The occurrence of the fusulinid *Pseudofusulina* ex gr. *karapetovi* Leven, suggests a Sakmarian age for the Haushi limestone, and brachiopod data supports this determination. Subsurface Haushi limestone palynology, though diverse, is poorly preserved, and no palynomorphs have been recovered from equivalent surface outcrops. However, the distribution of autochthonous algal spores in three subsurface Haushi limestone sections suggest a local biozonation that is consistent with that indicated by brachiopods. The terrestrially-sourced palynomorphs in these sections suggest an OSPZ3c age and correlation of the carbonates of the Haushi limestone with the highest part of the clastic lower Gharif member in south Oman, above the *Ulanisphaeridium omanensis* Biozone or Maximum Flooding Shale in that area. Facies evolution reveals an increase in carbonate deposition during the Sakmarian due to distancing of the terrigenous source, coupled with climatic warming, culminating with a regressive trend at the end of the cycle. Petroleum Development Oman is acknowledged for arranging access to cored well sections.

Paleobiogeography of the Alborz Mountains (North Iran) in the Early Permian: evidence from brachiopods and palynomorphs

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The set of continental blocks that form Iran have always been considered of Gondwanan affinity for several reasons. The first is their pre-Paleozoic basement that is thought to be related to the Panafrican orogenetic cycle. The second is the continuity of Proterozoic-Cambrian sedimentary rocks, which is thought to occur north and south of the Zagros Suture. Similarly, the region lacks Variscan deformation and is located south of the supposed position of the Paleo-Tethys Suture. Paleontological evidence has also been used to suggest Gondwanan affinity because north and central Iranian Devonian stromatoporoids, rugose corals and brachiopods were considered to be similar to those of Armenia, Afghanistan and Karakorum. But in fact the Devonian fauna has a cosmopolitan character and shares affinities with northern regions also (Western Europe and Russian platform). This study of the Lower Permian Dorud Formation of the Alborz Mountains (north Iran) illustrates how fossil groups can be used to infer the paleobiogeographic affinities of continental blocks. The assemblages of Asselian-early Sakmarian brachiopods and palynomorphs from Dorud have a south boreal or north paleoequatorial affinity, consistent with the southern provinces of the Boreal Realm and of the West Tethys province. Moreover, they are dramatically different from coeval faunas and microflora of the Gondwanan peripheral regions from Western Australia, India, Karakorum, Central

Afghanistan and Oman. It is difficult to explain the boreal affinity of the Dorud brachiopods and palynomorphs if north Iran is considered part of the Peri-Gondwanan fringe during the Asselian-early Sakmarian. A more northerly position for this block at this time is thus more likely.

Control of deep-seated salt tectonics and eustasy on the stratigraphic architecture of mid-Cretaceous carbonate strata in the Central Arabian Gulf, offshore Iran: a seismic sedimentological study

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The mid-Cretaceous (Albian to Turonian) stratigraphic interval of the eastern Arabian Plate is dominated by widespread carbonate accumulation. The Sarvak Formation of south Iran is part of this carbonate system. Seismic mapping of the entire Sarvak Formation interval within an extensive (c. 80 x 80 sq km) 2-D seismic survey located in the central Arabian Gulf, offshore Iran, allowed the reconstruction of the stratigraphic evolution of the carbonate systems in this area. The results of the seismic mapping point to four sequences within the Sarvak Formation. The first two seismic sequences (late Albian to early Cenomanian) comprise the deposition of the lower Sarvak Formation (Mauddud Member), while seismic sequences three and four cover the upper Sarvak Formation (Ahmadi Member). Further analysis of the results suggests that deep-seated salt tectonics, related to the rock salt of the infra-Cambrian Hormuz Formation, was a major controlling factor for the mid-Cretaceous platform development. Salt-related uplift, which also influenced basement structures like the Qatar-Fars Arch, started during the Early Cretaceous. Peak uplift and salt withdrawal-related subsidence occurred during the mid-Cretaceous (Cenomanian to mid-Turonian). These large-scale morphologic changes interacted with eustatic sea-level fluctuations and resulted in the formation of sub-aerially exposed topographic high areas within the entire Sarvak Formation (sequences one to four). In sequence three and four, intrashelf basins were created and filled during the late Sarvak Formation. The top of the Sarvak Formation is marked by the mid-Turonian Unconformity, which exposed the entire platform.

Integrating seismic multi-attribute classification and forward stratigraphic modeling in mid-Cretaceous carbonate sequences, Arabian Gulf, Iran

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The characterization of carbonate settings in seismic is often difficult, especially in areas with limited well control. This study presents an integrated approach where a geophysical method (seismic multi-attribute classification) is combined with a geological one (forward stratigraphic modeling). The combined results of both methods allow, to a certain extent, predicting the lithology distribution within the interval of interest and locating the position of the defined depositional settings within extensive seismic surveys. The study is based on a 2-D seismic survey located in the central Arabian Gulf, offshore Iran. The interval of interest is the salt tectonics influenced mid-Cretaceous Sarvak Formation, a stratigraphic equivalent to the Mauddud/Mishrif and Natih formations of the Arabian Peninsula. For the multi-attribute classification (neural networks-based; unsupervised and supervised) a set of six volume- and grid-based seismic attributes was utilized. The classification mapped the basic seismic facies distribution as well as large-scale depositional domains (e.g. shallow carbonate platform, intrashelf basin, salt withdrawal basin, platform progradation front). For the forward stratigraphic modeling several seismic lines from the 2-D survey were chosen as templates to be matched by the 2-D computer models. To support the interpretation of the modeling approach, outcrop analogue studies from the Natih Formation in Oman were used. The resulting stratigraphic models provided an overview of the general facies distribution and their packaging, which combined with the seismic attribute classification, resulted in a more realistic interpretation of carbonate depositional settings.

Anisian ammonoids from Socotra Island, Yemen

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In the Triassic succession cropping out along the eastern coast of Socotra Island (Yemen), two ammonoid-bearing intervals have been recognized. The first interval yielded very few and poorly preserved specimens, while several tens of rather well-preserved ammonoids were found in the second fossiliferous interval. The collected specimens provide a wide range of information. (1) Taphonomy: the ammonoids are preserved as internal moulds, however they often show features index of reworking, such as differential fillings not consistent with the matrix, disarticulated internal moulds, colonization of the internal moulds by borers and dwellers. As the maturity of the features index of reworking is very low, the ammonoids probably were reworked immediately after burial and they were moved over short distances. Reworking most likely was caused by storm events. Estimate of the duration of the interval between first burial and final burial is difficult, but most probably is less than one ammonoid chronozone. (2) Taxonomy and bio-chronostratigraphy: the ammonoids mostly belong to the genera *Beyrichites, Flexoptychites, Ptychites, Discoptychites, Monophyllites* and *Paraceratites*. These genera are typical of the upper Anisian Trinodosus Zone of the Tethyan scale. However,

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because of ammonoid reworking, the age of the beds yielding the ammonoids is slightly younger than the age of the ammonoids. (3) Paleobiogeography: the ammonoids are typical of the Tethyan paleobioprovince. No ammonoids of the Sefardic paleobioprovince have been found.

The Triassic succession of Socotra Island (Yemen): preliminary results

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The Triassic marine succession, exposed on the eastern coast of Socotra Island (Yemen), is of great interest for both the understanding of the evolution of Socotran Platform and the calibration of the correlations along the northern coast of Gondwanaland between Oman, Madagascar and the Himalayas. Despite its great significance, the succession is poorly known and only a short description of the first half of the about-300-m-thick succession was provided in the past. Two field excursions were carried out in 2004 and 2005. Two stratigraphic sections were measured at Ras Falanj and Ras Momi. The succession rests on crystalline basement and is truncated by Jurassic sediments with slight angular unconformity. At the present stage the following points can be summarized: (1) the marine transgression on the basement was very rapid. It is documented by bioclastic wakestones with microgasteropods above a 5–6 m-thick bed consisting of fluvial conglomerates and sandstones. (2) The succession was deposited on a shallow shelf, with fluctuations from protected to high-energy environments. (3) Age dating is provided by ammonoids and conodonts. Ammonoids mostly occur in two fossil bearing intervals, about 65 and 80 m above the base. The first occurrence of conodonts is recorded in the lowermost bioclastic wackestone levels. Brachiopods and bivalves are also common.

Carbonate margin progradation and clastic basin filling sequences Mesopotamian Basin

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The Mesopotamian Basin of Iraq contains known reserves of over 100 billion barrels of oil. It initiated as the deep-water Gotnia Basin in Jurassic time. During Cretaceous time, a prograding carbonate margins and clastic wedges stacked in a series of second-order highstand and lowstand sequence sets. In Tertiary time the Zagros Foredeep developed as the third basin in the same location. Regional well correlations, biostratigraphic, and seismic data are integrated into a stratigraphic framework of second-order Cretaceous sequences. Facies and environment of deposition (EOD) maps show a series of alternating carbonate shelf margins and clastic sequences, which prograde from the west and south, filling, and eventually covering, the NW-trending Gotnia Basin. A flooding surface near the base of the Cretaceous demarks a significant shift in environment and sedimentary type, from the evaporitic and carbonate conditions of the Jurassic Gotnia Basin, to the more marine conditions of the Cretaceous Mesopotamian Basin that led to the deposition of carbonate and clastic sequences. The stacking pattern and sedimentary facies of the Lower and middle Cretaceous sequences create reservoir-seal relationships composed of high-energy carbonate margins and bioherms, sealed by regional transgressive marine shales, and of shallow-marine sands, sealed by thin intra-formational and terminal transgressive marine shales. Source rocks in the Jurassic Gotnia Basin and Early Cretaceous Mesopotamian Basin underlie these trends. The stacking pattern of source rocks, numerous reservoirs, and seals gives rise to prospective strandline and shelf margin trends, that flank the western and southern margins of the Mesopotamian Basin, and a robust petroleum system with fields characterized by numerous pay zones.

Isolated platform and reef growth in the Hawasina Ocean: the Late Triassic Jabal Kawr of Oman

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In the realm of the Hawasina Ocean (Neo-Tethys), carbonate production of isolated platforms was discontinuous and interrupted by a large gap. The Neo-Tethyan platforms drowned shortly after the end-Guadalupian (middle Permian) mass extinction and did not recover before the Late Triassic times. Correlation of the Triassic sections at Jabal Kawr in the Oman Mountains points to a change in platform architecture and is characterized by lateral facies variations. The architectural style evolved during late Triassic Carnian/Norian time from a carbonate bank to a platform rimmed by reefs. The start of the carbonate sedimentation is characterized by an initial phase with volcaniclastic interruptions, followed by a bank stage with a shallow subtidal to peritidal interior and oolite shoals at the margin. In the Norian, vertical accumulation caused an increase of the platform height and developed a relief along the margins progressively increased through the aggrading reef stage. The possibility that a reef rim existed that was later removed by erosion, is suggested by the Sint reef and olistoliths of similar reef limestones in the surrounding areas. The reef clasts contain a diverse fauna with scleractinian corals, sponges and several different encrusting organisms. These clasts could have been derived from diverse platform margin reefs that were partly eroded from the margin. From the perspective of carbonate platforms, recovery in the Neo-Tethys Ocean

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was extremely retarded after the Permian-Triassic mass extinction. Carbonate production of isolated platforms ceased for about 30 million years, a period exceeding the recovery of most marine ecosystems.

Evolution of the Oligocene-early Miocene mixed sedimentary system in the Dezful Embayment (Asmari and Pabdeh formations), southwest Iran

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An extensive outcrop and subsurface dataset of the Asmari and Pabdeh formations in the Dezful Embayment of southwest Iran has been analyzed to provide a high-resolution, three-dimensional reconstruction of the stratigraphic architecture of this very complex sedimentary system. A basin-wide high-resolution time framework (resolution 1 to 2 My) resulted in the definition six third-order depositional sequences. Paleogeographical and isopach maps show the gradual infill of this basin, with systematic patterns in the distribution of sandstones, carbonates and evaporites. Both tectonism and eustatic sea-level fluctuations have influenced the sedimentation pattern. The time framework for this study is based on an integration of chemostratigraphic (Sr isotope curves), biostratigraphic and sequence stratigraphic principles. In particular the systematic application of Sr isotope measurements has greatly improved the stratigraphic resolution, notably in the platform successions. Extensive outcrop work has contributed substantially in defining the sedimentological processes involved. A three-dimensional representation of the evolution of this sedimentary system is shown, using stratigraphic forward modeling. A tangible result of this study is the insight that there are at least four Asmari-type reservoirs, each of which is different in stratigraphic architecture, lithological composition, and distribution of the sedimentary facies. In addition, the sequence stratigraphic model predicts the distribution of these different types within the basin.

Geomorphology and evolution of the Lower Cretaceous carbonate platform margin deposits in North Oman; correlation of seismics and well data

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The Lower Cretaceous platform deposits in north Oman rapidly prograded about 300 km northwards over a period of 15 million years. This resulted in a complex, varying slope-to-platform depositional setting, associated with equally varying lithological characteristics. The Habshan deposits are defined as coarse-grained oolithic shelf-edge deposits, outcropping in the Al Jabal al Akhdar and well known in the subsurface, from their striking clinoformal seismic reflections. Research was done in two steps. Firstly, the clinoform belt was traced by seismic interpretation of 2-D and 3-D datasets and amplitude extractions on a regional scale. Secondly, detailed petrophysical well log analysis of the Habshan Formation was conducted and the well data was calibrated to the seismically defined zones. The seismic mapping revealed five subsurface clinoform belts, which can be distinguished by high and low-angle slopes. Well calibrations showed that the low-angle clinoformal belts correspond to high gamma ray and low porosity. The steeper dipping belts are characterized by overall low gamma and high porosity. Core data indicate that these low-angle belts correspond to mud-dominated, lower-energy marine deposits, related to the platform slope. The depositional model for these low-angle, mud-dominated clinoform deposits is that of a carbonate ramp. The steeper dipping belts are dominated by the typical Habshan coarse-grained, shallow-marine high-energy deposits, which are associated with carbonate platform edges. The depositional model for these high-angle, grain-dominated clinoform deposits is that of a rimmed platform. Geometrical analysis and seismic interpretation show no clear evidence of possible relations between the depositional trends and any major structural features. The internal geometries of the huge Habshan progradation belt are therefore thought to be mainly controlled by the regional relative sea-level fluctuations and rates of carbonate deposition.

A new model for epeiric carbonate platforms

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Epeiric carbonate platforms host some of the most prolific hydrocarbon accumulations in the world. Models for epeiric platforms were so far limited because the recent does not provide any analogues for such large, epicontinental platforms and they had to be based on interpretations of snapshots provided by ancient deposits. The availability of 3-D high resolution seismic data covering large areas has enabled the investigation of the internal stratal geometries of the Cretaceous of Oman, which has led to a new model for epeiric carbonate platforms. Epeiric platforms developed during periods of high global sea level when shallow shelf seas covered large parts of the continents. This allows significant progradation of the carbonate platform margins over hundreds of kilometers, unlike the recent large platforms that are limited in their progradation by the bordering deep ocean floor. During relative rise in sea level open-marine conditions prevailed on these platforms and differential carbonate growth led to a topography of shallow carbonate shoals and intra-platform 'basins' with

water depths reaching several tens to 100 meters. These basins were progressively filled by prograding carbonate shoal complexes with depositional slopes of a few to several tens of degrees. Contrary to common belief, the carbonate ramp model, with low depositional gradients, broad facies belts and gradual facies transitions, is not appropriate to interpret epeiric depositional settings. The differentiation between shallow and deep-water areas within these epeiric platforms has important implications for the preservation of depositional sequences. Unlike flat-topped platforms, which are exposed during relative low sea level, large areas can still be flooded during relative sea-level lowstands, and lowstand system tracts can be preserved on the platform. This has an important impact on correlation strategies, the modeling of hydrocarbon flow units and stratigraphic trapping potential.

Pollen grains record from the early Miocene of the northern Red Sea

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Thirty-five subsurface samples from the Dib-1 and Gs-392/2 wells in the Gulf of Suez and 22 samples from the surface section at the Midyan region along the eastern Gulf of Aqaba, were palynologically analyzed. All studied samples were collected from the Nukhul Formation of the Gulf of Suez and from the Sharik and Musayr formations in the Midyan region. The palynological study of these samples confirmed an early Miocene age for these formations. The palynoflora was not sufficiently diverse to allow biostratigraphic applications. Twenty-two families and seventeen genera were identified. The recorded pollen grains indicated a transitional floristic change from warm to humid temperate that characterized the early Miocene deposits.

A method for determining the age of deposition of sediments using SHRIMP: a technology trial on the clastic sequences from the Haima and Huqf Supergroups of Oman

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The radiometric dating of igneous material is a well established technique, with zircon U/Pb derived ages at the forefront of studies applied to both *in-situ* and transported material. The application to sedimentary sequences is limited to broad, indirect age ranges. Interbedded volcanic tuffs can provide relatively accurate 'indirect' ages, but such ages are scarce and consequently our correlation and understanding of Oman's oldest rocks are based on limited data. An emerging methodology using SHRIMP (Sensitive High Resolution Ion Microprobe) directly samples and dates early diagenetic phosphatic cements giving a relatively well-constrained approximate age of deposition. One of the most useful earliest diagenetic cements in siliciclastics is xenotime, which forms overgrowths on detrital zircons. Previous studies have suggested that xenotime overgrowths occur in up to 50% of siliciclastics, irrespective of age, grain size or depositional environment. A trial study on the Haima and Huqf supergroups has now investigated almost 100 samples from various stratigraphic levels. Subsurface samples have yet to yield sufficiently large overgrowths (over 10 microns in size) to allow SHRIMP analysis, and further investigation is required to accurately predict good xenotime occurrence in the Omani subsurface. However, a much smaller surface sample set has yielded key data on the age of the Amdeh Formation in North Oman. An age of 445 ± 9 Ma suggests a latest Ordovician age and probable Hasirah Formation equivalence for the upper part of the Amdeh Formation. Such results prompt the need for a major rethink of subsurface-to-surface correlations (e.g. mapping reservoir facies across the basin).

Sequence stratigraphy of the Shu'aiba-Hawar (Biyadh) tectono-stratigraphic sequence: initiation, development, and demise of a carbonate platform in a siliciclastic-dominated setting

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Well-log and core data from Qatar and the Arabian Peninsula have been used to identify and evaluate the Lower Cretaceous Shu'aiba-Hawar (Biyadh) tectono-stratigraphic sequence. Consistent with tectono-stratigraphic terminology, the Shu'aiba-Hawar (Biyadh) sequence is bounded by prominent, regional unconformities. Between these unconformities, the sequence is a distinctive three-part succession of deposits that begins with siliciclastics and ends with carbonates. The initial, siliciclastic lowstand phase of deposition is characterized by thick fluvial sandstones typical of the Biyadh. These deposits transition upward into marginal marine deposits, ultimately grading into marine shales that characterize the Hawar. An abrupt shift from siliciclastic to carbonate deposition is recorded by transgressive carbonates that formed a relatively thin but laterally extensive ramp referred to as the Lower Shu'aiba Platform. The subsequent highstand phase of carbonate deposition was strongly influenced by the development of intrashelf basins. Within the intrashelf basins, the highstand is marked by thin basinal carbonate, while discrete, relatively thick carbonate platforms referred to as the Upper Shu'aiba Platform were developed along their margins. Carbonate deposition was terminated by tectonic tilting that uplifted the northeastern part of the platform while generating subsidence in the southwestern part. Subsequently, much of the uplifted platform in the northeast was removed

by erosion. The southwestern region was buried by the overlying, siliciclastic wedge that onlaps and thins onto the uplifted portion of the platform. This unconformity surface marks the upper extent of the Shu'aiba-Hawar (Biyadh) tectono-stratigraphic sequence.

Lag time in the sedimentary record at Bar Al Hikman: Part 1 – predominance of reworked material in the modern carbonate system

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The Bar Al Hikman sedimentary system is developed in shallow water, and under high energy, arid, southwest monsoonal climatic conditions. The "carbonate factory" is dominated by coral carpets as opposed to reefs, with a large component of molluscan and foraminiferal shell debris. Heavy micritization and abrasion of grains, strong obliteration of primary grain morphologies, and reworking of composite, early cemented grains within the modern sediment dominates assemblages, compared to the amount of fresh coral, molluscan or foraminiferal material. This indicates prolonged, perhaps multiphase reworking of modern sediment, and admixture of older grains to the present-day carbonate production. Surprisingly, in spite of the strong abrasion, only extremely minor amounts of carbonate mud have been found. High resolution satellite images clearly show the patterns and distribution of older geomorphic features such as beach ridges, lagoons, and littoral bars that have accreted seawards. These older features are truncated by the present-day coast, with its array of littoral environments. Uranium series dating of coral fragments from both older and younger features gives ages ranging between 600 and 1,200 years with error margins of less than 100 years. The modern carbonate system is thus seen to be at a pause in the seaward progression of littoral deposits through accretion, while undergoing a phase of reworking of slightly older deposits. This trend may have been caused by a slight downward shift in relative sea-level. Further age-dating should reveal whether the accretion of previous deposits was possibly linked with higher sedimentation rates, during a slightly higher stand of sea-level.

Lag time in the sedimentary record at Bar Al Hikman: Part 2 – constraints on modern analogs for carbonate geobodies in Cretaceous reservoir models

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Carbonate sediment of Bar Al Hikman indicates considerable reworking over long periods of time. Present-day geomorphic features are shown to be predominantly built by material cannibalized from earlier geobodies at least several hundred, and up to more than 1,000 years old. The modern geomorphic features such as beach ridges, lagoons, dune fields, and sand bars cannibalize older geomorphic features and are composed of sediments with strongly micritized, abraded grain populations, which have lost many primary biological or morphological features. Such admixtures and redistribution of older and younger grain assemblages, would not normally be expected among component grains from carbonate high-energy environments, where pristine skeletal grains are considered more to be the norm.

Geometrical attributes of carbonate geobodies for reservoir models are derived from the sedimentary textures and structures from cores, as well as from modern and ancient analogs. The "marginal" coral environments of Bar Al Hikman, with coral carpets as opposed to reefs, may provide a reasonable analog for carpets of Cretaceous rudists and the depositional environments of carbonate sands around them. Geobodies that compose Cretaceous reservoirs in the subsurface, identified from grain populations, may be misidentified if such admixing, reworking and redistribution of older grain populations into younger geomorphic features is not taken into account. Geobodies laid down as geomorphic features such as channels, beach spits, and lagoons, may be recognized with difficulty when relying on classic analogs characterized by pristine skeletal and non-skeletal grains such as the Bahamas, Belize, and the Great Barrier Reef.

Play fairway development within highstand and lowstand platform systems in the Late Cretaceous of Northern Arabia

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Deeper water conditions were established across most of northern Arabia during the Late Cretaceous (Turonian-Maastrichtian) at the same time as the opening of deep transtensional basins such as Sinjar, Anah, Euphrates, and Azraq. Stratigraphies show two distinct divisions; a paleohigh, shallow-water dominated stratigraphy; and a paleolow, deeper-water dominated stratigraphy. Paleohigh stratigraphies are dominated by shallow-water carbonate platform/sabkha-salina systems. The main and extensive shelf system was developed to the southwest, but towards the Zagros margin, platforms are present but are often isolated. Deeper-water sediments that represent maximum flooding surfaces are thin and are dominated by calcisphaerulids ('oligostegina'). Truly deep-water sediments rich in a globotruncanid fauna dominate paleolow stratigraphies. During lowstands, there was abrupt establishment of carbonate platforms (e.g. the Lopha Limestone and Emam Hasan members of Iran; the Hartha limestone in the Anah Graben) and there

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was localized input of siliciclastics and olistoliths (e.g. in Jebel Abd El Aziz, the Abba-1 well and in the Azraq Graben) whilst locally, volcanics and evaporites have been recorded (e.g. in the Euphrates and Azraq grabens).

This stratigraphic interval has not been economically significant, despite some small production from fields in the Najmah-Qaiyarah area, the Massive Limestone of northeastern Syria, and small fields in southeastern Turkey. One reason is that the majority of the exploration objectives have historically been surface anticlines that are often inversions of half grabens of Late Cretaceous age, which tend to find the basinal rather than shelf facies, as seen in surface exposures of the Abd-el Aziz anticline in northeastern Syria, and the Jabal Sinjar exposures in northwest Iraq. Wells targeted at paleohighs (often modern-day synclines) would be expected to encounter a greater degree of reservoir facies development but run the risk of lateral seal failure and possible trap/topseal/charge problems, whilst lowstand platforms in the shallower basinal areas may offer an ideal combination of reservoir within valid and sealed traps.

Multidisciplinary biofacies analysis of the Khafji and Safaniya members of the Wasia Formation (Cretaceous) of Saudi Arabia

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Conventional biostratigraphy based on palynology and nannofossils provides broadly spaced datums for age control within the Early Cretaceous Aptian-Albian deltaic sequences represented by the Khafji and Safaniya members of the Wasia Formation in Saudi Arabia. Higher resolution stratigraphy is achieved by using multidisciplinary biofacies that contribute to the recognition of higher-order marine flooding events, associated with reservoirs of the world's largest offshore oilfield. Integration with sedimentology is an ongoing part of this project. The intervals between biostratigraphic datums based on the appearances of elaterate palynomorphs (late Albian), pollen, dinoflagellate cysts and selected nannofossil control (late Albian and Aptian) are characterized by diversity/abundance peaks of dinoflagellate cysts, fresh water algae, foraminifera, coccolith and ascidian spicule nannofossils.

Benthic agglutinating foraminifera define the upper and lower estuarine and marine settings. This control has been developed from Recent assemblages from the Sedili River, Malaysia, where foraminiferal assemblages were calibrated to ebb and flood salinities from the South China Sea to 32 km upstream. These Recent assemblages form the basis for understanding paleoecology of *Trochammina*, *Ammobaculites* and *Orbitolina* biofacies of the Khafji and Safaniya members. Dinocysts also show similar patterns to the foraminifera responding to salinity, of which *Subtilisphaera* dominates brackish environments with assemblages diversifying with increasing salinity. Pteridophyte spores dominate the terrestrial successions. The integrated biofacies display isolated, but distinct, evidence of marine flooding events of variable extent within a depositionally complex thick succession of Khafji and Safaniya deltaic sediments.

Paleoenvironments of the Upper Hanifa in Saudi Arabia

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The Hanifa Formation in Saudi Arabia consists of a succession of carbonates, over 300 ft thick, that were deposited during the Late Jurassic, Oxfordian. It consists of a lower Hawtah Member and an upper Ulayyah Member, of which the Hawtah Member has been dated as "mid" Oxfordian on ammonite evidence and the local extinction of the calcareous nannofossils *Watznaueria manivitiae and Stephanolithion bigotii* together with an influx of *Ellipsagelosphaera britannica*. A late Oxfordian age for the Ulayyah Member is based on the first appearance of the benthonic foraminifera *Alveosepta jacardi*.

A detailed study of the micropaleontology, nannopaleontology, biofacies, sedimentology and wireline log character of the uppermost parts of 35 cored wells distributed across the Kingdom has revealed a variety of depositional environments. The late highstand succession of the formation displays a variety of biofacies and lithotextures, of which the grainiest host the Hanifa Reservoir. These are associated with stromatoporoid banks that developed on the flanks of intrashelf basins, although grain-dominated shoals within the lagoons also present reservoir potential.

A range of paleoenvironments has been determined, based on integrated biofacies and lithofacies that include shallow lagoon packstones and grainstones (foraminiferal dominated), deep lagoon wackestones and packstones (*Clypeina/Pseudoclypeina* dasyclad), stromatoporoid back-bank packstones and grainstones (*Cladocoropsis mirabilis*), stromatoporoid bank crest grainstones and intrashelf basin flank mudstones and wackestones (deep marine foraminifera, triaxon and tetraxon spicules and coccoliths). A map depicting these paleoenvironments, albeit in need of refinement from additional data points, reveals regions where sediments with potential reservoir fabric may have been deposited and therefore potential new exploration plays. Their juxtaposition to intrashelf locations where source rock may have accumulated provides exciting new prospects in areas hitherto uninvestigated for hydrocarbon reservoirs.

Biostratigraphy, biofacies, palaeoenvironments, lithostratigraphy and reservoir implications for the Shaqra Group (Jurassic) of Saudi Arabia

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The Jurassic sediments of Saudi Arabia consists predominantly of carbonates that have been termed the Shaqra Group and form a genetically linked succession that may be conveniently considered to represent a depositional supersequence. They overlie the Triassic succession with considerably unconformity, and are overlain by basal Cretaceous sediments with apparent disconformity. Micropalaeontological and nannopalaeontological studies of most of the exposed and subsurface successions of he Marrat, Dhruma, Tuwaiq Mountain, Hanifa, Jubaila and Arab formations, combined with existing ammonoid-based age determination, have refined the ages assigned to the component formations and members. A variety of shallow to deep marine micropalaeontological and nannopalaeontological biofacies from shallow lagoon to deep intrashelf basins, distributed both vertically and laterally, have added significantly to refining paleoenvironmental interpretations and provide significant new data to assist sequence stratigraphic interpretations and resulting hydrocarbon reservoir implications for each formation. The study explains the reasons for the development of the Jurassic reservoir-quality carbonates and their overlying impervious seals. The deep marine biofacies of the Hisyan Member of the Dhruma Formation suggest that it should now be considered as genetically associated with the overlying shallow marine carbonates of the lower Tuwaiq Mountain Formation as its transgressive systems tract, instead of being interpreted as the final member of the underlying Dhruma Formation. It is proposed that the Upper Fadhili Reservoir exists as a highstand unit represented as the Baladiyah member within the lower Tuwaiq Mountain Formation, for which the succeeding transgressive and highstand successions are represented by more argillaceous carbonates mapped as the Maysiyah member and the grainstones of the Daddiyah member respectively. The stratigraphic locations of the Sharar, Faridah, Lower Fadhili, Upper Fadhili, Hadriya, Hanifa and Arab reservoirs can now be explained within a sequence-based structure, in which shallow marine palaeoenvironments of the late highstand systems tracts are considered to be responsible for the grain-dominated reservoir texture.

Stratigraphic relationship of the exposed Wajid, Saq and Qasim formations in western Saudi Arabia: a geochemical and statistical approach

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An extended Neoproterozoic orogenic cycle (Pan-African Orogeny) related to the assembly of Gondwana resulted in the deposition of a massive volume of siliciclastics on the northeastern margin of Gondwana including the Arabian Peninsula. The exposed sections of the lower Paleozoic Wajid Formation in southwestern Saudi Arabia, and the Saq and Qasim formations in northwestern Saudi Arabia appear to have been deposited during this time. However, since these formations are physically separated by hundreds of miles around the eastern edge of the Arabian Shield, the exact stratigraphic relationship between these formations is not clear. Based on the elemental chemistry (major, minor, trace and rare earth elements) this study attempts to determine the relationship between these formations. We found that while the Wajid, Saq and Qasim formations do contain some common elements, there are differences in the bulk elemental chemistry. The bulk elemental chemistry revealed more similarities between the Wajid and Saq formations than that of the Qasim with either one of these formations. Multivariate cluster and factor analyses confirm the findings. Ternary plots of the factored bulk elemental data while showing distinctive compositional differences among these formations also show a distinct trend of transition between the Wajid and Saq formations. No such trend was observed between the Wajid and Qasim formations. Ternary plots of selected trace and rare earth elements including La-Th-Sc, Th-Sc-Zr/10, and Th-Co-Zr/10 suggest several different tectonic settings for the deposition of these formations including the oceanic island to continental island arc, passive and active continental margins.

Sequence stratigraphy, facies associations and petroleum system of Maastrichtian-Selandian-Thanetian-Ypresian and Lutetian successions, from Kurdistan Region, Northeast Iraq

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The Middle Paleocene-Middle Eocene successions in Sulaimanyiah area in Kurdistan region, northeast Iraq is represented by the Selandian Thanetian Kolosh Formation (flysch-siliciclastics) and Sinjar Formation (reefal shallow-marine carbonates and Nummulitic limestone), that are overlain by red molasses siliciclastics of the Gercus Formations. The sequence stratigraphic analysis based on facies associations, planktonic and shallow benthic zones indicates a second-order cycle consisting of six third-order cycles and 10 fourth-order cycles. The Kolosh marine siliciclastics and mixed siliciclastics-carbonates provide a record of two third-order cycles. The first third-order cycle manifests the early to late Selandian TST with a retrogradditional, aggradational stacking pattern. The maximum flooding surface (MFS Pg10) at the Selandian/Thanetian boundary overlies the first cycle. The second-order cycle reflects the early and late HST of aggradational to progradational, as well as PETM events. The Ypresian third-order cycle (TST and HST) reflects synsedimentary tectonic activities, and

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is divided into two fourth-order cycles. The Lutetian third-order cycle was deposited in a carbonate ramp setting, and mostly passes from a retrogradational-aggradational to a progradational stacking pattern. It is subdivided into two fourth-order cycles, passing through start-up, keep-up pace and sudden give-up stages of the carbonates factory. The red molasses indicate a lowstand fan deposit and a fifth-order cycle. The final third-order cycle is represented by the evaporites and carbonates of the Sagerma Formation, and implies climatic changes in the studied area. The Paleocene basin generally shows the progressive convergence of the Arabian and Iranian plates that affected relative sea level, basin geometry, dispersal of siliciclastics and mixed carbonate-siliciclastics sequences, subsidence rates and orogenic activity. The evidence indicates that the Nummulite sequence represents a good reservoir for oil in this region.

Glaciogenic reservoir intervals of North Africa and the Middle East: regional controls on sediment quality

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Reservoir rocks deposited during the Late Ordovician glaciation are productive in Algeria, Libya, and Saudi Arabia, and prospective in Iraq and Syria. Though geometrically complex, models are now available to explain processes of large-scale sediment redistribution/erosion that provide valuable insight into their regional prospectivity. Paleogeographic reconstruction enables the prediction of large, sandy sediment repositories at the ice sheet's margin, forming large "trough-mouth" fans. These were deposited beyond powerfully erosive, approximately 100-km-wide belts of fast-flowing ice (ice streams). The ice streams are considered to be major agents of sediment redistribution across North Africa and Arabia, repeatedly re-occupying pre-existing topographic lows during later phases of glaciation. Therefore, it is suggested that the character of the basin's source area/sediment provenance plays an important role in determining the quality of sands within the trough mouth fans.

At the prospect-scale, the quality of these glaciogenic reservoirs depends upon two key factors: (1) the scale, fill, and distribution of meltwater-related valley systems, coupled with (2) glacio-isostatic re-activation of deep-seated tectonic structures. Around uplifted blocks, fault re-activation not only eroded the reservoirs but also destroyed the source potential of the overlying Lower Silurian shales. The valley systems contain a geometrically predictable, two-stage fill that simply reflects the water depth in which the ice sheets grounded. Post-glacial sediment redistribution of sand produced clean target intervals immediately beneath Silurian "hot shale". A crossborder approach for glaciogenic reservoirs in North Africa and the Middle East is considered essential for understanding depositional controls on their geometric complexity.

A detailed Jurassic sequence stratigraphic framework for the formation of dolomites along southeastern Gotnia shelf margin

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The late Early to Late Jurassic (Pliensbachien-Tithonian) Surmeh Formation was deposited on the southeastern margin of the Gotnia Basin. A detailed sequence stratigraphic model was established by integrating outcrop, subsurface, and biostratigraphic data. In addition, petrographic and fluid inclusion data were used to better understand the dolomitization of these carbonates. The late Early to Late Jurassic of the southern Gotnia Basin is composed of two second-order sequences (Neyriz Formation and Surmeh Formation). Smaller-scale composite sequences are composed of mudstones/wackestones, which shallow upward into oolitic and oncolitic grainstones. Carbonate facies of the late highstand systems tracts of the second-order sequences, as well as the composite sequences, were preferentially cemented-up by early diagenetic meteoric cements. Mudstones and wackestones facies associated with the transgressive and early highstand systems tract of the sequences were preferentially dolomitized during burial with coarse anhedral to euhedral crystals. During burial and early structuration, hydrocarbons migrated into these dolomites. The abundance of petroleum inclusions at the outer rim of euhedral dolomite suggests that major hydrocarbon migration occurred during the later stages of dolomitzation. Continuous dolomitization occurred during deeper burial and formed saddle dolomites. Dolomite inclusions range in temperature from 90–120°C. Toward the end of the dolomitization process parts of the meteoric cemented seals were locally breached. Small-scale fractures and faults might have provided the pathways and small localized dolomite bodies (20 m x 20 m) formed within the lower part of the top seal. In summary, dolomitization is preliminary controlled by permeability contrast of the different facies during burial and is stratigraphically linked to transgressive parts of the depositional sequences.

Evolution of the Mesopotamian basin (Iraq): Campanian to Neogene

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A high-resolution biostratigraphic and sequence-stratigraphic study has been conducted to evaluate the hydrocarbon potential of the Cenozoic succession in the Mesopotamian Basin. Results suggest that the impact of tectonism on sedimentation has been increasingly important since the Campanian. The Turonian to lower Campanian is regionally uniform, widespread, and dominated by deep-shelf to bathyal hemipelagic sediments. The middle Campanian consists of mostly platform carbonates. This

style of deposition is consistent throughout the Middle East, suggesting a predominant eustatic control. From the late Campanian to early Maastrichtian, the platform was submerged and received deep-shelf to shallow-bathyal pelagic/hemipelagic sediments, reflecting the initial rifting of the Euphrates Graben and eustatic sea-level rise. During the middle to late Maastrichtian eustatic sea-level fall, open-marine conditions were restricted to basin center locations, a prominent hiatus developed on the northwest flank, and platform carbonates were deposited as late highstand systems set on the southeast flank of the Mesopotamian Basin.

During major Cenozoic limestone-forming (Thanetian and Lutetian-Bartonian) transgressions, hemipelagic sediments became increasingly restricted to a narrow NE-SW-oriented belt, and the center of open-marine sedimentation shifted towards the northwest. Deep-marine conditions did not reach farther west than Fallujah on the northwest side. The southeast flank of the basin received exclusively marginal-marine carbonates and evaporites for the entire Paleogene, suggesting tectonic uplift to the southeast. In the late Eocene, shallow-marine carbonates prograded simultaneously from the southeast and northwest. This bidirectional progradation led to rapid narrowing and final closure of the Mesopotamian Basin. Since the Oligocene, the remnant basin was filled with evaporites and siliciclastics derived from the Zagros region. Thick siliciclastics with evaporite caps may form stratigraphic traps for oil/gas migrated from the Mesozoic source rocks.

Origin and sedimentary fill of an upper Ordovician (Ashgillian) glacial paleovalley near Tabuk, northwest Saudi Arabia

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The Ordovician Sarah Formation in Saudi Arabia crops out as glacial paleovalleys radiating north and east from the Arabian Shield. One such paleovalley, including a shallow well downdip from the outcrop, demonstrates the mode of formation, and the nature of the depositional fill of these paleovalleys. The feature is flanked by a series of upthrusted blocks of Lower Ordovician sediments and Ashgillian Zarqa diamictites that are oriented strike-parallel to the paleovalley length. Other upthrusted units, striking orthogonal to the axis, are identified along the length of the paleovalley. These glacio-tectonically-induced structures were intimately involved in the formation of the paleovalley: at maximum glacial advance, subglacial ice-surges loaded down into the softened sedimentary substrate, enhancing the resultant elongate trough by lateral thrusting producing lateral 'squeeze' moraines. Subsequent ice-retreat involved minor re-advances that created the cross-valley thrust moraines. These served to 'compartmentalize' the valley feature. This irregular paleovalley floor was draped with extremely coarse-grained, very poorly sorted diamictite, deposited during initial glacial advance. It is overlain by a number of high density gravity flow sandstone facies, exhibiting a hierarchy related to high discharge from a subglacial tunnel valley system. Locally, poorly sorted diamictites also occur. All these sediments represent the products of pulsed glacial retreat, sequentially infilling the thrust-bounded compartments of the paleovalley. The down-valley cores provide evidence for a late stage glacial readvance, with further glacio-tectonic deformation, prior to deposition of a thin shallow marine succession suggestive of a final response to post-glacial isostatic uplift.

The sedimentology and stratigraphic architecture of Late Carboniferous to Early Permian glaciogenic deposits in lower 'Unayzah reservoirs, east-central Saudi Arabia

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In the subsurface of east-central Saudi Arabia, deposition of the Lower 'Unayzah reservoir (C and B members) commenced in Late Carboniferous times during the earliest stages of the late Paleozoic Gondwanan glaciation. The 'Unayzah C comprises quartzose sandstones, laid down upon the so-called Hercynian Unconformity during (probably several) glacial retreat stages, in a glacio-fluvial outwash braidplain depositional setting. These were overridden and deformed during intervening, major glacial readvances, when the sediments were thrust over each other with the construction of push moraines ahead of the advancing ice sheets. The uppermost surface of the 'Unayzah C is a significant unconformity representing the final sub-glacial contact of the Gondwanan ice-sheet. Subsequent (Early Permian) deposits of the 'Unayzah B represent the final glacial retreat phase. They are sharply divided into a lower Unit B1 and an upper Unit B2. Unit B1 is dominated by glaciogenic sediments, including highly deformed material attributed to localized push moraines (and hence representing minor glacial readvances); ice-proximal, subaqueous outwash fans (lacustrine turbidites and massive diamictites); and ice-distal, glaciolacustrine deposits including laminites and stratified diamictites. In contrast, Unit B2 is characterized by fine-grained redbeds, representing low-lying alluvial floodbasin deposits. Embedded within these occur eolian and fluvial sandstones. A significant drainage event is thus implied between Units B1 and B2. The end of 'Unayzah B time is represented in places by paleosol development, indicating a disconformable contact with the overlying 'Unayzah A. This study significantly extends the record of the advance and retreat of the Gondwanan ice sheets in southern Saudi Arabia, phases of which can now confidently be correlated with coeval deposits in Oman.

An early Silurian (Llandovery) graptolite succession from central Saudi Arabia: first documented record of Telychian faunas from the Arabian Peninsula

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Shales from three shallow boreholes penetrating the Early Silurian Qusaiba Member of the Qalibah Formation in central Saudi Arabia contain exquisitely preserved graptolite assemblages of middle Aeronian and early Telychian age. Two partially overlapping boreholes were drilled in the Baq'a area and one near the town of Qusaiba. The oldest graptolites, found in both areas, comprise assemblages including *Campograptus undulatus*?, *Lituigraptus convolutus, Metaclimacograptus bohemicus, Neolagarograptus rickardsi, Normalograptus*? aff. *scalaris*, cf. *Paradiversograptus capillaris, Petalolithus minor, Pristiograptus regularis* sl, *Pseudorthograptus insectiformis, Pseudoretiolites perlatus*? and *Torquigraptus? decipiens*, that identify the middle Aeronian convolutus Biozone. *Monograptus bjerreskovae, Monograptus* ex gr. *marri, Pristiograptus renaudi, Stimulograptus becki* and *S. halli*? indicate the presence of the early Telychian guerichi Biozone in the Baq'a area. The graptolite faunas are generally of low diversity, with most levels yielding between one and three species, but a few contain seven species.

The paleogeography of the depositional basin coupled with the low diversity and the abundance of *Pristiograptus* and *Normalograptus* suggests a marine shelf setting. This is also indicated by the common occurrence of benthic shelly fossils, including gastropods and articulated bivalves. In general, the graptolite faunas are of much lower diversity than contemporaneous more oceanic-influenced marine assemblages from the British Isles and Czech Republic, and probably represent a graptolite biotope of "cratonic invaders". The graptolites display well-preserved details of fusellar banding (growth increments) and perhaps ultrastructure. Damaged rhabdosomes observed at unburrowed levels, however, suggest unusually high rates of graptolite predation in the water column.

Sequence stratigraphy of the Asmari Formation in the Zagros basin (southwest Iran), implication for reservoir porosity prediction

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Three outcrops and two borehole sections of the Asmari Formation were studied. According to petrography and field observations the formation is divided into three parts and comprises five microfacies assemblages as: A (open marine); B (bar/shoal); C (lagoon); E (tidal flat) and F (supratidal). In a sequence stratigraphic framework, the lower Asmari was deposited in highstand system tract (HST), whereas transgressive system tract (TST) started during the deposition of underlying Pabdeh Formation. The transgression reached its highest level (MFS) at the boundary between the Asmari and Pabdeh formations. The HST stage is marked by algal boundstones and the late HST by lagoonal facies (dolomudstone, miliolidae wackstone). Dolomitization increased intercrystalline porosity of the Asmari carbonate reservoir. In the Renu outcrop section only the lower Asmari was deposited, whereas in the Siahgel outcrop section only the middle Asmari was deposited on shale beds of the Pabdeh Formation. The middle Asmari is marked as early HST (algal boundstone) and a late HST is composed of lagoonal facies (miliolidae wackstones and evaporites). This sequence terminated with sandstones with hematite cements that imply a type 1 sequence boundary. In brief, the middle Asmari comprises two HST stages, an LST and a TST. The upper Asmari is only exposed in the Dezful Embayment, and comprises two HSTs and two TSTs; the latter began with echinoderm wackstone microfacies. Early HST sediments are dolomitized lime mudstones whereas late HST sediments are miliolidae wackstone, algal wackstone, ostracod wackstone and pelletoidal grainstone that suggest a lagoonal setting. Dolomitization occurred in the early HST stage and developed porosity of the formation. The sequence boundary is type 2 and no evidence of exposure was observed.

Regional scale seismic interpretation in the Gulf and its implication for the understanding of the Khuff system

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The Permian-Triassic Khuff Formation is a major reservoir in the Middle East Gulf region and contains some of the world's greatest non-associated gas reserves. For this study 130,000 km of 2-D seismic (including 96,000 km of the "Persian Carpet" seismic covering most of the Iranian side of the Gulf) have been interpreted in order to: (1) establish a geotectonic framework for the Khuff system and evaluate the impact of pre-Khuff structuration on Khuff depositional patterns. (2) Assess the post-depositional tectonic evolution at the plate-scale and evaluate its possible impact on structuration, fracturing, stratigraphic architecture and diagenetic evolution, at the production scale. (3) Integrate structural observations and interpretations at the field scale (3-D high-resolution seismic, core data and image log data) with plate-scale features (regional scale seismic interpretation), and propose a tectonic calendar.

The hydrocarbon fields, which are located in different tectonic settings (including salt domes, horsts, folds of different ages, and draping over basement highs), display

a remarkable coherence in structural features across interpretational scales. Hence there is a coherence from structural features identified on cores and image logs, to those of the 3-D high-resolution seismic interpretation, all the way through to structures mapped on the regional seismic at the plate-scale. This coherence of structural interpretations at all observational scales illustrates the importance of a large-scale regional framework to better understand the reservoir-scale structural features, and their possible impact on production.

Depositional environment of the Devonian sediments in the Zagros Basin, southern Iran, and their comparison to the Devonian sediments of Arabian Plate

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A sequence of Devonian clastic sediments (Zakeen Formation) located 103 km north of Bandar Abbas, in southern Iran was studied. The objective of the study is to determine the sedimentary environment of the Zakeen Formation and compare it with sedimentary environment of Arabian Plate Devonian deposits. The entire 155 m thickness of Zakeen Formation was sampled. A total of 168 outcrop sample were collected, and the sedimentary structure and features and geometry of the sand bodies were recorded. Sand grain size was measured under microscope throughout the sequence. Based on this study, the Zakeen Formation was deposited in a siliciclastic shelf. These sediments were deposited in 5 sub-environments: (1) supratidal-high tidal flat, (2) medium tidal flat, (3) low tidal flat, (4) subtidal sand wave, and (5) muddy continental shelf.

Shallow-marine deposits are predominated in the lower half of the Zakeen Formation. Among the shallow-marine facies, cliff-forming sand waves are outstanding. In the upper half of the formation muddy deep-water shelf facies are well developed. From a petroleum geological point of view, the lower part of formation is prospective as a hydrocarbon reservoir. The Zakeen sandstone is cleaner than the Devonian sandstone of Saudi Arabia but the former is more cementated. The depositional environment of the formation is deeper than the equivalent sediments of Devonian in Saudi Arabia (Tawil, Jauf and Jubah formations) that varies from terrestrial to shallow-marine. Whereas the Zakeen Formation has a marine setting, the Saudi Arabia Devonian deposits are mostly terrestrial.

Probable Lower and Middle Unayzah-A eolian outcrops, southwestern Saudi Arabia

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Recent field reconnaissance work in the Wajid area of southwestern Saudi Arabia has identified a sequence of sandstones stratigraphically located between early Permian Juwayl Formation diamictites and upper Permian Khuff Formation. The sequence is interpreted as the early to middle Permian Unayzah-A equivalent eolian sandstones. Recognition of this thin (5–10 m) interval is critical in expanding the southwestern limit of the existing Unayzah-A reservoir dune fairway established in Central and Eastern Saudi Arabia.

Biostratigraphic and sedimentological modeling of the upper Shu'aiba Formation in north Oman: the key to effective correlation

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The Aptian Shu'aiba Formation is the subject of continued exploration in North Oman, with an ongoing Petroleum Development of Oman (PDO) drilling campaign in the greater Malaan and adjacent area. Current geological studies are focusing on the integration of seismic mapping, sedimentology, biostratigraphy and isotopic analysis. Seismic mapping has identified a series of clinoform geometries within the Upper Shu'aiba. Well-based correlations support this clinoform model, previously this work involved log-trace matching with limited lithological input, and the model required calibration with other well-generated datasets. Several similar clinoform-like shoal trends can be recognized in the area. Confidence in interpretation levels varies across the area and a well-based confirmation of the clinoform model can provide support for the validity of the exploration play concept.

In order to improve the understanding of these structures and the detailed internal reservoir architecture, biostratigraphic analysis has been undertaken using core samples primarily, together with ditch cuttings. Biostratigraphic analysis employs the integration of quantitative micropaleontological data (thin section and routine) together with nannofossil data. Significant lateral and vertical assemblage changes are evident between and within reservoir units, representing a range of paleoenvironments from lagoonal to open-marine. The frequency of biofacies and depositional cycles is dependant primarily on sampling interval. Small-scale changes in biofacies composition should allow for high-frequency cycle recognition. The recognition of discrete biofacies, related to specific depositional environments, has been used to fingerprint carbonate/mud cycles within the Upper Shu'aiba. Integration of these data with sedimentological and seismic information enables enhanced stratigraphic resolution of the reservoir units, improved inter-well correlation and reservoir modeling.

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Proterozoic succession of south Oman: new insights

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The Proterozoic series truncated by the pre-Mesozoic unconformity is exposed in south Oman in three different areas: (1) in the Mirbat basin, the Proterozoic Mirbat Formation rests over basement; (2) south-westward along the coast the Proterozoic Al Hotah Formation outcrop in the type locality; and (3) to the north of the Salalah harbor. The age of the Mirbat Formation was until recently attributed to the Late Carboniferous. However, carbon isotope stratigraphy led to reinterpret the series as Late Proterozoic. In the Mirbat basin, the Mirbat Formation is subdivided into three members. The lower member is a glaciogenic series related to the Sturtian Glacial event. The middle member consists of turbidite channels. The upper member shows a remarkable slope to shelfal succession including numerous third-order depositional sequences with well-defined, storm-dominated sharp base shoreface. The uppermost layer of the upper member is a diamictite related to the Marinoan Glacial events. To the southwest, a km-thick clastic series (Al Hotah Formation) ascribed to the Proterozoic starts with turbidites grading into stacked shelfal sandstones. The facies are different and difficult to correlate with those of the upper Mirbat member. Although attributed to the Proterozoic, the Al Hota Formation seems to be older than the Mirbat Formation. It is deformed, and truncated by the pre-Mesozoic unconformity. The deformation increases toward the southwest in the Al Hotah type locality where this deep-water series is intensively folded. Preliminary comparison with subsurface data and second-order Proterozoic stratigraphic cycles suggests that the Al Hotah Formation could be the oldest series deposited over the Arabian Plate.

Using elemental chemostratigraphy for improved zonation and correlation of the Cretaceous Mishrif carbonate reservoir, Arabian Gulf

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The Cenomanian Mishrif carbonate reservoir consists almost entirely of limestone (grainstones, packstones and wackestones) with little interbedded shale or dolomitization. The top of the reservoir is variably truncated by a significant unconformity. As the biostratigraphic zonation of the Mishrif is hampered by a lack of high-resolution faunal assemblages, a chemostratigraphic study was undertaken in three cored wells to better characterize this important reservoir. Cored well A, located downdip on the field structure, has the most complete Mishrif section. Four ascending chemostratigraphic units (M-1 through M-4) were recognized, primarily from changes in MnO, Sr, Ca/Sr, and Sr/Y with depth, and various crossplots. In addition, each unit can be subdivided, based on changes in Ca, Sr, Mn, Mg, P, Y, Fe, Al, Si, and K. These reflect subtle changes, both primary and diagenetic, in carbonate, phosphate, and siliciclastic content. The Mishrif zonation from well A can be readily correlated to well B, higher on the structure's flank, and to well C, on the structure's crest. Episodes of localized erosion or non-deposition are suggested by the absence of two chemostratigraphic subunits in well B. All cored sections display a karsted and mineralized alteration zone (unit M-T) related to the top-Mishrif unconformity. This zone extends downward as much as 16 ft below the unconformity surface, and is best developed in the crestal well C, where all of unit M-4 is missing (eroded?). The improved, high-resolution, core-based zonation of the Mishrif was extended over a wider area by analyzing cutting samples from two sub-vertical wells and one horizontal well. While the resolution with cuttings was predictably not as sharp, chemostratigraphic correlations to the subunit level could still be made with some confidence.

Sequence stratigraphy of the Carboniferous-Permian Unayzah reservoir in Saudi Arabia and its correlation with Oman

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The Unayzah Reservoir occurs in the thick Carboniferous-Permian siliciclastic sequences of Saudi Arabia. It is a large-scale heterogeneous reservoir, extending between the base of the Khuff Formation and the Pre-Haradh (Hercynian) unconformity. It is divided into four formations, which are separated by regional unconformities. The Haradh Formation in the lower part consists of fine- to coarse-grained, well-sorted but silica-cemented sandstone. It is formed as braid delta and cold desert eolianites during glaciation. It correlates with the Al-Khlata Formation in Oman. The Jawb Formation consists of dark gray shale, sandstone, and diamictite facies deposited in a marine and marginal marine environments during the deglaciation period. It correlates with the Rahab Shale and the Basal Sandstone in Oman. The Ruhaiya Formation (or the Ruhaiya Limestone) exposed in the Wajid Outcrop Belt is Early Artinskian in age, correlates with the Haushi Limestone in Oman, and represents the Maximum Flooding Surface. The Unayzah Formation occurs between the Pre-Unayzah and Pre-Ash-Shiqqah unconformities. It is a typical red-bed facies, consisting of conglomerate, sandstone, mudstone, siltstone, nodular anhydrite and caliche facies. It was deposited in alluvial fan, braided stream, hot desert eolian, and playa systems under arid- to semiarid climate. It correlates with the Middle, and the lower part of the Upper Gharif Formation in Oman. The Ash-Shiqqah Formation forms the upper part of the Unayzah Reservoir, overlain by the Khuff Carbonates.

It is divided into the lower and upper members through a type-1 sequence boundary (break-up unconformity). The lower Member is transgressive on the Unayzah Formation, and consists of interbedded shallow-marine sandstone and coastal plain shale facies. It correlates with the upper part of the Upper Gharif Formation. The Upper Member consists of conglomerate (lag), sandstone, and carbonaceous shale facies, deposited as incised valleys and associated lowstand deltas. It correlates with the Basal Khuff Clastics in Oman. The Maximum Flooding Surface at the Base Khuff D carbonates in Saudi Arabia and in Oman represents the same stratigraphic surface.

Sedimentology of the incised valleys and their associated lowstand deltaic sequences in the Ash-Shiqqah Formation of the Unayzah Reservoir, Saudi Arabia

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The incised valleys and their associated lowstand deltaic sequences occur in the Permian Ash-Shiqqah Formation of the Unayzah Reservoir, and provide significant reserves of Arabian super light oil, condensate and gas in Saudi Arabia. The incised valley-fill sequence, more than 37 km wide, is fully exposed in the Qasim area. Fluvial-dominated, estuarine-dominated, and tide-dominated lithofacies associations were identified in various parts of the valley-fill. In the subsurface, four incised valley-belts, extending in NE-SW directions, were encountered and mapped in many producing fields. The valleys cut into the Arabian Shield in the west and become wider and deeper towards the east. The base of the valleys represents an erosional unconformity surface. Tectonic uplift in the Arabian Shield was a significant factor for the high gradient. During this time, existing fluvial systems extended their courses and carried huge amounts of very coarse-grained sediments beyond the shelf edge into the basin. Uplifting also continued during the following sea-level rise and kept providing fresh coarse-grained sandstones. The valley-fill is a fining-upward sequence that is more than 100 ft thick, consisting of fluvial-dominated, estuarine-dominated, and marine-dominated facies associations.

The lowstand deltaic sequences are always encountered at the mouth of their genetically associated incised valleys. Their thickness may reach up to 585 ft, and covers large areas in Central Saudi Arabia. They generally rest directly on the erosional unconformity surface. They consist of one single coarsening- and thickening-upward, lobate-shaped progradational sequence. Basin floor-fan sediments, less than 50 ft thick, were sometimes found below this section. The incised valleys and lowstand deltaic sequences are overlain conformably by thin shallow-marine sediments of transgressive systems tract. They are conformably overlain by the Khuff Formation, representing the highstand system tract.

Arabian Plate sequence stratigraphy: potential consequences for global chronostratigraphy

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Sharland et al. (2001, 2004) have described 65 Phanerozoic maximum flooding surfaces (MFS) that can be identified and correlated across the Arabian Plate, providing a framework for understanding the regional lithostratigraphy and placing key petroleum elements into a predictive sequence stratigraphic model. Ongoing work has demonstrated that these MFS, plus many newly identified additional MFS, can be readily identified in the coeval stratigraphy of North Africa, along with intervening sequence boundaries (SB) and their correlative conformities. It can be demonstrated across the region that the majority of these surfaces occur within the same biozone, and are coincident with surfaces independently recognized in other (largely passive margin) sedimentary basins (e.g. NW Europe, West Siberia and Baltica). This suggests that there is strong eustatic control on sedimentary sequences and that a global sequence stratigraphic model is a reality. The chronostratigraphy community is currently in the process of defining GSSPs (Global boundary Stratotype Sections and Points) for each Phanerozoic stage. At the time of writing 46 of the 90+ stages have a ratified GSSP. Of these, a number continue to be the cause of dispute, and many of those yet-to-be-defined appear problematic. Since the evidence for eustatic control on sedimentation is strong, then sequence stratigraphic concepts can assist the definition of GSSPs. Because MFS and SBs relate to changing sea-level, they have associated changes in fossil assemblages making them readily recognizable and correlatable. Therefore SBs provide “natural” boundaries to stages. Indeed many stage boundaries, as currently perceived from their historical stratotypes, lie close to sequence boundaries dated in their correlative conformity position in a basin. It is now possible to envisage the conjugation of the global sequence stratigraphic model with the chronostratigraphic timescale.

Sequence chronostratigraphy: issues and examples

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Work by Neftex has demonstrated that many of the MFS and SBs identified by Sharland et al. (2001, 2004), plus many newly identified additional MFS and SBs, can be identified and correlated across the coeval stratigraphy of the Middle East and North Africa, and indeed also occur on other continental plates within the same biozone. It is clear to us that a global sequence stratigraphic model is a reality. This proprietary work has thrown up some

interesting relationships between our evolving sequence stratigraphic model and the chronostratigraphic timescale. The purpose of this poster is to discuss the key issues relating to the identification and correlation of MFS, SBs and GSSPs and to present examples highlighting these issues. There are clear benefits to chronostratigraphers in understanding the detailed sequence stratigraphic heartbeat, and to sequence stratigraphers in understanding the relationship of sequence stratigraphy to GSSPs. Such an approach links the biostratigraphic rigor of GSSP definition with the understanding of stratigraphic geometries in the industry through seismic interpretation and well log correlations. Although much work remains to be done, it is possible to envisage the conjugation of the global sequence stratigraphic model with the chronostratigraphic timescale.

Strontium, oxygen and carbon isotopes to date and investigate Permian events in Arabia

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Dating of important Permian events in the Arabian Peninsula is difficult due to imprecision of, and inconsistency between, different biostratigraphic disciplines. Absolute radio-isotopic dating cannot be applied because the succession lacks volcanics. To resolve this, isotopic ratios of brachiopod shells from the Saiwan Formation, Haushi Limestone and Khuff Formation of Oman, and from the Khuff Formation of Saudi Arabia were studied to: (1) resolve conflicting biostratigraphic ages suggested for the Saiwan Formation and the Haushi Limestone; (2) to understand, through integration of sedimentary organic $\delta^{13}C$ data, paleoclimatic change after the Carboniferous-Permian glaciation; and (3) to obtain a precise age for the base of the Khuff Formation in Saudi Arabia and Oman, and therefore investigate the degree of diachroneity of the Khuff transgression on the Arabian Platform. SEM ultrastructural analyses of brachiopods indicate they are pristine and capable of recording the original seawater signal, and $\delta^{13}C$ and $\delta^{18}O$ suggest normal Permian seawater within the accepted range. $^{87}Sr/^{86}Sr$ ratios from the Saiwan brachiopods indicate an age range of Sakmarian-Artinskian. Microfacies, paleoecology, $\delta^{13}C$ and $\delta^{18}O$ from shells, palynology, and sedimentary organic $\delta^{13}C$ all indicate climate change through the Lower Permian succession. $^{87}Sr/^{86}Sr$ ratios from brachiopods near the base of the Oman Khuff Formation confirm a Wordian age, as suggested by previous biostratigraphic work. Those from the Saudi Arabian Khuff Formation (Midhnab Member) indicate a Capitanian-Wuchiapingian age in agreement with the presence of the conodont *Jinogondolella* cf. *altaduensis*, but in conflict with other biostratigraphic age dates.

Depositional environment and sea-level history of the Abu Dhabi sabkha in the vicinity of Al-Qanatir Island, United Arab Emirates

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The giant coastal sabkhas of the United Arab Emirates are one of the few areas of the world where the geoscientist can observe the interplay between siliciclastic, carbonate and evaporite sedimentation. Supratidal (upper, middle and lower sabkha) to intertidal (upper, middle, and lower intertidal microbial mat), and lowermost intertidal to shallow subtidal (peloid-skeletal tidal-flat) environments were studied along the Abu Dhabi coastline in the vicinity of Al-Qanatir Island. Age-dating results from samples of nine hardgrounds, three microbial mats, and one anhydrite layer show an age range from about 3,500 years before present (upper sabkha environment: hardground) to about 900 years before present (intertidal environment: microbial mat); thereby supporting the seaward progradation of the facies belts since the last Flandrian sea-level highstand (formation of Cerithid gastropod stranded beach ridges) about 4,500 years before present. Significant amounts of dolomite (fine-crystalline, subhedral to euhedral dolomite rhombs embedded in organic matter) were found within subsurface crinkly-laminated microbial mats. Sulfate-reducing bacteria of the microbial mat environment are interpreted to be responsible for the precipitation of dolomite.

The distribution of radiocarbon ages indicates a complex stratigraphic history in which chronostratigraphic time lines clearly cross-cut depositional lithofacies and diagenetic boundaries. This is significant in that depositional lithofacies and diagenetic facies are commonly used in ramp settings to correlate continuous sedimentary packages. Careful attention to chronostratigraphic relationships elucidates complex stratal geometries that may have been previously missed. Furthermore, the analysis of modern analogs is one of the few means by which high-resolution spatial complexity of stratigraphic systems can be described. If the horizontal dimensions of facies belts are less than the typical well spacing, modern analogs, together with seismic and production data help to construct realistic geologic and simulation models of subsurface reservoirs.

AD

Depositional environment and reservoir characteristics of lower and upper Dibsiyah Member (Wajid Sandstone), southwest Saudi Arabia

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The Cambrian-Ordovician Dibsiyah Member of Wajid Sandstone at Wadi Ad Dawasir, southwest Saudi Arabia, has its subsurface equivalent to the east in the Rub' Al-Khali Basin, which is a frontier hydrocarbon province in southeast Saudi Arabia. This study characterizes the Dibsiyah Member by integrating facies and architectural analysis, petrographic and petrophysical (porosity, permeability) as well as geostatistical analysis. The Lower Dibsiyah Unit consists of medium to very coarse, moderately to poorly sorted sandstone facies. The recognized facies include channel massive to trough cross-bedded micro conglomerate, trough cross-bedded, planner cross-bedded and massive sandstone facies and minor massive to laminated mudstones, which occur as thin interbeds or drapes. These facies suggest deposition within channel and bar complexes of a bed-load dominated low-sinuosity stream. The Upper Dibsiyah Unit consists of fine to medium, pebbly moderately to well-sorted massive to cross-bedded conglomerate, trough cross-bedded, planner cross-bedded and horizontally bedded and herring-bone cross-bedded sandstone facies. Massive mudstone and laminated shale are subordinate. Skolithos-rich horizons dominate the sandy facies in the upper unit. These facies suggest deposition within shallow-marine environment. Both Dibsiyah units show variations in their texture, composition, sandstone body thicknesses, geometry, stacking patterns and vertical and lateral connectivity. These variations in macro to micro scale characteristics indicate both depositional and post-depositional controls. The results of the outcrop study are of considerable use in understanding and predicting the reservoir properties of the Dibsiyah's subsurface equivalent in the Rub' Al-Khali Basin.

Rock-type-based reservoir modeling in the upper Sarvak Formation carbonates: a case study, Southwest Iran

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The upper part of the Cretaceous Sarvak Formation in southwest Iran contains a complex reservoir unit because of heterogeneity by depositional facies and diagenesis. A facies analysis and sequence stratigraphic study demonstrated that this interval is a layer cake without lateral facies change. Core and thin section studies, supported with well log data, were used to recognize facies, diagenesis, rock types and the porosity-permeability distribution. Lagoonal and open-marine deposits were classified into four rock types, based on dissolution and the resulting vuggy porosity. Barrier deposits including shoal and reef-related facies were classified into three rock types, according to cementation volume. An intrashelf basin was used to characterize one non-reservoir rock type. The rock types were modeled by different scenarios (facies modeling tools), i.e. composites and belts (object- and pixel-based algorithms) to capture heterogeneity and uncertainty. The rock-type models were later used as constraints for modeling petrophysical properties.

The petrophysical data were transformed to a Gaussian distribution with zero mean and standard division 1.0 after removing trends. Co-simulation was also done for the transformed data, i.e. porosity and permeability. The Gaussian distributions are used as input to the algorithm simulating the different petrophysical properties. This was followed by variogram modeling for each rock type to determine the variability (or similarity) of the properties as a function of the distance between the data points. The results show facies and diagenetic processes control the reservoir properties. The model reveals that the vertical changes in rock types are a function of depositional facies and diagenesis, while the lateral variation is mainly controlled by diagenesis at the same facies. The results of the rock type-based modeling will be used for simulation and flow performance evaluation.

The Khuff Formation: outcrop analogues from the Oman Mountains

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The Khuff Formation is superbly exposed in the central and northern Oman Mountains. However, the outcrops are poorly known and they remain largely undocumented in the public domain. This neglect is remarkable given that these are amongst the best and most accessible exposures of the world's largest gas reservoir (the Khuff contains 15–20% of global non-associated gas reserves). The aim of this talk is to discuss selected features of the Khuff as seen in four outcrop reference sections. The issues focused on include:

(1) Cycle stacking patterns and sequence architecture, (2) Characterisation of systems tracts, (3) The mid-Khuff lowstand, (4) Base-K2 drowning, (5) Evidence for end-Khuff tectonism, (6) End-Khuff grainstones - a topmost Khuff sweet zone, and (7) Biostratigraphic resolution - potential for an integrated biozonation scheme.

This series of vignettes demonstrates the value of fieldwork, and will hopefully serve as a stimulus for further outcrop studies.

Sequence stratigraphy, a predictive tool to understand the interplay between basin tectonics and sedimentation: a case study from Muglad Basin, Sudan

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The Muglad and Melut basins represent the major rift basins in Sudan. These basins meet at an angle of about 45° in southern Sudan and terminate against the Central African Shear Zone (CASZ). From Late Jurassic-Early Cretaceous to Present, a complex system of connected rifts extending from Nigeria to Kenya, has recorded the complex history of South American, African, and Arabic Plate interactions. These rifts recorded very thick sedimentation in the Muglad Basin, essentially during the Cretaceous and Cenozoic times. The sequence stratigraphic analysis of these sediments, integrating biostratigraphy and sedimentological studies, led to an understanding of the operative processes during the sedimentation and the control of tectonics on sedimentation. These studies identified three mega-rift cycles, each followed by thermal contraction and a sag phase. During the rift phases, typical argillaceous facies were deposited mainly in a lacustrine environment giving rise to rich source rock, while during the sag phase dominantly arenaceous facies were deposited thus providing reservoir and seal facies. The unconformity associated with sub aerial exposure of these reservoir facies moderated the porosity in meteoric and vadose zones, while the proximity of provenance was detrimental to the quality of reservoir facies. Tectonics and syn-sedimentary faulting provided the much sought-after accommodation space. The juxtaposition of porous horizons against a footwall seal is the most favored structural style. Para sequence analysis of well logs indicated various reworked horizons encountered in wells on footwall. The erratic occurrence of older flora, with systematic occurrence of younger floral assemblage, created confusion in establishing the stratigraphy at well level. However, by correlating Para sequences and building a sequence stratigraphic model, authors provided a lead to understand interplay of tectonics and sedimentation and demarcated areas for extensive exploration to target stratigraphic and subtle traps.

Evolution of the Cretaceous sedimentation patterns in the Zagros, Southwest Iran

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An integrated biostratigraphic, chemostratigraphic and sequence stratigraphic study of the Cretaceous mixed carbonate/siliciclastic system in the Zagros of southwest Iran (Lurestan, Khuzestan, Fars and offshore) has resulted in a third-order sequence chronostratigraphic framework with a resolution of 2–3 My. This chronostratigraphic framework allowed us to unravel the complex Cretaceous history, which is characterized by the alternation of carbonate platforms and intrashelf basins, periods of siliciclastic influx, shifting depocenters and major basin re-organization. This sedimentation pattern is represented in a three-dimensional geomodel, constructed with detailed paleogeographical and isopach maps, and infilled with a stratigraphic forward-modeling program.

Extensive sedimentological work was conducted on the excellent outcrops of the Cretaceous rocks in the Zagros Mountains in southwest Iran, in combination with biostratigraphic work on ammonites, pelagic foraminifera and orbitolinids, and Carbon and Oxygen isotope curves. The analyses resulted in the definition of 15 third-order sequence boundaries and corresponding flooding surfaces in an area of 30,000 sq km. This high-resolution chronostratigraphic framework allowed us to reevaluate the stratigraphic relationships between the major rock units, which vary in thickness from several thousand meters in Lurestan to several hundred meters in Fars. A general subdivision of the Cretaceous succession into four stages is proposed, each of them characterized by a specific: (1) ecosystem of carbonate producing organisms; (2) architecture of the carbonate systems; (3) tectonic context; and (4) paleogeography. In order to test the coherency of our interpretations a 3-dimensional geomodel was constructed, and different infill scenarios were tested with stratigraphic forward-modeling software.

Quantitative stratigraphy in the Oligocene-early Miocene carbonate system in the Dezful Embayment (southwest Iran): an integrated chemostratigraphic, biostratigraphic and sequence stratigraphic analysis

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The Oligocene-early Miocene Asmari and Pabdeh formations in the Dezful Embayment of southwest Iran contain some of the largest hydrocarbon reserves in Iran. The sedimentary system of this interval is, however, very complex, consisting of a mixture of carbonate, siliciclastic, and evaporitic sediments further complicated by a diagenetic overprint. In order to construct a predictive geological model for this system an effort has been made to develop a basin-wide, high-resolution chronostratigraphic framework. An integrated chemostratigraphic, biostratigraphic and sequence stratigraphic approach was applied to define and apply at the basin scale. A total of eleven third-order sequence boundaries and maximum flooding surfaces were identified. The high-

resolution chronostratigraphic framework (resolution of 1 to 2 My) is primarily constraint by Sr-isotope data that were systematically measured in wells and outcrops. The ranges of index fossils were subsequently calibrated to this dataset, which led to a revision of the Chattian/Aquitanian boundary. In addition, the Sr-isotope curves built along the sections identified: (1) stratigraphic gaps and their duration in the platform setting, and (2) platform margin wedges that imply high sedimentation rates. The established chronostratigraphic framework will allow us to construct much more predictive geological models of the Asmari petroleum system, not only for the sedimentary heterogeneities (facies, discontinuities) within these fields, but also at a more regional scale for a more effective comparison between fields.

Potential and pitfalls of outcrop analogue studies: a comparative analysis of Permian carbonates from the Arabian Peninsula

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Published paleogeographic reconstructions agree that the middle to late Permian shelf of the Arabian Platform was an area with a hot and arid climate. Evaporite-rich deposits with a composition similar to modern sabkhas of the Arabian Gulf, as well as Permian carbonates locally enriched in calcareous algae, provide unequivocal evidence that the sediments of the formation indicate the presence of a vast tropical sea, covering large areas of the Middle East. With this concept in mind, one might come-up with the hypothesis that all middle to late Permian outcrops of central Saudi Arabia, the Oman Mountains and the interior of Oman are suitable analogues for the interpretation of the Khuff Formation in the subsurface. One might further speculate that sea-level change was the main controlling factor of carbonate production and platform development. By comparison of my own and published data, I will show that the eastern part of the Arabian Plate was dominated by non-tropical carbonates to a certain extent, indicating upwelling of nutrient-rich or probably temperate sea-water. In particular the outcrops of the Khuff Formation in the Haushi and Huqf area significantly differ with respect to sediment structures, sediment composition and diagenesis from contemporaneous sediments of the Arabian Plate. This example does not deny that outcrop analogue studies provide useful information below the seismic scale. However, existing paleoceanographic data should be considered prior to the start of a study in order to avoid inadequate models.