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Selected Abstracts from ICGAPOM
January 7–9, 2012, Sultanate of Oman

The *International Conference on the Geology of the Arabian Plate and the Oman Mountains* (ICGAPOM) was held on January 7–9, 2012. It was organized by Sultan Qaboos University (SQU) and held in Muscat, the capital of the Sultanate of Oman. The conference was held twice in the past, in 1990 and 2000. This conference presented the latest developments in Oman and the region across a broad spectrum of Earth-science disciplines, including sedimentary and hard-rock geology, base and precious metals industry, petroleum geology, groundwater, geophysics, and geohazards.

The 2012 conference consisted of several hundred presentations and numerous field trips. The following main themes were covered: the Arabian Plate Lithosphere and Boundaries, the Sedimentary Cover of the Arabian Plate, Hydrocarbon Systems of Arabia, Ophiolite Genesis and the Oman Mountains, and Environment and Water Resources. The objectives of the conference are to provide a forum for presenting recent research on the geologic framework of the Arabian Plate, to encourage the exchange of knowledge, ideas and experiences between scientists regarding the geological evolution of the region and to promote the sustainable development of Arabia. The following abstracts were selected for publication in *GeoArabia* because they are of particular interest to petroleum geoscience readers.

A special publication titled "Tectonic Evolution of the Oman Mountains" will be issued by the Geological Society of London (GSL) mainly based on the conference papers. A previous GSL Special Publication No. 49, "The Geology and Tectonics of the Oman Mountains", was extremely successful and was reprinted into a second edition. This proposed volume seeks to update the geological, geophysical and geochemical data on the greater Oman region. The volume will concentrate on the geology of the Oman Mountains, the foreland region, the salt basins of Central Oman, the Batain Coast and Masirah Ophiolite and the basement complex.

Sedimentology and depositional system of the Late Cretaceous Qahlah Formation, Oman Mountains, Sultanate of Oman

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Late Cretaceous ophiolite obduction over autochthonous shelf carbonates in Oman created isolated peripheral basins along mountain fronts. These basins were filled by sediments derived from the allochthonous sheet and consist dominantly of conglomerate, interbedded with subordinate amounts of coarse sandstone and siltstone. Siliciclastic sequences deposited in the peripheral basins record uplift history, paleo-drainage system and climatic changes associated with uplift of the mountain belts. Localized carbonate rocks characterized by marine fauna found interbedded with the siliciclastic sequences were deposited during occasional marine incursions in some parts of the basins. The sediments belong to the Qahlah Formation of Late Cretaceous age, which is sandwiched between the Semail Ophiolite/Hawasina Group below, and Cretaceous–Paleogene carbonate rocks above.

The Qahlah Formation is 140 m thick at its type locality near Qalhat village (Sur); however, its thickness is highly variable in different parts of the Oman Mountains, ranging from 5 m in parts of the Burayimi area to over 700 m in the Russayl section (Muscat). The formation is characteristically rich with red and green chert derived from the Hawasina Group rocks, ophiolite fragments and small amounts of carbonate clasts. High proportions of chert and ophiolite fragments in the formation suggest rapid erosion of obducted oceanic crust. Clasts in the conglomerates range from subangular to subrounded pebbles to boulders with both grain and matrix (sandstone) support. The conglomerate lithofacies is represented by a number of sublithofacies such as *Matrix supported conglomerate subfacies* (Gms), *Clast-supported conglomerate subfacies* (Gm), *Crudely-stratified conglomerate subfacies* (Gcs), and *Cross-stratified conglomerate subfacies* (Gt and Gp). The sandstone lithofacies is comprised of *Pebbly sandstone subfacies* (Ssp) and *Cross-bedded sandstone subfacies* (Sst). The lithofacies Gms, Gm and Gcs were deposited along the proximal reaches of alluvial fans draining through the uplifted oceanic crust and floor sediments, and underlying platform rocks in the source terrain. The lithofacies Gt, Gp, Ssp and Sst were deposited by channelized flows usually found along the middle and distal reaches of the alluvial fans. Presence of *Loftusia*-bearing carbonate beds and bivalve-bearing conglomerate beds in different sections indicates occasional interruption of alluvial deposition by marine transgressions. The marine transgressions were probably widespread though preserved only in a few places, such as in the Qalhat section near Sur.

Phosphorite regime in the Eastern Mediterranean and its relationship with the northward movement of Arabia

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Phosphorite deposits are widespread in the Eastern Mediterranean countries including Palestine, Jordan, southeast Syria, northwest Saudi Arabia, and western Iraq. High-grade deposits of commercial value in these countries amount to billions of tons. These deposits are now mined, utilized and exported from these countries, except Saudi Arabia, and contribute significantly to their development. The phosphorites consist of reworked granular deposits of peloids and vertebrate skeletal fragments and the sequence is associated with extensive bedded chert, porcelanite, and organic-rich marls. The main mineral is carbonate fluorapatite (francolite) with relatively enhanced uranium substituting for calcium in the crystal structure of francolite. The age is Late Cretaceous (Campanian–Maastrichtian) and Paleocene.

Three factors seem responsible for the deposition of the phosphorite and the whole exotic regime: chert, organic-rich marl and phosphorite. These factors include: (1) The compression associated with the northwards movement of Arabia (and Africa) from the Late Cretaceous onwards, thus producing paleohighs and lows (basins and swells), which were the sites for deposition of these exotic sediments; e.g. the Syrian Arc Fold system. (2) Upwelling currents of cold, nutrient-rich water from the deep

Neo-Tethys Ocean from the north and west, which enhanced bioproductivity and the consequent high organic-matter contents and its role in the formation of the exotic deposits. (3) The rather shallow nature of the southern epicontinental shelf of the Neo-Tethys Ocean where these countries were located, which helped in the preservation of the organic matter, and thus the formation of this exotic regime during the early diagenetic environments that prevailed after deposition.

Paleogene larger benthic foraminiferal stratigraphy of the Potwar Basin and Trans Indus Ranges, northwest Pakistan: A comparison with the Paleogene biozonation of Northern Oman

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The Paleogene rocks of the Potwar Basin and the Trans Indus Ranges of northwest Pakistan represent sediments of northern Neo-Tethys. These rocks are comprised of five lithostratigraphic units: Lockhart, Patala, Nammal, Sakessar and Chorgali formations in ascending order. The Lockhart Formation consists of thick-bedded to massive carbonates, which represents deposition in inner to distal middle-ramp platform setting. The Patala Formation includes deep-marine (outer ramp-basinal) shales interbedded with thinly bedded limestone that represent middle ramp setting. The Nammal Formation consists of bluish-grey limestone and marls, representing inner-ramp to deep basinal setting. The Sakessar Formation constitute thick-bedded to massive, ridge forming nodular limestone, deposited in inner ramp to distal middle ramp setting. The overlying Chorgali Formation is represented by thick bedded to massive cream coloured, nodular limestone with minor marls in the upper part and represent inner ramp to distal middle ramp setting.

All lithostratigraphic units have well-preserved larger benthic foraminifera, which have been used here for constraining the geological ages of these units to a much higher resolution than were previously assigned. We have defined the larger benthic foraminiferal biozones (BFZP 1 to BFZP 3) which represents the Upper Paleocene–Lower Eocene strata in the study area. All lithostratigraphic sections are biostratigraphically correlated and ranges of diagnostic foraminiferal species are described and discussed. These biozones are compared with the Tertiary foraminiferal biozonation of Northern Oman (White, 1989; Racey, 1995) and standard shallow benthic foraminiferal biozonation schemes in the Mediterranean region (Höttinger, 1960; Schaub, 1881; Serra Kiel et al., 1998). This comparison resulted in the identification of three common stratotypified nummulitid biozones (i.e *Assilina leymerie biozone, Nummulites globulus biozone*, and *Assilina laxispira biozone*) while common non-statotypified index species includes *Ranikothalia sindensis, Discocyclina despansa* and *Assilina dandotica*. The results are valuable because of comparably extended biostratigraphic ranges of certain species in Pakistan and shows an improved resolution for a precise dating of the synchronous depositional sequences. The biostratigraphic analysis implies that closure of the northern rim of the Neo-Tethys Ocean in the Potwar Basin and the Trans Indus Ranges occured in the Middle Cuisian (49.5 Ma) while the Tethyan sedimentation persisted up to Early Oligocene with an interruption of regressive phase in the Early Eocene (Cuisian) in Northern Oman.

Introduction

A total of 350 rock samples were collected from the six key stratigraphic sections in the study area for the foraminiferal biostratigraphic analysis. In this study four Paleogene larger benthic foraminiferal biozones are established which are abbreviated as BFZP (Larger Benthic Foraminiferal Zones of the Potwar Basin). Foraminiferal range distribution, abundance, biozonation and a biostratigraphic correlation chart of the studied sections are constructed.

In this study BFZP 1 to BFZP 3 biozones are identified and biozonal boundaries are established on the basis of first and last occurrences of *Ranikothalia sindensis, Assilina dandotica, Assilina granulosa,* *Assilina leymerie, Assilina* aff. *putulosa, Assilina putulosa, Nummulites globulus, Nummulites atacicus, Discocyclina despensa, Discocyclina sella, Discocyclina scalaris, Alveolina vredenburgi, Alveolina globula, Alveolina pasticilata* and *Alveolina rotundata* species. The biozones are described as follows:

BFZP 1 Biozone
Definition: the base of this biozone is taken at the first occurrence of *Ranikothalia sindensis* and the top is taken at the synchronous first occurrences of *Assilina dandotica* and *Discocyclina despensa*.
Associated assemblages: the larger benthic foraminifera that range through this zone include *Miscellanea miscella, Lockhartia haime, Lockhartia hunti, Lockhartia newboldi, Miscellanea stampi, Operculina salsa, Operculina subsalsa, Operculina petalensis, Discocyclina ranikotensis, Discocyclina seunesi, Operculina petalensis, Assilina spinosa, Nummulites thalicus* and *Nummulites pinfoldi*.
Age: Upper Thanetian

BFZP 2 Biozone
Definition: the base of this biozone is defined by the synchronous first occurrences of *Assilina dandotica, Alveolina vredenburgi, Alveolina globula, Alveolina pasticilata* and *Discocyclina despansa*, while the top is defined by the simultaneous first occurrences of *Assilina* aff. *pustulosa, Assilina putulosa, Ranikothalia sahini, Nummulites planulatus, Nummulites atacicus* and *Nummulites globulus*.
Associated assemblages: the larger benthic foraminifera that range through this zone are *Nummulites thalicus, Alveolina pasticilata, Alveolina conradi, Alveolina elliptica, Lockhartia conica, Lockhartia conditi, Lockhartia hunti, Assilina spinosa, Assilina laminosa, Operculian salsa, Operculina subsalsa, Discocyclina ranikotensis, Operculina petalensis* and *Ranikothalia nuttali.*
Age: Lower Llerdian 1 to Middle Llerdian 1

BFZP 3 (A) Biozone
Definition: the base of this biozone is taken at the synchronous first occurrences of *Nummulites atacicus, Nummulites globulus, Assilina pustulosa, Assilina leymerie, Assilina granulosa, Discocyclina scalaris, Discocyclina sella* and *Discocyclina undulata* while the top is defined by the last occurrences of *Alveolina globula* and *Alveolina pasticilata*.
Associated assemblages: the larger benthic foraminifera that range through this zone include *Ranikothalia sahini, Ranikothalia nuttali, Nummulites thalicus, Nummulites lahiri, Nummulites pinfoldi, Assilina spinosa, Assilina laminosa, Sakessaria cottorie, Rotalia trochidoformis, Discocyclina fortisie, Discocyclina scalaris, Lockhatia conditi, Lockhartia hunti, Lockhartia conica* and *Operculina petalensis.*
Age: Middle Llerdian 2

BFZP 3 (B) Biozone
Definition: the base of this biozone is taken at the first occurrence of *Alveolina rotundata* and the top is taken at the last occurrences of the *Assilina laxispira* and *Orbitolites complanatus*.
Associated assemblages: the larger benthic foraminifera that range through this zone include *Lockhartia hunti, Lockhartia tipperi, Lockhartia conditi, Discocyclina undulata, Assilina spinosa, Assilina laminosa* and *Rotalia trochidoformis*.
Age: Upper Llerdian to Middle Cuisian

Comparison and Conclusions

A biostratigraphic comparison of the study area with the foraminiferal fauna recorded in the Tertiary rocks of Northern Oman is elaborated and the following conclusions are drawn:

(1) Five Paleogene lithostratigraphic units are described that include Lockhart Formation (ramp platform carbonates), Patala Formation (inner ramp-deep basinal clastic-carbonate mixed sediments), Nammal Formation (inner ramp-deep basinal carbonates/marls), Sakessar Formation (inner ramp-distal middle ramp carbonates) and Chorgali Formation (inner ramp lagoonal-distal middle ramp carbonates/marls).
(2) Among the recorded larger benthic foraminiferal species, the first and last occurrences of *Ranikothalia sindensis, Assilina dandotica, Assilina granulosa, Assilina leymerie, Assilina* aff. *putulosa, Assilina putulosa, Nummulites globulus, Nummulites atacicus, Discocyclina despensa, Discocyclina sella, Discocyclina scalaris, Alveolina vredenburgi, Alveolina globula, Alveolina pasticilata* and *Alveolina rotundata* were found useful in establishing biozonal boundaries.

(3) The larger benthic foraminiferal species of *Ranikothalia sindensis/Ranikothalia sahini, Assilina dandotica, Assilina granulosa, Assilina leymerie, Assilina* aff. *putulosa, Assilina putulosa, Nummulites globulus* and *Nummulites atacicus* are commonly present in the study area, and in Northern Oman.
(4) The Late Paleocene (Upper Thanetian) to Early Eocene (Upper Llerdian) biozones in the study area are defined and are abbreviated as BFZP 1–BFZP 3 (B).
(5) The BFZP 1 Biozone represents the Upper Thanetian and it is recorded in the Lockhart Formation in all studied sections, but extends upwards into the overlying Patala Formation in the Sikki Village, the Chachali Nala, the Kalabagh Hills and the Nammal Gorge sections. On the basis of common fauna (*Miscellanea miscella* and *Lockhartia* spp.) it is compared with the lower member of the Jafnayn Formation in Northern Oman (White, 1989; Racey, 1995).
(6) The BFZP 2 Biozone represents the Lower Llerdian 1–Middle Llerdian 1 in the upper part of the Lockhart Formation and extends upwards into the overlying Patala Formation in the Ziarat Thatti Sharif Section. This biozone extends upward into the Nammal Formation, exposed in the Nammal Gorge Section. The BFZP 3 (A) Biozone represents Middle Llerdian 2 age. On the basis of *Assilina layemerie/Assilina granulosa/Assilina pustulosa* species which were recorded in the Patala and Nammal formations that represents BFZP 2 in the study area, it is possible to compare it with the upper member of the Jafnayan Formation (White, 1989) in Northern Oman.
(7) On the basis of *Nummulites atacicus/Nummulites globulus/Alveolina rotundata, Lockhartia hunti/ Orbitolites* spp. recorded in the Sakessar and Chorgali formations representing BFZP 3 A-B in the study area, it is possible to compare it with the Russayl Shale Formation representing Ypresian/ Cuisian age (White, 1989; Racey, 1995) in Northern Oman.
(8) The foraminiferal biostratigraphic analysis implies that closure of the northern rim of Neo-Tethys in the study area occured in the Middle Cuisian (49.5 M.A) while a proto closure of the Neo-Tethys in Northern Oman is recorded by the presence of regressive facies in the Rusayl Shale Formation of Ypresian/Cuisian age (White, 1989; Racey, 1995).

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Organic maturation, petroleum potential and palynofacies indicators in Upper Cretaceous succession of Qamar Basin, Eastern Yemen

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A subsurface Upper Cretaceous (Santonian–Maastrichtian) succession has been recovered from three exploratory wells located in the Qamar Basin, in the eastern part of the Republic of Yemen. This work deals with studying the maturation, hydrocarbon generation, source rock evaluation and palynofacies of the Mukalla and Dabut formations (Mahra Group). These two formations are lithologically composed of an intercalation of argillaceous, carbonates, siltstones, sandstones and coal

layers. Studied samples of the Mukalla and Dabut formations have moderate to high total organic carbon (TOC) contents, especially of the Mukalla Formation. The sediments of Mukalla Formation are marked by mature organic matter content with high T_{max} and moderate values of HI of up to 450 mg HC/g TOC of kerogen type II and III. On the other hand, the sediments of Dabut Formation are mostly of kerogen type III and thermally mature stage. Vitrinite reflectance reading values range between 0.34 R_0 and 2.2 R_0 of the studied samples. The results of this study indicate that the hydrocarbons generation potential of both formations is oil and wet gas prone. Gas chromatography data indicated a mature source rock with good generation and expulsion of hydrocarbons. Three palynofacies are identified through the studied sediments. The first palynofacies marks an offshore marine environment; the second characterizes deltaic-fluvial environment, and the third one marks marginal environment. These reflect marine transgression and regression multiple-cycles through the deposition of the Mukalla and Dabut formations.

The influence of listric faults on fold geometry in the Foreland Belt of Iraq

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Two sets of listric faults have affected the Foreland Belt of Iraq: (1) *foreland listric faults*, and (2) *suture listric faults*. The first is foreland-verging (synthetic), whereas the second is antithetic or verging towards the suture line of the collision. These faults formed as normal faults when the Arabian and Eurasian plates split apart and extensional tectonics was dominant during the Triassic Period. They were reactivated mainly as reverse faults in the Eocene time when these plates collided. Several anticlines were studied to determine the presence and sense of movements of these faults. This analysis was done by using the differences of formations thicknesses between the northern and southern limbs.

The Baikher Anticline revealed that there are two listric faults extending along its axis. The first foreland-type verged to the southeastern part towards the southwest whereas the second is a suture type with the northwestern part verging towards the northeast. The suture listric fault beneath the Shaikhan Anticline caused it to verge towards the north. A foreland listric fault affected the Brifca Anticline and verged it towards the southwest. The Gara Anticline was subjected to a suture listric fault which caused the anticline to verge towards the north. Lastly, the Sinjar Anticline also contains a suture listric fault, which broke up the sedimentary cover and verges the anticline towards the north. Study of these sample anticlines revealed that the faults had a normal sense of movement in pre-Late Cretaceous time. They were reactivated in Middle to Late Eocene as reverse faults accommodating the compression tectonic environment as a result of the collision between the Arabian and Eurasian plates.

Lithostratigraphy and rhythmic sedimentation of the Middle Jurassic Dhruma Formation, Al Jabal al-Akhdar, Sultanate of Oman

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The Jurassic Sahtan Group of the Al Jabal al-Akhdar area, Oman, consists of two formations, Lower Jurassic Mafraq Formation and overlying Middle Jurassic Dhruma Formation. The group unconformably overlies the Triassic strata of Mahil Formation (upper Akhdar Group) and is unconformably overlain by Upper Jurassic–Lower Cretaceous Raydha Formation (lower Kahmah Group). The two formations of the Sahtan Group are separated by an unconformity. This work addresses lithostratigraphic attributes and nature of cyclic sedimentation of the lithofacies units that build up the Dhruma Formation. Two well-exposed sections on the northern and southern flanks of Al Jabal al-Akhdar (Wadi Bani Kharous and Wadi Ma'idan, respectively) were studied. The formation is about 110 m thick and documents an overall, possibly third-order, transgressive-regressive cycle with internal higher-order cycles. The Mafraq/Dhruma contact is a well-developed karstic surface characterized by karst-dissolution pits filled with ferruginous sandstone.

In Wadi Ma'idan, the lowest five meters of the Dhruma Formation are defined by coarse-grained quartz arenite that becomes finer and more calcareous upward until it gradually merges with the overlying Dhruma carbonates. In Wadi Bani Kharous, the sandstone is interbedded with various lithofacies of bioclastic and oolitic limestone. The dominant carbonate portion of the Dhruma Formation is dominated by thick to medium beds of (shaly to non-shaly) bioclastic mudstone to wackestone, and bioclastic and/or oolitic packstone to grainstone lithofacies. The bioclastic mudstone, wackestone and packstone lithofacies show Thallassinoids burrows and hardground surfaces. The bioclastic, oolitic grainstone lithofacies is cross-bedded with minor, locally imbricated, mudstone intra-clasts. Other volumetrically subordinate lithofacies in the Dhruma Formation are fine-crystalline (calcareous), buff-weathering dolomudstone and bioclastic rudstone. The various lithofacies in the formation are arranged in shallowing-upward (commonly subtidal to intertidal) rhythmic units defined by lower shaly mudstone/wackestone lithofacies grading to the bioclastic and oolitic packstone/grainstone/rudstone lithofacies. Rare dolomudstone and microbially-laminated lime mudstones at the top of some cycles may indicate upper intertidal to possibly supratidal mudflats. Nine such shallowing-upward cycles with an average thickness of about 12 meters are recognized. The overall vertical lithofacies distribution of the formation suggests that the depositional system evolved from deposition of muddier facies during the transgressive stage (TST) whereas bioclastic and oolitic sand shoals dominate the regressive stage (HST) of the platform.

Investigating the source of thermal anomalies in the northern United Arab Emirates Desert using geophysical methods

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We conducted geophysical surveys to investigate the source of thermal anomalies and to delineate any potential water transport pathways from the recharge zones in the Oman Mountains to the location of the temporal thermal anomalies within the desert plain of the United Arab Emirates (UAE). In the visible region of the spectrum of both ASTER and MODIS satellite images, the desert plain of the UAE appears as a bare sandy surface. However, detailed examination of these images in the thermal bands reveal cooler thermal anomalies within the desert plain following major rainfall events. This anomaly has a cooler surface of approximately 20ºC lower than the surroundings with a lifespan of several days. It has been hypothesized that moist surfaces, following rainfall events in an arid hot desert could be an indirect indication of locations with groundwater accumulation. Two regional fault zones, Dibba (DFZ) (NE-SW) and Hatta (HFZ) (NW-SE) were traced from ASTER satellite images and SRTM (ca. 90 m) elevation data, but it remained unclear whether they extend into the thermal anomaly area. Audiomagnetotelluric (AMT) and ground magnetic data were acquired to verify the possible extension of these fault zones into the thermal anomaly area. AMT data were acquired along profiles positioned perpendicular to the DFZ and HFZ trends and over a 3-D survey grid covering the anomaly area. The ground magnetic survey delineated the extension of both fault zones into the gravel plains area but not into the anomaly area probably due to the thicker sand cover. 2-D AMT apparent resistivity sections show a low resistivity structure coincident with the thermal anomalies that parallel the DFZ trend. A conductive structure over the thermal anomaly area, coincident with the extension of the HFZ, was characterized from AMT 2-D inversions. The results suggest that the DFZ and HFZ extend from the recharge areas in the mountain into the desert plains. The results also suggest that these faults play a vital role in transmitting infiltrated rainwater from the Oman Mountains into the desert plain of the UAE where freshwater accumulates after rainfall events causing the thermal anomalies.

Gravity modeling of the Sur Area

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The mountains of Oman represent the Alpine belt that extends from Musandam in the north to the Batina coast in the southeast including the Sur area (study area) located at the northeastern bend of the Sultanate of Oman. The belt carries imprints of geological complexities resulting from several phases of deformation: Late Proterozoic, Paleozoic, Laramide and Alpine. The deformation effects observed in the Sur area post-date the final suturing of the Neo-Tethyan Ocean during Late Cretaceous and are associated particularly with the Huqf-Haushi Uplift, positive inversion of Jabal Jalaan, and movement on the north Jalaan Fault.

To look down under surfacial geology the area was studied by a gravity survey between Qalahat and Al Kamil (50 x 20 sq km) following an east-west line (Al Kamil to Sur), and four crossing lines (Sur-Qalhat, Al-Fulayj, Tahwah and Salil). The observation interval on these lines varied from 0.5 km to 2 km depending upon the terrain and access. The collected gravity data was processed and a Bouguer anomaly map of the area was prepared. The map shows four gravity features: gravity highs in the northeastern part of the area (Qalahat), NW-oriented contours pattern, a generalized gravity decreasing trend towards the southwest (Qalahat to Al Kamil), and a southwest-directed contour offset in the central part of the area. The gravity highs in Qalhat and Misliq are related to Precambrian basement outcropping in the area. The southwest-directed decreasing gravity trend suggests an increasing thickness in the sediments overlying the basement. The offset in gravity contours reflects faulting.

The gravity modeling of all the five gravity lines suggests that the basement, which is generally 4 to 5 km deep, is faulted. Faulting would give rise to basins such as the Sur and Al Kamel basins where the thickness of sediments is more than 4 km, and to a pop-up structure under the influence of NNW-trending reverse faults, i.e. Qalhat Fault in the northeast and North Jalaan Fault in the southwest. This pop-up also carries an Abat Trough where the sediments appear to be 2.0–2.5 km thick. In conclusion, basement configuration and faulting have a great relevance to the geology of Sur area.

Subsurface structural styles in various tectonic domains of the Sultanate of Oman

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The type and amount of tectonics vary significantly across Oman as a result of many tectonic regimes that affected the region. This resulted in different structural styles observed in subsurface data across different structural domains of Oman. The presence and thickness variation of the underlying Ara Salt is one of the key parameters used to define these domains. In places where the Ara Salt is absent or very thin, the effect and timing of far-field regional tectonic stresses can be clearly demonstrated (e.g. Lekhwair High). Faults and fracture corridors in these areas are usually uniformly distributed throughout the basin and tend to be semi-linear both in vertical and lateral views. On the contrary, the impact of far-field regional stresses is often difficult to distinguish from local stress perturbation caused by salt halokinesis in basins that have thick underlying salt (e.g. South Oman Salt Basin). Within these basins, the structural elements that form in the cover sediment are localized above salt ridges and depressions. These elements often form tortuous patterns. Salt halokinesis has also controlled the carbonate stringer deformation seen in South Oman.

In South Oman, salt halokinesis has dominated the deformation style and orientation of local stresses in Paleozoic times. This resulted in a tortuous framework of faults and folds. During Paleozoic time, sediments were deposited in local depo-centres (known as Haima pods). Simultaneous differential loading and salt dissolution is interpreted to have been the main driving mechanisms of the deformation in the South Oman Salt Basin. The final pod geometries are directly controlled by sediment supply, space accommodation and initial salt thicknesses. Younger deformation events that occurred during Cretaceous and Tertiary times and have been well documented in North Oman have been overprinted by local salt deformation in South Oman. Across South Oman, a number of depressions at the present surface topography formed above the deep thicker salt area, indicating that salt removal is still continuous today. Salt halokinesis is also the main driving mechanism of stringer deformation. In general, the observed faults in stringers are both extensional and compressional depending on the stringer position with respect to Haima pods. The intensity, style and type of stringer deformation can vary significantly in vertical and lateral senses between adjacent areas.

The regional stresses are more easily defined in North Oman. Within the Fahud and Ghaba Salt basins, two dominant fault/fracture orientations are observed, NW-SE and NE-SW. The former was formed during Late Cretaceous in response to a NW-trending compressional regime, whereas the latter developed in Late Tertiary in relation to a NE-SW compression. Pre-existing basement faults have been reactivated in both tectonic episodes, first as transpressional faults then as transtensional faults. The deformation within the northern salt basins is mostly localized within the pre-existing structural features. Outside the salt basins, faults mainly trend NW-SE. These tend to be uniformly distributed throughout the basin and have uniform throw and vertical continuity.

Tectonic controls on magma genesis in the northern part of the Arabian Plate: Geochemical constraints and hydrocarbon migration implication

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After the emplacement of the Yemeni-Ethiopian continental flood basalt plateau in the Late Oligocene (ca. 31 Ma), widespread volcanic activity erupted, accompanying the separation of the Arabian-Nubian Shield (development of Red Sea rift) and the convergence between the Arabian and Eurasian plates (building of the Bitlis-Zagros thrust belts). In the northern part of the Arabian Platform, the Syrian volcanism occurred in a general compressional context, surrounding the Palmyride fold belt and adjacent to other deformation zones (e.g. the Euphrates Graben and Dead Sea Fault System). The widespread lava flows are the subject of an open geodynamic debate on the origin of the intra-plate volcanism among such complex tectonic settings.

Previously our K-Ar ages dataset ranging from ca. 0.05 Ma to ca. 18 Ma allowed us to measure the timing of the volcanic activity in the northern part of the Arabian Plate. In this study we highlight the geochemical signature of the lava flows from Syria. We present a new tectonic evolution model including hydrocarbon migration and regional implications.

Geochemically, the Cenozoic Syrian lavas are alkaline and subalkaline rocks, typical of magma emitted in continental intra-plate contexts. They are basanites and tephrites, basalts, basaltic andesites, basaltic trachyandesites, and trachybasalts. Basaltic samples from different Syrian volcanic provinces show significant variation in terms of incompatible trace-element signatures. Crustal contamination plays a negligible role in the process of magma differentiation, as does crystal fractionation, essentially restricted to olivine and clinopyroxene. Our results show that the Syrian lava has been generated by variable rates of partial melting from different levels of a locally heterogeneous lithospheric mantle. The LREE/MREE ratio not only illustrates how the degree of partial melting was changed spatially and temporally during the last ca. 18 Ma, but it also illustrates how the degree and style of extension tectonics changed through time.

One of the consequences of this tectonic setting could be a prospective of westward hydrocarbon migration, which was probably triggered by a Pliocene–Quaternary extension in the crust at the Euphrates Graben in the east, and probably guided towards a previously stretched crust in northwest Syria.

We conclude that the Cenozoic Syrian volcanism is a consequence of extensional tectonic, under periodical influence of the north and eastward convergence at the Arabia-Eurasia margin, which induces rotational tectonic styles; this controls the partial melting at various depths in the mantle. The volcanism of northern Arabia developed in the framework of the Red Sea rifting and initiated at the same time as the southern Red Sea volcanism. It extends up to historical time, progressively smoothed to the north in a contradictory relation with the compression tensional setting of the Arabia-Eurasia margin.

Characteristics of clastic to carbonate allostratigraphic cycles and their bounding surfaces, Early Jurassic Mafraq Formation, Al Jabal al-Akhdar, Sultanate of Oman

Sameer Al-Mandhary (Oman Oil, Muscat) and
Osman Salad Hersi (Sultan Qaboos University, Oman)

The Jurassic sequence of North Oman is represented by the Sahtan Group which consists of two formations, the Mafraq Formation and the overlying Dhruma Formation. The lower and upper boundaries of the group are marked by regional unconformities separating it from the underlying Akhdar Group and the overlying Kahmah Group. This project intends to describe the unconformity between the Mahil Formation (uppermost Akdar Group) and the Mafraq Formation, as well as several discontinuity breaks within the Mafraq Formation. Deep canyons that cut through the dome of Al Jabal al-Akhdar furnish exquisite outcrops of the Mesozoic strata of North Oman. Three sections of the Mafraq Formation (Wadi Bani Kharous to the north, Wadi Ma'idan to the south and near Al-Ghalil village up on the mountain) were studied and the formation is 78 m thick at the Wadi Ma'idan section. In the other two sections, the formation is either incomplete or disrupted by faults.

Besides the basal Mahil-Mafraq unconformity, four prominent discontinuity surfaces were recognized allowing subdivision of the Mafraq Formation into five (A to E) allostratigraphic units defined by basal siliciclastics followed by carbonate strata. The top of the carbonates are commonly karstified with karst pockets filled by the overlying siliciclastics. The top of the Mahil Formation is also a karstic surface with *in-situ* breccia and irregular dissolution vugs partially filled by carbonate spherulitic cements. This is followed by Unit A consisting of basal mudrock followed by carbonate strata. The mudrock is a 2-m thick paleosol of reddish to brownish mudrock lithology; it is preserved only in the Al-Ghalil section. This is followed by 10.5 m thick fine crystalline, buff-weathering light grey dolomudstone with microbial liminations, flat pebble breccia and desiccation cracks. The top of Unit A is defined by a karstic surface followed by three meters of coarse-grained ferruginous sandstone (base of Unit B). The latter also fills deep (up to 2 m) dissolution pockets associated with the karstification process. The sandstone merges vertically to a 5-m thick sandy bioclastic wackestone to packstone that grade to fine crystalline dolomudstone lithofacies. The latter is surmounted by another discontinuity surface which marks the top of Unit B.

Unit C is defined by a basal 3.5-m thick, red to brown, cross-bedded, coarse-grained quartz arenite succeeded by 4.2-m thick intra-clastic, oolitic and bioclastic wackestone to packstone and lithiotis-bearing rudstone/floatstone lithofacies. This thin sandstone is followed by 45 meters of thickly bedded bioclastic mudstone to packstone with few thick beds of lithiotis-bearing floatstone to rudstone. Unit D terminates with thin to thickly bedded, yellowish-brown weathering, fine crystalline dolomudstone. Well-developed karstic surface forms the upper boundary of the unit. This is followed by 2-m thick, coarse-grained, ferruginous quartz arenite that grades into fine-grained, calcareous sandstone (Unit E). The latter merges with the carbonates of the Dhruma Formation. Thus, allostratigraphically speaking, the sandstone of Unit E is the basal clastic unit which heralded Dhruma transgression. The stratigraphic ranges of the breaks below, above and within the Mafraq Formation are not known and biostratigraphic dating is required to assess their temporal extensions. Regional correlations show comparable stratigraphic breaks within the stratigraphic range of the Mafraq Formation; possible correlations are envisaged.

Sedimentary facies description of the upper Musawa Formation sub-unit, Sur Tertiary Basin, eastern Sultanate of Oman

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This study focuses on the Wadi Musawa deltaic system within the Sur Tertiary Basin. The Sur Tertiary Basin is structurally tightly constrained by three main faults; Qalhat Fault in the north, North Ja'alan Fault in the south and a flexural fault to the east, parallel to Jabal Khamis. It provides a record of strong tectonic influence governing a carbonate platform margin to basin succession (Razin et al., 2005). The upper Musawa Formation deposits represent river-dominated deltaic sediments that accumulated as a local siliciclastic feature in a carbonate-dominated subtropical environment that fits on a broader scale into a dominantly carbonate system of the Sur Tertiary Basin.

The 300 m-thick westward dipping deltaic sediments of the Bartonian upper sub-unit of the Musawa Formation show two main facies successions over a five to ten km distance, grading from a proximal delta plain succession, to a distal delta front succession. Thirteen facies have been distinguished in these sequences. Out of the 13 facies there were six types of sandstone facies. These are: (1) conglomerate facies, clast to matrix supported; (2) channelized coarse-grained cross-bedded sandstone/pebbly sandstone facies; (3) channelized coarse to fine-grained sandstone facies with low-angle inclined cross-stratification; (4) channelized medium to fine-grained sandstone facies with sigmoidal cross-bedding; (5) lenticular coarse to medium-grained cross-bedded and bioturbated sandstone; (6) tabular medium to fine-grained wave-dominated sandstone facies; (7) wave-dominated calcareous sandstone facies; (8) heterolithic facies, which consists of fine-grained sandstone, siltstone and shale; (9) multicolored shale facies; (10) coal/carbonaceous shale facies; (11) mudstone and fossiliferous wackstone facies; (12) shelly carbonates facies; and (13) yellow marine marl/shale facies. The proximal delta plain succession is characterised by lenticular channel geometries, while the distal delta front succession is dominated by more tabular sheet-like geometries.

This upper sub-unit of the Musawa Formation is stratigraphically located between the Bartonian carbonate platform of the intermediate sub-unit of the Musawa Formation and the Priabonian deep-marine Oligocene Tahwah Formation. Both the lower and upper boundaries of the upper sub-unit of the Musawa Formation have not been previously characterized. The top of the carbonate platform shows intercalation of siliciclastics indicating a regressive pattern and a seaward shift of the sedimentary system (Razin et al., in press). The upper boundary with the Tahwah Formation is marked by a rapid change from deltaic sandstone to deeper marine shale.

Stratigraphic position of the Hawar Member, its relationship with the Shu'aiba Formation, and importance for hydrocarbon exploration and production, Al Jabal al-Akhdar, Sultanate of Oman

Hussam Al-Rawahi (Petroleum Development of Oman, Muscat) and
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The Hawar Member is a late Barremian to early Aptian lithostratigraphic unit that occurs between the Barremian Kharaib Formation and Aptian Shu'aiba Formation. It is well exposed on the walls of the deeply-cut valleys on the northern and southern flanks of Al Jabal al-Akhdar, Northern Oman. Sections of the member from two valleys, namely Wadi Bani Kharous to the north and Wadi Ma'idan to the south were correlated and petrographically and biostratigraphically analyzed. Despite documentation of a short unconformity between the Hawar Member and the underlying Kharaib Formation, most previous work considers the member as the uppermost lithostratigraphic unit of the Kharaib Formation. However, our study shows that the member is genetically akin to the Shu'aiba Formation and we propose to include it in this formation. This new stratigraphic relationship furnishes potential stratigraphic traps.

The Hawar Member thickens from the north (ca. 16 m at Wadi Bani Kharus) to the south (ca. 26 m at Wadi Mu'aydin) and is characterized by several cyclic units that indicate shallowing-upward successions. Lithofacies attributes of the member can be grouped under types that are arranged in a shallowing-upward succession. These lithofacies are bioclastic wackestone, argillaceous bioclastic packstone, and peloidal, bioclastic grainstone. The bioclastic wackestone consists of grey, thin to thick beds and shows thalassinoides burrows. Besides discoidal *Orbitolina* tests that are common in the facies, there are also *Hensonella dinarica*, mollusk fragments, algae, corals, and calcispheres. This lithofacies is interpreted to have accumulated in an open-marine, relatively deep subtidal environment. The packstone lithofacies is medium to dark grey, thinly to thickly bedded, with thin laterally discontinuous shale interlaminae that give wispy structure and nodularity.

The most common fossils are discoidal morphotype *Orbitolina* along with other fragmented fossils, such as, *Montseciella arabica*, echinoids, gastropods and bivalves. This lithofacies is interpreted to have accumulated in an open-marine, subtidal environment. The grainstone lithofacies is medium grey, thickly bedded, with rudist fragments and other disarticulated bivalve shells. Other fossils present in this lithofacies are gastropods, echinoids, *Montseciella arabica*, miliolids and *Orbitolina*. This lithofacies is interpreted as an accumulation of high-energy, normal-marine, shallow subtidal environment. The three lithofacies are arranged in shallowing-upward rhythmic units defined by complete to incomplete wackestone-packstone-grainstone cycles. The section at Wadi Mu'aydin (the thickest among the three studied sections) preserves ten such cycles.

The overall depositional environment of the Hawar Member is considered as an open lagoon on the lee side of platform margin Shu'aiba carbonate shoals. The grainstone lithofacies are very similar to the lower Shu'aiba carbonates and interpreted as carbonate sand "tongues" spelt on the lagoon by storms or high tidal currents. Thus, the Hawar Member intertongues with the lower Shu'aiba Formation. Thus, it is more appropriate to consider the Hawar Member as a lithostratigraphic unit of the Shu'aiba Formation. The interfingering stratigraphic architecture between the Hawar Member and the lower Shu'aiba Formation may result in the existence of potential stratigraphic traps and compartmentalization of lower Shu'aiba reservoirs.

Index fossils of the Late Palaeocene–Early Eocene Jafnayn Formation, Al Batinah Coast, Northern Oman

Abdul Razak S. Al-Sayigh (Sultan Qaboos University, Sultanate of Oman)

The Jafnayn Formation is an Early Paleogene carbonate unit that crops out widely along the Al Batinah coastal plain of Northern Oman. It unconformably overlies the uppermost Cretaceous Al-Khod Conglomerates and is overlain by the Lower to Middle Eocene Rusayl Formation. The Jafnayn Formation is informally divided into two members that are separated by a biostratigraphically identified unconformity. The lower member comprises an upsection sequence of low to moderate energy, inner-shelf to lagoonal strata of (1) mudstones and wackestones; (2) massively-bedded, pseudonodular, bioturbated wacke-packstones; and (3) bioclastic mudstones. The lower member is dated as Late Palaeocene (Thanetian) based on the occurrence of the foraminifera *Lockhartia diversa, Daviesina persica, Kathina* sp. and *Nummulitoides margaretae* (NP8?). The upper member is Middle to Early Eocene (Ypresian) as suggested by the occurrence of *Sakesaria cotteri, Heterostegina ruida* and *Nummulites globulus*. It comprises coral and red algal-rich, well-bedded, occasionally rudaceous, nodular packstones-grainstones and cross-bedded calcarenites deposited in a shallow (less than 10 m), fairly high-energy open-marine shoal environment with nearby patch reefs supplying coral debris. The base of the upper member is marked by a locally distinctive thin (1–3 m) pebble bed rich in various siliciclastic grains and clasts reworked from the underlying member. The pebble bed was deposited immediately after a distinctive depositional hiatus corresponding to the upper part of the Upper Palaeocene and lower part of the Lower Eocene i.e. approximately two nannoplankton zones (NP9–NP10) representing the upper part of the *Alveolina (Glomalveolina) levis* zone to the lower part of the *A. cucumiformis*/*A. trempina* zones. Although this hiatus is recognised lithologically and biostratigraphically at Wadi Rusayl, at other localities it is only detected through detailed micropalaeontological analysis.

The Tectonics of Abu-Jir Fault Zone in west and southwest Iraq

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The Abu-Jir Fault Zone represents the tectonic boundary that separates the stable part of the Arabian Platform from the unstable part, where it forms the eastern margin of the western and southern Iraqi deserts. The zone consists of several NW-trending faults that extend from Anah Graben along the Euphrates River valley down to meet Hafer Al-Batin lineament in west Basrah and northwest Kuwait. It forms an expressive linear feature across the Iraqi territory for about 600 km that is clearly visible from satellite images. The analysis of six seismic time sections distributed along and normal to the fault trend, showed the extension of a major stress in the region from northwest to southeast and considered to have caused the Abu-Jir Fault zone transmission and its influence on the tectonics and tectonic evolution of the region. According to seismic sections, the northern and southern parts of Abu-Jir Fault Zone represent positive and negative flower structures and their presence provides conclusive evidence to the occurrence of strike-slip movement along the fault zone with dominantly normal offsets for the negative flower structures and reverse offsets for the positive flower structures. The middle part of the fault zone appears as a graben structure along normal faults, with reactivation as reverse faults through opposing the stress regime in some locations.

Petroleum systems of the Middle East

A.S. Alsharhan (Middle East Geological Establishment, UAE)

More than 500 commercially significant oil and gas fields have been discovered in the Middle East since the beginning of the 20th century. The published recoverable petroleum reserves at the begining of 2010 was estimated as 754 billion barrels of oil and 2,690 trillion cubic feet of gas, which represents almost 56.6% and 40.6% of the world's oil and gas reserves, respectively. Most of the fields have more than one pay zone producing from shallow-water carbonates and clastics with pay zones ranging in age from Infracambrian to Oligocene–Miocene.

The most prolific oil-producing zones are: (1) fracture and reefal carbonates of the Asmari and its equivalent formation (Oligocene–Miocene) of SW Iran and Northern Iraq; (2) shallow-water carbonates of the Arab Formation (Upper Jurassic) and the Thamama Group (Lower Cretaceous) of Eastern Arabia; (3) rudist and associated facies in the Shu'aiba, Mishrif, Simsima (Aptian, Cenomanian and Maastrichtian) in the southern Arabian Gulf; (4) shallow-water clastics of the Zubair (Barremian) and Burgan/Nahr Umr (Albian) in Kuwait, South Iraq and NE Offshore Saudi Arabia; (5) shallow-shelf limestones and dolomitic limestones of the Khuff/Kangan formations (Permian) in the Arabian Gulf; (6) carbonate and clastic sediments of the Huqf Group (Infracambrian, Early Cambrian) in Oman and the clastics of the Permian Unayzah/Haushi Formation in Arabia.

The most prolific source rocks are: (1) shales of the Kazdhumi Formation (Albian) in SW Iran; (2) laminated argillaceous limestones of the Hanifa Formation (Kimmeridgian) or its equivalent Sargelu Formation in the Arabian Gulf; (3) argillaceous bituminous limestones of the Shilaif/Khatiyah Formation (Albian–Early Cenomanian) in the Arabian Gulf; (4) Upper Cretaceous marly limestones in Northern Iraq; (5) Silurian shales in Arabia and Iran and the Infracambrian carbonates in Oman. The major sealing rocks are: (1) anhydrite of the Hith Formation (Tithonian); (2) shales of the Nahr Umr (Albian); (3) shales of the Laffan Formation (Coniacian); and (4) anhydrite of the Gachsaran (Miocene).

The structure forming mechanisms that have operated in various parts of the Middle East include several types such as salt-cored structure, and/or halokinesis movements; deep-seated basement faulting; compressional folding, and transtensional/transpressional structures.

The depositional pattern of the sedimentary rocks through geologic time resulting from the interplay of many factors such as sea-level changes, climatic variations, epeirogentic movements and rejuvenation of relief. These factors have a direct influence on the regional distribution and occurrences of hydrocarbons in the region.The Middle East region will dominate world oil and gas reserves well after other producing countries have declined. The estimate of undrilled future hydrocarbon reserves is high, and many structures are being tested and reveal new reserves but not completely explored or evaluated in many areas in the region.

Microfacies analysis and depositional environments of Tertiary carbonate sequences in Socotra Island, Yemen

M. Al-Wosabi and A.A. Al-Aydrus (Sana'a University, Yemen)

A detailed study of the microfacies analysis and depositional environments of Tertiary sedimentary rocks exposed in Socotra Island were conducted. The investigation was based on 54 samples collected from five stratigraphic sections and included four formations from base to top: Umm er Radhuma (Paleocene–Eocene), Dammam (Eocene), Aydim (Upper Eocene) and Mughsayl (Oligocene–Miocene). These rock units are mainly composed of carbonates. The petrographic study of unstained and stained thin sections have been carried out to investigate its sedimentology, microfacies associations and depositional environments. Eight carbonate facies were distinguished: mudstone, dolomitic mudstone/wackestone, fossiliferous wackestone, packstone, marly limestone, sandy limestone, reefal limestone, brecciated wackestone/packstone and chalky limestone. The recognized microfacies associations were correlated with the standard microfacies associations, which were defined by Wilson (1975) and Flügel (1982, 2005). The detailed microfacies analysis shows that the studied rock units were deposited within the shallow-marine environment except the upper parts of the Mughsayl Formation, which were deposited in a slightly deep-marine environment.

Relationship between tectonic stylolites and minor fold morphology in limestones of the Pila Spi Formation in Taq-Taq Oil Field within the Zagros Fold and Thrust Belt, northeast Iraq

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Stylolites associated with axial plane fractures occur in clayey limestone within the Pila- Spi Formation, from the "TT-04" deep exploration well in Taq-Taq area. A genetic link has been observed between the origin of fractures and the process of stylolitization. Strong tectonic deformations are present which have been formed under the influence of reverse bed faulting. Deformation is pronounced in the shape of folded marl layers along with the creation of thick cleavage (0.3–0.5 cm). Along the fractures of axial plane cleavage, microlithons are separated and moved apart for similar values (2–5 mm) forming a moderate synform. Stylolites are formed in the last phase of structure shaping when the effects of the local compressional stress have weakened under the influence of which the breaking off and folding of marl layers occurred. Their strike cut the bedding and older fracture systems.

Proven and potential Palaeozoic exploration plays of Iraq

Adnan A.M. Aqrawi (Statoil, Norway) and Andrew D. Horbury (Cambridge Carbonates, UK)

The Palaeozoic is the most under-explored succession in Iraq, but it is considered to have significant exploration potential, particularly in the Western, Northwestern and Southwestern deserts. Its megasequence stratigraphy although little known, appears similar to other major Arabian Plate megasequences in neighbouring countries. The Lower Silurian marine (hot) shale is the main proven source rock for the Palaeozoic hydrocarbons (particularly light oils) discovered in western Iraq. This

is limited to the north of Iraq, by erosion beneath an intra-Devonian unconformity. However, some Upper Ordovician black shales (of the Khabour Formation) together with the lowermost Carboniferous Ora Shales are also expected to be additional local source rocks. Preliminary geochemical results of the Middle Cambrian Burj limestone in Jordanian boreholes shows that this may have some potential where deposited in a deeper marine setting within Iraq.

Several promising sandstone reservoir rocks (of Cambrian, Ordovician, Silurian, Carboniferous, and early Permian ages) are present across Iraq. Of these, only some Upper Ordovician subsurface sandstones (i.e. Khabour Formation) and some Lower Silurian sandstones have been proven as reservoirs in Akkas Field of Western Iraq. However, reservoir quality is a major exploration risk as most sandstones may be severely affected by quartz overgrowth and clay cementation. The Carboniferous Harur Formation reefal carbonates may also provide reservoirs in north and northwest Iraq. Seals are also available across Iraq; these include the shales and tight carbonates mentioned above as potential source facies. Traps are mostly present as large, broad, four-way dip closures, often of intra-Carboniferous age, but there is also considerable potential for very extensive combination or stratigraphic traps, e.g. turbiditic sandstones of Lower Palaeozoic age pinching-out updip onto regional highs such as the Salman Zone.

The widespread occurrence of potential source, reservoir and seal rocks suggests that the Palaeozoic plays and prospects are quite promising for future hydrocarbon exploration over two-thirds of Iraq's area. However, the reservoir targets would be controlled by the active regional/local petroleum system, which is mainly defined geographically by areas of source rock occurrence, maturation and reservoir burial depth. Analysis suggests that Upper Palaeozoic plays will be common targets in most of north and northwest Iraq. Lower Palaeozoic plays and the known discovery are located in the Western Desert. On the other hand, the Southwest Desert may have locally both Upper and Lower Palaeozoic plays.

Morphotectonic evolution of the alluvial fans east of the Wadi Araba Fault, Dead Sea Transform, Jordan

Mohammad Atallah (Sultan Qaboos University, Oman) and
Walid Saqqa (Yarmouk University, Jordan)

This study deals with the development of the alluvial fans that reside at the foot of a fault-controlled mountain chain which flanks Wadi Araba, Jordan. The alluvial fans are fed by a number of ephemeral streams flowing westward from the eastern highlands to the desert plain and/or inland sabkhas. Computations of fan surface area, drainage basin area and fan slope showed that the fan surface area is proportional to the drainage basin area in most of the study cases, and inversely related to fan slope. The architecture and evolution of fan/drainage network were controlled by vigorous tectonic forces in the Early Miocene. The bedrock geology, history and rates of sediment supply, and the intensity and duration of surface flow, may have contributed to more progressive changes of the fans and the drainage basin system. The increment of fan slope towards the fanhead pertinent to sediment buildup, and the occurrence of steep normal fault scarps at the mountain edges are signs of recent uplift in the catchment area. The alluvial fans were dislocated from their drainage basins as a result of strike-slip movement along the Dead Sea Transform Fault and its subsidiary faults. The fanglomerates are compositionally immature and matrix-supported. The angular-subangular clast shapes mean that the alluvial debris materials have suffered slight or little abrasion before sedimentation.

Advert

Paleokarst in the Saiq Formation, Saiq Plateau, Oman

Aymon Baud (BGC, Switzerland), Benoit Beauchamp (University of Calgary, Canada) and Sylvain Richoz (University of Graz, Austria)

The Saiq Plateau composite section of the Saiq Formation (Middle Permian–Lower Triassic) consists of a 725-m thick succession of limestone and dolostone arranged in shallowing-upward cycles (Kohrer et al., 2010). This formation has been subdivided into Members A, B and C (Baud et al. *in* Baud and Bernecker, 2010) and contains four main transgressive-regressive (T-R) third-order cycles. The members have been correlated to the Weidlich (2003) supersequences P2 to P4. They are also correlated with the following Kohrer et al. (2010) sequences: (1) Member A with Khuff sequences KS6 and KS5; (2) Member B with Khuff sequences KS4 and KS3; and (3) Member C (=lower part of the Mahil Formation in Koehrer et al., 2010) with Khuff sequences KS2 and KS1.

The Saiq Formation has been described earlier by Montenat et al. (1976) on the Saiq Plateau, with the determination of the Middle Permian foraminifera, calcareous algae, *incertae sedis*, bivalves, brachiopods, crinoids and bryozoans. Concerning the age, these authors have dated the lower part as the *Neoschwagerina schuberti* zone of Middle Murgabian, corresponding to a Wordian age. This is supported by the recent recovery of the conodonts *Hindeodus excavatus* and *Hindeodus wordensis* (Nicora et al., 2009) that range from mid-Roadian to Lower Capitanian (Wardlaw, 2000).

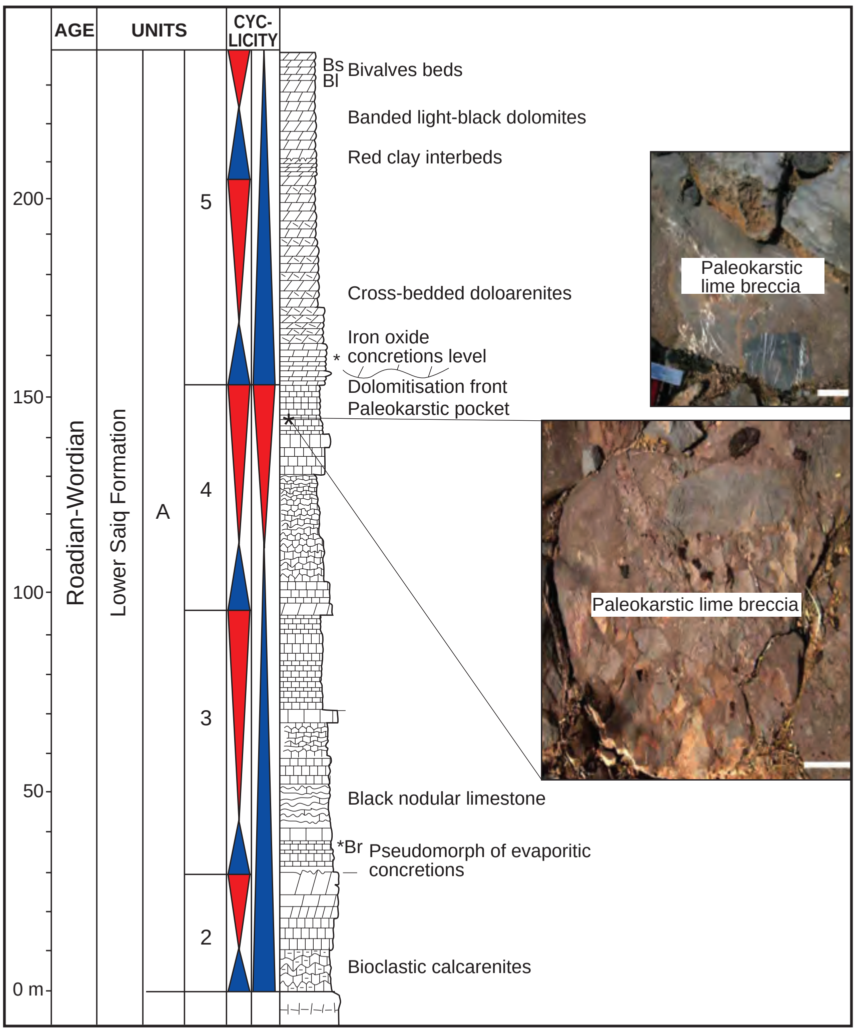

Figure 1: The Lower Saiq Formation on the Saiq Plateau (section east of the village of Hail Al Yaman) with the fourth- and third-order cycles with on the right 2 photos of the paleokarstic pocket. Scale bar = 5 cm.

The lower part of the Saiq Formation (Member A, 350-m thick, corresponding to P2 in Weildlich and Bernecker, 2003) has been subdivided into 6 units from the base up: unit A1 is partly terrigenous (= the lower Saiq of Rabu, 1988). Carbonate deposition starts with unit A2 and limestone is the main lithology from the A2 to A4 units. Units A5 and A6 are mostly high-energy sandy dolostone.

A paleokarstic pocket, up to 2 m in diameter, has been found in the lower part of the Saiq Formation, in unit A4, about 145 m above the base of unit A2, in a small valley that is about 2 km east of the village of Hail Al Yaman. The lithology from units A2 to A4 consists of about a 150-m thick pile of limestone that escaped late dolomitisation processes and with three shallowing upward transgressive sequences. This pocket is filled up by poorly sorted heterogeneous and angular lime clasts and rare rounded boulders up to 30 cm in diameter that record a local emersion of the shallow shelf. About 10 m above (top of unit A4) occurs the dolomitisation front and the top of the first transgressive-regressive cycle corresponding to the Khuff Sequence KS6 of Koehrer et al. (2010). We also note a concentration of iron oxides within these first dolomudstone levels.

During the last stage of continental distension, stretching paleotectonic and block tilting played an important role with large gaps and unconformities within the Saiq Formation as it has been shown recently by Chauvet et al. (2009) and by Weidlich and Bernecker (2011), in the Saih Hatat region. Until now there has been little evidence in the Al Jabal al-Akhdar and on the Saiq Plateau areas of early tectonic activity. But erosional and exposure surfaces have been illustrated by Baud et al. (*in* Baud and Bernecker, 2010, their figure 32) from Lower Triassic Member C of the Saiq Formation, 500 m above the paleokarstic pocket. These two findings confirm that the Middle to Upper Permian and Lower Triassic Arabian Plate carbonate platform was tectonically active, and that this tectonic activity should be taken into account when interpreting the sequence stratigraphy of the Saiq Formation.

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The Oman Exotics: Evidence for the development of isolated carbonate platforms in the Neo-Tethys Ocean

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The so-called "Oman Exotic" limestones form isolated masses, from boulder size to 1,000 m thick Middle Permian–Upper Triassic fossiliferous limestones, which crop out within imbricated thrust slices beneath the Semail Ophiolite in the Oman Mountains. They are commonly associated with a substrate of alkalic and transitional tholeiitic basalts and are interpreted as a series of reef-associated carbonate buildups deposited in part on oceanic islands or seamounts (Figure 1), close to the site of initial rifting of the Oman continental margin (Searle and Graham, 1982).

Three types of exotics, classified in three major tectono-stratigraphic groups, represent tilted blocks from the Arabian continental margin or atoll-like islands: (1) Qamar (Ramaq Group), (2) Ba'id Exotics (Al Buda'ah Group), and (3) Misfah type exotics (Kawr Group) (Pillevuit et al., 1997).

(1) The Ramaq Group crops out in Jabal Qamar and is characterized by an Ordovician to Carboniferous basement with Lower Permian to Triassic platform carbonates.

(2) The Al Buda'ah Group, defined in the Ba'id area comprises Upper Permian platform limestone (Weidlich et al., 1993) overlain by Triassic to Jurassic pelagic series.

(3) The Kawr Group defined in the Misfah area is composed of Middle Triassic volcanic series with Upper Triassic platform carbonates and Jurassic to Cretaceous pelagic sediments on top.

The nappes of the Hawasina complex document the evolution of the Neo-Tethys Ocean. The Subayb Formation of Jabal Misfah, comprises a succession of mafic volcanics and dark nodular limestones dated as Ladinian and Carnian (Pillevuit et al., 1997). It is the precursor of the Misfah Formation and is regarded as the lowermost unit of this Neo-Tethyan isolated carbonate platform. The Misfah Formation, exposed at Jabal Misfah, Misht, and Kawr ('Oman Exotics' *sensu* Glennie et al., 1974) consists of 700–900 m bedded shallow-water platform carbonates of Late Triassic age. The termination of shallow-water platform sedimentation at Jabal Kawr is indicated by platform drowning during the Early Jurassic.

The Misfah Formation (MF) at Jabal Kawr in the Oman Mountains, is interpreted as a relic of such an isolated Late Triassic platform of the Hawasina Ocean, a part of the Neo-Tethys. Correlation of three sections at Jabal Kawr points to a sequence architecture with four third-order sequences (MF1 to MF4). The maximum flooding surface (mfs) of MF3 can be correlated to the attached Arabian Platform. The shallow-water carbonates of Jabal Kawr comprise platform rim reef facies and bedded inner-platform.

The depositional profile of this Late Triassic isolated platform evolved during Carnian and Norian time from a low-relief carbonate bank to a high-relief platform rimmed by reefs. The onset of the carbonate sedimentation is characterized by an initial phase with volcaniclastic interruptions, followed by a carbonate bank stage with a shallow subtidal to peritidal interior and marginal oolite shoals. In the Norian vertical accumulation caused an increase of the platform height and developed a relief along the margins that progressively increased through the aggrading reef stage. The possibility that a reef rim existed and was later removed by erosion is suggested by the Sint reef and olistoliths of similar reef limestones in the surrounding areas.

Misfah Formation exposures at Jabal Misfah, Misht, and Kawr are 700–900 m thick and located in the western Oman Mountains in the area southwest of Al Jabal al-Akhdar. Three sections from Jabal Kawr were studied and cover positions of the Misfah Formation extending from Carnian to

Rhaetian (Bernecker, 2007). The size of the Kawr platform is about 15 x 20 km (300 sq km). Section Sint represents the rim of the platform; sections Ala and Amqah the platform interior. The base of the Misfah Formation at Jabal Kawr represents the onset of shallow-water carbonate deposition in the Carnian. Volcaniclastic extraclasts prove perturbations caused by volcanic activity. The upper part of the Misfah Formation at Jabal Kawr consists of shallow-water carbonates up to 800 m thick, and represents the development of the Kawr platform with reefs during the Norian–Rhaetian.

Correlation and Interpretation

Correlation of three measured sections of the Misfah Formation from Jabal Kawr points to a platform architecture with composite sequences MF1 to MF4. Basal sequence MF1 is exposed only at Wadi Amqah and lacks biostratigraphic microfossils. The occurrence of *Poikyloporella duplicata* (Figure 2.3), *Clypeina besici* (both calcareous algae), and *Aulotortus praegaschei* (foraminifer) at the base of sequence MF2 at Sint section point to a Carnian age. Sequence MF4 at the top of Wadi Ala yields *Triassina hantkeni* (foraminifer) (Figure 2.2) indicative of a Rhaetian age. The termination of Jabal

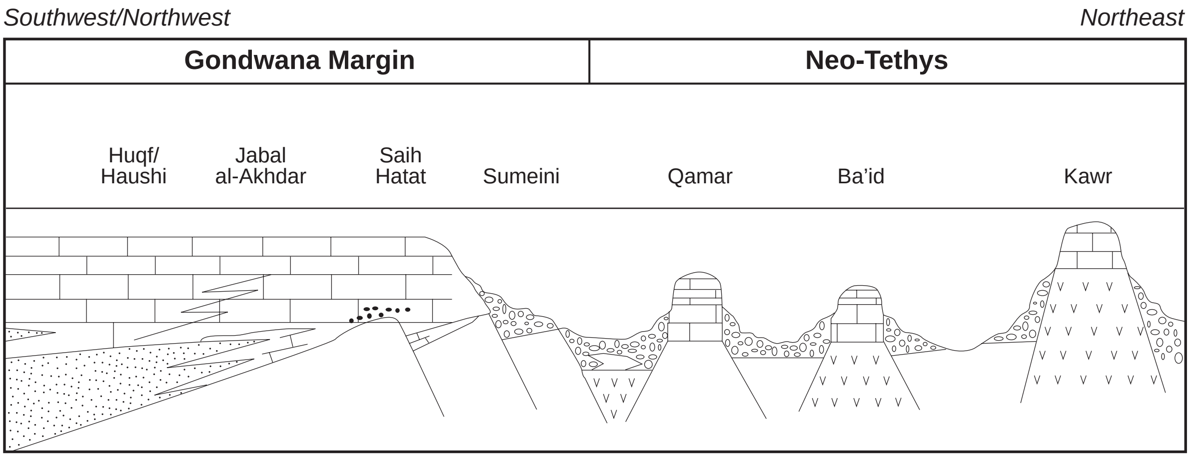

Figure 1: Arabian Platform and isolated carbonate platforms on seamounts in the southern Neo-Tethys Ocean: possible paleolocation of the Permian–Triassic Oman Exotics.

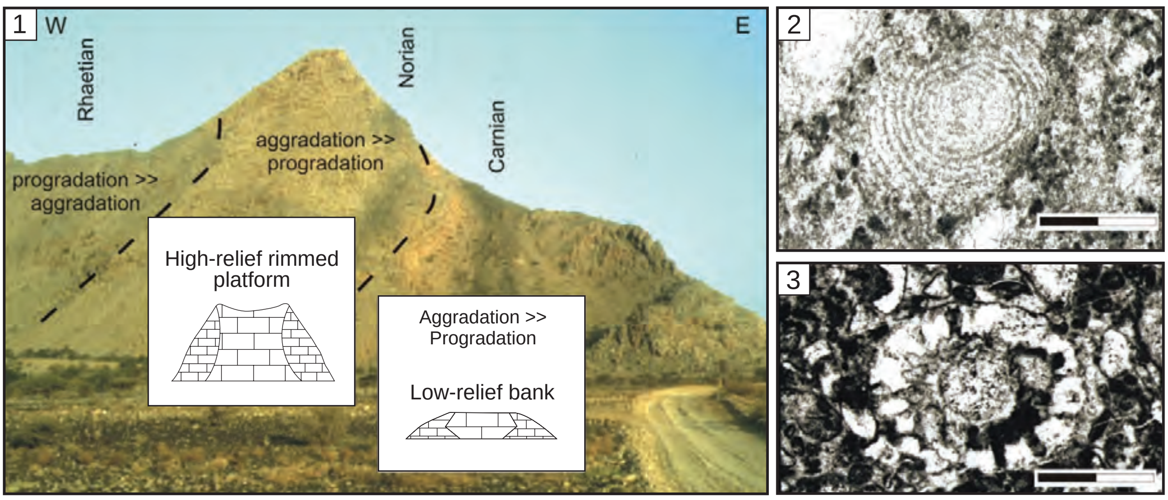

Figure 2: Late Triassic reef section of Jabal Kawr near the village of Sint. The occurrence of *Poikyloporella duplicata* (3), *Clypeina besici* (both calcareous algae), and *Aulotortus praegaschei* (foraminifer) at the base of the sequence section point to a Carnian age. The sequence at the top yields *Triassina hantkeni* (foraminifer) (2) indicative of a Rhaetian age.

Kawr shallow-water platform sedimentation is indicated by platform drowning during the Early Jurassic. Summarizing these data, a Carnian–Rhaetian age for platform development is indicated by biostratigraphic determinations (Bernecker, 2007). A Ladinian–Early Jurassic age has been postulated in the literature (Pillevuit et al., 1997) and cannot be ruled out.

Conclusion and Discussion

The Oman Exotic Jabal Kawr is the largest fragment of a carbonate platform preserved in the Hajar Mountains in the Hawasina Nappe. It is interpreted as an isolated Late Triassic platform, composed of four third-order sequences (MF1 to MF4). The maximum flooding surface (mfs) of MF3 can be correlated to the attached Arabian Platform (Bernecker, 2007).

The shallow-water carbonates of Jabal Kawr belong to the Misfah Formation and comprise platform rim as well as bedded inner-platform facies. Although platform-rim facies has been found only in the section near Sint, a margin with varying amounts of reef and cross-bedded oolite is preserved analogous to other Triassic isolated platforms known from the dolomites. The inner platform is characterized by stacked high-frequency cycles with subtidal to intertidal carbonate sequences.

Two stages of development are postulated for Jabal Kawr reflecting changes in the depositional profile of this Late Triassic isolated platform from low relief to high relief. Carbonate deposition commenced on a bank based on the following observations: (1) The lack of depositional relief is indicated by the absence of talus breccias close to the margin of the bank. (2) Oolites and crinoid floatstone, interpreted as rim of the bank, lack the capability to create a high-relief slope. (3) Published studies show that new carbonate depositional systems generally evolve from a low-relief bank to a rimmed platform (Cenozoic: Bahama Bank, Triassic: Great Bank of Guizhou, late Paleozoic: Capitan Reef Complex, southwestern USA). Shallow-water sedimentation at Jabal Kawr started with a phase of carbonate production interrupted by volcanic episodes. The bank consisted of a shallow subtidal to peritidal interior and oolite shoals at the margin.

The change in architectural style to a rimmed platform occurred during Carnian and Norian as evidenced by the presence of a reef at the margin. In the Norian vertical accumulation caused an increase of the platform height and developed a relief along the margins that progressively increased through the aggrading reef stage. The possibility that a reef rim existed and was later removed by erosion is suggested by the (1) Sint reef, (2) breccia intervals with clasts of reef limestone, and (3) olistoliths of similar reef limestones in the surrounding areas. The reef clasts contain a diverse fauna of scleractinian corals, sponges, and several different encrusting organisms forming a boundstone fabric. These boundstone clasts could have been derived from diverse platform margin reefs that were partly eroded from the margin and preserved only in the Sint reef.

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Advert

Structural analyses of Nahr el Mot Fault and its implication on the understanding of the Lebanese restraining bend, a segment of the Dead Sea Transform Fault

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The Lebanese restraining bend is part of the Dead Sea Transform Fault system which has created major activity and deformation in Lebanon's rocks. Activity along the major faults in Lebanon has created major debates among geologists and as a consequence the secondary E-W fault systems are under-studied. This study, through the analysis of one of them, the Nahr el Mot Fault, highlights their importance in the structural build-up of the restraining bend. The Nahr el Mot Fault is one of approximately 20 EW-trending faults in Lebanon. It is located in central Lebanon and extends from beyond the coast to Mount Lebanon, finally connecting with the Yammouneh Fault in the Bekaa plain. It most likely extends underneath the Neogene sediments of the Bekaa plain, through the Anti-Lebanon Range and into Syria.

In this presentation the section of Nahr el Mot Fault that will be studied is its extension from the coast to its connection with the Yammouneh Fault system. This section of the fault is approximately 35 km long. Six excavations were used for structural analysis along its path. One push-up structure 0.5 km wide and 2 km long in Jouret el Ballout was analyzed and one pull-apart structure in Sfaila was found to be over 1 km wide and 2 km long. The Nahr el Mot Fault offsets the Lebanese coastal monocline by nearly 3 km with an approximate 100 m normal vertical component. This study has shown that two sets of compressional stresses can be outlined from structural analysis of this fault and its surrounding areas. This makes it one of the most interesting dextral strike-slip faults in Lebanon. However, its activity and movement is much more complicated and many questions still need to be answered.

A recent seismic map has shown a series of epicenters on its trend indicating that it is still active. Nearly 20 epicenters on the fault have been documented between 2006 and 2011, ranging in magnitudes between 3 and 4, and a focal depth range between 10 and 50 km. The Nahr el Mot Fault trends along the edge of Beirut. It has shaped Beirut's northern coastline with the largest dent in the entire Lebanese coast. It also has a part in creating the two small topographic highs in Beirut, Ashrafieh and Ras Beirut. Since it is active it could be a major threat to Beirut's safety as this is the first time that the trend of the fault has been outlined so close to Beirut.

Mesozoic carbonate platforms of Oman

Henk Droste (Shell, The Netherlands)

As the Arabian Plate moved from southern latitudes into equatorial regions at the end of the Palaeozoic, deposition in Oman during Mesozoic times was dominated by carbonates. The total thickness of the carbonate deposits is more than 3.5 km and they host some of the main hydrocarbon accumulations in the country. Carbonate deposition was not continuous but was interrupted repeatedly by tectonic uplift and influx of siliciclastics following major changes in the plate tectonic setting that took place during this period. This resulted in the stacking of four platform sequences, each bounded by major unconformities and deposited in a different plate tectonic and palaeographic setting.

The lower sequence is formed by the Permo-Triassic Akhdar Group which, together with the underlying Haushi clastics, is onlapping the erosional topography of the mid-Carboniferous unconformity ("Hercynian event"). In the north this platform was bounded by a passive margin that was formed following the opening of the Neo-Tethys Ocean in the Late Permian. The sediments consist of shallow-marine to intertidal carbonate sands associated with evaporites grading in the north into alluvial to coastal plain clastics in the south. This platform was exposed and truncated in the Late Triassic–Early Jurassic when East Gondwana rifted from the southeastern margin of Gondwana and the Indian Ocean formed.

Lateral and temporal variations of the depositional environments of the Muti Formation (Upper Cretaceous) and their relation with the nappes emplacement in the Oman Mountains: Preliminary results

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In Northern Oman, shallow-marine platform sedimentation on the Arabian Platform is recorded in the Hajar Supergroup of Permian to Cretaceous age. During the Late Cretaceous (ca. 95 Ma), the obduction of the Semail ophiolitic complex is one of the most important tectonic events recorded in Northern Oman. This event led to the thrusting of the deep-marine sedimentary series previously deposited on the external margin (Hawasina Nappes) and the ophiolite itself (Semail Nappe) on the top of the Tethyan margin (Autochthonous Units). The emplacement of the nappes created a flexuration of the crust with (1) firstly a doming recorded by an erosional unconformity (Rabu et al., 1986; Al-Lazki et al., 2002) on the top of the Natih Formation of Cenomanian age, and (2) secondly a deepening recorded by the sedimentation of the Muti Formation of Turonian to Coniacian–Santonian age (Robertson, 1987). Indeed the Muti Formation, characterized by pelagic shales, carbonated and terrigeneous turbidites, conglomerates and olistolites in a shaly to cherty matrix, emphasizes the deepening of the depositional environments and the creation of a slope. The Muti Formation is then interpreted as a wild flysch indicating the transition from a passive margin to a foreland basin (Robertson, 1987; Béchennec et al., 1995).

In order to better constrain the palaeogeographical evolution of this foreland basin and the timing of the initiation of this basin, a detailed sedimentological and biostratigraphical study of the Muti Formation has been initiated. The main purpose of this study is to characterize the lateral and vertical variations of the depositional environments in order to: (1) constrain the timing of the deformation (nappe emplacement) as recorded in the basin, and (2) decipher the palaeogeometry and to determine an eventual asymmetry of the margin during the nappes emplacement. Intensive fieldwork and sampling have been performed in order to characterize the palaeoenvironments and to acquire new biostratigraphic constraints.

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Porosity-depth trends from sandstone and carbonate reservoirs: Seeing the forest for the trees

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Porosity-depth trends are useful as empirical input for exploration risking and reservoir modeling, but can also be valuable for characterizing burial diagenetic processes, recognizing cases of anomalous behavior, and calibrating the effects of lithologic or facies differences. Use of depth as the ordinate is justified by simplicity, in that no conversion is necessary using assumptions about geothermal gradient, fluid pressure, etc., but actual porosity-controlling processes are functions of temperature,

effective stress, and time rather than depth. Also, the relative importance of temperature and stress for particular processes and thus porosity is a matter of uncertainty and interpretation.

Porosity-depth data are commonly described by a least-squares fit, which reduces natural heterogeneity to a line with confidence limits. For larger datasets and for exploration risking, an alternative representation is to show the median porosity for each depth interval, together with P10 and P90 values (10% and 90%, respectively, of porosities are greater than these values). For both sandstones and carbonates, porosity-depth data are best explained as the result of mechanical compaction during the first kilometer or so of burial, followed by chemical (stylolitic) compaction and associated local cementation at greater depths. Available data do not show evidence of porosity being created during burial.

Numerical simulation programs, such as *Exemplar* and *Touchstone*, are available for calculating the porosity of quartzose sandstone reservoirs as a function of sand composition and texture combined with thermal history. The results, however, are evaluated and used by comparison with empirical porosity-depth data. Similar simulation is not yet possible for carbonates, but can potentially be developed by adjusting model parameters to produce results that best match porosity-depth data from well-characterized examples. Carbonates generally have much lower porosity for given depth than sandstones, reflecting the greater chemical reactivity of carbonate minerals than quartz during burial. Carbonates may also start out with systematically lower porosity than sandstones before being buried because of greater eogenetic porosity loss during accumulation, exposure, and submarine cementation, but this has not been established to be true.

Uplift and erosion has profound effects on porosity-depth trends, as illustrated by a recent comparison of data from the Arabian Plate between the simply subsiding Arabian Platform province and the uplifted Zagros province. Inclusion of data from uplifted terranes will tend to reduce the porosity for given depth in any compilation. This effect is likely to be an important reason for the lower porosity for given depth of both sandstones and carbonates as geological age increases.

Integrated computer-processed interpretation of the hydrocarbon potentiality of the subsurface reservoirs west Beni-Sweif area in Egypt using well-logs and seismic data

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Alaeddin M. Hassan (General Mineral Resources Authority, Egypt)

The present research focuses on the quantitative interpretation of the well-logs of ten oil wells and thirty migrated seismic sections scattered in the west Beni-Sweif area, in the Western Desert of Egypt. It aims to shed light on the hydrocarbon potentialities of the main Albian–Cenomanian reservoirs; namely: the Upper Bahariya, Lower Bahariya and Kharita formations, and to delineate the dominant subsurface structural controlling elements in the area. The petrophysical characteristics (H_{eff}, V_{sh}, Φ_{eff} and S_{hr}) and the structural elements of the studied formations are thoroughly investigated to elucidate the hydrocarbon potentialities using the computer programs (*Interactive Petrophysics* and *Las* tool) as well as a series of manual graphical and theoretical contributions.

The petrophysical analysis is represented as: (1) litho-saturation cross-plots (both manually and computerized) to reflect the vertical variation of the petrophysical characteristics and, (2) iso-parametric maps to verify the lateral variation of petrophysical characteristics. The seismic analysis which involved the construction of two structure contour maps at the top of the Bahariya and Kharita formations unveiled the subsurface structural elements of the area. The integration of the reservoir characteristics and structural attitude of Bahariya Formation indicate that, the most favorable places for hydrocarbon reservoirs are in the middle, southwestern and northeastern parts of the study area.

High-resolution sequence stratigraphy, diagenesis and porosity evolution: Outcrop analog of the Upper Jurassic Arab-D carbonate reservoir, Central Saudi Arabia

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(King Fahd University of Petroleum and Minerals, Saudi Arabia)

The Upper Jurassic Arab-D Reservoir is considered as the most prolific reservoir in the supergiant Ghawar Field in Saudi Arabia. It is composed of the uppermost section of the Jubaila Formation and Arab-D Member of the Arab Formation. Both were assigned to a third-order cycle within the large-scale Shagra Group second-order cycle. This study uses outcrop analog to investigate and evaluate the relationship between lithofacies, sequence stratigraphy, diagenesis and porosity evolution within the Arab-D Reservoir. The study revealed seven different lithofacies, which are interpreted to be deposited in distal to proximal lagoon and tidal flat. Ten high-resolution, fourth-order cycles were identified, three are in the upper Jubaila Formation and seven are in the Arab-D Member of the Arab Formation. These high-resolution cycles show repeated shoaling-upward cyclicity, which is recognized in several outcrop vertical sections.

The diagenesis and paragenesis analysis showed early marine dissolution and cementation, followed by replacement of aragonite and high Mg calcite to low Mg calcite. Porosity enhancement started with shoaling up of the system by meteoric dissolution. This produces most of the moldic and intra porosity in the study area and is expected to have its highest values. Porosity reduction started with rapid shoaling up of the fourth-order cycles and was marked in the grainy facies by heavy micritization and meteoric cementation. Although the outcrop section showed a degree of burial compaction, there is no pronounced effect of compaction on porosity reduction. With extensive progradation of the proximal lagoon and inner ramp along with meteoric realm, near-surface dolomitization was formed and resulted in porosity increase. This was very clear at the top of each of the three fourth-order cycles of the Jubaila Formation. Later, the whole system underwent fracturing which enhanced porosity dramatically.

Although, the outcrop section has little or no macro porosity due to subaerial exposure and recent meteoric cementation, the paragenesis study provides a predictive porosity distribution model within a high-resolution sequence-stratigraphic framework and its associated diagenetic events. This model could provide better understanding of porosity evolution and a valuable guide for subsurface exploration.

High-resolution sequence stratigraphy of the Maastrichtian–Ypresian succession along the eastern scarp face of Kharga Oasis, southern Western Desert, Egypt

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A thick Maastrichtian–Ypresian succession, dominated by marine siliciclastic and carbonate deposits of the regionally recognized Nile Valley and Garra El-Arbain facies associations, is exposed along the eastern escarpment face of Kharga Oasis. The succession contains ten planktic zones; two in the Early Maastrichtian (CF8b, CF7), four in the Paleocene (P2, P3, P4c, P5) and four in the Early Eocene (E1, E2, E3, E4). The succession comprises seven depositional sequences, which are bounded by unconformities and their correlative conformities that can be correlated within and outside of Egypt. These sequences are interpreted to be the result of eustatic sea-level changes coupled with local tectonic activity.

The Dakhla Formation, which spans Early Maastrichtian–Late Paleocene zones CF8b-P4c, comprises four sequences. Sequence DkSQ1 consists of the Maastrichtian Mawhoob Shale Member, which is unconformably overlain by the Beris Mudstone Member and Lower Kharga Shale, respectively of Late Maastrichtian age (DkSQ2). The Lower Kharga Shale is separated from the Upper Kharga Shale by a regional unconformity and sequence boundary that coincides with the Cretaceous/Paleocene boundary. Another sequence boundary is defined within the Upper Kharga Shale; it is recognized based on the absence of subzones P4a-b. This boundary separates the third and fourth sequences

present within the Dakhla Formation (DkSQ3 and 4). Towards the south in interpreted subtidal palaeo-highs, the lower part of the Upper Kharga Shale (DkSQ3) is replaced by the Late Danian–Selandian Kurkur Formation.

The Upper Thanetian Tarawan Formation (Subzone P4c, upper part) unconformably overlies the Dakhla Formation; it consists of chalky limestone with intensive branched burrows of *Thalassinoides* or thin conglomerate at the base. This formation thins southward and laterally changes into the Garra Formation, which unconformably overlies the Kurkur Formation in interpreted subtidal palaeo-highs.

In interpreted palaeo-lows, the uppermost Thanetian–Ypresian Esna Formation (zones P5 through E4) conformably overlies the Tarawan Formation with no biozonal break along the Paleocene/Eocene (P/E) boundary. This relationship is similar to that of the Global Standard Stratotype-section and Point (GSSP) of the P/E boundary which has recently been chosen at Dababiya Quarry, south of Luxor.

A short-lived hiatus, marked by a thin bioturbated band with reworked pebbles and an upper irregular surface, is interpreted near the base of the Esna Formation in Naqb Assiut at the P5/E1 zonal boundary. This hiatus is interpreted as the upper limit of the fifth depositional sequence in Kharga Oasis. This sequence includes the Tarawan Formation and the lower part of the Esna Formation (T/EsSQ5). Another hiatus is interpreted in the middle part of the Esna Formation at the top of Zone E3; this hiatus marks the top of sequence EsSQ6. The Esna Formation is overlain conformably by the late Ypresian Thebes Formation. This uppermost sequence includes the upper part of the Esna Formation and most of the Thebes Formation (Es/ThSQ7), and is capped by a well-developed karst surface.

Thermal regime of the Arabian Plate

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While recent research has produced a wealth of heat-flow data for the continental margin areas of the Arabian Plate, surface heat flow of the plate itself is not well constrained, with the bulk of the values being in the range of 40 to 60 mW/m^2. A major problem to be resolved is the question whether a low heat flow (≤ 45 mW/m^2), indicative of a "cold" plate, is compatible with known lithosphere properties. It was therefore desirable to generate first a detailed and comprehensive lithospheric model of thermal properties in an area for which reliable surface heat-flow values are available, and secondly to compare the resulting temperature-depth relation with geotherms of the continental lithosphere. The model developed is for the Arabian Shield in southeastern Jordan, for which a unique set of data from samples representative for the uppermost crust (outcrop samples) and the lithospheric mantle (xenoliths entrained in post-Oligocene basalts) was employed. Compositional data and petrophysical properties (density, thermal conductivity, radiogenic heat production), were integrated with data from seismology, gravimetrics, and receiver-function analysis in a conceptual model of the lithosphere. This model results in a heat flow at the crust-mantle transition of 24 mW/m^2, if a surface heat flow of 55 mW/m^2 (our preferred estimate) and a three-layered lithosphere are considered.

A steady-state geotherm based on *P-T*-dependent thermal conductivity results in a Moho temperature of ca. 530°C and suggests the depth of the lithosphere-asthenosphere boundary at 160 km. This depth figure is consistent with values from seismological surveys of the Arabian Plate outside of areas that have experienced post-Oligocene mantle upwelling and lithosphere thinning. It is consistent with lithosphere thickness derived from typical xenolith-derived geotherms for terranes of similar age. Thus, a "cold" steady-state Arabian Shield and Arabian Plate, previously inferred from heat flow ≤ 45 mW/m^2, is inconsistent with the thickness, composition, and petrophysical properties of the stable lithosphere of the region.

In regions affected by mantle upwelling, recent temperatures in the upper lithospheric mantle (derived from thermobarometric mineral data of Neogene xenoliths from Jordan and elsewhere in the Arabian Shield) are in excess of several 100°C compared to the steady-state temperatures. This T-increase, however, is not yet recorded by the surface heat-flow value owing to typical lapse rates of heat dissipation through the lithosphere.

Fluvial megafans of the Oman Mountains: Upper Miocene to Mid-Holocene palaeoclimatic framework

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The fluvial megafans of the Oman Mountain forebulge are an order of magnitude longer and flatter than the better documented classical alluvial fans. They belong to a fluvial-geomorphological category that is transitional between classical alluvial fans and typical large river systems. These megafans reflect the fluvio-sedimentary response to the interaction between a mountain and an active monsoonal system and are deposited in areas where the rivers undergo moderate to high intensity seasonal fluctuations in discharge due to distinctively seasonal rainfall distributions. Uniquely, both flanks of the Oman Mountain forebulge have developed megafans and they drain into the aggrading backbulge and forebulge basins depicted in the proposed tectonic model. The larger southern megafans drain into the interior basins of the Umm as Samim playa, the Rub' al-Khali and Wahiba sand seas. The smaller forebulge megafans of the Batinah plain drain into the Gulf of Oman foredeep. It is surmised that these fans reflect the underlying tectonic imprint of the arcuate Oman Mountains.

Although, Oman today is within the hyperarid, sub-tropical desert climatic zone, the fans themselves formed at times when southern Arabia was very humid and well within the Inter-Tropical Convergence Zone (ITCZ) and influenced by the Indian Ocean Monsoon (IOM). It is shown that these fans developed episodically from the Late Miocene to the late Quaternary (terminating in the mid-Holocene) and in concert with major regional tectonic and climatic changes, which reinforced each other. The major period of fan growth was probably the Early to middle Pliocene (ca. 5.2 to 2.8 Ma), following which, growth became episodic due to the onset of the Northern Hemisphere Ice-Ages. Strong, episodic pluvial events occurred in Oman (and Arabia) during the glacial-interglacial climatic cycles. The fans ceased to grow in the mid-Holocene when the ITCZ and associated rainfall belt moved away from the Arabian Peninsula, thus heralding the present aridity in Oman. Sufficient high-resolution proxy climate data are now available for prediction of phases of fan growth, quiescence, erosion/downcutting and hence the dissection history of the fluvial system. These megafans also give a unique insight into the changing fluvial and hydrological regimes in the southern Arabian region during the past ca. 10 to 12 million years.

Quite coincidentally, the late Neogene appears to be a time of widespread megafan formation in widely separated regions of the globe, which undoubtedly is related to the dramatic coupling of tectonics and climate during this time (e.g. the Himalayan, Andean and Oman fans).

Hydrocarbon source rock generative potential of the Red Sea Basin

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The evolution of the Red Sea-Gulf of Suez Rift followed two phases: pre-rift and syn-rift. Proto Red Sea rifting of the African-Arabian craton was initiated in Eocene–Oligocene times. During the Early Pliocene there was a further episode of doming during which further Red Sea extension took place and the Red Sea attained its current shape. Generally good reservoir quality, fluvio-deltaic and marginal to fully marine sediments were deposited and are partly preserved. Unlike the Gulf of Suez, potential Red Sea source rocks developed only within the synrift sequences, while in the Gulf of Suez, source rocks evolved during both pre-rift and syn-rift phases. In the Red Sea, the principle exploration plays are in Miocene syn-rift, pre-salt and post-salt successions.

The objectives of this study are to evaluate organic matter content, type and thermal maturity of the shales of the Miocene-aged Zeit and Rudeis-Kareem formations of the Sudanese Red Sea as well as to interpret their depositional environment and, thereafter, their hydrocarbon generative potential. These sediments were evaluated based on various petroleum geochemistry techniques including total organic carbon (TOC), Rock-Eval pyrolysis and gas chromatography mass spectrometry (GCMS).

To date, the Sudanese Red Sea, like the Red Sea as a whole, represents a grossly under-explored petroliferous basin. Few studies have investigated the geochemical characteristics of source rocks and their thermal and burial histories and, as such, the timing of hydrocarbon generation and accumulation are poorly understood. Recently, the basin has seen some exploration interest with more than 15 wells being drilled, some of which are petroleum discoveries ranging from gas to condensate with oil shows. The Rudeis-Kareem Formation of Early and Mid-Miocene age (pre-salt) consists of shale interbedded with sandstones deposited in a high-energy, shallow to deep marine environment and is considered a regional petroleum source rock for the basin. Moreover, shales in the lower part of the post-salt Zeit are considered the main source of the known accumulated hydrocarbon (gas and condensate) in the upper targets. The Red Sea's high pressure and temperature regimes have a significant impact on hydrocarbon maturation, generation and quality reserved.

The data obtained from organic petrological and organic geochemical analyses of seven exploration wells is discussed. The measured amount of TOC, HI, and hydrocarbon expelled from pyrolysis of kerogen (S2) of the examined samples indicate the source rock generative potential of these intervals. The TOC contents range from 0.60–5.4 wt%, while the hydrogen index (HI) values are in the range of 50–260 mg HC/g TOC suggesting dominant type III and type III-II kerogen. As the standards state (Tissot and Welte, 1984), the values of TOC and S2 recorded at the Suakin-1 well explain the condensate (API 52°) discovered at this well. Consequently, the source rocks are considered good to very good for condensate and gas generation for these intervals.

Based on these geochemical results, the source of condensate in the Suakin-1 and Bashayer-1 dry gas discoveries is probably in the lower part of the Zeit Formation, an organically-rich deltaic facies. Oil generation from the Rudeis-Kareem Formation cannot be ruled out based on the oil shows encountered in many drilled wells. Vitrinite reflectance (R_o) of 0.64–1.1% and T_{max} values ranging from 423–450°C suggesting source rocks are thermally mature for oil and gas generation. Based on biomarker parameters, these sediments were deposited in shallow to deep marine and deltaic environments under anoxic-suboxic conditions. Despite the minimal exploration activities in the Red Sea Basin, the presence of potential petroleum source rock is not fully understood. The imaging of the sub-salt is a main challenge in pre-salt targets recognition. Hence, this paper hopefully will spark regional interest among Red Sea Basin countries (Saudi Arabia, Egypt, Sudan, Yemen, Eritrea and Ethiopia) and lead to collaboration to investigate the deeper targets since all activities were dedicated to the marginal and shallower sectors.

Petroleum System of the Upper Cretaceous Mukalla Formation in the Qamar Basin, Eastern Yemen

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The Qamar Basin is one of Yemen's Mesozoic sedimentary basins and is located in the Mahara region of Eastern Yemen. The Qamar Basin is dominated by a thick Mesozoic and Cenozoic sedimentary sequence, but wells have not penetrated deeper than the Upper Cretaceous Mukalla Formation in the offshore Qamar Basin. The Mukalla Formation is composed of sandstones, organic-rich shales and coal seams. Published data related to petroleum geology of the Qamar Basin are very limited and the origin of the hydrocarbons in the basin is not fully understood.

This paper will describe the source, reservoir and seal rocks of the Mukalla Formation and their relation to petroleum system in the Qamar Basin. In this regard, the Mukalla Formation sediments in the Qamar Basin have been selected and samples collected from exploration wells to evaluate the petroleum system of the Mukalla Formation. Our systematic analysis of the petroleum system in the basin has identified the coal and organic-rich shales of the Upper Cretaceous Mukalla Formation as the most important source rocks in the basin. They are characterised by a high total organic matter, which meets the standard as a source with good to excellent hydrocarbon-generative potential. Kerogen typing carried out on whole rock samples revealed that the Mukalla samples consist predominantly of type III vitrinite kerogen and type II liptinite kerogen. Vitrinite is the most abundant macerals in the studied samples of the Mukalla Formation. The type II kerogen mainly consists of liptinitic constituents, particularly sporinite, suberinite, resinite, liptodetrinite, cutinite and exsudainite. The kerogen type was also characterised by Rock-Eval pyrolysis analysis. Based on the Rock-Eval data, the Mukalla coal and shale samples contain predominantly a mixture of type II-III kerogen with minor contributions from type II and type III kerogen. This is suggested by the hydrogen index with values ranging from 90 to 410 mg HC/g TOC. Most of the Upper Cretaceous Mukalla samples have vitrinite reflectance (%R_o) ranging from 0.65 to 1.0%, indicating that they are thermally mature and have entered the mature to late mature stage. This is in agreement with T_{max} values (432–453°C). The Mukalla Formation, therefore, contains an effective source rock that has the greatest source potential within the Qamar Basin based on thermal maturity, TOC content, thickness, and widespread distribution.

In this study, the reservoir quality assessment of Mukalla Formation carried out is based on the thin section petrography of selected sandstones from the cored Mukalla Formation in the two wells in the Qamar Basin. The Mukalla sandstones are very fine to medium-grained, moderate to well-sorted quartzarenites. The detrital mineral suite is dominated by monocrystalline quartz grains with minor k-feldspar and plagioclase, and rare heavy minerals and lithic fragments. The most common geologic controls on reservoir quality of the reservoir sandstones in the Mukalla Formation are the framework grain composition, sorting and precipitation of authigenic cements in the pore spaces.

The authigenic mineral is dominated by authigenic quartz, which is ubiquitous on thin syntaxial overgrowths. Kaolinite occurs as clay cements which spill out into adjacent macro pores. Dolomite occurs as minor cements. It is typically patchily developed, partially filling pores and replacing detrital grains. Minor pyrite is also present and is associated with detrital grains. The reservoir quality of the cored interval is moderate to good quality (porosity ranging from 3.5 to 19.3% and permeability ranging between 0.01 and 210 mD), with the better porosity and permeability values recorded from the coarser grained and clay-poor sandstones. The shales of the Mukalla Formation serve as a local seal rock in the Qamar Basin.

In this study the results of the Mukalla source rock have been integrated with the results of basin modeling to improve our understanding of burial history and timing of hydrocarbon generation. Based on basin modeling analysis, thermal and burial histories models indicate that the hydrocarbon generation began in the early Tertiary (Paleocene) and maximum rates of hydrocarbon have been generated during the Eocene time.

Oil in Oman – the main plays so far

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The subsurface geology of Interior Oman is no less spectacular, challenging and scientifically rewarding than the geology of the Oman Mountains. There are multiple hydrocarbon plays, with distinctive oils generated mainly from ancient Ediacaran and Cambrian life, trapped in younger clastic and carbonate reservoirs. Some Palaeozoic sandstone reservoirs have never been buried to any great depth, are barely consolidated and can be crumbled between the fingers. Cambrian salt is involved, in one way or another, in the formation of many of the traps. Much oil in shallow well-connected reservoirs has been altered to heavier viscous oil by anaerobic bacteria.

Hundreds of billions of barrels of oil were probably generated, of which some 9 billion barrels of 'easier to extract' oil has been produced to date, the bulk of this from four well-established plays: Natih, Shu'aiba, Gharif and Palaeozoic Clastics. Continuing to find and extract more oil from these and other plays fundamentally depends on geoscientists and petroleum engineers integrating data to understand how the reservoirs really 'work' and where more oil may remain.

Echinoids from the mid-Cretaceous Umbaraaf and Khadrafi members (Dhalqut Formation) of Dhofar, southern Oman, and their biostratigraphical significance

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The Dhalqut Formation constitutes the upper lithostratigraphic unit of the Albian to Turonian Qamar Group in the eastern part of the Jeza-Qamar Basin of Dhofar. The basin lies across the Yemen-Oman border and is delimited by the Fartaq High in the west (Yemen) and the Marbat High in the east (Oman). The formation thins out towards the eastern edge of the basin (Jabal Samhan area), but increases in thickness towards the international border with Yemen, where it reaches up to 800 m (e.g. Sarfait area). The formation is subdivided into three members that document a major transgressive-regressive cycle. The lowest unit (Umbaraaf Member) is dominated by *Orbitolina*-rich shales and marls with interbedded bioclastic mudstones to wackestones. The middle unit, the Khadrafi Member, is characterized by metre-scale, shallowing-upward rhythmic units defined by basal *Orbitolina*-rich marls, followed by bioclastic (mainly foraminifera, including tests of *Prealveolina* sp.) wackestone to packstone lithofacies with fairly well-preserved echinoid tests and capped by rudistid grainstone to rudstone shoals. The uppermost unit, the Sarfait Member, comprises thick-bedded rudistid packstone, grainstone and rudstone lithofacies (western localities, e.g. Jabal Qamar) with muddier facies at easterly sections within the study area (e.g. Jabal Samhan). The Umbaraaf and Khadrafi members have yielded numerous, fairly well-preserved echinoid tests, both of regular and irregular forms. These include (preliminary identifications): *Heterodiadema libycum, Pedinopsis (P.) sphaerica, Emiratia raskhaimahensis, a pseudodiadematid, Goniopygus* sp., *Orthopsis miliaris, Coenholectypus larteti* and *Hemiaster* spp. These taxa allow to date the Umbaraaf and Khadrafi members as Cenomanian and correlate these units with the Natih Formation of the central Oman Mountains, the Cenomanian of the northeast United Arab Emirates and of the Galala Plateau in Egypt. Previous reports have already demonstrated the close links between Dhofar and other regions in Oman with Lebanon, Jordan, Syria and Egypt. A detailed taxonomic and palaeoecological appraisal of the present material is in preparation.

Prediction improvement of fracture distributions in Middle East carbonate reservoirs by the performing of fracture development mainly in folded carbonates in the Zagros Fold and Oman

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Fractures play a noteworthy role in both the porosity and migration pathways of Middle East carbonate reservoirs. Fracture distribution in folded carbonate reservoirs is controlled by a blend of the tectonic evolution and the mechanical properties of the strata. In order to improve prediction of fracture distributions in Middle East carbonate reservoirs, we are performing studies of fracture development in folded carbonates in the Zagros fold and thrust belt in Iran, Iraq, and the Adam Foothills of Oman. Scales of observation range from satellite imagery studies, through fieldwork, to micro-structural analysis. The orientations and spatial distribution of fracture sets mapped around fractured/faulted anticlines are allied to the deformation history, particularly with respect to folding mechanisms and the likely evolution of stresses during folding. Such genetic controls are thought to be important in ballpark figuring likely reservoir fracture geometries from large-scale, regional information such as tectonic deformation history and evolution of stress regime. Also important in controlling fracture development during folding are the presence of pre-fold and syn-fold faults, at the same time as late or post-fold faulting commonly develops independent fracture clusters. The relationship between lithofacies and fracture properties is discussed, from a number of points of view. Firstly, strain partitioning along weak beds during folding may affect the vertical continuity of fractures. Secondly, fracture characteristics (e.g. density and aperture) depend on the mechanical properties of a given lithology. Thirdly, diagenetically altered units along key surfaces such as hard-

ground surfaces or paleokarstified units exert a geo-mechanical control affecting the development of later fracture arrays. An important issue in fractured carbonate reservoirs is whether much of the fracture porosity has been shattered by calcite cementation. On the other hand, micro-structural observations show that even cemented fractures can resurrect, under certain stress conditions, to act as conduits to fluid flow or as surface cracks held open during reburial by porous sediment infill. Such diagenetic controls highlight the sensitivity of final fracture array properties to the burial and uplift history in relation to folding and fracture cohort.

The Permian–Triassic shark fauna of Oman

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Sharks are predominantly marine top predators that are believed by some to have been relatively unaffected by the Late Permian mass extinction (Schaeffer, 1973; Patterson and Smith, 1987): a view supported by an apparent radiation of fish families across the boundary (Benton, 1998). In contrast, others have stated that chondrichthyan diversity closely follows diversity fluctuations in other aquatic organisms, including a drastic decline during the Late Permian and a subsequent Early Triassic recovery (Compagno, 1990). To ascertain which view is correct, detailed local elasmobranch records from Permian–Triassic (P–Tr) oceanic basins need to be correlated and compared in terms of preservation and biodiversity. Anomalies in the quality of the fossil record, as well as changes in the global shark community can then be identified, and ultimately significant evolutionary developments as a result of the end-Guadalupian crisis and the late Changhsingian extinction event.

The P–Tr deposits of Oman (western Neo-Tethys) have not previously been studied in terms of elasmobranch remains. However, preliminary work showed the potential recovery of rich and well-preserved faunas. Since then, sample residues from the Haushi-Huqf area, Jabal Safra and Wadi Alwa have been picked for material, and a complementary detailed field study has been performed on sections at Wadi Alwa, Wadi Sahtan, Wadi Aday, the Saiq Plateau, Wadi Wasit, Al Buday'ah, Wadi Maqam, Wadi Shuy'ab and the Batain Plain. All samples have been processed using buffered acetic acid and formic acid digestion techniques (Jeppsson and Anehus, 1995; Jeppsson et al., 1999) depending on a limestone or dolomite lithology, respectively. Preliminary data from this study show that the Middle Permian fauna consists of *Glikmanius, Gunnellodus*, three new hybodontiform and three neoselachian genera, and one hybodontiform and three euselachian unidentified taxa. The Early Triassic fauna contains generically different hybodontiforms and is dominated by synechodontiforms. Basic comparisons with key sections elsewhere have shown that the Middle Permian faunas of Oman and Japan are similar, with at least *Glikmanius* in common, but that the East Greenland Middle Permian–Lower Triassic record is distinct, currently sharing no genera with Oman. This new analysis of P–Tr elasmobranchs shows a clear divide between local Permian and Triassic shark communities in Oman, suggesting a possible influence of the extinction on evolutionary patterns, and also expands our knowledge on global distribution patterns and diversity.

Structure and evolution of the southern boundary of the Arabian Plate: From rifting to spreading in the Gulf of Aden

Sylvie Leroy (ISTEP UPMC/CNRS, France), Francis Lucazeau (DFG, IPGP/CNRS, France), Philippe Razin (University of Bordeaux III, France) and YOCMAL Project Team

Rifting in the Red Sea and the Gulf of Aden was a long-term process that started in the Permian–Triassic and ended with the separation of the African and Arabian plates. With its extensional system affecting the intra-cratonic basement, the Gulf of Aden is undoubtedly one of the best places to improve our understanding of continental rifting and ocean crust formation. The relatively young rift (< 35 Ma) was followed by the emplacement of an active spreading ridge (17.6 Ma). The conjugate margins are easy to correlate and the pre-rift sediments, the basement and syn-rift sediments as well as the geometry of the associated faults can be visualised and sampled locally. The crustal structure of the entire system and its ocean-continent transition (OCT), as well as the oceanic accretion, can be visualised on a kilometric scale; and the kinematics can be finely resolved. These conjugate margins are volcanic to the west, where they are influenced by the Afar hotspot, and non-volcanic east of longitude 46°E. The combined use of magnetics, gravity, seismic reflection, field observations (tectonic and sedimentological) and oil-well data allow us to obtain better constraints on the timing of continental rifting and seafloor spreading (Encens Cruise, 2006). From the Permian–Triassic to the Oligocene, the African-Arabian Plate was subject to distributed extension, probably due, at least from the Cretaceous, to tensile stresses related to the subduction of the Tethyan slab in the north. In Late Eocene, 35 Ma ago, rifting started to localise along the future area of continental breakup (Leroy et al., submitted).

Initially guided by the inherited basins (Bellahsen et al., 2006; d'Acremont et al., 2005; d'Acremont et al., 2006), continental rifting then occurred synchronously over the entire gulf before becoming localized on the northern and southern borders of the inherited grabens, in the direction of the Afar hotspot. In the areas with non-volcanic margins (in the east, Oman part), the faults marking the end of rifting trend parallel to the inherited grabens. Only the transfer faults crosscut the inherited grabens, and some of these faults later developed into transform faults. The most important of these transform faults follow a Precambrian trend. Volcanic margins were formed in the west of the gulf, up to the Guban Graben in the southeast and as far as the southern boundary of the Bahlaf Graben in the northeast. Seaward dipping reflectors (SDRs) can be observed on many oil-industry seismic profiles. The influence of the hotspot during rifting was concentrated on the western part of the gulf. Therefore, it seems that the western domain was uplifted and eroded at the onset of rifting, while the eastern domain was characterized by more continuous sedimentation (Leroy et al., submitted).

The phase of distributed deformation was followed by a phase of strain localization during the final rifting stage, just before formation of the Ocean-Continent Transition (OCT), in the most distal graben (DIM graben) (Autin et al., 2010a; Autin et al., 2010b; Leroy et al., 2010). About 20 Ma ago, at the time of the continental break-up, the emplacement of the OCT started in the east with exhumation of the subcontinental mantle (Leroy et al., 2010b). Farther west, the system was heated up by the strong influence of the Afar hotspot, which led to breakup with much less extension. In the Gulf of Aden (*sensu stricto*), up to the Shukra El Sheik Fracture Zone, oceanic accretion started 17.6 Ma ago. West of this fracture zone, oceanic accretion started 10 Ma ago, and 2 Ma ago in the Gulf of Tadjoura (Leroy et al., submitted).

Post-rift deformation of the eastern margins of the Gulf of Aden can be seen in the distal and proximal domains (Bache et al., 2011). Indeed, the substantial post-rift uplift of these margins could be associated with either the continental break-up, or activity of the Afar hotspot and related volcanic/magmatic activity. Uplift of the northern proximal margin was still active (e.g. stepped beach rocks) and active volcanoes can be inferred at depths of between 70 and 200 km beneath the margin (at 5–10 km distance from the coast) (Basuyau et al., 2010). On the distal margin, heat flow measurements show a high value that are associated with post-rift volcanic activity and the development of a volcano (with flows and sills) shortly after the formation of the OCT (Lucazeau et al., 2009; Watremez et al., 2011; Autin et al., 2010b; d'Acremont et al., 2010). Heat-flow measurements on the whole margin suggest the emplacement of a recent thermal anomaly in the upper mantle below the distal margin, emplaced after continental break-up and onset of seafloor spreading. Such an anomaly could be an intrinsic feature of several other continental margins, related to the temperatures differences between continents and the newly formed ocean creating small-scale convection cells. This may be one possible explanation for the late syn-to early post-rift shallow water sediments in the deep offshore of the Atlantic margins (Lucazeau et al., 2008, 2009, 2010; Leroy et al., 2010b).

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Tracking the paleolatitude and paleo-azimuth variations of the African and Arabian plates since coalescence of Pangaea in the Late Carboniferous using the paleomagnetic poles of the stable Europe and North American craton

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The present research is an attempt to predict the track of the African and Arabian plates, the remnant heart of Gondwanaland, since Late Carboniferous. A six-step analysis was adopted by the authors to define nine successive paleo-tectonic positions at nine adequately-spaced geologic boundaries, since the amalgamation of Pangaea in the Late Carboniferous, using paleomagnetic poles of the well-studied Stable Europe, Greenland and the North American craton. The selected high-quality poles are rotated to the African coordinates using the Paleomagnetic Euler Pole (PEP) rotation technique.

(1) In the first step 92 poles from Stable Europe and Greenland were selected from the world database covering the chosen post-Carboniferous time stations. (2) These poles are rotated to the North American coordinates through closing the North Atlantic Ocean using published Euler Poles with appropriate rotation angles for each of the selected geologic times. (3) In the third step, 72 reliable poles representing the North American were selected from the database. (4) The rotated Stable Europe Poles together with the North American poles were, then, rotated to the African Coordinates via closing the Central Atlantic Ocean using variable Euler Pole parameters. (5) The pre-Late Cretaceous poles (rotated from Stable Europe and the North American craton to Africa) were, then, internally rotated from NW Africa to NE African coordinates using Euler Pole rotations. (6) Finally, the paleomagnetic directions (inclinations/declinations) corresponding to the rotated poles were calculated at the reference latitude of Cairo (30°N and 31°E), then the mean paleo-inclination, mean paleo-latitude and the mean paleo-declination (which reflects the paleo-azimuth of Africa and Arabia) were determined at each of the chosen geologic boundaries.

Based on the above-mentioned analysis, the reliable paleomagnetic poles rotated from Stable Europe, Greenland and the North American craton to the African coordinates revealed that:

(1) In terms of paleo-latitudes, the African and Arabian plates seem to have moved northwards about 60° of latitude during the last 300 Ma. In the Early Pangaea time (Late Carboniferous–Early Permian), Cairo (presently at 30°N was at 30°S within Africa), generally was between 30°S and the South pole. Just before the dispersion of Pangaea (Late Triassic–Early Jurassic), North Africa and the Arabian Plate became almost equatorial but still mostly south of the Equator. The first time that northeast Africa crossed the Equator was during the Late Cretaceous.

(2) In terms of paleo-azimuth, from the Carboniferous to the end of the Cretaceous, the African and Arabian plates have generally been in a clockwise position with respect to the present-day N-S meridians but at variable degrees. At the Cretaceous/Tertiary boundary the paleomeridian of the African Plate was almost in the same present-day orientation but with Cairo just north of the Equator.

Thermal regime of the Arabian Plate, Red Sea and Gulf of Aden

Francis Lucazeau (DFG, IPGP/CNRS, France), Frédérique Rolandone and
Sylvie Leroy (ISTEP UPMC/CNRS, France)

The present-day thermal regime of the Arabian Plate is primarily affected by the dynamics of the Afar plume and the rifting of the Red Sea and Gulf of Aden since Oligocene. This rift-plume interaction is now unique on the Earth, but represents a modern example of a common process at geological times, for example, during the formation of the Atlantic margins. Therefore the present-day thermal regime in this area can shed light on some key questions related to the early stages of older continental margins. We describe here some characteristics of the Arabian Plate's thermal regime and the possible consequences for mature margins. This work is mostly based on the analysis of heat flow data, including a large set of new acquisitions in Oman, surface topography and subsidence, and global and regional seismic tomography.

The Arabian Plate is mostly a Precambrian shield covered on its eastern part by a Phanerozoic platform. One would therefore expect that the thermal regime of the Arabian Plate, before the Afar plume and rifting activity, was related to a thick and stable lithosphere, as other shields on the Earth. First heat flow measurements on the shield in Saudi Arabia (Gettings, 1981) supported this idea, as the values (36–45 mWm^{-2}) were similar to the typical shields values. But the recent seismological results based on S-waves receiver functions (Hansen et al., 2007) have shown that the lithosphere is rather thin, 100 km or less below the shield and 150 km below the platform. At about the same time, new heat flow measurements on the Arabian Shield in Jordan were published (Förster et al., 2007), showing significantly higher values (ca. 60 mWm^{-2}) than in Saudi Arabia. Förster et al. (2007) claimed that their measurements are more reliable than the previous ones and that the average represents the true regional value for the Arabian Plate, consistent with the observed lithosphere thickness.

In 2007, we started the YOCMAL project including a task of heat flow and heat production measurements in Yemen and Oman. Heat flow was obtained by processing oil exploration data in both Yemen and Oman, and by conventional measurements (thermal gradient in wells and thermal conductivity in the lab) in the south and north of Oman. The surface heat flow in these different locations is homogeneously low (45 mWm^{-2}). The heat production from the Mirbat Precambrian basement is also low (0.7 μWm^{-3}). A theoretical stable geotherm for the Arabian Platform can be inferred from these values and its intersection with the isentropic temperature profile predicts a thermal lithosphere thickness of about 140–150 km, consistently with the seismological observations. Therefore, we suggest that the surface heat flow can vary significantly within the Arabian Plate as a function of crustal radiogenic heat production, as it varies in other shields on the Earth. The stable lithosphere thickness would be 150 km, and the progressive thinning from the Red Sea would be caused by the thermal erosion of the plume material, not old enough to be detected at surface.

The Afar plume mostly affects the base of the Arabian lithosphere along the Red Sea and the western part of the Gulf of Aden. The common interpretation for this widespread influence is attributed to the channeling of the asthenospheric magma by the rift (e.g. Ebinger and Sleep, 1998). The weak penetration in the Gulf of Aden is probably due to the important segmentation of the rift, which introduces discontinuities: the major one is the Alulah Fartak transform fault, which introduces a ridge jump of more than 100 km. This represents probably the easternmost limit for the influence of the Afar plume. Therefore, the comparison of the eastern Gulf of Aden and the Red Sea, although they have not evolved simultaneously, can provide some information on the thermal processes related to "passive rifting" and those related to the plume.

Therefore, the eastern Gulf of Aden can be considered as a passive rift structure, now in a stage of post-rift subsidence since the beginning of break-up at 17.6 Ma (Leroy et al., 2004). In addition to the unaffected deep structure revealed by seismological tomography, one can notice the absence of significant rift shoulders. We conducted a detailed marine heat flow survey in 2006 (ENCENS-FLUX) that provided 162 new measurements along 8 profiles collocated with seismic profiles (Lucazeau et al., 2008, 2010). The transition from a low heat flow near the continent to a high heat flow near the ocean is quite abrupt and occurs at the limit between the continental part of the margin and the so-called OCT (Ocean-Continent Transition, in the deep margin). The other interesting feature is the uniformly high heat-flow (ca. 120 mW/m^2 after sedimentation corrections) observed in the OCT and oceanic domains, when one expects a progressive increase with decreasing age. Similarly, there is almost no differential subsidence of the ocean floor from the ridge axis. We have interpreted these observations as a consequence of small-scale convection that homogenizes temperatures in the deep margin and oceanic domains. In addition to these large-scale processes, we have observed some evidences of meteoric hydrothermal circulations through the identification of recharge zones that mine the nearby surface heat flow. However, it seems that these circulations are totally inhibited when the basement relief is totally covered by sediments.

The Red Sea rift is less mature than the eastern Gulf of Aden, as only parts have now reached the oceanic stage. No heat flow survey was carried out recently, but existing data from literature show fundamental differences with the eastern Gulf of Aden. First, the heat flow is high at the rift axis (200–300 mW/m^2) and then decreases rapidly up to ca. 90 mW/m^2 on the Arabian Plate. This trend in the axial part of the rift requires an extremely high extension focused in the axial part, as noticed by Martinez and Cochran (1989) and the absence of small-scale convection process that would homogenize surface heat-flow. Secondly, an abrupt transition from high value in the rift to the low values in the continent occurs 50 km within the continent, while it occurs near the OCT in the Gulf of Aden. Regarding the topography, the borders of the Red Sea are flanked by high amplitude shoulders that post-dates rifting (McGuire and Bohannon, 1989).

The comparison of these two domains on the borders of the Arabian Plate shows that the thermal effect related to rifting should be limited to the deep margin only. With the additional effect of the Afar plume, the proximal margin is also affected by thermal erosion: this explains the thinner lithosphere and the preeminent rift shoulders. In order to explain higher heat flow in the proximal margin, one should probably have non conductive processes, but further interpretation requires more data in the transition zone. As a general consequence for mature continental margins, the thermal regime during the late stage of rifting and the early post-rifting stage is "hotter" than initially thought with the assumption of pure shear extension.

Dynamics Basin and petroleum potential of the Lower Cretaceous series in the Jeffara Basin in southeastern Tunisia

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The Jeffara escarpment spans 400 km from southeastern Tunisia to southwestern Libya, and marks the northern edge of the Ghadames Basin. The sedimentary series in the study area and wells correlations indicate sedimentary sequences fluctuate considerably in lithofacies and thicknesses. The correlation of subsurface sections along the study area shows the major tectonic unconformity divides the Early Cretaceous sedimentary pattern. It is dated as Late Aptian and is commonly associated with the European "Austrian" tectonic phase marked by the transition from a siliciclastic sedimentation in the Lower Cretaceous to a carbonate-dominated sedimentation regime in the Upper Cretaceous. These important regional unconformities can be associated with intra-plate deformation linked with the opening of the central segment of the South Atlantic and the Equatorial Atlantic oceans. The stratigraphical modeling based on petrologic evidence from log details helps to describe petrophysics parameters, which integrated geological interpretation and reservoir distribution for 3-D model building. The objectives of the study were to assess Lower Cretaceous reservoirs in the Jeffara domain, offshore Tunisia, and to indicate a development plan, including the Lower Cretaceous facies distribution.

Upper Cenomanian – Lower Turonian ammonite biostratigraphical framework for the southern Neo-Tethys Margin from Morocco to Oman

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The Cenomanian–Turonian ammonite biostratigraphical framework for the southern Neo-Tethys Margin (North Africa, Middle East and Arabian Peninsula) is more and more well known. This allows proposing rather precise correlations with ammonites along a West-East transect from Morocco to Oman. On the basis of a critical review of the ammonite taxonomy of this period, 11 Upper Cenomanian–Lower Turonian bioevents (A-K) can be highlighted. They are reproducible throughout several regions of the southern Tethyan margin even if some gaps remain, at least at the stage

boundary. Here they are correlated with the stratotype (GSSP) defined in the Western Interior (USA) for the base of the Turonian. Making correlations with the standard zonation remains sometimes very hypothetic because the major part of the southern Tethyan ammonite taxa are not present in the stratotype and their time-ranges remain not well known with different time-interval interpretations.

Upper Cenomanian bioevents
A - *Neolobites vibrayeanus*
B - *Calycoceras naviculare* and *Eucalycoceras pentagonum*
C - *Euomphaloceras septemseriatum* and *Nigericeras gadeni*
Metengonoceras dumbli and *Metoicoceras geslinianum* occupy an unclear position, possibly longer range species covering partly A, B bioevents for the first one and B, C for the second.
D - *Pseudaspidoceras pseudonodosoides, Cibolaites (?) africaensis* and *Pseudaspidoceras tassaraensis*
E - *Vascoceras gamai*
Pseudaspidoceras paganum and *Fikaites* maybe included in E-F
F - *Vascoceras cauvini*
G - different species of *Vascoceras*

Lower Turonian bioevents
H - *Pseudaspidoceras flexuosum* and *Vascoceras durandi*
? including *Thomasites gongilense*
I - *Pseudotissotia nigeriensis*
J - *Wrightoceras wallsi*
probably including *Eotissotia* and *Hoplitoides*
K - *Kameruniceras turoniense* and *Mammites nodosoides*
Thomasites rollandi range covers partly H, I, J bioevents and *Choffaticeras luciae* partly J and K bioevents.

Special attention is dedicated to Oman. At least 5 ammonite assemblages based on the literature [Kennedy and Simmons 1991; Meister and Rhalmi 2002; Meister and Abdallah, 2005] and recent collections in the Wasia Group of the Natih Formation in Jabal Madmar, Jabal Khaydalah, Jabal Salakh, Jabal Nahda and Jabal Fitri can be recognized for the Upper Cenomanian–Lower Turonian. They correspond to the *Neolobites vibrayeanus - Calycoceras* assemblage [A], *Metoicoceras geslinianum – Gentoniceras assemblage* [B-C], *Vascoceras durandi - ?Pseudaspidoceras* assemblage [H], *Thomasites* cf. *gongilensis – Parammamites* assemblage [I] and the *Eotissotia – Wrightoceras* assemblage [J].

The ammonite paleogeographical distribution for three Oman ammonite bioevents is illustrated.

(1) The *Neolobites vibrayeanus* bioevent [A] can be followed from Morocco until Oman. It precisely corresponds to the *Calycoceras guerangeri* Zone (lower part of the Upper Cenomanian) and marks the maximum southern extension of the sea on the African craton at this period. Almost everywhere this bioevent seems to be associated with a marine transgressive event.
(2) *Metoicoceras geslinianum* (d'Orbigny) also is present along this West-East transect. This species represents the index species of the *M. geslinianum* Zone (middle part of the Upper Cenomanian) and corresponds to the bioevent B-C.
(3) The *Wrightoceras*, again presents from Morocco until Oman, correspond to the bioevent J and is a marker of the upper part of the *Watinoceras coloradoense* Zone (middle part of the Lower Turonian).

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Geological constraints on reserves distributions and fluid migration in carbonate-reservoired petroleum systems

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Geological processes for the distributions of oil and gas reserves, as a function of burial and thermal history, are under evaluation. The main objective of this work is to provide factual constraints for quantitative predictions and risk reduction in the hydrocarbon exploration, regulatory and government policy operations. Recent advancements in diagenesis have resulted in predictive models as a function of burial and thermal history (Bjørkum and Nadeau, 1998; Buller et al., 2005; Nadeau, 2011). Reservoir quality in these carbonate reservoired petroleum systems has also been examined by Ehrenberg and Nadeau (2005), as well as Ehrenberg et al. (2008, 2009). This study establishes a framework for evaluating this "Golden Zone" model in carbonate settings, particularly in the Rub' al-Khali and Central Arabian Foreland basins. Global observations of carbonate reservoirs, their top seals and overpressure are examined for their use in predicting the distribution of oil and gas reserves in sedimentary basins.

Global reservoir data provides information on the distribution of oil (Figure 1) and gas reserves as a function of reservoir temperature. Globally, 75% of total reserves (86% of oil) in carbonate reservoirs occur within the range of ca. 80° and 120°C (Darke et al., 2004).

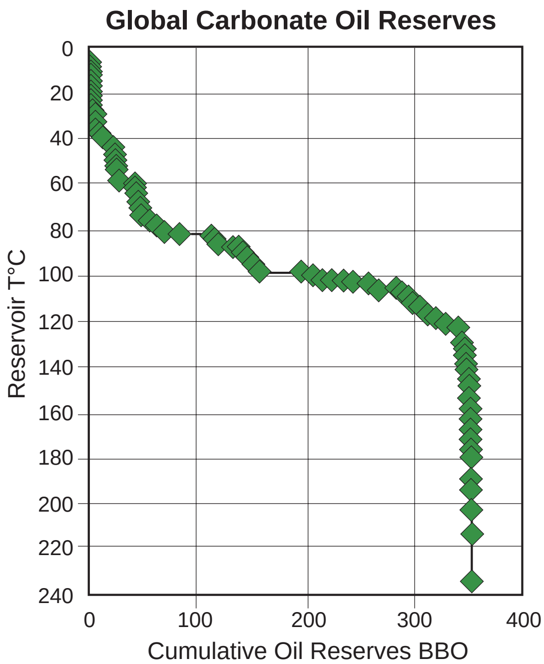

Figure 1: Cumulative global oil reserves as a function of reservoir temperature. Note that ca. 86% of the reserves occur in reservoirs between 80°C and 120°C (after Darke et al., 2004).

Socotra volcanics: Age and tectonic significance

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The Socotra Archipelago, Yemen, in the Arabian Sea lies south of the Yemen/Oman border and east of northernmost Somalia. The archipelago comprises the main island of Socotra and a number of smaller uninhabited islands. Socotra has been the subject of limited geological investigation despite the fact that it represents the largest exposure of basement in the region. Prior to Miocene rifting, Socotra occupied a position adjacent to the Precambrian rocks east of Marbat in Oman (Fournier et al., 2007), an area now devoid of basement exposure. Thus the age and geochemical signature(s) of Socotra's volcanism is important for defining the time and tectonic setting associated with their genesis.

Socotra comprises ca. 860–800 Ma granitoids and granitic gneisses (Whitehouse et al., 2012) intruded by granitoids and their inferred extrusive equivalents; the latter include effusive and pyroclastic volcanic rocks, as well as hypabysal dikes. These are overlain by a thick sequence of Cretaceous and younger cover rocks (mostly limestones). The best exposures of the volcanic association occur in the eastern part of the island, south and east of the Haggier Mountains, and these were sampled for age, petrographic and geochemical analysis in order to determine the tectonic setting associated with this volcanism.

The sequence is dominated by rhyolites and basalt is relatively rare. In thin-section the samples are dominated by disequilibrium textures, e.g. resorption, sieving, incongruent phenocryst zoning and incompatible phenocryst compositions, reaction rims, and mineral pseudomorphs, associated with the mixing of discrete magma batches which may explain the relative absence of basaltic compositions. U-Pb zircon SIMS geochronological results indicate that the rocks are Neoproterozoic (ca. 720 Ma) in age. Younger cross-cutting dikes are high-silica rhyolites and associated with rifting of continental crust; these have yet to be dated but are likely to be similar in age to the youngest granitoids on the island which are also ca. 720 Ma. This would indicate Cryogenian rifting of the Arabian Shield.

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Foraminifers of the Natih Formation (Cenomanian–Turonian) of the Adam Foothills, Oman: Preliminary results

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Along the southern edge of Al Jabal al-Akhdar, the Adam Foothills offer some quality outcrops of autochthonous Cretaceous series of Northern Oman. They form a row of abraded anticlines named from east to west: Jabal Madar, Jabal Madmar, Jabal Khaydalah (or Hinaydil), Jabal Salak, Jabal Nadah and Jabal Fitri (or Qusaybah). Part of the Wasia Group (middle Cretaceous), these rocks form a thick sequence of carbonate rock made up of two formations. The upper one, the Natih Formation, ranges from uppermost Albian to Lower Turonian and is subdivided into seven informal members designated by the letters A to G from top to base (van Buchem et al., 1996, 2002 cum biblio). The few outcrop studies of the Natih Formation consider most often the biostratigraphic and lithostratigraphic aspects of a limited number of sections. Detailed field sections together with accurate data on foraminifers and ammonites are the aim of this work. Six sections representing an East-West 100 km transect through the Adam Foothills and ranging from Natih E to Natih A members are under study. Hardgrounds 5a, 6a, 7a and 8a of van Buchem et al. (1996) are recognized and allow good correlations mainly through the Natih C and D members. Ammonites allow precise dating as well as good correlations with the *Acompsoceras* and *Metengonoceras* beds within Natih E, *Neolobites* and *Metoicoceras* within Natih B, and *Vascoceras*/*Wrightoceras* beds within Natih A. The echinoderm level of Smith et al. (1990) within Natih C is also a good marker.

Distinct environments through Natih time are reported by Philip et al. (1995) and van Buchem et al. (1996, 2002). The different ramp facies of these authors (mainly discriminated by stratonomical –

sedimentological dissimilarities) contains very similar microfauna. Largely developed during Natih E and Natih C-D, these ramp limestone reveal an association mainly made up of *Biconcava bentori, Biplanata peneropliformis, Cisalveolina* sp., *Praealveolina* gr. *cretacea, Dukhania conica, Chrysalidina gradata, Cuneolina* gr. *pavonia, Dicyclina schlumbergeri, Epistomina* sp., *Glomospira* sp., *Haplophragmoides* sp., *Montcharmontia compressa, Nezzazata* spp. *(N.* gr. *simplex, N.* gr. *gyra, N.* gr. *isabellae), Nezzazatinella* cf. *picardi, various Orbitolinids (Orbitolina conica, Orbitolina spA., Heterocoskinolina ruskei), Praebulimina sp., Pseudonummo loculina sp., Pseudorhapidionina cf. laurinensis, diverse and abundant miliolids (Quinqueloculina* spp.*), Pseudolituonella reicheli, Rotorbinella mesogeensis, Spiroloculina* spp., *Spiroplectammina* sp., *Trochospira avnimelechi, Trocholina* spp. *(T. altispira, T. arabica, T. lenticularis)*, textularidae, various algae, ostracods, microbivalves shells.

The intra-shelf basin of Natih B also has its typical association composed of various small hedbergellids (*Asterohedbergella asterospinosa, Muricohedbergella?*), *Macroglobigerinelloides ultramicrus, Heterohelix moremani, Epistomina* sp., *Praebulimina* sp., *oligosteginids* (mostly *Pithonella spaerica* with possible *Calcisphaerula innominata*), *Saccocoma*, microbivalve shells and ostracods. Some *Trocholina* spp. (*T. altispira, T. arabica), Rotorbinella mesogeensis,* textulariids*, Spiroplectammina* and rare miliolids and algae are coming back within Natih A.

Specific determination and systematic, as well as detailed repartition along our sections is in progress. Along with the dating with ammonites and correlations of hardgrounds, this work will give an accurate image of the microfaunal evolution of the Natih shelf along a transect through the Adam Foothills of Oman.

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The Sumeini Group in Oman: Northern Gondwana Slope development in a Permian–Triassic Environment

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The Oman Mountains expose the Middle Permian to Cretaceous Sumeini Group belonging to the southern margin of the Neo-Tethys Ocean. The Sumeini Group is a thick sequence (about 2,500 m) of slope carbonate deposits that crops out near the border between Oman and the United Arab Emirates. It tectonically overlies autochthonous Eocene limestones and is overlain by sediments from the Hawasina Nappes. The group is also described as para-autochthonous with a 5–30 km displacement with respect to the "autochthon". The Sumeini Group includes four formations: Maqam Formation (Middle Permian to Lower Jurassic), Mayhah Formation (Middle and Upper Jurassic), Huwar

Formation (uppermost Jurassic to Cretaceous) and Qumayrah Formation (Upper Cretaceous). The Maqam Formation (ca. 1,700 m thick) is further subdivided into six members, A, B, C, D, E and F. We focus in our study on the Permian to Lower Triassic part of the Maqam Formation (members A to D) with new results including paleontology, stratigraphy, sedimentology and geochemistry.

Member A is 80–250 m thick and tectonically truncated at the base. It begins with shales and thin-bedded limestone or dolostones followed in its upper part by outer-shelf fossiliferous limestones. New conodont dating give a Roadian to Wordian age for its base and Late Capitanian age close to the Guadalupian/Lopingian boundary for its top.

Member B consists of a 415 m thick sequence of thin-bedded to massive dolostone with numerous dolorudite intervals and in the lower part locally abundant breccia. This member is latest Capitanian and Lopingian in age. The upper part consists of 50 m of dm-sized bed of cherty dolostone and cherts rich in sponge spicules. It must be emphasized that a silica-rich interval is widespread on NW Pangea margin but the biogenic silica factories collapsed near the end of the Permian Period throughout the world. The conodonts *C.* cf. *zhangi* near the top of unit B, and the decrease in $\delta^{13}C$ carbon-isotope values typical for the end-Permian extinction interval, indicate a Late Changsinghian age.

Member C comprises a thin (25 m) Griesbachian–Dienerian part and a thick (up to 900 m) Smithian part. It starts with 3 m of red shales and siltites, overlain by platy lime, and then dolo-mudstone more or less marly comprising several slump levels. The first lime mudstone bed gave the conodont *H. parvus*, markers of the base of the Triassic. *H. postparvus* and *I. isarcica*, index of the second Griesbachian conodont zone follows. In sharp contrast to the well-bioturbated Member B, the overlying basal meters of Member C are well laminated with no evidence of bioturbation. This dramatic loss of the burrowing infauna indicates the appearance of oxygen-poor waters. This interval of the end-Permian extinction and base of the Triassic records a gradual decrease in $\delta^{13}C$ values marked by a sudden significant drop of ca. 6‰ at the extinction boundary. Contrary to most sections that show an onset of carbonate deposition right after the extinction event, this location shows a significant drop in total carbon content suggesting disruption of carbonate sedimentation associated with the extinction event.

The overlying thin Lower Smithian (7 m) is characterized by vermicular limestones. The incredibly thick Middle and Upper Smithian sediments (up to 900 m) consist essentially of platy limestones and calcarenites. Channelizing beds of intra-formational calcirudite are also part of this succession. Carbonate sedimentation of the C member ended abruptly in the Early Spathian. The overlying Member D is characterized by deposition of 10 m brown shale with rare mm-thick sandstone and marls beds, follow by a 75 m thick sequence of green terrigenous siltstone. There are no age diagnostic fossils (Spathian–Anisian?).

This succession records the break-up and the early development of the Oman continental margin, subsidence and possible tectonic flexure or faulting during the Mid- and Late Permian. Almost no platform export during the Induan and the Spathian are observed, but an incredible high sedimentation rate during the Mid- to Late Smithian is developed with submarine fan deposits.

Magmatic and tectonic development of the Oman Ophiolite: High precision U/Pb zircon geochronology of the plutonic crust

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New high-precision single grain U/Pb zircon geochronology from the Oman Ophiolite provides insight into the timing and duration of magmatism during formation of the plutonic oceanic crust and the tectonic development of the ophiolite. We have dated 29 gabbro, gabbroic pegmatite and trondhjemite/tonalite samples from the Wadi Tayin, Sumail, Rustaq, Haylayn and Fizh massifs. Single grain 206Pb/238U dates, corrected for initial Th exclusion, range from ca. 95.1–99.2 Ma, with most dates clustered between ca. 95.1–96.4 Ma. Single grain analyses have uncertainties that are generally between ± 0.05–0.4 Ma.

Wadi Tayin massif: The center of the Wadi Tayin massif includes a well preserved and exposed crustal section that is one of the best areas in the ophiolite to study oceanic crustal accretion. The dated samples were collected along a ca. 30 km transect perpendicular to the sheeted dike trend. Eight upper-level gabbros, one trondhjemite, one tonalite and two gabbroic pegmatites have 206Pb/238U dates that range from ca. 95.5–99.2 Ma, with most dates clustered between 95.5–96.4 Ma. Three upper-level gabbros and a gabbroic pegmatite from the base of the crust have > 1 Ma intra-sample variability in single grain dates, suggesting assimilation of older crust during formation or crystallization of the magmas. Whole rock Nd isotopic data from eight samples have eNd(96 Ma) ca. +8, indicating that either the assimilated material had an isotopic composition that was similar to other ophiolite gabbros or only a small volume of material was assimilated. The data are consistent with crustal assimilation during propagation of a younger ridge into older oceanic crust. The range in dates along the length of the studied Wadi Tayin transect also provides a quantitative estimate of the spreading rate and is most consistent with formation at a fast- to super fast-spreading ridge with half-rates of 50–100 km/Ma.

Sumail massif: The seven dated samples in this massif were selected to better constrain the tectonic development of the ophiolite. Previous mapping and structural analyses in the Sumail, Wadi Tayin and Rustaq massifs have demonstrated systematic changes in the orientation of the sheeted dikes: in the Sumail massif, dikes in the center of the massif are oriented NW-SE, while dikes in northeast of the massif are oriented NE-SW, although there is some variability in this area. The change in orientations has been attributed to a younger NW-SE trending ridge propagating into older crust formed at a NE-SW trending ridge (e.g. Boudier et al., 1997). To test this model we dated gabbros and felsic plutonic rocks from each area. Two gabbroic samples from the center of the massif yielded 206Pb/238U dates of ca. 95.7–96.4 Ma. In contrast, a gabbro and two felsic intrusions from the north of the massif yielded significantly younger 206Pb/238U dates that are consistent with crystallization ages of ca. 95.3–95.5 Ma. The offset in dates is the opposite of that expected for propagation of a younger NW-SE ridge and suggest that either the NE-SW oriented dikes formed at a younger ridge that propagated into older crust formed at a NW-SE trending ridge, or the dated samples from the northeast of the massif reflect late magmatism that intruded older crust. Two tonalite and trondhjemite samples that intrude the middle and lower crust in the center of the massif yielded 206Pb/238U dates of ca. 95.0–95.4 Ma and may be related to either the younger magmatism in the north of the massif or initial emplacement of the ophiolite.

Rustaq, Haylayn and Fizh massifs: More limited data from these northern massifs provide insight into temporal variations in magmatism from south to north in the ophiolite. Two gabbros from the Rustaq and Haylayn massifs have dates of ca. 95.5–95.6 Ma, and a single gabbro from the Fizh massif records dates of ca. 95.2–95.3 Ma, suggesting that the northern massifs are younger than the southern Wadi Tayin and Sumail massifs. Trondhjemite/tonalite dikes and plutons in each of the northern massifs yielded similar, but less precise dates. A trondhjemite intrusion into the mantle in the Haylayn massif yielded a younger date of ca. 95.2 Ma. Similar intrusions in the Haylayn massif are enriched in light rare earth elements (LREE) and fluid mobile trace elements (Rollinson, 2009) and have evolved Sr isotopic compositions (Briqueu et al., 1991), and have been interpreted as either syn- or post emplacement intrusions (Rollinson, 2009).

Taken together, the new U/Pb dates from throughout the ophiolite constrain the relative timing of different magmatic series. The dated samples include six pairs of tonalite/trondhjemite plutons or dikes and adjacent or nearby upper-level gabbro from directly below the sheeted dikes. In each of these pairs, the tonalite/trondhjemite and gabbro dates overlap within uncertainty, indicating that the felsic and mafic magmas were coeval. To constrain the timing of wehrlite intrusions in the Wadi Tayin massif, we dated a pegmatitic gabbro dike that intrudes layered gabbro in the middle crust. Nearby pegmatite intrusions cross cut a wehrlite body, suggesting that the pegmatites are coeval with or younger than the wehrlite. The pegmatite data are within uncertainty of the dates from the two closest upper-level gabbro samples, suggesting that the age difference between the wehrlite and upper-level gabbros is smaller than the analytical uncertainties or intra-sample variability in single grain dates. Finally, late felsic intrusions in the middle and lower crust and upper mantle in the Sumail and Haylayn massifs are ca. 0.2–0.5 Ma younger than nearby upper-level gabbros. If these intrusions are related to ophiolite emplacement, the data provide a tight constraint on the time interval between the end of ridge magmatism and initial emplacement of the ophiolite.

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Barremian to Turonian stratigraphy of the Jeza-Qamar Basin and its hydrocarbon potential, Dhofar, Oman

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The Jeza-Qamar Basin is a Mesozoic rift basin which straddles the Oman-Yemen border; about one-third of the basin occurs within the Oman territory (Dhofar) whereas the rest is in Yemen. The basin is filled by Jurassic (confined in the axial center in Yemen) and Cretaceous sedimentary sequences. The Cretaceous sedimentary sequence onlaps uplifted flanks of the basin, becoming progressively younger towards the highs: Fartaq High in Yemen and the Marbat High in Oman. In the Dhofar, Barremian to Maasctrichtian strata that include, in an ascending order, Qishn, Kharfot, Dhalqut, Qitqawt, Samhan and Sharwayn formations form Cretaceous basin-fill. The lower three formations that span from Barremian to Turonian in age were studied in this project and consist of prominent intervals with high potential reservoir qualities, structural and stratigraphic traps and promising source rock horizons. The Qishn Formation (Barremian to Aptian) is characterized by a basal (ca. 40 m thick) sandstone (Shabon Member), a middle *Choffatella*-bearing lime mudstone to packstone lithofacies and subordinate dolomudstone interbeds (Hinna Member) and an upper, *Praeorbitolina*-bearing, bioclastic packstone to grainstone lithofacies interbedded with sucrosic dolostone lithofacies (Hasheer Member). The latter is unconformably overlain by the Kharfot Formation (Albian) which is characterized by shallowing-upward rhythmic units of *Orbitolina*-rich marls that grade into bioclastic packstone to rudstone lithofacies.

The Dhalqut Formation (Late Albian–Turonian) conformably overlies the Kharfot Formation and consists of lower member (Umbaraaf Member) dominated by *Orbitolina*-rich shales and marls, oyster- and rudist-rich biostromes and subordinate storm-deposited bioclastic and/or oolitic grainstones. A middle member (Khadrafi Member) consists of meter-scale, shallowing-upward rhythmic units of *Orbitolina* marls grading to bioclastic wackestone to packstone, which is in turn succeeded by rudistic rudstone lithofacies. This member contains *Prealveolina* foraminifera and well-preserved echinoid shells. The Surfait Member is the uppermost unit of the Dhalqut Formation; it is characterized by thickly to massively bedded, clean bioclastic packstone to rudistic rudstone lithofacies (western sections). Bioturbated and unbioturbated bioclastic mudstone to wackstone lithofaces dominate the eastern sections of the study area (e.g. Jabal Samhan).

The most attractive reservoirs in this stratigraphic succession are the Shabon sandstones (up to 25%) and Hasheer dolomites (up to 15%), and some horizons within the Dhalqut Formation. The Late Jurassic Madbi shales and Naifa carbonates, rock units that sourced the oil in the adjacent Say'un-Al-Masila Basin, occur in the axial part of the Jeza-Qamar Basin. Total organic carbon (TOC) content analysis of a few samples from petroleum-smelling mudstone horizons in the Kharfot and Dhalqut formations gives low TOC content but more work is required. Structural elements associated with opening of the Gulf of Aden and lateral facies changes define significant structural and stratigraphic traps. Existence of tight mudstone, wackestone and marl lithofacies (e.g. the Hinna Member and the Kharfot and Dhalqut formations) form potential cap rocks that could potentially contain hydrocarbons in the reservoir zones. A recent gas discovery in the Yemeni side of the basin underscores existence of functioning, mature petroleum system in the basin. It is therefore a high time for intensive petroleum exploration on both sides of the Jeza-Qamar Basin.

Distribution of stratigraphic breaks within the Cretaceous sequence of the Jeza-Qamar Basin, Dhofar: Implications for regional tectono-eustatic fluctuations

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The Jeza-Qamar Basin is a Mesozoic basin that resulted from the tectonic activities related to the disintegration of Gondwanaland and the opening of the Neo-Tethys Ocean. The sedimentary fill of the basin includes strata of Jurassic and Cretaceous age punctuated by prominent stratigraphic breaks. About one-third of the basin lies in the southern Dhofar Governorate of Oman, whereas most of the basin, including its central, NW-oriented axial depression, lies in the Mahra Region of Yemen. The Jurassic strata are confined in the axial zone while progressively younger Cretaceous strata onlap the uplifted margins of the basin. The Fartaq High in Yemen forms the western margin whereas the Marbat High in Dhofar forms the eastern margin of the basin.

In Dhofar, the Cretaceous sequence is represented by rocks of Barremian to Maastrichtian age along with well-developed stratigraphic breaks. The sequence consists of, from oldest to youngest, Qishn, Kharfot, Dhalqut, Qitqawt, Samhan and Sharwayn formations. In the study area, the lowest Qishn Formation (Barremian to Aptian) lies on different Mesoproterozoic to Neoproterozoic rocks with nonconformity to pronounced angular unconformity. The formation is characterized by basal sandstones that grade into shallow-marine carbonates. The long pre-Qishn Formation stratigraphic gap was developed during Paleozoic to lower Mesozoic exposures, domal uplifting and subsequent erosional and non-depositional conditions. The Qishn Formation shoals upward, indicating a relative sea level drop that terminated with wide platform exposure and development of an unconformable contact marked by the Qishn-Kharfot contact. This contact is a type-1 sequence boundary that resulted from a regionally to globally recognized, Late Aptian eustatic sea-level drop. The Kharfot Formation is characterized by rhythmic units of *Orbitolina*-rich marls and bioclastic wackestone to packstones deposited in subtidal outer- to inner-shelf environments. The formation terminates with high energy, rudistic rudstone to grainstone lithofacies that indicate inner-shelf carbonate shoals. The top of the formation is a prominent hardground surface overlain by muddy and orbitolina-rich marls (Umbaraaf Member of Dhalqut Formation). The Kharfot-Dhalqut boundary is a lithologically well-defined, abrupt contact but biostratigraphic data do not warrant a significant stratigraphic break. Thus, this contact can be considered as a type-2 sequence boundary. The middle portion of the Dhalqut Formation (Khadrafi Member) consists of rhythmic units of marls that grade into bioclastic packstone/grainstone to rudistic rudstone with *Prealveolina* tests. The uppermost part of the member is marked by dark to medium grey mudstone to wackestone lithofacies rich in calcispheres and some planktonic foraminifera and sponge spicules. This unit is considered as the maximum flooding facies. This is followed by massively bedded, bioclastic (mainly rudists) grainstone and rudstone lithofacies. The overall vertical lithofacies distribution of the Dhalqut Formation suggests a transgression-regression cycle which culminated in a complete exposure of the carbonate platform. This sea-level drop is also regionally recognizable and most likely eustatic in nature generating a type-1 sequence boundary.

A long hiatus separates the Dhalqut and Samhan formations. The two formations are locally intervened by very thin kaolinitic paleosol (Qitqawt Formation) which is not mapable. The Samhan Formation (Late Santonian–Campanian) is dominated by bioclastic and rudistic wackestone to rudstone. The formation is erosionally removed from many sections within the study area. Thus, where the Samhan Formation is missing, the Maastrichtian Sharwayn Formation succeeds the Dhalqut Formation. The Dhalqut-Sharwayn unconformable contact is characterized by nodular paleosol rich in poorly-sorted, grain- to matrix-supported limestone breccia. The Sharwayn Formation is mainly formed by bioclastic mudstone to wackestone lithofacies and terminates with a prominent coarse-crystalline dolostone. It is unconformably overlain by Upper Paleocene Umm Er Radhuma Formation. The dolostone unit at the top of the Sharwayn Formation has been interpreted as being related to late Maastrichtian–Early Paleocene subaerial exposure and resulted from fresh-water and marine-water mixing zone dolomitization.

Geology of the Sultan Qaboos University campus, Wilayat Seeb, Muscat, Oman

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The campus of Sultan Qaboos University (SQU) is built upon a sedimentary sequence that consists of rocks of different lithologic nature. The stratigraphic sequence of the rocks sheds light on the tectono-sedimentary evolution of the Batina coast, in general, and of the Seeb area in particular. Oligocene carbonate, informally known as Mu'askar Al-Murtafa' reefs (MAM reefs) form the youngest Paleogene carbonates in the region surrounding the university. These are unconformably overlain by a clastic-dominated sequence of possibly Miocene to Recent age which belongs to the Barzaman Formation. The formation is well exposed in the SQU campus and consists of five distinct units (A to E).

Unit A consists of rhythmic units of fining-upward successions characterized by a lower conglomeratic part that grades to sandstones. The sandstone lithofacies is commonly represented by lithic arenite and most of the lithic grains are of ophiolite origin. High clay content is most likely due to alteration of the ophiolitic grains. The base of Unit A is not exposed within the SQU campus and the thickest measured section reaches 50 m. Scoured to sharp surfaces, some clast imbrication and rare root casts are present. Casts of disoriented plant remains (twigs and leaves) are present throughout the sandstone lithofacies but become more common in the uppermost 10 m. This unit is unconformably overlain by a carbonate unit (Unit B). The carbonate unit is about 20 meters thick and is characterized by poorly-bedded coral framestone to floatstone and bioclastic packstone to grainstone lithofacies. Besides large, partially silicified corals heads, there are also calcareous red algae, foraminifera, echinoids, gastropods, and bivalves. The corals locally coalesce and form a well-developed coral reef, several meters high. Subordinate conglomeratic horizons are present in this unit. This unit is an important one in terms of biostratigraphic dating and consists of foraminifera tests that suggest middle Miocene age. The top of the carbonate unit is characterized by karstic features with irregular dolomitized zones.

Unit C is well developed, grain-supported conglomerates which become finer-grained and interbedded with sandstone and mudrock lithofacies in its upper part. Ophiolitic grains dominate these conglomerates and they are partly altered into serpentine. The interbedded mudrocks are also dominated by serpentine phyllosilicates and locally show some orange- to red-weathered root casts. The upper layers of Unit C show lateral facies migration with steep angle of deposition. Unit C is interpreted as being deposited in a fluvial environment (lower part) that ended in a deltaic system in a lacustrine environment. Unit C merges upward to Unit D; the latter is characterized by poorly-sorted, conglomerate with white, koalinite clay matrix. The unit includes both grain- and matrix-supported lithofacies. No fossils or sedimentary structure of marine origin are recognized in this unit. It is interpreted as debris flow facies deposited in a lacustrine environment. Based on their stratigraphic position, units C and D are most likely latest Miocene to Pliocene in age. Units A to D are tilted to the north (ca. 20°) and overlain by Unit E with a remarkable angular unconformity. Unit E includes all Quaternary (Pleistocene to Recent) deposits in the study area and is characterized by uncemented sands punctuated by gravels.

The lithofacies units and their stratigraphic relationships indicate that the study area has been affected by different tectono-eustatic episodes. The coral-rich sediments of the MAM reefs followed by the fluvial sediments of Unit A clearly indicate a relative sea-level high followed by uplifting of the hinterland, exposure of the carbonate platform and deposition of the Unit A clastic sequence. A second stage of sea-level rise is manifested by the biota-rich carbonates of Unit B deposited in a shallow marine environment. The karstic feature at the top of Unit B followed by the conglomerates of Unit C indicates a rejuvenation of the tectonic uplift in the hinterland and withdrawal of the sea. Alluvial fan and fluvial sediments of Unit C (lower part) prograded into a body of fresh-water lake where mudrocks and deltaic sediments in the upper part of Unit C accumulated. Further uplifting of the hinterland may have destabilized the unconsolidated sediments of the alluvial to fluvial sediments of Unit C causing them to be deposited as debris flows in the lacustrine environment (i.e. Unit D). Deposition of Unit D was followed by tectonic disturbance of the study area, tilting sediments of units A to D, termination of the lacustrine environment and reestablishment of a fluvial system which deposited the youngest Quaternary sediments of Unit E.

Paleogene mammal faunas from the Sultanate of Oman, and plate tectonics

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Paleogene terrestrial mammal faunas are quite rare in the Middle East as well as in the North African countries. However their interest is great for understanding the timing of terrestrial connections between the southern and northern landmasses. Terrestrial connection between the African-Arabian and Eurasian landmasses is the result of the tectonic motion of the African-Arabian Plate and its collision with the Eurasian Plate. The emerged lands served as a corridor for migration of terrestrial animals. In return, the biochronology of these migration events provides landmarks for timing of the collision.

Three localities in the Sultanate of Oman yielded Late Eocene–Early Oligocene mammal faunas. These faunas are well documented, and they include a large number of mammal species providing a good image of their diversity and environments. In addition, these faunas include some characteristic elements having affinities with their African and Eurasian relatives, thus having some interest for plate motions and terrestrial connections between these continents.

These mammal localities (Aydim, Thaytiniti and Taqah) are situated in the Dhofar Province. Thaytiniti and Taqah are included in the Shizar Member of the Ashawq Formation, while Aydim is much older. These localities yielded mammalian taxa having African affinities, such as simiiforme primates, proboscideans, hyracoids, arsinoitheres, and phiomyid and anomaluroid rodents. In addition to these mammals, the locality of Taqah also yielded two groups of rodents, cricetids (relatives of hamsters) and diatomyids (relative of Indochinese rats) that have clearly Asiatic affinities. The material representing these two groups is under study.

The Dhofari mammal localities are dated by several methods. First, the Shizar Member is included in marine deposits, which are rich in foraminifera and other marine invertebrates, and its age is bracketed as Rupelian (Early Oligocene). Magnetostratigraphic analyses of samples across the Thaytiniti and Taqah sections provided an age between 31 and 33 Ma. Faunal comparisons with North African localities, in particular with that of Fayum in Egypt, suggest the correlation of the Thaytiniti fauna with that of Fayum L 41, and the Taqah fauna with that of the lower Jebel Qatrani faunas. The locality of Aydim, which yielded the remains of an arsinoithere is correlated to the Late Eocene, based on foraminiferal content of marine deposits in which this locality is intercalated.

The mammalian faunas from Aydim and Thaytiniti are entirely composed of African elements. The Taqah fauna include two Asiatic groups of rodents, indicating a land connection with Asia. One of them belongs to the family Cricetidae, which appear first in Asia in the Middle Eocene, and than invade all Eurasia during the Late Eocene and Early Oligocene. The Diatomyidae are also an Asiatic group related to the Baluchimyinae, which exist in Asia since the Early Eocene. Both groups are strictly terrestrial. The Taqah represents their earliest record on the African-Arabian Plate. Taking into account the age of the Taqah locality, this event can be dated as 31 Ma. This discovery implies that a continuous land connection existed between the Arabian Peninsula and Asia during the Early Oligocene.

This terrestrial connection was probably interrupted during the Late Oligocene since there is no one Asiatic element in the African mammal faunas, neither African element in Asia. From the Early Miocene, a new phase of mammalian migrations is observed from Africa to Eurasia (elephants, hyraxes, aardvarks, etc.), and from Eurasia to Africa (carnivores, ruminants, rhinos, rodents, rabbits, etc.). This phase is strongly marked by the large number of taxa involved in these migrations, and it probably lasted for several millions of years. Also, this is the consequence of a permanent landbridge formed in the Middle East, definitely connecting Africa to Eurasia via the Arabian Peninsula.

A Tale of two glaciations

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Glacial deposits form important hydrocarbon reservoir successions in the Palaeozoic of Gondwana. Focusing on Arabia in a 'mid-latitude' position during the entire Palaeozoic, two major glacial events can be recognized. Glacial and post-glacial sediments of the Al Khlata and Unayzah formations are the reservoirs of numerous Permian–Carboniferous fields in southern and Central Arabia. Latest Ordovician glacial deposits and erosional remnants form the target of wells and prospects in south and north Arabia. Following the Ordovician glaciation, the large-scale, second-order 'base' Silurian flood is linked with the most significant (Qusaiba) source rock of the region, which can be traced over vast areas in North Africa. The extent of the Late Ordovician and Permian–Carboniferous 'ice-sheets' is tremendous, covering in both cases very large parts of Gondwana. In that context, it is remarkable that during the Devonian, ice-cover over Gondwana was limited, notwithstanding a 'very polar' position of the super-continent in that period.

In this contribution the observations outlined above are illustrated in the form of reconstructed palaeogeographic maps. Reviewing these reconstructions, we suggest that the appearance of the relatively ice-free Devonian, sandwiched between two glaciations, was caused by the disruption of the normal oceanic-driven Hadley Cell circulation. During the Devonian the vast Gondwana landmass was centered over the South Pole and dominated the entire southern hemisphere. This configuration dramatically reduced the continental precipitation required to create and support large ice sheets. During the bracketing Late Carboniferous and Late Ordovician, the South Pole was close enough to the margin of the super-continent to allow a more 'normal' Hadley Cell circulation, with associated precipitation at high latitude.

Localisation of fault controlled fluid flow during growth of a normal fault network, Al Jabal al-Akhdar Dome, Oman

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Field and stable-isotope studies of calcite vein systems are combined to explore the localization of fluid flow during the growth of an exceptionally well-exposed normal fault system in the Al Jabal al-Akhdar Dome of Oman. Here, a limestone-dominated, Mesozoic continental shelf sequence hosts an EW-trending normal fault network. One of the larger faults within this network is the Dar Al Bayhda (DAB) Fault. The fault is 25 km long and has a maximum displacement exceeding 800 m. It is associated with numerous other faults with strike lengths ranging from metres to kilometres. During its growth, the fault network breached an overpressured fluid reservoir. Fluid redistribution through the fault network, in response to episodic fault slip and permeability enhancement, has developed large fault-fill veins, breccia complexes and extension vein arrays in the fault zones. The exposed

levels of the fault system formed at depths of at least 5 km. Episodic fluid flow was associated with fault-valve behaviour. $\delta^{18}O$ compositions of vein calcite in the fault vary from host-rock buffered (ca. 26‰) to strongly fluid-buffered (13‰). Fluid-buffered vein calcite, and hence domains of high fluid flux, are localised in structural complexities such as jogs, splays and termination zones. Veins from planar segments of the fault are more host-rock buffered. The network of smaller faults, adjacent to the main fault, hosts a similar range of calcite compositions (15–27‰). This similarity of oxygen-isotope compositions between the main fault and the associated, lower-displacement network highlights the role of both the high-displacement and low-displacement components of fault networks in localizing crustal fluid redistribution.

The geochronological framework of the Precambrian basement of Socotra, Yemen

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The Socotra Archipelago (Yemen), which lies ca. 400 km southeast of Qishn on the southern coast of Yemen and between 100 and 300 km east of Ras Asir (Cape Guardafui), Somalia, comprises the main inhabited island of Socotra and a number of smaller uninhabited islands. Until recent times, Socotra has been difficult to access and has therefore been the subject of only limited geological investigation. Fracture zones in the Gulf of Aden indicate that prior to Miocene rifting, Socotra would have occupied a position immediately to the east of the Precambrian Marbat Block of southern Oman (Fournier et al., 2007), an area devoid of basement exposure. Thus Socotra has the potential to yield important constraints on the distribution, age and nature of the largely hidden collage of Precambrian terranes of the eastern Arabian basement.

The earliest detailed geological mapping of Socotra (Beydoun and Bichan, 1970) indicated that the eastern part of the island comprises granitoids and granitic gneisses, which were assumed to be Precambrian. Much of the rest of the island lies below a thick sequence of Cretaceous cover rocks (mostly limestones) although Precambrian basement is also exposed in a narrow strip along the northern coastline at the base of the cliffs and in deeply eroded antiformal cores in the west around Qulansiya and Shuab. In contrast to the earlier mapping of schists and gneisses, our fieldwork has revealed a dominance of relatively undeformed granite and granodiorite cut by rhyolite and dacite dykes in the northern coastal and Qulansiya regions; gneissic and schistose rocks are subordinate to absent. An extensive outcrop of migmatitic (para?) gneisses containing deformed amphibolite dykes occurs inland of Shuab. These may actually be large xenoliths in a granitic batholith.

Ion microprobe U-Pb zircon geochronology has been used to place age constraints on the Socotra basement. The oldest components of the igneous basement are ca. 860 Ma granodiorites from the easternmost basement outcrops at Ras Momi; slightly younger ages of ca. 850–840 Ma have been obtained from the Shuab, Ras Kadama and Qulansiya areas. In all basement areas, a ca. 800 Ma component is present either as a discreet igneous crystallisation age or as an overprint on older rocks that has resulted in Pb-loss. Metasediments are rare on Socotra. A single sample from the Shuab inlier yields a spread of zircon ages from ca. 1,060–800 Ma with a single discordant grain of > 2,350 Ma. Granite of the Haggier Mountains and apparently related volcanic rocks (rhyolites) yield ca. 720 Ma ages and represent the youngest igneous component in the basement of Socotra.

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