Reservoir Characterization of the Shu'aiba Formation, Ghaba North Field, Oman

Abdulrahman A. Al-Awar,
Dubai Petroleum Company, UAE
and **John D. Humphrey**,
Colorado School of Mines, USA

The Aptian Shu'aiba Formation is subdivided into two major reservoir zones in Ghaba North field, the lower and upper Shu'aiba. The lower zone was deposited in shallow inner-shelf setting with restricted to partially restricted water circulation conditions. The upper zone was deposited under open conditions in a shallow outer-shelf setting. The succession of facies in the Shu'aiba indicates an overall major shallowing upward cycle superimposed on it several meter-scale high frequency cycles.

The Shu'aiba in the study area is a very heterogeneous reservoir. It produces from secondary macroporosity, fracture porosity, and matrix microporosity. Reservoir storage capacity is controlled primarily by matrix microporosity, which occurs as intercrystalline porosity within a microrhombic calcite matrix. Reservoir quality is enhanced vertically in proximity of two-recognized subaerial exposure surfaces and laterally toward the northeast. The lateral improvement in reservoir properties toward the northeast reflects the complexity of the facies mosaic in the Shu'aiba depositional environment. Sedimentologic evidence indicates that higher energy conditions resulted in deposition of grainier lithofacies with higher primary porosity in that direction.

Meteoric water diagenesis of the Shu'aiba led to stabilization of the Shu'aiba matrix development of both secondary macroporosity and microporosity within microrhombic calcite matrix. The regional unconformity at the top of the Shu'aiba and the local subaerial exposure surface capping a rudist bioherm within the Shu'aiba have provided the means for this alteration. This interpretation is supported by the decrease in secondary macroporosity and matrix permeability downward from the exposure surfaces. In addition, the meteoric origin for the microrhombic calcite matrix is evident from the isotopic data

The upper zone in the Shu'aiba is characterized by overall higher porosity and permeability values than the lower zone. This is due to proximity to exposure surfaces and to the better primary reservoir properties of the lithofacies forming the high frequency cycles interpreted within the outer-shelf setting. Furthermore, the development of crystal mosaic texture in the matrix instead of blocky-crystal framework texture and/or precipitation of neomorphic calcite microspar in interparticle pore spaces within peloidal lithofacies led to the reduction of matrix microporosity and permeability and thus reservoir quality of the lower zone. Therefore, the observed spatial and vertical variability of the reservoir, in addition to fracture distribution and orientation, should be considered in any infill drilling or flooding programs planned for the Shu'aiba.

Sedimentologic and Palaeogeographic Evolution of Syria during the Jurassic and Cretaceous (Northwestern Arabian Platform)

A. Khaled Al-Maleh
University of Damascus and General Establishment of Geology and Mineral Resources, Syria
and **M. Mouty**
University of Damascus, Syria

The Syrian Jurassic and Cretaceous terranes were studied in detail in the mountain ranges of Palmyrides, Anti-Labanon, Harmoum, Coastal and Kurd-Dagh. These were compared with their subsurface extensions in drill holes. The structure and composition of these terranes is dominantly carbonates with some limited clastic intercalations which are locally ferruginous with some volcanic intrusions of basaltic rocks.

The Jurassic and Cretaceous stratigraphic column was divided into formations, members and sequences. The study of their characteristics and evolution provides the general framework for the sedimentologic and palaeogeographic evolution of this important and distinctive part of the Arabian Platform.

The lithostratigraphic studies reveal that the Jurassic carbonates of Syria and the adjacent areas are dominated by shallow-water dolostone, limestone and limited marly interrelations. Beginning in the Jurassic, these strata were deposited in a shallow sea, transgressed the entire region with the exception of the northeast-southwest, elongated Al Hammad Uplift in the east and southeast Syria.

The correlation of the geologic sections shows that since the end of the Early Jurassic, this uplift has further expanded. At the end of the Middle Jurassic the sea regressed northwestward, where an important subsiding structure oriented north northeast-south southeast (Homs-Lebanon trough), received in excess of 1,000 meters of Jurassic sediments.

By the end of the Late Jurassic the sea regressed further from the last submerged areas. Consequently, all of Syria remained emergent until the Cretaceous transgression of Barremian-Aptian time.

The Cretaceous sequences consist of three sedimentary series of different facies. They are generally detrital at the base (pre-Aptian to Aptian), neritic carbonates in the middle (Albian-Turonian), marly and pelagic limestone in the upper part (Coniacian-Maastrichtian), with some phosphatic deposits locally in the upper part (Upper Campanian-Maastrichtian).

Major sedimentological cycles comprise the neritic carbonates of the Jurassic, and Cretaceous platform. Many stages of maximum flooding differ in appearance according to the region. Maximum flooding is dated as Lias, Bathonian, Callovian and Oxfordian-Kimmeridgian, Aptian, Albian, the Middle and Upper Cenomanian, and the Lower Turonian. These sediments included ammonites, some planktonic foraminiferas and other pelagic and/or hemipelagic organisms. Special sedimentological conditions led to the deposition of phosphate on the flanks of the Hamad Uplift.

The Hamad Uplift was a distinctive palaeostructure in the South; and the Aleppo Plateau in the north played major roles in the distribution and differentiation of sedimentation during the Jurassic and Cretaceous, especially in the differentiation of the major structures inside the platform and on its margins. Some structural activities affected the facies variations and the sedimentation process in general, and some of them helped in conducting magma to form basaltic intrusions and flows, especially during the Late Jurassic, the earliest Cretaceous and even in the Albian.

The ophiolite complex and the associated rocks at the northwestern boundary of the Arabian platform were emplaced in northwestern Syria (the Syrian platform), during the Maastrichtian. Resulting special palaeogeographic conditions are represented by tectonic instability, local emersion of the transported body, submarine slides, and the movement of detrital debris (silici-carbonate) to the marginal African basin which alternated with pelagic sedimentation and turbidites.

Depositional Setting, Diagenesis and Reservoir Properties of the Maastrichtian Platform Carbonate Sequences of the Southern Arabian Gulf

Abdulrahman Alsharhan
United Arab Emirates University, UAE

The Late Maastrichtian, known as the Simsima Formation, is the terminal sedimentary event in the Arabian Cretaceous sequence. It represents the regressive phase of the second subcycle of the Upper Cretaceous section and can be correlated with one of the cycles of Exxon sea-level chart.

The Simsima Formation in the subsurface exhibits rapid lateral lithologic changes both locally and regionally and can be divided into two members which were deposited in two large-scale depositional cycles. The Lower Member is characterized by a coarsening-upward cycle of lime mudstone/wackestones and rudistid packstones/grainstones with microcrystalline dolomites and a common fauna such as *Lepidorbitoides*, *Orbitoides media*, *Orbitoides tissoti*, *Loftusia* as well as algae and echinoid debris deposited in a shallow marine setting with occasional influxes of open marine water under moderate energy conditions. The Upper Member consists of black, argillaceous/organic matter, rudistid and bioclastic carbonates, algal and foraminiferal assemblages (*Loftusia* and *Lepidorbitoides*) and muddy carbonates with micro to cryptocrystalline dolomite which collected in a semi-restricted marine, subtidal setting. The hard grounds found within the upper Simsima reflect the eustatic sea-level change which caused with the unconformity at the end of the Cretaceous. In outcrop (western Oman Mountains) the formation consists of bioclastic wackestones and packstones with abundant large benthic foraminifera and buildups of coral and large rudist bivalves. It can be divided into a caprinid limestone Member, followed upward by an Orbitoidal Limestone Member, both of which were deposited within a shallow marine open shelf setting.

In subsurface, the Simsima Formation disconformably overlies the Fiqa Formation, except in southeast Abu Dhabi where the formation unconformably overlies the Cenomanian-Albian Shilaif, Mauddud or Nahr Umr formations and is separated from them by a long hiatus. The top of the Simsima is marked by an unconformity surface, which represents the end of the Cretaceous. This is marked by a hiatus which separates it from the overlying Tertiary basal shales of the Umm Er Radhuma Formation. It ranges in thickness from 77 to 110 meters and shows a general and gradual decrease in thickness from central to northwest Abu Dhabi. Towards the southeast the Simsima progressively decreases in thickness until it pinches out. A prominent and consistent thinning is noticed over the structures of the producing fields. This indicates that the deposition of the Simsima was influenced by continued structural growth. In outcrop, the Simsima ranges from 30 to 80 meters, forming a narrow belt along the western Oman Mountain front and partly overlying the truncated margins of the Semail ophiolites or Lower Maastrichtian Qahlah clastics. The upper part is unconformable with the Paleogene limestone.

Diagenesis was active during the periods of subaerial exposure which occurred prior to deposition of the Upper Simsima Member. Dolomitization occurs and is comprised of two phases: one produced tight, interlocking, locally fissured dolomite which results from

pervasive dolomitization of originally lime mud in a stable mixing zone. The second is porous, very permeable, sucrosic dolomite which envelopes the mass of tight dolomite as well as filling the fissures and karstic voids dissecting the tight dolomite. This rock fabric is the result of partial dolomitization of both the original sediments and the later lime muds and silts filling the karstic pipes/channels.

The distribution of the almost syndepositional leaching and dolomitization is linked to the exposure periods and is interpreted to have been strongly controlled by depositional processes and patterns. The most likely source for the fresh water which leached the section is a series of emergent banks which appear to have occurred over the structures. The most significant banks are assumed to have been over the main mass of tight dolomite. Other diagenetic processes which affected the entire Simsima Formation include fracturing, dedolomitization and calcite cementation. The meteoric water responsible for the calcite are interpreted to have penetrated the section during late fracturing which may have connected the Simsima to an Early Tertiary exposure surface on the top of the structures. The Simsima contains large collapse breccias that apparently were produced by the dissolution of dolomites interbedded in the sequence.

The geochemical characteristics of the Simsima diagenesis include the stable compositions of dolomite which show an average oxygen isotopic composition of about ~ - 2.9‰, which is consistent with a mixed salinity origin for the Simsima, while the stable oxygen isotopic composition for calcite about ~ 5.8‰ is consistent with a meteoric fresh water derived origin. The dolomites in the lower part of the Simsima have a Sr content in the range of 100-200 parts per million (ppm), and a Na content of 400-900 ppm, while the dolomites in the Upper part of the Simsima have slightly higher Sr and Na contents which is ranged from 100-300 ppm and 900-1200 ppm, respectively. This indicates that the upper Simsima dolomitization may have occurred in a slightly more saline mixing zone than lower Simsima dolomitization.

Based on variations in petrophysical characteristics and lithology, the Simsima is divided into a three-fold reservoir subdivision, (R1, R2 and R3). The R1 reservoir represents the Upper Simsima Member and R2 and R3 reservoirs correspond to the Lower Simsima Member. The average porosities and permeabilities of the Simsima vary considerably responding to vertical, lateral and regional lithostratigraphic changes. The porosity averages between 1 and 30% whereas the permeability ranges from 0.1 to 700 millidarcies. The limestone possesses interparticle, moldic, vugular and karstic porosities associated with good permeabilities, and is improved locally by fracturing, while the dolomite has good intercrystalline porosity.

The Simsima is producing oil from one field in onshore Abu Dhabi, with oil gravity of 30° API and sulphur content of about 1.45%. The sources of the oil are the Middle Cretaceous intrashelf basin from which oil is interpreted to have migrated upward through faults, and also partially from the black argillaceous shale and mudstones rich in organic matter found in the Simsima. The dense non-permeable carbonates and interbedded dolomites may provide effective seals over porous shallow-shoal platform carbonate facies representing a potential exploration target outside the present producing area.

Stratigraphy, Petrology, Chemistry and Hydrocarbon Potential of the Aptian Shu'aiba Formation, United Arab Emirates

Abdulrahman S. Alsharhan
United Arab Emirates University, Al Ain, UAE
I.S. Al-Aasm
University of Windsor, Ontario, Canada
and **Mohammed G. Salah**
United Arab Emirates University, Al Ain, UAE

The Aptian shallow-water carbonates of the Shu'aiba Formation of United Arab Emirates form one of the most important petroleum reservoirs in the Arabian Gulf. The formation consists, in ascending order, of three members: the lower Shu'aiba, the upper Shu'aiba and Bab Member. It ranges in thickness from 50 to 133 meters and represents a wide range of depositional settings from shallow outer- to inner-shelf. Several lithofacies have been identified within the Shu'aiba Formation. These are: peloidal grainstone/packstones, skeletal algal floatstone; intraclastic packstone/grainstone, coated packstone/ grainstone and skeletal wackestone/packstone. These facies reveal third-order sequences, including two Highstand Systems Tract, separated by a Transgressive Systems Tract, with two sequence boundaries.

Diagenetic alteration of original carbonate components proceeded through marine, meteoric exposure and then deeper burial settings. These changes can be traced through diagenetic stabilization of the carbonate matrix, cements and rudist shells. Oxygen and carbon isotopes of calcitic matrix show the least altered component in these rocks (av. $\partial^{18}O$ = -5.7% PDB, $\partial^{13}C$ = +2.5% PDB), whereas late calcite cements occluding shell porosity and veins have more depleted isotopic values (av. $\partial^{18}O$ = -8.8% PDB, $\partial^{13}C$ = +0.5% PDB). The variations of oxygen and carbon isotopes signify variable magnitudes of water-rock interactions.

The reservoir quality is highly affected by diagenetic processes that developed within early shallow burial to deep burial environments. Detailed well log evaluations, petrography of samples from cores, cuttings from both onshore and offshore fields and outcrops in United Arab Emirates, X-ray diffraction, cathodoluminescence microscopy and oxygen and carbon isotopic determinations allowed us to evaluate stratigraphic and depositional framework of the Shu'aiba Formation, its diagenetic history and to predict its reservoir potential in the area.

The lower and upper Shu'aiba members form good reservoirs and have porosities ranging from 12 to 30% and permeability between 1.0 and 160 millidarcies. The reservoir quality is highly affected by the diagenetic processes which include recrystallization, cementation dolomitization, stylolitization, leaching and secondary pore filling. The Bab Member, deposited in a basinal settings, is organically rich and forms a fair source rock in the eastern and northeastern parts of central UAE and is mature enough in deep troughs to generate and expel hydrocarbons to reservoirs.

Geochemical Evaluation of the Upper Jurassic Diyab Formation in Abu Dhabi, United Arab Emirates

Ahmed S. Al-Suwaidi, Ahmed K. Taher
Abu Dhabi National Oil Company, Abu Dhabi, UAE
Abdulrahman Alsharhan and **Mohammad Salah**
United Arab Emirates University, Al Ain, UAE

The Diyab Formation (Oxfordian to mid-Kimmeridgian) in Abu Dhabi is widely distributed and consists of argillaceous lime mudstones/wackestones (rich in organic matter) with intercalated peloidal packstones and grainstones. It thickens to greater than 500 meters toward the present onshore Abu Dhabi. The formation can be divided into three members in western Abu Dhabi, but these cannot be traced eastward because of facies change.

Identified rich source rock intervals are present in the basal part of the Upper Jurassic carbonates, Diyab Formation in western Abu Dhabi, whereas it is lean source rock in eastern Abu Dhabi. The Diyab source rock hosts oil- and gas-prone kerogen and was deposited in a carbonate platform, prograding shelf, and slope. The Diyab intrashelf basin developed progressively westward, reaching a maximum thickness in western offshore Abu Dhabi.

Combination of geological and geochemical information was used to trace the burial and thermal histories of the potentially petroliferous intervals within the Diyab source rock. This source rock was sufficiently mature in most of the deep "kitchens" to generate hydrocarbons since Late Cretaceous time. Currently, it lies within the gas generation window in most of the synclines in Abu Dhabi.

Comparative analysis of oil and source rock characteristics, using both bulk and specific parameters, carbon isotope analysis, gas chromatography, and gas chromatography-mass spectrometry, were carried out. Both Thamama and Arab oils are typical of oils derived from carbonate source rocks. However, maturity indicators show that the oils reservoired in the Thamama are in general, significantly more mature than the underlying Arab oils.

The secondary migration scheme is based to a large extent on a series of structure and paleostructure contour maps at top Arab-D level. Migration direction in the Arab Formation was mainly controlled by the presence of western synclines. However, to the east of these synclines migration direction was predominantly northeastward into the Umm Shaif field. The influence of the developing Ras Al Khaimah Trough resulted in some reversal o dips where migration directions, since Dammam time (38 million years ago), are towards the north and northwest.

Diagenesis of the Middle-Upper Jurassic Carbonate Platform (Amran Group) in the Sana'a Region, Yemen

Khallid A. Al-Thour
Sana'a University, Yemen Arab Republic

The Middle to Upper Jurassic shallow-marine carbonate platform (Amran Group) is predominately limestone in the west and northwest, and limestone and dolomite in the east and northeast of Sana'a. Diagenesis of the Amran Group encompasses many processes with conspicuous effects such as cementation, dissolution, compaction (both physical and chemical) producing secondary microporosity, micritization, and dolomitization. Dolomite cements are common and mostly precipitated during later diagenesis in cavities and fractures. Replacive dolomitization occurred during shallow burial (small rhombic types) and during burial diagenesis with the formation of saddle dolomite. Integration of field, petrographic and geochemical analyses indicates that lithification of these carbonates occurred during synsedimentary and burial diagenesis, with much of the alteration controlled by eustatic sea-level change and regional tectonism.

Four major subenvironments where diagenesis of the Amran Group was operative can be recognized. (1) Synsedimentary diagenesis is characterized by the

formation of isopachous and syntaxial cements, hardgrounds (with associated borings, burrows, shelter and fenestral porosity), geopetal structure, and intraclasts, indicating deposition under marine conditions. (2) Shallow burial diagenesis shows other specific features such as leaching, recrystallization and early dolomitization (both replacive and void filling) and mould-filling cements. Mouldic and vuggy porosity distribution, early compaction, collapse breccia and silt deposition indicate that the Amran Group continued to receive meteoric water after sediment stabilization, enlarging by solution some moulds and vugs. (3) Deep burial diagenesis characterized by dissolution, blocky calcite cement, late compaction (fractures and sutured grains) and saddle dolomite. (4) Uplift diagenesis is characterized by the reopening of stylolites through fractures and the development of dolomitization under meteoric conditions. The occurrence of non-ferroan calcite and ferric oxides in rhombohedral zones in dolomite indicate that dedolomitization occurred by the oxidation and alteration of ferroan dolomite zones and probably reflects alteration related to recent weathering.

Structural Analysis of the Upper Jurassic Intra-shelf Basin and Hydrocarbon Habitat in the Abu Dhabi Onshore Area

Mohamed Ayoub and **I.M. Ennadi**
Abu Dhabi Company for Onshore Oil Operations,
Abu Dhabi, UAE

The Upper Jurassic sequence exhibits lateral variation in both thickness and lithology over the Abu Dhabi area. These variations are related to eustatic changes in sea-level, structural growth of the Qatar Arch and Mender/ Lekhwair high, spreading of the Neo-Tethys and local diapiric movements.

The Upper Jurassic section in the eastern part of Abu Dhabi is subdivided, from bottom to top, into the following formations; Tuwaiq Mountain with Hydriya reservoir, Diyab source rock with Hanifa reservoir, Diyab source rock with Hanifa reservoir (southeast area), Jubaila dense section and the Asab/Asab equivalent with the Asab Oolite reservoir. In the western area, the section contains the Tuwaiq Mountain, Diyab, Jubaila with Arab D reservoir at the top overlain by Arab Formation with Arab A, B and C reservoirs and Hith anhydrite which affect the hydrocarbon distribution.

The Late Oxfordian structural growth of Mender/ Lekhwair high and Qatar Arch led to the development of the main intra-shelf basin between, where the Diyab (Hanifa) Formation was deposited. The Diyab Formation is the main source rock for the Arab and the Thamama hydrocarbons.

Approximately 75% of the present structural configuration of Abu Dhabi onshore area resulted from the Late Cretaceous structural compressional movements due to Oman Nappes overthrust zone. The Late Cretaceous subsidence in the Falaha Trough enhanced the organic and inorganic gas generation.

Exploration Model for the Middle Cretaceous Mishrif Carbonate Platform along Shilaif Basin in Abu Dhabi, United Arab Emirates

Ibrahim Azzam
Abu Dhabi National Oil Company, Abu Dhabi

The Middle Cretaceous Mishrif/Shilaif formations of Abu Dhabi have been interpreted applying sequence stratigraphic concepts. This integrated study used regional well and seismic data, as well as sedimentological interpretations and electrofacies correlation. Three depositional sequences were recognized and tied to the global eustatic cycle chart of the Cretaceous between 98 and 94 Ma. (Haq et al., 1987).

The Shilaif basin occupied most of the onshore and offshore Abu Dhabi in Late Albian time (Lower Shilaif); the basin became significantly smaller in the Cenomanian due to progradation of the surrounding Mishrif carbonate banks. The basin is typically filled with pelagic limestones in which euxinic conditions favored the preservation of organic matter. The bioclastic shoal facies of the Mishrif Formation were deposited on the margins of the Shilaif intra-shelf basin and prograded basinwards during the global sea-level rise of the Cenomanian. The transition from Mishrif depositional sequences to the time-equivalent Shilaif Formation is characterized by a steep platform margin clearly influenced by the structural regime operative during deposition. Reservoir characteristics in the Mishrif are good with the greatest potential occurring at the platform margins where shoals/ buildups were best developed.

The Upper Cenomanian Tuwayil Formation and the Turonian Ruwaydha Formation over western and eastern Mishrif platform exhibit a similar, although less abrupt, platform-to-basin distinction as the underlying Mishrif. The two formations constitute two distinct sequences that are younger than Mishrif/Shilaif formations.

Application of sequence stratigraphy to the Mishrif/ Shilaif depositional pattern proved to be an essential technique in modeling and predicting reservoir geometry, continuity, seals and mature areas which are critical factors in hydrocarbon exploration. This model forms a template for further sequence stratigraphic architecture of the Mishrif/Shilaif deposition in Abu Dhabi.

Event Stratigraphy of the Apulia Platform Margin: The Gargano Transect (Upper Jurassic-Cretaceous, Southern Italy)

A. Bosellini, C. Neri, V. Luciani and **M. Morsilli**
Universita di Ferrara, Italy

The Upper Jurassic-Cretaceous Apulia platform margin and the eastward transition to adjacent basinal deposits are well exposed in the Gargano Promontory, a carbonate block which is part of the slightly deformed foreland of the Southern Apennine thrust belt. The outcropping succession can be subdivided into four (third-order) depositional sequences, separated by three very distinct unconformities resulting from regional or global events.

The base of the first sequence, Monte Sacro Sequence, Late Jurassic-Berriasian in age, is not exposed; its upper boundary is defined by a drowning unconformity of Valanginian age (Bosellini and Morsilli, 1997) which correlates well with similar coeval drowning unconformities from the Atlantic and Tethyan continental margins.

After this drowning event, the platform margin backstepped and during the subsequent relative highstand prograded (Mattinata Sequence) until the Middle-Late Aptian to Albian, when several anoxic events, well-documented both in basinal and slope settings (Scisti a Fucoidi Formation) (Luciani and Cobianchi, 1994; Cobianchi et al., 1997), produced an environmental deterioration and halted the progradation of the depositional system; the carbonate platform became temporarily inactive. After these globally documented anoxic events the platform and its margins started to prograde again (Monte degli Angeli Sequence). But during the latest Albian and the Cenomanian, a general emergence (eustatic, tectonic?) of the entire Apulia Platform, documented by a major unconformity and karst-hosted bauxite deposits, caused vast margin failures. Huge megabreccia wedges overlain by thin pelagic units and a thick package of cyclically arranged calciturbidites and debrites constitute the Monte San Angelo Sequence of Late Albian-Paleocene age (Bosellini et al., 1993). This megasequence, spanning some 35 Ma, may be subdivided into two lower order sequences by a pronounced tongue of pelagic carbonates, Campanian in age (Neri and Luciani, 1994).

The depositional profile of the Apulia Platform is typical of the Tethyan platforms, with slope declivities in the order of 25-28°. Most typical sediments of the Late Jurassic-Berriasian platform-to-basin transect include peritidal meter-scale cycles, oolitic shoals, massive *Ellipsactinia* wackestone, gravity-displaced breccias and calciturbidites and pelagic slumped mudstones. Valanginian to Maastrichtian margin deposits are characterized by the occurrence of rudist mounds and coarse skeletal calcarenites; inner platform deposits consist of thick, peritidal cycles, while slope and base-of-slope settings are characterized by the common occurrence of megabreccias.

Maastrichtian Echinoides from the Simsima Formation, Northwestern Oman Mountains, UAE: A Systematic View and Ecological Implications

M.A. Boukhary[1],
B.D. Carter,
Georgia Southwestern State University, USA
Abdulrahman Alsharhan[1] and **M.F. Ali**[1]
[1]United Arab Emirates University, UAE

The present work gives a systematic study, abbreviated description and synonymies of the echinoid taxa, yielded from the Simsima Formation at Gebel Buhays (El Fayah region), and focusing on criteria for their recognition. A total of 17 echinoid species were collected and classified among them, eight species are regular, four are holectypoids and five are classiduloids. The echinoids from this locality appear to represent several of the shallow inshore assemblages. There appear to be no taxa characteristics deeper more than 20 m (Smith's Habitat F) assemblage at Gebel Buhays. Thus, as recorded in Smith (1995) slightly over half the taxa are regular, though the irregular echinoides are numerically dominant. The echinoid assemblage indicates that the Simsima Formation was deposited in on carbonate platform through the earliest incursion of the epicontinental (Epeiric) sea post nappe of the Oman mountains.

The Arab-D Reservoir Exposed: Evidence for Vadose Diagenesis in Ghawar Field, Saudi Arabia

Richard D. Bray
Saudi Aramco, Saudi Arabia

In northern Ghawar field, Saudi Arabia, approximately 1,500-kilometer thin sections illustrate in detail the lithologic and diagenetic characteristics of reservoirs. Petrographic evidence suggests that the Arab-D reservoir was deposited in a relatively shallow subtidal setting and was periodically exposed, for an indeterminate length of time, during high-frequency sea-level oscillations. Incontrovertible evidence for vadose diagenesis includes meniscus micrite and pendant calcite cements. These vadose features are very subtle, invariably unrecognized on the slabbed core surface, and neither uniformly

distributed nor especially conspicuous in petrographic thin sections. Other petrographic features not necessarily indicative of exposure, but found in association with the vadose cements, are secondary micrite infilling of voids, small cracks and fissures, microcrystalline silica, dedolomite and kaolinite.

Although evidence for subaerial exposure is manifest throughout the reservoir, it is most pronounced and best developed in the grainstones and mud-lean packstones of the upper, higher energy portion of the Arab-D reservoir (Zone 2). In the lower, cyclical portion of the Arab-D reservoir (Zone 3), vadose features are associated with coated grain grainstones and mud-lean packstones which overlie *Glossifungites* firmgrounds. The grainstones are transgressive lags deposited during subsequent sea-level rises. Vadose cements probably were emplaced in the grain-supported fabrics after the deposition and subsequent exposure of an overlying firmground.

Geochemical Study of Some Cretaceous Rocks from Kuwait: Comparison with Oils from Cretaceous and Jurassic Reservoirs

J. Connan
Elf Exploration & Production, France
and **Fowzia H. Abdullah**
Kuwait University, Kuwait

A set of 18 Cretaceous rocks (Raudhatain and Minagish oil fields) and 10 oils that accumulated in Cretaceous reservoirs (Raudhatain, Bahra, Burgan, Minagish and Miqua oil fields) were analyzed using the geochemical tools including molecular and isotope data on individual compounds, namely n-alkanes and isoprenoids. To complete the study, one oil (Miqua) from the Jurassic (Marrat Formation) of the Great Burgan field has been added to the Cretaceous set.

The Burgan sandstone and the Zubair and Ratawi shales, of Albian to Valanginian age, are not the source rocks of the crude oils for several reasons: too low maturity (between 0.5 and 0.7% vitrinite reflectance), humic type of organic matter poor in sulphur-bearing moities, and different molecular and isotope chemistry ($\delta^{13}C$) of asphaltenes between -23.1 and -25.7‰/PDB instead of a range between -26.8 and -27.6‰/PDB in the asphaltenes of the 11 oils). These results are consistent with the corresponding environmental conditions of deposition which are deltaic/estuarine in the Burgan Formation and littoral/deltaic in the Zubair Formation.

The Minagish and the Sulaiy formations, Cretaceous to latest Jurassic age, appear as potential candidates on the basis of their molecular and bulk isotope geochemistry. $\delta^{13}C$ of asphaltenes, for instance are between -27.3 and -28.1‰/PDB, i.e. close to the crude oils data. In addition to these studied formations, a bibliographical study pointed out that the Najmah Formation in the Late to Middle Jurassic is also an excellent source rock. Maturity studies, however, reveal that the samples of the Minagish and the Sulaiy formations are more mature than the effective source rocks which have generated the crude oils studied. The detailed isotopic study, at a molecular level using the individual n- and isoprenoid C_{15+} alkanes did not end with a perfect match between the most likely source rock candidates and the crude oils. Nevertheless one sample from the Sulaiy interval was found to be rather close from the crude oil group.

The crude oils belong to the same genetic family and were expelled from a source rock with a dominant limestone lithology, i.e. like in Sulaiy-Minagish (Cretaceous) but also Najmah (Jurassic) formations. These formations contain sulphur-rich, morphous kerogens as currently observed in shallow marine shelf deposits.

The Miqua oil, accumulated in the Marrat Formation which is Jurassic, does not differ from other crudes in terms of genetic characteristics. This crude oil, also the deepest, is the most mature of the set. Maturity assessment has not been possible using some well known parameters on steranes (e.g. αααR to αααS ratios), terpanes (e.g. Tm to Ts ratios) or methylphenanthrenes (Mp_1 and Mp_{13}). Sulphur-bearing aromatics comprising alkylated BT and DBT have, fortunately, shown important changes which have been mainly ascribed to maturity variations. Parameters on BT and DBT have been, consequently, applied as tools to evaluate maturity changes.

The oil from the Burgan reservoir in the Minagish field appears as the least mature. None of the oils, except this one, have been affected by biodegradation. Their maturity is typical of the so-called 'oil window' and has not been found to be simply related to the present depth of the reservoir. However, it has been established that on the same field, the oil maturity increases with the reservoir depth. This conclusion on oil maturity is not fully understood yet and should be discussed in future in relation to the major chronological events, especially the major tectonic ones which have enabled the oil to successively fill different reservoirs. The reconstruction of the most important phases, i.e. genesis and migration through active faults, will provide guidelines to understand the present-day pattern.

The origin of the oils remains, still, an open question which may find a solution when a detailed study of the Jurassic will be carried out. Up to now, the geochemical

characteristics of the Jurassic source rocks are largely unknown and there is a need to document that key interval which contains obvious source rocks, prior to drawing definite conclusions.

Architecture of the Minagish Oolite Reservoir in the Umm Gudair Field, Kuwait

R.B. Davies, Davies Geoconsulting Ltd., UK
C.D. Bishop, British Petroleum Kuwait
C.E. Hollis, Badley Ashton and Associates, UK
R.S. Gaur and **A.A. Haider**
Kuwait Oil Company, Kuwait

The Berriasian-Valanginian Minagish Formation in Umm Gudair field, was deposited on a homoclinal carbonate ramp. Three systems tracts, representative of 3rd order sea-level cyclicity, are defined. A lowermost, late Highstand Systems Tract (HST) comprises typically low-permeability, parasequences with outer ramp, bioturbated peloidal wackestones shallowing into mid ramp peloidal packstones. A forced regression at the top of the late HST resulted in a significant basinward facies shift into a Lowstand Systems Tract (LST), dominated by progradational, high-permeability, inner ramp oolitic sandsheet.

The base of the overlying Transgressive Systems Tract (TST) is marked by significant flooding. Within the TST, 4th order flooding surfaces are overlain by thin mid-outer ramp bioturbated peloidal packstones and wackestones which, form laterally extensive low permeability zones. Parasequences, in comparison, comprise dominantly clean, high-permeability, mid-ramp, skeletal packstones and grainstones.

Increased frequency of sea-level fluctuations and relative deepening towards the late TST results in an upward increase in the proportion and continuity of deeper water facies. The increased heterogeneity impacts reservoir performance. New reservoir models are currently being designed to investigate the impact of these conclusions to guide future reservoir development.

The Stratigraphy and Sedimentation of the Middle Jurassic, United Arab Emirates

J.E. De Matos, Parexpro, Portugal
and **G. Walkden**, Aberdeen University, UK

Wadi Naqab, southeast of Ras Al Khaimah in the United Arab Emirates, exposes an 800-meter thick shallow-water, Middle Jurassic succession. The base of the Bajocian is interpreted as coincident with a sequence boundary at ca. 460 m above the top Triassic and 45 m beneath the horizon which yielded the ammonite *Poecilomorphus* sp. The Bajocian/Bathonian contact is marked by the highest occurrence of *Haurania deserta*. The questionable Bathonian/Callovian boundary either coincides with the last occurrence of *Alzonella cuvillieri* or is near the base of the *Trocholina palastiniensis*-zone. The last occurrence of *Kilianina blancheti* indicates the top of the Callovian. A new Bajocian foraminifera *Pseudodictyopsella jurassica*, n. gen., n. sp., has been identified.

In Wadi Naqab, the Middle Jurassic and Upper Jurassic corresponds to a single shallowing-upward 3rd-order cycle comprising multiple meter-scale fifth-order cycles. The Bajocian is predominantly subtidal and cycles are commonly terminated by thick, massive oncoidal/peloidal packstones or grainstones. Most of the Bathonian and Callovian cycles start with spicular wackestones and end with cross-bedded peloidal/oolithic grainstones and/or stromatoporoid/coral rudstones.

A direct comparison is established between the Middle Jurassic of Wadi Naqab and the subsurface of the Emirates. In the subsurface of Abu Dhabi, the Bajocian Izhara and Bathonian-Callovian Araej formations are the rock units which make up the Middle Jurassic. As a result of regional comparisons performed in this study, the Izhara Formation is redefined and a new type-section proposed.

Stable Isotope Records from Atlantic Deep-sea Cores: Implications for the Maastrichtian Ocean-climate System

T.D. Frank and **M.A. Arthur**
Pennsylvania State University, USA

Although Maastrichtian climate is generally characterized by long-term cooling, synchronous excursions in $\delta^{13}C$ and $\delta^{18}O$ values of pelagic carbonates from the Southern, South Atlantic and Pacific ocean basins suggest that this trend was overprinted by short-lived perturbations in the ocean-climate system. Oxygen isotope proxies of Late Maastrichtian sea surface temperatures (SSTs) suggest that tropical SSTs were well-below present values and challenge the applicability of traditional "green-house" interpretations of latest Cretaceous climate. Shifts in Maastrichtian marine $\delta^{13}C$ values have been interpreted to represent either changes in oceanic circulation patterns or variations in the relative sizes of the sedimentary reservoirs of carbon. One of the most prominent excursions in marine carbon and oxygen isotope compositions coincides temporally with a range of mid-Maastrichtian events, including fluctuations in the carbonate compensation depth (CCD)

in all major ocean basins, latitudinal migrations of foraminifer taxa, and an eustatic fall in sea-level. Taken as a whole, such relations describe a dynamic ocean-climate system that differs substantially from traditional interpretations that depict stable and climatically equable conditions in the latest Cretaceous.

In this context, paleogeographic reconstructions indicate that the Atlantic Ocean basin was effectively isolated during much of the Maastrichtian. As such, the North Atlantic may have played an important role in the generation of oceanic deep water and, in turn, in the governing of oceanic circulation patterns during that time. Despite this potential importance, the Atlantic is currently under-represented in the context of Maastrichtian stable isotope data. Thus, in an effort to resolve climate and oceanic circulation patterns during the latest Cretaceous, carbon oxygen and sulfur isotope data are being generated from well-preserved foraminifers and carbonate-associated-sulfate in bulk sediment samples from Deep Sea Drilling Program Sites 357 (South Atlantic) and 390 (North Atlantic). Synthesis of new data from the Atlantic and previously published data from other ocean basins into an existing chronostratigraphic framework will lend important insight into controls on the Maastrichtian ocean-climate system.

Tectonic Evolution of the Oman Mountains during the Cretaceous

K.W. Glennie
University of Aberdeen, UK

Plate-tectonic movements made the Cretaceous a time of major change in the area of the modern Oman Mountains. Neo-Tethys was created in the Late Permian by the calving of microcontinents (Anatolia, Central Iran) along the northeast margin of Arabia (today's north). A passive continental margin developed during the Triassic and Jurassic as the Afro-Arabian portion of Gondwana moved westward away from an actively spreading oceanic ridge. Sedimentation along Arabia's new continental margin sourced carbonate turbidity currents that flowed basinward to the abyssal plain until the early Late Cretaceous.

Early in the Cretaceous, the South American and Afro-Arabian portions of Gondwana began to separate to create the South Atlantic Ocean. South America continued to move to the west, but Afro-Arabia reversed its sense of motion. The ensuing build-up of horizontal compression led to an eastward-dipping subduction zone within Neo-Tethys. The old oceanic crust of Neo-Tethys was subducted and its sedimentary cover of carbonate turbidites and radiolarian cherts were scraped off to form the Hawasina series of imbricate nappes. Back-arc spreading created a hanging wall of new oceanic crust (future Semail Nappe) that, together with the Hawasina, were obducted onto the continental margin in the Late Cretaceous.

Arabia's continental margin was eventually carried part way down the subduction zone, but was too thick and buoyant for subduction to succeed, and the process halted. Continuing horizontal crustal compression resulted in another subduction zone forming west of Central Iran and the Makran. Reduced compression on the first subduction zone allowed Arabia's continental margin and its cover of Hawasina and Semail to rise isostatically to around sea-level. The latest Cretaceous was a time of tectonic adjustment and shallow-marine carbonate sedimentation across the area of the present Oman Mountains.

Depositional Geometries and Stratigraphic Architecture of the Mauddud Formation Reservoir in Raudhatain and Sabiriyah Fields, North Kuwait

I.G. Goodall, N.E. Cross, D.P. Payne
Badley, Ashton and Associated Ltd., UK
N.R. Rothwell, British Petroleum Kuwait
and **M.A. Ali**, Kuwait Oil Company, Kuwait

The Aptian-Albian Mauddud Formation forms a major under-developed reservoir in the Raudhatain and Sabiriyah fields of North Kuwait. A major, integrated study has been undertaken on this reservoir, incorporating core, biostratigraphy, wireline logs, image logs, and available surveillance data acquired over 40 years of the producing life of these fields. Most of this material has not previously been systematically described.

The Mauddud Formation was deposited on a carbonate-dominated homoclinal ramp interrupted by two progradational clastic incursions. The bulk of the reserves are held in variably macroporous packstones deposited in a mid-ramp environment.

Whilst third-order cyclicity controls the gross architecture of the reservoir it is higher order cyclicity, expressed by upward-shoaling parasequences, bounded by widely correlatable flooding surfaces, which are the basis for a zonation of the reservoir into ten flow units.

These flooding surfaces are tight zones because they transgressively rework sediment into highly-compacted, clay-prone condensed horizons in which calcite cements are concentrated.

Inner ramp grainstones and rudistid floatstones, probably reworked from buildups, are volumetrically minor, but are highly permeable. Hence an understanding of their distribution and impact on reservoir performance is crucial to well placement and implementation of an enhanced oil-recovery strategy.

The Formation and Evaluation of the Porous Network in the Hauterivian-Aptian Carbonate Sequence of the Southern Arabian Gulf

Kassim Habib
United Arab Emirates University, UAE

The prolific middle and upper Thamama Group cyclic reservoirs of the southern Arabian Gulf are grain-rich packstones and grainstones in which remnant primary porosity appears to have been enhanced by fresh water leaching related to exposure at the tops of the depositional cycles.

The studied sequence is bounded from below by a poorly defined unconformity surface; and from above by a well-defined erosional boundary. This sequence is a well known cyclic carbonate section consists of shelf porous limestone that generally alternate with lagoonal dense dolomitic limestone and occasionally with deep water argillaceous limestones. The sequence have prolific reservoirs, of extensive lateral continuity; large thickness and characterized by complex and heterogenous porosity network.

This study found the evolution of porosity in this sequence is largely controlled by the original depositional history. Most of the major diagenetic process that affected the known reservoir rocks were largely related to sedimentological textures. The diagenetic products (from micritization/ dolomitization/pyritization through stylolitization) are abundant and associated with component of the lagoonal or deep water facies.

Applying the sequence-stratigraphical analysis and better delineation of the low-high stand tract could contribute toward defining more workable exploration/exploitation models.

Geochemical Signatures in the Upper Cretaceous Dolomites and their Relation to Deposition and Diagenesis, Egypt

H. Holail
Alexandria University, Egypt

Porosity patterns in the Upper Cretaceous strata in northern Egypt are a result of diagenetic modification of this sequence. Shallow shelf carbonate sequence is partially to pervasively dolomitized. Maastrichtian chalk range from well lithified limestones to poorly indurated, high porosity/permeability microcrystalline limestones. Thus, the diagenetic evolution of this sequence includes potential alteration in marine, burial marine and meteoric fluid settings.

On the basis of petrographic, cathodoluminescent, trace elemental and isotopic compositions, three distinct dolomite types are present. Within the Red Bed Series, microcrystalline dolomite formed syndepositional from hypersaline marine fluids. This dolomite is distinct from zoned, sometimes Fe-rich dolomite which comprises the bulk of dolomite within the Cenomanian and Campanian strata. Isotopic and trace elemental compositions of these dolomites implicate an early replacement of limestones in the presence of marine fluids. A later stage of dolomite is superimposed on this marine dolomite fabric as overgrowth rims, partial replacement of dolomite cores, recrystallization of early dolomite, and as inter rhomb cements. This episode of dolomitization is related to early influx of meteoric water and records a mixed, meteoric-marine diagenetic setting. The excess radiogenic Sr of this dolomite reflects an increased supply of meteoric water which intensified weathering of overlying more radiogenic clastic sources. Continued influence of regional influx of meteoric water is evidence by late stage of calcite which forms both replacive dedolomite and intergranular sparry cements (mean $\delta^{18}O$ = -9.8‰PDB).

Petrographical and geochemical examination of the Maastrichtian chalks from Bahariya Oasis and Abu Roash provides insight into factors that control porosity development in fine-grained calcitic carbonates. High porosity chalks at Bahariya Oasis have depleted isotopic values ($\delta^{13}C$ = -5.0, $\delta^{18}O$ = -8.9‰ PDB) and low concentrations of minor elements. In contrast, the low porosity chalks at Abu Roash have more enriched isotopic values ($\delta^{13}C$ = +1.0, $\delta^{18}O$ = -4.0‰ PDB) and elevated concentration of Sr, Na, Mg, Fe and Zn. These differences in chemistry and fabric reflect varying degrees of early lithification and compaction prior exposure and meteoric diagenetic alteration associated with the regional erosional exposure.

Petrographic Examination and Isotopic Variations of Middle Jurassic Limestones and Cements in Sinai, Egypt

H. Holail
Alexandria University, Egypt

The Middle Jurassic carbonate of north Sinai, Egypt, was deposited under shallow-marine shelf to lacustrine environments. The ratio of grainstones to mudstones increases towards the upper part of the sequence, reflecting a regional shallowing phase. The complex diagenetic history of this sequence, inferred from cross-cutting features from thin section and from the detailed trace elemental and isotopic compositions are different coated grains and cements. Replacement of Middle Jurassic carbonates by dolomite is localized over few intervals. Subsequent burial diagenetic history can be charted from early to late by the sequential appearance of microstylolites, partial dolomitization, macrostylolites, burial calcite and dolomite cements and late leaching.

The stable carbon oxygen isotope values suggest that the precursor matrix was originally more enriched in ^{18}O and was modified by the ^{18}O-depleted water during burial. Meanwhile, the isotopic composition of ooids could not reflect equilibrium with the Jurassic marine water, where the low oxygen values are most likely the result of alteration by meteoric water. The well-preserved oncoid grains have isotopic compositions similar to those of the original Jurassic marine carbonates. Based on the oxygen isotopic composition of the well-preserved oncoid grains, the Middle Jurassic seawater temperatures, ranged from 22.8 to 27.5°C. The isotopic compositions of the radiaxial calcite, the cryptocrystalline calcite and the geopetal calcite cements revealed that these cement types were originally precipitated through sub-marine conditions. Whereas, the intergranular sparry calcite cement is of burial environments and exposed to temperatures ranging from 69 to 87°C.

Three zones of coarse-grained calcite cementation at different depths were documented in this sequence. Petrographic and geochemical techniques were used to investigate the genesis and textural relationships of these calcite cements. All are distinctly similar in trace element contents. Oxygen isotope ratios range from -8.8 to -12.1 ‰ vs. PDB, whereas the carbon isotope ratios range from +1.6 to +2.3‰ vs PDB. The considerably light $\delta^{18}O$ values reflect a meteoric fluids influence. Values of $\delta^{13}O$ represent initial composition of marine carbonates during Middle Jurassic time.

The Early Cretaceous Basin-to-shelf Sequence Exposed in Ras Al Khaimah, UAE

R.F. Hulstrand, Abu Dhabi Company for Onshore Oil Operations, Abu Dhabi
and **Harry W. Mueller III**,
Exxon Production Research Company, USA

A 2,100-foot thick section of the Lower Cretaceous Habshan Formation and its deeper water, Rayda Basin equivalent units was measured, sampled and described from excellent exposures along the mountain front north of Al Khatt. The section can be divided into lowstand, transgressive and highstand system tracts. Additional units include debris flows, slump and slide blocks and olistoliths. The litho and biofacies compare very well with the thinner (1,230 ft) section described for the Sajaa field of Sharjah Emirate, 65 km to the southwest. Known hydrocarbon reservoirs occur in the formation. Recent papers have demonstrated that multiple shelf-margin complexes prograded into the Rayda Basin during the Berriasian and Valanginian.

The Habshan and equivalent rocks have been subdivided by previous workers into shelf, slope and basinal units using environments and fauna. The basal and basinal Rayda unit is composed of calpionellid, fine-grained peloidal limestones. The Rayda is 225 ft thick. The overlying Sahil laminated limestones and marls of the slope environment are 1,000 ft thick.

The Habshan is composed of bioclastic, oolitic, peloidal and oncoidal grainstones with buildups of stromatoporoids, branching and massive corals, caprotinid rudists and forams. The thickness is 875 ft thick compared with 480 ft in Sharjah and 152 ft in Wadi Bani Kharus, Oman. This thick section suggests the potential for additional exploration plays.

Albian Sea-level Fluctuations Constrained by Stable Isotopes, Fluid Inclusions and the Morphology of Benthic Foraminifera (Nahr Umr Formation) Oman

A. Immenhauser, **W. Schlager**,
Vrjie Universiteit, The Netherlands
S.J. Burns, University of Bern, Switzerland
and **R.W. Scott**, Precision Stratigraphy Associates, USA

The Late Aptian to Late Albian interval of the Arabian Platform was studied in northern Oman (Nahr Umr Formation) for its paloceanographic and sea-level record. The outcome of this project indicates seven

transgressive-regressive events overprinted by smaller sea-level fluctuations. The peak of regression lead to emergence of the sea-floor and created subaerial exposure surfaces. These surfaces are found and correlated throughout five sections measured in a paleo-margin to paleo-basin transect approximately 100 kilometers in length. Investigation on a nearby carbonate platform margin suggests a paleo-water depth of approximately 50 meters prior to sea-level drop. The subaerial character of those surfaces was not recognized during fieldwork due to the lack of diagnostic features. However, three independent lines of evidence document emergence. These are 1) pronounced negative excursions in carbon and oxygen isotope composition directly underneath hardground surfaces documenting the influence of light soil carbon and meteoric water. 2) Blocky sparite in rudists shells underneath hardgrounds comprise primary brackish fluid inclusions interpreted as "pollution" of meteoric water by residual salt. 3) Symbiom-bearing *Orbitolina* sp. display small, conical morphotypes in the shallow, strongly illuminated water prior to exposure whereas large, flat morphotypes are characteristic in the transgressive shales above those surfaces documenting deeper, less illuminated waters. Most of the exposure surfaces rest directly on subtidal sediments but evidence for deep-cutting erosion is absent. Correlation of transgressive-regressive events recorded in the Albian of Oman with sea-level curves of the Anglo-Paris Basin and the Texas Gulf Coast suggest a predominately eustatic nature of these signals.

Aptian Depositional Cycles of the UAE - A Response to Eustatic Events which Match those of South Africa and Alaska

C.G.St.C. Kendall
University of South Carolina, USA
Abdulrahman S. Alsharhan
United Arab Emirates University, UAE
Kurt Johnston, Animikj Sen and **Sean Ryan**
University of South Carolina, USA

Ten depositional shoaling-upward cycles are expressed in the Shu'aiba Formation at the Bu Hasa field and in measured sections for the Aptian. Similar numbers of cycles are recognized in South Africa and Alaska for this time interval. The inference is that these cycles are a response to high-frequency changes in eustatic sea-level position.

The Aptian in the United Arab Emirates contains two major third order cycles which are bounded by erosional unconformity surfaces. These third-order cycles influence the character of the higher frequency events, so these latter begin as lowstand sequences which evolve upward into those with a more transgressive character. Towards the end of the third-order cycles these are replaced by highstand systems. In the adjacent intershelf basin the cycles reflect lowstand and highstand systems, but accumulated in relatively deep, more marine water dominated by shale deposition. These cycles of the United Arab Emirates match similar events in South Africa and in Alaska, pointing the way to more accurate models for world-side depositional systems during this time interval.

Sequence Stratigraphy of Cretaceous Units, Sinai, Egypt

J. Kuss, M. Bachmann and **S. Lüning**
Universitat Bremen, Germany

The onshore Cretaceous units of Sinai and neighboring areas are subdivided into more than 20 minor depositional cycles, and reflect imprints of two major sea-level fluctuations. During the first, Late Aptian marine sediments were confined to the northern areas. The following southward steplike progradation in the transgressive Albian-Coniacian sea resulted in widespread carbonate deposits over the region. After a major retreat, the second rise of the sea-level culminated in Maastrichtian times with ubiquitous hemipelagic chalks and marls.

The Early-Mid Cretaceous deposition in northern Sinai took place along a passive continental margin which slightly deepened towards the north. Here, east northeast-west southwest trending faults mark the southern rim of a Triassic-Jurassic rift system. The Early-Mid Cretaceous carbonate ramp is situated at the southern edge of a northward deepening intrashelf basin following the older rift margin.

During the first sea-level rise, the ramp developed in two stages with different sequence stratigraphic patterns: the Late Aptian-Early Albian delta-dominated ramp in the north evolved into the Middle Albian-Cenomanian carbonate-dominated ramp. Local emergence of the carbonate shelf system during the Late Turonian-Coniacian times are indicated by regional lithologic changes.

From Late Coniacian, regional tilting and subsidence prevailed, especially along the now inverted rift-graben-system ("Syrian Arc"). Sedimentologic and biostratigraphic studies along domal anticlines of the "Syrian Arc" exhibit shallow-water carbonates interfingering with intrashelf basin sediments, composed of widespread hemi-pelagic marls and chalks. They reflect drowning of the Early-Mid Cretaceous carbonate shelf within both the "Syrian Arc" and the tectonically unaffected area further south. The monotonous

hemipelagic chalk-marls are subdivided as to sequence stratigraphy based on paleobathymetric estimations of benthic/planktic microfaunas. However, these proxies may be complicated by other ecologic factors like currents and productivity changes; the latter can be proved for the latest Cretaceous interval.

Transition Facies from Carbonate Platform into Basin, the Oxfordian, North Caucasus, Russia

Vitaly Kuznetsov
State Academy of Oil and Gas, Russia

Carbonate sedimentation started on the northern shallow Tethyan shelf in the Callovian and continued until the Valanginian. The result was a thick and vast carbonate platform which is now located between the Black, Azov and Caspian seas. It is composed mostly of biogenic, pelletic and oolitic limestones with some secondary dolomites. Type of sediments presence of algae, and character of benthic fauna indicate shallow-water sedimentation and normal oceanic salinity.

The character of the transition from carbonate platform into basin is studied in the Oxfordian of the Central Caucasus. The carbonate turbidites are described here. Crinoidal, pelletoid and polydetritic grainstones with intraclasts occur at the base of the cycles. This lower member features gradational bedding. Bituminous mudstones and wackestones with cherts are located in the cycle top. This member is thinly laminated. Thickness of the cycles can be 0.5 to 2.0 m. They are divided by sharp, usual erosional boundaries. Another type of the slope sediment is channelized mass flows. They are lenticular, rudaceous carbonate deposits with numerous large intraclasts.

Occurrence of turbidites and mass flow indicates considerable energy of transporting environment and directional current. This can happen when basin depth is great enough. Sequences described characterize in general proximal turbidites. The distal turbidites are represented by dark-gray marls with interlayers of mudstones and shales of Kasaeskaya suite, which are located in the central axial part of the Great Caucasus.

Cretaceous Reef Corals - State of Knowledge and Current Research

Hannes Löser
Universitat Erlangen-Nürnberg, Germany

With the beginning of the Cretaceous, corals lost their role as the primary reef builders, but still remained a very diverse group. The systematics of all post-Paleozoic corals are quite inconsistent, because of their complicated morphology and wide range of infraspecific variation. Hundreds of genera and thousands of species have been previously reported, but their phylogeny is still a matter of controversial discussion, and data on their distribution are rare.

Since 1991, the author has built up an extensive computer database containing all data on Cretaceous corals obtainable from publications and from his own observation of more than 3,000 samples. The known species are evaluated using a single unified species concept, resulting in a large reduction in the number of taxa.

This critical evaluation of the taxonomic data is used to estimate the stratigraphic and palaeogeographic distribution of genera as well as species. In addition, a smaller number of more consistent taxa shed more light on the relationship between faunas and should allow the tracing of the evolution of the group during the Cretaceous.

First results on the development and stratigraphic and palaeogeographic distribution of Cretaceous Scleractinia are presented. The Early Cretaceous (Berriasian-Hautervian) corals are dominated by genera which are known previously from the Jurassic. The Barremian to Cenomanian is characterized by a first diversity maximum with numerous new groups. The Cenomanian-Turonian boundary is marked by an extinction event and a faunal change. Many of the typical Jurassic groups disappeared. In the Late Cretaceous a new evolutionary phase began and reached a high in the Santonian. From the Late Campanian the number of taxa decreased and at the Cretaceous-Tertiary boundary most Cretaceous general became extinct.

Gas Productivity Increases Over Time by Seismic Activity, Lacq Field, France

G. Massonat and **C. Pabian-Goyeneche**
Elf Exploration Production, France

Production of hydrocarbons usually causes pore pressure to decrease within the reservoir, and thereby, actual stress to increase. This entails a reduction of pore-threshold and absolute permeability. Surprisingly, in the huge gas field of Lacq, France, a sharp increase in productivity has been recorded from well testing on most wells over a 40-year period of production.

The reasons for this phenomenon have been discussed and the increase in absolute permeability with depletion is undoubtedly caused by and correlated with the earthquakes recorded within and in the vicinity of the reservoir.

This paper presents the different hypotheses utilizing the mechanical aspects of seismicity induced by gas production, an analog model built to validate the interpretation, micro-seismicity as guideline for reservoir properties mapping, and the effects of the input of a mean variation of permeability with depletion on the flow-simulation results.

The poro-elastic stresses resulting from production-generated decreases in pore pressure are at the origin of the earthquakes in the field. Indeed, the reported low heterogeneity of the depletion supports reservoir seismicity. The locations of seismic events show that seismic fractures occur on existing pre-fracture discontinuities. New fractures could also be generated, as evidenced by the analog model constructed with silicone putty and dry quartz sand. The spatial distribution of the induced field earthquakes allows the flow paths within the reservoir to be understood. Induced earthquakes are the best candidates for mapping the organization of stress heterogeneities within the reservoir as a function of time, the fluid flow paths, the organization of fracture space and time within the reservoir.

The fracture-related parameters in the dual porosity model are distributed using well indexes and fluid flow path mapping from micro-seismic analysis. In the model, the reservoir is divided into several areas in which fracture density is a stationary parameter. Constant values of the different properties required for modeling the fracture network are inferred for each area. An average variation of permeability with depletion (20 times greater than the initial value) is input in the 3-dimensional model used to simulate flows. Among the parameters, the increase in permeability was proved to be the most critical for matching production history.

Cretaceous Carbonate Deposition in Indian Subcontinent and Southern Tibet: A Resume

Manmohan Mohanti
Utkal University, India

In context of wider studies on regional tectonics and sedimentation models, the Cretaceous carbonate facies scenario in the Indian subcontinent and the Himalayan region in southern Tibet in the Tethyan realm may provide useful comparative information for the Jurassic/Cretaceous carbonate depositional model studies in the Middle East. In the rift-drift processes during the Mesozoic, the Indian plate was disposed in a passive margin setting. A number of marginal pericratonic rift basins and intracratonic rift/transtentional basins developed in cratonic peninsula India. While there was restricted carbonate deposition in marginal pericratonic rift/transtensional basin setting during the Cretaceous, the orogenic collisional setting in the southern Tethyan passive margin in the Himalayas-Tibet region showed well developed carbonate platform development and slope-basin transition during the Mesozoic.

The pericratonic Cauvery Basin of southern India exhibits shallow shelf-carbonate facies types variably intermixed/interlayered with siliciclastics during the Late Albian-Maastrichtian reflecting 2nd- and 3rd-order cycle of sea-level changes. While in Late Albian reefal muddy/biogenic carbonate "mounds" and associated facies developed under Low-Transgressive-High Stand System Tract close to the basement "High" and structural hinges of basement fracture patterns: the Cenomanian-Maastrichtian interval was marked by spectacular formation of biogenetic/biostromal bivalve banks. Rudists were of very restricted occurrence in the Maastrichtian interval was marked by spectacular formation of biogenetic/biostromal bivalve banks. Rudists were of very restricted occurrence in the Maastrichtian shelf facies. In the Narmada transtentional basin, nodular limestone and coralline limestones were deposited in shallow marine environment and the Lameta carbonates may have been generated under transitional coastal environment.

Mesozoic was represented by shallow- to deep-water environments in the passive margin of the southern Tethyan Himalayas with variable carbonate deposition. The depositional facies types were controlled by variable subsidence, rate of sedimentation, sea-level changes and siliciclastic influx. Carbonate platforms in the Himalayas generated during the Triassic, further developed in the Jurassic and in the Middle Jurassic the platforms were half-graben-like, fault controlled and shallowing rimmed platforms.

The Lower Cretaceous in the southern Tethyan shelf zone of the Indian passive margin south of Tibet in the Central Himalayas exhibit shallow marine deposits with development of oolite shoals evolving into relatively deeper marine setting from the Albian to the Santonian with deposition of calcareous black shales and thin bedded marls/micritic limestone. In the Campanian-Maastrichtian stable, isolated, rimmed carbonaic platformal setting was generated, with rudist and orbitoid dominated by turbidite clastics of slope aprons, deep-sea fans, pelagic shales and micritic carbonates and large olistostomes indicating steepening and faulting of continental slope and rise. Carbonate platform in parts of the area has drowned due to crustal warping and some platforms have slumped into deeper marginal basins, continental collisional tectonics/orogenic movements have terminated the Himalayan carbonate platforms.

The Significance of Events around the Jurassic-Cretaceous Boundary in the Arabian Gulf Area, Greater Arabian Basin

A.E.M. Nairn
University of South Carolina, USA
and **Abdulrahman Alsharhan**
United Arab Emirates University, UAE

In the history of the Middle East the Late Jurassic and Early Cretaceous is a unique interval during which the rocks which contain the abundant hydrocarbon resources accumulated, despite the not insignificant contributions of the Silurian, Late Carboniferous-Permian (the Late Devonian-Early Carboniferous are poorly developed).

The abundance of data from surface and subsurface exploration has permitted the development of a sequence of paleogeographic maps extending from Late Jurassic to Middle Cretaceous which, combined with reasonable inferences about the source areas, illustrate a pattern of lithofacies changes within the very shallow water environments of the Arabian Shelf Basin and the continental margin. The shallow water depth changes, attributed to sea-level fluctuation emphasize the relative importance of basin highs in the development of isolated intrashelf basins with their facies variations.

Economically the association of argillaceous limestones which provide source rock and reservoirs with shale and anhydrite which form seals, and their persistence over a considerable period of time, without subsequent deformation has given the region its dominant position in the energy field. It is generally thought that the sea-level fluctuation are due to eustatic sea-level change, but the cyclicity/repeatability requires more detailed high resolution stratigraphic control.

Structural Setting and Stratigraphic Evolution of the Northwestern Oman Mountain Front, United Arab Emirates

M.A. Noweir, A.S. Alsharhan and **M.A. Boukhary**
United Arab Emirates University, UAE

The Faiyah range belongs to a group of large-scale, post obduction structures that deform the Late Cretaceous-Tertiary sediments exposed along the western margin of the Northern Oman Mountains front. It consists of three en echelon anticlines generally trending along north northeast-south southwest direction with eastward-directed thrust faults dipping westerly and striking parallel to the fold axis. The en echelon folds are proposed to overlie pre-existing deep-seated faults which could have been formed by the Late Cretaceous emplacement of the Semail Ophiolite. These faults were probably reactivated by a regional northeast-southwest oriented compressional event of post Middle Eocene age. This range may have originated as a result of a post-emplacement regional compressive event of post Middle Eocene age correlatable with the Zagros fold orogeny.

The Late Cretaceous to Tertiary neoautochthonous sedimentary rocks are divided into three units; the Qahlah and Simsima and Dammam formations. Stratigraphical and sedimentological evidence shows that the Qahlah Formation was deposited in a non-marine environment with probable induction of the sea invasion in the later stage of sedimentation. The Simsima Formation was deposited in a shallow marine environment. These units unconformably overlap the allochthonous Semail Ophiolite. The sequence of the so named Muthaymimah Formation (Tertiary) by previous authors has been re-examined and the microfaunal content clearly indicates that this sequence belongs stratigraphically to the Maastrichtian Simsima Formation.

Calpionellids and the Jurassic-Cretaceous Boundary in Arabia

Ross G. Peebles
Halliburton Energy Services, USA

Calpionellids are pelagic microfossils with a Pan-Tethyan distribution and provide some of the highest-resolution biostratigraphy for the Late Jurassic-Early Cretaceous (Late Tithonian-Early Valanginian). In Arabia, calpionellids occur in Iraq, Kuwait, Saudi Arabia, UAE, Oman and Yemen as well as in the neighboring countries of Iran and Somalia. Calpionellids are generally found in thin- to medium-bedded lime mudstones and wackestones such as those of the Rayda Formation of Oman and the United Arab Emirates. Published reports of Arabian calpionellids have generally interpreted Tithonian-Berriasian ages for the observed assemblages which typically include *Calpionella alpina* and *Calpionella elliptica*. Such interpretations resulted in the modeling of a regionally extensive pelagic environment around Arabia during this time and the placement of the Jurassic-Cretaceous boundary within these calpionellid-bearing pelagic limestones.

However, new outcrop and subsurface studies from across Arabia as well as re-evaluation of published material show that calpionellids did not appear in most of Arabia until the Early Berriasian and actually occur in the first Cretaceous deposits in many parts of Arabia. In many cases, Early Berriasian calpionellid-bearing lime

mudstones directly overlie Late Jurassic (Oxfordian-Kimmeridgian) shallow-water platform carbonates marking the Jurassic-Cretaceous boundary. This boundary is unconformable with most, if not all, of the Tithonian missing. Strontium isotope dating has been integrated with calpionellid biostratigraphy to provide high-resolution dating of this large-magnitude Early Cretaceous transgression over the Jurassic carbonate platform. In addition, calpionellids provide evidence of unconformities within the Berriasian-Valanginian.

Paleohydrological Model of Fluid Flow and Differential Diagenesis of the Shu'aiba Formation from the Subsurface in the UAE to Outcrops in Jebel Akhdar, Oman

S. Duffy Russell
Abu Dhabi Company for Onshore
Oil Operations, Abu Dhabi, UAE
and **Gordon M. Walkden**
University of Aberdeen, UK

The Shu'aiba Formation is one of the largest oil reservoirs in the United Arab Emirates and the Sultanate of Oman. In attempting to obtain a clearer and more predictable picture of its reservoir characteristics, much attention has previously been given to the distribution and correlation of sedimentary facies in the Shu'aiba, but in terms of reservoir quality and the distribution of flow zones at least as much depends upon its diagenetic cementation history. Although buried to nearly 3 kilometer in the subsurface of Abu Dhabi, equivalent facies in the Shu'aiba are well exposed and accessible in Jebel Akhdar. Comparison of the diagenetic history between the two areas reveals substantial diagenetic contrasts and shows that dissimilar but laterally linked paleohydrological regimes can overprint identical facies with very different reservoir/non-reservoir characteristics.

Dolomitization and stylolitization affected both areas, but a primary control appears to have been the interaction of early and late meteoric-phreatic environments with a less dynamic burial environment. Following early aragonite dissolution and inversion, Shu'aiba reservoirs quickly subsided into a protective burial environment where they experienced little diagenetic change, retaining early porosity-permeability characteristics. Tight cemented horizons could reflect inversion of early flow zones rather than the local effects of stylolitization. Elsewhere, limited growth of syntaxial cements could have been driven by aragonite inversion. In the updip outcrop areas, where there was a replenishing supply of early meteoric pore fluids in a shallow burial environment, cementation was more pervasive. Occlusion of all reservoir quality was probably completed by the precipitation of unconformity-derived calcites prior to reburial associated with the emplacement of the Semail Ophiolite and Hawasina sediments.

From Leeward Ramp to Block-faulted Shelf: Sequence Stratigraphy and Petroleum Prospects of the Cretaceous Sediments of Southern Iraq

F.N. Sadooni
Eden Petroleum Services Ltd., New Zealand

Cretaceous sediments host around 80% of Iraq's proven oil reserve. They represent the main reservoirs in the southern super-giant fields.

Three major factors controlled the deposition of the Cretaceous sediments in southern Iraq. These are the culmination of the Neo-Tethys rifting, the advent of the Arabian Plate to the tropical and subtropical climatic zones and the contemporaneous growth of giant structures due to salt diapirism. The sediments are divided among seven megasequences; each contains source, reservoir and cap rocks.

Sedimentation started with the development of a leeward carbonate ramp of the Yamama Formation on the gentle slope of the Arabian Platform. From the middle Valanginian, that ramp underwent a gradual clastic influx from the southwest, represented by thin siltstone and sandstone units within the Ratawi Formation. The clastic front reached its peak with the deposition of the Zubair Sandstone Formation during the Hauterivian-Barremian and reached as far as Kirkuk field in the north. This regional clastic invasion that covered most parts of the Arabian Plate retreated with the establishment of a new carbonate shelf of the Shu'aiba Formation during the Aptian.

The shelf was subjected once again to a heavy clastic influence of the Nahr Umr Formation during the Albian. Strong tectonic activity lead to the formation of a block-faulted shelf during the Cenomanian, where rudist reefs of the Mishrif and Hartha formations flourished on highs, while deep-water marly limestones of the Rumaila and Shiranish formations occupied the lows in between. During the upper Campanian, the basin received flysch sediments of the Tanjero Formation from the newly formed Zagros Mountains in the northeast. The Cretaceous sedimentation was interrupted by a regional unconformity during the upper Maastrichtian.

Geological Controls on Pore Geometry of Upper Kharaib Reservoir Offshore Abu Dhabi, UAE

J. Saotome, T. Shibasaki,
T. Shikama and **K. Kawaguchi**
JODCO, Japan

The Upper Kharaib (Thamama II) reservoir, belonging to the Lower Cretaceous Thamama Group is one of the major oil-producing horizons offshore Abu Dhabi in the United Arab Emirates and is traced over the area as a well-defined rock unit. The reservoir is composed of three lithofacies, (1) rudistid-peloidal grainstone/packstone, (2) algal-peloidal grainstone/packstone, and (3) bioclastic mudstone/wackestone. Sediments were deposited on a broad carbonate shelf and show an upward-shallowing sequence. Reservoir quality is determined by both original depositional fabric and subsequent diagenetic processes. In general, permeability is variable while porosity is relatively constant throughout the sequence, except for stylolitized intervals.

In the "A" field, six, highly permeable facies are identified within the grain-supported interval. These facies are characterized by unique pore throat distribution(s) resulting from depositional textures and diagenetic modification. Grain sorting and preferential dissolution, as well as preservation of primary pores, are significant factors in controlling pore geometry. Dolomitization is also locally important. Highest permeability is present within well-sorted, coarse grainstone at the basal part of upward-fining bedsets where well-connected intergranular pores are preserved. Identification of highly permeable facies is crucial if one is to understand the performance of the reservoir under water flood. Based on the vertical and lateral distribution of highly permeable facies and pore-throat distribution, the reservoir was divided into 22 layers as a basis for reservoir simulation study.

Cyclic Sedimentation and Rudist Settlement in the Campanian, Central Oman

Dietrich Schumann
Institut der Technischen Universitat, Germany

Complete in-situ rudist associations are preserved in the Campanian of central Oman. They developed during a transgression onto the Arabian Plateau. Microfacial analysis reveals that vigorously turbulent conditions prevailed throughout the Lower Campanian. The development and preservation of in-situ rudist associations are obviously rare events. As a rule, turbulence prevents the development of such structures. The absence of vast rudist reefs is not a consequence of an inherent inability of rudists to build reefs, but can be attributed to exogenus, abiotic factors. The associations investigated here inhabited a restricted shallow-marine environment. Rapid growth of a few rudists have been verified. Vertically growing rudist associations of 5-8 in-situ generations represent a period of only 100-200 years.

There is no known locality throughout the whole Saiwan region of Central Oman where these associations are more than 2 meters thick. As a rule they are no thicker than 80 centimeters. However, this does not mean that rudists are not potentially capable of building thicker reefs. The structure allows unlimited colonial succession upon existing surfaces. This principle capability is demonstrated in many cases. The reason of such massive reef structures, as seen in coral reefs, did not develop on a worldwide scale is solely due to exogenous factors. Colonization evidently took place during a transgression in very shallow waters with very specific turbulences. The factors and levels of tolerance controlling growth differ widely from those influencing coral reef growth. Such extensive flat reef bodies, as the rudist associations of the Central Oman type, could only develop on low angle open-shelf margins, a relief which existed along the Arabian Plateau margin.

Are Mid-Cretaceous Eustatic Events Recorded in Middle East Carbonate Platforms?

R.W. Scott
Precision Stratigraphy Associates, USA

The mid-Cretaceous is an informal term that, in the Middle East, includes the Cretaceous stages of Hauterivian through Cenomanian. During this time interval of 36.7 million years ago (Ma) to 44.5 Ma, twenty cycles of relative change of coastal onlap were proposed by Haq et al. (1988), and, since that time, some of these changes have been subdivided further. The average duration of these so-called third-order cycle is 1.8 to 2.2 million years depending upon which time scale is used.

The challenge is to accurately identify these cycles in the Middle East platform record and to correlate them precisely with a reference section of cycles. Quantitative stratigraphic techniques, such as graphic correlation, achieve this goal. Graphic correlation is a numerical correlation technique that is simple to apply and gives precise and reproducible correlations. Graphic correlation is based on an integrated data base of fossil tops and bases and other geologic events. The technique creates hypotheses of correlation that make no assumptions about the completeness of each fossil range.

A composite standard database from the Aptian through the Turonian has been constructed using 30 geologic sections in the Tethyan Realm. More than 1,000 bioevents of ammonites, inoceraminds, planktic foraminifers, selected rudists, benthic foraminifers, nannofossils, dinoflagellates, and spores and pollen have been integrated with nearly 100 depositional and geochemical events. Among these fossils are many of the zonal indicators. The stadial boundaries are defined by key taxa in generally accepted reference sections in France, Tunisia and Texas. The scale is calibrated to the Harland time scale. Platform exposures of the middle Cretaceous in Oman record six or more global cycle boundaries at the Habshan/Lekhwair contact, at the Shu'aiba/Nahr Umr contact, several within the Nahr Umr, possibly at the base and top of the Natih 'F' Member, at the top of the 'E' Member, and at the contact between the 'C' and 'B' Members. Other cycles may be recognized as more detailed stratigraphy is completed.

Sediment accumulation rates progressively increased during the deposition of the Albian-Cenomanian carbonate platform. Rates of the Nahr Umr range between 0.0 and 1.42 centimeter/1,000 years (cm/ky). Rate of the lower part of the Natih 'E' through 'G' Members averages 2.22 cm/ky, and the rate of the upper Natih is 4.59 cm/ky. Clearly, during deposition of the Nahr Umr many submarine hiatuses developed. Possibly the number and/or duration of exposure and hardground development decreased from Albian through the Cenomanian.

Microfacies Analysis and Depositional Setting of the Early Cretaceous Succession in Central Arabia

H.T. Shebl, Core Laboratory, United Arab Emirates
and **Abdulrahman S. Alsharhan**,
United Arab Emirates University, UAE

The Early Cretaceous carbonates of the Sulaiy, Yamama, and Buwaib formations have been described in the outcrop in Central Arabia. Based on sedimentological interpretation and fossil contents, these formations have twenty-two successive microfacies correlated with the published standard microfacies types and belts. The Sulaiy, Yamama and Buwaib formations were deposited under open-platform and shelf lagoon conditions. Such deposition was only slightly interrupted by the pre-Buwaib disconformity which is marked by an abrupt change from the fine-grained lime mudstones of the upper Yamama to the quartzose cyclamminid wackestone of the basal Buwaib. Another break between the Buwaib bioclastic wackestone and the overlying Biyadh Sandstone is here suggested and is believed to have been more pronounced.

The deposition of the Lower Cretaceous is interpreted within the framework of simple, easterly dipping carbonate ramp model, that was established as a result of the extensive flooding of the Arabian Plate during Early Berriasian time. This ramp was only slightly disturbed by a minor Early Hauterivian regression and was terminated by the Barremian regression during which clastic deposition dominated most of Central and Eastern Arabia.

Jurassic and Cretaceous Carbonate Platforms of the Middle East - The Role of Biostratigraphy

M.D. Simmons
University of Aberdeen, UK

In hydrocarbon exploration in the Middle East, microfossils have been used in a traditional sense to provide a stratigraphic understanding of wildcat wells and correlation to other regional datapoints. With an increasing emphasis on efficient production, biostratigraphy has proved itself useful by developing pragmatic, localized, high-resolution biozonation schemes that enable horizontal wells to be "biosteered". At the same time, high-resolution biozonation schemes, which rely on localized biofacies (paleowater-depth related) changes, can be useful in developing reservoir layering models to enhance production from fields.

Novel studies on the palaeoecology of microfossils (e.g. by relating their paleowater-depth tolerances to their photosynthetic requirement) have enabled them to become extremely useful tools in reconstructing palaeoenvironments. Vertical changes in microfossil assemblages (biofacies) can now be used to record changing palaeo-water depth and hence relative sea-level. Localized sea-level curves, so developed, can be compared (stratigraphic resolution permitting) from basin to basin, developing an understanding of regional relative sea-level events and the influence of eustasy on the region.

Notwithstanding the above remarks, there is still much progress to be made in Mesozoic biostratigraphy in the Middle East. Stratigraphic resolution is often not of a precision that meets the needs of either industry or, for instance, for studies of relative sea-level change. This is because the identity and stratigraphic range of many key microfossils remain poorly understood. These can only be constrained by unfashionable detailed taxonomic studies. Therefore, geoscientists must be aware that continued progress in the application of biostratigraphy in the region must be underpinned by advances in the taxonomic basis on which biostratigraphy is built.

Lower Aptian Rudists of Arabia

Peter W. Skelton
Open University, UK

Detailed study of Lower Aptian rudists from a number of Arabian localities has revealed the presence of eight species, assigned to seven genera.

Dominating the outer platform facies are the abundant elevator caprotinid, *Glossomyophorus costatus* (Masse, Skelton and Sliskovic) and the large elevator to recumbent caprinid, *Offneria murgensis* (Masse). These are accompanied locally by *Agriopleura* and common examples of a new taxon, a thick-shelled caprotinid elevator showing some internal similarities with *Monopleura michaillensis* (Pictet and Campiche), though with a spirally extended left (free) valve. Much rarer is a straight, pencil-like, elevator growth form of the small *Offneria nicolinae* (Mainelli). The elevators are mainly displaced, and often broken, though some are intact in upright life position, in wackestones to packstones. Transported shells and more or less worn fragments of *O. murgensis*, by contrast, are more common in rudstones to pack/grainstones especially those deposited on the outermost platform zone.

The most characteristic component of the chalky inner platform facies is the elevator caprotinid *Agriopleura blumenbachi* (Studer), showing a variable morphology ranging from a slender cylindro-conical shape to the more broadly conical form usually referred to the probably synonymous *taxon A. marticensis* (D'Orbigny). Accompanying this are less common *Glossomyophorus costatus* and other rarer elevator caprotinids, including some large conical forms, *Horiopleura distefanoi* (Parona) and *Himeraelites douvillei* (Di Stefano), and a more slender *?Monopleuriform* sp.

This rudist association can be considered diagnostic for the Lower Aptian. The absence of radiolitids, known from the Upper Aptian elsewhere, is noteworthy. The fauna is also distinctively southern Tethyan in character. Such a diversity of rudist taxa offers considerable scope for detailed facies modelling from core material.

Cenomanian Coral-rudist Associations near Kozani (Northern Greece)

Thomas Steuber and **Hannes Löser**
Universität Erlangen-Nürnberg, Germany

Corals and rudists are abundant both in basal, predominantly siliciclastic deposits and overlying platform limestones of a transgressive Cenomanian sequence at Nea Nikopoli, northern Greece. Basal sandstones and lithobioclastic limestones contain gastropods, pectinids and oysters. Associated are thick-shelled radiolitids, abundant *Apricardia* and small caprinids. Corals are represented by cupolate morphotypes that were not attached to the substratum and cylindrical as well as laterally compressed solitary taxa. In overlying horizons massive colonial corals dominate. Particularly large shells of caprinids are found in coarse-grained bioclastic limestones.

Coral-rudist associations of overlying limestones are preserved in life position and have been studied on bedding planes and in stratigraphic successions. They thrived in shallow-marine environments above wave base. Levels of subaerial exposure of bioclastic grainstones separate several depositional cycles that are superimposed on a general trend deepening environments.

Corals and rudists were the main carbonate producers of level-bottom communities that formed dense, though unbound fabrics. Among rudists, recumbent morphotypes (*Caprina, Caprinula, Sphaerucaprina, Ichthyosarcolites*) dominate, but small elevators (*Radiolitidae, Ichthyosarcolites*) are also present. Corals are mainly colonial; they remained small and occur in various morphotypes: massive (*Adelocoenia, Eohydnophora, Felixigyra, Fungiastrea*), dendroid (*Calamophylliopsis*), cupolate (*Aspidiscus*) and flabellate (*Lasmogyra*); solitary corals are rare.

With increasing water depth there is a general trend of decreasing colony size of corals and reduction of diversity of both corals and rudists. These patterns of diversity and abundance of corals in relation to water depth and sedimentation are remarkably similar to extant coral communities. Rudists shared the same environments but some groups exploited slightly deeper environments.

Carbonate Production by Rudist Bivalves in Tethyan Late Cretaceous Shallow-marine Environments

Thomas Steuber
Universität Erlangen-Nürnberg, Germany

Rudist bivalves were among the dominant faunal elements in most shallow-marine environments of the Cretaceous Tethys and must have contributed significantly as primary producers of carbonate. Stable isotope chronology of numerous shells of hippuritid rudists from various depositional settings has yielded cyclic variations in oxygen isotopic compositions which are interpreted to reflect seasonal changes in paleotemperature and, thus, delineate annual skeletal growth. In radiolitid rudists, annual growth increments are reconstructed from cyclic patterns of the cellular cell structure. Both methods result in consistent rates of shell accretion in three studied communities from siliciclastic

and calcareous sedimentary settings. Annual shell accretion of up to 40 mm and the generally sediment-supported growth fabrics indicate that the rate of ambient sedimentation was important for the establishment of fast growing elevator rudists.

Estimates of carbonate production by rudist communities on the basis of skeletal growth rates results in amounts that exceed the productivity of modern coral reefs. A comparison of the three studied sedimentary settings reveals that the productivity of rudist associations was governed by factors that are different from those that control the production of coral-algal-hydrozoan communities. This includes the type and amount of background sedimentation, light, nutrition and turbidity. Consequently, environments of maximum carbonate production of the Cretaceous Tethys must have been different from those of modern, and perhaps most Phanerozoic, tropical shallow-marine settings.

The Influence of Rudists on Platform Evolution: the Maiella Platform Margin, Abruzzi, Italy

Iwan Stössel, Maria Mutti and **Daniel Bernoulli**
ETH-Zentrum, Switzerland

Carbonate producing organisms exert a major control on carbonate platform development. In this study we document patterns of sediment production and redistribution in rudist-dominated cyclic strata on the Upper Cretaceous Maiella platform margin, and how this impacted facies architecture. Here, km-scale outcrops reveal the three-dimensional organization of 250 m of cyclic Cenomanian-Campanian shallow-water limestones. The platform is a pure carbonate system characterized by a shallow shelf, continuously eroded at a submarine escarpment. Cycles of the outer platform are mainly composed of coarse cross-bedded rud- and grainstones with intercalated rudist lithosomes, and show shallowing-upwards trends. Cycles of the inner platform are thinner, also shallowing upwards, but dominated by peritidal mudstones and packstones, and subordinate rudist lithosomes. The facies transition from the outer to the inner platform is gradual, but exposures are not physically continuous. In both settings, the cycle stacking pattern reveals three orders of cyclicities.

Coral/rudist- and rudist-lithosomes are most abundant in the external platform, and, both diversity and abundance decrease landward, away from the platform margin. Lithosomes of the internal platform are characterized by a simpler, sheet-like geometry and a paucispecific faunal assemblage. The cycle stacking pattern and the generally low ratio of rudists in growth position to rudist debris suggest that lithosomes were rarely preserved, but the preservation potential was higher during times of increased accommodation. Most sediment was produced on the most external part of the platform. Sedimentary structures, and the areal distribution of bioclastic sediment, indicate extensive destruction and redistribution of sediment, which is at least partly due to the lack of wave-resistant organogenic framework in rudist associations. This clearly affected the facies architecture by presenting the formation of a pronounced hydrodynamic barrier along the platform margin.

A Sequence Stratigraphic Reference Section for the Uppermost Jurassic of Lebanon

Christopher Toland
Oolithica Geoscience Ltd., UK

Central Lebanon provides some of the most complete and readily accessible Upper Jurassic (Kimmeridgian-Tithonian) sections in the Middle East, and is one of the few places where lateral equivalents of the prolific Arab Formation (Kimmeridgian-Tithonian) reservoirs of peninsular Arabia can be studied at outcrop.

At the Bikfaya outcrop section (35 kilometers east northeast of Beirut), the uppermost Jurassic comprises at least two disconformity-bounded 3rd-order depositional sequences. Sequence 1 (Falaise de Bikfaya) is 61 meters-plus thick and comprises a progradational succession (Highstand Systems Tract) of foreshoal micropeloid packstones, shoal-crest stromatoporoid floatstones, immediate back-shoal algal-bank *Permocalculus* wackestones and (?attached mainland) shoreface facies culminating in tidal-flat deposits. This interval is of inferred Early Tithonian age.

Sequence 2 (Calcaire de Salima) is approximately 63 meters thick and commences with an abrupt transgressive surface and an associated influx of calcareous dinocysts. The lower part of this sequence comprises strongly argillaceous micropeloidal packstones with local peloid-intraclast-superficial ooid packstone ribs, interpreted as an offshore transition zone facies association. The initial marine flooding event is of late Early Tithonian (late *fallauxi-ponti* zone) age.

A candidate for maximum flooding surface (MFS) is recognized in southwest Arabia, and is perhaps coincident with the basal Arab-B or Arab-A of eastern Arabia). The recessive middle part of Sequence 2 is largely unexposed, while the upper cliff-forming part comprises approximately 22 meters of Late Tithonian ooid-skeletal grainstones which coarsen and thicken up-section. These grainstones are characterized by pronounced planar cross-stratification with east southeast-facing (i.e. onshore-directed) foresets and set heights of up to 3.6 meters and are interpreted as a wave-dominated shoal complex culminating in emergent

foreshore facies. Sequence 2 is terminated by a prominent paleo-karst (Type 1 sequence boundary) corresponding to the Jurassic-Cretaceous boundary, and is overlain by approximately 17 meters of basal-Cretaceous wacke-ironstones.

The top Jurassic hiatus is poorly age-constrained, but is no older than (?Late-) Late Tithonian, and perhaps no younger than Berriasian if the overlying wacke-ironstones are associated with weathering of nearby (?penecontemporaneous) volcanics which have recently been radiometrically dated at 146±2.5 Ma. Elsewhere in Arabia, a well-developed transgressive surface occurs within the basal Middle Berriasian (Late Calpionella Zone B), broadly coincident with the *subalpina* Subzone transgressive surface of the Berriasian type section and the 'Cinder Bed' transgression of the Dorset Coast.

The Stratigraphic Architecture of the Cenomanian/Turonian Carbonate Petroleum System in Natih Formation, Northern Oman

F.S.P. Van Buchem,
Institut Français du Pétrole, France
P. Razin, P. Casanova,
Bureau Recherches de Géologique et Minieres, France
P.W. Homewood, F. Walgenwitz, A. Schwab,
Elf, France
H. Oterdoom, Petroleum Development Oman, Oman
and **J. Philip**, Provence University, France

The stratigraphic architecture of the Cenomanian/Turonian carbonate system, studied in outcrops in northern Oman, is characterized by a distinct hierarchical organization of depositional sequences. This organization allowed for the introduction of high resolution timelines documenting geometries, nature and lateral variability of both the basinal source rocks and shallow water carbonate reservoir facies. The presence of boreholes close to the studied outcrops facilitates the comparison with the local lithostratigraphical subdivision, while two $\delta^{13}C$ stable isotope curves provide a powerful tool for inter-regional correlations of the model.

Based on 20 detailed field sections, a three dimensional, high resolution (down to the meter-scale) correlation scheme has been constructed covering an area of 100 x 60 kilometers (Adam Foothills and southern side of the J. Akhdar). Three orders of stacked depositional sequences have been found based on the occurrence of facies. The large scale sequences (3rd-order, 10 to 100 meter scale) show distinct seismic scale geometries: sequence I and III are characterized by platform aggradation and basin starvation (creation of intra-shelf basins) during long term decrease of accommodation, and by low-angle progradation and infill during the long term decrease of accommodation. Sequence II, is on the contrary, virtually flat-bedded. At the medium-to-small-scale (4th- to 5th-order) depositional sequences are bounded by regional shifts of the facies belts; within these sequences important lateral facies variations have been recorded. The most heterogeneous facies are found in times of minimal accommodation space, when incisions and subaerial exposure produce lateral variable strata (e.g. top Natih E).

Considering the relative stability at the time of the Arabian Peninsula, this sequence stratigraphic model, backed up by significant trends in the carbon stable isotope curve, provides a powerful, predictive tool both at the exploration and reservoir scale for the Cenomanian/Turonian carbonate petroleum system in the Arabian Gulf area.

Diagenetic Masking of Cycle Tops in the Liassic of United Arab Emirates

Gordon Walkden, Aberdeen University, UK
and **J.E. de Matos**, Parexpro, Portugal

The Lower Jurassic of the Musandam Peninsula (United Arab Emirates/Oman) is strongly cyclic carbonate succession, at least in the lower part of which is poorly constrained biostratigraphically. The sediments consist of proximal shallow-shelf carbonates arranged into meter-scale cyclothems, containing many subaerial exposure surfaces. The nature, scale, and abundance of cyclothems, together with comparison between these and equivalent cyclic successions in Europe and North Africa, point to Milankovich-type eustasy as the main cyclic forcing factor. Such cyclic successions provide scope for high resolution lithological and chronostratigraphic correlation and create strong anisotropy in reservoir successions, with a particular influence on the distribution of diagenetic heterogeneities.

A fundamental requirement in cycle definition, however, is the accurate identification of cycle tops. In Musandam many discontinuities have a complex diagenetic history requiring discrimination between the effects of marine diagenesis (e.g. hardgrounds), pressure dissolution (e.g. low amplitude stylolites and stylobreccias). Each of these processes can operate singly or in combination to create discontinuities with similar characteristics. Such recognition problems would be compounded when dealing with core. Since some of the main analytical tools for the analysis of cyclic successions, such as Fischer plots, spectral analysis and computer simulation depend on accurate positioning of cycle boundaries, the result of such uncertainty can be wrong inferences on cycle frequency and the rate of creation of accommodation, poor definition of sequences and incorrect long-distance correlation. This work has implications for all studies of cyclic shallow-water carbonate successions.