Characterization of Fractures in a Lower Cretaceous Carbonate Formation, Onshore Abu Dhabi

Azhari Abdalla, Abu Dhabi Company for Onshore Oil Operations
Fernando Silva, PARTEX, Lisbon
Andrew Mann and Gill Scott, Robertson Research, UK.

Integrated diagenetic, structural, lithological and facies association data were used to assess the distribution and orientation of fractures and their impact on reservoir quality of a Lower Cretaceous carbonate formation in the ‘A field’, onshore Abu Dhabi. The formation is composed of several, relatively thin porous carbonate reservoirs interbedded between thicker dense limestone intervals. Most observed natural fractures are cemented and their distribution seems to be influenced by the type of host lithology and proximity to fault zones. Fracture density is highest in stylolitised dense zones in the tight and dense carbonate intervals, and is commonly low in the porous carbonates. Several diagenetic processes such as dissolution, fracture cementation and cement replacement have played a role in the evolution of fracture networks and their distribution. The major types of fracture cements are anhydrite and calcite (early cements) and dolomite and fluorite (late cements). Anhydrite cement in fractures was partially replaced by calcite and later dolomite.

Natural fractures in the studied formation can be classified into four main types based primarily on the degree of fracture continuity and size observed on the core samples. These are small-scale faults, macro-fractures, meso-fractures, and micro-fractures. Fracture orientations are predominantly perpendicular to the field axial trend and vary from west-northwest to northwest. These trends are sub-parallel to the mapped seismic faults located adjacent to several wells drilled in the field, and parallel to underlying basement lineaments interpreted from potential field data. Macro-fractures and faults may constitute linked, fluid conductive systems with some potential for connectivity and communication both within and between reservoir zones.

Azhari Abdalla is Lead Geologist with Abu Dhabi Company for Onshore Oil Operations (ADCO). He has 20 years of experience in the oil industry and related research in Sudan rift basins, in the Anadarko and Gulf Coast basins of Oklahoma and Texas, and, currently, in the extensive carbonate platform of UAE. He has a MSc in Sedimentary Diagenesis. He has presented several papers at the Denver AAPG Hedberg conference and OGS in Oklahoma, and has authored and co-authored more than 15 papers. Azhari is interested in carbonate diagenesis, basin analysis, and deep sedimentary basin diagenetically induced sealing and compartmentation.

Fernando Silva is a Reservoir Geologist and Geomodeller with Petroprimo S.A., Lisbon, Portugal. He received a BSc (1990) in Geology from Lisbon University–FCUL, and a MSc (1998) in Reservoir Evaluation and Management from Heriot-Watt University, Glasgow. He has worked on various aspects of reservoir geology in different geological settings in the Middle East, Africa, Europe, and Kazakhstan. His work has included research and development of fractured reservoir characterization techniques and reservoir modeling studies in both carbonate and clastic settings. Fernando’s interests are focused on reservoir characterisation and data integration, the application of numerical geology and quantitative techniques to the modeling of reservoirs, and visualization technologies. He is a member of SPE, EAGE, PESGB, and AAPG.

Andrew Mann is Co-ordinator of the Structural Geology Group at Robertson Research International. He has a BSc and PhD from the University of Wales (Cardiff). Andrew has 18 years petroleum exploration experience and has been involved in modeling studies of fractured carbonate and clastic reservoirs throughout the Middle East. Prior to joining Robertson, he worked as a field geologist undertaking a number of mapping projects for petroleum exploration in thrust belts (Oman Mountains and Southeast Turkey) and in extensional and strike-slip settings (Arctic Region and Europe). He is a member of the Geological Society of London.

Gill Scott has a PhD from Southampton University, UK in Carbonate Sedimentology. She joined Robertson in 1982 and has worked extensively on the carbonate reservoirs of the Middle East. Her particular expertise is in Lower Cretaceous and Upper Jurassic reservoirs. She has studied them regionally for new exploration opportunities and in detail for reservoir appraisal and production. Gill is particularly interested in the upscaling of reservoir geology for reservoir characterization and reservoir modeling and simulation studies.
The Najmah and Sargelu formations in West Kuwait are a Middle Jurassic fractured carbonate source-rock system, producing light oil via an extensive fracture network. Existing geological fracture models based on the variable well data have proven unreliable in predicting open fracture distribution. A joint Kuwait Oil Company/BP study was begun in late 1997 to determine if a reliable fracture distribution model could be derived using estimates of azimuthal anisotropy from existing compressional P-wave seismic data. To provide calibration of the seismic response to fracturing observed in wells, a multi-azimuth walk-away vertical seismic profile (MAW A VSP) was designed and acquired in a shut-in well. The MAW A VSP used a 5-level receiver tool at two depth settings; one across the evaporite cap rock and the second within the fractured reservoir. Vibroseis walk away lines were acquired at each depth setting at 45° azimuths around the well and up to 4 kilometer offset from the well-head. Additionally, walk-around data were acquired every 9° around the well between 2 kilometer and 2.5 kilometer offset. The walk-away and walk-around data have been analysed for azimuthal anisotropy variations in P-wave velocity and amplitude (AVO and AVOA).

The velocity analysis indicates that the evaporitic cap rock, which is dominated by ducite salt, has negligible anisotropy. However, significant velocity anisotropy is observed in the Najmah/Sargelu reservoir interval. The fast-velocity azimuth aligns with the direction of maximum horizontal stress and the dominant open fracture orientation from core and log data. Azimuthal variations in amplitude measured on intra-reservoir reflectors are also seen at offsets present in the existing surface seismic data. Seismic velocity and AVOA modeling studies have been undertaken to assess whether the level of anisotropy observed in the vertical seismic profile (VSP) is detectable on the existing surface seismic data. However, seismic data quality, the number and spacing of available seismic lines, as well as their azimuthal distribution, ultimately controls whether anisotropy methods can reliably predict open fracture distribution in West Kuwait.

Andrew Hill is a Senior Geophysicist currently working with BP Kuwait. He has 16 years experience gained with BP Amoco in a variety of development and production reservoir description roles in the North Sea, Alaska, and the Middle East. Major interests include integration of subsurface and dynamic data in the production environment, geocellular modeling methods, seismic attribute and rock property/fluid analysis, and seismic fracture characterization. Andrew received a BSc in Geology from the University of Southampton in 1982 and a MSc in Geophysics from Durham University in 1983.

Colin Slater is currently working as a Geophysicist for BP Kuwait. He has four years industry experience with BP Amoco Exploration and Geco-Prakla working on seismic processing and modeling projects including surface-seismic and VSP detection of fractures, 3-D seismic repeatability, and AVO analysis. His interests include seismic anisotropy, direct detection of hydrocarbons, and multi-component seismic processing. He has a BSc and PhD in Geophysics from the University of Edinburgh.

Frank Wijnands is a Senior Geophysicist with Schlumberger Wireline and Testing in Al Khobar, Saudi Arabia. He has 10 years experience in the oil industry. Previous assignments were with Geco-Prakla and GeoQuest in The Hague and Aberdeen, specializing in surface and borehole seismic methods. Frank has a MSc in Exploration Geophysics from the State University of Utrecht, The Netherlands.
Epeiric Versus Layer-Cake Stratigraphic Models for Middle East Carbonates: Lessons for Future Exploration from the German Cratonic Basin

Thomas Aigner
University of Tübingen, Germany

Many Middle East carbonate units are known for their uniformity and ease of correlation over long distances. They are often referred to as ‘layer-cake’ systems, for example, the Khuff, Hanifa, and Arab formations. However, the assumption of extremely broad and uniform facies belts is a problem in a process-oriented context as every stratigraphic time-line should cross a series of facies tracts along a depositional gradient. Correct correlation lines are critical for predictions of reservoir continuity, internal architecture, flow behaviour, and reserve calculations.

High-resolution sequence stratigraphic studies in the Germanic Basin may serve as outcrop analogs for some Middle East carbonates. Detailed facies analysis and outcrop gamma-ray logging have shown that the stratigraphy does not, as previously assumed, represent a true ‘layer-cake’ system. In fact, each unit displays a subtle, but significant, lateral facies differentiation along very gentle depositional profiles.

The evidence favors an ‘epeiric’ model and the following patterns were found to characterize epeiric carbonate systems that contrast with common sequence stratigraphic models:

1. Largely uniform and gentle subsidence on an extremely low-relief profile provides an overall ‘low accommodation’ setting;

2. The epeiric zonation is characterized by an offshore, very broad high-energy belt caused by dissipating waves. High-energy reservoir facies are therefore found in a broad, shore-detached zone;

3. The lack of accommodation space severely limits cycle progradation. Fundamental cycles are mostly aggradational, rather than progradational ‘parasequences’. High-energy reservoir facies are thus found in generally thin, but widely distributed, sheet-like bodies; and

4. Paleotectonics of the pre-cratonic basement plays a significant role in controlling subtle differential subsidence and facies distribution. Therefore, the thickest reservoir development is often found in zones of maximum differential subsidence inherited from basement tectonics. Computer simulations can help to identify the controlling mechanisms in epeiric carbonate stratigraphy.

Effect of Hith Anhydrite on Hydrocarbon Distribution in Abu Dhabi

Karim Akrawi and Mohamed Ayoub
Abu Dhabi Company for Onshore Oil Operations

The Upper Jurassic Hith Anhydrite is the major seal rock for most Upper Jurassic oil fields in the central and western part of the Arabian Peninsula. It plays an important role in hydrocarbon migration, distribution, and accumulation within the Lower Cretaceous Thamama reservoirs and Upper Jurassic Arab/Asab reservoirs in the area. Numerous other factors also have significant effects on hydrocarbon distribution. The major hydrocarbon source rocks are within the Upper Jurassic Diyab/Hanifa Formation.

This case study discusses the possible reasons behind the unexpected tested water from Thamama Zones A and B in well U-1. Test results contrast with the Habshan and Arab zones, which tested hydrocarbon in the same well and also with the surrounding structures where Thamama Zones A and B are hydrocarbon bearing. ‘U’ field is located west of ‘B’ field between the ‘M’ and ‘Q’ fields, both of which are oil-bearing in the Upper Thamama zones. The entire Hith Anhydrite shows progressive thinning eastward and disappears in central Abu Dhabi and further east. Where present, the Hith thickness varies as much as 600 feet and occurs in almost half of the Abu Dhabi area.

This study concludes that the Hith Anhydrite strongly controls the present-day distribution of hydrocarbons, mainly in the structures surrounding the Hith zone edge. Hydrocarbons in the western area are trapped in the Upper Jurassic Arab Formation. In the central area the traps are in Lower Cretaceous Thamama Group/Upper Jurassic Arab Formation. In the eastern area, they occur in the Lower Cretaceous reservoirs of the Thamama Group. Other factors that also have a significant effect on the hydrocarbon distribution include vertical migration due to vertical faults and lateral migration associated with structural tilting.

Karim Akrawi biography not available; Mohamed Ayoub see p. 48

Thomas Aigner studied Geology at the universities of Stuttgart, Tübingen, Reading, and Miami, and received his PhD in 1985. From 1985 to 1990 he worked as a Research Geologist in the Shell Laboratories of Rijswijk, The Netherlands and Houston, Texas. Since 1991, Thomas has been Professor of Sedimentary Geology at the University of Tübingen, Germany. His interests include genetic stratigraphy and applied sedimentology (reservoirs, aquifers, and raw materials).
The complex continental facies architecture of the Unayzah reservoir presents many problems for 3-D modeling and reservoir management. The results of the study suggest that the rock architecture of the Unayzah reservoir is, in fact, much better organized than originally believed and a sequence stratigraphic scheme can be applied in order to allow a better understanding of reservoir prediction and connectivity.

The Unayzah reservoir in the Hawtah Trend can be divided into three major units; the basal Unayzah-B, the middle Unayzah-A, and locally well-developed basal Khuff clastics on top. The basal Unayzah-B represents the early rift/synrift alluvial fan to braidedplain fluvial deposits filling structurally controlled irregular topography following the Hercynian Orogeny. The Unayzah-A signals a major shift in depositional and tectonic styles from the underlying Unayzah-B sandstones. The youngest reservoir unit, the basal Khuff depositional sequence is characterized in the study area by localized incised valley-fill sandstones that form locally prominent high-quality reservoir bodies. The Unayzah-A, the principal reservoir unit, can be divided into six major aggradational cycles that are laterally correlatable. Individual cycles show upward-cleaning characteristics, most commonly starting with trangressive lacustrine and associated sabkha and interdune facies in lower parts, followed by eolian and ephemeral fluvial channel deposits in variable proportions. These cycles are identified as overall upward-drying sequences developed as a response to fluctuating climatic conditions probably caused by global Milankowich cycles. Lake transgressions are attributed to the periods of deglaciation of gradually diminishing icecaps. Thickening of cycles toward the flanks of the field is attributed to ongoing subtle differential tectonic subsidence.

The 3-D facies, porosity and permeability models which are built based on this new multilayer zonation scheme suggest that the new layering scheme captured the lateral correlatability of reservoir units much better than that of the old scheme.

Sequence Stratigraphy and Reservoir Architecture of Unayzah Continental Deposits, Hawtah Trend, Saudi Arabia

Gürhan Aktas, Mohammed Al-Khalifa and Hesham Al-Qassab, Saudi Aramco, Dhahran

Mohammad Al-Khalifah is a 3-D Geocellular Modeler in Saudi Aramco. He currently works in Reservoir Characterization. Prior to joining Saudi Aramco he received his BSc in Geology from King Fahad University of Petroleum and Minerals, Dhahran, Saudi Arabia in 1992. His current area of interest is reservoir development and characterization.

Hisham Al-Qassab see p. 33

Edinburgh University. His current interests include sequence stratigraphy, sedimentology, and reservoir characterization, of both clastic and carbonate reservoirs. Gurhan is a member of AAPG and the Geological Society of London.

Mohammad Al-Khalifah

Sequence Stratigraphic Framework of Shu’aiba Formation, Shaybah Field, Saudi Arabia: a Basis for Reservoir Development of an Aptian Carbonate Ramp Complex

Gürhan Aktas, G. Wyn Hughes, Abdul-Jaleel Abu-Bshait and Saad Al-Garni

Saudi Aramco, Dhahran

The Shu’aiba Formation forms a most prolific reservoir in the eastern part of the Arabian Peninsula. Although some of the previous studies advocated laterally stacked carbonate wedges, this study proposes a sequence stratigraphic framework for the Shu’aiba Formation in the Shaybah field area with a ‘layer-cake’ style of cycle stacking patterns. These resulted from deposition on a carbonate ramp along the irregular margins of an intrashelf basin. It is also highly plausible that some basinward-inclined younger sequences may exist along the distal parts of the outer ramp toward the north-northeast.

The Shu’aiba Formation is divided into three depositional (composite) sequences, Sequence C (upper Shu’aiba), Sequence B (middle Shu’aiba) and the Sequence A (lower Shu’aiba). The Shu’aiba sequences (3rd order) comprise at least nine high-frequency sequences (4th-5th order) encompassing sixteen recognizable cycles. Individual cycles in Sequences B and C are typically composed of inner ramp, ramp crest (represented by rudistid barrier banks) and outer ramp facies, developed along the gentle carbonate slopes. Inner ramp facies show significant variations depending on the trend of the 3rd order sea-level curve. The lower sequence A is composed of vertically aggraded sheet-like cycles showing distinct upward-shallowing. Recent 3-D seismic in the Shaybah area has revised earlier interpreted ‘well developed onlap features’ within Shu’aiba level as only multiples of younger reflectors. This revelation, coupled with new sequence stratigraphic correlation and new

Gürhan Aktas is in the Reservoir Characterization Department of Saudi Aramco. Prior to joining Saudi Aramco in 1993, he worked for Robertson Research, UK, and EIE in Turkey. He has a BSc in Geological Engineering from Istanbul University, a MSc from Leeds University, and a PhD from
biostratigraphic data, indicate the presence of both upper and lower Aptian sediments within the shelfal Shu’aiba facies as opposed to only a lower Aptian age, as previously assumed. The upper and lower Aptian boundary roughly corresponds to the basal part of the upper Sequence C. Sequence stratigraphic organization of the Shu’aiba reservoirs provide crucial clues in the prediction and correlation of reservoir geobodies, especially of the high permeability rudist shoals/banks.

Gürhan Aktas see p. 11; G. Wyn Hughes see p. 110

Abdul-Jaleel Abu-Bshait is a Carbonate Geologist in the Geological Research and Development Division of Saudi Aramco. He has a BS in Geology from the University of Southern California. His main areas of interest include characterization of carbonate reservoirs and FMI image interpretations. Abdul Jameel is a member of AAPG and DGS.

Saad Al-Garni is a member of the Reserves Team in the Reservoir Characterization Department of Saudi Aramco. He has a BS in Geology from the King Fahd University of Petroleum and Minerals, Dhahran (1994). On graduation, he joined Saudi Aramco and worked for five years in carbonate sedimentology and petrography in the Geological Research and Development Division. Saad is a member of DGS and AAPG.

Paleozoic Hydrocarbon Habitat of the Arabian Plate

Abdulkader Al-Afifi, Saudi Aramco, Dhahran
Geert Koner, Shell International, The Netherlands
Sa’id Al-Hajri, Saudi Aramco, Dhahran
Kees de Groot, Shell International, The Netherlands,
Abdulla Al-Naim, Saudi Aramco, Dhahran, and
Henke Droste, Petroleum Development Oman, Muscat
(This presentation summarizes the efforts of many geoscientists from Shell, Saudi Aramco, and Petroleum Development Oman.)

The Paleozoic sequences were deposited in continental to deep-marine clastic environments along the northeastern continental margin of Gondwana. Carbonates only became significant during the Late Permian. The drift of this region during the early Paleozoic towards high, southern latitudes is reflected by glacial sediments of Late Ordovician age and locally of Carboniferous age. This was followed during the Permian by rapid drift towards the Equator.

Basin development started during the late Proterozoic, when rifting of the peneplaned Precambrian basement formed salt basins in Oman and the Arabian Gulf region. Cambro-Ordovician carbonates were deposited over a passive continental platform that extended from Africa to interior Iran. However, this platform probably differentiated into two terranes along the Zagros fault zone during the Late Ordovician.

The region was extensively affected during the Carboniferous by the Hercynian Orogeny that caused broad regional upwarps and sags as well as basement-cored block uplifts. The Hercynian uplift resulted in widespread erosion of the Devonian-Carboniferous section, and is attributed to a collision along the northern margin of Gondwana. The Hercynian Orogeny was followed during the Permian by the opening of the Paleo-Tethys Ocean along the Zagros fault zone, and the formation of a passive eastern margin over which carbonates and evaporites of the Khuff Formation were deposited.

The Paleozoic includes two major petroleum systems. The first was charged by the prolific Early Silurian shale and includes reservoirs spanning the Silurian to Permian section. Hydrocarbon expulsion estimates, after accounting for secondary migration losses, suggest that approximately one trillion barrels of oil equivalent may have been trapped from the Silurian ‘hot’ shale alone. A second petroleum system occurs in areas charged from late Precambrian source rocks in the salt basins.

Exploration and development of the Paleozoic section presents several technical challenges, including difficulties with deep seismic imaging, tight and heterogeneous reservoirs, and a hostile subsurface environment. The critical success factor is the continuous innovative effort of earth scientists and reservoir engineers to find integrated technology solutions that will render the Paleozoic plays economically viable even in a low-price environment.

Abdulkader Al-Afifi is Chief Explorationist, Southern Area Exploration with Saudi Aramco. He has a BSc in Geology from King Fahd University of Petroleum and Minerals, Dhahran, a MSc from the Colorado School of Mines, and a PhD from the University of Michigan, Ann Arbor. Abdulkader worked with the
Permeability Estimation Using Hydraulic Flow Units in a Central Arabian Reservoir

Fahad Alajmi, Saudi Aramco, Dhahran
and Stephen Holditch, Schlumberger

Knowledge of permeability is critical to developing an effective reservoir description. Well log data can be used to derive permeability for less cost than is possible with coring. However, well logs do not provide a direct measurement of permeability; logs respond to porosity, pore size distribution, and water saturation that together can provide an estimate of permeability. The strength of wireline-log permeability data lies in their capability to provide a continuous permeability profile throughout a particular interval. Porosity is generally independent of grain size, whereas permeability is strongly dependent on grain size. Therefore, the traditional graph of porosity versus permeability cannot be used reliably to accurately estimate permeability from porosity data.

This presentation focuses on the evaluation of formation permeability for a sandstone reservoir in central Arabia from well log data using the concept of hydraulic flow units (HFU). Cluster analysis is generally used to identify HFUs. In this study, we have developed a new clustering technique that is unbiased and easy to apply. Moreover, a procedure for determining the optimal number of clusters that should be used in the HFU technique was introduced. In this procedure, the error sum of squares was used as criterion for determining the required number of HFUs to describe the reservoir. The statistically derived HFUs were compared with the core description made at the wellsite by the wellsite geologist. The grain size classes from core descriptions match very well with the statistically derived clusters from the HFU method. This match indicates that these HFUs reflect the different rock types in the analyzed formation. Moreover, it shows the practical efficiency of the procedure used to determine the number of HFUs in the formation. Direct measurement of cores is the ideal method to determine HFUs, but because of costs, few core measurements are routinely available. Hence, it is crucial to extend the flow unit determination to the uncored intervals and wells. Permeability estimation using the HFU method was extended to uncored wells by implementing the alternating conditional expectation (ACE) algorithm. ACE provides a data-driven approach for identifying the functional forms for the well log variables involved in the correlation. The reservoir porosity permeability relationship was represented with a single equation by using the different HFUs as indicator variables. Permeability profiles generated by HFUs using well log data agree with core data, which illustrates the potential and developed to perform HFU analysis. Three main processing

U.S. Geological Survey Mission in Jiddah prior to joining Saudi Aramco in 1991. He is a member of AAPG and SPE.

Geert Konert graduated from the University of Amsterdam in Geology, Structural Geology, and Geochemistry in 1981 and joined Shell the same year. He has worked on assignments in Brunei, The Netherlands, and Oman, and has been involved in exploration and production projects in the Middle East. Geert is Principal Geologist for Shell International E&P in Research and Technical Services. His main area of interest is the tectonic evolution of the Middle East.

Sa’id Al-Hajri see p. 154

Kees de Groot received his MSc in Chemical Engineering from Delft University in 1962. He joined Shell Research (Kon Shell E&P Laboratory, KSEPL) in 1963 starting in geochemical research. He has worked in various E&P research management positions in The Netherlands, USA, and Canada, and was E&P liaison for Africa and later for the CIS. He returned to research in 1993 as Research Director of KSEPL. Kees is now Vice President of Shell International E&P, Research and Technical Services.

Abdulla Al-Naim has been Manager of the Area Exploration Department of Saudi Aramco since 1996. He received a BS in Geology from King Saud University, Riyadh in 1978. He joined Saudi Aramco as a Wellsite Geologist and later worked in the Exploitation and Exploration divisions. He was successively Supervisor of Wellsite Geology, Chief Hydrologist, Chief Geologist in Reservoir Geology, Manager of the Geological Department, and General Supervisor in Reservoir Management. Abdulla attended courses in Petroleum Management at Oxford in 1989 and at Berkeley Center for Executive Development in 1997. He joined AAPG in 1986 and served on its International Committee during 1989. He received its International Special Commendation Award in 1999. Abdulla was a co-founder in 1989 and first president of DGS. He is a member of the Organizing Committee of GEO 2000.

Henk Droste see p. 84
GEO 2000 Abstracts

NMR Permeability Calibration Using Non-Parametric Algorithm in Central Arabia

Fahad Alajmi, Saudi Aramco, Dhahran
and Stephen Holditch, Schlumberger

Nuclear magnetic resonance (NMR) logging provides a wealth of information to the field of formation evaluation. NMR logs respond to the fluids in the pore space and yield lithology-independent effective porosity, pore-size distribution, bound and movable fluid saturation, and permeability on a foot-by-foot basis.

Permeability models that include pore size distribution are better than those based on porosity alone. Algorithms for estimating permeability from NMR measurements are based on the estimation of either an average/critical pore size or irreducible water saturation. These algorithms, which are based on empirical relationships, will identify trends in permeability. However, they should be calibrated against core data before placing too much weight on absolute values. Moreover, the NMR tool is primarily sensitive to pore bodies and insensitive to the size of pore throats that control permeability. Therefore, NMR calibration with core data is needed for reconciling permeability from these two sources.

In this presentation, optimal nonparametric transformation of variables with the alternating conditional expectations (ACE) algorithm was used to calibrate NMR permeability to core permeability for a sandstone reservoir in central Arabia. The use of the ACE algorithm significantly improved the correlation between the NMR and core permeability. Calibration of NMR permeability has improved the accuracy of NMR estimation of formation permeability. The permeability estimated using calibrated NMR response is positively correlated with core permeability with a correlation coefficient of 0.87. Neural networks were also used to generate synthetic NMR-effective porosity and permeability. A back-propagation neural network was used to associate and predict the relationship between conventional openhole logs, NMR permeability, and NMR effective porosity in control wells that have both NMR log and conventional openhole logs. The trained neural network was then used to generate synthetic NMR permeability and effective porosity to extend NMR curves to cover unlogged intervals and zones where borehole washouts affect the logging data. In addition, synthetic NMR porosity and permeability was generated for wells with no NMR logs. However, neural network successfully predicted NMR porosity and permeability that would have occurred if NMR logs had been run and created reliable synthetic NMR porosity and permeability.

Western Atlas Magnetic Imaging Resonance Log (MIRL) and Schlumberger Combinable Magnetic Resonance (CMR) porosity was compared with porosity from core, density log, neutron log, sonic log, and calculated effective porosity. Also, MIRL and CMR porosity and permeability measurements were compared with core data at the same well. The CMR tool showed lower porosity and permeability readings. The differences can be attributed to the different vertical resolution of the tools, the effect of rogusity (loss of pad contact), and shallow depth of investigation of the CMR tool. Core porosity matches very well with measured porosity from the MIRL tool.

Fahad Alajmi and Stephen Holditch see this page.
Two Years After: Integration of Waterflood Pilot, Rock Fabric and Dynamic Data with Implications for Full-Field Mauddud Waterflood Startup

Hussain Al-Ajmi, Kuwait Oil Company
Dirk Bodnar and Byron Haynes, BP Kuwait
Ahmed Mousawi, Zaid Al-aqeel, Saed Mostafa El Shorbagi, Malik Stinder, Raja Mukherjee and Hom Bahadur Chetri
Kuwait Oil Company

The Lower Cretaceous Mauddud limestones are multi-billion-barrel depletion-drive reservoirs undergoing redevelopment with a planned increase in production through waterflood. Injection-production history and dynamic data integration with a static reservoir description of the two waterflood pilot projects, illustrate much of what can be expected in the larger-scale waterflood. The integration of multi-disciplinary data, including rock fabric and performance data, is enhanced through the use of geocellular static (conditioned to seismic data) and simulation models. Two years of pilot studies and reservoir surveillance included interference testing, production and injection-profile logs, cased-hole pulsed-neutron logs, static bottom-hole pressures, pressure build-up surveys, and RFT sand openhole logs on new wells (including gathering data on a twinned injector). The information was combined with detailed geologic descriptions from cores, logs, mapping, and waterflood performance. Other factors affecting flood performance include mechanical downhole injector and producer conformance, surface gas-lift optimization, and injector up-time controlled by source water-well ESP performance.

Water breakthrough has occurred at producing horizons controlled by the distribution of high-permeability rudistid floatstones or glauconitic sandstones. It also occurs in relatively high-permeability grainstones. Injected water remains high in these zones in some directions but appears to slump in the others due to breaches in permeability barriers. Cemented zones act as vertical permeability barriers or baffles to water movement as shown by twinned injector sweeps and RFT logs. The major controls on the pilot water movements are: (1) injector conformance and thief zones; (2) regional reservoir pressure gradients around the pilots; and (3) facies changes controlling permeability in zones across the patterns. Other possible controls are also under examination; for example, thermal fracturing effects, regional stress regimes, fault impacts, and primary depositional or diagenetic influences. Surveillance outside the pilot patterns has shown that there is pressure connectivity over the planned 250 acre/well, inverted 9-spot development. This adds confidence to predictions of flood performance success across the development area and confirms that the planned pattern flood is appropriate.

Injection water breakthrough on the 40-acre (inverted 5-spot) scale is confirmed. Water breakthrough in thief zones has illustrated the primary mechanism of water movement in the Mauddud. However, production, pulsed-neutron logging, and infill drilling have also shown that there is water movement in the relatively lower permeability facies. RFT data have identified three vertical hydraulic units within the more depleted upper zone of the Mauddud. These characteristics are expected in the larger-scale waterflood. Perforation strategies are designed to optimize conformance between injector and producer and to minimize early injection breakthroughs and maximize vertical and area sweep efficiency. The observed time to water breakthrough, observed vertical and areal sweep, and the controlling geologic description have been used to refine reservoir simulators, so allowing them to more accurately predict production, water-cut profiles and recovery factors for this important redevelopment.

Hussain Al-Ajmi is a Reservoir Engineer with Kuwait Oil Company. He has been working in the North Kuwait fields for seven years in various field and reservoir assignments.

Dirk Bodnar is a Production Geologist with BP Kuwait. Dirk has 15 years experience, 13 of which have been in production geology and 2 in production engineering. He is working on the Sabiriyah and Raudhatain fields of North Kuwait.

Byron Haynes is a Senior Reservoir Engineer with BP Kuwait seconded to Kuwait Oil Company. He has been with BP for 12 years on various field and reservoir engineering assignments in Alaska, Houston, and the Middle East.

Ahmed Mousawi has worked as a Petroleum Engineer with Kuwait Oil Company since 1997. He has participated in waterflood pilot projects and data management activities. Ahmed is interested in well interventions and workover programs.
GEO 2000 Abstracts

Zaid Al-aqeel has been a Petroleum Engineer with Kuwait Oil Company since 1997. He is a member of the Sabriyah Team involved in waterflood pilot monitoring and well intervention (rig/rig-less workover programs).

Saed Mostafa El Shorbargi is a Petroleum Engineer with Kuwait Oil Company (KOC). Prior to joining KOC in 1998, Saed worked for Gulf of Suez Petroleum Co., Egypt for 10 years.

Malik Stinder is a Senior Petroleum Engineer with Kuwait Oil Company. He has 15 years experience in well stimulation, gaslift, and well intervention in offshore and onshore fields. He is the overall Coordinator and Lead Implementor of the waterflood pilot project for a North Kuwait field.

Raja Mukherjee is a Geologist with Kuwait Oil Company (KOC). He has more than 17 years experience in the oil industry. Raja worked for Oil & Natural Gas Corporation of India on numerous exploration and field development projects before joining KOC in 1995.

Hom Dahadur Chetri is the Lead Reservoir Engineer for Kuwait Oil Company on the Sabriyah Mauddud reservoir. He has a MSc in Petroleum Engineering. He has 16 years experience of production and reservoir management in oil fields in India, the North Sea, and Kuwait and is the author of 14 technical papers.

The Late Paleozoic Glaciation in Oman: Hydrocarbon Plays, Paleogeography, Comparison with Similar Sequences from West Australia and Implications for Exploration

Juma Al-Belushi
Petroleum Development Oman, Muscat

The late Paleozoic Gondwanan glaciation affected at least some parts of the Arabian Peninsula. Glacial and peri-glacial sediments have been confirmed in Oman and Yemen, as well as locally in Saudi Arabia. The glaciogenic, glacio-fluvial and glacio-deltaic sediments of the Al-Khlata Formation in south and central Oman pass into more peri-glacial (both fluvial and aeolian?) sediments of the Unayzah in Saudi Arabia. This paleogeography fits well with a northeasterly site of continental glaciation during the Perm-Carboniferous. In Oman, the Haushi (Al-Khlata and Gharif formations) is one of the most prolific hydrocarbon plays. It continues to be a major contributor to Oman’s oil production. It is sourced by underlying source rocks and is sealed by regional and intraformational shale units.

In the Australian Canning Basin, the Hoya hydrocarbon play shows a general setting that is similar to the Haushi play. The reservoirs are complex and the seals are provided by regional and intraformational shales. The scouring of the Hoya into the underlying sequence, together with faults, provides the access for hydrocarbon migration from the underlying source rocks. The Hoya contains the entire glacial sediments of the Canning Basin. Both the Hoya and Al-Khlata overlie a basal unconformity separating them from the underlying carbonate unit. The Hoya starts with a basal tillite, consisting of angular dolomite clasts among others. These dolomites have been reworked from the underlying basement. The Al-Khalkata Formation is similar, to the extent that it starts with a sandstone unit of reworked angular dolomite clasts from the underlying Precambrian carbonates. The clast components of the Hoya are predominantly dolomitic limestone and siltstone of a similar composition to the immediate substrate. The dolomitic clasts are predominantly angular to sub-angular and range in size from a few millimetres to a maximum of 10 centimetres. The Al-Khlata Formation in south Oman starts with an interbedded fine- to medium-grained sandstone and diamictite with clasts that include dolomite, granite and metamorphic rocks.

This poster integrates all lines of evidence of this glaciation and discuss the suite of sediments in the context of the paleogeographic and paleoenvironmental setting. It also reviews the hydrocarbon potential of these sediments and discusses implications for further oil exploration in these sediments.
The Late Permian Khuff Formation is a carbonate-evaporite rock sequence that, in the sub-surface of eastern Saudi Arabia, has been divided into four major depositional cycles. From top to bottom these cycles are formally referred to as the Khuff-A, B, C and D. Each cycle consists of a dominantly carbonate interval overlain by a dominantly anhydritic interval. The carbonate intervals of the Khuff-A, B and C, because of their reservoir potential, have been further subdivided into layers with the layer boundaries based mainly on regionally correlatable gamma-ray wireline markers. A new layering scheme for the Khuff-C was developed, which is simpler than previous schemes, sensitive to lithofacies distribution, and depositionaly compatible. It is consequently easily detected on FDC/CNL wireline log curves and in rock core, in addition to gamma-ray signatures.

The Khuff-C carbonates average 317 feet in thickness across the southern Ghawar field, and appear to be a third-order sequence cycle sandwiched between the underlying Khuff-D Anhydrite, a prominent supratidal deposit, and the ‘B/C Interval’, a thick overlying stacking of thin subratidal anhydrites alternating with high intertidal dolomites. Within the Khuff-C sequence are two deepening-upwards cycles. The first cycle starts with a thick deposit of anhydrite-rich tidal dolomites (Layer 6), overlain by a pelletal shallow subtidal dolomudstone (Layer 5), and capped by a shallow-marine lime mudstone (Layer 4). A very shallow subtidal dolomudstone (Layer 3) abruptly ends this first deepening trend and starts a second deepening event, as it is overlain by a second marine limestone (Layer 2). The Khuff-C sequence is finally capped by intertidal dolomites (Layer 1). The Khuff-C reservoir layers are easily traceable over wide distances by wireline log signatures due to their contrasting lithologies. These same contrasts give each layer distinctive reservoir properties, allowing for meaningful reservoir layering for reservoir modeling and simulation purposes. The best reservoir development occurs in the dolomitized shallow subtidal deposits. Over the southern Ghawar field, lateral heterogeneities within the two dolomite layers and thickening of the B/C Interval over structural highs have combined to allow determination of the early growth history and growth rates of the Haradh and Hawiyah substructures during the Late Permian.

Ra’id Al-Dakhil received a BSc degree in Geology in 1996 from King Fahd University of Petroleum and Minerals, Dhahran. On graduation, he joined Saudi Aramco as a Reservoir Geologist in the Reservoir Characterization Department. He has experience as an Operations Geologist and Field Geologist. Ra’id helped to build the Permian carbonate Khuff-C reservoir depositional model and the layering scheme for the Ghawar field. His interests are carbonate reservoir quality distribution, sequence stratigraphy, and 2-D modeling. He is a member of AAPG and DGS.

Depositional Model of the Jauf Formation in the North of Ghawar Area: a Pertinent Tool to Gain Information on the Controls Affecting Distribution and Quality of the Jauf Reservoir

Abdulaziz Al-Duaiji, Muhittin Senalp, Sa‘id Al-Hajri and John Filatoff
Saudi Aramco, Dhahran

The Devonian Jauf Formation in the Ghawar Area is conformably underlain by the Tawil Formation and overlain by the Jubah Formation. It contains a sweet-gas sandstone reservoir discovered in 1980 on a high-relief anticline in the Shedgum area. The Jubah and Jauf formations together form a thick progradational fluvo-marine sequence. The sedimentology and depositional models of the Jauf Formation were based on the detailed core description and palynostratigraphy of all the available cores in Shedgum, Uthmaniyah, Qatif, Dammam, and Abu Safah fields. The Jauf is characterized by palynozones D3 and D4, and palynozone D3A. Palynozones D3A is a poorly defined sub-zone that characterizes the upper Jauf Formation but may extend into the basal part of the Jubah Formation.

The Jauf Formation can be divided into two parts. In the upper part the good-quality reservoir sandstone facies are interbedded with black, carbonaceous shales. Each sandstone interval is about 15 feet thick, medium-grained, well-sorted, cross-bedded, and has up to 25 % porosity. The lower part of the Formation, where the main Jauf reservoir occurs, consists of thick and continuous sandstone facies. It is composed of 8-13 foot thick, stacked coarsening-upward
sequences. The lower 70 feet of the coarsening-upward sequence is very fine-grained, shaley, and silica cemented. The upper 200 feet of the sequence are fine- to medium-grained, gently cross-bedded, well-sorted, friable and have porosities between 20 and 25 percent.

The Jauf Formation in the North Ghawar, Shedgum, Qatif and Abu Safah fields was deposited in fluvial-dominated deltaic and interdeltaic environments. The main delta lobe occurs in the Shedgum area. It has a thick section of stream-mouth bar sandstones overlain by delta-plain facies. On the other hand, both the Qatif and the Abu Safah fields indicate deposition in a more wave- and tide-dominated beach environment. The composition of the deltaic sandstones in the Shedgum area is markedly different from the beach sands in more northern areas. All the evidence indicates that the Jauf reservoir is heterogeneous and therefore it is necessary that its depositional model should be understood clearly. This study will help to gain a better understanding of the controls affecting distribution and quality of the Jauf reservoir in the north of the Ghawar prospect area. Furthermore, it will provide information pertinent to understanding facies distribution, which in turn governs both areal and stratigraphic variations in reservoir quality.

Abdulaziz Al-Duaiji is currently a Team Leader in the Geological R & D Division of Saudi Aramco. He joined Saudi Aramco in 1984 as a Wellsite Geologist. In 1985, he became a Northern Area Exploration Geologist and since 1992 has been a Research and Development Geologist. Abdulaziz received his BSc in Geology from the King Fahd University of Petroleum and Minerals, Dhahran and a MSc in Geology from Texas A&M University (1991). His interests include the regional geology and environment of deposition of central Saudi Arabia, in particular the Permian Unayzah Formation and the Devonian Jauf Formation.

Muhittin Senalp is a Senior Geological Consultant with Saudi Aramco in the Geological R & D Division. He has developed models of the Khafji reservoir, and a regional depositional model of the Unayzah. He has also worked on the Late Ordovician glacial deposits of Saudi Arabia. Before joining Saudi Aramco in 1981, Muhittin was Chief Geologist of the Mineral Research and Exploration Institute of Turkey. He has a BSc in Geology (1965) from the University of Istanbul, and a MSc (1970) and PhD (1974) from Imperial College, London. He is a member of AAPG, SPE, and DGS. Muhittin has professional interests in reservoir characterization, sequence stratigraphy, and clastic depositional environments.

Sa’id Al-Hajri see p. 154; John Filatoff see p. 88

Depositional Model For Minagish Formation, Kuwait: an Integrated Approach

Ahmad Al-Eidan, Khalid Shams Al-Deen, Thekriet Hussain, Salah Abdul Malek and Kumar Sukhdarshan, Kuwait Oil Company

The present study deals with the high-resolution sequence stratigraphy of sequence-II, which forms part of the Early Cretaceous Mega Sequence-I and constitutes mainly the Minagish Formation and its equivalent in North Kuwait. Wire line logs of all exploratory and key development wells, core data, ditch samples, biostratigraphic, petrographic, 2-D and 3-D seismic data were used in order to construct depositional model and demarcate the reservoir limits.

Sequence-II (Minagish Formation) was deposited in a prograding carbonate ramp set up with wide spread oolitic/peloidal and bioclastic shoal development in South and West Kuwait and deeper water carbonates in North Kuwait. The parallel oblique seismic reflection character with top lap and down lap relationship in a series of north-oriented seismic profiles has further confirmed the carbonate ramp model and reservoir distribution. The new depositional model, inter-field relationship and reservoir distribution will contribute to the development of existing fields and mature exploratory leads in Kuwait.

Ahmad Al-Eidan is a Geologist with Kuwait Oil Company (KOC). Ahmad received a BSc in Geology from Kuwait University in 1992 and joined KOC in January of 1993. He has worked as Wellsite Geologist for three years and Development Geologist for another three years. Currently he is working as Exploration Geologist and is also leading the Exploratory Drilling Team. In addition, Ahmad has been a Prospect Evaluation Team member since 1996.

Khalid Shams Al-Deen is a Geophysicist with Kuwait Oil Company. Khalid received a BSc in Geology and has 5 years experience. He has worked 6 months as Wellsite Geologist. He also has 3 years experience in supervising and monitoring 2-D and 3-D seismic, and one year in processing. Currently Khalid is working as a Seismic Interpreter in the Exploration Department.
The Development Plans of the Nahr Umr Field, Iraq for the New Millennium

Mohammad Al-Gailani
GeoDesign Limited, London, UK

The Nahr Umr field, 15 kilometers north of Basra in southern Iraq, was first delineated by gravity surveys in 1939-41 which were followed by seismic surveys in 1946-47. It was drilled in 1948. Over half a century has passed and as yet no plans have been put into place to develop this super giant field. The field consists of a single anticlinal dome 40 kilometers long and 25 kilometers wide. The structural closure for the various pay zones varies with depth and ranges from 200 meters for the Dammam (Eocene) to about 800 meters for the Lower Cretaceous Yamama reservoir. Thirteen boreholes have been drilled and confirm the presence of at least eight pay zones ranging in age from Miocene to Early Cretaceous. The present reserves for the Nahr Umr field are estimated at 20.7 billion barrels of oil (API gravity, 19°-41°) and 19.4 trillion cubic feet of gas. In the early 1980s, a 15-year plan was designed to develop the field to produce 438,000 barrels of oil per day from the Yamama, Zubair, and Mishrif reservoirs together with about 1.12 billion cubic feet of associated gas per day. The plan has not been implemented, but with such huge reserves the field will surely be a major development project for the New Millennium.

Triassic Stratigraphy of the Ghawar Area and its Structural Implications

Ibrahim Al-Ghamdi and Murdy Al-Zahrani
Saudi Aramco, Dhahran

The Triassic System in Saudi Arabia consists of the Sudair Shale, the Jilh Formation, and the Minjur Sandstone. The lithostratigraphic parameters of the Triassic formations over the Ghawar field have been used to predict the development of deep structures and to set critical casing and coring intervals during drilling operations. Sixty wells were used in this study in an area of 150 kilometers east-west by 340 kilometers north-south.

The Sudair Shale consists of shales and from one to three dolomite marker beds. The dolomite beds are used in predicting the top of the underlying Khuff Formation for casing and coring purposes. They indicate minor marine incursions within dominantly continental rocks. The Sudair Shale ranges in thickness from 450 feet over the Ghawar field to 1,000 feet in the flanking basins.

The Jilh Formation is 1,200 feet thick over the Ghawar field and has a thickness of at least 1,800 feet in the flanking basins. The Permian Khuff to Jilh isopach is a valuable exploration tool that has been used to define basement highs. The Formation isopach alone was observed to mirror the basement structure map, and this is attributed to re-activation during the Middle Triassic of deep-seated faults.

The Minjur Sandstone consists of sandstones and shales. It has a thickness of only 100 feet over the crest of Ghawar structure but is about 800 feet thick in the flanking basins. The Permian Khuff to Jilh isopach is a valuable exploration tool that has been used to define basement highs. The Formation isopach alone was observed to mirror the basement structure map, and this is attributed to re-activation during the Middle Triassic of deep-seated faults.

The Minjur Sandstone consists of sandstones and shales. It has a thickness of only 100 feet over the crest of Ghawar structure but is about 800 feet thick in the flanking basins. It marks the end of the deposition of clastics and the cessation of tectonic activity within the Arabian basin in the Early Cretaceous.
Mesozoic. The Minjur Sandstone was eroded on most structures by the pre-Jurassic (pre-Marrat) unconformity.

Ibrahim Al-Ghamdi is currently supervising the Wellsite Geology Unit of Saudi Aramco’s Exploration Department. He has been employed by Saudi Aramco since 1985. He has been involved in prospect generation, reservoir characterization, and wellsite geology, and special projects (including reservoir modeling with Exxon in 1989). Most of his work has concentrated on Jurassic and Cretaceous carbonates of Saudi Arabia. Ibrahim is interested in play concepts, sequence stratigraphy, artificial intelligence, and field geology. He is a member of DGS, AAPG, and SPE. He was a co-author of, Sequential Stratigraphy of Outcropping Strata Equivalent to Arab-D Reservoir, Wadi Nisah, Saudi Arabia (GeoArabia, v. 1, no. 3, 1996).

Murdy Al-Zahrani has been employed by Saudi Aramco as an Exploration Geologist since 1983. He has been involved in wells site geology, reservoir, regional exploration, and special projects (including seismic interpretation with Mobil in 1989). Most of his work has been concentrated on Paleozoic sections. Murdy is interested in clastics, seismic sequence stratigraphy, geostatistics, and field geology.

A New Technique to Predictively Map Occurrences of Abnormally High Permeabilities in the Arab-D Reservoir, Ghawar Field, Saudi Arabia

Ibrahim Al-Goba and Rami Kamal
Saudi Aramco, Dhahran

Parts of the Arab-D Reservoir in the Ghawar field are plagued by premature, erratic, and unpredictable injected-water encroachment. When it occurs, the irregular water sweep plays havoc with reservoir performance/simulation history matching. In 1997, a project was launched by Saudi Aramco to create super permeability (Super-K) risk assessment maps that would predict the probability of encountering zones of Super-K. The project involved 226 wells in a large area of the central Ghawar field. Intervals where Super-K was documented by reservoir engineering were carefully identified and quality controlled. The occurrence of Super-K was considered as a modeling attribute in itself. A simple binary coding system was used. At six-inch intervals, all Super-K occurrences were coded as 1; all other intervals were coded as 0. Advanced stochastic modeling software was used to create and laterally distribute the Super-K facies for each of the resultant 220 layers. The Super-K facies distribution patterns were then validated against cases where unexpected water-ing-out occurred in updip producers. The Risk Assessment Maps are a major breakthrough in our ability to predict areas of potential Super-K. Efforts will continue to upgrade the maps by using other geological and geophysical data.

Ibrahim Al-Goba is a Senior Geologist in Saudi Aramco. He graduated in Petroleum Geology from King Abdul Aziz University, Jiddah in 1988 and joined Saudi Aramco as a Reservoir Geologist. He worked with the Southern Area Reservoir Geology unit for one year and with the wells site unit for two years. Since 1991, he has been working on the ’Ain Dar field. Ibrahim is a specialist in the modeling of Super-K permeability.

Rami Kamal see p. 120

Applying Curvature Analysis to the Modeling and Prediction of Waterflooding Patterns Across the Arab-D Reservoir in the Ghawar Field, Saudi Arabia

Ibrahim Al Goba and Rami Kamal
Saudi Aramco, Dhahran

Curvature analysis fracture modeling software, MEDICA, was acquired by Saudi Aramco through the Institut Français du Pétrole IFP-led TRANSFRAC Consortium. It was applied to the southern part of the Ghawar field in support of fracture characterization of both premature sweep and low sweep areas on the flanks of the Hawiyah area at the Arab-D reservoir level. Predictive subseismic resolution fracture distributions from MEDICA were compared with water-arrival maps, faults mapped from 3-D seismic data, dolomite distribution maps, and super-permeability risk assessment maps. The results illustrate that curvature analysis is one of several valid tools that can be used in the meaningful characterization and modeling of fractures in the Arab-D reservoir.

Ibrahim Al-Goba see this page; Rami Kamal see p. 120
The Lower Cretaceous Stratigraphic Plays in East Abu Dhabi

Abdul Rahman Al-Habshi, Mohammad Ghiath Ajlani, Abdul Rahman Darwish, Mohamed Abd El Sattar, and Ahmad Taher, Abu Dhabi National Oil Company

The Lower Cretaceous Thamama section in East Abu Dhabi is a major sequence about 2,500 feet thick of limestone with minor dolomite and shale. The sequence is of Barriasian to Aptian age. It is overlain unconformably by the Middle Cretaceous Nahr Umr Shale and underlain by the Upper Jurassic Asab Formation. The succession was deposited over an extensive carbonate ramp platform.

Several depositional environments with associated facies are recognized. Subsidence, eustatic sea level and tectonic movements created an intrashelf basin in the central Abu Dhabi area, whereas shallow shelf sediments were deposited to the east. Seismic modeling and inversion have indicated that there is a reasonable chance of detecting certain Shu'aiba and Habshan stratigraphic anomalies, facies variations, and porosity changes. Sequence stratigraphic analysis, lithofacies description, and depositional environment modeling revealed the two main stratigraphic plays of the Shu'aiba and Habshan oolite reservoirs within East Abu Dhabi. Commercial hydrocarbons have been discovered in both reservoirs in East Abu Dhabi and the surrounding areas.

The presentation will discuss the stratigraphic plays, entrapment mechanism, reservoir development, and hydrocarbon potential of the Lower Cretaceous in the East Abu Dhabi region.

Abdul Rahman Al-Habshi is Team Leader of the Strategy and Exploration Team of the Petroleum Resources Division, Abu Dhabi National Oil Company (ADNOC). He has a BSc in Geology from Baghdad University (1971). He has 27 years of geological experience of which 7 were with the Bureau de Recherches Géologique et Minières Mission in Jiddah, 4 with the Petroleum Department, Abu Dhabi, and 16 with ADNOC. Abdul Rahman is Chairman of SEE and a member of SPE.

Mohammad Ghiath Ajlani is Team Leader of the Geophysical Technology Support Group in the Abu Dhabi National Oil Company (ADNOC). Before joining ADNOC in 1996, he was a Geophysical Advisor for Conoco from 1984 in North America and the Middle East. His major areas of interest are seismic modeling, inversion, land and marine multi-disciplinary geophysical feasibility studies, seismic acquisition and processing, and reservoir geophysics for oil and gas exploration and development. Mohammad has a BSc in Geology from the University of Damascus, a BSc in Geophysics from the University of Missouri-Rolla, and a MSc in Geophysics from the University of Utah-Salt Lake City. He is a member of SEG.

Abdul Rahman Darwish is a Senior Geologist with the Abu Dhabi National Oil Company (ADNOC). Prior to joining ADNOC in 1980, he worked for the National Oil Company of Libya (1975-80). Abdel Rahman has a BSc in Geology from Cairo University (1974). He is a member of SEE and SPE.

Mohamed Abd El Sattar is a Senior Exploration Geologist with the Abu Dhabi National Oil Company (ADNOC). His 25 years experience in the petroleum industry consists of 11 with Amoco's Egyptian Operating Company and 14 with ADNOC. Mohamed has a BSc and MSc in Geology from Ain Shams University, Egypt.

Ahmad Taher is a Senior Geologist with the Abu Dhabi National Oil Company (ADNOC). He joined ADNOC in 1982 as an Explorationist and is now a member of the Strategy and Exploration Team. Ahmed has a BSc from UAE University and is a member of SEE. He is interested in stratigraphic trap and basin modeling evaluation.

A Technique to Predict Extreme Overpressures in Intra-Salt Exploration Drilling

Rashid Al-Hashmi, André de Kuijper and Steve Norton, Petroleum Development Oman, Muscat

The acquisition of reliable pressure data in recent exploration wells and the drive to extend the play created by continued discovery of new oil (165 million barrels to date) has led to an attempt to derive a model to predict the level of overpressure in intra-salt wells prior to drilling. Over 20 deep exploratory wells in the South Oman salt basin have encountered overpressured carbonate stringers with pressure...
gradients which are nearly lithostatic (depending on the presence or absence of an evaporitic pressure seal). The elevated pressures are associated with Precambrian oil-bearing dolomite and limestone formations encased in evaporites (largely halite but with some anhydrite). The carbonate stringers are self-charging hydrocarbon systems, containing organic-rich carbonate source rocks interbedded within the dolomite reservoirs.

A regional analysis of the overpressures measured in these carbonate stringer reservoirs has shown that a well-defined trend, increasing with depth and overburden pressure, is observed. This trend can be extrapolated to new exploration prospects to reduce the pre-drill overpressure uncertainty. Drilling operations are further complicated because of the presence of hydrostatic pressure conditions at the base of the salt below the stringers. Through probabilistic well design, the reduction in uncertainty related to the formation pressure, can be translated into a reduction of the well costs (up to 25%), and moreover a minimization of the operational risks by reducing the chance of a kick occurring. The present work will show our analysis of the pressure data from the exploration wells drilled to-date and the way this is used to numerically predict formation pressure in exploration prospects to come.

Rashid Al-Hashimi is the Operations Geologist for the South Oman Frontier Exploration Team of Petroleum Development Oman (PDO), Muscat. Rashid graduated from the University of Arizona in 1990 with a BSc in Geoscience. He joined PDO in 1991 and worked as a Wellsite Geologist until 1994, when he moved to the exploration laboratory as a Stratigrapher. Currently, Rashid is in charge of operational support for the deep-oil exploration team.

André de Kuijper see p. 80

Steve Norton joined Shell E&P in 1989 after graduating from the University of Hull in England with an Engineering degree. He has worked in a variety of rig-based and office-based Well Engineering positions in The Netherlands and Petroleum Development Oman (PDO). In 1997 he transferred to Frontier Exploration as a leader of the operations team responsible for co-ordinating the exploration drilling and testing evaluation activities in PDO.

Jauf Formation Subsurface Mapping Guided by Seismic and Gravity, its Sand Distribution, and Reservoir Quality: a Regional Integrated Overview to Help Exploration in the Northern Ghawar Area

Ibrahim Al-Jallal, Saad Aba Al-Hassan, Joshua Cocker, Luay Ismail, Jung Kim, Muhammad Al-Bannagi and Husam Al-Mustafa, Saudi Aramco, Dhahran

The increase in the demand for gas in recent years has accelerated the need to develop new prospects for deep exploration near existing facilities. Such a development study of the northern part of the Ghawar field and the Berri field involved sedimentology, palynology, petrography, stratigraphy, extensive log correlation, and geological mapping. This presentation summarizes the geological mapping phase.

The presence of distinct palynozones was used to identify the Jauf Formation, its base, the Jauf reservoir, and areas of total and partial erosion. This step was necessary during mapping so as to eliminate any erosional influence on the interpretation of the depositional model and facies trend. The Jauf Formation was mapped regionally using well data guided by seismic and gravity interpretations between wells. The Jauf reservoir, total sand, and approximate porosity-footage were all mapped.

In the Shedgum area, the suboutcrop of the Jauf Formation was not affected by post-depositional erosion and is about 400 feet thick. It is 250 feet thick in the Qatif area and increases to 500 feet and more southeast toward Dammam, but decreases again to 200 to 300 feet in northern Uthmaniyah due to partial erosion. The Formation has been totally eroded at ‘Ain Dar and western Shedgum. Several faults trend north-south and east-west and are probably related to regional uplifts. As a result, the Silurian to Lower Permian rocks have been eroded so that the Khuff Formation is unconformable on Qasim/Quwara sandstone. The erosion probably extends northward to Khursaniyah. These observations are supported by seismic isochronal thinning over the eroded area, and thickening in the area with complete Jauf sections. Gravity data analysis supports the existence of uplifted areas and faults.

The Jauf reservoir is thickest (400 feet) in the Shedgum area, but is partly eroded in northern Uthmaniyah to be about 300 feet thick. It gradually decreases in thickness northward as a result of depositional thinning to be about 200 feet thick near Abu Sa’fah and Qatif. The total sand content of the reservoir in the Shedgum area is about 300 feet decreasing to 250 feet in the Abqaiq and Dammam areas and to about 150 feet in Qatif and Abu Sa’fah. In north Uthmaniyah, it is
about 250 feet thick. The approximate porosity-footage of the Jauf sand is less than 15 in the Qatif, Abu Sa’fah, north Uthmaniyah, and south Shedgum areas. In south Shedgum, the low value is due to silica cementation, in Abu Sa’fah it is the result of depositional thinning, the interdeltaic depositional environment, and silica cementation; in northern Uthmaniyah it is due to the partial erosion of the upper part of the Jauf, in addition to cementation. The porosity-footage in northern Shedgum area and Abqaiq is about 25 or more, as they are located depositionally within the deltaic environment. The highest porosity-footage is in Dammam area, and for the rest of the region studied it is between 2 and 15. Observations supported by petrographic and scanning electron microscopic analysis of reservoir samples indicate that the reservoir quality of the Jauf sandstones is controlled by pore-lining and pore-filling illite. Both illite forms reduce the permeability of the reservoir but pore-filling illite greatly reduces the flow capacity.

By using this multidisciplinary approach of regional mapping, depositional modeling, petrographic analysis, sand accumulation determinations, porosity-footage trends, and erosional interpretation has enabled us to locate on a regional scale, better and thicker sand bodies to help exploration and the delineation of drilling targets.

Ibrahim Al-Jallal is Chief Geologist in the Geological R&D Division of Saudi Aramco. He has a BSc in Geology and Chemistry from King Saud University, Riyadh (1973) and a MSc in Geology from Western Michigan University (1979). He was awarded a PhD in Petroleum Geology by Imperial College, London in 1990. His work experience has involved wellsite operations, reservoir development, prediction and layering, and depositional modeling. His involvement in Geological R&D projects have included reservoir characterization support for field development and geological studies, and participation with international consortia in E&P activities. He was recently in charge of a team that studied the depositional and stratigraphic characteristics of the Jauf reservoir in North Ghawar. Ibrahim is a member of the Editorial Advisory Board of GeoArabia.

Saad Aba Al Hassan is a Senior Geologist with the Geological Research and Development Division of Saudi Aramco. He has a BSc in Geology from King Saud University, Riyadh. He joined Saudi Aramco as a Reservoir Geologist. He worked as Wellsite Geologist in 1985 and from 1986–96 as an Explorationist in the Exploration Department. His work experience was involved reservoir geology, wellsite operation, exploration, and an overseas assignment with Mobil in 1989–1990. He is a member of AAPG and DGS.

Joshua (Josh) Cocker is a Consultant Geologist with the Geological R & D Division of Saudi Aramco. He received his BSc and PhD from the University of Tasmania, Australia. After teaching for 7 years in Alberta and Oregon, Josh joined Mobil Oil and began a 20 year journey as a clastic Petrographer. His main interests at Saudi Aramco are the origin of authigenic clays and their effect on rock properties.

Luay Ismail joined Saudi Aramco in 1987 where he has been a member of the Gravity and Magnetic Unit since 1995. He received a BSc in Geophysics from the University of Tulsa, Oklahoma in 1990 and a MSc from the University of Southern California (1995) focused on the integration of potential fields with existing geophysical data. Luay is a member of SEG, EAEG, and DGS.

Jung Kim is a Geophysical Specialist in the Geophysical Research and Development Division of Saudi Aramco. He has a BSc in Geology from Seoul National University in 1973 and was awarded a PhD by the University of Texas at Dallas in 1981. He joined Saudi Aramco in 1991 having worked previously in Calgary for Petro Canada (1981–82), Texaco Canada (1983–88), and Esso Canada (1989–1991). He has more than 18 years experience in the oil industry, primarily in geophysical research. His professional interests include 3-D reservoir characterization, seismic inversion, seismic 4-D, 3-D geological model building, seismic attribute analysis, rock physics, and geophysical software development. Jung is a member of SEG.

Muhammad Al-Banagi has a BSc in Geophysics (1996) from King Fahd University of Petroleum and Minerals, Dhahran. Since 1996, Muhammad has been with Saudi Aramco. His area of interest includes wave propagation and multiple elimination. He is a member of SEG and DGS.
Husam Al-Mustafa has a BSc in Geophysics (1988) from King Fahd University of Petroleum and Minerals, Dhahran and a MSc in Geophysics (1993) from Texas A & M University. His area of interest includes neural networks, rock properties, shear wave propagation, and fractured reservoirs.

Pre-Stack Kirchoff Time Migration and Velocity Analysis for Complex Media: an Application Using Data from the Red Sea

Tariq Al-Khalifah, King Abdul Aziz City for Science and Technology, Riyadh and Yi Luo, Saudi Aramco, Dhahran

Constructing the seismic image in vertical time, as opposed to depth, eliminates the inherent ambiguity of resolving the vertical P-wave velocity from surface seismic data in transversely isotropic media with a vertical axis of symmetry (VTI media). By ray-tracing in the space-time domain, a travel-time map is built by interpolating the travel-time information along the rays onto a regular grid in space and time. This travel-time map is used in the pre-stack Kirchoff time-migration to obtain migration summation trajectories. Because the travel-time map is extracted using ray-tracing, the migration can handle any lateral velocity variations.

Specifically, the pre-stack time-migration yields good images of the isotropic and anisotropic Marmousi models. However, the real advantage of time-migration is in the migration velocity analysis step, where the depth of an event (given in vertical time), is practically insensitive to the velocity. This limits the influence of velocity to the move-out behavior of reflections with offset. Such a feature has always enhanced the robustness of conventional time-migration and velocity analysis, and it does the same for the ray-traced based time-migration described here. In fact, this approach for velocity analysis reduces to the conventional time-migration velocity for homogeneous media. The benefits of this approach are fully demonstrated on data from the Red Sea as both better velocity models and better images are obtained.

Tariq Al-Khalifah is an Assistant Professor in the Astronomy and Geophysics Research Institute of the King Abdulaziz City for Science and Technology, Riyadh. He received his BSc in Geophysics (1988) and his MSc in Geophysical Engineering (1993) from the University of Petroleum and Minerals, Dhahran. He was awarded his PhD in Geophysics from the Colorado School of Mines in 1997. Tariq received the J. Clarence Karcher award from SEG in 1998. His research interests include ray tracing, and velocity inversion and imaging especially in anisotropic media.

Abdulaziz Al-Laboun, Consultant, Riyadh

The Paleozoic Geology of the Wajid Area: a New Approach

The Paleozoic of the Wajid region of south-central Arabia consists of a thick sequence of siliciclastics of fluvial, eolian, shallow-marine, and glacial origin. The rocks range in age from Cambrian to Permian. The six main lithostratigraphic units, in ascending order, are the Dibsiyah, Sanamah, Madarah, Khusayyayn, Juwayl, and Ruhayah formations. The Dibsiyah can be divided into three subunits (1) a lower high-energy fluvial cross-bedded sandstone; (2) a middle ‘deformed facies’ of massive contorted coarse- and medium-grained sandstone; and (3) an upper subunit of shallow-marine sandstone containing extensive beds of tigillites. The Sanamah Formation is composed of discontinuous paleovalley-fill deposits of sandstone, conglomerate, and tillite; the Madarah of fine-grained sandstones, mudstone, siltstone and shale; the Khusayyayn of stacked fluvial and eolian sandstone; the Juwayl is lithologically similar to the Sanamah; and the Ruhayah formation is composed of calcareous sandstone.

During the Paleozoic, the region went through a series of major uplifts and subsequent erosion that are marked by pronounced unconformities and incised paleovalleys subdividing the succession into the four mega-depositional cycles of Middle Cambrian to Early Ordovician, Late Ordovician to Early Silurian, Middle Devonian, and Middle Carboniferous to Late Permian. In the subsurface of south-central Arabia, the Cambro-Ordovician is represented by a thick succession of stacked fluvial sandstones with extensive tigillites-bearing sandstone in the upper part. The Hanadir and Ra’an shales are not well developed and the succession is therefore difficult to correlate with the Saq and Qasim formations of northern and central Saudi Arabia. The lower fluvial sandstone is equivalent to the lower subunit of the Dibsiyah, and the upper tigillites-bearing sandstone is equivalent to the middle and upper subunits. The Sanamah is well correlated with the coarse-grained and conglomeratic sandstone and tillite penetrated below the Silurian Qusaiba shale. The regional Silurian shale is not as well developed in the Wajid region. However, based on its age, the Madarah is correlated with the Qusaiba Formation. The Devonian Jauf Formation is composed of sandstone, limestone, and siltstone in northern Saudi Arabia. However, as no limestone or shale are developed in the subsurface of south-central Arabia, the term Jauf is not applicable here and a new term should be introduced. The Devonian succession is probably
the downdip facies of the Khusayyayn Formation. The stratigraphic relationships of the Carboniferous sandstones with the Juwayl in outcrop is not clear but it is possibly equivalent to the Al-Khlata Formation of Oman. The Ruhayyah sandstone may be equivalent to the basaltic clastic unit of Upper Permian Khuff Formation.

Abdulaziz Al-Laboun obtained his BSc in Geology/Chemistry from King Saud University, Riyadh in 1973 and a MSc in Petroleum Geology from University of Tulsa, Oklahoma. He was awarded a PhD by King Abdul Aziz University, Jiddah. Abdulaziz is interested in field geology. He is a member of several geological and scientific societies and is a member of the Board of the Saudi Society for Earth Sciences. He has published many papers on the geology of Arabia mainly concerned with the Paleozoic rocks. He also published Part I of the Lexicon of Arabia: Lexicon of the Paleozoic and Lower Mesozoic of Arabia. Abdulaziz was a Geological Consultant in Saudi Aramco until 1999. He is currently active as a Consultant, teaching courses, and organizing field trips. Abdulaziz is now based in Riyadh.

3-D Seismic: a Key to Intra-Salt Exploration Success (Precambrian Ara Carbonates, Oman)

Radha Al-Lawatia, Joachim Reinhardt, Sultan Al Harthy, Mohammed el Tonbary, Jack Woodward, Mia Van Steenwinkel, Roland Muggli and Marco vander Veen, Petroleum Development Oman, Muscat

The most critical success factor for the Precambrian intra-salt carbonate play of southern Oman is 3-D seismic imaging of the ‘stringer’ prospects. During the past three years, applications of new, high-quality 3-D seismic data have resulted in three significant new oil discoveries and the revival of the play which had remained dormant for almost 15 years. This followed an earlier exploration campaign based on 2-D seismic data in the late 1970s to early 1980s.

Long-offset, high-fold and deep recording during the seismic acquisition stage has proven to be crucial for illumination of prospects located at target depths ranging from 2,000 to almost 6,000 meters within a geologically complex intra-salt setting.

During data processing, careful velocity picking and imaging of steep dipping events such as the flanks of the salt and the prospects themselves, and the removal of seismic multiples, have significantly improved the 3-D seismic data quality. On seismic, the prospects constitute high amplitude reflective packages of parallel to slightly domal, often multi-layered, stacked, well visible, and coherent intra-salt events.

For prospect maturation, it has proven crucial to attempt to unravel the internal connectivity, size and number of stringer layers. For an improved structural definition, pre-stack imaging techniques are being routinely applied. Lateral prediction and seismic inversion methods are now being applied to better predict reservoir development and to help position exploration and appraisal wells.

During the interpretation stage, careful seismic-to-well matching, seismic attribute mapping, a careful selection of display parameters, and the application of an inverse ‘bottom-to-top’ seismic stratigraphic correlation method has proven to be of importance. The integration of 3-D seismic data with sedimentological, geochemical, and structural geological data is essential for the improved regional understanding of the play.

To enable effective regional mapping, all existing 3-D surveys in southern Oman have been post-stack merged to large ‘Mega-grids’ covering several thousand square kilometers each. These regional 3-D seismic datasets have been the key to building an integrated play model which addresses the key risk factors in reservoir development, charge, trap and seal integrity. This integrated play model has been instrumental in helping validate and manage the large prospect portfolio of the play.

Radha Al-Lawatia is a member of the Stringer Play Exploration Team for South Oman in Petroleum Development Oman (PDO). He has a BSc in Physics from Sultan Qaboos University, Muscat (1993). He has been a Seismic Interpreter in PDO for the past few years. Radha has worked on the various Huqf, Haima, and Haushi plays.

Joachim Reinhardt, Sultan Al Harthy see p. 169; Mohammed el Tonbary see p. 114; Jack Woodward see p. 109; Mia Van Steenwinkel see p. 84; Roland Muggli see p. 186

Marco vander Veen has a MSc in Mathematics from Amsterdam University. On graduating in 1990, he joined Shell in The Netherlands where he worked on travel-time inversion techniques. In 1995, he moved into experimental seismic processing and later into velocity model building and depth migration methods. He joined Petroleum Development Oman in 1997 and is working in the SIPMAP processing team.
Slip-Sweep Seismic Development in Petroleum Development Oman

Said Al-Mahrooqi, Bart Duijndam and Cees van der Schans
Petroleum Development Oman, Muscat

The slip-sweep seismic acquisition method, conceptualized in late 1994 by Petroleum Development Oman (PDO), has now been developed into a proven system. Since October 1998, it has been used in two full-scale production surveys, covering 600 square kilometers. This development has only been possible because of very successful cooperation between PDO, seismic acquisition contractors, and one of the leading seismic instrument manufacturers.

Slip-sweep recording is a method whereby a vibrator group starts sweeping without waiting for the other group’s sweep to be completed. The result is a significant gain in productivity of up to 50%, at the cost of a relatively small additional capital expenditure of 15%. The increase in productivity can be traded for increased fold or denser surface sampling, improving seismic data quality. A number of tests between 1995 and 1998 have demonstrated that interference on records, from distortions due to the previous record, is negligible. Distortion at stack levels has not been detected.

Since October 1998, the method has been used in normal production surveys at Rima (high resolution) and Mazraq (3-D). Both surveys were recorded with three source groups of three vibrators each, with a 15 second sweep, 6 second listening time, and a slip-time of 14 second between records. The Rima high resolution 3-D survey was 80 square kilometers full-fold, amounting to 88,830 vibration points (VP). It was recorded with an orthogonal geometry with a source and receiver line spacing of 125 meters. Source and receiver station spacing was 25 meters. This resulted in a 144 fold dataset with 12.5 x 12.5-meter bins. The Mazraq 3-D survey was 522 square kilometers full-fold, amounting to 151,332 VP. The survey was recorded as a triple zig-zag with four active receiver lines 300 meters apart and six source lines in between. The source and receiver station spacing was 50 meters. The resulting dataset was 100 fold. Productivity gain in both surveys was 50%, while the incremental cost to record with slip sweep was 15%. It was estimated that $1.75 million was saved on these two surveys by utilizing slip-sweep recording.

A further slip-sweep development has been identified and field tested. Acquisition with four source groups of two vibrators each and a reduction of the slip-time to 10 seconds has been successfully tested. This has the potential of further efficiency and/or quality improvements. PDO considers the slip-sweep method as a break-through in technological development with a demonstrated significant reduction in seismic unit costs.

Said Al-Mahrooqi has a BS in Geological Sciences (with emphasis on Geophysics) from San Diego State University (1992), and an MSc in Exploration Geophysics from Leeds University (1996). Since 1996, he has been working in Petroleum Development Oman’s Geophysical Operations section.

Bart Duijndam joined Shell in 1986 as a Geophysicist, starting in the area of Seismic Equipment Advice. With experience in seismic acquisition gained in The Netherlands and Thailand, he is presently Head of Geophysical Operations at Petroleum Development Oman.

Cees van der Schans joined Shell in 1984. He has completed assignments in The Netherlands, Madagascar, Thailand, and Colombia, in geophysical research, acquisition, and processing. Cees joined Petroleum Development Oman in 1997 as an Operations Geophysicist.

Simsima Carbonate Wedges and their Impact on Shu’aiba Prospectivity in North Oman

Sheikha al Mahrooqi, Jos Terken, Paul Senycia, Mohammed al Rawahy, Paul Veeken and Jack Filbrandt, Petroleum Development Oman, Muscat

Musallim Deep-1, a recent exploration well drilled for Paleozoic objectives on the south flank of the Musallim field, failed to penetrate the Top Shu’aiba at the predicted depth and came in deeper than expected. As no major faults exist across this part of the structure, the Late Cretaceous/Tertiary overburden was examined in detail. Newly acquired 3-D seismic data were analyzed in terms of features that could cause a lateral velocity variation and thus produce the observed depth discrepancy.

A large wedge, consisting of several hundred meters of Simsima (Maastrichtian) carbonates, was observed extending across the southern part of the field. The presence of an incised slope margin complex is suggested by such features as, a locally erosive basal unconformity with an onlapping infill, northwest-trending channeling, and a location downdip of a small graben that is thought to represent a valley feeder channel. The complex most likely drained the inverted salt-structured core of the Ghaba Salt...
Basin (and its uplifted eastern flank) following deformation in the Late Cretaceous. The depression was subsequently filled in the latest Cretaceous by a lowstand wedge of southward-prograding, transgressive Simsima carbonates. These carbonates have a distinctly higher seismic velocity than the incised Fiqa shales. Several similar small grabens, that may have acted as feeder channels, have been mapped in North Oman. Consequently, incised-slope margin complexes may be common and more wedges are expected to be found.

It is the first time that a carbonate wedge in the Late Cretaceous/Tertiary foreland basin sequence has been documented to have such an impact on depth conversion. Its finding has forced a review of the Cretaceous and Tertiary velocity maps and is expected to increase the prospectivity of the shallow plays in North Oman. Several noses and flanks have been converted into potential closures and viable prospects. The importance of proper depth conversion is highlighted, with emphasis on careful well-to-seismic calibrations and investigations of seismic velocities, for trends that will allow improvements in accuracy in the ongoing quest for exploitable hydrocarbons in Oman.

Sheikha al Mahrooqi joined Petroleum Development Oman in 1985 as Evaluation Team Technical Assistant. In 1993, she received her BSc in Geology from Oxford Brookes University, UK. After one year in Exploration Evaluation, she joined the Exploration Computing section as Application Support Geophysicist. In 1996, Sheikha moved to the Regional Team as Associated Regional Geologist and in 1998 joined in the Frontier Commercialization Team as Team Geologist/Interpreter.

Jos Terken see p. 185

Paul Senycia has worked in the oil industry since 1979. He has broad exploration experience having worked as a seismic contractor for Seismograph Services Ltd. in Europe, Africa, and Southeast Asia; a small onshore exploration company (Beach Petroleum NL); and a large offshore explorer (Woodside Offshore Petroleum). He worked for Petroleum Development Oman as Theme Leader for the Gharif Reservoir in Frontier Exploration and was Senior Interpreter in the Safiq-Ghudun Theme. He is now employed by Woodside evaluating North African and Middle East opportunities.

Mohammed al Ruwahy is a Seismic Processor with Petroleum Development Oman (PDO). He has a BSc in Physics and Applied Physics with Electronics from Nottingham University (1995). He joined PDO in 1996. His work involves processing 2-D and 3-D seismic lines using ProMAX and SIPMAP software. Mohammed also supervises an in-house seismic contractor for special processing projects.

Paul Veeken joined Compagnie Générale de Géophysique (CGG) in 1996 as a Senior Geophysicist. He is currently seconded to Petroleum Development Oman where he works on reservoir characterization studies. After graduating with a degree in Geology, he joined Shell International as a Seismic Interpreter. He was then employed by ENSG (France) as an Associate Professor in Applied Geophysics before joining CGG. Paul’s special interests are seismic stratigraphy, deep-sea sedimentation, and basin analysis.

Jack Filbrandt is a Senior Geologist/Interpreter in Frontier Exploration with Petroleum Development Oman (PDO). He has a BSc in Earth Sciences from Leeds University and a PhD in Structural Geology and Geophysics from University College, Cardiff. He joined the Appraisal Division of Shell Expro in 1985. Jack spent three years in Shell Oil, New Orleans, in the Deepwater Sub-salt Play Team, and was Leader of the Structural Geology Team between 1992 and 1996. Jack worked in New Ventures at Central Office for two years being responsible for developing greenfield opportunities, mainly in East Africa and the Middle East. He joined PDO in 1999 and his main responsibilities are new play evaluation and prospect generation.

Mesozoic Depositional Trends in the Northern Arabian Platform in Syria: Regional Tectonic Implications

Khaled Al-Maleh, Mikhael Mouty, Damascus University, Tarif Sawaf, Syrian Petroleum Company
Graham Brew and Muawia Barazangi
Cornell University, New York

Mesozoic deposits are important in Syria where the vast majority of hydrocarbon source, reservoir and seal rocks are of Mesozoic age. Understanding the framework in which
Mesozoic strata where deposited is key to the further understanding of hydrocarbon occurrence in the northern Arabian Platform. Within Syria, the full thickness of Mesozoic rocks, except for the Lower and Middle Triassic, is exposed in several mountain ranges. Deep drilling has penetrated the entire section, and also provides information on the Mesozoic section beyond the exposed regions. Thus, there is a wealth of data pertaining to the thickness, facies, and distribution of the Mesozoic in Syria. We are using these data to construct a depositional model for the Mesozoic that includes tectonic, paleoenvironmental, and paleogeographic factors. The thickest and most complete Mesozoic section is encountered in the Palmyride region. A sedimentary trough persisted there for most of the Mesozoic, with continuation to the Sinjar area in the northeast. Facies variations and sediment distribution on the margins of this trough can help to establish the timing of the tectonics and the paleoenvironment during this deposition.

The Mesozoic section is predominantly carbonate, intercalated with some marly beds and some clastics. The Jurassic is absent in much of south, east, and north Syria, and regional emergence continued until transgression before the end of the Barremian depositing Lower Cretaceous sandstones across much of eastern Syria. Late Cretaceous time was dominated by pelagic deposition in the basins of Syria. Sequence stratigraphic analysis has helped in the determination of the sedimentary cycles (11 main cycles), maximum flooding periods, paleoenvironment and the paleogeographic evolution of Syria. Further analysis, using both outcrop and seismic reflection and well data, will aim to further refine our understanding of the Mesozoic sedimentary sequences and cycles.

Khaled Al-Maleh is Professor in the Geology Department of Damascus University. His career has included time as Head of Geology Department, Damascus University, Head of the Division of Nuclear Ores Exploration with the Syrian Atomic Energy Commission, and General Director of the Syrian General Establishment of Geology and Mineral Resources. He has published widely in French, Arabic and English, and is currently focused on issues of the Mesozoic development of Syria, especially in relation to phosphate deposition in the Upper Cretaceous, and of basin evolution.

Mikhail Mouty is Professor of Stratigraphy in the Department of Geology, Damascus University. He has a BS in Natural Sciences from Damascus University and a PhD in Geology from Geneva University. Mikhail’s professional experience includes geological studies of the Mesozoic and Cenozoic sedimentary series in the mountain chains of Syria.

Tarif Sawaf, Graham Brew, Muawia Barazangi see p. 62

Frequency Analysis as an Interpretation Tool

Maher Almarhoon, Emad Aljanoubi, and Yi Luo

Saudi Aramco, Dhahran

Some features in seismic data cannot be easily detected from conventional displays, and we may need to look at the data from different perspectives or in different, possibly non-physical domains. Seismic-attribute technology that became more popular and frequently used as an interpretation tool provides an alternative for viewing seismic data in non-physical domains. One way of analyzing the data is to look at it in the frequency domain. Seismic high frequencies tend to be absorbed by hydrocarbon accumulations, especially gas. The degree of such frequency absorption typically varies with reservoir quality (for example, porosity, hydrocarbon saturation). Hence, the frequency content associated with any reservoir can be indicative of the quality of that reservoir. Moreover, the geometry of the reservoir affects the response of the frequency spectrum, a phenomenon that can be very useful in detecting pinch-outs and geological features.

We show that the frequency response of real data that contain clear pinch-outs and channels is consistent with that modeled with synthetic data. Also, as we verify using core information, this method is capable of detecting changes in depositional environments. We demonstrate that those results can be readily used as an input for a pattern-recognition process that can identify different depositional environments.

Maher Almarhoon is currently working in Eastern Area Exploration Division in Saudi Aramco. Maher has nine years experience of seismic data processing and stratigraphic analysis. He has a MS in Geology from King Fahd University of Petroleum and Minerals, Dhahran. He is a member of SEG and DGS.

Emad Aljanoubi is a Geophysicist with Saudi Aramco’s Geophysical Technology Division. He has a BSc in Geophysics from New Mexico Institute of Mining and Technology. He is professionally interested in seismic attributes. Emad is a member of SEG and DGS.

Yi Luo see p. 134
An Integrated Approach to Long-Period Statics

Saeed Saad Al-Menhali, Abu Dhabi Company for Onshore Oil Operations, Dave Burkepile and Geoffrey King, Western Geophysical, Abu Dhabi

A 2-D seismic project from southeastern Abu Dhabi sparked the development of an integrated method of near-surface model building and statics computation. The method includes the combination of all possible sources of near-surface information, that is, well data, uphole surveys, seismic refraction information, seismic reflection information, field geological observations, and accumulated regional knowledge. A team of acquisition personnel, seismic data processors, geologists, and seismic interpreters integrated this information and built an initial near-surface interpretation and model. Comprehensive and diagnostic analyses designed by the team, allowed evaluation of the statics computed from this model. After several iterations, a final near-surface interpretation and the resultant static solution produced improved seismic sections. Most importantly, the structural interpretation could proceed based on superior understanding of the near-surface issues and implications. The integrated team approach to near-surface modeling provides the possibility of significant enhancements to seismic exploration and development projects with near-surface travel time variations.

Saeed Saad Al-Menhali received his BA (1996) in Applied Geophysics from the University of Tulsa, Oklahoma. He worked as an Operations Geophysicist at Abu Dhabi National Oil Company, where he was involved in 2-D seismic projects. He was seconded to Abu Dhabi Company for Onshore Oil Operations in 1997. Since then, he has been involved in 2-D, 3-D, and 3-D time-lapsed seismic projects. He is a member of SEG. Saeed's professional interests include statics, modeling, designing 3-D seismic surveys, reservoir characterization, and time-lapsed seismic.

Dave Burkepile is currently Manager of Technology Implementation, EAME Regional Data Processing Centers, for Western Geophysical, based in Abu Dhabi. Dave began his career in 1978 after receiving a Master’s degree from the University of Chicago. He has worked in processing, technical, and management positions for Western Geophysical since 1985. He is a member of SEG and EAGE.

Geoffrey King is currently Manager of Geophysical Technology, EAME-FE Data Processing, and a Senior Research Scientist for Western Geophysical. Since receiving his PhD in Applied Geophysics from the Royal School of Mines, Imperial College, University of London, Geoff has worked for GSI, HGS, and Western Geophysical in research and management positions. He is a member of SEG, EAGE, SPE, PESGB, and is currently a member of SEG’s Production and Development subcommittee. Geoff’s professional interests include statics, reservoir characterization, and time-lapsed seismic.

Aspects of Exploration Data Management at Saudi Aramco

Said Al Qahtani, Peter Attewell, Lloyd Long, Sulaiman Al Otmy, and Haytham Al Tayyar, Saudi Aramco, Dhahran

Core responsibilities of Exploration Data Management (EDM) at Saudi Aramco include putting together policies, guidelines, and procedures to be applied to all Exploration and Producing (E&P) data types. EDM must also ensure that E&P data are delivered consistently within a stable environment. To reduce overlap and data redundancy between the large vendor systems, a Data Flow Chart (covering storage, delivery systems, and applications) is kept current, and EDM strives to maintain a common Data Model that is shared by all disciplines of Exploration and Reservoir Characterization. The model shows a Corporate Database consisting of several linked databases that have the benefit of powerful but overlapping delivery systems. This new paradigm necessitates fresh policies, standards and procedures for quality management of the various types of data, and avoidance of data redundancy by placing self-imposed limits on the use of some systems. Other aspects of the data model to consider are, for instance, the geo-knowledge of E&P personnel, and the growth in the use of E-mail for disseminating data.

Data are delivered to the many exploration applications on various platforms, including the Intranet. EDM identifies the generic types, and addresses the problem of communication between different applications across the disciplines of Exploration, Reservoir Characterization, and Management. Strategic EDM Policies applied now will have important positive impacts for many years, and are already having an effect on major regional evaluation projects where the need for large amounts of variable data is paramount. EDM is facilitated by a stable environment that changes only slowly with time. The challenge is to reconcile this process with the current rapid changes and productivity improvements in hardware and software capabilities.
Constraining Permeability Field to Engineering Data: an Innovative Approach in Reservoir Characterization

Hisham Al-Qassab
Saudi Aramco, Dhahran

Reservoir characterization can yield major improvements in reservoir management and hence in reservoir forecasting. The use of engineering data in reservoir characterization has become increasingly important particularly when it comes to permeability modeling.

This study presents a new technique in integrating engineering data, such as pressure buildup tests and flow meter surveys, in conditioning core-permeability data to capture high-flow zones in stratified reservoirs. Flow-meter data is used to allocate total permeability from pressure buildup tests. As a result, a permeability log is produced that has the same vertical resolution as the flow meter. A series of cross-validations are performed between core permeability and permeability derived from engineering data. Such validations provide statistical comparison between the two sources of permeability for each facies. A comparison of the porosity relationship is also made between both sources of permeability. Upon completion of the cross-validation phase, an integration phase is undertaken. Subsequently, the permeability obtained from engineering data is used to sample the cumulative density function of the core permeability cloud transform. Finally, the spatial correlation of permeability is obtained from the radial diameter of the pressure buildup test to construct a permeability model. Such a model is then compared with a conventionally built permeability model. This approach was applied to a Saudi Arabian oil field and the results show that a model conditioned to engineering data is better at capturing the high-flow zones in a highly stratified reservoir.
A New Layering Scheme for the Khuff-B Depositional Cycle in the Subsurface of Eastern Saudi Arabia

Saleh Al-Raimi and Rami Kamal
Saudi Aramco, Dhahran

The Upper Permian Khuff Formation is a carbonate-evaporite rock sequence that in the sub-surface of eastern Saudi Arabia has been formalized by Saudi Aramco geologists into four major depositional cycles. From top to bottom these cycles are the Khuff-A, -B, -C, and -D. Each cycle consists of a dominantly carbonate interval overlain by dominantly anhydrite. The carbonate intervals of the Khuff-A, -B, and -C, because of their reservoir potential, have been further subdivided into layers with the layer boundaries based mainly on regionally correlatable gamma-ray wireline markers.

A new layering scheme for the Khuff-B was developed, which is simpler than previous schemes (five layers rather than eight), sensitive to lithofacies distribution, and easily detected on compensated formation-density/compensated neutron wireline log curves and in rock core, in addition to gamma-ray signatures. Being sensitive to lithofacies, the new layers more meaningfully double as reservoir layers for reservoir modeling purposes.

The Khuff-B carbonates are characterized by a medial oolite that in the sub-surface of Eastern Saudi Arabia is from 68 to 81 feet thick. The other Khuff depositional cycles are devoid of prominent, thick oolites. The Khuff-B oolite volumetrically comprises the bulk of the Khuff-B reservoir. The oolite has several tight interbedded mudstones, the thickest of which averages 15 feet. It occurs in the lower one-third of the oolite and, unless fractured, is an effective seal between two oolitic lobes. The upper oolite lobe, the mudstone separator, and the smaller lower oolite, have been designated as layers 2, 3 and 4 of the Khuff-B reservoir. Over Ghawar field substructures, the Khuff-B oolite is a lime-grainstone reservoir with good moldic porosity, but only poor to fair permeability. In saddle areas, the oolite is dolomitized, creating areas of very good to excellent combined moldic and intercrystalline porosity, and very good to excellent permeability. It has been shown that present-day structural highs closely correspond to Late Permian topographic highs that were spared early dolomitization.

Layer 1 overlies the oolite and averages 46 feet in thickness. The upper part of the layer is a peloidal dolostone rich in anhydrite and of poor reservoir quality. The lowermost 8 to 12 feet of this layer is a dolomudstone with only a minor anhydrite content and is a good to excellent reservoir rock. Layer 5 underlies the oolite and consists of dense dolomudstones and skeletal dolostones with anhydrite cements. It averages 70 feet in thickness and is of poor to fair reservoir quality.

Saleh Al-Raimi has worked as a Reservoir Geologist in the Reservoir Characterization Department of Saudi Aramco since 1981. He has been involved with wellsite operations, hydrology, area exploration, and reservoir geology. Most of his work is now concentrated on modeling reservoirs in Cretaceous, Jurassic, and Permian carbonates.

Rami Kamal see p. 120

Multiple Elimination in Oman

Jalila Al Riyami and Maarten Ligtendag
Petroleum Development Oman, Muscat

Over a large part of the Petroleum Development Oman (PDO) concession area, multiples are a major geophysical challenge. Several multiple elimination techniques have been tested and applied but, as the geology of Oman is complex, no single method has been identified that gives optimal results for the whole country. In North Oman, multiples tend to be long period with some velocity discrimination between multiple and primary energy. In the South, resistant shallow-carbonate layers generate a sequence of high-amplitude shorter period surface and interbed multiples that stack roughly at the same velocities as the much weaker underlying top reservoir reflector. In this presentation, we present overviews of deconvolution, velocity discrimination, the Verschuur method, and post-stack techniques.

Deconvolution in the time domain works well in areas with short period multiples if the target level is typically below 1.5 seconds. In this case, the filter can be derived over a number of traces without serious deterioration through differential moveout. In cases where the target area is shallower, tau-pi deconvolution yields better results.

Velocity discrimination methods are only effective in areas where the vertical velocity gradient and the period of the multiples are such that the moveout difference at maximum effective offset is at least half the length of the wavelet. Frequency-wave number multiple elimination methods can yield good improvement on the stack but will change the amplitude versus offset (AVO) characteristics. Parabolic Radon multiple elimination has the potential to maintain the AVO characteristics of the data but care needs to be taken to include all events within the p-range while avoiding over-determination of the transform on one hand and aliasing through too small a delta-p on the other.
The Verschuur method can effectively predict and remove multiples even if the vertical velocity gradient is small. While 1-D application on the stacked data is cheap, application on Marmul data did not work very well. The 1-D method does not predict correct multiple amplitudes, and also yields incorrect multiple period prediction in cases of dipping multiple generators. As shown by the Habur example, 2-D application of the Verschuur method can be very effective. Results of 3-D application indicate that further improvement can be obtained, although at high computational costs.

Post-stack techniques are generally considered methods of last resort. CHEAT, SUPERCHEAT, and SPLAT generally make use of assumed dip differentiation between primary and multiple energy, and involve identification and interpretation of the multiple generating layer. In some areas of Oman, especially along the Eastern Flank, they still give the best multiple suppression. Acquisition parameters can have a significant impact on the effectiveness of some methods. A small offset range and poor stack operator sampling can both limit the use of the velocity discrimination methods. The Verschuur method requires small minimum offsets and a 2-D-type of acquisition. Surface-generated noise can both limit the effect of deconvolution and decrease the effective offset range.

The conclusion to be drawn is that no single solution exists for resolving multiple problems in the PDO concession area. Moreover, in order to achieve optimal results, multiple elimination should not be regarded as a processing-only problem. It requires an integrated approach involving acquisition, processing, and interpretation.

Jalila Al Riyami received her BSc (1988) in Geophysics from Tulsa University, Oklahoma and joined Petroleum Development Oman as a Seismic Processing Controller. From 1991 to 1996, she was in a seismic processing production team where she processed 2-D/3-D land data using Shell proprietary processing software. Jalila is now involved in pre-stack imaging projects.

Maarten Ligtendag works in the Shell Processing Center in The Netherlands. He graduated in 1988 in Applied Geophysics from the Faculty of Mining Engineering at Delft University of Technology. He joined Shell International in 1989 and worked as a Seismic Processing Geophysicist at Shell Expro, London until 1993. After one-year with Shell Australia working on seismic data processing, Maarten was transferred to Petroleum Development Oman and worked as a Seismic Processing Controller until the beginning of 1999.

Biozonation of the Ordovician Acritarchs from the Subsurface of Saudi Arabia

Mansour Al-Ruwaili
Saudi Aramco, Dhahran

Ordovician acritarchs have been recovered from siliciclastic cores and cuttings from the subsurface of northwestern and eastern Saudi Arabia. The Early Ordovician assemblage (upper part of the Saq Formation) is characterized by Cymatio galea spp., Acan thodiacrodium spp., Vergatasporites sp., Solisphaeridium solare, S. solidispinosum and Coryphidium elegans. The Middle Ordovician assemblage (Hanadir and Kahfah members of the Qasim Formation) is characterized by Stelli feridium spp., Frankea spp., Dicro diacrodium normale and Petein osphaeridium trifurcatum. The Late Ordovician assemblage (Ra’an and Qawarah members of the Qasim Formation and Sarah Formation) is characterized by Veryhachium subglobosum, V. lairdii, V. oklahomense, Vellosaccapula irrorata, V. setosapellecula, Actinotodissus crassus, Orthosphaeridium spp. and Ordovicidium spp.

These three broad categories are further subdivided into a local biozonation scheme and the stratigraphic range of the species recorded is established. Comparisons are made with Ordovician biozonations of adjacent countries, North Africa and Europe. Paleoenvironment is discussed based on acritarch abundance and diversity and the presence or absence of other palynomorphs, particularly the terrestrial cryptosporonts. Since acritarchs are marine micro-organisms that can be recovered from cuttings, and in some cases the only microfossil available to age-date a stratum, the acritarch zonation has a significant role to play in hydrocarbon exploration of the lower Paleozoic in the region.

Mansour Al-Ruwaili obtained his BSc in Geology from King Fahd University of Petroleum and Minerals, Dhahran in 1987. He worked for Saudi Aramco in the Area Exploration Department until 1993 when he joined the University of Sheffield for postgraduate work in the field of early Paleozoic palynology. In 1997, Mansour joined the Geological Research and Development Department in Saudi Aramco and he is presently working on early Paleozoic palynostratigraphy.
Detection of hydrocarbons at the wellsite using conventional chromatographic tools is sometimes limited, both in terms of the information provided and as a result of contamination by drilling fluids. In particular, as Petroleum Development Oman penetrates deeper formations, oil-based mud (OBM) is used to enable faster penetration of sequences such as the pre-Haushi. This poses a problem where the drill bit generates hydrocarbons from the drilling fluids and so masks the presence of any real hydrocarbons.

In order not to miss finding new hydrocarbon accumulations, two methods have been applied in detecting minute amounts of hydrocarbons. They are fluid-inclusion screening and headspace gas analyses. In wells where there are not enough hydrocarbons to perform a production test, and maybe not even enough to perform an extract analysis, we have to rely on these methods to at least get an idea of what hydrocarbons may be (or have been) present.

Fluid-inclusion screening is a commercially available technique that can be carried out extremely rapidly and on many samples. It may be used in an OBM system since the samples are carefully washed and the fluid inclusions are not affected. The resulting logs give an accurate representation of oil and gas hydrocarbons present throughout the well.

Headspace analysis can yield information on the presence of residual gas hydrocarbons present in reservoir formations. In an OBM system, the presence of hydrocarbons is not sufficient evidence on its own for an accumulation. Compound specific isotope analysis (CSIA) on headspace gases can also be utilised in determining the presence of residual gas hydrocarbons, especially in Oman where Huqf-sourced gases are characteristically light. Headspace analyses coupled with CSIA have been applied in Abu Butabal-1, Saih Nihayda-36, Makarem-1 and 3. In Abu Butabal-1, wet gas was apparent in the Barik Sandstone that coincided with an isotopic shift towards a true Huqf isotope, thus identifying a gas column.

The only disadvantage in these techniques is that analyses are undertaken remotely and the main delay in receiving data is the transport of samples. The continuing challenge is to develop reliable, low-maintenance, and environmentally tolerant tools for the wellsite and achieve an even more rapid turnaround.

Nashwa Al Ruwehy is a Petroleum Geochemist in the Hydrocarbon Modeling Team of Petroleum Development Oman (PDO). She has a BSc from Portsmouth University, (1977) and a MSc in Palynology from Sheffield University (1990). Nashwa joined PDO in 1981. In the past four years she has been involved in source-rock and oil typing and operational and surface geochemistry.

Jan Kleingeld is a member of the Shell’s Geochemical Applications and Consultancy Team. He has a PhD from the University of Amsterdam. He joined Shell in 1983 as a member of the Mass Spectrometer Group in the Analytical Department. In 1990, he transferred to Shell’s Exploration and Production Laboratory where he conducted research in the interpretation of large data sets by chemometrics. He assisted in the setting-up of mass-spectrometer facilities. His main responsibilities are the interpretation and reporting of the analytical data obtained on (mud) gas, crude oil, and source-rock samples.

Raymond Berhitoe joined the Rigid-Polyurethane Department of Shell’s Plastic Laboratory, Delft in 1974. In 1983, he became a member of the Production Services Group in Rijswijk and in 1986 he joined the Geochemical Applications and Consultancy Team. His main responsibilities are sample handling for geochemical fingerprinting, on-site analyses, contracting out samples and quality control of data from contractors, and the interpretation and reporting of analytical data.

Residual Oil Saturation Determination in the Greater Burgan Field: a Comparison Between Time-Lapse and Log-Inject-Log Methods

Salem Hamad Al-Sabea
Kuwait Oil Company

Pulsed Neutron Capture logging is widely used for calculating current water saturations and for monitoring oil-water contact movement during production. Use of advanced techniques, such as Time-Lapse Pulsed Neutron Capture logging or Log-Inject-Log allows the accurate measurements...
of Residual Oil Saturation that can be used to refine booked reserves, among other applications. In this presentation, data from the Greater Burgan field is examined to establish Residual Oil Saturation using both Time-Lapse and Log-Inject-Log techniques. In Burgan, the Time-Lapse method captures Residual Oil Saturation to reflect the vertical sweep, whereas the Log-Inject-Log suggests Residual Oil Saturation in a frontal-displacement mode. For the major sands in the Burgan field, bottom-water drive is the operative mechanism.

Time-Lapse Pulsed Neutron Capture logging requires more than one Pulsed Neutron Capture log be run in a well. The zone of interest requires the initial log to show hydrocarbon-full, and the second log, run significantly later, shows the zone to be swept to naturally produced residual hydrocarbon conditions. Residual Oil Saturation for the zone of interest is calculated from the differences in Pulsed Neutron Capture sigma curves between the two logs. Log-inject-Log involves two (or more) logging runs, each run after the formation has been injected with waters of known, but contrasting salinity. Practical application of this technique is not quite as simple as the equations make it appear. Three important elements must be considered. First, injection of a sufficiently large volume of brine is needed for the formation sigma to change evenly throughout the volume that the log investigates. Second, rapid injection is needed to reduce operating expenses. Third, the need for rapid injection must be balanced with avoiding changes in the Residual Oil Saturation that is representative of the reservoir.

Comparisons between the two sets of results show significantly different values of Residual Oil Saturation. Time-Lapse techniques yielded lower Residual Oil Saturation values than Log-Inject-Log. This is probably due to the different oil displacement mechanisms that the two methods employ. Since conventional core samples in nearby wells show the ‘clean’ Burgan sandstone to be laminated with ripples and cross-beds, the bottom-water drive represented by the Time-Lapse technique gives a better vertical sweep than the frontal-displacement drive represented by Log-Inject-Log.

Salem Hamad Al-Sabea has a BSc in Geology from Kuwait University (1990). He joined Kuwait Oil Company in 1991 as a Wellsite Geologist. Since 1994, Salem has worked as a Petrophysicist in the Field Development Division (South). He has participated in pilot Log-Inject-Log, cased hole surveillance, and other South Kuwait cased and open-hole interpretation projects.

Extracting the Most Value from Vintage Log Data: a Real-World Problem with an Inexpensive Solution for the Greater Burgan Field, Kuwait

Mariam Al Saied
Kuwait Oil Company

The Greater Burgan field was discovered in 1938 and its development spans more than 50 years. Although most of the field’s well-log data was collected prior to 1980 using various vintages of logging tools, valuable data can still be extracted from these old logs. In order to create reservoir simulation models for field management, data from 780 wells were loaded, edited, and analyzed. Out of these 780 wells, only 20% had modern porosity logs. The older wells generally only had open-hole self-potential and resistivity logs. The gamma-ray and single-detector count-rate neutron tools were run through casing. Due to the variations between different generation of logging tools, it was necessary to normalize the log data to modern data standards.

Because of the large number of wells in the study, batch-processing routines were created to calculate parameters of shale content ($V_{sh}$), porosity, water saturation, and permeability for all wells. After this first pass, careful screening on a well-by-well basis and parameter correlation between wells was necessary in order to identify interpretation and processing problems. These problems are generally associated with poor-quality old log data and were corrected using customized (and sometimes unconventional) processing methods for estimating $V_{sh}$ and sediment grain size ($\phi$) from combined old open-hole and modern cased-hole data. Reasonable $V_{sh}$ and $\phi$ values were estimated from Sigma and old open-hole neutron (single-detector count rate) data. About 40% of the wells required reprocessing of at least one parameter to ensure reliability and consistency of our petrophysical data as input for geological, geostatistical, and reservoir simulation models.

Mariam Al Saied is a Senior Geologist with the Kuwait Oil Company (KOC). She has a BSc in Geology from Kuwait university (1982). Mariam joined KOC in 1996 and has worked as a Petrophysicist/Geologist.

Downloaded from https://pubs.geoscienceworld.org/geoarabia/article-pdf/5/1/8/4553260/geo2000.pdf by guest
Patterns of Zonal Statistical and Spatial Distributions of Porosity in Arab-D Reservoir, Harmaliyah Field

Ali Al-Salem, Saudi Aramco, Dhahran
and Ali Sahin, King Fahd University of Petroleum and Minerals, Dhahran

The Arab-D Carbonate reservoir in the Harmaliyah field of the Eastern Province of Saudi Arabia has an average thickness of about 40 meters (136 feet). It has been subdivided into six zones by means of stratigraphic markers based on the correlation of the available well-logs and the lithology of cores.

The statistical analysis of well-log porosity data from 44 vertical wells intersecting each zone of the reservoir revealed that distributions display asymmetry with a minor positive skewness for all zones except Zone 2. Minor negative skewness in Zone 2 is explained by the dominant grainstone facies consisting of fine to medium, well-sorted grains with good interparticle porosity. This texture generally results in high porosity with a small proportion of low values forming the tail of the distribution. Coefficient of variation values for Zones 2 to 5 are less than 0.5, thereby indicating a relatively homogeneous porosity distribution. In contrast, the top and bottom zones (Zone 1 and 6, respectively) have higher coefficient of variation values that indicate greater variability and a relatively heterogeneous distribution.

Variograms were employed to determine the spatial patterns of porosity within the reservoir. Vertical variograms from wells display excellent examples of hole-effects indicating the zonal character of the reservoir. Directional variograms on the horizontal plane indicate isotropic distribution of well-log porosity. Although there are some minor variations in their parameters, variograms for Zones 2 to 5 exhibit similar spherical behavior with zero nugget variances.

Ali Al-Salem is an Exploration Systems Analyst working in the Geologic and Interpretation Applications Division of Saudi Aramco. He provides supports to 3-D geological modeling applications. Currently, he is assigned to Shedgum/Ain Dar and Hawiyah Integrated Reservoir Modeling Projects in the Gas Fields Characterization Division. Ali received his BSc in Computing and Information Sciences/Mathematics from Oklahoma State University in 1988 and his MSc in Geology from the King Fahd University of Petroleum and Minerals, Dhahran in 1996. He is a member of AAPG and DGS.

Tectonic Fracture Analysis of the South Fuwaris Field in the Kuwait-Saudi Arabia Partitioned Neutral Zone

Osama Al-Shaarawy, Kuwait Oil Company
Pablo Vera and Falah Al-Yami, Saudi Arabian Texaco

The South Fuwaris field anticlinal structure is located in the southwestern part of the Partitioned Neutral Zone between Kuwait and Saudi Arabia. An oriented core-fracture analysis integrated 3-D seismic attribute maps with geology, rock properties, pressure, and production data to investigate the nature, orientation and geometry of the reservoir fractures. The study showed the presence of open fractures in the Lower Cretaceous carbonate reservoir. The FMI analyses of vertical and horizontal wells were used to verify the open fracture orientation. The in-situ stress was confirmed from the induced fracture orientation.

The kinematic analysis of the South Fuwaris structure indicated that compressional stress was responsible for creating the main axis of the structural culmination and the induced fractures, whereas an extensional stress created the open fractures. The dynamic analysis indicated that the main axis of the anticlinorium, together with the induced and extensional fractures, are caused by a right-lateral shear couple. This simple shear tectonic model with compressional and extensional components was responsible for producing similar Cretaceous tectonic trends elsewhere in the region. Structural deformation probably occurred throughout the Early Cretaceous.
By using this model, a better understanding of the fracture system of the South Fuwaris was obtained. The new information was in turn used to design the horizontal trajectory of two South Fuwaris wells. Encouraging results were obtained for both wells. The field is currently undergoing a reservoir evaluation aimed at designing an optimum depletion strategy. It is expected that the exploitation and development plan will include the drilling of several horizontal wells. The application of the tectonic model described here will have a direct impact on the design of the horizontal well trajectories.

Osama Al-Shaarawy received his BSc, Diploma of High Study, MSc, and PhD from Ain Shams University, Egypt in 1981, 1983, 1988 and 1994, respectively. In 1989, he received a Diploma in Higher Studies from the University of Tulsa. From 1980 to 1996 he was employed by Amoco Egypt (GUPCO) where his last position was Departmental Head for Exploration and Exploitation. Since 1996, Osama has been a Senior Geologist in the Joint Operations Group of Kuwait Oil Company and Saudi Arabian Texaco. His major interests are tectonics, sequence stratigraphy, regional geology, hydrocarbon system, basin analysis, reservoir geology, field studies, and geologic modeling on Workstations and PCs. He has published numerous technical papers. He is one of GeoArabia’s reviewers.

Pablo Vera joined Saudi Arabian Texaco (SAT) in 1997. He is currently the Team Leader for the South Fuwaris Team. Before joining SAT, Pablo was a Special Studies Engineer in Caltex, Indonesia. He obtained his BSc and MSc from the University of Texas at Austin. He has extensive reservoir management experience through his assignments around the world.

Falah Al-Yami joined Saudi Arabian Texaco in 1990 as a Technical Assistant in the Petroleum Engineering Division. In 1994, he received a scholarship in Petroleum Engineering at the University of Tulsa and completed his BSc in Petroleum Engineering in 1998. Falah has been a Reservoir Engineer in the Reservoir Control Division of the South Fuwaris team since 1998. He is a member of SPE.

The Role of 3-D Seismic in Explaining a Fluid Communication Problem in the Shedgum Area

Abdullah Al-Shamsi and Paul Lawrence
Saudi Aramco, Dhahran

In the Shedgum area of the northern part of the Ghawar field, fluid communication between the Arab-D reservoir and the deeper Hanifa and Hadriya reservoirs is confirmed by engineering data. Evidence for cross-formational communication is based on pressure, temperature, and chemical-fluid analysis, as well as early water breakthrough in the early drilled wells. This area has become known as the ‘Shedgum Leak’.

A 3-D seismic survey in 1995 contributed significantly to our understanding of the production problems by revealing the presence of large and small-scale faults. Large-scale faults were mapped using the standard interpretation method of looking for offsets in reflectors. Small-scale faults, with no obvious offset on vertical seismic sections, were mapped as lineaments on seismic attribute maps such as dip-azimuth and dip-magnitude.

The 3-D seismic interpretation shows that the dominant trend of the large-scale faults is northwest. However, small-scale faults were found to be trending both northwest and northeast. Some of the large faults extend for several kilometers and have throws of more than 50 feet. Small-scale faults were found to have less than 30 feet of throw and may not extend far. Integration of the 3-D fault interpretation data provides evidence that both the large and small-scale faults cut the Arab-D and deeper reservoirs and are responsible for the cross-formational fluid migration.

Abdullah Al-Shamsi received his BSc in Geology from King Fahd University of Petroleum and Minerals, Dhahran in 1989. After graduation, he joined Saudi Aramco as a Carbonate Geologist in Ghawar field studying the Arab-D reservoir by means of cores and thin sections. In 1994, he was in Canada on a nine-month training assignment with Chevron Canada Resources. Abdullah is working on 3-D seismic interpretation of the Abqiaq field.

Paul Lawrence see p. 130
In-Situ Stress, Wellbore Stability, and Fracture Conductivity in the Shu' aiba Reservoir, Idd El-Shargi North Dome Field, Offshore Qatar

Shahin Al-Sharif, Jack Klotz, Occidental Petroleum of Qatar, and Tony Batchelor, GeoSciences, Falmouth, UK

As the industry embraces horizontal well technology, understanding the local stress tensor within each field becomes more important to the success of the operation. In this study we have defined and parameterized the stress field within the Idd El-Shargi North Dome field. The stress field was found to affect the fluid conductivity of faults and fractures and the stability of the wellbores.

Idd El-Shargi North Dome field is located offshore Qatar and is operated by Occidental Petroleum of Qatar under a development production sharing agreement with Qatar General Petroleum Corporation. The field is a north-south elongated salt-cored anticline and currently produces oil from six separate reservoirs. The Cretaceous age Shu'aiba reservoir contributes approximately 40% of total production for Idd El-Shargi North Dome. The Shu'aiba in Idd El-Shargi is a chalky textured, outer-shelf limestone with high porosity and relatively low permeability. The stress field was resolved by integrating existing data gained from fall-off tests, drilling records, core tests, and borehole breakouts calculated from caliper data. This data was integrated within a 3-D wellbore-modeling program. The method involved numerical inversion to match the present conditions and then solved for the maximum horizontal stress component. This investigation gave us valuable insight into the relationship between stress, permeability, fracture networks, rock mechanic properties, and wellbore stability in the Shu'aiba reservoir.

Shahin Al-Sharif is a Petroleum Engineer with Occidental Petroleum of Qatar. He joined Occidental on graduating with a BSc in Geological Engineering from the University of Arizona in 1997. Shahin has experience in operations, drilling and completions, reservoir characterization, reservoir simulation, and production geology.

Jack Klotz is a Geologist with Occidental Petroleum of Qatar. He has 20 years of experience as a Production and Exploration Geologist on projects in North and South America, Russia, China, and Qatar. Jack has a BA in Geology from Capital University and a MSc in Geology from Bowling Green State University, USA.

Tony Batchelor is Managing Director of GeoScience Ltd. in Falmouth, England. He has 30 years experience in applied rock mechanics working in Europe, the Middle East, Africa, and the Far East. He has taught courses on wellbore stability and in-situ stress assessments the SPE and others. He has a BSc and PhD in Mining Engineering from the University of Nottingham.

Basin Architecture and Phases of Structural Evolution of the Central Wadi Al Jawf-Marib Basin, Yemen Republic

Khalid Al-Thour, University of Sana’a

The Wadi Al Jawf-Marib Basin formed in association with the breakup of Gondwana during Jurassic times. East Gondwana began to separate from West Gondwana by means of a rifted transform fault system along the present east coast of Africa. After a long period of passive subsidence and cooling, the basin was uplifted, tilted and reheated in association with rifting of the Arabian Peninsula from Africa. The basin architecture introduces a half-graben structural style of several sub-basins. The history of the basin has been unraveled using cored well data. The basin is about 300 kilometers long and varies in width southeastward from 20 to 80 kilometers. It is flanked to the north, west, and south by exposures of Precambrian crystalline rocks, Mesozoic-Cenozoic sedimentary rocks, and Cenozoic volcanics. The structural development of the basin can be recognized from a sequence of events that is dominated by Jurassic rifting. Zonal fossils from outcrops to the west of the Wadi Al Jawf-Marib Basin allow precise dating and provide clues to the timings of initial marine transgression into the basin. The early rift phase was marked by a slight thickening of the Amran Group during late Callovian-early Oxfordian times. The main rift phase began during the late Oxfordian and culminated in the middle Tithonian and is characterized by the deposition of marine sediments of the Amran Group. The post-rift phase is marked by a decrease in the rate of subsidence that led to the deposition of a cyclic sequence of deep-water evaporites, claystones, sandstones, and organic-rich marine shale of the Sabatayn Group during latest Jurassic to Early Cretaceous times (late Tithonian-early Hauterivian).

Khalid Al-Thour joined Sana’a University as a Sedimentologist in 1982. He has served as an Associate Professor and Chairman of the Stratigraphy and Oil Unit in the Department of Earth & Environmental Sciences. He has a BSc in Geochemistry, a Diploma in Applied Geology, and a MSc in Sedimentology.
from Sana’a University. He was awarded a PhD in Sedimentology by Birmingham University, UK. Khalid is a supervisor and co-supervisor of PhD and MSc students of San’a, Cairo, and Yarmouk (Jordan) universities. He is a member of SEPM and IAS, a fellow of the Yemen Geological Society, Chairman of the Yemen Sedimentary Research Group, President of Environment & Development Society of Yemen, and Executive President of the Scientific Consulting Centre. Khalid contributed to the Geology of Yemen and has published papers on stratigraphy, sedimentology, tectonics, education, and the environment.

Anatomy of a Leaking Trap and Related Production Potential for the Marmul Natih-E Reservoirs in South Oman

Yahya al Toobi, Petroleum Development Oman, Muscat and Jos Terken, Shell, The Netherlands

Clastic reservoirs (Haima, Al Khlata and Gharif) are the main producers in the Marmul field. Oil has also been found in the carbonate Natih and Umm er Radhuma formations and about 100 million cubic meters of stock-tank oil initially in place is trapped in the Natih-E reservoir on the southwestern flank of the field. To determine the producibility of this oil, horizontal well Marmul-293 was drilled and was tested in 1997 using a beam pump at low drawdown. No economic oil-flow rate was established and a recent re-test with Coiled Tubing nitrogen lift produced only water. The much higher drawdown associated with the test apparently preferentially sucked in water (the more mobile phase) probably by creating direct communication links through open fractures.

Subsequent integration of geological, petrophysical, and well-test data has indicated that it is very unlikely that oil can be extracted economically. The Natih-E is part of an oil-bearing sequence of reservoirs, in which the clastic reservoirs at the base leak oil through the Nahr Umr shale into the Natih carbonates. In turn, the Natih-E leaks through the Natih-D shale to the Umm er Radhuma carbonates where the oil is biodegraded into non-producible tar. Multiple oil/water contacts in the deeper fluvialite Gharif formation on the southwestern flank indicate that individual reservoir units leak by different amounts, suggesting poor and variable seal integrity in the overlying Nahr Umr Shale. In the Natih-D, calculated seal quality is best in the high oil-saturation area in the Natih-E on the Marmul southwestern flank and decreases (together with oil saturation in the Natih-E) towards the northeast due to diminishing shale content. Petrophysical evaluations of the Natih-E show that the oil distribution is controlled by a 120-meter-long transition zone. Saturations and porosity trends in the Natih-E suggest that the oil is migrating vertically and that significantly more oil was once trapped in this interval. Both the Nahr Umr and Natih-D seals are thin and most probably always leaked. However, leakage is thought to have increased, and exceeded charge since the mid-Tertiary when faulting linked to a reactivated basement trend caused breaching. The southwestern flank of the Marmul field is interpreted as an active charge migration path, along which oil, once trapped in the Gharif, escapes into the Natih-E interval to finally accumulate in the Umm er Radhuma as tar. Oil in the Natih-E is interpreted to be largely residual. Only small fault-bounded structures on the southwestern flank, such as the one tested by Marmul-293, are likely to yield movable hydrocarbons. Production will only be effected at low drawdowns and uneconomic rates to avoid early water breakthrough. The study has terminated all exploratory appraisal effort in the Natih-E in the Greater Marmul area and removed the booked scope for recovery from our reserves volumes. It also permitted us to focus our resources on more attractive exploration activities.

Jos Terken see p. 185

Three-Tier Computing Environments for Exploration and Production Asset Teams

Kamal Al-Yahya, Mohammed Tayyib, and Malik Al Shobbar, Saudi Aramco, Dhahran

Multi-disciplinary asset management team concepts are being adopted and accepted as the best Exploration and Production (E&P) decision-making process. As a result, the importance of the following three information technologies has increased dramatically: (1) team-oriented reservoir characteristic visualization; (2) application software workflow integration; and (3) data management and archival technologies.

Based on these technologies, we propose the following Three-Tier Computing Environment as the E&P asset team’s best work environment: (1) Visualization Tier; (2) Workflow Integration Tier; and (3) Data Management and Archival Tier. For the Visualization Tier, we survey the technologies...
and the various implementation approaches of adopting the Immersive Computing Environment as the asset team’s working environment and will summarize various implementation possibilities. For the Work Flow Integration Tier we propose the ‘One Asset-One Environment’ workflow integration as the best E&P application for the asset team’s oriented integration policy. We present recommendations and an plan for adopting this policy. For the Data Management and Archival Tier, this presentation summarizes the E&P evaluation of the various data-management concepts and approaches. We propose Environment Level Data Integration strategies as the best way for petroleum companies to adopt the asset team’s work environment.

Kamal Al-Yahya is Manager of the Exploration Applications Services Department of Saudi Aramco. He has a BS in Physics from King Fahd University of Petroleum and Minerals, Dhahran (1980), a MS in Engineering Geoscience from the University of California at Berkeley (1983), and a PhD in Geophysics from Stanford University (1987). Kamal has worked for Saudi Aramco since 1980 in geophysical research, seismic acquisition and processing, and computer applications. He is a member of SEG, EAGE, DGS. Professional interests include seismic acquisition and processing and application integration.

Mohammed Tayyib is Head of the Geological and Interpretation Application Division of Saudi Aramco’s Exploration Applications Services Department. He has a BS (1984) and MS (1997) in Computer Science from King Fahd University of Petroleum and Minerals, Dhahran. He joined Saudi Aramco in 1985 and has worked in various fields of Earth Science computer applications. Mohammed is a member of DGS. His professional interests parallel computing distributed databases, and artificial intelligence.

Malik Al Shobber is Team Leader for Application Integration of Saudi Aramco’s Exploration Application Services Department. He has a BS in Applied Mathematics from Chapman University (1985). He joined Saudi Aramco in 1983 and has worked in mapping, modeling, interpretation and visualization. He is a member of AAPG, DGS. Malik’s professional interests include application integration, data management, and visualization.

From Ice to Salt: Frontier Oil and Gas Exploration in the Huqf Supergroup of Oman

Joachim Amthor, Ibrahim Al Zadjali and Graham Tiley
Petroleum Development Oman, Muscat

The Huqf Supergroup consists of the oldest sedimentary sequences in Oman which, until recently, have been referred to as Infracambrian in age. Integration of new stratigraphic data with global correlations, however, place the Huqf Supergroup now firmly into the Neoproterozoic (1600–543 million years old). As presently defined, the Supergroup consists of the Abu Mahara, Nafun, and Ara groups subdivided into six lithostratigraphic units. These include syn-rift volcanics, siliciclastics, and glacio-marine diamictites (Ghadir Manqil Formation), siliciclastics (Masirah Bay and Shuram formations), carbonates (Khufai and Buah formations), and a thick carbonate-evaporite unit (Ara Group). They can be grouped into at least four main depositional sequences. These are a strike-slip setting (Ghadir Manqil), subsequent deposition of siliciclastics and carbonates during a period of relative tectonic quiescence (Masirah Bay/Khufai and Shuram/Buah), and evaporite/carbonate deposition in a subsiding foreland trough (Ara).

These tectonic and depositional processes have produced several petroleum systems and associated play types that account for more than half of Petroleum Development Oman’s defined exploration oil and gas prospect portfolio. The intra-salt petroleum system consists of the Ara ‘Stringer’ carbonate and the Athel Silicilyte plays of the South Oman Salt Basin. They are unconventional source-reservoir plays with source, reservoir and seal rocks deposited during a single depositional sequence (the Ara Group) in the latest Precambrian. The pre-salt system consists of several proven and potential new play types. Karstified and fractured Buah carbonates below the base Haima unconformity on structural highs in north Oman are the reservoir for the giant Makarem gas field, whereas karstified and fractured Buah/Ara carbonates contain the shallow oil fields on the uplifted eastern margin of the South Oman Salt Basin. The hydrocarbons in these plays are typed to Huqf-related source rocks and the seal is provided by Paleozoic Haima mudstones and siltstones.

By integrating outcrop geology with the available subsurface data, a number of potential pre-salt play types have been identified in the Petroleum Development Oman concession. They are: (1) coarse, possible lowstand clastics at the Khufai/Shuram boundary; (2) Khufai shallow-water carbonates in north and south Oman; (3) Masirah Bay marine sandstones sealed by intra-Masirah Bay shales or tight carbonate mudstone at the base Khufai; and (4) Ghadir Manqil volcanic
and glacio-marine clastics. All these potential plays have a significant reservoir and hydrocarbon-retention risk. However, the Abu Mahara plays, by their widespread distribution and the great thickness of coarse clastics, have a high upside potential.

**Joachim Amthor** is a Senior Geologist in the Frontier Exploration Asset Team of Petroleum Development Oman (PDO). He received a Diploma (MSc equivalent) in 1986 from the University of Würzburg, Germany and was awarded a PhD in Geology from the City University of New York in 1990. After two years as a postdoctoral fellow at McGill University in Montreal, Joachim joined Shell Research in The Netherlands in 1992 as a Research Geologist. In 1996, he was posted to PDO. He provides geological support for the evaluation of intra- and pre-salt oil and gas plays. Joachim has published numerous papers in international journals. He was a recipient of the 1994 Medal of Merit of the Canadian Society of Petroleum Geologists for the best paper published on a subject related to Canadian petroleum geology, and of the 1998 George C. Matson Award of the AAPG for the best oral technical presentation at the Annual Meeting.

**Ibrahim Al Zadjali** has a BSc in Geology from the University of Toledo, Ohio (1996) and a MSc in Petroleum Geoscience from Aberdeen University (1997). He joined Petroleum Development Oman in 1997 and is currently working as a Geologist in the Frontier Exploration Asset Team on the Huqf prospectivity of the South Oman Salt Basin.

**Graham Tiley** see p. 186

---

**Precambrian Carbonates of Oman: a Regional Perspective**

**Joachim Amthor**

Petroleum Development Oman, Muscat

Carbonate rocks of the Neoproterozoic Huqf Supergroup of Oman make up a significant part of Petroleum Development Oman’s undrilled prospect portfolio. Penetrated by numerous wells and exposed in several surface outcrops in Central Oman and the Oman Mountains, carbonates occur in varying proportions and facies throughout the Huqf Supergroup. The oldest carbonates are found in the Abu Mahara Group and are known as ‘Cap-Dolomites’. These dolomites cap glacio-marine deposits and mark a distinct change in style of deposition related to the melting of ice caps. They are useful stratigraphic markers for correlation within Oman and with other sections worldwide where Neoproterozoic glacial successions are capped by similar dolomite units.

Carbonates of the Khufai Formation are dark bituminous dolomites overlain by dolomitized peritidal carbonates that include shallow-water grainstones and stromatolites. The Formation is a 250 to 350-meter-thick unit that was deposited in a carbonate ramp setting and can be correlated throughout the surface and subsurface in Oman. Well penetrations in South Oman indicate mostly cemented reservoir types whereas in the Huqf region outcrops, and in well penetrations in North Oman, the shallow-water carbonates show favorable reservoir facies with up to 8% porosity. Carbon isotope analysis of Khufai carbonates indicates a relatively high percentage of organic carbon buried during deposition and, thus, the presence of source rocks.

Carbonates of the Buah Formation in South and Central Oman are characterized by shallow-water carbonate ramp deposits. A lower carbonate mudstone member is overlain by a stromatolite-dominated middle member that is followed by an upper member with well-developed cross-stratified grainstones. In the Oman Mountains, a platform-to-basin transition is exposed with the slope-break following a north-northeasterly trend. The slope setting is characterized by turbidites and debris flows, punctuated by platform- and slope-derived megabreccias. The shallow-water carbonates of the upper grainstone-dominated member have their primary reservoir potential enhanced by karst and fracturing in carbonates underlying the base Haima unconformity.

The Ara Group consists of a cyclic sequence of carbonates, evaporites, and siliciclastics. Ara carbonates contain the most prolific proven reservoirs of the Huqf Supergroup. This can be ascribed to a combination of rich carbonate source rocks and porous dolomite reservoirs sealed in thick Ara salt. The carbonates were deposited in rimmed shelf or carbonate ramp settings. The deeper parts of the basin were periodically anaerobic, resulting in the preservation of substantial amounts of organic material and the formation of hydrocarbon source rocks.

Source rocks were deposited as sapropelic laminites in basinal settings. Reservoir rocks include shallow-water ooid/peloidal grainstones, thrombolite buildups, and laminated source rock facies where primary porosity has been preserved. To date, the total proven oil reserves in the intra-salt carbonates exceed 150 million barrels.

**Joachim Amthor** see this page.
Structural Analysis of the Main Intra-Shelf Basins and their Impact on Hydrocarbon Generation in Abu Dhabi Onshore Area

Mohamed Ayoub, Ibrahim EnNadi
and Azhari Abdalla
Abu Dhabi Company for Onshore Oil Operations

The Abu Dhabi area is an unstable part of the Arabian shelf. Three main intra-shelf basins developed in the area during the Late Jurassic to late Middle Cretaceous. The Hanifa (Diyab) Formation, the Bab Member of the Shu'aiba Formation, and Shilaif Formation are the main source rocks for the Upper Jurassic and the Cretaceous hydrocarbons in the area, with the total organic carbon (TOC) ranging from approximately 1.4 to 7% (by weight). In addition, three main troughs and anticlinal ridges developed during the Late Cretaceous (90-70 million years ago) as a result of the thrust zone emplacement of the Oman Nappes.

Source rocks were identified using wireline logs and the geochemical analysis of more than 2,000 cuttings and core samples. The Shilaif, Bab, and Hanifa contain immature to post-mature II/It type source rocks. Basin models of the Hanifa, Bab, and Shilaif source rocks indicate that the Shilaif is mature only in the Falaha trough at present, and that the Bab Member matured during the Late Eocene, whereas the onset of hydrocarbon expulsion from the Hanifa Formation occurred during the Late Cretaceous (about 77.5 million years ago). The generated oil potential of the Hanifa source rocks in the central Abu Dhabi area varies from 0.2 to 0.45 grams of hydrocarbon/gramTOC. The tectonic history of the area is the result of regional structural events, such as the development of the Qatar Arch and the Mender/Lekhwair high, emplacement of the Oman Nappes, uplift of the Oman Mountains, and the Zagros Orogeny. The Late Cretaceous subsidence in the central Abu Dhabi troughs enhanced the oil, and organic and inorganic gas generation.

The development of the Upper Jurassic Hith Anhydrite in the western part of the Abu Dhabi area affected the hydrocarbons distribution and hydrogen sulfide concentration in the area, and the Nahr Umr Shale acted as an effective seal for the Thamama reservoirs. In general, multiphased hydrocarbon generation and migration is envisaged for the Abu Dhabi area.

Prior to his present position with ADCO, he was an Exploration Geologist and Lead Reservoir Geologist (1982–91), and Senior Review Geologist (1991–96).

Ibrahim EnNadi is the Exploration Team Leader in the Abu Dhabi Company for Onshore Oil Operations (ADCO). He has 34 years of exploration experience in the Gulf region having worked for the Government of Kuwait, Saudi Aramco, and ADCO. He graduated from the American University of Beirut with a BSc and MSc. Ibrahim has authored and co-authored several papers dealing with exploration in Abu Dhabi. He is interested in exploration methods for stratigraphic traps in carbonate rocks and the depositional and tectonic settings of hydrocarbon source-rock facies in the Gulf region.

Azhari Abdalla see p. 8.

Applications of Borehole VSP Data for AVO and Anisotropy Analyses in the Offshore Nile Delta, Egypt

Mohammed Badri.
Schlumberger Oilfield Services, Egypt,
and
Jochen Rebelsky and Hesham Abdel Maksoud,
Deminex Idku Branch, Egypt

Gas exploration in the offshore Nile Delta, Egypt, has been targeting large-amplitude anomalies seen on surface seismic data. These anomalies are associated with young unconsolidated sediments of the Kafr El Sheik Formation of Pliocene age at depth of less than 2,500 meters. In recent exploration drilling in the area, two exploratory wells were drilled to reservoir targets based on the presence of large amplitude anomalies on 3-D surface seismic data. The first well encountered gas-bearing sand leading to a new gas discovery while the second well encountered silt formation with some gas shows. Drilling of the second well was supported by the Amplitude Versus Offset (AVO) response observed on Common Mid Point (CMP) gathers. This case brought the question of AVO response reliability and uncertainties on CMP gathers.

To address this problem, multi-offset VSP and well-log data were acquired in the second well. The objective of the survey was to determine the cause of the AVO response observed on CMP gathers using borehole measurements. To meet the objective, multi-offset VSP data acquisition and true amplitude processing of 3-component data have been performed. Log-based forward AVO modeling using compressional and dipole shear sonic data was performed and synthetic traces for various offsets were generated on
both wells. Travel times from various source offsets to a common receiver position in the borehole were analyzed to derive information on transverse anisotropy. The multi-offset VSP and well-log data were integrated to provide a complete AVO interpretation of the Kafr El Sheik Pliocene Formation. The results of the borehole AVO analysis showed that the observed AVO response on CMP gathers was due to lateral changes in lithology of the target zone. In conclusion, borehole AVO analysis of VSP data provides a powerful approach to calibrating AVO response on CMP gathers independent of borehole conditions and processing-related effects.

Mohammed Badri is Geosciences Manager for Schlumberger Oilfield Services in East Africa and the East Mediterranean region. He earned his MSc in 1983 and PhD in 1985 in Geophysics from the University of Minnesota. After graduating, he became Professor of Geophysics at King Saud University, Saudi Arabia, between 1985 and 1990. In 1990, he joined Schlumberger Wireline & Testing Services in Saudi Arabia. Currently, Mohammed is in charge of the Geosciences Group including formation evaluation and interpretation, and development. His main interests are reservoir imaging technology, anisotropy, permeability, and shear waves. He is a member of SEG and EAGE.

Jochen Rebelsky is Chief Geophysicist for Deminex Idku Branch in Cairo, Egypt. He earned his Diploma in 1977 and PhD in 1982 in Geophysics from the Technical University of Clausthal-Zellerfeld, Germany. In 1981, he joined Deminex in Essen, Germany, as a Geophysicist. His first assignment to Cairo was from mid 1982 to 1985. After staying for three years in the head office as Geophysicist in the computer application center, he worked for one year in Kalimantan, Indonesia, as company representative during a seismic campaign. Until his present assignment to Cairo, he worked in the Production Department as Senior Geophysicist in Head Office. He was involved in several time-limited projects in Norway and UK.

Hesham Abdel Maksoud has been Senior Geophysicist with Deminex Idku Branch Egypt since November 1998. He earned a BSc in Geology in 1982. Previously, he worked for Repsol Exploration Egypt from 1992 to 1998 as Senior Geophysicist. From 1985 to 1992 he was employed by BP Egypt as Senior Geophysicist. From 1982 to 1985 he worked for Western Geophysical as Field Observer. Hashem’s main interest is seismic interpretation, seismic imaging and AVO.

Overview of Demultiple Techniques Applied in Egypt and the Middle East

Simon Barnes, Rick Sinno, Abdelgelil Meguid, and Mahmoud Hedefa, Petroleum Geo-Services, Cairo

This presentation is a practical overview of the application of multiple attenuation techniques to Egypt in particular, and the Middle East in general. There are several distinct oil provinces in Egypt including the Gulf of Suez, Red Sea, Western Desert, Nile Delta, and deep-water Mediterranean. Each of them has its own geological history and structural characteristics requiring different approaches for correct seismic imaging. However, in many of these areas, the presence of multiples can seriously hinder seismic imaging and subsequent interpretation.

Multiple attenuation techniques can be divided into the following two broad groups: (1) those that exploit some difference between multiple and primary; and (2) those that utilize a wave-theoretic concept to predict and subtract multiples from the data. The first group has been widely used in the region where differences between multiple and primary may be accentuated in a particular domain. Characteristics such as: (a) the moveout difference before stack; (b) the dip difference after stack; and (c) the periodicity of multiples before and after stack, are exploited by Radon demultiple, frequency-wavelength filtering, the stack array response, and predictive deconvolution either in the time-distance or linear Radon domains. The second type of demultiple techniques have been used more recently in Egypt and are attractive because they are theoretically independent of subsurface structure. They include methods that carry out wavefield extrapolation and subtraction (wave-equation demultiple) and those that are based on establishing a relationship between the recorded data (containing free-surface multiples) and the desired data with these multiples absent (Delft University approach). Examples of multiple attenuation in the region illustrate that the appropriate method can be applied if its strengths and limitations are understood in conjunction with the cost and processing objectives.

Simon Barnes has nearly 20 years experience in seismic data processing and interpretation and engineering geophysics. He is currently the Area Geophysicist for Petroleum Geo-Services (PGS), Cairo. Prior to Cairo, he was in the Special Projects Group in the PGS London processing center for three years. He has MSc degrees in Geophysics from the University of Clausthal-Zellerfeld, Germany. In 1981, he joined Deminex Idku Branch Egypt since November 1998. He earned a BSc in Geology in 1982. Previously, he worked for Repsol Exploration Egypt from 1992 to 1998 as Senior Geophysicist. From 1985 to 1992 he was employed by BP Egypt as Senior Geophysicist. From 1982 to 1985 he worked for Western Geophysical as Field Observer. Hashem’s main interest is seismic interpretation, seismic imaging and AVO.
GEO 2000 Abstracts

Rick Sinno is the Offshore Processing Manager for Petroleum Geo-Services (PGS) in Cairo. Rick has a MSc in Geophysics from the University of Arizona (1980) and a PhD in Geophysics from the University of Texas at El Paso (1984). He began his career in 1985 as an Assistant Professor of Geophysics at King Saud University in Riyadh. In 1990, he relocated to Houston where he joined Grant Geophysical as a Processing Geophysicist. In 1993, he joined PGS Tensor and worked as a Marine Processing Supervisor.

Abdelgelil Meguid has 14 years experience in 2-D and 3-D land and marine seismic data processing. He is currently the Geophysical Development Supervisor for Petroleum Geo-Services (PGS) in Cairo. Prior to PGS, he worked for Western Geophysical as Special Projects Supervisor. He holds a MSc in Well Logging from Ain Shams University, Cairo.

Mahmoud Hedefa has 11 years experience in ocean-bottom seismic and marine seismic acquisition and processing. He is currently working in the Petroleum Geo-Services (PGS) Technology Department as Project Leader for PGS in Cairo. He has a BSc in Science, Geology and Geophysics from Tanta University, Egypt, and a Diploma in Computer Science.

The Stratigraphic Evolution of the Lower Cretaceous Sulaiy-Yamama Platform (Berriasian-Valanginian) of Bahrain

Philip Bassant, William Jackson, Ronald Camp, Chevron Bahrain, Rachel Preece, Chevron COPI Aditya Chaube and Yahya Al-Ansari, Bahrain Petroleum Company, Stephen Packer and Jake Jacovides, Millennia Ltd, Hampshire, UK

Growing interest in Arabian Gulf stratigraphic plays is demanding a better understanding of regional correlation and depositional architectures. This understanding is necessary to resolve the vertical and lateral facies variations that are required for stratigraphic traps. This study describes the chronostratigraphy and depositional geometries of the Sulaiy and Yamama formations (Berriasian-Valanginian) of Bahrain and their relationship to equivalent formations in Kuwait and the United Arab Emirates.

The study interval spans the Berriasian to the early Valanginian, and reaches a maximum thickness of 300 meters. It is defined at the base by the top of the Hith evaporites, and at the top by a major temporal hiatus surface representing the middle-late Valanginian and separating the early Hauterivian from the early Valanginian. The study interval is divided into two second-order sequences, of Berriasian (up to 200 meters thick), and Berriasian-early Valanginian (up to 100 meters thick) ages. The lower sequence (Berriasian) is in turn sub-divided into several third-order sequences. The major middle-late Valanginian unconformity identified in this study provides a key surface, allowing direct correlation of the study interval with similar time-equivalent events in Kuwait, Saudi Arabia, and the United Arab Emirates.

Formation ages were determined by an integrated biostratigraphic study. Depositional environments were interpreted from microfacies analysis of cuttings and from faunal assemblages observed during the biostratigraphic analysis. Facies were described and classified from microfacies observations and electric-log information, and depositional geometries were observed from 3-D and 2-D seismic surveys in the study area. The data were combined in a sequence stratigraphic framework consisting of two cross-sections (approximately parallel and orthogonal to depositional dip), illustrating the sequential organization and the distribution of facies within the study interval.

The Sulaiy-Yamama formations in the study area were deposited as a broad, shallow-marine carbonate platform. An outer-platform edge to the northeast is characterized by stacked grainstone deposits whereas, in the inner-platform, muddy sediments were deposited in a low-energy, shallow sub-tidal, often stagnant, brackish environment. Increased subsidence rates on the inner-platform are indicated by a thickening of the sediment column compared to the platform edge. However, sediment production in the inner-platform was sufficient to keep pace with subsidence, and deep-water conditions did not develop. The outer platform grainstones are clearly defined from seismic lines as organized into a series of aggrading and prograding clinofoms. These clinofoms were mapped out from the 3-D seismic, and in plan view show a complex, embayed platform-edge morphology.
Philip Bassant is a Carbonate Geologist working with Chevron Bahrain. He received his BA in Natural Sciences from Cambridge in 1994, then studied at the Institut Français du Pétrole (Paris) for a Masters degree in Exploration Geology, and then a PhD in Carbonate Sedimentology (also with the University of Fribourg, Switzerland). His PhD was a field-based study focusing on the stratigraphic architectures of Lower Miocene mixed systems of Southern Turkey. Most recently he has been working for Chevron on petroleum exploration in Bahrain.

William (Bill) Jackson is a Senior Staff Geologist currently working as Operations Manager for Chevron Bahrain. He received his BA in Geology from State University of New York at Buffalo in 1977 and his MSc in Geosciences from Texas Technical University in 1982. Previous assignments have included management and technical positions in Indonesia (Duri Steam-Flood, Sumatra), California (Bakersfield Steam Flood), Texas/New Mexico (Permian Basin), Oklahoma (Arbuckle Mountains), Colorado (Rocky Mountain Front). He has authored or co-authored several papers on technological and scientific topics relating to topics from the above assignments.

Ronald Camp is a Senior Staff Geophysicist with Chevron Bahrain. He received his BSc in Geophysics from the University of British Columbia in 1982 and a MBA from the University of Calgary in 1996. During his 17 years in the oil industry he has held a number of technical and supervisory positions working on exploration and development projects in Canada, the Democratic Republic of Congo, Sudan, and Bahrain.

Rachel Preece is a Biostratigrapher with Chevron COPI. She received her BSc in Geology from the University of Wales in 1994, and her PhD in Micropalaeontology from University College London in 1999. Since joining Chevron she has worked as a Foraminiferal Stratigrapher, gaining experience in West Africa, Paratethys provinces, South America, the Middle East, Borneo, China, Thailand, and the North Sea.

Aditya Chaube is a Senior Explorationist with the Bahrain Petroleum Company (BAPCO). He worked for the Oil & Natural Gas Commission, India between 1959 and 1981 prior to joining BAPCO in 1981. He received his BSc (hons) in 1958 and a MSc in Geology from Lucknow University in 1959. Aditya received professional certification from the Institut Français du Pétrole in 1968. He has published 14 papers in various international publications. He was the recipient of the Outstanding Performance Award from BAPCO. Aditya also received a commendation from UN ESCAP for preparing the Oil & Gas Map of Asia. He is a reviewer for GeoArabia. His interests are basin analysis and exploration economics.

Yahya Al-Ansari is Exploration Geologist for the Bahrain Petroleum Company (BAPCO) working in onshore and offshore areas. He received his BSc in Geology from Qatar University in 1993. He joined BAPCO as a Trainee Geologist in 1993. He later worked as Development Geologist for three years and was involved in reservoir evaluation research.

Stephen Packer is a stratigrapher with Millennia Stratigraphic Consultants (UK). He completed an MSc in Micropalaeontology at Hull University in 1986 and PhD at Plymouth Polytechnic in 1991. Steve has worked for 10 years in a variety of locations, including North West Europe, the Middle East, and South America.

Jake Jacovides is a Stratigrapher with Millennia Stratigraphic Consultants (UK). He completed an MSc in Micropalaeontology at Aberystwyth University in 1981. In the early part of his career, Jake worked for Robertson Research International and Paleoservices and later moved to BP. He has worked in a wide variety of locations worldwide, including North West Europe, the Middle East, West Africa, the Far East, and South America.
The Western Algerian Sahara Gas Province: Hydrocarbon Potential and Future Perspectives

Djamel Bekkouche and Athmane Rohmani
Sonatrach, Boumerdies, Algeria

The Western Algerian Sahara Gas Province consists of the Ahnet and Timimoun basins separated from the Bechar-Oued Namous and Reggane-Tindouf-Sbaa basins by the Azzel-Matti and Ougarta ranges. The Idjerane High and the Allal Arch form the boundary with Eastern Sahara. The source rocks are Middle and Upper Devonian and Lower Silurian shales and, to a lesser degree, Visean and Ordovician shales. Geochemical studies show a very mature state in the gaseous phase. The maximum period of hydrocarbon generation was at the end of the Paleozoic in two phases. One phase was synchronous with the Hercynian Orogeny and the other was post-Hercynian. The reservoirs are mainly Ordovician, Early Devonian (Gedinnian, Siegenian, and Emsian), and Late Devonian to Early Tournaisian sandstones. Most traps are of the structural type. However, the nature of the sediments and of the environment suggest the presence of mixed traps and/or stratigraphic pinchout traps.

Gas is produced from the Ahnet/Timimoun, Sbaa and Reggane basins, and oil is present in the Sbaa basin. A total of 55 oil and gas fields have been discovered and reserves are estimated to be 33 trillion cubic feet of gas and 70.1 million tonnes of oil. The hydrocarbon resources generated, expelled and likely to be trapped are estimated at 500 trillion cubic feet of gas. In addition, gas remaining to be discovered, mainly in subtle stratigraphic traps, is estimated to be 380 trillion cubic feet. The acquisition of high-resolution 2-D seismic and 3-D seismic, together with seismic modeling and reservoir characterization may lead to the discovery of these subtle traps.

Djamel Bekkouche is Exploration Area Manager (Western Algerian, Sahara) in the Exploration Division of Sonatrach. He graduated in Petroleum Geology from the Algerian Petroleum Institute and has a PhD from the University of Grenoble, France. Djamel has over 20 years of experience in petroleum exploration in Algeria.

Athmane Rohmani is working in the Exploration Division of Sonatrach. He graduated in Petroleum Geology from the National Institute of Hydrocarbons, Algeria. Athmane has over 18 years of experience in gas and oil exploration.

Tunisia, the Western End of the Middle Eastern South Tethyan Platform Deposits

Hela Ben Jemia, Entreprise Tunisiennne d’Activités Pétrolières (ETAP), Tunisia,
Pierre Burollet, International Consultant, France,
Fathia Mejri, ETAP, Tunisia

Late Paleozoic, Mesozoic, and Cenozoic marine platforms of the Middle East extend westward across Egypt and Libya. Many similar facies are present throughout the region as far west as eastern-central Tunisia and into easternmost Algeria. Recent studies by Entreprise Tunisiennne d’Activités Pétrolières allow comparisons with other Middle East oil-bearing series. Among numerous examples that can be compared are formations of Late Permian and Late Triassic age, Jurassic and Cretaceous carbonates, and Paleocene and Eocene rocks. Many stratigraphic sequences in the Arabian Gulf area and North Africa may be correlated by means of the same major unconformities and transgressions.

The fusulinid-rich Upper Permian Tebaga Formation with its reefal intervals, greatly resembles the Khuff Formation of the Arabian Gulf. The Late Triassic transition between restricted evaporitic facies and open marine limestone series in Tunisia may be compared with similar evaporitic facies on the Arabian and Syrian platforms that graded into the open marine zones of Iran and Oman. Similarities also exist between Jurassic and Cretaceous limestone series of the two regions where the same ammonite, foraminiferal, and algal associations are known.

Tunisian lithostratigraphic units such as the Aptian Serj Limestone or the Cenomanian Isis reefal limestone, correspond to the prolific oil-bearing Thamama, Shu’aiba, and Mishrif formations of the Gulf. In Campanian and Maastrichtian times, similar chalky limestones were deposited in Tunisia (the Abiod Formation) and in Egypt and Palestine (the Judea Chalk). However, the phosphate deposits of the Middle East are Late Cretaceous whereas they are younger in Tunisia (Late Paleocene). Large accumulations of Nummulites are present throughout the Middle East and North Africa in Eocene and Oligocene rocks.

These stratigraphic comparisons are encouraging elements for petroleum exploration in Tunisia. However, in Tunisian sedimentary basins, the source beds are generally thinner than farther east. In addition, Tunisia was more strongly affected by the Alpine Orogeny with its youngest phases occurring in the Early Pleistocene. This is a possible cause for the fragmentation of potential traps and for petroleum dispersion. Nevertheless, although less prolific than their counterparts in the Middle East, many Tunisian basins have a high hydrocarbon potential.
Hela Ben Jemia was awarded her PhD in Geology by the University of Franche-comte, France. Her doctoral research (1985-91) concentrated on reservoir characterization and sedimentology of the larger foraminifera accumulations. She has been involved since 1986 in the Agelfi (AGIP-ELF-FINA) group and a French-Tunisian joint research project investigating petrophysical properties and sedimentology of carbonates. She joined the Regional Studies Department of ETAP in 1992 as a Geologist and since 1995 been in charge of regional studies for Central Tunisia. Her recent work has focused on regional geology and reservoir evaluation within a project team that is evaluating the hydrocarbon potential of Tunisia.

Pierre Burollet is a Doctor of Science of the University of Algiers. He retired in 1987 after 42 years of exploration activity for SEREPT, Gulf and Total. He was Exploration Manager of TOTAL in Libya from 1958 to 1963 and later was Head of TOTAL’s Geology Department in Paris. He has undertaken exploration work in Tunisia, Algeria, Angola, Indonesia, the North Sea, and Canada. He is currently working as a Consultant for ETAP.

Fathia Mejri is a Senior Geologist with ETAP. She joined ETAP in 1978 and was Head of the Thematic Studies Department from 1992 to 1994. She is currently Chief of the Regional Studies Department and in charge of the geological synthesis in the project to evaluate the hydrocarbon potential of Tunisia. She is involved in the promotion of exploration in Tunisia. Fathia has published on the petroleum geology of Tunisia, Cretaceous type-sections, and new plays in Tunisia.

Steven Bergman is a Volcanologist-Geochronologist/Hard Rock Petrologist - Tectonist. He has worked for ARCO Exploration Research Laboratory and ARCO International for the past 19 years. He received a BSc from the University of Dayton in 1977, and a MA and PhD in Geology from Princeton University in 1979 and 1982, respectively. Steve was a Visiting Scholar at the Bullard Laboratories, University of Cambridge, 1996–97. His main interests include increasing the efficiency of hydrocarbon exploration by the integration of field geology and high-technology laboratory data to characterize basin

Apatite Fission-Track Thermal History of Proterozoic Granitic Basement Rocks from Oman: a Reconnaissance Study

Steven Bergman, ARCO International, Plano, Texas, Jeff Corrigan, Williams, Tulsa, Oklahoma and Van Mount, ARCO International, Plano, Texas

The Proterozoic granitic basement that crops out north and east of the Oman Ghaba Salt Basin was dated by the fission-track method. The Proterozoic rocks are coarse-grained, garnet-bearing granodiorite gneisses and granitic to dioritic intrusives. Samples from Jobah, Jabal Ja’alan, Qalhat, and Wadi Beni Kharus yielded apatites for high-quality fission-track determinations. The weighted-mean ages are in the range of 38 to 320 million years.

The Wadi Beni Kharus granite found as boulders in the Oman Mountains underwent at least 95°C of mid-Cenozoic cooling in two phases from temperatures that exceeded 130°C. The cooling was probably related to Oligocene uplift and compressional denudation associated with the Makran collision zone to the north that followed burial by the Oman ophiolite in Late Cretaceous and early Cenozoic times. Denudation rates were more than 0.3 to 0.7 kilometers per million years during the Oligocene. In contrast, granitic rocks from Qalhat on the north coast and from near Jabal Ja’alan on the Huqf Arch were for the most part at temperatures of 80° ± 5°C from the late Paleozoic until the Late Cretaceous. Various short-term heating events to temperatures of 90° to 110°C occurred during ophiolite obduction. About 2–3 ± 0.5 kilometers of post-Paleozoic denudation is indicated. The Jobah granite from the crest of the Huqf Arch 200 kilometers to the south was not subjected to temperatures greater than 70° to 80°C for more than a 1 to 5-million-year interval during the last 300 to 500 million years. Post-Paleozoic denudation was of the order of 1.8 ± 0.5 kilometers.

Thermal modeling of the fission-track data show that tight constraints can be placed on the thermal, burial, and denudation history of the granitic basement, and therefore of the timing and magnitude of structural events and associated unconformities. The results place constraints on the thermal history of potential source and reservoir rocks that overlie the granitic basement in the adjacent subsurface. The results from Qalhat, Jabal Ja’alan, and Jobah limit the total amount of erosion associated with Paleozoic or Mesozoic unconformities to less than 1 to 2 kilometers along the sampled parts of the Huqf Arch, and provide important thermal history constraints for the basin modeling of Proterozoic source rocks and reservoir rocks. The method is recommended for a more expanded study of Proterozoic and Paleozoic rocks in Oman.
evolution, thermal evolution, and other elements of the petroleum system.

**Jeff Corrigan** is a Quantitative Analyst for Williams in their Energy Trading & Marketing Group. He received a BSc from the University of Notre Dame in 1984 and a PhD from the University of Texas at Austin in 1990. He worked at the ARCO Exploration Research Laboratory from 1990 to 1998. His interests involve developing and applying quantitative models to characterize physical systems and energy markets.

**Van Mount** has a BA degree in Geology from Hamilton College and a PhD in Structural Geology from Princeton University. He joined the Structural Geology Research Group of ARCO Exploration and Technology Company in 1989. His work with ARCO concentrated on quantitative analysis and interpretation of complexly deformed prospect-scale structures. Van is now an Exploration Geologist in the Middle East Exploration Group of ARCO International Oil and Gas Company.

**Anti-Multiple Processing in the Egyptian North Red Sea**

Adam Betteridge, Compagnie Générale de Géophysique, Cairo and Claude Etienne, Compagnie Générale de Géophysique, Paris

A 2-D marine seismic survey acquired for IEOC in 1998 in the northern Red Sea was dominated by long period surface-related multiples generated not only by the sea bed but by a strong, shallow top-salt reflector. In addition, a zone of intense short-period ‘ringing’ energy was usually concentrated below the sedimentary basins. This multiple energy masked any potential primary reflectors below the thick evaporite sequences. In order to remove the effects of the surface-related multiples, several anti-multiple techniques were employed. They consisted of surface-related multiple modeling with subtraction by pattern recognition, radon transform anti-multiple, deconvolution, and inner-trace mute. Stack displays were produced at every step of the processing to demonstrate the gradual attenuation of multiple energy. The anti-multiple processing was successful in revealing the sub-salt geology and it was concluded that a variety of anti-multiple techniques is required to obtain the optimum stack. Anti-multiple techniques should be tested in combination not isolation. In addition, the use of a non-velocity dependent technique such as surface-related multiple modeling as a first pass of anti-multiple is reliable and efficient in areas of unknown or complex velocities.

Adam Betteridge graduated in Geophysical Sciences from the University of Southampton. He joined Compagnie Générale de Géophysique (CGG) in 1985 and worked in seismic processing at CGG’s London Processing Centre. In 1995, Adam became Supervisor of the CGG Dedicated Shell Processing Centre in London, and in early 1998 he moved to CGG’s Middle East Processing Centre in Cairo as Processing Supervisor.

Claude Etienne is a Geophysical Advisor for the processing centers of Compagnie Générale de Géophysique (CGG) in Continental Europe, the Middle East, and Africa. He has been employed by CGG since 1972 in various capacities, such as Party Chief, Area Geophysicist, Manager of the ELF Processing Center in Houston, and Deputy of Research and Development at Massy (France). He has worked in the Middle East, North America, and Africa.

**Value of 3-D Seismic Data for Understanding the ‘D’ Field, Abu Dhabi**

Gérard Bloch

Abu Dhabi Company for Onshore Oil Operations

The ‘D’ field contains hydrocarbons mainly in the Lower Cretaceous Thamama-B reservoir. The reservoir has an average thickness of 150 feet and hydrocarbons are trapped in a large low-relief structure (150 to 200 feet vertical closure). The overall poor permeability of the reservoir (0.5 to 5 millidarcies) results in a thick transition zone, the extent of which is very sensitive to the structural configuration of the field. Furthermore, poorly explained variations in pressure-volume-temperature properties and hydrogen sulfide content led to the acquisition of the world largest transitional 3-D seismic survey in 1995 to 1998 (1,800 square kilometers), as part of an extensive data-gathering program prior to a Full Field Development Plan.

The new 3-D seismic data led to major structural changes and new insights as follows: (1) the structure is not closed at the oil-water contact level; (2) northeast-trending strike-slip fault zones are present; (3) the static effects on depth conversion have been largely removed; and (4) inversion results reveal a paleo-porosity distribution.
3-D seismic data are critical to address the complexity of the field. The impact of the newly defined fault zones is particularly important in better understanding the hydrocarbon distribution across the accumulation. Overall, the field is more complex than previously mapped from 2-D data but, at the same time, the level of uncertainty has been significantly reduced. Interestingly, the overall stock-tank oil initially in place remains relatively unchanged, as an increase in rock volume is compensated by a previously unmapped gas cap.

Gérard Bloch is a Senior Interpretation Geophysicist working as a Shell secondee in the Abu Dhabi Company for Offshore Operations since 1998. He has a MSc in Geology and a Certificate in Hydrogeology, both from Neuchâtel University, Switzerland. After five years of hydrogeological related research he joined Shell in 1981. He has developed a broad expertise in exploration and development issues (both geological and seismic) from assignments in The Netherlands, Bangladesh, Indonesia, Tunisia, Gabon, Tanzania, and Malaysia. In his present position, Gérard is involved in multi-disciplinary integrated reservoir characterization studies where seismic data are used as constraints to static models.

New Lower Paleozoic Exploration Plays in Southwest Oman

Mark Blood
Phillips Petroleum Middle East Exploration, Woking, UK

An undrilled Proterozoic-lower Paleozoic basin is believed to be present in the onshore Dhofar area of southwest Oman where Phillips Petroleum is a leading player with two large concessions. Regional seismic, gravity, and aeromagnetic data all indicate the basin to be located immediately northwest of a major south-orientated basement high (the Ghudun Khasfah High) and centred over the southern part of the Phillips-operated Al-Hashman Block 36. Studies conducted in-house suggest that the basin has a similar structural history and pre-Silurian stratigraphy to the nearby prolific South Oman Salt Basin. Source degradation through widespread post-Huqf deformation and subsequent metamorphism is possible, but structural modeling and analysis of seismic facies-character suggest otherwise.

New stratigraphically deeper Paleozoic exploration plays are therefore proposed for this area that rely on an as yet unproven Infracambrian Huqf source rock. The Huqf is known to be the primary source rock for the South Oman Salt Basin and for the other salt basins in Oman. In addition, seismic facies analysis and gravity modeling tentatively support the presence of Lower Cambrian salt swells that are thought to be equivalent in age to the Upper Huqf Ara Salt section, present in the South Oman Salt Basin. The salt swells are thought to have created low-relief drape and compaction structures in the overlying Cambrian-Ordovician section, evidence for which can be seen on the existing seismic data. Phillips Petroleum is pursuing these plays through the acquisition of a light-hydrocarbon survey and the extensive reprocessing of existing seismic data. (This paper complements that of I. Webster, Basement Structure and Escape Tectonics in the Eastern Arabian Peninsula: Applications to Early Paleozoic Hydrocarbon Prospectivity; this issue GeoArabia v. 5, no. 1)

Mark Blood has worked as a Geophysicist in the oil and gas industry since 1985 with Phillips Petroleum and BP Exploration. He graduated from Southampton University, and obtained a MSc from the University of Birmingham. Mark has worked extensively on hydrocarbon exploration and development in the North Sea and the Atlantic Margin, and internationally in South America and the Middle East.

Dorood Field, Iran: Optimization of a Producing Field—Evaluation Versus Data and Time Constraint

Marie-Odile Bockel-Rebelle, Patrick Calatayud, Henri Soudet, Daniel-Pierre Gustin
Elf Exploration Production, France, and Ali-Asghar Omrani, IOOC, Tehran

A rapid evaluation of a producing field is possible even when some of the geological and geophysical data are missing. In such a case, the production data and the regional knowledge of a major petroleum operator is used to guide geological modeling. The offshore Iranian Dorood oil and gas field provides an example of such an evaluation.

The field is located within an elongated anticline that partly underlies Kharg Island in Iranian territorial waters of the Gulf. The main productive units are Neocomian carbonates of the Fahlayan Formation. The available geological and geophysical data consisted of conventional logs, a few cores and plugs, an old seismic interpretation (1959) covering part of the field, and a former geological model. However, the dynamic data are based on more than 30 years of production, the geological and geophysical studies provided a good regional understanding of the reservoir, and the program was backed by a fully integrated professional asset team. The analysis of the dynamic data in association with the
geological knowledge defined three orders of vertical and lateral heterogeneity.

In Order 1, the components of vertical heterogeneity (pressure, fluid contacts, and production data) were correlated with the regional stratigraphy. This allowed the stratigraphic units to be divided into independent reservoirs with differing fluid characteristics. Lateral heterogeneity is supported by the complex fault system. These faults, defined by the structural interpretation, are probably filled with bitumen, as observed in the cores, but their dynamic behavior has not been fully assessed. Fault throws suggested local displacement of the vertical heterogeneity components. In addition, regional sedimentological studies indicated a northeast to southwest facies evolution that was confirmed by the northeastward degradation of the geophysical properties.

In the case of vertical heterogeneity at the Order 2 level, a review of repeat formation tests, drillstem tests, and production logging data was made in conjunction with a reinterpretation of the sedimentology of the reservoir. As a result, local multi-layering was defined within the independent reservoirs, with or without dynamic communication. No evidence of lateral heterogeneity occurs.

In the case of Order 3’s vertical heterogeneity, numerous local tight levels defined by the regional high-sequential stratigraphic framework of the reservoir, were calibrated through core and log analyses. This heterogeneity was also confirmed by a close analysis of the RFT data. Lateral heterogeneity caused discrepancies in well productivity and although there were no clear causes of heterogeneity at field scale, diageneosis probably played a role.

The recognition of the three scales of heterogeneity was the result of a coherent and integrated analysis of both the dynamic and geological data that led to the construction of a reliable geological model. Such an evaluation applied to the Dorood field allowed us to propose a suitable re-engineering project that matched the new geological concepts and optimized reserves by water and gas injection. The proposal was in accordance with the project economy and national objectives.

Marie-Odile Bockel-Rebelle is a Reservoir Geologist with Elf, mainly working on fractured reservoirs. She previously spent nine years as a Structural Geologist in Elf’s exploration team. Marie-Odile graduated from the University of Strasbourg and from the École Nationale Supérieure des Pétroles et Moteurs in Rueil-Malmaison, France in 1989.

Patrick Calatayud is a Senior Production Geologist with Elf. He is a graduate of the École Nationale Supérieure des Pétroles et Moteurs, Rueil-Malmaison, France. After seven years of consulting for independent oil companies, he joined Elf EP in 1991 and is Manager of the Geological Modeling-Skill Network.

Henri Soudet graduated as an Engineer from the École Nationale Supérieure de Géologie, Nancy. He joined Elf in 1975 as a Sedimentologist working in the Gulf of Guinea and Mediterranean countries. He later specialized in reservoir geology and is involved at present in studies on oil and gas in limestone environments. As an expert, he plays a leading role in co-ordinating scientific research projects in these fields.

Daniel-Pierre Gustin has 20 years experience as a Reservoir Geologist in the Elf group. He is a graduate of the École Nationale Supérieure de Géologie, Nancy and the École Nationale Supérieure des Pétroles et Moteurs, Rueil-Malmaison, France.

Ali-Asghar Omrani is a Senior Geologist and Head of Operations Geology in IOOC. He is a graduate of Tehran University (1972) and has 25 years experience in subsurface and surface geology. He has worked as a Wellsite Geologist onshore (Zagros) and offshore (Kharg Island and elsewhere in Iranian territorial waters of the Gulf). Ali-Asghar has made a study of the causes of oil accumulation in the Shu’aiba Formation in various offshore fields.

The Zagros Structural Investigation for Deep Petroleum Traps

Marie-Odile Bockel-Rebelle, Jean-Michel Temps, Jean-Paul Xavier and Jean-Marie Flament
Elf Exploration Production, France

A structural study of the Zagros Mountains-Iraqi/Iranian platform had the main objective of understanding the style and timing of deformation in order to determine the existence and style of deeply buried structures. It integrated an interpretation of Landsat Thematic Mapper images, gravimetric analysis, and a structural synthesis.
The formation of the Zagros Mountains is a recent and continuing event. As a result, the topography is directly linked to the structure. In addition, part of the unstable Iraqi-Iranian platform is influenced by the Zagros deformations that overprint the strong influence of the Precambrian basement. The two main features that characterize the geometry of the external Zagros and the eastern Iraqi and Iranian areas are thin-skin deformation (folding and thrusting) and thick-skin deformation involving the basement. The presence of basement-involved active thrusts are deduced mainly from seismicity and the present-day topography. Also, inherited oblique features that acted as strike-slip faults during the main Zagros deformation affect the basement and influence some of the major thrusts; for example, the sinuosity of the Mountain Front Fault. The thin-skin deformation is largely observed within the Simple Fold Zone and the Folded Foreland Zone. The geometry of these outcropping folds shows up well on satellite imagery. The analysis of their wavelengths and dimensions indicates the presence of one or more decollement levels in addition to the two well-known ductile Hormuz and Lower Fars salt formations. Furthermore, a small wavelength indicates a very shallow decollement which, in some places, is within Jurassic or Cretaceous formations. This direct relationship between wavelength and depth of the decollement allows the definition of structural domains on the basis of their geometry of folding. The transition between two adjacent domains can be interpreted as a ramp with transfer of the displacement from one decollement to another. Each decollement separates sequences of rocks that deformed in different ways. For example, very narrow folds at the surface that were induced by a detachment within Cretaceous formations probably overlie a sequence of rocks broadly folded as a result of the Hormuz salt mobilization.

In relation to petroleum traps, because the active decollement is very shallow, the related structures located above this level are small and may present risk of leakage due to erosion of their cover rocks. It thus becomes necessary to focus further exploration toward the underlying broader structures that are related to a deeper decollement. The Iranian and Iraqi Zagros region may have the potential to host such large hydrocarbons traps.

Marie-Odile Bockel-Rebelle see p. 59

Jean-Paul Xavier is a Senior Geologist with Elf. He has a doctorate in Structural Geology from the University of Paris IV. Jean-Paul joined Elf Aquitaine in 1982 as a specialist in structural geology and remote sensing. He is in charge of the Structural Interpretation and Modeling Network in the Technology Division of Elf Exploration and Production.

Jean-Marie Flament is a Senior Geologist with Elf. He received his PhD in Structural Geology from the University of Lille. Jean-Marie joined Elf in 1978 as a Structural Geologist and has worked in France, Italy and The Netherlands. He was in charge of Elf’s Structural Department for four years. Jean-Marie is now Study Supervisor of the Structural Interpretation and Modeling Network.

The Path to Success for the Development of a Fractured Cretaceous Carbonate Reservoir: Integrated, Data-Driven, Multi-Scenario Modeling

Jean Borgomano, Anthony Cortis, Karen Foster, Lex Rijkels, Ben Stephenson
Shell, The Netherlands,
Julian Bessa, Shell EXPRO, UK,
Eduardo Vargas and Antonio Vizamora,
Shell Venezuela

Successful hydrocarbon exploitation in fractured carbonates is often hindered by development strategies that rely heavily on a single model to constrain future well locations, despite large identified uncertainties. Stand-alone use of sequence-stratigraphic, or structural concepts are useful in providing partial explanations of reservoir heterogeneity, but rarely provide a reliable means for production forecasting. An evaluation of one such Shell-operated field, using a combination of proprietary and commercially available tools, has demonstrated the power of integrated dynamic simulations for history matching of past well behavior, forward-looking production forecasting, and selection of workover locations. Synthetic modeling and multi-variate attribute analysis of reflection and acoustic impedence data were incorporated with well log and core data into a 3-D static model of the field that describes the location of matrix sweet spots across the area. Simultaneously, a static fracture
model was created from a structural interpretation of the seismic by calculating the stress perturbations across the field due to slip on the numerous faults. This was integrated and constrained by borehole image interpretation and mud-loss data. These models of matrix and fracture distributions were combined with well production histories in a dynamic simulation. Only a few combined scenarios, from more than 20, match historical production data, as matrix properties and fracture network extent act almost independently in the simulated well response. Rates from nine out of ten wells could be matched with one scenario, consisting of a seismic porosity map with a vuggy frequency-wave number relation, and an extensive, well-connected, tensile fracture network. That so many wells could be matched simultaneously without local changes to the global predictions of reservoir quality and fractures is a very powerful result. This model was then used to successfully predict production performance in a well re-completed into the target interval. The modeling path forms a key element in a revised approach to asset exploitation, with significant follow-up drilling planned by the operating unit.

Jean Borgomano is a member of Shell’s Carbonate Development Team in Rijswijk. He has a PhD in Geology. Jean has worked in carbonate geology for Shell for over 10 years in Shell Research, Petroleum Development Oman, and Norske Shell. His special interests include Cretaceous platforms, platform-to-basin transition, controlling factors and processes, and rudist carbonates.

Anthony (Tony) Cortis is a member of Shell’s Carbonate Development Team. He has a MSc in Geology. He has spent over 10 years working on various carbonate exploration and development plays with Shell Canada and in Shell Research. Tony’s special interests lie in Paleozoic carbonate systems, seismic visualization of reservoir geometries and flow unit definition.

Karen Foster has a BSc in Geology. She completed her thesis on isotope signatures in the Zechstein of England and joined Shell in mid 1999. She is a member of Shell’s Carbonate Development Team in Rijswijk.

Lex Rijkels holds a MSc in theoretical physics and joined Shell in 1994. Since 1996 he has worked as a reservoir engineer in the Fractured Reservoirs and the Carbonate Development teams in Rijswijk.

Julian Bessa joined Shell International in 1996 after graduating with a DPhil from Oxford University. He was posted to Shell Venezuela as a Production Geologist in the Urdaneta Oeste field and later became Team Leader of the Cogollo Asset. In 1999, Julian moved to Shell UK Exploration and Production, Aberdeen.

Ben Stephenson has a PhD in Structural Geology from Oxford University. He joined the Fractured Reservoirs Team at Shell Research in 1998, prior to which he worked for a consultancy specializing in Arctic research. He has published on the regional geology of Greenland, India, northwest China, and Spitzbergen. He is a member of Shell’s Carbonate Development Team in Rijswijk.

Eduardo Vargas joined Shell in 1996 as a Reservoir Engineer. Since then he has focused on Integrated Reservoir Simulation, with proven experience in heavy oil and fractured reservoirs. He is currently Shell Venezuela’s Technology Focal Point and Deputy Team Leader of the Cogollo Asset. He has a BSc in Chemical and Petroleum Refining Engineering and a Minor in International Political Economy, both with High Scholastic Honors from Colorado School of Mines.

Antonio Vizamora graduated from Simon Bolivar University in Venezuela in 1993 with BSc in Geophysics. He joined Schlumberger in 1993 and worked as a Field Geophysicist in 2-D and 3-D seismic acquisition, in Venezuela and Mexico. He joined Shell Venezuela in 1997 as a Production Seismologist, focusing on the integrated characterization of clastic and carbonate reservoirs. He is currently the Geophysical Applications and Seismic Database Administration Focal Point, and Seismic Interpreter of the Rio Negro and Cogollo reservoirs.
GEO 2000 Abstracts

**A New Tectonic Map of Syria and Surrounding Regions**

Graham Brew, Muawia Barazangi, Cornell University, New York
Tarif Sawaf, Syrian Petroleum Company, Damascus
and Khaled Al-Maleh, Damascus University

Cornell Syria Project scientists, and colleagues at the Syrian Petroleum Company and Damascus University, are working to produce new structural and tectonic maps for the whole of Syria. No similar modern maps for the region exist. For more than 10 years, the Cornell Syria Project has studied the paleogeography and deformation of tectonically active zones in Syria, including the Palmyride fold and thrust belt, the Euphrates fault system, northeast Syria, and the Dead Sea fault system. These studies have revealed the Phanerozoic tectonic evolution of these zones, and have enabled us to describe and map the style and timing of deformation in each of these areas in detail.

Our investigations are now complete and we are synthesizing and integrating our findings on a country-wide scale. This regional approach involves new interpretations of large amounts of seismic and well data, merged together with previously generated maps. End-products of this research will include a new Tectonic Map of Syria, structural maps on various subsurface geologic horizons, remote sensing imagery interpretations, and models for the Phanerozoic tectonic evolution of the country. The majority of the mapping is being conducted at 1:500,000 scale. We envisage that these maps will be published on a CD-ROM along with other data taking full advantage of a GIS-type approach for distribution.

Findings from our tectonic syntheses show the interconnected and contemporaneous nature of many of the tectonic episodes within the different mobile zones in Syria. These episodes can, in turn, be related to activity on nearby Arabian Plate boundaries. We have evidence that the response of a tectonic zone to a plate boundary event is related to the paleogeographic orientation of that tectonic zone with respect to the plate boundary. Many of the tectonic episodes within Syria can be directly related to the polyphase opening and closing of the nearby Neo-Tethys Ocean.

Graham Brew is currently finishing his PhD in Geophysics at Cornell University under the direction of Muawia Barazangi. His research with the Cornell Syria Project is focused on the interpretation of Syrian tectonic history through geophysical analysis. He obtained a BSc in Geophysics from University College, London, and worked for a short time with RTZ Mining and Exploration in Santiago, Chile.

Muawia Barazangi is a Professor in the Department of Geological Sciences at Cornell, Associate Director of the Institute for the Study of the Continents (INSTOC), and is the leader of the Cornell Syria Project. He has a BSc in Physics and Geology from Damascus University, a MS in Geophysics from the University of Minnesota, and a PhD in Seismology from Columbia University's Lamont-Doherty Earth Observatory. His research history includes global tectonics, seismotectonics of continental collision zones, intracontinental mountain belts, and Middle East tectonics.

Tarif Sawaf is working for the Al-Furat oil company in Syria while seconded from the Syrian Petroleum Company. Previously, he was Senior Geologist and Associate Head of the Regional Mapping Department of the Syrian Petroleum Company. Before that, he worked for seven years with Sonatrach, Algeria. He has a BSc in Applied Geology from Damascus University.

Khaled Al-Maleh see p. 31

**Evaluation of Anhydrite Seals in the Arab Formation, Al Rayyan Field, Qatar**

Alton Brown and Robert Loucks
ARCO, Plano, Texas

Porous carbonates in the Jurassic Arab Formation are separated by three anhydritic units that can act as pressure and petroleum seals. The upper anhydrite unit is thin and dolomitic. The middle anhydrite consists of two correlative thick anhydrite beds and an intervening dolomudstone; most dolomite is concentrated in thin beds between relatively pure anhydrite. The lower anhydrite unit consists of three correlative anhydrite beds with interbedded porous and oil-stained dolomudstone. The uppermost lower anhydrite bed is pure and massive, whereas the lower two contain dispersed dolomite.

Although anhydrite thickness and fabric change laterally, the anhydrite beds appear to be continuous. Both anhydrite and dolomudstone porosity is low and capillary displacement pressure is high, indicating a high capillary sealing capacity. Wireline pressure tests before production showed that the anhdyrites separated slightly different water pressures and salinities, indicating that they prevented free fluid exchange. The middle and lower anhdyrites act as seals to thin oil accumulations. Porous zones within the lower anhydrite are in pressure communication with the underlying unit.
After production began, reservoir pressure dropped in both the producing Arab-A and C zones and the non-productive Arab-B zone, indicating pressure communication across the upper anhydrite. The lower anhydrite remains a pressure seal. We conclude that seal failure in the upper anhydrite is due to both its thin anhydrite section and its high dolomite content. The unit is offset by faults or fracture zones in the structural closure, and the high dolomite content prevents healing of fracture pathways through the unit. Similar juxtaposition and fracture leakage effects allow charging of porous dolomites in the lower anhydrite.

**Alton Brown** is a Senior Exploration Advisor with ARCO International. He has worked for ARCO since graduating from Brown University with a PhD in 1980. Alton’s research interests are carbonate and evaporite sedimentation, petroleum migration, seals, and hydrodynamics.

**Robert (Bob) Loucks** is a Senior Research Advisor in the Engineering Reservoir Geology Group of ARCO Exploration and Production Technology. He received a BA from the University of New York at Binghamton in 1967 and a PhD from the University of Texas at Austin in 1976. Before joining ARCO in 1983, Bob had 15 years of research and exploration experience with Texaco, the Texas Bureau of Economic Geology, Mobil, and Cities Service. His work has emphasized developing reservoir descriptions by utilizing sequence stratigraphy to delineate reservoir continuity, facies analysis to define reservoir heterogeneity, and petrography to understand the rock fabric control of reservoir quality. Bob has worked extensively on carbonates in the Middle East, North Africa, the Far East, West Texas, and the US Gulf Coast. His overall interests include carbonate sequence stratigraphy, carbonate depositional systems, and carbonate clastic diagenesis.

**Pre-Development Reservoir Characterization of the Ha’py Field, Nile Delta, Egypt**

William Bryant, Jonas Bailey, Mark Wallace, Wail Shaheen, BP Amoco-Egypt and Paul Freeman, BP Amoco-Scotland

The Ha’py field is located in the frontier development area of the outer shelf of the Nile Delta, Egypt, and is expected to become an anchor for future Nile Delta offshore gas developments. The field, discovered by Amoco and IEOC (AGIP) in 1996, is one of the more significant discoveries in the emerging Pliocene Trend. It has an estimated gas-in-place of approximately 70 billion cubic meters (2.5 trillion cubic feet). The main reservoir is the A20 Sand of the Pliocene Kafr El Sheikh Formation that in this area consists of interbedded turbidite sands and pro-delta shales. The A20 Sand is an unconsolidated clay-rich prograding fan built of slump deposits. It’s thickness varies widely across the field and in places exceeds 100 meters. The average porosity of the sand is 30 % with an average permeability of 10 millidarcies. No interbedded shales have yet been identified within the A20 Sand reservoir. Structurally, the Ha’py field lies within a province of northwest-trending growth faults. The field is a structural trap formed where two of these growth faults merge. The trap is sealed by Kafr El Sheikh pro-delta shales, and is gas filled to the synclinal spill point. The reservoir ranges in depth from approximately 1,350 to 1,750 meters for a 400 meter gas column.

Ha’py field was first recognized on the basis of a high-amplitude seismic anomaly, or ‘bright spot’ that was confirmed as gas in the A20 Sand by the Ha’py-1 discovery well. Seismic mapping of the anomaly indicated a gas accumulation covering 46 square kilometers (11,350 acres), but the accurate determination of resources within this area proved a difficult task. The anomalous interval exhibited variations in thickness and intensity, with numerous internal reflections. Furthermore, test results indicating flow potential of up to 1.6 million cubic meters per day (56 million cubic feet per day) appeared inconsistent with the shaly nature of the reservoir.

To address the uncertainties in resource size and deliverability, a reservoir characterization study was conducted. The study was completed in five phases. (1) In an appraisal-drilling phase, two wells were drilled to collect additional data. (2) The evaluation phase analysed the logs, cores and test data acquired by appraisal drilling. (3) The calibration phase related the log responses to seismic expression and to rock and fluid properties. Four different rock types were identified and the criteria were established for recognising fluid flow units. (4) In the modelling phase, a geologic model was developed from rock properties and seismic geometry, and a multi-layered reservoir model was built based on the geologic model and seismic reflection mapping of flow units. (5) Finally, in the simulation phase, the reservoir performance was simulated to test various development scenarios.

William Bryant is a Petrophysicist with BP Amoco’s Nile Delta Appraisal Team. He joined Schlumberger in 1971 as a Field Engineer after receiving his BS in Engineering Science from Florida State University. He joined Amoco International in 1981 as a Staff Engineer and worked on projects.
outside the USA and Canada. In 1989, William became part of Amoco’s World-Wide Formation Evaluation Department and later started Amoco’s Image Processing Team. In 1994, he joined the Petrophysical Training Staff at the Amoco Research Center in Tulsa, Oklahoma. He has been a member of the Nile Delta Appraisal Team in Cairo since 1997.

Jonas Bailey is a Geologist with BP Amoco’s Nile Delta Appraisal Team. He received his BS in Geology from the University of Southwestern Louisiana and his MA in Geology from the University of Texas at Austin. In his 18-year career with BP Amoco, he has worked on offshore exploration and development projects in the Gulf of Mexico, Trinidad, and Egypt.

Mark Wallace is a Geophysicist with BP Amoco’s Nile Delta Appraisal Team. He received his his BS in Geophysics from Pennsilvania State University, and his MS in Geophysics from Stanford University. In his 20-year career with Amoco and BP Amoco, he has worked on exploration and exploitation projects both in the USA and internationally, including various Mid-Continent and Rocky Mountain basins, the Timan Pechora Basin (Russia), and the Nile Delta (Egypt).

Wail Shaheen is a Reservoir Engineer with BP Amoco’s Nile Delta Appraisal Team. He received his BSc in Petroleum Engineering from Cairo University in 1993. Wail worked as a Reservoir Engineer for AGIP spa in Italy; for IEOC (AGIP) in Egypt, and as a Petroleum Engineer for Deutag in Oman. He has been a Senior Petroleum Engineer for BP Amoco in Cairo since 1997.

Paul Freeman graduated in Geology from the University College Cork, Ireland, in 1990. He received a MSc in Petroleum Geology from Aberdeen University, Scotland in 1991 and joined Amoco (UK) Exploration Company the same year. Since then he has worked in operations geology and exploration mostly in the Central Graben of the North Sea. In 1997, he moved to Amoco’s Tulsa Technology Center in Oklahoma to study Petrophysics as part of a one-year training program that involved the detailed petrophysical characterization of the Ha’py field reservoir. In 1998, he joined the Everest and Lomond gas fields development team in UK as a Field Development Geologist/Petrophysicist focusing on phase-two development programs. Paul worked on satellite development to the Harding oil field in the South Viking Graben, North Sea for BP Amoco Exploration (UK) until 1999. He is now employed by Enterprise Oil (Dublin).

Jonas Bailey is a Geologist with BP Amoco’s Nile Delta Appraisal Team. He received his BS in Geology from the University of Southwestern Louisiana and his MA in Geology from the University of Texas at Austin. In his 18-year career with BP Amoco, he has worked on offshore exploration and development projects in the Gulf of Mexico, Trinidad, and Egypt.

Mark Wallace is a Geophysicist with BP Amoco’s Nile Delta Appraisal Team. He received his his BS in Geophysics from Pennsilvania State University, and his MS in Geophysics from Stanford University. In his 20-year career with Amoco and BP Amoco, he has worked on exploration and exploitation projects both in the USA and internationally, including various Mid-Continent and Rocky Mountain basins, the Timan Pechora Basin (Russia), and the Nile Delta (Egypt).

Wail Shaheen is a Reservoir Engineer with BP Amoco’s Nile Delta Appraisal Team. He received his BSc in Petroleum Engineering from Cairo University in 1993. Wail worked as a Reservoir Engineer for AGIP spa in Italy; for IEOC (AGIP) in Egypt, and as a Petroleum Engineer for Deutag in Oman. He has been a Senior Petroleum Engineer for BP Amoco in Cairo since 1997.

Paul Freeman graduated in Geology from the University College Cork, Ireland, in 1990. He received a MSc in Petroleum Geology from Aberdeen University, Scotland in 1991 and joined Amoco (UK) Exploration Company the same year. Since then he has worked in operations geology and exploration mostly in the Central Graben of the North Sea. In 1997, he moved to Amoco’s Tulsa Technology Center in Oklahoma to study Petrophysics as part of a one-year training program that involved the detailed petrophysical characterization of the Ha’py field reservoir. In 1998, he joined the Everest and Lomond gas fields development team in UK as a Field Development Geologist/Petrophysicist focusing on phase-two development programs. Paul worked on satellite development to the Harding oil field in the South Viking Graben, North Sea for BP Amoco Exploration (UK) until 1999. He is now employed by Enterprise Oil (Dublin).

Origin of Dolomite from the Ghawar Field, Saudi Arabia

David Cantrell, Saudi Aramco, Dhahran
Peter Swart, University of Miami
Hildegard Westphal, University of Hanover
C. Robertson Handford, Consultant, Austin, Texas
and Christopher Kendall, University of South Carolina

The Ghawar field is the world’s largest and most productive oil field. It produces primarily from the prolific Arab-D Member that locally contains zones of extremely high flow, many of which occur in dolomitized units. An integrated stratigraphic, petrographic, and geochemical study suggests that four episodes of dolomitization affected these sediments. The lower portion of the Arab-D (Zone 3) is only partially dolomitized, with the dolomite frequently being associated with non-depositional surfaces. It is proposed that these dolomites were formed during the period represented by non-deposition, promoted by the oxidation of organic material. Magnesium was supplied by diffusion from the overlying seawater. The dolomites in Zone 2B are geochemically distinct from those in Zone 3 and have relatively heavy oxygen isotopic compositions. This heavy oxygen isotopic composition and the geochemical similarity to the dolomites in Zone 1, which are intimately associated with the overlying evaporites, has led to the conclusion that the Zone 2 dolomites were formed by the reflux of hypersaline fluids through the sediments. These hypersaline fluids passed through Zone 2A moving rapidly through the relatively grain-dominated sediments and dolomitized the underlying Zone 2B. Early cementation and dolomitization made these units more susceptible to the later fracturing that affected the entire Arab-D. This fracturing allowed higher-temperature fluids to leach the dolomites, thereby removing the remaining calcite and partially resetting the oxygen isotopic composition of the dolomites. As a result of this later dolomitization event, rocks that were only partially dolomitized were leached, creating units with extremely high permeability and porosity known as the ‘Super-K’. Dolomites in the lower Zone 3 were recrystallized during burial as they responded to the normal geothermal gradient.
David Cantrell has over 16 years of worldwide exploration and development experience in the oil industry. He graduated from the University of Tennessee with a MSc in Geology in 1982. Dave began his industry career with Exxon where he conducted numerous reservoir characterization and geologic modeling studies on reservoirs in the Middle East; the Permian Powder River, Williston, and Gulf of Mexico Basins of the USA; and the Maracaibo and Barinas Basins of Venezuela; among others. He has been responsible for several studies on large carbonate reservoirs since joining Saudi Aramco in 1997.

Peter Swart received his PhD from the University of London in 1980 for work on modern coral reefs. After three years at the University of Cambridge, he started a project on dolomite geochemistry at the University of Miami where he is now Professor of Marine Geology and Geophysics in the Rosenstiel School of Marine and Atmospheric Sciences. His professional interests include carbonate geochemistry and diagenesis, hydrology, and paleoclimatology.

Hildegard Westphal studied geology at the universities of Tübingen, Brisbane, and Kiel. She received her PhD in 1997. From 1998 to 1999, she was a postdoctoral researcher at the Rosenstiel School of Marine and Atmospheric Sciences, University of Miami. Since 1999, Hildegard has been an Assistant Professor of Carbonate Sedimentology at the University of Hannover. Her interests include carbonate reservoir characterization focusing on diagenesis, petrophysical properties of carbonates, and the application of artificial intelligence methods to prediction problems.

Seismic Attribute Analysis of the Jurassic Najmah-Sargelu Formations, Western Kuwait

Daniel Cassiani, Gianni Matteucci
ExxonMobil, Houston
and Abdul Latif Mohammed
Kuwait Oil Company

A seismic attribute analysis and calibration were conducted on the Najmah and Sargelu formations to constrain the 3-D reservoir model. Attribute analysis of a thick, multi-loop, relatively tight fractured carbonate interval is a complex process. Fracturing plays a dominant role in reservoir performance but is difficult to model seismically. Map patterns of a number of seismic attributes suggest significant reservoir changes are taking place. To evaluate these changes, a detailed multiple seismic trace attribute study was conducted. To understand the character of the seismic reflection, a large suite of geophysical attributes was modeled. In addition, structural (geometric), geological and reservoir engineering attributes were included in the analysis. Seismic attributes were extracted on total impedance data and calibrated to reservoir properties. Signal response of the reservoir unit was broken down to its individual components to estimate the part of the seismic signal contributing most to the attribute maps. A calibration between seismic data and reservoir performance was made for Minagish field, and the resulting relationship extrapolated into two other surveys, including Kra Al-Maru. Great care was exercised to ensure stability and robustness of predictions when additional wells were included. Forward seismic models were constructed to validate the signal response to geologic change. This is a critical step to ensure that the geologic significance of the statistical relationships is maintained. The calibration results were then included in the reservoir model to guide our predictions and simulations of reservoir performance.

Daniel Cassiani is a Senior Exploration Geophysicist with the Middle East Venture Department of Exxon Exploration Co. in Houston. He received his BS in Geology from Boston College in 1979. In 20 years with Exxon, his assignments have ranged from frontier exploration to new and mature field development. His fields of specialization include seismic interpretation, seismic attribute analysis and seismic stratigraphy. He has worked in many of the producing basins of the USA, SE Asia and the West Coast of Africa. Daniel is a member of the Kuwait team working the Kra Al-Maru Joint Technical Study in Western Kuwait.

Christopher Kendall is Professor of Geology at the University of South Carolina. He has worked extensively in the oil industry and in academia. His research interest and publications have concentrated on the Arabian Gulf. Having started his career in carbonate sedimentology and petrology, Christopher is interested in sedimentary simulations and sequence stratigraphy and has numerous publications on these topics.
Gianni Matteucci is Geophysicist/Geostatistician with the Seismic Reservoir Characterization section at Exxon Production Research Co. in Houston. He has a BS (1983) and MS (1985) in Physics from the University of Bologna, Italy, and a MPhil (1986) and PhD (1991) in Geophysics from Yale University. He is one of Exxon’s main developers and instructors of seismic attribute technology, lecturing and consulting extensively for the affiliates worldwide. Gianni has applied attribute technology in the USA (offshore and onshore), Chad, China, and Kuwait. He is an Adjunct Professor of Geology and Geophysics at Rice University, Texas.

Abdul Latif Mohammed biography not available.

Palynological Correlation of Latest Devonian and Carboniferous Miospore Assemblages from Saudi Arabia: some Geological Implications

Geoffrey Clayton, Trinity College Dublin and Bernard Owens, University of Sheffield

Latest Devonian and Carboniferous miospore assemblages are recorded infrequently in Saudi Arabia. This is partly due to the limited number of well penetrations of this part of the stratigraphical column and partly reflects the dominantly arenaceous character of the sequences. A limited number of well-preserved assemblages have however been recovered which permit detailed correlations to be drawn with adjacent parts of the Gulf Region, Middle East and North Africa, notably Libya and Algeria. Direct comparison with these areas permits an outline palynological zonation to be established despite the fact that all recovered assemblages lack any independent biostratigraphical calibration.

Subsurface evidence now exists for the presence of in-situ latest Devonian (Strunian) deposits containing representatives of Retispora lepidophyta, the zonal marker for the recognition of the Devonian/Carboniferous boundary. Despite the fact that in-situ records of this species appear to be rare, it’s frequent occurrence in later reworked populations suggests the former existence of widespread deposits of that age which have subsequently been subjected to sub-aerial erosion during the remainder of the Carboniferous and into the Permian.

Incomplete records of the Tournaisian and Viséan are now known from both northern and central Saudi Arabia although a significant hiatus is proven during late Tournaisian and early Viséan times. Assemblage composition permits correlation with previously documented sections in Syria, Libya and Algeria. Major compositional differences are noted with contemporaneous miospore populations from the Euramerican landmass.

Palynological definition of the Mid-Carboniferous (Mississippian/Pennsylvanian) boundary in Gondwana currently lacks the precision possible in western Europe. However, assemblages recovered from the Ghawar oil field in central Saudi Arabia suggest correlation with comparable datasets recovered in Cyrenaica, northeast Libya. If substantiated, this correlation would imply that at least part of the Berwath Formation is of Namurian age and might represent some of the first sediments deposited on the post-Hercynian orogeny landsurface.

Latest Carboniferous deposits from northern Saudi Arabia have been re-examined. The assignment of a late Westphalian or early Stephanian age is based on the close comparison with assemblages from western Europe with implications that either the Arabian and Euramerican Plates had moved closer together at this time, or significant climatic changes related to the end of the Gondwana glaciation had major impacts on the palaeobiogeography of the time.

Geoffrey Clayton is Associate Professor of Geology at Trinity College Dublin, and was President of the Commission Internationale de Microflore du Paléozoïque. He is involved in palynology and organic maturation projects in Saudi Arabia, the USA and Europe. Geoffrey received his PhD in Geology from the University of Sheffield in 1972.

Bernard Owens see p. 154

Petroleum Geochemistry and 2-D Modeling of the Berkine Basin, Algeria

Gary Cole, Z. Alan Yu, BHP Petroleum, Houston
Mohamed Arab, Djaouida Kassab, Sonatrach Exploration, Boumerdes, Algeria,
John Exton, Jim Binnie, Paul McIntosh and Michael Jones, BHP Petroleum, London

The petroleum system of the Berkine Basin in Algeria (including the Hassi Messouad area), is dual-sourced from basal Silurian and Upper Devonian ‘hot’ marine-clastic shales. Oil and gas expelled from these source rocks were trapped primarily in the Triassic TAG-I Formation and sealed by overlying Triassic carbonates and evaporites. The basin type is a steady-state hydrostatic system where migration is predominantly lateral along carrier beds, but modified by faulting (Cretaceous to Tertiary) and subcrop flow.
Basic source-rock data (percent total organic carbon, pyrolysis and maturity measurements) are available for the entire Paleozoic section as determined from selected wells throughout the Berkine Basin. The primary source rocks are radioactive (gamma-ray ‘hot’) shales of the basal Silurian Tannezuft Formation, together with Frasnian (Upper Devonian) ‘hot’ shales acting as a major secondary source. Both source rocks represent maximum transgressive events that resulted in the deposition of organic-rich, highly productive marine-clastic source rocks.

Hierarchial cluster analysis/prinical component analysis does not appear to show any true end-member oil families in the Berkine Basin, except possibly oils of the Hassi Messaoud area. The wide maturity ranges within the reservoir oils contribute to the difficulty in distinguishing specific end-members. Statistical analysis of the source-rock extract and oil data suggest that the oils are primarily derived from the Silurian ‘hot’ shales, together with variable contributions from the Frasian source.

The TemisPack 2-D basin-modeling software package was used to evaluate the oil and gas charge within the Berkine Basin. The most important result from the 2-D modeling confirms that the Berkine Basin has a mixed petroleum system of mostly Silurian-derived oils but with varying contributions from the Devonian source rock depending upon position within the basin. The Silurian shales contributions are mostly in the form of light oils and wet gas. Migration is mainly vertical to first carrier bed, then lateral migration dominates the system. Lateral migration is a key role where there are carrier beds. Major northeastrytrending faults act as seals and compartmentalize the basin into distinct drainage areas.

Gary Cole is the Principal Geochemist for BHP Petroleum based in the Americas (Houston) office. He received his MS in Geology from Southern Illinois University. Since joining BHP Petroleum, Gary has been responsible for implementing geochemical and basin modeling studies in several of BHP’s exploration areas, primarily the Gulf of Mexico, West Africa, and Algeria. His primary role is in applying petroleum system concepts to the understanding of the source, maturity, and charge risks in each basin. Prior to joining BHP, Gary spent 10 years at BP Exploration and 3 years at Saudi Aramco. He has published numerous papers on petroleum geochemistry and basin modeling as applied to the petroleum systems of the Red Sea, the Jurassic of eastern Saudi Arabia, the Paleozoic systems of the Middle East and North Africa, the Lower Congo basin of offshore Angola, and the Gulf of Mexico.

Z. Alan Yu is with BHP Petroleum, Houston. He has a BS in Petroleum Geology (1982) from the Daqing Petroleum Institute, China, and a MS (1990) and PhD in Geology (1992) from the University of South Carolina. Alan has worked on basin modeling for the past 10 years, including code development and applications in the Gulf of Mexico, Alaska, Venezuela, Bolivia, and Africa. In addition to conventional geochemistry modeling, he has been developing and applying basin modeling for pre-drill pressure prediction and trap-seal integrity analysis. Alan has co-authored and published numerous papers in the fields of basin modeling, salt influences on petroleum accumulation, and data processing.

Mohamed Arab has been a Petroleum Geologist with Sonatrach since 1994. He has an Engineering Diploma from the Petroleum Institute of Algeria (1993). He has worked on many projects in the Illizi basin of the Algerian Sahara. His professional interests are petroleum geochemistry and basin modeling.

Djaouida Kassab graduated in 1992 from the Algerian University of Science and Technology. She joined Sonatrach in 1993 as a Geochemist and has worked on several basins in the Algerian Sahara and northern Algeria. Djaouida has presented papers at conferences in Algiers and elsewhere, including the Hydrocarbon Geology of North Africa (London, 1995) and the 6th Tunisian Petroleum Exploration and Production (Tunis, 1998). She is now studying the migration pathways of the Hassi-Messaoud oil field in southeastern Algeria.

John Exton is a Senior Geologist with BHP Petroleum in London. He received his BSc from Kingston Polytechnic (London) in 1975 and a MSc from Carleton University (Canada) in 1977. After working for PetroCanada for five years, John returned to UK to join Murphy Petroleum, and then Hamilton Brothers Oil and Gas (later BHP Petroleum) in 1991. While with BHP Petroleum, he has worked on exploration and appraisal projects in the central North Sea and, more recently, in North and West Africa.
The petroleum system for the Illizi basin of Algeria is dual-sourced from basal Silurian ‘hot’ marine clastic shales and from the Devonian Frasian series. Oil and gas expelled from these source rocks are trapped primarily in Devonian F6 and Ordovician Unit-IV reservoir sands. Seals are provided by overlying interformational shales for the F6, and the Tannezuft shales for the Unit-IV sands. With regard to migration, the basin type can be summarized as a steady-state hydrostatic system where migration is predominantly lateral along carrier beds, but modified by faulting.

Basic source rock data (percentage of total organic carbon, pyrolysis, and maturity measurements) are available for the entire Paleozoic section from selected wells throughout the Illizi basin. The primary source rocks are radioactive (gamma-ray ‘hot’) shales of the Lower Silurian Tannezuft Formation. They range in thickness from 10 to more than 30 meters, are source-rich ranging from 5–12% total organic content, and are oil-prone marine Type II kerogens. A contributing secondary source are the Devonian Frasian ‘hot’ shales. These source rocks will generate and expel crude oils that are light in gravity (usually greater than 38°–40°API), low sulfur (less than 0.25%), and low viscosity (they flow and produce well with higher than normal recovery factors). The source rocks expelled significant amounts of wet gas following oil expulsion, and finally dry gas upon attaining advanced maturity.

Statistical analysis of the source rock extract and oil data suggest that the oils are primarily derived from the basal Silurian hot shales, but contain variable contributions from the Devonian source rocks. The Illizi basin oils are very similar to those in the Berkine basin and the wide maturity range within the oil reservoirs also contribute to the difficulty in distinguishing specific families of oils.

Basin modeling using the TemisPack 2-D software package evaluated the oil and gas charge in the Boukhechba Permit of the western Illizi basin. Modeling this part of the basin required geological reconstruction since there were a minimum of two periods of basin inversion. The Hercynian event removed from 800 to 2,300 meters of the Paleozoic section and a Miocene event removed 500 to 1,200 meters. By using the most likely reconstructions for the permit area, the 2-D models indicated two periods of kerogen transformation in the north, and a single period to the south. In the north, the Silurian source had some of its oil expelled during Paleozoic burial and Mesozoic burial reinitiated the kitchen and expelled its remaining hydrocarbons. Therefore, the northern part the basin is likely to be prospective for volatile oils and gas whereas to the south, where the main period of expulsion was during Mesozoic burial, the system is more prospective for oil if valid traps are present.

Petroleum Geochemistry and 2-D Modeling of the Boukhechba Permit, Illizi Basin, Algeria


The petroleum system for the Illizi basin of Algeria is dual-sourced from basal Silurian ‘hot’ marine clastic shales and

**Jim Binnie** is a geologist with BHP Petroleum. He has been involved in exploration activities in the Berkine and Illizi basins in Algeria since 1997. He obtained a BSc (hons) in Applied Geology from Strathclyde University, UK in 1991.

**Paul McIntosh** is a Senior Geologist with BHP Petroleum in London. He has a MSc in Geology from Otago University, New Zealand (1989). Since joining BHP Petroleum, Paul has been involved in a variety of roles and basins. He was initially based in Australia where he worked in the Timor Sea and North West regions and subsequently on new ventures throughout South East Asia. Paul then coordinated regional studies in the Middle East including Iran and Saudi Arabia. He has been based in London since the beginning of 1998 as part of the Algeria Asset Team.

**Michael (Mike) Jones** is the Exploration Manager for Algeria/North Africa with BHP Petroleum, London. He has a BSc (hons) in Geology and Geophysics from Manchester University (1975). After six years working in service industries in the North Sea, Nigeria, and Kuwait, he joined Hamilton Brothers Oil and Gas (later BHP Petroleum) in 1981 as a Wellsite Geologist in the North Sea. Mike was appointed Exploration Manager for the African Region in 1993, evaluating new-venture activities in West Africa and managing BHP Petroleum’s interests in North Africa, and managing BHP Petroleum’s interests in Algeria. As a result of increasing activity in Algeria, he became the dedicated Exploration Manager for the Algeria Asset in 1996.
Peter Cutts is a Senior Geologist with BHP Petroleum in London. He received his BSc in Geology from St. Andrews University, Scotland in 1980 and a MSc in Petroleum Geology from Imperial College, London in 1985. He began his professional career with Geoservices International in 1980 before joining Phillips Petroleum Co. in 1986 to work in the North Sea. He joined Hamilton Brothers Oil and Gas (later BHP Petroleum) in 1990 and has been involved in exploration and development projects in UK, Russia, and Algeria.

Terrence (Terry) Pimble is a Senior Geophysicist with BHP Petroleum in London. He received his BSc in Geology from the University of London in 1972 and a MSc in Geophysics from the University of Leeds in 1978. He worked first for Garmac Libya from 1973 to 1975 before joining Welltrade as a Petroleum Engineer in Nigeria. Between 1979 and 1982, he was a Processing Geophysicist with Compagnie Générale de Géophysique in London. In 1982, he joined BHP Petroleum in Australia working on exploration projects in Australia and South East Asia. Terry transferred to BHP Petroleum's London office in 1989 and has worked on exploration and development projects in Europe, Africa, and the Middle East. He is currently assigned to the Algerian exploration team.

Michael Jones see p. 69

Transitional Environments of the Basal Khuff Formation at Wadi Birk, Ar Rayn, and Quwayiyah, Central Saudi Arabia

John Cole, Rami Kamal, Saudi Aramco, Dhahran
Joerg Mattner, Baker Atlas, GEOScience, Bahrain
and Thomas Aigner, University of Tübingen, Germany

The basal part of the Late Permian Khuff Formation and the nature of the pre-Khuff Unconformity along the eastern edge of the Arabian Shield were studied. The basal Khuff Formation and a thin underlying sliver of the Unayzah Formation in a 590-foot well core at Wadi Birk, was compared with outcrops of equivalent strata at Quwayiyah and Ar Rayn.

In BIRK-2, the basal Khuff siliciclastics are 71 feet thick and were intersected at a depth of 500 feet. Only a six-foot interval is composed of sand. The upper part of the siliciclastic unit is composed of green and black shales 10 feet thick. The shales are underlain by 26 feet of mottled dolomudstone punctuated by five upward-thinning black shale units from a few inches to one-foot thick. Below the lowermost dolomudstone is a 2.5-foot-thick friable red claystone that overlies a 32-foot-thick lower section dominated by green and black shales. Two calcareous quartz sandstones occur within this lower shale section: a 5-foot-thick unit at 557 feet, and a one-foot interval between 564 and 565 feet. Below the lowest sand is a 5-foot-thick red silstone assigned to the Unayzah Formation, that overlies granitic basement.

In the Ar Rayn reference section, the lowermost 38-meter thick unit of the Khuff consists of a thin (inches to one-foot thick) basal conglomeratic sandstone overlain by green gysiferous shales followed by dolomite. The evidence suggests that a fairly rapid marine transgression took place over the exposed and weathered basement complex. At nearby ‘Gazelle Hill’, a more complex but gradual transition is evident. The basal unit of 25 to 50 centimeters of red, poorly sorted, feldspathic, trough cross-bedded sand and gravel overlies a regolith of highly weathered granitic basement. The sand and gravel are succeeded abruptly by 3 to 5 meters of red and green marls overlain by 3 meters of interbedded thin sands and sandy dolomites followed by 10 meters of finely laminated dolomites.

At Quwayiyah, the entire section from the basement to the uppermost part of the Khuff is well exposed in road cuts on the Riyadh-Makkah highway. Thin-section petrography of samples from the road cuts provides a rare insight into lithologies, textures, environment of deposition, biofacies, and reservoir character. A basal clastic succession of well-developed trough cross-bedded red and green sands are point-bar deposits. The exposures clearly reveal the oscillation between clastic and carbonate sedimentation. The overlying 3 to 5 meters of cross-bedded red and green feldspathic sands, gravels, and marls contain interbedded dense, dolomitic mudstones 10 centimeters thick. Large salt hoppers are present in the marls.

The basal clastics and mixed clastic and dolomitic series of the Khuff Formation indicate a gradual environmental change from fluvial to shallow-marine. Between the continental and marine end members, a transitional coastal-plain environment with hypersaline lagoons was established. Conditions oscillated between peritidal marine (laminated dolomites) and marginal marine to coastal-plain (marls and sands with salt hoppers). Continuing arid conditions led to the establishment of extensive evaporite deposits throughout the Khuff (not preserved in outcrop) whose dissolution has caused localized structural disturbances in the overlying beds.
Moving from Seismic to Layered Impedance Cube and Porosity Variation Prediction in the Natih-E Member, Oman

Jean-Philippe Coulon, Patrice Duboz and Yves Lafet
Compagnie Générale de Géophysique, Massy, France

This presentation considers the enhancement of resolution of seismic data in order to detect and delineate porosity variations in the Natih-E Member of the Natih Formation using the layered inversion tool ‘TDROV’ of Compagnie Générale de Géophysique.

The Natih-E is subdivided into eight geological layers whose porosity variation is well-defined on sonic and density logs.
The six upper layers are oil-bearing and their total thickness is 38 meters. The six layers represent an interval of 18 millisecond two-way travel time that can be extracted from the 25 milliseconds of the wavelet period (the bandwidth extends from 8 to 50 hertz).

The main characteristics of ‘TDROV’ are: (1) 3-D, post-stack, model-based inversion; (2) a Bayesian approach; and (3) Stochastic modeling implemented through the Metropolis algorithm (simulated annealing). The uncertainties estimation is by means of posterior probability sampling at the temperature of the ‘seismic noise’.

The study demonstrated that, despite band-limited seismic data, TDROV described the six Natih-E oil-bearing layers by four impedance layers within a 20-millisecond two-way travel time interval. The impedance was converted to porosity, and the results were validated at the well locations.

Jean-Philippe Coulon joined Compagnie Générale de Géophysique, Massy, in 1998. He is a Senior Geophysicist in the Reservoir Characterization Group. Jean-Philippe has a PhD and is an expert in seismic facies recognition.

Patrice Duboz is Senior Geophysicist and Head of the Reservoir Characterization Group of Compagnie Générale de Géophysique, Massy. He has a PhD. Patrice was a co-author of, Moving to a layered impedance cube: advantages of 3-D stratigraphic inversion, published in First Break, September 1998. He presented papers at EAGE, Geneva in 1997.

Yves Lafet is a Senior Research and Development Geophysicist in the Research Department of Compagnie Générale de Géophysique, Massy. He was co-author of, High-resolution impedance layering through 3-D stratigraphic inversion of post-stack seismic data, published in The Leading Edge, September 1997. He was also co-author of papers presented at the SEG Annual Meeting in Denver in 1996, and at EAGE in Geneva in 1997.

Facies Analysis of a Precambrian Carbonate Gas Reservoir: the Buah Formation, Huqf Supergroup, North-Central Oman

Andrea Cozzi, Trinity College Dublin

Late Precambrian carbonates of the Buah Formation, Huqf Supergroup, crop out extensively in the Jabal Akhdar (North Oman) and Huqf region (Central Oman). In Jabal Akhdar, a marked differentiation of the paleodepositional environments has been studied, where a shallow-water carbonate ramp was flanked by a relatively deeper basin, the slope-break following a north-northeasterly trend. The platform facies are characterized by a lower member in which fine-grained carbonates (edgewise conglomerates and mudstones) prevail, followed by a stromatolite-dominated middle member, overlain by an upper member of cross-stratified dolostones and breccias. The slope depositional setting was characterized by resedimentation processes such as turbidity flows and debris flows, punctuated by the emplacement of platform-derived and slope-derived megabreccias. Field evidence suggests that synsedimentary extensional tectonics might have controlled the differentiation of the paleodepositional environments. Moreover, the strike of the slope-break coincides with the main northeasterly tectonic trends of the incipient early Paleozoic rifting.

In the Huqf Region, sedimentary facies analysis has revealed a uniform depositional setting during Buah times, characterized by a shallow-water carbonate ramp to which the same threefold partition recognized in the Jabal Akhdar can be applied. In particular, the upper member of the Buah Formation is well developed in the Huqf region and the cross-stratified grainstones have undergone intense massive dolomitization.

The preliminary results of this study are in good agreement with the already existing well-log and seismic data. It is concluded that the lower and middle members of the shallow-water Buah carbonates acted as impermeable layers whereas the porous upper member became the gas reservoir.

Andrea Cozzi completed his undergraduate studies in Geology (cum laude) at the University of Trieste (Italy) in 1994 and then went to the USA on a nine-month postgraduate scholarship. At John Hopkins University he obtained a MA in 1997 and a PhD in Geology in 1999. Currently, he is on a two-year postdoctoral fellowship at Trinity College Dublin sponsored by Petroleum Development Oman. His research interests are carbonate sedimentology, sequence stratigraphy, and the effects of extensional tectonics in carbonate depositional settings.
Challenging Surface Conditions for the First 3-D Seismic Survey of Bahrain Island

Philippe Crémiere, Michel Combe, Compagnie Générale de Géophysique, Massy, France and Hassan Radhi, Bahrain Petroleum Company

The 3-D survey of Bahrain acquired in 1998 by Compagnie Générale de Géophysique (CGG) covers the wide depressed zone centered on Jabal Dukhan and surrounded by a low escarpment. Because of the morphology, the Bahrain Petroleum Company committed CGG to build a detailed near-surface velocity model compensating for the expected diagenetic heterogeneity of the outcropping layers that constitute the upper part of the Awali anticline. The survey utilized uphole shooting with holes terminating in the Rus and Khobar formations. The uphole data were used to build the 3-D model of the shallow low-velocity layers. As a result, seven velocity units ranging from the Quaternary sands to the base of the calcareous and dolomitic Eocene rocks were mapped, revealing significant lateral and vertical velocity changes within identified geological units such as the Khobar and Rus formations. These variations are partly attributed to the diversity of the lithologic facies, and also to the effects of re-crystallization, pore-fluid content and karstification. An immediate application of the model was the derivation of primary statics for the 3-D processing. Another was the evaluation of the impact of the near-surface on stacking velocities and depth modeling. In addition to the geophysical implementations, the model will provide a database for further geotechnical works in the surveyed area.

Philippe Crémiere is 3-D Project Leader of the Land Processing Group of Compagnie Générale de Géophysique (CGG) in Massy, France. He has a PhD in Earth Sciences from the University of Bordeaux. He joined CGG in 1975 and was a Senior Seismologist and Party Chief on field surveys in Europe, Africa, and the Middle East. Since 1984, he has been involved in 2-D and 3-D land/ marine seismic processing in CGG’s Massy and Middle East Processing Centres. He was promoted to Project Leader in 1986.

Michel Combe has been the Land Processing Group Manager of Compagnie Générale de Géophysique (CGG) in Massy, France since 1997. He has a BSc in Physics from the University of Toulouse. He joined CGG in 1981 and was a Processing Geophysicist (later Senior) in France, North Africa.

South America, and India until 1992. From 1992 to 1994, he was Project Leader of 2-D and 3-D Processing at Massy and, from 1994 to 1997, Processing Manager in Lagos and Moscow.

Hassan Radhi is Head Exploration Geologist of the Bahrain Petroleum Company (BAPCO). He graduated with a BSc in Geology/Geophysics from the University of Baghdad in 1976 and joined BAPCO as a Development Geologist. He was a Geophysicist in BAPCO’s Exploration Section from 1981 to 1989. Hassan has participated in many exploration assignments with major service and oil companies in Europe and the USA.

Impact of Volume Interpretation and Calibration Environment (VOICE) on Seismic Interpretation for Reservoir Characterization and Exploration

Dick Dalley, Christian Höcker, Hugo Poelen and Peter van Toorn Shell, The Netherlands

3-D seismic surveys are increasingly used for oil and gas exploration as well as for delineation and characterization of hydrocarbon reservoirs in the Middle East and the world as a whole. The acquisition and processing technology has undergone considerable evolutionary changes through the years. The 3-D seismic volumes, which result from these efforts, are subsequently loaded onto workstations for detailed interpretation by the operating units. With the results, reservoir models are being built and updated by multi-disciplinary teams in combination with results from drilling and production. In Shell-operated companies, this interpretation workflow has been accelerated considerably by application of the Volume Interpretation and Calibration Environment (VOICE) technology alongside traditional methods. VOICE was developed and refined in Shell’s Laboratory for Research and Technical Services in Rijswijk. With VOICE, volume processing is first applied to improve the quality of the 3-D seismic volume or highlight special features. Secondly, the resulting 3-D volumes are scanned and analysed. These Volume Interpretation techniques are used to quickly probe key features of the data. The results are usually produced faster and in more detail than with conventional interpretation techniques. For example, it is not necessary to produce a laborious subsurface model from horizons and faults by repetitive analysis of 2-D sections and time slices.

VOICE has helped Shell to considerably enhance its evaluation processes. It has had a significant impact on the
speed of reservoir delineation and the assessment of reservoir compartmentalization. In addition, drilling operations have benefited from improved definition of well targets and drilling hazards. Examples of these techniques will be presented and their impact discussed.

Richard (Dick) Dalley has a BSc in Physics and Mathematics from St. Andrews University, Scotland (1967). He joined Seismograph Services Ltd and served as Party Chief on seismic acquisition teams in Mozambique for ELF and in Oman/Dhofar for Shell. In 1977 he joined Shell, first as a Seismic Interpreter and later as Head of In-House Processing in NAM. He transferred to Shell Expro in 1984 to work on field development in the Northern North Sea before becoming Senior Geophysicist in Aberdeen. From 1990 to 1999, Dick worked at Shell's Research and Technical Services Section in The Netherlands on the development of Computer-Aided Seismic Interpretation and, in particular, on the use of 3-D image processing and image analysis for the interpretation of 3-D seismic datasets. In 1999, he left Shell to form his own company, 3-D Computer Vision Ltd, based in Dunkeld, Scotland. Dick is a member of SEG and EAGE. In 1989, he received (with co-authors Gevers et al), the Hagedoorn Award of EAGE for work on dip and azimuth displays of seismic horizons.

Christian Höcker is a Technical Process Advisor in Shell's Integrated Acreage, Basin and Field Evaluation Services. He has a Dipl. Geol. (MSc Geology) from Cologne University, Germany. He started his professional career in 1984 when he joined Shell as a Research Sedimentologist. He has worked in reservoir geology, dipmeter processing, and production geology. Christian's main interests are in seismic interpretation, both R&D and operating environments. He has been the originator of several of Shell's proprietary interpretation tools.

Hugo Poelen graduated in 1973 from the University of Utrecht, The Netherlands, where he studied Geophysics, Geology, and Computer Sciences. He joined Shell in 1974 as a Geophysicist. Hugo was an Interpreter in exploration and production teams in Petroleum Development Oman (5 years), NAM (8 years) and MAERSK (2 years). Since 1990 he has contributed to research and application of volume interpretation technology in Rijswijk and Aberdeen. Hugo is a member of EAGE and PESGE.

Peter van Toorn has a PhD in Theoretical Physics (1979) from Groningen University, The Netherlands. After postdoctoral work in Electron Microscopy and Astronomy at London University, he joined Shell's Geology Department in 1981 and worked on the analysis of computer-aided seismic facies. After some years developing interactive seismic interpretation research, he became a Geophysicist in seismic interpretation research. Peter is interested in volume interpretation techniques, pattern recognition, seismic filtering, and related software development.

Brittle Deformation Features and Paleostress in the Palymride Fold Belt of Syria

Abdul Nasser Darkal, Damascus University, Samir Bouaziz, École Nationale D’Ingenieurs de Sfax, Tunisia, Eric Barrier, University Marie Curie, Paris, Mikhail Mouty and Khaled Al Maleh, Damascus University

The Palmyride fold belt is a major structure in the northern part of the Arabian Plate. The understanding of the Palmyride tectonics is important for the geodynamic reconstruction in the region. Paleostress analysis based on the study of the fault data sets and other brittle deformation features, is a powerful tool to reconstruct the tectonic evolution of the sedimentary basins.

The work presented has been undertaken in the framework of the international Peri-Tethys program. The tectonic analysis was carried out at 93 sites in the southern part of the Palmyride fold belt. Brittle tectonic analysis consisted of the analysis of fault-slip data sets and the study of joint systems.

From several tens to more than one-hundred measurements were made at each site. The sites were vertically distributed over the formations that crop out in the southern Palmyride region, and range in age from Late Triassic to Neogene. Computer analysis of the data was by the Angelier method. It permitted reconstruction of the axes (1, 2 and 3) of the stress that affected the southern Palmyride region, and are registered in the outcropping formations. A total of 133 paleostress tensors have been compared. The main directions of compression are NW-SE, N-S, NNE-SSW, ENE-WSW, and NNW-SSE. Among them are pre-folding and post-folding stresses comparable with the main folding phase (Neogene-Quaternary) in the Palmyrides. This is related to the complex structural development of the region. The distribution of the extensional stresses are somewhat different but some synsedimentational normal faults provide indications of the chronology of various stress fields.
Our aim is to reconstruct a geodynamic model depicting the deformation of the Palmyride basin and its regional relationships to other major structures in the Middle East. The model will be important in the evaluation of hydrocarbon provinces in the region.

Abdul Nasser Darkal is an Assistant Professor in the Geology Department of Damascus University. He has a BSc in Applied Geology from Damascus University, and a Promotion A from EMA, University Greifswald, Germany. Abdul Nasser’s current interests are the paleostress study of the Palmyride fold belt and the active tectonics of western Syria.

Samir Bouaziz, Eric Barrier biographies not available; Mikhail Mouty, Khaled Al-Maleh see p. 31

Optimizing Arab-D Reservoir Development by Integration of 3-D Seismic Data in a Common Earth Model

Shiv Dasgupta, Ming-Ren Hong, Jung Kim, Harold Triebwasser, Sulaiman Al-Bassam, Charles Wagner and Paul Lawrence, Saudi Aramco, Dhahran

The Upper Jurassic Arab-D carbonate reservoir in the Ghawar field of Saudi Arabia is cyclical and heterogeneous. The reservoir consists of layers of evaporite and limestone punctuated by local areas of dolomite diagenetically derived from limestone. In addition, the Arab-D is intersected by near-vertical faults and fractures that have a profound influence on fluid flow. Detailed and accurate 3-D reservoir characterization plays a vital role in developing and managing the reservoir and optimizing oil production. The goal of reservoir characterization is to construct a model of inter-well heterogeneity by the integration and analysis of seismic data, core measurements, petrophysical data, and dynamic data (such as production, pressure or water breakthrough information). A Common (or Shared) Earth Model generated from this multi-disciplinary data in GOCAD (a 3-D earth-modeling package), is used in planning the trajectory of horizontal and deviated wells. The model is visualized and manipulated in 3-D to provide a better understanding of reservoir heterogeneities.

Seismic data provide the structural and stratigraphic framework for the reservoir. Acoustic impedance from inverse modeling of 3-D seismic data provides the porosity and reservoir-quality distribution between the well control points. Petrophysical and fluid properties are determined and incorporated into the Common Earth Model together with fault and fracture swarms interpreted from 3-D seismic coherency attributes. Understanding the fracture and fault distribution and their orientation is critical for planning and completion of the horizontal wells. Ideally, the wells should intersect fractures in low permeability layers but the fractures should be avoided where they form conduits for premature break-through of water. Horizontal and deviated wells being drilled in the Arab-D reservoir are designed to collect bypassed or trapped oil from zones underlain by water and to produce from selected tight layers in a multi-layer sequence.

Shiv Dasgupta is a Geophysical Consultant with Saudi Aramco. He worked for Continental Oil Company between 1974 and 1976; Seismograph Service Corporation, Tulsa (1976–77); and Amoco Production Company in Tulsa and Houston (1977–82) prior to joining Saudi Aramco. He has a BSc in Geophysical Engineering from the Indian School of Mines (1971), a MSc in Geophysics from St. Louis University (1973), and a MBA from Southern Illinois University (1975). Shiv completed graduate studies in Petroleum Engineering from the University of Houston in 1981. He is a member of AAPG, SEG, EAGE, SPE, and AGU. His professional interests include multi-disciplinary reservoir characterization, the application of new technology for improved subsurface definition, computer applications, and database interconnectivity.

Ming-Ren Hong is a Geophysical Specialist with Saudi Aramco. Before joining Saudi Aramco he was a Senior Research Geophysicist from 1984 to 1991 with ARCO Oil and Gas Company. He worked at the Center for Lithospheric Studies, University of Texas at Dallas as a Research Engineer from 1982 to 1984. Ming has a BSc in Atmospheric Physics (1973) and a MSc in Geophysics (1977) from the National Central University, Taiwan. He received his PhD in Geophysics from the University of Texas at Dallas in 1982. Ming is a member of SEG and SPE. His professional interests include seismic modeling and inversion, reservoir characterization, and integrated interpretation.

Jung Kim see p. 25

Harold Triebwasser joined Saudi Aramco in 1988 as a Seismic Processing Geophysicist. He has worked for the past 10 years on stratigraphic analysis and modeling in the Geophysical Technology Division. Harold has 25 years experience as a geophysicist in seismic acquisition, processing, and analysis. He has a BS in Physics and Mathematics and is a member of SEG, EAGE, and SPWLA.
Sulaiman Al-Bassam joined Saudi Aramco in 1984. He is a Geophysicist in the Geophysical Technology Division. He holds a BSc in Mathematical Sciences from King Fahd University of Petroleum and Minerals, Dhahran and a MSc in Geophysics from the University of Southern California. Sulaiman's professional experience and interests include seismic data processing, stratigraphic modeling/inversion, and geostatistics. He is a member of EAGE and DGS.

Charles Wagner is a Senior Petroleum Engineering Systems Analyst with Saudi Aramco. Before joining Saudi Aramco in 1992, he spent 12 years (8 on loan to Saudi Aramco) with Chevron as a Mining Technician, Well Log Analyst, and Programming Analyst. Charles has a BA in Geology from the University of Tennessee at Knoxville.

Paul Lawrence see p. 130

Reduced Drilling Risk by Accurate Characterization of the Khuff-C Reservoir in the Ghawar Field

Shiv Dasgupta, Ming-Ren Hong and Mohammed Al-Nasser, Saudi Aramco, Dhahran

The Khuff-C reservoir in the Ghawar field is a stratified sequence of cyclic carbonate-evaporite deposits within the Permian Khuff Formation. The reservoir consists of interbedded, tight and porous limestone and dolomite sandwiched between thicker anhydrite-rich intervals. Syndepositional stratiform diagenetic changes influenced by the depositional environment were responsible for Khuff-C reservoir porosity. In addition, the reservoir fabric appears to be punctuated with islands of tight or low porosity of various sizes distributed randomly. Inverse modeling of the 3-D seismic data has identified these localized high acoustic impedance or tight porosity areas in various parts of the field.

Most wells drilled in the Khuff-C are prolific producers of gas but some produce little or no gas. As the depth of the reservoir in most parts of the Ghawar field is in excess of 12,000 feet, wells penetrating poor reservoir-quality Khuff-C would have to be abandoned at a cost of many millions of dollars. The challenge is to predict drilling locations having good reservoir quality. Recently, 3-D seismic attributes calibrated with existing well data have been successful in predicting locations that will drain the reservoir more effectively. After disappointing results in three recent development wells in the Uthmaniyah sector of Ghawar, a 3-D seismic survey was conducted in the area. The interpretation of the data, specially processed for the purpose, produced an accurate image of layering in the reservoir. Eight optimum drilling locations were selected based on the interpretation of 3-D seismic and six of these were drilled. All of these wells intersected productive zones in the Khuff-C gas reservoir.

Shiv Dasgupta, Ming-Ren Hong see p. 77

Mohammed Al-Nasser is Area Supervisor with Saudi Aramco with primary responsibility for the North Ghawar gas development. He has a BS in Petroleum Engineering from Louisiana State University (1984). He began his professional career with Saudi Aramco on various engineering assignments working primarily as a Reservoir Management Engineer on offshore clastic reservoirs. Since 1995, he has been in the Gas Reservoir Management Division.

Sedimentological Analysis and Permeability Prediction Within an Heterogeneous Carbonate Reservoir Using Borehole Images

Jean-Michel Dawans, Abu Dhabi Company for Onshore Oil Operations, Graham Aplin, Ajay Sapru and Mark Lawrence, Baker Atlas GEOScience, Aberdeen

Carbonate reservoirs often display considerable heterogeneity ranging from the reservoir to the micro-scale, which can result in significant variations in permeability and hence producibility. Porosities within these heterogeneous reservoirs can be fairly constant, but permeabilities may vary by several orders of magnitude for a given porosity value, reflecting changes in the character of the pore system.

An integrated core and borehole image study was undertaken on the Lower Cretaceous Thamama Group from a field in the United Arab Emirates, in order to predict lithofacies and permeability distribution within heterogeneous reservoirs. The borehole images and open-hole log data were calibrated using core and an image-log facies scheme was established. These image facies were used to predict lithofacies distribution and porosity-permeability characteristics in uncored wells. The image facies displayed an overall coarsening-upward trend, reflecting deposition within a shallowing/shoaling-upward, storm-influenced carbonate shelf succession. Analysis of image-facies stacking patterns also allowed the identification of smaller-scale
Formation Evaluation: Carbonate-Stringer Petrophysics

Mark Lawrence is a Sedimentologist with Baker Atlas GEOScience where he has worked on core data and borehole image data interpretation and integration for the past five years. He specializes in sedimentological, ichnofabric, and environmental analysis of fluvio-deltaic to shallow-marine clastic sediments and carbonates. Mark has a BSc and M.Sc from the University of Waikato (New Zealand) and a PhD from the University of Canterbury (New Zealand). He is a member of the New Zealand Institute of Chemistry.

Intra-salt carbonate stringers form an important exploration play in the southern Oman salt basins. The stringer reservoir sections consist of dolomite and limestone mixtures with typical anhydrite streaks at the top and bottom, encased completely in salt. During drilling operations, mudweights can be extremely high (>21 kilopascal/meter) due to the overpressured nature of the formations. Porosities tend to be mediocre at about 5 to 10% bulk volume, oil saturations can be very high (>85 % pore volume), and permeability is generally quite low (1–50 millidarcies). All these conditions make successful data acquisition and correct interpretation of the static reservoir properties from wireline log data quite challenging. The currently adopted evaluation method is based on combining Nuclear Magnetic Resonance (NMR) porosities with the resistivity, density, neutron, and shear- and compressional sonic curves in an integrated statistical evaluation. This technique results in reliable porosity, saturations, and mineral fraction estimates. The better porosity zones, as observed by the NMR, can be linked to features on the image logs acquired in these wells. Recent developments in the wireline logging—for example, new generation geochemical tools—have been tested for their possible added value.

Several stringer wells have been cored. In the case of one well, the entire reservoir section was included. Invariably, there is evidence for secondary porosity at different length scales, of organic material, and of authigenic salt playing a role in reduction of the original pore space. Core from the recently drilled wells is undergoing an extensive special analysis program of NMR, resistivity index measurements, capillary pressure curve analysis, and geochemical analysis, aimed at quantifying these effects. These results form the basis for the present microscopic petrophysical model behind the carbonate stringers and are used to reduce the uncertainty in the petrophysical evaluation.
This presentation will specifically address the operational experiences of running advanced logging tools under these difficult conditions. It will deal with the methods used in the petrophysical evaluation, and the benefits of the integration of core data with openhole log data, which alone has already led to significant increases in reserves bookings.

André de Kuijper has a PhD in Theoretical Physics from the University of Amsterdam (1991). On graduating, he joined Shell Research and worked on the development of new saturation models and the integration of core analyses in log interpretation. Since 1997, he has worked for Petroleum Development Oman as a Petrophysicist in Frontier Exploration and as a member of the Carbonate Stringers Team. In addition to dealing with newly drilled wells and providing support to ongoing studies, André acts as a focal point for the Carbonate Stringer technology plan.

To aid the pilot design, a detailed 3-D numerical reservoir model consisting of porosity, oil saturation and permeability data was constructed. Given the small number of wells, the study constituted a significant challenge for a geostatistical approach. To help guide the mapping of porosity, a 3-D seismic volume, acquired in 1996, was inverted from amplitude to pseudo acoustic impedance using an L1-norm ‘sparse-spike’ technique. A detailed petro-acoustic calibration of both well-log impedance and seismic pseudo impedance to porosity enabled the significant inverse correlation between impedance and porosity to be quantified. This established the basis for using the inverted seismic as a mapping constraint. Kriged (well data only) and co-kriged (seismically constrained) estimates of porosity were generated and tested via cross-validation. To generate a corresponding 3-D estimate of oil saturation, each model was input to a saturation-height function consisting of several porosity classes. Subsequent volumetric analyses derived from the kriged and co-kriged models allowed the impact of the seismic constraint to be appraised. A 3-D model of permeability was generated using a regression relationship between permeability and porosity.

Both the well-derived and seismic-constrained static models will be upscaled for dynamic simulation modeling. After history matching the past production performance of the reservoir, water injection scenarios will be tested. If these give greater confidence in the rewards of the conceptual development plan, pilot water injection will be fast-tracked.

3-D Seismic Characterization of a Matrix Carbonate Oil Reservoir, Natih-E Member, Burhaan Main Field, North Oman

Lennert den Boer, Western Geophysical, UK
Pascal Schoepfer, Petroleum Development Oman, Muscat.
J. Kim Hughes, Western Geophysical, UK,
Patrick Denby, Petroleum Development Oman, Muscat.
Philippe Doyen, Western Geophysical, UK

The Burhaan Main field consists of a fault dip-closure, potentially fractured at the crest, covering an area of about 25 square kilometers. The reservoir, consisting of layered marine-shelf limestones of the Cenomanian Natih-E Member of the Natih Formation, is affected by both vertical and lateral variations in rock quality, exhibiting metric alternation of permeable versus tight (cemented or shaly) intervals. The tight zones act as potential flow baffles between adjacent productive layers.

The five vertical wells and two side-tracks drilled to date have typically suffered from rapid pressure depletion, possibly contributing to development of a secondary gas cap. Although the pressure drop was initially attributed to reservoir compartmentalization, a more likely cause is the lack of natural drive energy. Although the field is currently closed-in, a water injection pilot is planned to test the potential for increasing recovery. A significant uncertainty thus concerns the possible presence of open fractures and highly permeable thin layers, which could act as thief zones to bypass producers.

The five vertical wells and two side-tracks drilled to date have typically suffered from rapid pressure depletion, possibly contributing to development of a secondary gas cap. Although the pressure drop was initially attributed to reservoir compartmentalization, a more likely cause is the lack of natural drive energy. Although the field is currently closed-in, a water injection pilot is planned to test the potential for increasing recovery. A significant uncertainty thus concerns the possible presence of open fractures and highly permeable thin layers, which could act as thief zones to bypass producers.

Patrick Denby is a Production Seismologist in Petroleum Exploration and Appraisal in the UK, having 10 years experience in the Shell Group companies in the UK and Oman. In London, he worked for Shell as an Exploration and Appraisal Geophysicist, focusing on the evaluation of the Central Graben area of the North Sea. As a Production Seismologist in Petroleum Exploration and Appraisal, Patrick has been working on a range of projects in the UK and Oman.
Development Oman, he has been involved in 4-D seismic evaluation of a carbonate reservoir in North Oman. He is now Senior Production Seismologist, in charge of coordinating production seismology and Near Field Exploration efforts in the Central Oman area. Pascal has an MSc in Geology and Geophysics (1985) and a PhD in Geology (1989) both from the University of Fribourg, Switzerland. He is a member of AAPG and the Swiss Geological Society.

J. Kim Hughes is a Senior Reservoir Geophysicist with Western Geophysical. He received a BSc (hons) in Geophysics from the University of Witwatersrand, South Africa in 1979. He first worked in mining exploration specializing in seismic reflection methods in hard-rock environments. In 1992, he joined Western Geophysical in London as Software Support Geoscientist before moving on to special seismic processing projects. Since 1997, Kim has been involved with time-lapse seismic analysis and reservoir characterization projects. He is a member of SEG, EAGE and SPE and has authored and co-authored papers presented at SEG and SPE meetings.

Patrick Denby was a Wireline Logging Engineer for Schlumberger in Africa for three years prior taking a MSc in Petroleum Engineering at Imperial College, London in 1987. Since then he has worked as a Shell Reservoir Engineer in The Netherlands, Brunei, and Oman.

Philippe Doyen has a Masters in Mining Engineering from the University of Louvain, Belgium (1982), and a MS (1984) and PhD (1987) both in Geophysics from Stanford University. Upon graduation, he joined Western Geophysical in Houston, as a Research Geophysicist. In December 1989, Philippe transferred to Western Geophysical in London where he is managing the Reservoir Characterization Research and Development Department. His activities include research in statistical reservoir description from geophysical data, the development of 3-D geostatistical reservoir modeling software and integrated reservoir studies.

Quantifying Uncertainty in Depth Conversions and Volumetrics

Jacques Deraisme, Geovariances, Avon, France

Advanced geostatistical techniques can improve the accuracy of depth conversions and resulting volumetric evaluation and can also quantify the associated uncertainties. They have been applied to North African and North Sea fields. The depth-conversion techniques are based on customized kriging methods that make optimal use of the available data whether it is just a few vertical wells and some 2-D seismic or a complete 3-D seismic survey with wells that are either vertical or deviated. The techniques offer powerful solutions that handle the different relationships between the true vertical depth at the wells (either deviated or vertical), the seismic time picks, and the seismic velocities (Vstack, Vint, etc.). The depth conversion respects the characteristic correlation of the different layers, whether it is between the seismic two-way travel time and the thickness or with the Vint. Having chosen the most suitable depth model, quantifying the uncertainty associated with it can be done with one of the conditional simulations. These provide optimum volume evaluations (gross rock volume, hydrocarbon pore volume, and stock-tank oil initially in place) and associated uncertainties by providing the complete range of scenarios from the most pessimistic to the most optimistic.

The innovative aspect of these geostatistical techniques relies on adapting them to real practical problems such as handling deviated wells and complex fault systems, and quantifying uncertainty when optimally integrating seismic and well data. Case studies have shown extremely high accuracy in depth mapping. Less than 2 meters separated the depth map from the real depth as found in wells drilled to more than 3,000 meters after the study. Risk maps associated with the depth maps helped in positioning new wells and in handling uncertainties associated with the gross rock volume of the reservoir that is so critical in project valuation. These techniques can be applied to any reservoir where seismic time-horizon picks (stacking velocities) and well data are available.

Jacques Deraisme is Technical Manager of Geovariances in charge of the Consulting and Training Department. After graduating as a Mining Engineer from the École des Mines de Nancy in 1969 he worked as a Research Engineer then Senior Researcher at the Centre de Géostatistique de l’École des Mines de Paris from where he received his
This case study of the Ghadames Basin combines outcrop and sub-surface data, and reviews the regional tectonic and stratigraphic history and the regional depositional facies. The basin is an east-west sag extending from northwestern Libya through southern Tunisia. Its extension in Algeria is the Illizi Basin. Structurally, it is bounded to the north by the present-day Atlas flexure represented by the Jeffara fault zone that was several times a mobile belt. To the east, it is bounded by faults trending N140°. A composite stratigraphic section ranging in age from Precambrian to Late Cretaceous is present in the Ghadames Basin and includes Tertiary sediments localized in a downwarped sub-basin in the north. However, the lithostratigraphic column shows several unconformities, truncations, erosions, and transgressions in relationship to sea-level changes and tectonic movements of the Pan-African, Caledonian, Hercynian, and Alpine orogenies.

The Paleozoic rocks are more than 3,500 meters thick and are dominated by marine to fluvial siliciclastics. The late Paleozoic rocks were strongly eroded or not deposited. They are marine siliciclastics and carbonates with local occurrences of Permain reefs. The Mesozoic rocks are over 3,000 meters thick and consist of marine to fluvial sandstones, shales, shallow-marine carbonates, and evaporites organized in several mega-sequences.

The main structural framework of the region is marked by the uplift of mega-structures, such as the Telemzane Bou Nemcha Arch in Tunisia and Algeria, and the Gargaf High in Libya uplifted during late Paleozoic and early Mesozoic times. These major tectonic features created several sub-basins and controlled the sedimentology patterns and the distribution of petroleum resources. Alpine tectonics were predominately compressive during the Miocene. They formed the present-day structures and caused the emergence of the region since Eocene times. However, as the effect of the Alpine compression decreases from north to south, this has considerably influenced the extent and the volume of the structures.

The source rocks are represented mainly by Silurian and Devonian ‘hot’ shales and locally by Jurassic limestones. In general, the source rocks reached the oil window by Cretaceous times and yielded their major hydrocarbons during the Miocene. Several proven sandy reservoirs occur within Paleozoic and Triassic rocks. Limestone and dolomite reservoirs are present within Permian and Jurassic rocks and are localized in downwarped basins. Oil production in the Ghadames Basin started in the 1960s. Recent exploration has led to the discovery of huge amounts of oil and gas and confirmed the importance of the basin. Studies suggest that a large amount of generated hydrocarbon is still to be discovered.

Mohamed Dridi is a Senior Geologist with Entreprise Tunisienne d’Activité Pétrolière (ETAP). He has a MSc in Geology from the University of Franche Comté (France) and a Diploma of Petroleum Geology from the Algerian Institute of Petroleum. He has been successively Head of Regional Studies, Head of Basin Studies, and Deputy Manager of Exploration Studies of ETAP since 1992.

Mohamed Dridi
Entreprise Tunisienne d’Activité Pétrolière, Tunis

Strata Geometries and Patterns Within Cretaceous Platform Carbonates: the Natih Formation of Oman

Henk Droste and Mia Van Steenwinkel
Petroleum Development Oman, Muscat

The interiors of the large Mesozoic carbonate platforms of the Middle East are often visualized as undifferentiated, extensive shallow-water areas, where carbonates accumulated by aggradation. However, seismic studies and well-log correlations of the Middle Cretaceous Natih Formation of Oman show a complex internal architecture rather than a ‘layer-cake’ configuration for these carbonates.

The limestones of the Alban to Cenomanian Natih Formation form the upper part of an extensive carbonate platform that covered Oman during the Cretaceous. The formation consists of a number of repetitive sedimentary cycles of several tens to 150 meters thick. Each cycle contains a thin shale at the base, followed by a thick, deepening and shallowing-upward carbonate unit. The shale beds are clastic wedges derived from the south and pinch out toward the northern carbonate-dominated domain. They are key horizons that can easily be followed over hundreds of kilometers and are used to divide the formation into seven members, lettered ‘A’ to ‘G’ downward. Within the Natih-E, which is one of the thicker members, seismic data and detailed well-log correlations show the presence of clinoform complexes and intra-platform basins. Mapping of the clinoform belts and directions of progradation show that this extensive carbonate member consists of several separate platforms from a few thousand square kilometers to 10,000 square kilometers in area, that merged by lateral accretion. The platforms started to grow in areas with relatively low subsidence rates, such as basement highs and...
salt domes, following a regional rise in sea level. Merging of the platforms was not complete and in the intervening areas relict intra-platform basins developed (several hundred to 2,000 square kilometers in area) that were later filled with shales.

The clinoforms and the differentiated nature of the platform carbonates are not restricted to the Natih-E Member as clinoforms have also been observed in the Natih-F. However, as the other cycles are much thinner than the Natih-E Member, the internal geometries are usually not resolved by seismic. Similar geometries have also been recognized on seismic in other platform carbonates such as the Lower Cretaceous Shu’aiba and Kharai formations, as well as the Upper Permian Khuff Formation.

Recognition of these stratal geometries within the historically called ‘layer-cake’ carbonates has three important implications for hydrocarbon prospectivity and development in these sequences. (1) It explains ‘random’ variations in reservoir properties observed in the Shu’aiba and Khuff formations. (2) It has led to the definition of possible combined stratigraphic traps in the Natih-E along the edge of intra-platform basins, where the shale-fill acts as a lateral seal. Mean recoverable success volumes of such traps are estimated to be of the order of 2 to 3 million cubic meters. (3) The recognition of clinoforms that dip into the aquifer and act as a conduit for water in the Shu’aiba of the Al Huwaisah field helped to optimize the field development and reduce the water-cut.

Mia Van Steenwinkel is a Senior Geologist/Seismic Interpreter in the Frontier Exploration Asset of Petroleum Development Oman (PDO). She joined PDO in 1992, and has worked as a Production/Operations Geologist on the Natih, Fahud and Al Huwaisah carbonate fields. Before joining PDO, she worked as a Carbonate Geologist with Shell Research in The Netherlands. Mia has a PhD from the University of Leuven, Belgium.

Sintgenetic Textural Evolution of Modern Sabkha Stromatolites in Kuwait

Michael Duane, Kuwait University

Analogies between modern sediment-binding cyanobacterial mats and ancient stromatolites have been described, but the debate continues as to the exact mechanisms that lead to the building of both ancient and modern sabkha stromatolites. In sabkhas in Kuwait in the northern Arabian Gulf, two morphologically different stromatolite communities build a carbonate bioherm by alternating their roles in the construction process. The ejection of fingerlike microcolumns of aragonite by Type 1 communities (‘cinder type’) occurs in irregular weathering fractures, and growth is arrested only when exposed by spalling of the bioherm during erosion. Subsequently, an invasion of the Type 2 community (‘polygonal type’), not only allows vertical and horizontal build-up in the intertidal zone, but also provides opportunities for utilizing the free carbonate scaffolding erected previously. This process allows forbiorolothermal healing during severe erosion created by winter storms and may help explain the tenacity of stromatolites in the sabkha environment. As some abiotic cemented carbonates are virtually indistinguishable from biotic carbonates even in lithified Holocene reefs, these observations on stromatolite architecture have important implications for both modern and Precambrian sabkha models of carbonate growth.

Michael Duane received his PhD in 1981 from Trinity College Dublin. He worked at the University of Natal, Durban, South Africa from 1990 to 1997 and as a Senior Research Officer at the University of Witwatersrand, Johannesburg. Michael is now an Associate Professor in the Department of Earth and Environmental Sciences, Kuwait University.

Integrating Sequence Stratigraphy and Multiple 3-D Geostatistical Realizations in Constructing a Reservoir Model of the ‘Second Eocene’ in the Wafra Field, Partitioned Neutral Zone Kuwait-Saudi Arabia

Dennis Dull and Theodore Doerr, Texaco, Houston

The integration of 3-D geostatistical computer modeling with sequence stratigraphic principles has significantly enhanced the ability to accurately build a reservoir model.
of the ‘Second Eocene’ reservoir. The Paleocene ‘Second Eocene’ is one of several prolific reservoirs in the giant Wafra oil field of the Partitioned Neutral Zone between Kuwait and Saudi Arabia. It has several billion barrels of oil-in-place and has produced over 320 million barrels of oil from 185 wells since 1958. It is a stacked series of complex ramp, dolomite reservoir units. Four High Frequency Sequences are used as the framework in the layering of the reservoir and are interpreted as having formed in response to eustatic sea-level changes.

The ‘Second Eocene’ reservoir is a complex heterogeneous carbonate reservoir with an intricate porosity-permeability/facies relationship. The development of the reservoir facies, primarily from subtidal peloidal dolopackstones to dolograinsstones, was influenced by the Wafra platform that was a positive structural feature during the time of deposition. A geostatistical approach captured the observed heterogeneity of the ‘Second Eocene’ in a reservoir simulator using 3-D geostatistical software. Multiple, equally probable 3-D geostatistical distributions of porosity, permeability, water saturation, and lithofacies were created. The P10, P50, P90, mean and variance 3-D statistical models of the reservoir properties were generated to evaluate the uncertainty of the data, the geologic model, and upscaling of the detailed geologic model for reservoir simulation. The large detailed 3-D geostatistical models of the ‘Second Eocene’ covering 45.8 square miles (119 square kilometers), 157 layers and 1.8 million total grid cells, were upscapped vertically using multiple realizations of permeability to select the optimum layer combination. An equivalent permeability based on fluid flux was the basis for vertically coarsening the permeability grids in order to reduce the number of layers. The assumption is that the upscaled permeability of the coarsened grid should, with the same pressure gradient, result in the same fluid flux observed in the fine grid. The goal of the calculation is to preserve the local 3-D flow characteristics of the detailed geologic model.

**Dennis Dull** is a Senior Geoscience Specialist with Texaco’s Upstream Technology Department as a member of the Partitioned Neutral Zone Team in Houston. He has worked with Texaco since 1982. Dennis holds a BSc in Education from California State College, Pennsylvania, and a MSc in Geology from Millersville State College, Pennsylvania. His work has primarily been the characterizing and 3-D geostatistical modeling of carbonate reservoirs for Enhanced Oil Recovery. He contributed to the 1995 SEPM Core Workshop on Hydrocarbon Reservoir Characterization with the paper, Reservoir Characterization and the Application of Geostatistics to the Three-Dimensional Modeling of a Shallow Ramp Carbonate, Mabee San Andres Field, Andrews and Martin Counties, Texas.

**Theodore Doerr** is a Research Consultant with Texaco’s Upstream Technology Department in Houston. He is currently conducting engineering studies of reservoirs in the Middle East to assist in the development of operating plans and enhanced recovery schemes for improved reservoir management. Theodore obtained his BSc, MSc and PhD in Petroleum Engineering from the University of Texas at Austin. He joined Getty Oil Company in 1971. Theodore has contributed to the development of large gas-condensate fields, developed hydrocarbon miscible flood and operating plans for carbonate-reef reservoirs, reviewed attic-oil recovery projects, and performed well-log and pressure build-up analysis on various Gulf Coast and Middle Eastern reservoirs. He has extensive experience with Black Oil, Gas, and Enhanced Oil Recovery simulation models.

**Optimization of Horizontal Well Performance/Placement by Forward Modeling of Geological and Petrophysical Data**


Placing a horizontal well successfully within target reservoir zones of small thickness is a great challenge, particularly in areas that are structurally disturbed. The level of difficulty increases when the well unexpectedly intersects a sub-seismic fault of unknown attributes. In such cases, it becomes very difficult to determine which way to steer the well while it is being drilled, so as to re-enter the zone of interest. Similarly, when the well has been drilled, it is not always easy to know which part of the reservoir, or non-reservoir zone, the well has entered into after intersecting the fault.

Conventional techniques do not always help in determining the exact placement of the well. Moreover, integration of borehole images with logging-while-drilling (LWD) or TLC logs may only help in those cases where enough true-vertical-depth sections are available for log correlation. To circumvent such problems, a new technique has been introduced whereby a structural cross-section along the well trajectory is constructed through the integration of openhole logs (LWD or TLC) with borehole electrical images or, sometimes, with LWD formation-bulk-density and photo-electric-factor images. The structural model is validated by the close match between the actual LWD or TLC logs and the modeled log output by means of the forward-modeling
technique for a specific arrangement of strata in a particular structural environment.

In this presentation, we discuss a case history from onshore field ‘A’ in Abu Dhabi in order to demonstrate the technique. It helped us to know the exact positions of the lower and upper laterals (about 75 feet apart vertically and drifted in the same direction) in the faulted reservoir and also assisted in steering the upper lateral correctly when it had entered a non-reservoir zone after intersecting a normal fault.

The technique has tremendous applications in planning the drilling of horizontal holes and for the assessment of the drilled holes. The advantage of this technique is further highlighted when the horizontal holes are to be used as injectors.

Mohamed Saleh Efnik is Lead Petrologist in Abu Dhabi Company for Onshore Oil Operations (ADCO) in the study group concentrating on horizontal hole interpretation. He has a BSc from Bright Star University of Technology, Brega, Libya and a MSc in Computer Applications and Well Logging from the University of Glasgow. Mohamed worked as a Wellsite Geologist and Petrophysicist for Sirte Oil Company in Libya from 1985 to 1994. He the joined Schlumberger-GeoQuest in Libya and was involved in various geological and petrophysical projects. Has been working for ADCO since 1998.

Faisal Mohamed is a Senior Production Geologist with Abu Dhabi National Oil Company (ADNOC). He graduated in Geology from Mosul University, Iraq in 1973. He worked for Petrobras from 1974 to 1980. He was a Senior Geologist with Umm Al Dakh Development Company, Abu Dhabi from 1981 until he joined ADNOC in 1998.

Mahmood Akbar is a Division Geologist for Schlumberger in Abu Dhabi. He has a BSc (1983) and MSc (1985) in Applied Geology from the University of Punjab, Pakistan. He has done research on fracture characterization in the Lower Himalayas. He joined Schlumberger Wireline & Testing in 1985 and has worked in Pakistan, Oman, and the UAE. Mahmood is the author of several papers on fractured carbonate reservoirs, stress analysis, and the applications of borehole-imaging tools. He is a member of AAPG and SPE.

Ahmed Madjidi is a member of Schlumberger’s Logging-While-Drilling interpretation support team based in Abu Dhabi. He has a BSc in Electronics Engineering from the Iran College of Science and Technology and a MSc in Petroleum Engineering from the University of Oklahoma. Ahmed is a member of SPE, SPLWA, and SEE.

The Benefits of Seismic Modeling when Designing the Templates for 3-D Surveys in the Middle East

Mark Egan, Schlumberger Geco-Prakla, Dubai

The requirements for some aspects of source-receiver template geometries are well understood. For instance, if a reservoir is deep, we know that the template should include long offsets. But where do we go from there? Should the template be wide or narrow? Should it be symmetric or perhaps off-end? Typically, geoscientists rely on attribute plots to make such decisions but, unfortunately, sometimes these are not sufficient. There is often a need in survey design to tune the geometry so as to address specific problems that are prevalent in the area. A powerful way to do this is through the use of seismic modeling.

Ray-trace modeling shows if a particular template properly illuminates the target. Even in simple structures it is found that symmetric templates can provide better illumination than asymmetric ones. Ground roll modeling shows which templates provide adequate offset distribution for suppressing the surface waves in stack. It is often found that narrow receiver-line spacing is best for this. Reflectivity modeling shows the degree of contamination from multiples. In this case, it is often seen that wide spreads can be preferred since they provide distributions that are rich in far offsets. Many times, design criteria for imaging the signal and suppressing the various types of noise can be in conflict. The benefit of modeling is that it can indicate which criteria should be given priority. Examples to this effect are shown in the presentation.

Mark Egan is the Middle East/North Africa Division Geophysicist for Schlumberger Geco-Prakla stationed in Dubai. Prior to this assignment, he worked for five years as Area Geophysicist in Dhahran, and before that Mark was in Houston where he started in 1975. Mark holds a BSc in Physics, a MSc in Acoustics and a PhD in Geophysics. He is a member of SEG, EAGE, and SPE.
West Ghawar Tectonostratigraphic Model and its Impact on Hydrocarbon Exploration Plays

Mohammad Faqira and Randall Demaree
Saudi Aramco, Dhahran

Saudi Aramco has had great success in Permian and Devonian gas exploration east of the Ghawar field. This success called for additional drilling and seismic activities that led to a better understanding of the geology and petroleum system. The pre-Khuff section west of Ghawar has not yet been penetrated, and there is much debate regarding the existence of Devonian strata in this area. A new tectono-stratigraphic model for the west Ghawar area from the Arabian Shield to the Arabian Gulf has an impact on the hydrocarbon exploration plays.

The area underwent five major tectonic events subsequent to the deposition of the Devonian section. These events are: (1) Late Devonian east-west compression leading to high-angle reverse faulting. (2) Late Devonian-Early Permian regional erosion took place after the faulting, and stripped older strata off all high blocks. (3) A Late Permian major flooding event occurred that led to the deposition of the Khuff carbonate rocks. (4) Late Triassic-Early Jurassic regional tilting toward the west followed by a major unconformity eroded most of the section in the east. (5) Late Cretaceous-Early Tertiary re-activation of Hercynian faults developed the trends responsible for Ghawar, Abqaiq, and several other fields.

This model has a great impact on exploration plays. The following play concepts can be developed from the model: (1) Reverse-fault traps west of Ghawar; (2) updip pinch outs of Unayzah sandstone east and west of Ghawar; (3) pre-Marrat angular unconformities; (4) pre-Aruma angular unconformity; and (5) Aruma onlapping the pre-Aruma unconformity.

Mohammad Faqira has been an Explorationist with the Central Area Exploration Unit of Saudi Aramco since 1994. He has a BSc from King Abdulaziz University, Jiddah (1985) and a MSc from the Colorado School of Mines (1991). He joined Saudi Aramco in 1987 and since then has worked in the Geophysical Processing, Red Sea Area Exploration, and Central Area Exploration units. Mohammad is currently working in the West Berri Area.

Randall Demaree is an Explorationist with the Central Area Exploration Unit of Saudi Aramco. He has a BS from California State University, Sonoma (1979) and a MS in Geology from California State University, San Diego (1981). He worked for Exxon for 17 years on a variety of exploration and production projects, both domestically and internationally, before joining Saudi Aramco in 1998. He is currently working in the West Berri Area. Randall is a member of AAPG and DGS.

Sedimentary and Palynofloral Successions of the Permo-Carboniferous in Saudi Arabia

John Filatoff, Saudi Aramco, Dhahran, and Michael Stephenson, British Geological Survey, Nottingham

The Permo-Carboniferous period spans approximately 100 million years (353–250 Ma). Cumulative maxima of six lithostratigraphic units that were deposited during this period in eastern and central Arabia account for more than 5,000 feet of section. The uppermost Jubah Formation, Berwath Formation, and the newly identified and informally named ‘Haradh’ siliciclastic unit represent Carboniferous sedimentation, whereas the Unayzah Formation, Basal Khuff Clastics (Ash-Shiqqah Member) and Khuff Carbonate sequence were deposited in the Permian. In the Wajid area of southwestern Saudi Arabia, the Ruhaiyah Formation equates approximately to the Khuff Formation and the Juwayl Formation to the remaining older units.

The Khuff Formation, which probably extends into the Triassic in its uppermost part, accounts for more than half of the accumulated sediment thickness but no more than 8 percent of the Permo-Carboniferous time span. Khuff sedimentation was essentially continuous on a stable shallow shelf in contrast to the underlying succession which is marked by numerous unconformities that are the result of episodes of both tectonic uplift and sea-level fall. Gondwanan Permo-Carboniferous glaciation undoubtedly interrupted the relatively continuous Silurian to Early Carboniferous (Qusaiba to Berwarth) sedimentary sequence (since the previous major glacial event of the latest Ordovician) and affected sedimentation character from the Namurian to Sakmarian (‘Haradh’ unit and lower Unayzah Formation).

The palynofloral succession has been subdivided into 11 zones. In addition to facilitating correlations and differentiation of the various sedimentary units, the succession reflects vegetational changes brought about by climatic shifts associated with the glaciation and provincial shifts (Gondwanan to Cathysian/European) brought about by plate movements.
John Filatoff is a Specialist Geologist (Palynologist) with the Saudi Aramco as a member of the Exploration Support Team within the Geological Research and Development Division. His activities, since joining the company in 1992, focused initially on Tertiary, Red Sea exploration and, in the past four years, on Paleozoic deep-gas exploration in central and eastern Saudi Arabia. John has 30 years of oil industry experience, mostly in Australia, but also in Iran, Venezuela, and now Saudi Arabia. He has BSc and PhD degrees in Geology from the Universities of Queensland and Western Australia, respectively. John is a member of DGS, GSA, AASP, and CIMP.

Michael (Mike) Stephenson received his BSc in Geology from Imperial College in 1982 and an MSc in palynology from the Centre for Palynology at the University of Sheffield in 1996. Mike worked in education and publishing between 1982 and 1995, mainly in southern Africa. He has recently completed his PhD project, based at the Centre for Palynology, University of Sheffield, concerning regional correlation of oil-bearing sediments in the Arabian Peninsula. Mike is a member of AASP and is currently working with the British Geological Survey as a Stratigrapher.

3-D Seismic Reservoir Characterization of the Wara Sand, Minagish Field, West Kuwait

Dave Foster, BP Kuwait and King Hoi Lau, Kuwait Oil Company.

The Wara Sand of the Minagish field, West Kuwait is a giant clastic reservoir secondary to the Minagish Oolite carbonate reservoir. The Wara reservoir is a highly heterogeneous fluvio-marine sandstone system containing oil of average gravity 19°API, and is in the early stages of appraisal and development. The Wara Formation is approximately 200 feet thick and contains several levels of sand as much as 60 feet thick. Despite approximately 70 well penetrations, sand net-to-gross distribution is still one of the main uncertainties in understanding oil-in-place, reservoir productivity, and ultimate choice of a field development scheme. The interval is also highly faulted.

This study presents the results of 3-D seismic interpretation of the Wara Sand. Structural mapping and initial feasibility work established the potential of the data for 3-D seismic reservoir characterization. The structural seismic interpretation clearly defines the depth and fault structure of the reservoir, thus constraining the size and shape of the overall reservoir tank, and also indicates possible structural compartmentalization. Synthetic seismograms, petrophysical analysis, and 3-D seismic voxel interpretation and visualization of a preliminary acoustic impedance dataset have been used to characterize the nature of possible sand geometries within the Wara Formation.

The visualization reveals many low-acoustic impedance bodies that, from petrophysical data and calibration to well control, are identified as the relatively thicker, more porous and oil-saturated sand intervals. Many geometric details of these bodies are also revealed that, in conjunction with detailed analysis of well logs and core description, could result in a much better description of the depositional environment and geometry of each sand body. The current interpretation shows that it is possible to differentiate on the seismic records between narrow, often sinuous sandbodies, and wider and more continuous sand sheets. These two geometries probably represent significantly different depositional environments—perhaps meandering fluvial channels, and near-shore sheet sands, respectively.

The 3-D voxel visualization of the Wara interval has demonstrated the potential of the seismic data to identify and laterally map many of the main sandbodies within the Wara for the first time. This is a breakthrough in terms of the Wara reservoir characterization. Future modeling and interpretation work is now planned to realise the potential of seismic data to map out the vertical and lateral sand distribution.

Dave Foster has worked for BP since 1981 when he received his BSc in Geology with Geophysics from Leicester University. He has extensive 2-D and 3-D seismic interpretation experience in Kuwait, Tunisia, the North Sea, onshore UK, Egypt, Canada, and the Gulf of Mexico in both exploration and reservoir geophysics. He is currently seconded to the Kuwait Oil Company, where he is West Kuwait Fields Seismic Interpretation Team Leader. His professional interests include workstation seismic interpretation and staff development and training.

King Hoi Lau has 14 years of seismic interpretation experience, initially with Petro Canada and and currently with Kuwait Oil Company (KOC). He also has one and a half years of seismic processing experience. He was a Research Assistant at the University of Alberta. He has worked in Western Canada, British Columbia plains, the Mackenzie River plains and the Northwest Territories. His recent experience in KOC has included reservoir...
How to Constrain 3-D Reservoir Stochastic Simulations with Seismic: a Case Study in Carbonate Deposits

Frédérique Fournier, Jérôme Rozanski, and Brigitte Doligez
Institut Français du Pétrole, Paris

This paper examines through a case study, two possible approaches for introducing seismic-derived information in 3-D stochastic simulations of lithofacies. The reservoir is a highly heterogeneous series of tidal to supra-tidal carbonates mixed with clastic sandstones. Three wells and a 3-D seismic data set are available. We used an algorithm based on the truncated Gaussian formalism for generating 3-D stochastic simulations that image possible distributions of lithotypes and associated porosities at the reservoir level.

Seismic data is often noise-contaminated, indirectly related to reservoir properties, and at a scale much different from the log scale used for building the reservoir model. We therefore adopted a conservative approach for integrating seismic into the stochastic simulation process, whereby the seismic information (post-stack amplitudes and associated attributes) is translated into soft constraints related to the lithofacies. The seismicly derived information constrains, in a second step, the construction of the 3-D matrix of lithofacies proportions used in non-stationary truncated Gaussian simulations.

The first methodology consisted of estimating local averages of facies proportions from relevant seismic attributes. In the case study, it was possible to derive the proportion of tight facies. The second approach consisted of inferring the dominant rock type with the associated probability of error, using a statistical pattern-recognition technique. The occurrences of porous sandstones and tight facies were reliably predicted based on this approach. A strong convergence between the proportions of tight facies and their occurrence as dominant rock types was noticed.

Both types of constraints are compatible with the simulation process. They led to significant variations of the facies distribution in the stochastic simulations due to the impact of the seismic information. Both approaches are complementary tools whose use depends on the nature of relationship between lithotypes and seismic parameters, and on the degree of vertical heterogeneity. For both, a good calibration between the lithofacies distribution in depth and the seismic parameters in time is crucial for the reservoir interval. This calibration issue was examined using synthetic and real traces in the vicinity of available wells.

Accurate Charge Risking of Unconventional Source Rock/Reservoirs in South Oman

Neil Frewin, Sarah Indrelid, Petroleum Development Oman, Muscat, Isabelle Kowalewski, Bernard Carpentier, Alain Y. Huc, Institut Français du Pétrole, Paris, François Gelin, Shell, The Netherlands and Pierre Albrecht, Louis Pasteur University, Strasbourg, France

A combination of detailed geochemistry, charge modeling and regional data validation has been used to constrain risk of no charge and assess the probability of gas in complex
intra-salt source rock/reservoirs in south Oman. The intra-salt source rock/reservoir systems are part of the Precambrian/Cambrian Huqf Supergroup, some of the oldest sedimentary rocks in Arabia, and are characterized by ‘stringer’ carbonate and ‘silicilyte’ chert reservoirs. The reservoirs are generally highly overpressured and discoveries so far have found light oil (30°–50° API). With notable exceptions, source rock analysis and charge modeling have demonstrated that almost all of the intra-salt reservoirs so far penetrated must have been self-charging, assuming almost 100% retention. A detailed evaluation of the very unusual Precambrian-Cambrian organic matter within these source rock/reservoirs has yielded results that have a substantial impact on the play with respect to fluid properties.

The assessment of organic maturity in relatively shallow silicilyte reservoirs (less than 3,500 meters deep) has demonstrated that the expelled hydrocarbons may be too heavy to recover using conventional means and thus uneconomic to produce. The maturity assessment alone has lowered oil expectation in the shallow silicilyte by 4.4 million cubic meters of oil. Furthermore, for the relatively deep silicilyte reservoirs (more than 3,500 meters deep), molecular evidence suggests that there may be a mineral matrix retention effect on higher molecular weight polar hydrocarbons. This effectively increases the produced API gravity to ± 50°, compared with an API gravity of ± 30° in the stringers. By proving that the oil is more stable with increasing depth and temperature, gas risk is reduced. The oil expectation for the deep intra-salt play has recently been revised upward by 3.8 million cubic meters. Improved understanding of the play, taking into account these factors, has greatly assisted quantifying the probability of success.

Additionally, new technologies for the surface detection of hydrocarbons are being used to constrain prospectivity still further.

**Neil Frewin** is a Petroleum Geochemist for Petroleum Development Oman (PDO) where he leads the Hydrocarbon Modeling Team. Prior to being posted to PDO in 1997, he worked for Shell International in The Netherlands as a Research Geochemist. Whilst there, he worked on global studies in Abu Dhabi, Albania, China, Germany, Kuwait, Nigeria, Pakistan, and other countries. He holds a BSc (Geology) from the University of Wales and a PhD (Geology/Geochemistry) from the University of London. Neil spent a postdoctoral year researching biomarker technologies at Delft University and NIOZ in The Netherlands.

**Sarah Indrelid** joined Shell in 1993 and is currently Senior Basin Modeler for Petroleum Development Oman (PDO). Prior to being posted to PDO in 1998, she worked for Shell International in The Netherlands as a Research Geologist on thermal and pressure modeling. She has a BA in Geology from the University of Cambridge and a DPhil in Geology from the University of Oxford.

**Isabelle Kowalewski** is a physical chemist with Institut Français du Pétrole. She has more than nine years of experience in geochemistry and has worked on asphaltene precipitation in petroleum reservoirs. She has also researched the physico-chemical characterization of asphaltenes and the molecular modeling of macromolecules. She is now working on pyrobitumen occurrences and thermal sulphate reduction.

**Bernard Carpentier** is a Senior Research Scientist at the Institut Français du Pétrole (IFP). He has a background in geophysics and petroleum geology. He joined the geochemistry group of IFP 10 years ago. He is involved in research into the sedimentology of organic matter, organic matter wireline log detection, basin modeling, and sedimentary cycles in evaporitic series. He is the author of more than 25 scientific publications. Bernard is now working on asphaltene precipitation and tar-mat deposition in petroleum reservoirs.

**Alain Y. Huc** is Head of the Geochemistry Group at Institut Français du Pétrole. He has 22 years research experience and is author or co-author of more than 70 publications. His scientific work encompassed sedimentology of organic matter, migration studies, and asphaltene structure. His current research deals with the application of reservoir geochemistry.

**François Gelin** graduated from Chemical Engineering School in Paris and from the University of Houston with a MS in Chemistry. In 1996, he was awarded a PhD in Geochemistry by the University of Utrecht, The Netherlands. He joined Shell International E & P in 1997 as a Research
Petroleum Geochemist where he is currently working on new geochemical tools for application to the industry and the integration of these tools with charge modeling software.

Pierre Albrecht is Director of Research in the Department of Chemistry, University Louis Pasteur, Strasbourg. He is leading a research team specializing in organic geochemistry of sediments and petroleum and, in particular, molecular markers of biological origin. Pierre has published more than 200 articles in international journals.

Detecting the Undetectable: the Development of Surface Geochemical Techniques in Oman

Neil Frewin and Nashwa Al Ruwehy, Petroleum Development Oman, Muscat
Richard Hatton, Consultant, and
Olaf Podlaha, Shell, The Netherlands

Petroleum Development Oman has undertaken an evaluation of commercially available surface geochemical techniques. If successful, the ability to detect near-surface micro-seepage could represent a cheap and effective tool for assessing prospectivity in greenfield and near-field exploration strategies. Following a thorough evaluation of different available technologies, the following three techniques were selected on the basis of environmental considerations: (1) adsorption of passive soil gas; (2) butane microbe counts; and (3) methane-to-propane microbe counts. Target areas for both soil-gas and geomicrobial surveys were the Hazar field and the Maradi Fault Zone south of Qarat-Al-Milh. The soil-gas technique was also applied to the Ghafeer area in south Oman. Details of the methods will not be discussed here but, instead, this presentation will focus on the results from the soil-gas method, their interpretation and the impact on future exploration.

Anomalies identified as four live petroleum phases and potentially two residual hydrocarbon fingerprints were interpreted over the Hazar oil field and in the surrounding area. The live hydrocarbon anomalies were associated with fault structures in 3-D seismic. Micro-seepage of compounds higher than C₅ (pentane) seemed to be driven by a deep gas-flux passing through the sediments at shallower levels. Gas anomalies defined a distinct halo that coincided with the oil/water contact of the field. In the area of the Maradi Fault Zone, a 4-double transect-layout perpendicular to the main fault direction was used. Anomalies coincided with existing fields (Qarat-Al-Milh and Gabah North) and the main faults. There was no distinct signal along the shoulders of the Jebel Majahiz salt dome. The reinterpretation of the 65 compound signal suggests that much of the length of the fault zone is depleted of live gas and light liquids. Instead, deep gas and heavier oil characters prevail. The associated live-gas signature shows a northward-trending depletion with its minimum immediately to the west of the Qarat Al Milh oil field. Strong oil-only anomalies occur on the eastern flanks of the major faults of the Maradi Fault Zone. In the Ghafeer area the results are still under evaluation. Preliminary results, however, show that the recently successful Ghafeer well is located on the shoulder of a positive oil-type anomaly. Similar correlations were observed at a new prospect that will be drilled later this year.

Neil Frewin see p. 90; Nashwa Al Ruwehy see p. 36

Richard Hatton is a Geochemist with 17 years exploration experience in onshore and offshore geochemical surveys. Upon completing MSc studies in Geochemistry at Louisiana State University, he undertook field and laboratory studies for Woodward Clyde Consultants in the environmental and exploration sectors onshore and offshore in the southern USA. Latterly, he was a leader of marine coring operations in the Gulf of Mexico, Alaska, California, and Europe. In 1987, he joined Robertson Research International in Wales, UK, as a Senior Scientist. He was exposed to conventional petroleum geochemistry, global studies and surface prospecting while working in South America, South East Asia, and Africa. As an independent Consultant since 1993, Richard has undertaken operational and interpretative assignments for prominent exploration companies in North West Europe and the Middle East.

Olaf Podlaha joined Shell in 1997 after gaining a MSc (Geology) and PhD (Geosciences) from Ruhr-University, Germany. He spent two postdoctoral years at Indiana University and Woods Hole Oceanographic Institute (Organic Geochemistry) and Ottawa University (Inorganic Geochemistry). He works at Shell’s Research and Technical Services Division in The Netherlands, primarily on surface hydrocarbon detection methods. Olaf also has a part-time lecturing position at the Department of Geology, Ruhr-University. In his remaining spare time he is studying for a MBA.
An Analysis of Some Common Vibroseis 3-D Geometries

Mike Galbraith
Seismic Image Software Ltd., Calgary, Canada

Vibroseis is the preferred source for many of today’s 3-D surveys. Efficient geometrical arrangements of sources and receivers generally favor parallel arrangements. The vibrators follow a path between the central two receiver lines of a rectangular receiver patch. This path may be absolutely parallel, thus simulating a marine style of geometry or the path may be one of the many styles of ‘zig-zag’ (regular, mirror, single, double, etc.). This study examines these different geometries for their effect on attenuation of shot noise (ground roll) and multiples. Also examined is the effect of the geometry on the quality of image for various dipping events of interest, in particular the effects of dip moveout and pre-stack time-migration on potential targets for each of the geometries. The conclusions are that both noise and multiple attenuation and pre-stack imaging requirements are best served by a wide-azimuth, double zig-zag using close line spacing. The limitations of the other geometries will be discussed and will lead to practical guidance on the circumstances in which one or another geometry can be used.

Mike Galbraith received his BSc (hons) in Mathematical Physics from Edinburgh University in 1967. From 1968 to 1970 he worked as a Research Advisor for the British Gas Council. In 1971, he joined RB Cruz and Associates as a Programming Manager. Mike is now President of Seismic Image Software Inc. He is a member of CSEG, SEG, EAEG, PESGB, APEGGA, ASEG and OPI.

Lowering Risk in the Exploration Process: What Can We Get from Basin Modeling?

Jean-Michel Gaulier, Beicip-Franlab, Frédéric Schneider, Jean-Luc Rudkiewicz, Sylvie Wolf and Johannes Wendebourgh, Institut Français du Pétrole, Paris

Basin modeling techniques have undergone a tremendous evolution within the past ten years. Simulators are nowadays allowing quantification at any part of the exploration process. They allow a geological evaluation integrating sophisticated concepts of physics (such as, thermal diffusion and fluid flow dynamics) closely linked to geochemistry (source rock maturity, quality of the generated hydrocarbon, compositional evolution of the fluid, and so on). After the realization of a consistent geological database (1-D well, 2-D cross-section or 3-D digital cube), a simple simulation is not time-consuming. It varies from less than a minute for 1-D simulation, less than 1 hour for a 2-D line integrating fluid-flow simulations, and only a few hours for a 3-D simulation. Testing the impact of various geological hypotheses in a consistent framework is easily done. Moreover, basin simulators can be used in a systematic manner linked to risk evaluation tools. Among the proven applications of basin modelling are: (1) pressure predictions for exploration purpose or for establishing a drilling program; and (2) hydrocarbon charge quality and quantity. Examples illustrating these applications will be shown.

Jean-Michel Gaulier leads the Petroleum Systems Analysis team at Beicip-Franlab. He has a PhD in Geodynamics from the University of Paris and joined the Institut Français du Pétrole in 1990. Jean-Michel has worked in South America, Saudi Arabia, the North Sea, and West Africa. He has published papers on basin modeling.

Frédéric Schneider is Chief of Research for IFP’s 3-D Basin Modeling. He graduated from Paris School of Mines and obtained a Doctorate in Geology from University of Paris.

Jean-Luc Rudkiewicz is Head of Basin Modeling in the Institut Français du Pétrole (IFP). He was awarded a PhD by the Paris School of Mines in 1988. He joined IFP in 1987 as a Researcher in the Reservoir Characterization group. In 1992, he became a Researcher in the Basin Modeling group and was appointed Head of Basin Modeling in 1995. He currently applies IFP’s modeling tools to basins world-wide in cooperation with industrial partners. His professional interests are integrated hydrocarbon generation and migration modeling, geochemistry of hydrocarbon fluids in source rocks and reservoirs, geological description of reservoirs, and upscaling of fluid-flow properties from core-scale to reservoir-scale. Jean-Luis teaches Basin Modeling to postgraduate students of the École Nationale Supérieure des Pétroles et Moteurs.

Sylvie Wolf is a Research Scientist in the Geology Division of the Institut Français du Pétrole (IFP). She was awarded a PhD in Applied Mathematics from the University of Paris VI in 1994. She joined IFP in 1987 after being involved in
Rifting of the Arabian Platform During the Proterozoic-to-Phanerozoic Interval

Antonin Genna, Denis Vaslet, Dominique Janjou, Joël Le Métour, Bureau de Recherches Géologiques et Minières, France and Mohammed Halawani, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah

In the Arabian Shield, the Pan-African transcurrent deformation came to an end about 600 million years (Ma) ago. This event, now known as the Nabitah Orogeny, caused the emplacement of gneiss domes and the transcurrent movement along the Najd faults skirting these domes, as well as structural control of the late Proterozoic Murdama molasse basins. This tectonic phase marked the end of cratonization of the Shield. A new look at the geology of the Saudi Arabian basement has shown the presence of latest Proterozoic (590–530 Ma) crustal thinning. This extension was accompanied by the bimodal volcanism of the Shammar Group. The Najd faults were reactivated as transform faults for the crustal thinning. The extension ended with a marine transgression, the remnants of which are found as carbonate-platform deposits of the Jibalah group. A similar magmatic and structural evolution for the same period has been described from Egypt. In interior Oman, this extensional event is correlated with the syn-rift formations of the Huqf Supergroup, including the bimodal volcanism of Halfayn, Saqla, and Hatat, and the clastic deposits of the Abu Mahara Group, followed by with the post-rift uniformly stratified platform carbonates and siliciclastics of the Nafun Group. Renewed volcanic activity of the Fara Formation and the genesis of northeast-trending salt basins is possibly related to a new a new rift event during the Early Cambrian. The closing of the salt basins by Middle Cambrian times is related to a compressive event before being sealed by the Haima Supergroup over the Angudan unconformity.

In Saudi Arabia, the Jibalah and Shammar rocks are interpreted as syn-rift deposits on the passive margin of the North Gondwana paleo-continent. These rocks and their basement, were affected by a deformation expressed as tilting blocks and local thrusting, before being sealed by undeformed Phanerozoic Cover Rocks. The first undeformed Phanerozoic rocks (the continental Siq Sandstone), is seen as a post-rifting deposit that drowned the last paleorelief of the craton. The whole succession then was transgressed by the Middle Cambrian detrital and carbonate marine deposits of the Burj Limestone. Starting in the Middle Cambrian about 520 Ma, most or all of the Arabian plate became covered by shallow-marine to continental deposits that, in so far as they are preserved in a vertical sense, seem to have had a great lateral extension during the Paleozoic. Subsidence during this long period was controlled by the gradual cooling of the crust.

The crustal thinning in the Proterozoic Shield has been demonstrated by the presence of extensional structures, whose complex geometry is outlined by dikes and normal faults. The basement thus shows the continuation of the axes of the Paleozoic basins preserved in the Cover Rocks. This relationship between sedimentary basins and their substrate is particularly well documented for the Tabuk Basin. The north-south axis of this basin can be traced southward for about 250 kilometers as far as the Ar Rayyan formation south of Al Madinah.

Antonin Genna received his PhD in Structural Geology from the University of Montpellier. He joined Bureau de Recherches Géologiques et Minières in 1989 and worked on mineral exploration and research in Bolivia, Morocco, Gabon, Romania, and France. He also participated in oil exploration in Peru. Since 1990, he has been involved in mapping, mining exploration, and geologic synthesis of the Arabian Shield. Antonin’s main interests concern deformation of sedimentary rocks and relations between basements and basins.

Denis Vaslet has 20 years of experience in the geology of Saudi Arabia. He was responsible for the Cover Rocks mapping project of the Saudi Arabian Deputy Ministry for Mineral Resources from 1979 to 1991. Denis has been involved in the complete lithostratigraphic revision of the Phanerozoic rocks of central Saudi Arabia, for which he received his Doctorate of Sciences from the University of Paris in 1987. Denis is currently in charge of the basic geology and mapping at the French Geological Survey.

Dominique Janjou see p. 116

Mohammed Halawani is a Geologist in the Saudi Arabian Deputy Ministry for Mineral Resources, Mapping Department. He received his BSc from the Faculty of Earth Sciences at King Abdul Aziz University, Jiddah in 1981, after which he worked on various projects in the Arabian Shield. Since 1990, he has been involved in several mapping projects of Phanerozoic rocks, especially in the Paleozoic of north and northwestern Saudi Arabia.

Burial History Reconstruction and Thermal Modeling of the Bangestan Group in the Khuzestan Plain, Southwest Iran

Fereydoun Ghazban, Aita Bijariipour
Tehran University, Iran
and Mohamad Kamali
Research Institute,
National Iranian Oil Company, Tehran

The Khuzestan plain is considered to be part of the Zagros foothills that contain some of Iran's most important oilfields. The area is part of the ancient Arabian-Nubian Platform that is bounded to the northeast by the Zagros orogenic belt. The region has many potential source rocks that were deposited intermittently throughout Jurassic, Early Cretaceous, and Paleogene times in an intra-shelf silled depression connected to the southern Neo-Tethys Ocean. The source rocks are defined as having a Total Organic Carbon (TOC) content greater than 1%. The most important source rocks in the Bangestan Group include the Kazhdumi Formation (with an average TOC content of about 5%), the Pabdeh Formation (3–5.5%), and the Sargelu Formation (2–9%).

An analysis of the burial/thermal history was constructed for about 40 wells in the Khuzestan oilfields using the LOPATIN model. An evaluation of the source rock potential indicates that the Kazhdumi, Laffan, Garau, Gadvan, and Sargelu formations have passed through the oil window. In most of the wells, the Pabdeh Formation (in spite of its richness in organic material) is either immature or just below the oil window and has not produced oil. According to the constructed thermal index maps, the maximum oil maturity occurs in the Darkhoain and Solabedar fields. Thermal modeling of the source rocks indicates that oil generation and expulsion began about 70 million years ago and has continued up to the present time.

Fereydoun Ghazban has been a member of the Environment Faculty and Geology Department at Tehran University since 1994. In 1979, he received a MSc in Engineering Geology from McGill University, Canada. He was a Research Associate at McMaster University from where he received his PhD in Isotope Geochemistry. Fereydoun has presented several papers at international conferences and has published in several international journals.

Aita Bijariipour, received her BSc in Geology in 1997 and a MSc in 1999 in Sedimentary Geology from Azad University of Iran. Aita currently works for the ITOK Mineral Company in Tehran.

Mohamad Kamali see p. 120

3-D Stratigraphical Modeling of the Natih Formation (Upper Cretaceous, Northern Oman)

Didier Granjeon and Frans van Buchem
Institut Français du Pétrole, Paris

3-D forward stratigraphical modeling is a powerful tool to reconstruct the sedimentary architecture of a basin in-fill at a scale of tens to hundreds of kilometres, and hundreds of thousands to tens of millions of years. DIONISOS, an in-house developed stratigraphical model, progressively quantifies erosion, transport and deposition of sediment using macro-scale fluvial, wave and gravity sediment transport laws. This deterministic simulation provides a reconstruction of the physiographic evolution of a basin and a 3-D insight into its stratigraphic architecture. DIONISOS can be applied to exploration case studies in order to better
understand the basin history, test different correlation schemes and exploration scenarios, and predict possible reservoir locations; and to field-appraisal case studies to more precisely characterize the geometry and facies of sedimentary units.

A Middle East case study applied DIONISOS to the Upper Cretaceous Natih Formation of Oman. The Formation is part of the Wasia Group (Cenomanian and early Turonian) that is one of the principal carbonate petroleum systems in the Gulf region. The excellent outcrops in the Adam foothills of Northern Oman offer a unique opportunity to study the stratigraphic architecture of the Formation and construct a high-resolution sequence stratigraphic model. Based on this model, a simulation was fitted to three outcrop logs, with a 10 to 50 kilometer spacing. It illustrates the carbonate production algorithm in a complex platform to ramp setting. The evolution of the basin paleogeography indicated that intra-shelf basin environments dominated by deep-water oyster-bearing limestones and shales progressively evolved to shallow-water carbonate platform deposits dominated by rudist species. The modeling resulted in a 3-D quantification of depositional geometries and facies in a high-resolution framework, such as the location, thickness and extension of reservoirs, and their rudist-shale ratio.

Didier Granjeon graduated from the Paris School of Mines in 1990 and received his doctoral degree in Geology from the University of Rennes in 1996. He joined the Sedimentology and Reservoir Characterisation Group of the Institut Français du Pétrole in 1992. His work has focused on the development of 3-D stratigraphic modeling, research on long-term fluvial and gravity sediment transport laws, and the link between reservoir heterogeneities characterization and regional stratigraphical modeling. Didier has been involved in reservoir and basin 3-D stratigraphical modeling in the North Sea, Middle East, and the Western USA.

Frans van Buchem see p. 191

Ghawar Time-to-Depth Conversion

Arthur Gregory, Jung Kim, Edgardo Nebrija, Harold Triebwasser, Charles Wagner and Carl Anderson, Saudi Aramco, Dhahran

Depth models for the Ghawar area fields have been generated in order to map structural features, provide a framework for Khuff stratigraphic interpretation and attribute analysis, select well locations, and assist well planning and drilling. The modeling is part of an integrated depthing, inversion, interpretation, and visualization effort for exploration and development of Khuff and pre-Khuff gas. Initial depthing work included the generation of regional maps to help establish Ghawar area-wide velocity control, and mapping trends using appropriate well marker, check shot, and seismic data. Within individual field areas of interest, useful depth-sensitivity cross-plot and map displays were constructed for comparing maps generated from various depth-conversion methods. These methods include apparent velocity, check-shot velocity, and geostatistical procedures with depthing results compared for smoothed surface elevation datum and Aramco seismic referenced datum. Seismic data volumes have also been converted to depth using several depth reference horizons, and resampling all trace data at a regular depth-sample interval. Velocity maps, depth maps, and depth-seismic volumes were displayed with associated well data using visualization software to assist quality-control assessment and updating of the depth model. As a result of this time to depth conversion, seismic inversion and related well and reservoir-modeling data can be displayed simultaneously in the depth domain, which enables a more rigorous integrated subsurface characterization.

Arthur (Greg) Gregory is a Geophysicist in Saudi Aramco's Geophysical Technology Department. He received a BSc (hons) in Geology from Emory University in 1977 and a MSc in Geophysics and Geology from the University of Hawaii in 1980. Greg worked for Exxon for 17 years as a Seismic Interpreter and Seismic Modeler before joining Saudi Aramco. He is a member of AAPG, SEG, EAGE, DGS, and NSS.

Jung Kim see p. 25; Edgardo Nebrija see p. 150; Harold Triebwasser see p. 77; Charles Wagner see p. 78

Carl Anderson is a Geophysicist with Saudi Aramco in the Gas Reservoir Characterization Division. He received a BSc in Geology (1975) from the University of Wisconsin-Superior and a MSc in Geology (Geophysics thesis) (1977) from Michigan State University. Carl worked for Texaco as a Seismic Interpreter for 16 years, 13 of which were spent with Saudi Aramco. He joined Saudi Aramco in 1994. He is a member of SEG and EAGE.
Integrated 3-D reservoir characterization in carbonate fields is a topic of ongoing discussion whereby data preparation and data requirements (as well as actual modeling procedures), vary considerably throughout the industry, in general, and from field to field, in particular. The ability of integrated software to present solutions is evolving rapidly and has shifted the emphasis on what a best-practice modeling approach should be. One of the issues often raised is the link between a facies-based model incorporating depositional and sequence stratigraphic characteristics, and its use during dynamic simulation. In this presentation, we will suggest an approach that introduces the concept of modeling based on the reservoir rock type.

The example used is a giant oil field in Abu Dhabi. The general structure trends northeast and has dimensions of 30 by 10 kilometers. Its main reservoir zones are part of the Lower Cretaceous Thamama Group, in particular the Kharaib and Shu’aiba formations. The overall depositional environment is characterized by its location on the Arabian carbonate platform within an intra-shelf basin. Third-order depositional sequences are characterized by shallowing-upward trends. They are mainly reflected as an upward increase in permeability within large- and small-scale cycles. Major sequence boundaries are characterized by field-wide early diagenetic cementation of the shallowmost depositional facies. In the field, a clear, general trend occurs of down-flank porosity reduction of more than 10% from crest down to the water-bearing zone. This is mainly due to the increased abundance of stylolite-bearing dense intervals formed during burial diagenesis (after formation of the anticline), during oil migration and infill of the structural trap. With the exception of the identified third-order sequence boundaries, stylolite-bearing dense units are not continuous over the field, but rather form discrete bodies. Integration with structural data from ongoing 3-D seismic acquisition and processing shows that vertical density of these bodies is controlled by transpressional wrench zones. This suggests that diagenetic fluid movement and oil migration are fault-related and occurred at the same time in the Upper Cretaceous.

Jürgen Grötsch has a MSc and PhD in Geology from the University of Erlangen, Germany. He has been a Research Fellow at the University of Vienna and the Scripps Institute of Oceanography, California. He joined Shell International in 1991. He is currently assigned to the Abu Dhabi Company for Onshore Oil Operations where he is leading the Integrated Reservoir Characterization Studies for some of the giant onshore fields. Jürgen’s professional interests include sedimentology, reservoir rock typing, 3-D reservoir modeling, and integration of 3-D seismic and dynamic data into reservoir characterization processes.

Peter Melville is a Senior Geophysicist in the Abu Dhabi Company for Onshore Oil Operation. He is seconded from BP Amoco for whom he has worked for 23 years. He has a BSc in Geology and Geophysics from the University of Durham. Peter has worked on geophysical exploration and field development projects in the UK Atlantic Margin, the North Sea, onshore Europe, the Americas, and Australia. He also worked in the Geophysical Research and Technical Group in BP’s Head Office. Peter specializes in interpretation and optimization of the use and integration of geophysics in reservoir team studies working on new and mature field reservoir models.

Omar Al-Jeelani has a BSc from UAE University in Al-Ain (1993). He joined Abu Dhabi National Oil Company in 1993 and was seconded to Abu Dhabi Company for Onshore Oil Operation in 1995 as an Operations Geologist in the Exploration and Production Department. In 1997, Omar joined the Asab Field Team as a Reservoir Geologist and is currently involved in reservoir characterization and 3-D modeling.

Karl Leyrer has a MSc in Geology from the University of Erlangen, Germany, and a PhD from the University of Heidelberg. He worked for 10 years as a Consultant in Europe and the Middle East and has wide experience in core description, reservoir characterization and modeling, particularly of carbonate and evaporite settings. He is now a...
Precambrian carbonates on a world-wide basis are known to locally contain hydrocarbons in rocks as old as the Archean. However, the first significant hydrocarbon resources are in rocks of Mesoproterozoic and younger age. In particular, the terminal Proterozoic carbonates of Siberia and Oman contain well-developed platform facies. Source rocks were deposited as sapropelic mudstones in basinal or deeper ramp settings and owe their high organic content to settling of pelagic microorganisms during episodes of restricted sediment influx. Reservoir facies include ooid/ intraclast grainstones deposited in shoal settings, thrombolite buildups deposited in both shoal and downslope settings, and vuggy porosity developed beneath karst. In Oman, reservoir rocks also include source rocks where high porosities are preserved within sapropelic mudstones.

**Precambrian Carbonates: Facies, Secular Variability, and Hydrocarbon Systems**

*John Grotzinger*

Massachusetts Institute of Technology

In the Precambrian world, devoid of higher organisms except near its end, carbonate sediments formed by a variety of abiotic and microbial processes. Patterns of deposition were determined by tectonic, eustatic, and climatic processes. These ancient rocks demonstrate that the fundamental tenets of carbonate production and accumulation were initiated early in the Earth’s history, with the basic attributes of carbonate sedimentation being well established by Neoproterozoic time.

The broad temporal patterns of Precambrian carbonate facies composition and disposition parallel the long-term evolution of the Earth’s oceans and atmosphere. Archean and Paleoproterozoic carbonates commonly contain abundant sea-floor precipitates, whereas the Neoproterozoic record is dominated by clastic-textured facies and abundant carbonate mudstones; Mesoproterozoic carbonates are transitional. Grainstones, dominated by centimeter-scale giant ooids, are characteristic of many Neoproterozoic carbonates. Texturally unusual carbonates, featuring a reprise of Archean-style sea-floor precipitates, often cap glacial deposits of middle Neoproterozoic age.

The influence of biology on sediment texture is best expressed in the history of Precambrian reefs. Archean through Mesoproterozoic reefs are dominantly stromatolite-based. Lamination textures reveal the progressive shift from in-situ precipitation of aragonite and calcite encrusting the sea floor in Archean through Paleoproterozoic stromatolites, to textures consistent with accretion of loose sediment through trapping and binding in Neoproterozoic stromatolites. This trend is interpreted to reflect the progressive decrease of abiotic factors, and the progressive increase of benthic microbial mats, on controlling stromatolite growth. Neoproterozoic reefs witness the appearance of more complex textures that probably involved the participation of calcified microbes and non-calcified higher algae in colonizing the seafloor, increasing its surface complexity and resulting in highly porous frameworks for the first time in geologic history. Terminal Proterozoic thrombolitic reefs additionally contain the first calcified metazoans.
argillaceous dolomicrite and packstone/wackestone; Sequence ‘B’ (mid-ramp setting)—thick cycles dominated by packstone/wackestone with a lesser abundance of packstone/grainstone; and Sequence ‘C’—thin cycles of interbedded thin argillaceous dolomicrite and packstone/wackestone capped by laminated mudstone/wackestone.

Evaporitic brines generated during low-stands were flushed through the carbonate ramp during transgressions to cause dolomitization. Anhydrite nodules, present throughout the reservoir, were formed by infiltration of saline brines during drawdown. Porosity consists of intercrystal and biomicritic elements formed during dolomitization augmented by vugs formed by dissolution of anhydrite nodules during oil emplacement, and by minor fractures. Porosity/permeability varies with rock type. The argillaceous dolomicrite and laminated mudstone/wackestone is dominated by intercrystal microporosity. Porosity is high but permeability is low due to the very small pore throat size. The packstone/grainstone has high porosity but moderate permeability as the biomicritic pores are poorly connected. Porosity and permeability is best developed in the packstone/wackestone that has larger intercrystal pore throats connecting biomicritic porosity.

It is critical to identify the better permeability trends within the reservoir for the purpose of development drilling and in planning for secondary/tertiary recovery. The technique used was to separate out the laminated mudstone/wackestone and the argillaceous dolomicrite based on their log characteristics. Cut-offs were established and the remaining higher permeability packstone/wackestone and packstone/grainstone facies were individually mapped. This resulted in the identification of well-developed north-northwest oriented permeable trends within each of the three sequences that parallel ancient shorelines.

Peter Gutteridge received his PhD for work on Dinantian carbonates at Manchester University. He then worked as a Wellsite, Exploration and Production Geologist with Britoil in the North Sea. This was followed by a spell in academia as a Sedimentology and Petroleum Geology Lecturer, researching UK Dinantian basin development and carbonate platform evolution. Peter is a co-founder of Cambridge Carbonates Ltd, a carbonate sedimentology consultancy working world-wide. He has particular expertise in late Paleozoic carbonates and evaporites in NW Europe, Tethyan carbonates, and carbonate reservoir studies.

Kenneth Lewis received his MBA/BSc Geology from the University of Calgary, Alberta, Canada. After graduation he joined Husky Oil Operations as Senior Geologist. This was followed by developing prospects in the Provost area of Alberta in the Viking, Mannville and Bakken sandstones for Pinnacle Resources. Ken is now working for Kuwait Santa Fe and focusing his efforts on developing the ‘Second Eocene’ reservoir in the Partitioned Neutral Zone between Kuwait and Saudi Arabia.

Joseph Laing is a Senior Geoscientist with Saudi Arabian Texaco, Kuwait. He has 20 years of industry experience and has worked on various assignments in the USA, the Middle East, Asia, and the UK. He has a wide range of skills in reservoir development/production geology, focusing on 3-D geologic modeling, geostatistics, input to reservoir simulation, operations, and optimizing recovery in ‘heavy oil’ reservoirs.

Euphrates Graben, East Syria—Basin Evolution and Petroleum Habitat

Claude Guyot, Elf Hydrocarbures Syrie and Hassan Zeinab, Syrian Petroleum Company

Syria is located in the northern part of the Arabian Plate, which is bounded by the Levant Fault System to the west, the Turkish-Anatolian Plate to the north and by the Zagros foreland to the northeast. In between these features, the Euphrates Graben, Sinjar and Palmyrids form three major intracratonic basins, separated by relatively stable areas. These basins and the neighbouring Mesopotamian foldbelt are major hydrocarbon producing provinces. Of these, the Euphrates Graben accounts for about two-thirds of the present Syrian crude oil production and about 40% of its gas production. This successful story was started in 1984 by the Shell/Pecten/Deminex discovery of Thayyem field, followed by several other large to mid-size fields, such as Omar and El Isba. The Elf Group undertook exploration in the area from 1988 to 1994 after Shell, and discovered the Jafra, Qahar, and Tabiyeh (oil and gas condensate) fields. About 40 fields are now on stream, operated by Syrian Petroleum Company (SPC), Al Furat Petroleum Company (Shell-Weba/SPC), and Deir Ez Zor Petroleum Company (Elf/SPC). The present study was based on data acquired by the Elf Group in exploration of the former Deir Ez Zor licence, and by general information provided by SPC with the authorization of the Ministry of Oil and Mineral Resources.
The Euphrates Graben extends for 120 kilometers in a northwesterly direction and is 90 kilometer wide. These unusual dimensions relate to a limited extension of a rift system. Some of the features and events that controlled basin evolution are: (1) Transition from pre-rift to early rifting sedimentary environments, with the deposition of the main Rutbah-Mulussa clastic play during the Triassic and Lower Cretaceous; (2) Evolution of the basin during rifting, leading to a succession of clastic/volcanoclastic/organic-rich, carbonate-dominated sequences, affected in their distribution by alternating active faulting directions; and (3) Post-rift depositional history and tectonic reactivation of the graben by inversion of limited amplitude.

The key elements and relationships that made the Euphrates Graben a major oil provinces are: (1) extension and vertical distribution of the reservoirs; (2) maturation of the hydrocarbons, their origin, and the related trapping potential; and (3) the structural history, and limitations of the seals. The complexity of these elements, as well as related events will be highlighted.


**Hassan Zeinab** is Chief Geophysicist and Deputy Exploration Manager of Syrian Petroleum Company (SPC). He has an Engineering degree from Bucharest University, Romania (1981) and was awarded his PhD in Geological and Geophysical Interpretation from Bucharest University in 1988. He was Senior Geophysicist in processing in SPC’s Exploration Department from 1981 to 1989, and Deputy Manager of Service Contracts Directorate and Chief of the Technical Department from 1989 to 1996. He was promoted to his present position in 1996.

**Monitoring Gas-Injection Performance in Abu Dhabi Company for Onshore Oil Operations**

**Asbjorn Gyllensten**
Abu Dhabi Company for Onshore Oil Operations

Evaluating gas-injection performance is an on-going activity in one of the large onshore fields of the Abu Dhabi Company for Onshore Oil Operations (ADCO). The objective is to investigate the gas-flooding process and evaluate the viability of future large-scale gas injection operations. This presentation will focus on the monitoring techniques adopted and experiences to date.

Detailed monitoring of the pilot areas is vital in order to predict gas breakthrough, achieve pattern balancing, and evaluate the next phases of field development. Various approaches to monitoring were reviewed at the design stage. These included 4-D seismic, installation of permanent sensors in pilot wells, and cased-hole logging in injectors, producers and observers. ADCO chose to drill dedicated fibre-glass observation wells to enable gas and water-advance monitoring using repeat cased-hole Induction Resistivity and Neutron logs.

During the course of the project, several problems related to the fibre-glass completion became apparent. Conductive glass-reinforced epoxy joints (GRE) affected Induction logs. Leaks in the GRE liners caused wellbore fluid loss with time. Lack of a primary cement bond raised concerns about zonal isolation. Well-integrity problems triggered workovers of two of the three original fibre-glass observers. The wells were sidetracked, logged in open hole and re-completed with steel liners. The main monitoring objectives were not jeopardized since valuable data can be acquired in these wells, using conventional Neutron logs and the new Through Casing Resistivity tool.

Gas breakthrough times have been estimated and the amount of gas in the flooded zones evaluated as a function of time. Uncertainty analysis helped build confidence in the results. Conclusive evaluation of pilot schemes designed to investigate various recovery processes provide crucial input for field development planning of giant oil fields in Abu Dhabi. Experiences with the monitoring approach adopted in this field led to best-practices that will be applied to other pilots schemes by ADCO.

**Asbjorn Gyllensten** has a MSc in Electrical Engineering from Trondheim Technical University, Norway. After graduation, he joined Schlumberger as a Logging Engineer in the Far East and Africa. In 1978, Asbjorn received a MBA from INSEAD, Fontainbleau, France and joined Shell. He provided petrophysical support for the Shell Group Operating Companies and Single String Ventures before transferring to Petroleum Development Oman (PDO) as a Petrophysicist. From 1983 to 1987 he was a Senior Petrophysicist for Shell EXPRO UK. He then moved to Shell Nigeria as Head of Petrophysics and Petroleum Engineering Area Team Leader in Warri Development. In 1993, Asbjorn returned to PDO as Team Leader Exploration Petrophysics. He recently transferred to Abu Dhabi Company for Onshore Oil Operations as Petrophysical Coordinator, Petroleum Development Division. Asbjorn is a member of SPWLA and SPE and serves on the SPE Well Logging Technical Committee.
Geochemical fingerprinting of oils from the Lower Fadhili reservoir of the Khurais and Qirdi fields was performed in order to assess the possibility of communication between the two fields. Fingerprinting was accomplished through the use of high-resolution gas chromatography of the whole-oil sample. Peak matching between oils identifies differences in chemical composition. Compositional differences among oils produced from the same reservoir imply a barrier to fluid communication because those differences should be eliminated in a well-mixed reservoir over relatively short periods of geological time.

The major findings are that in the Khurais field, Lower Fadhili oil from Khurais-A is not in communication with any of the other Lower Fadhili oils studied. Therefore, a barrier to communication exists between it and Khurais-B (the closest well studied). However, of the Khurais and Qirdi oils available for study, all those south of, and including, Khurais-B shared virtually identical geochemical fingerprints. Although identical fingerprints do not prove that there is mixing within the reservoir, they strongly suggest it. The economic significance is that at the Lower Fadhili level, the Khurais and Qirdi fields are probably joined at least south of Khurais-B. If so, the combined reserves will make the reservoir a better candidate for development. In addition, a thermal maturity progression, increasing to the south, was found among the oils and this may have a bearing on the filling sequence of the field.

Henry Halpern is a Research Scientist with the Laboratory Research and Development Center of Saudi Aramco. He worked with Sohio between 1981 and 1985; with ARCO between 1985 and 1989; and with Shell between 1989 and 1992 prior to joining Saudi Aramco. He received a BSc in Chemistry from Lafayette College in 1977 and a PhD in Organic Geochemistry from the University of California, Los Angeles in 1981. His research interests are reservoir and source rock geochemistry.

Peter Jones see p. 119

Mark Tobey is a Research Scientist with the Laboratory Research and Development Center of Saudi Aramco. Before joining Saudi Aramco, Mark worked with Exxon Chemical Company as a Senior Analytical and Process Chemist. He received a PhD in Chemistry from Texas A&M University. His current research interests include oil fingerprinting and its applications to petroleum geochemistry.

William Carrigan has been with the Laboratory Research and Development Center of Saudi Aramco for the past eight years as a Research Scientist. Prior to joining Saudi Aramco, William was employed by the Geological Survey of Canada and the University of Ottawa where he specialized in stable isotope geochemistry and mineral geochemistry. He received a BSc in Geology from Queen's University and a PhD also in Geology from the University of Ottawa. His areas of interest are basin evaluation, stable isotope geochemistry, and petroleum geochemistry.

Mohammad Al-Amoudi has been employed by Saudi Aramco since 1988. He is a Laboratory Technician with the Laboratory Research and Development Center.

Depositional Facies and Sequence Stratigraphy of the Arab-D Carbonates, Haradh Area, Ghawar Field, Saudi Arabia

C. Robertson Handford, Consultant, Austin, Texas
David Cantrell, Saudi Aramco, Dhahran
Christopher Kendall, University of South Carolina

Arab-D carbonates form the most prolific Jurassic reservoirs of the Arabian Gulf, and include the principal reservoir of Ghawar field, the world’s largest oil field. A detailed sequence stratigraphic analysis of the Haradh area in the southern part of the Ghawar field suggests that the Arab-D carbonates were deposited by storm and normal wave/current processes in a shallow-marine platform-interior setting. Environments included shallow mud banks, rudstone-filled tidal channels, stromatoporoid buildups and biostromal sheets, prograding Cladocoropsis banks, peloidal
grain shoals, terminal ooid-sand shoals, and shallow to desiccated salinas.

Stacking pattern analysis has led to the recognition of six high-frequency sequences bounded by base-level fall-to-rise turnaround surfaces. Each sequence is made up of retrogradational (transgressive) and progradational (highstand) cycle sets. Base-level rise deposits in the lower Arab-D (Zone 3) are mud-dominated carbonates that are interpreted as shallow (<30 ft) skeletal mud-banks. Rudstone-dominated carbonates at the top of Zone 3 are base-level fall deposits consisting of the cannibalized remains of eroded highstand deposits. Deposition was in the upper shoreface to foreshore as shallow storm-dominated channels and amalgamated lenses and lobes. The overlying stromatoporoid-coral facies (Zone 2) record a major transgression under which buildups and biostromal sheets developed across a relatively well-circulated platform. Water depths were less than 30 feet. An overlying succession of Cladocoropsis packstones was deposited during base-level fall. Peloidal packstones and thin ooid grainstones cap Zones 1 and 2 of the upper Arab-D carbonates and they represent shallow shoal facies deposited under low accommodation. Capping evaporites probably represent lowstand deposits laid down in a shallow salina.

There is a general correspondence between the Saudi Aramco porosity-based reservoir zonation scheme and the current sequence stratigraphic analysis. However, this analysis adds considerable detail for future zonation, or layering, and a chronostratigraphic basis that was previously lacking.

C. Robertson Handford is a consulting sedimentologist and stratigrapher based in Austin, Texas. He received his PhD in Geology from Louisiana State University in 1976. Since then he has spent most of his professional career in petroleum industry research chiefly in the fields of sedimentology and stratigraphy. He has worked for the Texas Bureau of Economic Geology, and the research laboratories of Unocal, Amoco, and ARCO. He has been an invited lecturer to numerous geological societies and universities, and was the AAPG Distinguished Lecturer for 1995–96 on carbonate stratigraphy. He received the SEPM Excellence of Oral Presentation Award on two different occasions, the SEPM Excellence of Poster Presentation Award, second runner-up for the AAPG Jules Braunstein Memorial Award, and SEPM Excellence of Presentation Honorable Mention. He also received Honorable Mention for Best Paper published in SEPM’s Journal of Sedimentary Research in 1995. He is a member of AAPG, SEPM, IAS, and NSS.

David Cantrell and Christopher Kendall see p. 66

Wide-Azimuth 3-D Swath Acquisition

Richard Hastings-James, Peter Green, Riyadh Al-Saad and Mustafa Al-Ali
Saudi Aramco, Dhahran

Saudi Aramco has developed a 3-D wide-azimuth-swath (WAS) geometry as an alternative to conventional 3-D swath acquisition designs. The flexibility of WAS geometry generally offers significant design opportunities for obtaining improved data attributes and increased operational efficiency when faced with crew-recording channel limitations. All 3-D data acquired by Saudi Aramco now uses WAS.

Increasing the cross-line fold normally improves both the suppression of scattered near-surface noise and statics resolution in processing. Based on experience at Saudi Aramco, a cross-line fold of at least 5 or 6 is normally desirable in 3-D data, which may not be easy to achieve using conventional swath geometries. A cross-line fold of 6 using conventional 3-D swath acquisition requires 12 receiver lines. With a 1,440-channel 3-D crew, this permits a maximum of 120 channels per receiver line. With a 50-meter group interval and a required far trace offset of 6,000 meters, the data must be recorded using an off-end configuration, which is generally undesirable. The equivalent WAS geometry uses only 6 receiver lines, making it possible to record 240 channels per receiver line. Thus, the survey can be recorded split-spread, resulting in a superior azimuthal distribution.

In large survey areas, the maximization of recording-block width can enable substantial cost reduction by minimizing the number of overlap or zipper zones. The ability of WAS to maintain cross-line fold and aperture with half the number of receiver lines enables significantly wider 3-D acquisition blocks to be achieved. WAS also permits the use of an odd number of receiver lines, providing additional flexibility for recording channel deployment.

Re-occupation of source points using WAS permits the simulation of conventional swath acquisition with an arbitrary number of effective recording channels. Occupying each source point twice, for example, can double an effective recording channel count from 1,440 to 2,880, and four times from 1,440 to 5,760. WAS is also well suited to 3-D stack-array acquisition, which is difficult using conventional swath designs due to the limited space available for vibrators to move between geophone arrays. Various WAS configurations and data examples will be presented, including both 1,440-fold and 720-fold 3-D stack-array data acquired in an area of well-developed karst where conventional data quality is poor.
**GEO 2000 Abstracts**

**Richard Hastings-James** is a Senior Geophysical Consultant with Saudi Aramco. He has 20 years of exploration industry experience, 12 of which were with Amoco Production Company in Canada, Houston, and various locations in Africa and the Middle East. Prior to that, Richard was an Associate Professor at the Technical University of Nova Scotia, Canada and a Research Fellow at Pembroke College, Oxford. He has been with the Geophysical Data Acquisition Division of Saudi Aramco since 1992. Richard has a BEng in Electrical Engineering from the Technical University of Nova Scotia and a PhD from Trinity College, Cambridge. He is a member of SEG, EAGE, and DGS. He was co-author of, 3-D Land Seismic Acquisition in Saudi Arabia, published in GeoArabia, v. 1, no. 4 (1996).

**Peter Green** is a Geophysicist with Saudi Aramco’s Geophysical Processing Division. He was employed by Digicon Geophysical, Houston, from 1983 to 1985 and was Processing Manager with Tensor Geophysical, Cairo from 1986 to 1990. Peter received his BSc in Geologic Engineering (Geophysics) from the University of British Columbia in 1983. He is a member of EAGE, SPE and SEG. His professional interests are seismic processing and image processing.

**Riyadh Al-Saad** is a 3-D Seismic Data Processor with Saudi Aramco. He has seven years of experience in the exploration industry including one year in the field with seismic acquisition crews and eight months training with Western Geophysical Company. For the past five years Riyadh has been a processor of 2-D, swath, and 3-D seismic data. He is a member of SEG and DGS.

**Mustafa Al-Ali** is a Geophysicist in the Geophysical Data Acquisition Division of Saudi Aramco. He obtained a BSc in Geophysics (hons) from King Fahad University of Petroleum and Minerals, Dhahran in 1992 and joined Saudi Aramco the same year. He has worked on various seismic exploration assignments. Mustafa received the 1999 Saudi Aramco Professional Contribution award in Geophysics. His main area of interest is seismic acquisition. Mustafa is a member of SEG and DGS.

**Zhiyong He** is a Research Geologist at ARCO Exploration and Production Technology. He has a MS in Petroleum Geology from China’s Petroleum University (1985) and a PhD from the University of South Carolina (1989). His research work has focused on analyzing and modeling fluid, thermal, and other geological processes in the history of sedimentary basins. Zhiyong applies advanced petroleum systems modeling techniques to exploration in basins around the world.

**Charge Modeling of Jurassic and Cretaceous Petroleum Systems, Qatar Arch Area**

Zhiyong He, Thomas Berkman and Weldon Beauchamp, ARCO, Plano, Texas

The Qatar Arch is a broad, north-trending anticlinorium that separates two deep salt basins. Salt structures surrounded by an actively generating kitchen were already forming 65 million years ago. Calculated charge volumes show that the salt structures trapped most of the oil generated in the oil window so that the crest of the Qatar Arch produces only limited amounts of mostly lower-maturity (lower-gravity) oils from under-charged reservoirs. The occurrence and distribution of Jurassic and Cretaceous fields and shows appear to be principally related to charge and entrapment. Charge modeling has been used to evaluate exploration risk in the area. Migration modeling based on the Upper Jurassic Hith Anhydrite structure surface that mimics the structure of the main Arab reservoir, shows that migration patterns are affected by small-scale variations on the structure surface. Focusing by these minor features produced meandering ‘migration channels’ as well as large ‘migration shadows’. Active shows and production occur on or near the migration channels, but wells in the migration shadows are characterized by poor shows and no production. The predicted Jurassic migration patterns are consistent with geochemical analyses that demonstrate the existence of several oil families across the Arch, each of which resides in a separate fetch area defined by the migration modeling.

Charge is a significant factor in evaluating risk in many of the Cretaceous plays. This is due to the lack of identified mature Cretaceous source rocks and the 250 to 300 foot-thick Hith Anhydrite that acts as a seal between the Upper Jurassic Hanifa source and potential Cretaceous reservoirs. Cretaceous migration pathways were simulated by taking into account hydrodynamic processes and using salt piercements as possible entry points for Hanifa-sourced oil. The predicted locations and shapes of Cretaceous accumulations coincide with existing production located northeast of the structural crest.
Thomas (Tom) Berkman has a BS from Colorado College (1982) and a MS from Oregon State University. His career in ARCO, and more recently in Vastar Resources, has included assignments in exploration and production in California, the Middle East, Latin America, and deepwater Gulf of Mexico.

Weldon Beauchamp received a BA in Geology from New England College, New Hampshire, and a MSc in Geology from Oklahoma State University. He worked for Sun Exploration and Production Co. in Oklahoma City and Dallas as a Geologist in the mid-continent region before joining Sun International Exploration and Production Co. in Dallas and London to work as a new-venture Exploration Geologist in the North Sea, West Africa, South America, and the Middle East. He was awarded a PhD in Geophysics by Cornell University and joined ARCO as a Senior Geophysicist in the Middle East new venture group. His recent interests are in the structural styles and tectonic evolution of the Zagros and Atlas mountains.

Karen Higgs has a BSc in Geology from the University of Leeds (1989) and a PhD in Diagenetic and Basin Modeling (1993). She joined the Reservoir Geology Group of Robertson Research International in 1993. Karen has coordinated single well, multi-well, and diagenetic modeling studies from North West Europe and the Middle East (especially Oman and UAE). She has particular expertise on the Permo-Carboniferous sandstone reservoirs of the Gulf region. Karen left Robertson Research International in 1999.

Guy Oliver has a BSc in Geology from the University College of Wales in Cardiff, a MSc in Petroleum/Reservoir Development Geology from Imperial College, London (1992), and a PhD in Sequence Stratigraphy from the University of Plymouth (1997). After working for the Reservoir Geology Group of Shell UK Expro, he joined the Reservoir Geology Group of Robertson Research International. His work has included single well, full field, and basinal studies primarily throughout the Middle East and North Africa.

Xavier Le Varlet see p. 132

Advances in Middle East Microseepage Detection: Integrated Hydrocarbon Prospect Evaluations Using Surface Geochemistry

Daniel Hitzman, Dietmar Schumacher and Kimberley Cunningham, Geo-Microbial Technologies, Inc., USA

Recent advances in hydrocarbon microseepage detection techniques are now being applied in the world-wide exploration arena, including both frontier basins and mature...
basins in the Middle East. Hydrocarbon microseepage occurs when light hydrocarbon gases escape from petroleum reservoirs, migrate to the surface, and then create direct and indirect signatures that can be measured by surface geochemical tests. The results of these tests can easily be integrated with geophysical and geological data in order to establish whether a trap or structure is actually charged with hydrocarbons. Adding this geochemical dataset to conventional exploration programs leads to better prospect evaluation and risk assessment. One microseepage technique that has been successfully applied recently in Egypt, Oman, and Yemen is the Microbial Oil Survey Technique (MOST). First developed by Phillips Petroleum and modified by Geo-Microbial Technologies, MOST measures specific soil micro-organisms that exist only in an active hydrocarbon microseepage environment. MOST methodology includes the collection of shallow soils/sands/sediments that are then tested in the laboratory for concentrations of hydrocarbon-utilizing microbial populations. These concentrations are mapped and then compared to seismic and geologic features so that exploration leads and prospects can be screened to identify those most likely to be charged with hydrocarbons. Case studies from recent surveys will be presented in an integrated format.

**Daniel Hitzman** graduated with a BA in Geology from Carleton College and founded Geo-Microbial Technologies (GMT) in 1985. Daniel coordinates GMT’s worldwide petroleum exploration and production services, as well as petroleum microbiology R&D programs. He is a member of AAPG, SEPM, APGE, AEG, TGS, SPE, and TMS.

**Dietmar (Deet) Schumacher** is Geo-Microbial Technologies’ Director of Geochemistry and has worked for Phillips Petroleum Company, Pennzoil, and the Energy and Geosciences Institute at the University of Utah. He was awarded his PhD by the University of Missouri. Deet recently co-edited AAPG Memoir 66, Hydrocarbon Migration and its Near-Surface Expressions, and is currently editing a surface exploration case-histories volume for AAPG.

**Kimberley Cunningham** is Director of International Geology and Exploration for Geo-Microbial Technologies (GMT). Before joining GMT, and during 17 years with the U.S. Geological Survey in Denver, Kimberley conducted research in all aspects of surface geochemistry. He has authored over 44 publications and is a member of AAPG.

**Reservoir Quality Evaluation of the Oligocene-Miocene Qum Formation, Qum Basin, Central Iran**

**Javed Honarmand, Mohammed Reza Rezaee,**

University of Tehran, Iran, and **Mohammad Kamali,**

Research Institute, National Iranian Oil Company, Tehran

The Oligocene-Miocene carbonates of the Qum Formation in the Qum Basin of central Iran are reservoir rocks for oil and gas. A study of the reservoir quality of the Formation was based on 590 meters of core samples from wells Alborz-6, -7, and -11. The lithofacies were grouped into five petrofacies on the basis of lithology and petrophysical properties, including core porosity and permeability and visual porosity. The petrofacies are: (1) marl and marly limestone (core porosity 1.2–14.73%, permeability 0.01–49.55 millidarcies; the large variations in permeability are due to extensive fracturing); (2) skeletal grainstone/packstone (core porosity 10–12.9%, permeability 0.01–0.09 millidarcies); (3) dolomitized ooid grainstones (core porosity 15–20%, permeability <0.01–0.15 millidarcies); visual porosity in petrofacies 2 and 3 is more than 20% and is biomoldic, vuggy, intraskeletal and oomoldic; (4) skeletal packstone (core porosity 0.86–5.21%, permeability <0.01–0.1 millidarcies); and (5) wackstone (core porosity 1.18–6.42%, permeability <0.01 millidarcies).

The Qum Formation was deposited in a carbonate ramp environment during the last regional marine transgression. The rocks have undergone complex diagenetic changes represented mainly by various generations of calcite cementation, dissolution, dolomitization, and fracturing. Reservoir porosity is controlled by secondary porosity, (moldic, vuggy, fracture and intercrystalline), by primary porosity, and by microporosity.

The results show that although primary depositional facies influence the petrophysical characteristics of lithified rock, the petrofacies and lithofacies are not congruent. This is because the petrophysical characteristics of a rock are controlled by diagenetic processes that do not have the same effects on all rocks.

**Javad Honarmand** obtained his BSc in Geology from the University of Mashhad in 1995 and an MSc in Petroleum Geology from the University of Tehran in 1999. He focused his study on the reservoir characterization of carbonate rocks.

**Mohammad Reza Rezaee** see p. 169; **Mohammad Kamali** see p. 120.
The intra-salt carbonate stringers and silicilyte slabs of the Precambrian Huqf Group are complex deep-oil exploration plays in South Oman. They constitute a significant part of the prospect portfolio of Petroleum Development Oman. Most carbonate stringer discoveries were drilled from 1978 to 1983, but after a few disappointing wells, the play received little attention until 1996 when new (3-D) seismic data became available. The Precambrian age of the mostly shallow-water carbonates poses a challenge both in understanding the origin and spatial distribution of the various lithofacies and in building a more predictive set of reservoir models.

The Athel Silicilyte play took off in 1990 after the Al Noor-1 discovery. The Athel silicilyte is a unique source and reservoir rock characterized by light and sour oil, high overpressures (19.8 kilopascals/meter) and a high-porosity, micro-Darcy permeability, siliceous matrix rich in organic matter. After initial successes in Al Noor and Al Shomou, exploration for further silicilyte reservoirs with producible oil ran into eight commercially disappointing wells. For exploration for further silicilyte reservoirs with producible oil ran into eight commercially disappointing wells. For both intra-salt plays, the main critical success factors are seismic imaging and discrimination between the different intra-salt lithologies.

A multi-disciplinary team embarked on an integrated study, aiming at discriminating between high and low potential prospects. An improved prospect appraisal framework covers the critical elements and highlights the following prospectivity discriminators: (1) Paleogeographic setting: Areas of likely deposition of Athel silicilyte have been identified through recognition of mutually exclusive stratigraphic settings for deposition of intra-salt carbonate stringers and silicilyte. (2) Relation to structural trends: Salt tectonics created the striking salt-pillow and Haima pod geometry of the South Oman Salt Basin. Asymmetric deposition into these Haima depocentres caused flowage in the salt and swept intra-salt Athel slabs preferentially into the side of salt walls. (3) Reservoir and pressure preservation: Well reviews emphasized the importance of having both top and base salt seals to retain charge, pressure, and porosity since early Cambrian maturation. (4) Hydrocarbon charge: Measurements of a geochemical, RockEval-based productivity index in the Athel penetrations restrict the depth at which producible Athel oil may be encountered. The intra-salt carbonate stringers are interpreted as a self-charging hydrocarbon system containing carbonate source rocks in close proximity to (or even within) the dolomite reservoirs.

Prospect ranking based on these geological criteria is used to prioritize targets for application of 3-D Pre-Stack Depth and Time Migration. This is the only proven risk-controlling, potential break-through technology to increase the seismic resolution and to allow proper prospect imaging. Newly acquired high-quality 3-D seismic data and the integration with new seismic methods (for example, Pre-Stack Time Migration and new geological concepts were the main contributing factors to the successful drilling of three new deep-oil discoveries in carbonate stringers (Harweel Deep, Sarmad, and Ghafeer).

**Folco Hoogendijk is a Seismic Interpreter in the South Oman Frontier Exploration Team of Petroleum Development Oman (PDO). He has a MSc in Geology/Geophysics from the State University of Utrecht, The Netherlands. He joined PDO in 1996 and has been involved in prospect evaluation and maturation of both Athel silicilyte and carbonate stringers. Prior to joining PDO, he had worked for six years for Shell Exploration and Production in London as a Central North Sea Exploration Team Geologist, Operations Geologist, and Northern North Sea Exploration Team Seismic Interpreter.**

**Joachim Amthor see p. 47**

**Marcus Antonini has been Corporate Economics and Planning Engineer of Petroleum Development Oman (PDO) since 1999. He has an MSc in Geophysics from the University of Munich. He worked as a Seismologist from 1986 to 1989, and then joined BEB Oil & Gas Co. in Germany as an Exploration Geophysicist. He joined to PDO in 1995 in Frontier Athel exploration in South Oman and from 1996 to 1999 he was involved in the acceleration of reserve additions. He developed the Athel exploration portfolio as Theme Leader in PDO’s Athel Team during 1998, focusing on risk management through improved seismic imaging and interpretation.**

**Ide van der Molen was awarded a PhD by the Australian National University. He was a Lecturer at Utrecht University, The Netherlands, and a Researcher at Cornell University, New York. He joined Shell Exploration and Production Research in Rijswijk, The Netherlands and later transferred to Shell International Exploration and Production in The Hague. He was Senior Interpreter with the Christobal**
Biostratigraphic evidence indicates an Aptian age for the Formation, with nanofossils giving an intra-Shu’aiba lower-upper Aptian boundary and an Aptian-Albian boundary within the overlying Nahr Umr Formation. Biofacies enable the Formation to be divided into three general layers, of which the middle one has the most intensive lateral and vertical differentiation. The lowermost layer includes the underlying orbitolinid-dominated unit known regionally as the ‘Kharaiib lower dense’. It is extensively developed with only slight lateral variations. This poly-cyclic layer consists of a cyclic succession of deep marine, planktonic foraminiferal-bearing (Hedbergella delrioensis) beds that shoal upward into calcareous algal (Lithocodium aggregatum) and platey coral beds. It also includes the benthonic foraminiferal species Palorbitolina lenticularis (low morphotype), Debarina hahounerensis, Lenticulina spp., Nodosaria spp., Praechrysalidina infracretacea, and Choffatella decipiens. The ‘middle layer’ is characterized by considerable variations in the biofacies of which rudists are well-represented. A significant paleoenvironmental event caused sudden termination of the laterally extensive ‘lower layer’, and the development of submarine relief may have been caused by faulting. Colonization of local submarine highs by rudists resulted in differentiation of the basal middle layer into lagoon, rudist bank, and slope environments, each of which is characterized by a unique biofacies. The lagoon environment typically contains a lower biofacies that consists of encrusting Lithocodium aggregatum and platey corals together with the benthonic foraminifera Trocholina alpina, Palorbitolina lenticularis, and various unornamented miliolids. In the upper part, increasingly adverse environmental conditions caused a decrease in biotic diversity and a concentration of miliolids. The rudist assemblages are spatially clustered into a network of banks, and display an orderly species range from the deeper lagoonal flank to the bank complex with small elevator morphotypes (Agriopleura blumenbachii to Glossomyophorhus costatus). Elevated energy conditions near the bank crest enabled colonization by robust elevator rudists (aff. Pachytraga spp. and Petalodonta spp.) and rare specimens of the pencil-like caprinid elevator Offneria nicolinae. High-energy conditions on the crest allowed colonization by the recumbent caprinid rudist Offneria murgensis. The fore-bank regime is dominated by rudist debris that passes laterally into deeper water dominated by Palorbitolina lenticularis and the planktonic species Hedbergella delrioensis. There is evidence for tempestite-triggered allochthonous beds of shallow-marine bioclasts within this regime that fine upward into authochthonous, planktonic foraminiferal-bearing muds. The marked contrast in biofacies between the middle and upper layer suggests a sequence boundary, as paleobathymetry increased substantially.

The upper layer is typically characterized by the widespread occurrence of Agriopleura blumenbachii, although...
Glossomyophorus costatus and Offneria murgensis are also present but with a much reduced extent. The elevator rudist Himerelites douvillii is particularly well-developed along the eastern flank of the region. Two distinct morphotypes of A. blumenbachii are present, characterized by a rapidly enlarging ‘V’ form and a slower enlarging, cylindrical ‘U’ form. Intermediate morphologies have not been seen, and this may suggest two distinct species. The upper layer is dominated by deep lagoonal conditions in which foraminiferal diversity is typically high. Species include Praechrysalidina infracretacea, Debarina hahuonerensis, Vercorsella arenata, textularids and miliolids. Within the lagoon, the dasyclad alga Hensonella/Salpingoporella dinarica is well-represented. On the outer flanks of the banks, it is replaced by Coptocampylodon lineolatus. The upper layer contains localized layers or pods of gray, non-calcareous, pyritic clay that may be related to karst-fill that took place during emergence of the top of the Shu’aiba Formation.

G. Wyn Hughes is a Consultant Geologist in the Research and Development Division of Saudi Aramco. He received his BSc, MSc, and PhD from Prijysgol Cymru (University of Wales), Aberystwyth, UK. His nearly 30 years of experience in biostratigraphy include 10 years as a field geologist/biostratigrapher with the Solomon Islands Geological Survey, and 10 as a Biostratigraphic Consultant and Unit Head of the Middle East-India region with Robertson Research based in Singapore and Wales. His professional activities are focused on the integration of micropaleontology with sedimentology to enhance sequence stratigraphic interpretations of Saudi Arabian carbonate rocks. Wyn maintains links with academic research through his activities as an external examiner for the University of Wales and as an Adjunct Professor of the King Fahd University of Petroleum and Minerals, Dhahran. He is a reviewer for GeoArabia, and a member the British Micropaleontological Society and DGS, and a Fellow of the Cushman Foundation for Foraminiferal Research.

Recognition of Cryptic, High-Frequency Depositional Cycles Within the Khuff-C Carbonates in the Subsurface of South-Central Saudi Arabia

G. Wyn Hughes and Rami Kamal
Saudi Aramco, Dhahran

Carbonates of the Permo-Triassic Khuff Formation form major and important hydrocarbon reservoirs in Saudi Arabia. Cores from two Khuff penetrations, and one measured exposed section, in central Arabia have been examined by means of sedimentology, petrography, and micropaleontology in order to improve the regional interpretation of the depositional environment. The resulting model will effect current developments toward elucidating the sequence stratigraphy of the Khuff carbonate-evaporite cycles in this region, and favourably impact modeling of the reservoir-prone facies.

Although the carbonates are typically poor in both macro and micro biocomponents, and diversity is typically low to very low, they are documented here for the first time from Saudi Arabia. Semi-quantitative micropaleontological analysis has shown that the carbonates consist of a series of composite cryptic layers up to 30 feet thick, each of which is composed of up to 10 thinner layers. The base of each layer is characterized by a relatively rich and diverse benthonic foraminiferal assemblage, the diversity of which gradually decreases upwards and is gradually replaced by an almost exclusively algal-gastropod assemblage. Benthonic foraminiferal species include Nodosinelloides ronda, Cryptoseptida fragilis, Geinitzina spp., Pachyphloia cukurkoyi, Pachyphloia ovata, Globivalvulina spp., Hemigordinia schlumbergeri, Eoelasiodiscus spp., Glomodiscus spp., cf. Rapoconilia spp., Frondina permica, Calvezina spp., cf. Yangchienia spp., Agathammina spp., Glomospira tenuifistula, and Lunucammina spp. Calcareous alga include Gymnocolodium belerophontis, Pseuoepimastopora spp., and Mizia velerbitiana. Slight variations of this biofacies succession are repeated within each cycle and are considered to represent a biotic response to a gradual decrease in water depth. In terms of sequence stratigraphy, this cyclic succession may be subdivided into parasequences, as there is no evidence for unconformities within the carbonates. There is no evidence for biofacies associated with lowstand conditions, but the relatively richer foraminiferal assemblages at the base of each cycle are related to the transgressive part of a depositional cycle, and the upper, shoaling succession is associated with highstand conditions. It will be demonstrated that the biofacies cycle boundaries are readily equated with textural and lithological variations in the core.

G. Wyn Hughes see this page; Rami Kamal see p. 120

Motion of the Arabian Plate from the Late Devonian to the Present-Day: Relationships to Regional and Global Tectonics

Michael Hulver
Saudi Aramco, Dhahran

A series of maps have been generated to illustrate the motion of Arabia and adjacent continents from the Late Devonian to the present-day. Using global plate motion data and software from the Paleogeographic Atlas Project at the
University of Chicago, Eastern Hemisphere continental positions were reconstructed at 10 million year intervals from 360 to 0 million years ago (Ma). Each individual image shows geologic time (in millions of years), stratigraphic time, and the appropriate Saudi Arabian geologic unit. These images have been integrated to produce a computer animation of Late Paleozoic to Recent plate motions, using Quicktime video software from Apple computer.

In Late Devonian times (360 Ma), Arabia was positioned at 30°S latitude, and had moved to 50°S by the mid-Carboniferous (330 Ma). This relatively poleward position allowed the formation of glaciers in southern Arabia that were the source of significant coarse clastic reservoir rocks in Oman. At the same time, the Appalachian-Hercynian Orogeny was occurring in Europe, North Africa, and North America, after which Arabia began to move northward. The northern margin of Gondwana was the site of continental rifting from the Late Carboniferous through the Permian, when several microcontinents (such as, central Iran, Turkey, Lhasa, Sibumasu) began moving northward across the Tethys. The precise shapes, rates of motion, and trajectories of these continental fragments are poorly understood, but it is known that most of them collided with the southern margin of Eurasia during the Mesozoic. By the Early Jurassic (190 Ma), Arabia had moved northward to straddle the Equator. It moved southward, however, when the central Atlantic began to open between North America and Africa, and the Indian Ocean began to open between Africa and East Gondwana (India, Australia, Antarctica, and Madagascar). From the Cretaceous onwards, the Indian Ocean is characterized by the dispersion of its continents and the eventual collision of Arabia and India with Eurasia in the Tertiary.

These late Paleozoic to Recent plate movements provide an important regional context to Arabian sedimentary facies and petroleum habitat. In the late Paleozoic, for example, Arabia was in the temperate belt below 30°S latitude, thus explaining the propensity of Devonian through mid-Permian clastics. Arabia’s post mid-Permian position within 30 degrees of the Equator facilitated the maintenance of an enormous carbonate platform, future home of the Middle East’s huge petroleum reservoirs. With reference to late Paleozoic microcontinent rifting, it follows that the so-called ‘Hercynian’ events of the eastern Arabian plate may be related to an extensional, rather than collisional tectonic regime.

The utility of these maps can be enhanced by the addition of sedimentary facies, fault patterns, or petroleum occurrences. For example, the Ghawar oil field is highlighted in each image, and thus it can be easily evaluated in a paleogeographic context. Using such an approach, improved understanding of the local petroleum geology can be gained by studying its relationships to global hydrocarbon habitats. This plate tectonic visualization is already being used by several groups within Saudi Aramco to examine the regional and global contexts of Arabian geology, petroleum habitat, and biostratigraphy.

Michael Hulver joined Saudi Aramco’s Exploration Technology Department in late 1998, where he is concentrating on Paleozoic regional studies. He holds a BA in Geology from Williams College, and a MSc and PhD in Geology from the University of Chicago. He is a longtime member of the Paleogeographic Atlas Project at the University of Chicago, where he worked on regional and global studies of carbonate distributions, paleogeography, paleoclimates, denudation, and plate tectonics. Michael spent a year as a postdoctoral fellow at Argonne National Laboratory, studying the relationships between Milankovitch cycles, climate, sediment flux, and depositional systems. His industry experience includes internships and consulting with Marathon and Amoco, working on projects from the Mediterranean Basin, North Africa, and the Middle East. He is a member of the Geological Society of America and DGS.

Jens Hustedt, Volker Köhler, Baker Atlas GEOScience, and Wouter Smits, Petroleum Development Oman

The Athel silicilyte in the Al Noor field, located in the South Oman Salt Basin, is a unique source and reservoir rock, entrapped in a salt dome at depths of 4 to 5 kilometers. The reservoir was discovered in 1989. It is characterized by a high-porosity, low-permeability silica matrix rich in organic matter, filled with light sour oil at hard overpressures. Without any analogs, correlation in this unique reservoir has posed major challenges. Image logs of six wells were studied to evaluate the structural environment of South Oman’s Al Noor silicilyte field in support of a structurally consistent reservoir framework prior to 3-D reservoir modeling. The image data covers most of the Lower Cambrian Athel Formation with its Al Shomou Silicilyte and Thuleilat Shale Members as well as the top of the underlying ‘U’ Shale Formation. The main focus of the image-log studies has been on the identification and statistical analysis of bedding anomalies, fractures and faults.

A new classification of bedding disturbances was developed to geometrically and statistically analyse anomalous bedding features and their attitudes from image logs. Specific types of bedding disturbances have proven to be indicators of low-
angle detachment surfaces (confirmed by observations from core and seismic data) that frequently separate sections of anomalous structural dip in several structural sub-units. A consistent apparent direction of mass transport related to ductile early gravitational sliding has emerged from the reconstruction of the orientation of overturned folds. The direction is oriented away from the basin center and, as a result, the paleo-slope direction has had to be reconstructed. Different bedding and fracture orientations in the upper and lower parts of the Al Shomou Silicilyte, separated by a major potential detachment correlating with a pronounced seismic marker horizon, indicate a key tectonic event of field-wide significance.

In the absence of outcrop analogs, this integrated work allowed a detailed insight into the structural complexity of this unique intra-salt play. The results of this study, integrated with a detailed 3-D seismic interpretation has helped to constrain a 3-D reservoir model that will be used to optimize the locations of the first development wells, to be drilled in 2000.

**Jens Hustedt** graduated in 1996 from the Technical University of Clausthal (Germany) with a MSc in Geology. During his studies, Jens worked on several assignments in the Department of Geology. In 1996 he joined the Bahrain Geoscience Center of Western Atlas Logging Services (now Baker Atlas) as a Geologist and is presently assigned to the Oman Geoscience Center. Jens has been involved in the geological interpretation of several Middle East oil fields and is currently specializing in sedimentary and structural interpretations of borehole image data from miscellaneous hydrocarbon reservoirs in Oman.

**Volker Köhler** graduated from the Technical University of Clausthal, Germany in 1993 and received his MSc (hons) in Geology in 1997 from Rhenish Westfalian Technical University of Aachen, Germany. His research, in collaboration with several companies, investigated the occurrence and development of natural and hydraulically induced fractures in coal with respect to potential pathways for coal bed methane. During his studies, Volker worked on several assignments in the geology and petroleum departments of Clausthal and Aachen universities. In January 1998, he joined the Bahrain Geoscience Center of Baker Atlas where he specializes in geological characterization of Middle East reservoirs using borehole image logs.

**Muhammad Ibrahim**
Target Exploration Consultants, UK

Global hydrocarbon exploration records attest to many early ‘dry holes’ or ‘dry’ anomalies becoming hydrocarbon producers or oil fields with advancement in seismic, gravity, magnetic, geochemical, risk-analysis, logistics, exploration, drilling and/or production methods. Examples from Libya are wells J1-85, and K1-13 classified as ‘dry holes’ on completion but which proved to be producers at later dates. J1-85 (Aquitaine) is now located in Block NC177 of Lundin Oil and Red Sea Oil and K1-13 (Mobil Oil) is in Block NC149 operated by Sirte Oil. They are probably only two of several ‘un-discovery wells’.

Anomalous geothermal gradients occur in rocks overlying hydrocarbon traps. The anomalies are mainly caused by focused migration of heat-convective subsurface fluids into shallow reservoir closures. A quick-look analysis and mapping method of the geothermal gradient was tested on databases of two exploration time-frames of the Al Hagfa area of the central Sirte Basin of Libya. Early (pre-1970) bottom-hole temperature data of exploration and development wells were used to generate geothermal gradient contour maps and identify geothermal gradient anomalies associated with proven hydrocarbon traps. The identified models were then used to delineate similar geothermal gradient anomalies that are probably associated with untapped or bypassed hydrocarbon traps. Late (pre-1994) bottom-hole temperature data from the same area were similarly analysed and mapped, and compared with the earlier (pre-1970) maps and anomalies.

The test found high geothermal gradient anomalies to be associated with most of the known oil and gas fields in the...
two exploration time frames, as well as with some anomalous ‘dry holes’. Analysis of the pre-1970 database delineated a geothermally anomalous ‘dry hole, which when recognised as an ‘un-discovery well’ became a producer in 1988. High geothermal gradient anomalies are associated with oil and gas fields in basins world-wide. They can be used to locate hydrocarbon migration fairways and identify potential ‘un-discovery’ wells.

Muhammad Ibrahim is the Regional and Development Geologist with Target Exploration Consultants, UK. He holds a BSc in Geology and a MSc and PhD in Petroleum Geology. He has more than 15 years experience in exploration and development geology. He has worked as a Geologist with Lasmo Grand Maghreb and Lasmo International, London, in 1991, and with Mobil Oil Libya/Jebe Oil Operations in Tripoli, Libya. Muhammad was Assistant Professor and Head of Department of Petroleum Geology at King Abdul Aziz University, Jiddah from 1978 to 1980. He is a member of the Iraqi Geological Society, AAPG, SPE, PESGB, and COGS.

The Huqf/Haima Hydrocarbon System of Oman and the Terminal Phase of the Pan-African Orogeny: Evaporite Deposition in a Compressive Setting

Peter Immerz, Consultant
W. Heiko Oterdooom, Consultant
and Mohammed el Tonbary
Petroleum Development Oman, Muscat

Newly available deep regional seismic data have led us to describe the geological development of Oman during the Vendian and Cambrian in terms of the latest phase of the Pan-African orogeny. Pre-Vendian basement accretion was followed by deposition in a strike-slip setting (escape tectonics of the Ghadir Manqil Formation) and subsequent carbonate platform development (Nafun Group) during a period of relative tectonic quiescence. Renewed compression during Early Cambrian Ara/Nimr times caused regional warping and folding, locally progressing into reverse faulting and even thrusting, and produced a pattern of arches (anticlines and basement highs) and compressive sag basins (synclines). Restricted conditions in those basins initially led to syntectonic deposition of salt, source rocks, and Athel Silicilies in their deeper parts, rimmed by and interfingering with carbonates and anhydrites on the basin flanks. This was followed by the influx of coarse clastics (in particular from the west and southwest) that overpowered the restricted, clastics-starved setting and caused the onset of halokinesis. Eventual uplift and erosion are documented in the Angudan or base Amin unconformity.

It is speculated that the salt basins of Oman represent the eastern extension of the much more extensive Gulf Salt Basin Complex farther west that, by this analogy, should also represent a series of basement arches and intervening synclines developed in the same compressive tectonic regime.

The association of tectonic and ensuing depositional styles observed in the Huqf Supergroup and the overall dimensions of the system, as well as the geochemical characteristics of the Ara volcanoclastics and their intrusive equivalents, are compatible with a compressive intra-plate setting in the deformed foreland of a major orogen (for example, the Rocky Mountains foreland in the northwestern United States). This leads us to conclude that the welding together of the East and West Gondwana continents was completed during the Vendian and Early Cambrian. Only in the Middle Cambrian was an extensional to transtensional tectonic regime established, which is characterized by the rapid deposition of clastics sourced from the Pan-African orogen and its uplifted foreland in the west and south and eventual backstepping over the eroded remnants of the orogen. These late Proterozoic and early Paleozoic structural and depositional processes have produced a set of stacked basins that make up the deep Huqf/Haima hydrocarbon system and contain the least explored portions of Petroleum Development Oman’s portfolio.

Peter Immerz received an MSc in geology from the University of Munich in 1980. From 1980 to 1998 he worked for Shell as an Exploration and Production Geologist in The Netherlands, Norway, Papua New Guinea, Oman, Yemen, and Canada in various structural and depositional settings on basin evaluation, prospect appraisal, and field development. In 1998, he returned to Petroleum Development Oman and was responsible for a tectonostratigraphic review of the South Oman Salt Basin. Peter is currently working as an independent Consultant.

W. Heiko Oterdooom joined Petroleum Development Oman in 1995 as a Senior Exploration Geologist in diverse functions ranging from operational stratigraphy and geological studies to frontier exploration. He has 18 years exploration experience as Regional Geologist with Shell in oil shales, the North Sea-Norwegian Sea, and the Far East. Heiko was educated at Berkeley and Zürich and was awarded a PhD in Petrography from the Federal Institute of Technology, Zürich in 1981. He is now an independent Consultant. Heiko is also a licensed guide to the Dutch tidal flats.
Carbon and Oxygen Isotope Stratigraphy of the Upper Thamama Group (Lower Cretaceous), Abu Dhabi

Masatoshi Ishibashi, Japan National Oil Corporation and Masayoshi Suzuki, Abu Dhabi Oil Company, Ltd., Japan

The upper part of the Thamama Group is one of the most important reservoir successions in Abu Dhabi. The Group is mainly composed of limestones deposited on a vast carbonate platform during the Early Cretaceous. Carbon and oxygen isotopic analyses were carried out in order to study the following parameters relating to the upper Thamama Group: (1) paleo-oceanographic conditions during deposition; and (2) the relationship between paleo-oceanographic conditions and reservoir quality. Samples were collected at intervals of 5 feet from cores in an offshore field. Although some abnormal peaks in the stable isotope intensity profiles were found, the carbon and oxygen isotopes appear to have maintained their original oceanic values. The small-scale variations in profiles, which correspond to third-order sea-level fluctuations, show a good correlation with porosity curves. Dense zones, which have a relatively high lime mud content and abundant stylolites, were deposited during transgressive phases, whereas the overlying porous zones of grain/packstones were deposited during highstand phases. The abnormal peaks are confined to tight zones and are considered to be due to diagenetic processes and/or influx of terrestrial materials.

Masatoshi Ishibashi received his MSc in Geology from the University of Tsukuba in Japan in 1987 and joined Japan Energy Corporation as an Exploration Geologist. In 1991, he was transferred to the Abu Dhabi Oil Company (Japan), (ADOC), and in 1994 Masatoshi joined Japan National Oil Corporation on secondment to ADOC. Since working for ADOC, he has been involved in studies of carbonate reservoirs in the Middle East.

Masayoshi Suzuki is Chief Geologist with Abu Dhabi Oil Company (Japan), (ADOC). He has been with ADOC since 1980. Masayoshi received a BSc from Hokkaido University in 1980. He is interested in carbonate petrology and reservoir geology.

Recent and Imminent Developments in Multicomponent Seismic

Ian Jack and Leon Thomsen, BP Amoco, London

3-D seismic technology is well documented as being a major contributor to the successful finding and development of hydrocarbons. However, its rate of technical development has slowed as it has matured, and there remain strong business incentives to find radical improvements to the technology if at all possible. For example, the vertical resolution of the seismic method far short of what is needed for good reservoir characterization, the attenuation of “noise” such as multiples is inadequate, and our ability to visualize fluids is very limited so far. One result of these shortcomings is that the average recovery factor from our reservoirs is very low—typically around 50%. Meanwhile, visualization technology is racing ahead, and is waiting for better input data. Seismic technologies which show the clearest potential for a major step forward are in multicomponent and time-lapse seismic, and this presentation will show several examples of both of these technologies.

Earlier research work conducted on multicomponent seismic during the 1980s was land-based, and some encouraging results were obtained, especially following the discovery of the ubiquity of azimuthal anisotropy. However, in general the technique failed to find routine acceptance, probably due to the generally low frequencies recovered and to the limitations on spatial sampling imposed by the instrumentation of the day. It was not until a marine example was shown, with excellent data quality, that interest picked up again. Initially, this was directed at the problem of imaging through gas clouds or chimneys, and several good examples have now been demonstrated. But gas clouds are only one of several problems which can be impacted—the potential benefits to be had from multicomponent seismic data, especially in the marine environment, are tremendous. They include improved bandwidth and resolution, improved multiple rejection, improved illumination and image quality, additional information on fluids and rocks, and interpretation of anisotropy giving information on stress and fractures. All this will lead to much better reservoir characterization.

If emplaced or ‘permanent’ detector systems were to become readily available, further advantages would accrue due to the improved coupling and the low noise environment, which

114
would be achieved. The other technology with major potential is time-lapse seismic—already enjoying some commercial success using conventional techniques. Here too, the use of emplaced detector systems will give additional benefits resulting from the lower noise environment and improved repeatability. These will improve the threshold for detection of the seismic effects of pressure and fluid changes. Furthermore, once emplaced, these detector systems will allow re-shoots at minimal cost, on a schedule driven by the reservoir engineers. Frequent low-cost re-shoots will allow oversampling in time, which will improve yet again the signal-to-noise ratio and hence the detectability of fluid movement.

It seems inevitable that these two major new technologies will merge. We will then have what we might call an ‘electric oilfield’, and we will begin to manage our reservoirs using the additional information available, combining this with the data which will come from downhole instrumentation. The challenge will be to speed the implementation of these systems because, historically, new technologies take years to achieve acceptance. ‘Cost’ and ‘value’ have to be understood and reconciled, and this takes time. A strong enabler would be the availability of affordable emplaceable detector systems.

**Ian Jack** graduated in Physics from the University of St. Andrews, UK. He began his career with GSI in 1968, initially in the field, and subsequently in seismic data processing before moving to seismic software and systems development in Dallas. He joined the Technical Service Division of BP Exploration in 1978, and became Adviser and Technology Leader for 4-D and multicomponent seismic in BP Amoco’s London office. Ian is a member of SEG, EAGE, EAPG, and PESGB. He is an editorial adviser for SEG’s First Break, and has served as a member of the UK’s Earth Science and Technology Board of NERC. He was a Vice-President of the SEG in 1992–93 and has served on SEG’s Technical Standards Committee since 1981. He was the SEG’s inaugural Distinguished Instructor in 1998 with a course entitled, Time Lapse Seismic in Reservoir Management. He has interests in most aspects of geophysics and has published in SEG, EAGE, AAPG, and OTC.

**Leon Thomsen** has a BS from Caltech (1964) and a PhD from Columbia. He joined Amoco in 1980 following an earlier career at State University of New York, Binghamton. He was first at Amoco’s Tulsa Research Center, and in 1994 joined Amoco’s world-wide Exploration Department in Houston. Following the merger with BP, he is now Principal Geophysicist in BP Amoco’s Upstream Technology Group in Houston. Leon was given the Fessenden Award in 1994 by SEG and was its Distinguished Lecturer in 1997. He is the current Chair of its Research Committee. He and his colleagues received EAGE’s Best Paper Award in 1997. He was recently named an Honorary Member of the Geophysical Society of Houston.

**Land Seismic Data Improvement**

Ian Jack, BP Amoco, London, Mike Golding and Andy Peters, Schlumberger, Gatwick, UK

It is much more difficult to improve the seismic method on land than in the marine environment. Offshore, we have seen dramatic technological improvements over the last 5–10 years, with ever more efficient vessels capable of towing as many as 20 detector cables. These boats acquire good quality data very fast, and with much of the data processing taking place on the vessels themselves, the first seismic data volumes are available to the interpreter within a short time of the completion of the work. Again in the marine environment, we have seen technology advance with converted wave imaging, utilising multi-component data via ocean-bottom detection systems. The early results shown by Statoil, BP Amoco, Geco-Prakla, Chevron, and some university groups, have been exciting demonstrations of the potential of these methods.

On land however, it is unusual for a large 3-D seismic survey to deliver results within a year of commencement. The cost is much higher than offshore, the environmental impact is greater, data quality is inherently poorer, and is reduced further by the lower fold of cover (‘seismic effort’) that prevails on most land surveys. Naturally, attempts have been made to improve land-data quality and cost. The recording instrumentation, the vibratory seismic sources, and the understanding of the methodology have all progressed in recent years. These have worked, but have been much more incremental than in the marine environment, and we have not seen any significant take-up of the multi-component technology that has been available for much longer on land.

In general, progress in one area of technology is often held back by lack of progress in others. Conversely, major breakthroughs in one area are often made possible by breakthroughs in other areas. It is beginning to look possible that the dramatic improvements in capabilities, performance and reliability of digital electronic hardware might enable significant improvements to be realised in land-seismic quality and cost. Utilization of new technology of course needs proof-of-concept to be demonstrated. This presentation discusses some of the future technology and will show some of its proofs of concept in experimentation designed and conducted by a joint exercise between Schlumberger Geco-Prakla and BP Amoco.

**Ian Jack** see this page; **Andy Peters** biography not available.
Mike Golding is Vice President, New Business Development and Industry Affairs with Schlumberger Geco-Prakla based in UK. He has a BSc in Geology (with Math and Physics) from London University and a MBA from Southern Methodist University, Dallas. He joined Texas Instruments/GSI Ltd. in 1963 as a Marine Quality Control Seismologist (working on analog recordings) in the North Sea. He worked for Texas Instruments/GSI for 26 years. From 1965 to 1970, he was Data Processing and Interpretation Supervisor for Europe, Africa, and the Middle East based in UK and the Middle East. In 1971, he became Land Exploration Manager for the region. He was Vice President/Technology Development and Worldwide Data Processing from 1980 to 1990 based in Dallas and Houston. In 1991, he became Vice President/General Manager—Saudi Operations of Haliburton Geophysical/GSI SA in Dhahran. In 1996, he joined Schlumberger Geco-Prakla as Vice President/General Manager-Land/TZ Operations.

A Geologic Curiosity in NW Saudi Arabia: the Jabal Rayah Ring Structure

Dominique Janjou, Robert Wyns, Philippe Chevremont, Bureau de Recherches Géologiques et Miénières, Orleans, France, Mohammed Halawani and Abdallah Memesh, Saudi Arabia Deputy Ministry for Mineral Resources, Jeddah

During regional geologic mapping at 1:250,000 scale by a Deputy Ministry for Mineral Resources/Bureau de Recherches Géologiques et Miénières joint team, a curious and isolated ring structure with a diameter of 5 kilometers was discovered in the Jabal Rayah area 68 kilometers northeast of Tabuk. It was mapped in detail at a scale of 1:20,000.

The Jabal Rayah structure deforms rocks of the Qusaiba and Sharawra members of the Silurian Qalibah Formation and, to a lesser extent, the Late Silurian to Early Devonian Tawil Formation, resulting in nearly 600 meters total thickness of deformed sedimentary succession. The deformed zone is structurally bound by a flexure that passes laterally into a normal fault inclined towards the center of the structure (‘crater rim’). Fracture cleavage appears in strongly folded fine-grained silty-sandstone of the Sharawra, in relation with subhorizontal subtractive thrust faults and folds verging to the center of the structure.

The heart of the structure is intensely folded; this zone of disharmonic folding also corresponds to a slight swell in the central part of the structure (central uplift). The central uplift (4 kilometers in diameter) is surrounded by a major synclinal fold. The circular axis of this syncline is concentric with the external limit of the structure, and corresponds to the main ridge which is about 150 meters high on average, with a peak of about 230 meters that dominates the surrounding plain. The central part of the ring, about 2 kilometers in diameter, is concave with a ‘scooped-out’ appearance. The geomorphologic and structural characteristics of the Jabal Rayah ring structure are not consistent with either a diapiric, glacial or magmatic origin, but they appear to be the result of a meteorite impact. Large fragments of the meteorite are unlikely to have survived vaporization on impact. Furthermore, Mesozoic and Cenozoic erosion have scattered any remaining fragments. The exact age of this astrobleme is unknown (the youngest deformed rocks are post-Early Devonian), but it predates the present drainage pattern.

Robert Wyns received his PhD in tectonics from the University of Paris in 1980. He joined the Bureau de Recherches Géologiques et Miénières in 1981. He worked mainly on the Hercynian Belt in western France during the 1980s. He was involved in the geologic mapping program of Oman between 1989 and 1992, and in geologic mapping in Saudi Arabia between 1992 and 1994. Robert has been in charge of research and development projects on surficial deposits characterization and mapping in France since 1995. He is a member of the French Geologic Society, and the Scientific Council of the French National Research Program.

Philippe Chevremont received his PhD from the University of Lyon (France) in 1975. He joined the Bureau de Recherches Géologiques et Miénières in 1975. He was involved in mineral prospecting and geologic mapping in Saudi Arabia (1975–81), Oman, Togo and Morocco. Since 1981, he has worked mainly on the Hercynian Belt in France and
particularly in the Rochechouart area where he mapped and studied an eroded astrobleme with an initial diameter of about 20 km, displaying all the stages of the shock metamorphism due to a meteorite impact.

Mohammed Halawani see p. 95

Abdallah Memesh is a Geologist in the Mapping Department of the Bureau de Recherches Géologiques et Minières Geological Mission in Jiddah. He has a BSc from King Abdul Aziz University, Jiddah (1993). Since 1994, he has been involved in Phanerozoic mapping projects particularly of the Paleozoic of north and northwestern Saudi Arabia.

Tectonic Development, Basement Architecture and Hydrocarbon Potential of Northern Arabia

Saad Jassim, Leeds University
and Ian Somerton, GETECH, Leeds University

An integrated geological and geophysical study of the northern part of the Arabian Plate (including southwest Iran and southeast Turkey) was made to establish the history of the sedimentary cover down to the Precambrian basement. It is the most comprehensive basement-depth evaluation and basin analysis of the region to date. It made use of surface geology, gravity and magnetic data, and information from more than 400 wells; in addition, over 200 published and unpublished papers were evaluated. It provides for a better understanding of the basin history, petroleum potential and source-rock maturation of northern Arabia.

The depth to the basement was calculated from the thickness of accurately correlated time-rock units and enhanced by regional 2-D gravity modeling and 3-D magnetic and gravity inversion. Thickness and depth maps were produced for the sedimentary units together with tectonic zones based on similar geological histories. The northern part of the Arabian Plate was strongly influenced by ‘Caledonian’ and ‘Hercynian’ events in its western part and by ‘Alpine’ events in the east. The most prominent basement feature, reflected by a strong gravity high, is the north-south oriented Hercynian Salman-Summan basement that forms a divide between an inverted Paleozoic basin to the west and a subsiding Alpine basin to the east. It is an activated segment of the Precambrian Ar-Rayyan collision zone of central Arabia that was reactivated in Late Carboniferous to Early Permian times. It truncates earlier Caledonian blocks oriented northeast that were activated during the Late Silurian to Middle Devonian. The Late Jurassic to Late Neogene Alpine trend overprints both systems of blocks and progressively truncates the older units toward the north.

Saad Jassim received his BSc from Baghdad University and his PhD from Leeds University in 1965 and 1970, respectively. From 1970 to 1976, he was an Assistant Professor at Baghdad University. In 1976, he joined the Geological Survey of Iraq as Chief Geologist. Since 1993, he has been working as a Research Fellow and Consultant in the School of Earth Sciences, Leeds University. Saad has undertaken multi-client studies dealing with the petroleum geology of Iraq and northern Arabia. He is currently engaged in basin evaluation studies of North Africa.

Ian Somerton received his BSc in Physics from Bristol University in 1976 and a MSc in Applied Geophysics from Birmingham University in 1980. Ian worked for Robertson Research International, UK as a Geophysicist before joining GETECH at Leeds University as Senior Geophysicist. He specializes in the processing and interpretation of gravity and magnetic data and has undertaken many studies related to oil and mineral exploration.

Subsurface Velocity Variations in Awali and Adjoining Areas—a Comprehensive Case Study

Waleed Ahmed Jawad and Kusampudi Nagaraju
Bahrain Petroleum Company

This study is based on sonic, vertical seismic profiles, and checkshot data of about 100 wells drilled in Bahrain’s Awali field and adjoining offshore areas. Interval and average velocity data collected from various geological formations/units were extensively evaluated through simple statistical and cross-plotting techniques that facilitated a better understanding of lateral and temporal velocity distribution patterns. Formation-based velocity distribution maps highlighted the anomalous areas while realizing their geological significance in terms of reservoir fluids and/or depositional environment. A qualitative and quantitative assessment of sonic velocity drifts from typical geological units was also attempted in order to establish a reliable area-dependent drift-correction pattern. The study helped in deriving better layer-velocity estimation in areas of insufficient or no velocity control, and in preparing depth maps from seismic time data. It also helped in appreciating the impedance behavior of reservoir and non-reservoir rocks. General drift trends established by the study enable sensible corrections to be made while deriving time-depth functions based on integrated sonic transit times in the absence of checkshot surveys.
GEO 2000 Abstracts

Waleed Jawad joined the Bahrain Petroleum Company (BAPCO) in 1996 as an Exploration Geologist. He has a BSc in Geology from Cairo University (1994). He is involved in the exploration and development activities of BAPCO and his most recent studies have been the exploration and evaluation of the Awali and East Bahrain Offshore areas and the hydrocarbon assessment of the pre-Khuff Unayzah reservoir on Bahrain Island. He was instrumental in conducting a comprehensive seismic study by consolidating various velocity datasets. He is now working on a group exploration evaluation of the Mishrif ‘Rubble Zone’ and the NahrUmr Formation on the flanks of the Awali Dome. Waleed’s professional interests are in the field of sequence stratigraphy.

Kusampudi Nagaraju is a Geophysicist associated with the Exploration and Development Division of the Bahrain Petroleum Company (BAPCO). He received a MSc in Marine Geophysics from Andhra University College of Science and Technology, India in 1979. He started his professional career in 1980 as a Geophysicist with the Indian Oil and Natural Gas Corporation (ONGC). He worked for ONGC for 15 years in various capacities and as Manager (E&P) of Reliance Industries Ltd. for 3 years. He joined BAPCO in 1998. Kusampudi has more than 10 years experience in 2-D and 3-D seismic data interpretation, 5 years in 3-D data processing, and 4 years in seismic data acquisition quality control. He is at present involved in the exploration evaluation of Bahrain Island and adjoining offshore areas with the help of recently acquired 3-D seismic surveys.

The Permian Gharif Formation, Oman: Development of a High-Resolution Sequence Stratigraphic Framework and Implications for the Paleogeographic Evolution of a Transgressive-Regressive Depositional System.

Neil Jones, Robert Knox, Aida Al Harthy and Masoud Al Mahrazi
British Geological Survey, Nottingham
Petroleum Development Oman, Muscat

A stratigraphic study was made of the Permian Gharif Formation across Oman. Its aims were to place the Gharif into a consistent sequence stratigraphic framework and to construct regional paleogeographic maps to characterize the observed facies changes. Information from about 280 wells was used, integrating core data, geophysical logs, and borehole images, together with biostratigraphic and heavy mineral datasets.

Traditionally, a threefold division (lower, middle and upper) of the Gharif is made. However, this study recognized eight new major units, two each in the lower and middle parts and four in the upper part. Transgressive and highstand marine facies characterize the two cycles of the lower Gharif. Overall regression at the base of the middle Gharif (Cycle 3) is marked by sequence boundary formation and a prominent shift in facies belts. Alluvial-plain deposits consisting of northerly directed sheetflood-sandflat complexes become dominant. A terminal ephemeral fluvial system is indicated by the presence of 30-meter-thick stacked, well-drained mudstone paleosols in the north. A fundamental change in the paleogeography occurs in the upper part of the Gharif, marked by the establishment of large, westerly flowing fluvial-channel systems, and floodplain areas. This paleocurrent switch is supported by provenance-related changes in heavy mineral assemblages. Stacked channel systems occur above sequence boundaries and produce gross upward-fining cycles, each about 30 meters thick. Cyclicity can be related to variations in sediment flux and accommodation space. Fluvial deposition was terminated by the Khuff transgression.

This work is significant as it integrates all of the stratigraphical and sedimentological data for the Gharif Formation throughout Oman. The recognition of important changes in paleogeography, sandbody type and orientation has important applications for a variety of geological studies. These include frontier and near-field exploration (for example, play analysis and prospect identification) and also production geologists’ understanding of field-scale sandbody connectivity and reservoir modeling.

Neil Jones joined the British Geological Survey (BGS) in 1991 after receiving a PhD for his work on the sedimentology and sandbody architecture of Upper Carboniferous fluvio-deltaic sediments in the UK. He is currently a lead Sedimentologist within the BGS and specializes in the application of sedimentological and sequence stratigraphical studies to solving stratigraphical and reservoir geological problems for the hydrocarbons industry. Neil has carried out a range of geological studies in the UK and overseas, including Germany (Upper Carboniferous, Rotliegend, Bunter), Hong Kong, and Oman.

Robert Knox see p. 127

Aida Al-Harthy is a Studies Stratigrapher with Petroleum Development Oman (PDO). She has worked for PDO for five years providing stratigraphic services to Exploration and Production. Aida has a BSc in Geology and a MSc in Petroleum Geology from the University of London.

Masoud Al Mahrazi joined Petroleum Development Oman (PDO) in 1982 as a Draughtsman in the Topographical Section. In 1992, he received an ONC in Engineering and in 1995 undertook a one-year geology course at Oxford.
Brookes University, UK. Subsequently, he rejoined PDO to work in the Exploration Team as a Technical Assistant, contributing to the Regional Structural Cross-Sections of Eastern Flank of Oman. In 1997, he joined the North Oman Shallow Oil Team and participated in the Gharif Framework Study. Masoud is now working in the Frontier Exploration Asset Team as an Assistant Interpreter.

Paleozoic Hydrocarbon Migration-Path Modeling in the Northeastern Part of the Arabian Basin, Saudi Arabia

Peter Jones, Patrick Rutty, Robert Johnson, William Carrigan, and Henry Halpern, Saudi Aramco, Dhahran

Thermal maturity/migration path modeling in the northeastern part of the Arabian Basin has shown a complex interrelationship between source rock facies, reservoir development, and structural growth history. The primary source rock for Paleozoic hydrocarbons is the organic-rich facies of the Qusaiba Member of the Lower Silurian Qalibah Formation. In this part of the basin, the Qusaiba source rock facies varies from being mixed oil-gas prone to exclusively gas prone. It can be generalized that oil expulsion in the area began in the Early Jurassic and continued into the Cretaceous. Wet-gas generation commenced in the Early Cretaceous and current maturation levels over an extensive area have reached the dry-gas generation phase. However, the specific details of the hydrocarbon charge history in this part of the basin may include an original charge of oil into Paleozoic reservoirs that was later displaced by thermally mature gas/condensate, and even late-generated dry gas. In order to lessen exploration risks, detailed interpretations of source-rock geochemistry, reservoir development, and the depositional history were used to model hydrocarbon generation and migration in the area, and explain differences in known hydrocarbon accumulations.

Peter Jones is a Research Scientist at Saudi Aramco’s Research and Development Center. Prior to joining Saudi Aramco in 1991, he worked in exploration and production geology for Mustang Production, OKC from 1982 to 1986, and Union Pacific Resources Company between 1986 and 1991. Peter received his BA in Earth Sciences from Dartmouth College in 1986 and his MSc in Geology from University of Oklahoma in 1986. His areas of interest are basin-wide thermal maturity modeling, hydrocarbon migration timing/path assessment, and reservoir geochemistry.

Patrick Rutty is a Geophysical Specialist with Saudi Aramco. He has a BA in Earth Sciences from Dartmouth College (1988) and a MS in Exploration and Development Geophysics from Stanford University (1991). Before he joined Saudi Aramco in 1998, most of Patrick’s work was in the Anadarko and Arkoma basins of the USA, first with Amoco in Denver and later with Sonat Exploration in Oklahoma City.

Robert Johnson has a BA in Geology and Psychology from Hope University (1976) and a MSc in Geology from the University of Kentucky. He worked with Amoco Oil Company from 1979 to 1984 in onshore and offshore exploration in southeastern USA. In 1984, he joined Amoco International and worked in North Africa, mainly specializing in Egypt. Robert joined Saudi Aramco in 1989 and has been involved in exploration in the Red Sea and central Saudi Arabia. He is currently working on deep exploration plays in the area north of the Ghawar field.

Ooid Diagenesis in the Khuff Formation as Indicators of Reservoir Development

Rami Kamal, Saudi Aramco, Dhahran

In the subsurface of eastern Saudi Arabia, the Late Permian Khuff Formation is a carbonate-evaporite sequence that is divided into four major depositional cycles formally named Khuff-A, B, C, and D (from top down). The Khuff-B is characterized by a thick medial oolite. Diagenetic fabrics within the oolite have a direct impact on reservoir performance and provide valuable clues on the depositional history of the oolitic bodies. The oolitic strata are mainly limestone over present-day structural highs but dolomite elsewhere. The limestone fabric is characterized by oomoldic porosity due to the selective leaching of ooid centers. The outer rims of the leached ooids are commonly retained and are cemented to adjacent grain rims, rendering permeability between the oomoldic pores poor. The oomoldic limestones produce a ‘gas effect’ on the FDC/CNL wireline log track. Dolomite oolites, on the other hand, commonly have good intercrystalline porosity between the ooids, good intergranular porosity, good to very good permeability, and no ‘gas effect’.

As leached limestone oolitic grainstones are usually caused by fresh water phreatic diagenesis it is concluded that the lime oolites were deposited on offshore sand bars shallow enough to harbor fresh water lenses. In that case, the present-day structural highs were probably paleotopographic highs in Late Permian times. Post-burial compaction of the leached lime oolites caused unleached grains to collapse into

William Carrigan, Henry Halpern see p. 102
underlying oomoldic voids. If the voids were partially to totally infilled and reinforced with precipitated minerals, the molds were spared collapse and distortion. The collapse of leached ooids caused pressure solution and the merging and interlocking of the squashed grains and rinds into ‘pseudolaminae’. Microcrystallization along the pseudolaminae transformed them into permeability barriers that consist of lens-shaped envelopes 1 to 5 millimeters thick within which the original fabric, with good oomoldic porosity, remains undisturbed. Mimetic dolomite ooids are common in the dolomitized oolites. They are taken to indicate marine or mixed marine diagenesis whereby early dolomitization occurs at concentric ooid surfaces and replaces the aragonite skin with fine sucrosic dolomite rhombs. Early leaching can remove the aragonite cores leaving behind the dolomite rhomb spheres. If the ooids are not leached they may be completely dolomitized by invasion through micropores created by algal boring.

Mohammad Kamali received his BSc (1982) and MSc (1984) from the University of Mysore, and a PhD (1996) in Petroleum Geology from the University of Adelaide. He joined NIOC’s Research Institute of Petroleum Industry in 1987 where he is Head of the Organic Geochemistry Group. His research interests are petroleum geochemistry, reservoir geology, and basin modeling. Mohammad is a member of AAPG and the Geological Society of Iran.

Bahman Esmailzadeh Kanddjani received his BSc in Geophysics from Tabriz University in 1970 and was a PhD candidate at Institute of Solid Earth, Strasbourg/France during 1976 to 1978. He joined NIOC’s Research Institute of Petroleum Industry in 1982. Bahman has been actively involved in several exploration projects and presented papers at international level.

Ghorbanali Sobhi received his BSc in Mathematics from the University of Tarbit-e-Moellem, Iran (1985) and a MSc in Industrial Management Engineering from the University of Science and Technology, Tehran (1993). He also completed a ME in Reservoir Engineering at the Research Institute of Petroleum Industry, Tehran in 1990. Ghorbanali has worked on many reservoir simulation and characterization projects and has had eight papers published.

Ayoub Sadeghazad is a Senior Researcher at the Research Institute of Petroleum Industry, NIOC. He has seven years experience in reservoir simulation, characterization, and engineering, and in core laboratories. He has a BSc in Petroleum Engineering from the Middle East Technical University, Ankara (1992). Ayoub’s professional interests are reservoir simulation, characterization, and engineering, EOR, fluid flow through porous media, reservoir geology, and numerical analysis.
Strontium Isotope Stratigraphy of Abu Dhabi: a Precise Record of the Strontium Isotopic Composition of Late Permian to Recent Seawater


High-precision strontium $^{87}$Sr/$^{86}$Sr isotope analyses have been carried out on more than 1,000 core and cuttings samples from Abu Dhabi. Analysed samples include whole-rock carbonates and fossil isolates, and were taken from five wells. The host rocks range in age from Upper Permian to Recent. $^{87}$Sr/$^{86}$Sr isotopic data yield a remarkably well-defined and robust Sr isotope curve. The Abu Dhabi curve represents the most continuous Sr isotopic record of seawater composition from a single depositional environment yet reported. The results indicate that sediments from Abu Dhabi preserve an excellent record of the Sr isotopic composition of global seawater. The dataset has thus allowed the global Sr seawater curve to be more tightly constrained.

The Jurassic to Recent parts of the Sr curve provide an excellent means of correlation between individual wells. Triassic sediments clearly show the influence of global seawater. Inflection points on the curve for the Triassic are geodynamically significant. Radiogenic ratios exhibited by Permian sediments show the influence of terrestrial influxes that suggests deposition in an intracratonic basin prior to influence by open-ocean currents. The oldest part of the curve thus only appears to be of value for local correlation.

The variation of Sr isotopic ratios with depth from different wells has allowed recognition of a local unconformity at the top of the Aptian. The relationship between formation boundaries, and inflections and discontinuities in the Sr curve for each well provides a new basis for stratigraphic correlation in Jurassic and Triassic sediments. Results demonstrate that Sr isotope stratigraphy is an excellent tool for basin analysis and correlation in the Abu Dhabi oil fields. Details of accuracy and precision of Sr isotope ratios and lithological control on isotopic compositions will be presented.

Mitsuyoshi Kaneko is a Senior Geologist with Japan Energy Development Co., Ltd. He received his BSc and MSc from Tohoku University, Japan in 1981 and 1983, respectively. He has worked on exploration projects in Japan, Western Canada, the Gulf of Mexico, Papua New Guinea, and elsewhere.

He carried out a kinetic basin modeling study of Abu Dhabi in 1993.

Kenneth Collerson is Professor of Earth Sciences at the University of Queensland and Director of the Radiogenic Isotope Laboratory. He received his BSc (hons) from the University of New England, Australia in 1967 and PhD from the University of Adelaide in 1972. He has an international reputation in the field of isotope geochemistry and crustal evolution. Kenneth has taught at Memorial University of Newfoundland, the University of Regina, and the University of California, Santa Cruz, and was a Research Fellow at the Australian National University.

Masayoshi Suzuki see p. 114

Ahmed Al-Suwaidi is Manager Offshore Division with Abu Dhabi National Oil Company (ADNOC). He received his BSc in Geology from University of South Carolina in 1985. He joined ADNOC in 1985 and worked in the Geology Department until 1996. He is the chairman of SPE Abu Dhabi section and a member of AAPG and SEE. He is interested in basin modeling, structural geology, and carbonate petrography.

Abdul Rahman Al-Habshi is Team Leader of the Strategy and Exploration Team of the Petroleum Resources Division, Abu Dhabi National Oil Company (ADNOC). He has a BSc in Geology from Baghdad University (1971). He has 27 years of geological experience, of which 7 were with the Bureau de Recherches Géologique et Minieres, Jiddah, 4 with the Petroleum Department, Abu Dhabi, and 16 with ADNOC. Abdul Rahman is Chairman of SEE and a member of SPE.

Sabah Aziz is a Senior Production Geologist with Abu Dhabi National Oil Company (ADNOC). He received his BSc in Geology from Baghdad University in 1973. He joined ADNOC in 1975. Sabah is a member of SPE and SEE. He is interested in sequence stratigraphy and carbonate reservoir geology.
**Does the Garu Formation Contribute to the Rich Reserves of Oil Fields in Southwestern Iran?**

Mohammad Kassaie, Mohammad Kamali and Minoo Angajivand, Research Institute, National Iranian Oil Company, Tehran

Previous work had indicated that only the Kazhdumi and Pabdeh formations were major contributors to the rich petroleum reserves of the Asmari reservoir in southwestern Iran. However, it was thought that the Neocomian Garu Formation in the Dezful Embayment of the Zagros Basin in Khuzestan Province might also have hydrocarbon source potential. This hypothesis was tested by qualitative and quantitative studies of cores and cuttings from a 480-meter interval in the Haftkel-61 well. The methods used were RockEval pyrolysis, column chromatography of the extracted organic matter, gas chromatography of the saturated hydrocarbons, and organic petrography. Biomarker correlation studies using gas chromatography-mass spectrometry are in progress. The results show that samples of argillaceous limestones and shales are rich in mainly type II and III organic matter that is thermally mature and lies in the oil generation window. The prevailing anoxic conditions during deposition resulted in good preservation of organic matter. The results indicate that the Garu Formation represents a good-to-fair source rock in the area investigated. Source-oil and oil-oil correlations that were undertaken will be reported later.

Mohammad Kassaie received a BSc (1985) from the University of Toledo, Ohio, and a MSc (1990) from the University of Tehran. He joined NIOC’s Research Institute of Petroleum Industry in 1987 where he is a Senior Researcher. His research interests are petroleum geochemistry and basin modeling, Mohammad is a member of the Geological Society of Iran and PES.

Mohammad Kamali see p. 120

Minoo Angajivand received her MSc (Chemical Engineering) from Istanbul University in 1972. She was awarded a PhD in Applied Polymer Science in 1976 by Strathclyde University, UK. She joined NIOC in 1976 as a Project Leader in the Organic Geochemistry Department. Minoo has supervised several projects in NIOC and has published papers in national and international journals.

**Utilising New Technologies on 3-D Seismic Interpretation Volume Visualization, Interpretation and 3-D Image Processing**

Recep Kazdal
Petroleum Development Oman, Muscat

In the past few years, several new 3-D visualization, volume interpretation, and 3-D image processing techniques have been developed as a result of advances in computer technology. The Shell group is using these techniques with proprietary and selected third-party applications. The visualization of 3-D seismic data using volume-rendering techniques is successful in many phases of the interpretation sequence. In particular, it may save a significant amount of time in the early stage of interpretation. Interpreters can grasp the structural setting of the area and immediately highlight areas of interest. Opacity functionality, three-dimensional auto tracking and mapping methods help to identify the three-dimensional shapes of features such as channels, direct hydrocarbon indicators, salt bodies, intra-salt floaters, and reservoirs. 3-D image-processing techniques such as Smack, SuperSmack, CorrSmack, Structurally Oriented Filter, and Semblance are used extensively by interpreters who work with poor-quality 3-D seismic datasets. These techniques were successfully applied to eliminate noise, to enhance continuity, and to minimize multiples, especially on the notorious eastern-flank seismic data where noise and multiples are a major problem. The benefits of the visualization technology will be demonstrated using Petroleum Development Oman’s data. Examples will include: (1) Visualization of intra-salt geobodies such as Al Noor, Al Shomou, and Ghafeer fields. (2) Visualization of subsurface channel systems from Natih, Shu’aiba, Gharif, Al Bashir, and Huqf levels. (3) Advanced fault interpretation using the CorrSmack image-processing technique on the Hazar and Zauliyah fields. (4) Fault visualization using optical stacking that resulted in extra gas bookings in the Sath Nihayda field. (5) Examples from various datasets for seismic-data quality improvements using 3-D image-processing techniques.

Recep Kazdal graduated from the University of Istanbul with honors and received a MSc in Geological Engineering from South Dakota School of Mines and Technology in 1985. He worked for two years for the Turkish Petroleum Corporation before joining Shell in 1987. From 1987 to 1991, he was a Seismic Interpreter for NV. Turkse Shell. He was transferred to Petroleum Development Oman as a Seismic Interpreter in 1991. His has experience in field geology, exploration reviews, seismic interpretation (8 years), and advanced interpretation support (4 years). Since
The Near-Surface Problem in Land Seismic Data Processing: a Wave Equation Approach

Panos Kelamis, Kevin Erickson, Saudi Aramco, Dhahran; Denis Mougenot, ARGAS, Dhahran and Eric Verschuur, Delft University, The Netherlands

One of the fundamental obstacles in the processing of land seismic data is the proper definition of the near-surface. Variable topography and unconsolidated sediments combined with karstic carbonates are a few examples of near-surface conditions. Wave propagation and scattering in such geological settings produce chaotic seismic signatures that tend to mask and defocus the imaging of deeper hydrocarbon-bearing targets. As a result, exploration for low-relief structures, (such as ones encountered in the Middle East), becomes risky and the success of wildcat drilling programs is marginal. Routine processing techniques attempt to correct for near-surface conditions by applying vertical time shifts to the seismic traces but, in general, they fail to properly compensate. The alternative is to employ wave equation-based algorithms for datuming the seismic data just below the complexities of the near-surface. Datuming schemes are usually successful in marine datasets where both the water depth and velocity are readily available. On land, however, detailed knowledge of the near-surface velocity-depth model is always questionable, and thus the application of conventional datuming methods produces unreliable results.

In this study, we present a novel, wave-equation datuming methodology for seismic reflection data based on the principles of Common Focus Point (CFP) technology. The CFP approach, implemented in the time domain, provides a way of describing the effects of the near-surface in terms of propagation operators without knowledge of the corresponding velocity-depth model. Because the propagation operators can be easily updated, a complete wavefield datuming can be applied to the seismic data by defining one of the sub-weathering reflectors as the new acquisition surface. After datuming, the gathers are better suited for velocity analysis whereas the resulting stacks exhibit improved focusing at the target. The applicability of this CFP-based datuming scheme is demonstrated with synthetic examples and with land data acquired in a complex near-surface environment.

Panos Kelamis is a Geophysical Consultant with the Exploration Technology Department of Saudi Aramco. He has a BSc (hons) in Physics from the University of Athens (1977), a MSc and DIC in Geophysics from Imperial College, London (1978), and a PhD in Geophysics from the University of Alberta, Canada (1982). He worked for the Research & Development group of Western Geophysical in Houston and for Dome Petroleum in Calgary before joining Saudi Aramco in 1985. In 1982, he received the Best Paper Award for the CSEG meeting and a Honorable Mention in 1990 and 1995 for papers presented at SEG meetings. He is an Associate Editor for Signal Processing for Geophysics and a member of the Editorial Board for the Journal of Seismic Exploration. He is a member of SEG and EAGE. His research interests include wave equation studies, imaging, and reservoir geophysics.

Kevin Erickson is a Research Geophysicist with the Geophysical Research and Development Division of Saudi Aramco. He has a BSc (1982) from the Colorado School of Mines. He worked for GSI, Halliburton Geophysical Services, and Western Geophysical before joining Saudi Aramco in 1997. Kevin is a member of SEG. His research interests are in the field of signal processing and imaging.

Denis Mougenot is an Area Geophysicist for ARGAS, working in the Geophysical Research and Development Division of Saudi Aramco. Previously, he was head of Seismic Imaging of Compagnie Générale de Géophysique in France. He has 26 years of seismic processing and interpretation experience, including 16 as an Assistant Professor at the University of Paris. Denis has published many papers on the geodynamics of continental margins and on reservoir characterization. He is a graduate of École Normale Supérieure, and has a PhD and a DSc in Geodynamics from the University of Paris. He is a member of AAPG, DGS, SEG, and SGF.

Eric Verschuur is Assistant Professor of Geophysics at the Delft University of Technology in The Netherlands, and a project leader of the industry-sponsored DELPHI Consortium. He obtained his MSc (1986) and PhD (1991) from Delft University for multiple prediction and elimination. In 1996, he received the Shell Young Scientist Award and in 1998 the SEG Karcher Award. Eric is a member of SEG and EAGE. His research interests are seismic data processing, wave theory, and computer technology.
Multiple Elimination in Land Seismic Data: the Saudi Aramco Experience

Panos Kelamis, Saudi Aramco, Dhahran

The problem of multiple elimination in seismic data processing is an old and long-standing issue in the oil and gas industry. The presence of multiple reflections distorts the image of the primary events and thus introduces uncertainty at the interpretation stage of the seismic data. Multiple elimination techniques, from the simple statistical deconvolution to the more sophisticated wave equation-based algorithms, continue to develop, evolve and reach maturity, driven by technological advances and increased demand to reduce economic risk. Particularly for land seismic data acquired over low-relief structures, such as those found in the Middle East, the success of multiple elimination is crucial for the subsequent imaging and delineation of reservoirs.

This study presents Saudi Aramco’s research efforts and experience towards the development of practical multiple-elimination methodologies applicable in the processing of land seismic data. First, a fast Radon-based, multiple-elimination methodology is presented. It is applicable for datasets with velocity discrimination between primaries and multiples. This is followed by a wavefield prediction and subtraction methodology in which the data itself is used as a prediction operator. This wave-theoretical, data-driven approach requires no assumptions about the subsurface and it can accommodate seismic data with no moveout difference between primaries and multiples. It is shown that proper pre-processing of the input data is the key to obtaining satisfactory results. This pre-processing step aims to improve signal-to-noise ratio and balance the amplitudes, resulting in smooth operators for the multiple prediction. The merits of these two different approaches are discussed with emphasis on the underlying assumptions and limitations. The performance of each methodology is demonstrated with a series of land datasets from the Arabian Peninsula.

Panos Kelamis see p. 123

3-D Facies Architecture and Paleomagnetic Pole Determination of a Glaciomarine Depositional Sequence: the Precambrian Mirbat Sandstone Formation, Oman

Philipp Kellerhals, Oliver Kempf, Albert Matter, University of Berne and William Lowrie, Technical University of Zürich

The late Proterozoic Lower Member of the Mirbat Sandstone Formation in south Oman is a sequence of mainly glacial origin more than 300 meters thick. Facies analysis revealed six depositional systems that were formed by eight different facies associations. Due to the nearly ideal outcrop conditions, it was possible to study the facies architecture in three dimensions and to get detailed insights into these strongly interfingered facies.

The crystalline basement shows considerable relief due to a valley system that is covered by sediments of the non-glacial scree facies at its base, followed by a thick sequence of distal glaciomarine deposits consisting mainly of rain-out diamictites. They are covered by termino-glacial deltaic deposits. The middle part of the succession is formed by deposits of proximal glaciomarine, subglacial and ice-front origin. The proximal glaciomarine deposits are strongly interfingered rain-out diamictites, turbidites, and bottom-current channel-fills. Intercalated with the latter are layers of subglacial deposits indicated by marine glacial tunnel-mouth deposits, glacial striations, and channel-fill deposits from the ice-front. The upper part of the Lower Member is again dominated by rain-out diamictites of the distal glaciomarine environment. The entire succession leads to a general facies model of a temperate glaciomarine environment. Deposition occurred in an active tectonic setting, probably in an extensional (horst-graben) system during the breakup of the late Proterozoic supercontinent.

A paleomagnetic study was carried out in the rarely occurring laminated claystones and siltstones, and carbonates. Limited exposure and geographical distribution of outcrops restricted sampling to six sites. Of these, three were in laminated fine-grained claystone to siltstones, and three in laminated carbonates. One site was rejected and the remaining five, represented by a total of 21 samples, displayed a similar magnetic component during progressive thermal demagnetization between 0° and 500°C. The site mean pole calculated from this component is at 86.5°N, 328.1°E (δp=11.2°, δm=19.7°). This low-temperature component is interpreted as the direction of the average recent geomagnetic field in Oman. Two sites (10 samples) revealed a consistent magnetic component above 500°C. The sample mean declination of 68.4° and inclination of 18.4° (k=46.4, α95=7.2°) are interpreted as the characteristic remanent magnetization. The late Precambrian Arabian pole position computed from the samples at these two sites lies at 23.3°N, 141.8°E (δp=3.9°, δm=7.5°). Rotated into West African coordinates, the resulting pole position is at 31.6°N, 153.2°E, in good agreement with published poles from Gondwana of late Precambrian age (about 550 million years ago). The resulting paleolatitude is about 9.4° indicating a low-latitude of deposition for the glaciomarine deposits of the Mirbat Sandstone Formation.
Philipp Kellerhals is working for the Geological Survey of Switzerland. He was awarded a PhD in Geology in 1998 by the University of Bern where, as a postdoctoral researcher, he focused on facies analysis.

Oliver Kempf is a postdoctoral researcher at the University of Bern. He graduated from the University of Tübingen, Germany, and was awarded his PhD in geology in 1998 by the University of Bern. His current research interests include the geodynamics of sedimentary basins and the interactions between sedimentation, tectonics, and climate.

Albert Matter is a Professor at the University of Bern from where he received his PhD in geology in 1964. Following postdoctoral appointments at Rice University and Johns Hopkins University, he returned as Professor to Bern in 1966. His major research interests are in clastic sedimentology and diagenesis applied to petroleum exploration. Albert and his students are currently working in collaboration with petroleum companies in Germany, Hungary, Oman, and Switzerland.

William Lowrie is Professor of Geophysics at ETH Zürich. He received his PhD in Geophysics from the University of Pittsburgh in 1967. After periods of research with Gulf Oil Corporation and at the Lamont-Doherty Geological Observatory of Columbia University, he was elected Professor of Geophysics at ETH Zürich in 1974. His research focuses on rock magnetism and paleomagnetism with particular application to geologic-tectonic problems, as well as the polarity history of the geomagnetic field over geological time. He has authored 120 scientific articles and a recent textbook Fundamentals of Geophysics. In 1990, he was elected a Fellow of the AGU.

A Comparison of Water-Cut Prediction Based on NMR Results with Production Data in Middle East Carbonate Reservoirs

Mosleh Khalil, Abu Dhabi Company for Onshore Oil Operations and Austin Boyd, Schlumberger, Abu Dhabi

Recently, a well was drilled in Abu Dhabi that penetrated several productive carbonate reservoirs. An extensive coring, logging, and testing program was carried out on this well and nuclear magnetic resonance (NMR) was included in the logging suite. This presentation will compare the results based on NMR measurements to predict water cut with actual well production data.

One of the main applications for NMR logs is to predict water cut based on the irreducible water saturation. In the carbonate reservoirs of the Middle East, it has been observed that the T2 cut-off for partitioning capillary-bound fluid volume from free-fluid volume can vary from 80 milliseconds to 460 milliseconds. This wide range of free-fluid cut-offs is primarily due to variations in formation surface relaxivity and capillary pressure. Alternative techniques have been developed to address the inadequacy of a single fixed cut-off for carbonate reservoirs. One approach, known as the ‘Tapered Cut-Off’ has shown promise in some carbonate reservoirs. Another technique (when permeability is known) is inverting the Coates-Timur permeability equation to determine free-fluid cut-off. A new method based on forward modeling eliminates the need for a fixed cut-off in the TD domain.

The techniques mentioned above for predicting free-fluid cut-off will be evaluated and compared with laboratory NMR results from core and production data. Additional NMR applications such as permeability, formation wettability estimation, and facies identification will also be discussed and compared with core data.

Mosleh Khalil has been a Lead Petrophysicist with Abu Dhabi Company for Onshore Oil Operations since 1997. He has a BSc in Engineering from Suez Canal University, Egypt (1981). He started his career as a Drilling Engineer. From 1984–86 he was a Petroleum Engineer on the Zeit Bay field. He was a Logging Engineer for all SUCO fields (1986–89) and Senior Logging Engineer to 1993. Mosleh was head of Reservoir Engineering Studies (1993–95) and head of the Department of Reservoir Engineering for the Ras Budair field to 1997.

Shahnawaz Khan, Olivier Chardac, Schlumberger
Christian Heine and Saleh Al-Raimi
Saudi Aramco, Dhahran

Directions of the in-situ stress tensor in the Khuff and pre-Khuff formations of the Ghawar structure are determined from borehole image logs and shear wave anisotropy. Horizontal principal stress orientations are indicated by borehole breakouts and drilling-induced fractures. The orientation of the breakouts identified in wells along the Ghawar trend are within 5º of a due north strike direction, implying that the maximum horizontal compressive stress (SHmax) is oriented east-west. Image log data also indicate that the strike direction of conductive (open) drilling-induced fractures trend east-west. This observation is supported by borehole acoustic anisotropy measured in wells.

The structural dip of the Khuff Formation ranges from horizontal on the crest of the Ghawar structure, to 2º to 3º on the flanks. Similarly, the Unayzah Formation is generally flat over the crest of Ghawar and has a gentle 3º to 5º dip on the flanks. The structural dip of the pre-Unayzah formations is also generally flat on the crest of Ghawar but then dips from 5º to 18º on the flanks of the structure. In all cases, the dip direction of the formation evaluated parallels that of the present-day structure.

The Late Permian Khuff Formation unconformably overlies the Unayzah Formation. The Unayzah Formation is bounded by two regionally significant unconformities—the pre-Khuff Unconformity and the pre-Unayzah Unconformity. Image logs suggest a well-developed paleosoil or caliche in the upper part of the Unayzah Formation, indicative of the exposed surface at the time of the pre-Khuff Unconformity. The change in dip magnitude from the pre-Unayzah through the Unayzah and into the Khuff Formation suggests reactivated, or possibly continuous structural growth, throughout the Carboniferous and into the Permian, punctuated by unconformities.

Shahnawaz Khan has a degree (Cand. Scient) in Geology from Oslo University, Norway. Since 1997, he has worked for Schlumberger Middle East. His present job focuses on image log characterization, in-situ stress determination, and facies analysis. He has carried out research on diagenesis of deeply buried sandstones of the North Sea.

Olivier Chardac biography not available.

Christian Heine joined Saudi Aramco in 1991 as a Geologist. He has a MSc in Geology from the University of Tennessee (1982) and a MSc in Petroleum Engineering from Tulane University (1990). He worked for Mobil Oil 1982–90 and was an Associate Professor at Tulane University from 1990–91. Christian is a member of AAPG and DGS.

Saleh Al-Raimi see p. 34

Adaptive Wavelet-Based Seismic Compression

Faouzi Khène and Samir Abdul-Jauwad
King Fahd University of Petroleum and Minerals, Dhahran

Seismic compression has, until recently, been considered useful solely for reducing archiving space and cost. However, nowadays the scope of seismic compression has broadened to encompass satellite or Internet transmission and 3-D data visualization on workstations. For these new endeavors, the investigation of new, powerful, and sophisticated techniques borrowed from statistical and harmonic mathematical theory and digital signal processing becomes a necessity.

We illustrate our ideas with a new compression technique based on the association of a 2-D discrete wavelet transform and an adaptive nonlinear thresholding. We first generate a
multi-resolution decomposition of the NxN dataset with a separable nonstandard bi-orthogonal wavelet transform. We select a mother wavelet from the Cohen-Daubechies-Feauveau class. This choice ensures linear phasing of the digital wavelet filters and prevents the appearance of visual artifacts in the reconstructed image. It also offers great flexibility in the design of the decomposition and reconstruction filters with different degrees of smoothness and regularity. Moreover, the computational load of the overall compression scheme is order $N \log(N)$.

We then achieve compression by shrinking the detail wavelet coefficients using a scale-dependent non-linear soft thresholding. The different thresholds are determined to minimize the Stein’s Unbiased Estimate of Risk (SURE) cost for each resolution.

Finally, we have tested the proposed compression scheme on marine seismic data from the Midyan basin in the Red Sea. The dataset represents a variable and complex structure due to Miocene rifting and to salt diapirism. Preliminary results show that, with as much as 70% of the detail coefficients being discarded, 98% of the data energy is preserved. Even with such a large compression rate, the reconstructed data do not exhibit perceptible degradations. These results corroborate our expectations concerning the substantial qualitative improvement gained by the association of the powerful wavelet transform with non-linear statistical methods for seismic compression.

Faouzi Khène has a BSc in Electronics (1990) and a MS in Electrical Engineering (1993) from École Polytechnique d’Alger, Algeria. He is a PhD student in the Electrical Engineering Department at King Fahd University of Petroleum and Minerals, Dhahran. His research interests include theoretical and implementation aspects of the wavelet transform and its application to seismic data compression and denoising. Faouzi is a student member of SEG, EAGE, and IEEE.

Samir Abdul-Jauwad has a BSc (1973) and MSc (1976) in Electrical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He was awarded a PhD in Electrical Engineering by the University of Sheffield in 1985. In 1974, he joined KFUPM’s Electrical Engineering Department where he is now an Associated Professor. His professional interests include signal processing and communications. Samir is a member of IEEE, ACM, and AGU.

### Changing Sand Provenance in the Permian Gharif Formation of Central Oman: Results of a Pilot Heavy Mineral Study

**Robert Knox**, British Geological Survey, Nottingham

Heavy mineral analysis is a powerful tool for correlation purposes and can be used for providing both a stratigraphic framework on an exploration scale and for high-resolution correlation of individual sandbodies within a field. A pilot heavy mineral study has been carried out on core and cuttings material from a Petroleum Development Oman well through the Gharif Formation of Central Oman. Its aim was to assess both changes in sand provenance with time and the potential use of heavy mineral assemblages in correlation at regional and reservoir scales. Analysis has been carried out using 2-mineral ratios.

The Gharif Formation is divided into three informal members. Sandstones in the lower member display assemblages identical to those in the underlying Al Khlate Formation, characterized by relatively consistent proportions of the main heavy mineral components. The base of the middle member is marked by marked increases in the apatite/tourmaline, rutile/zircon and monazite/zircon ratios, reflecting significant changes in provenance with time. A further change at the base of the upper member is marked by an influx in euhedral zircons and a marked increase in the apatite/tourmaline ratio. Within the upper member, assemblages show little evidence of changing provenance, but reflect a progressive change toward a more humid depositional environment, with leaching of unstable minerals taking place in poorly drained soil profiles.

These results demonstrate that heavy mineral signatures within the Gharif Formation are of potential value in the reconstruction of sand-dispersal systems and in the regional correlation of sand units in a succession that is poorly constrained biostratigraphically. The potential also exists for the establishment of sand stratigraphy at the reservoir scale, with application to connectivity prediction and to geosteering of high-angle production wells.

Robert Knox is a Stratigrapher/Sedimentologist at the British Geological Survey where he has worked for over 25 years on petroleum basins of the UK and overseas. He played a major role in the UKOOA North Sea lithostratigraphic study. His current activities are focused on the applications of heavy mineral analysis to exploration (reconstruction of sand dispersal systems, regional correlation of sandstone units) and production (reservoir sand architecture and connectivity, and geosteering).
Interpretation of Vp/Vs Ratios and Acoustic Slowness in Pre-Khuff Siliciclastics of Saudi Arabia

William Lauten, Mohammed Al-Ghamdi and Saleh Al-Ruwaili, Saudi Aramco, Dhahran

The ratio of compressional (P) wave to shear (S) wave velocities (Vp/Vs) is often used by geophysicists as a lithological indicator. When coupled with an analysis of compressional slowness, it may act as a hydrocarbon indicator, particularly for gas. The interpretation works best in clean, unconsolidated sandstone. Small amounts of clay may dramatically affect the Vp/Vs ratios and compressional slowness in sandstone. It is well-known that the pre-Khuff siliciclastics of Saudi Arabia contain varying amounts of clay and this study investigates the sensitivity of Vp/Vs ratios and compressional slowness to clay volumes in the range of 1% to 15%. Ultrasonic measurements have been made of P and S velocities in pre-Khuff sandstones from a several wells. Analyses of the Vp/Vs versus compressional slowness crossplots has led us to conclude that small volumes of clay in the rock can lead to the incorrect interpretation of gas-bearing sand, unless great care is taken. Interpretation of gas from such plots made from well logs should be restricted to zones where the gamma-ray log indicates very clean sand.

William Lauten is a Senior Laboratory Scientist with the Saudi Aramco Laboratory Research and Development Center (LR&DC) and is group leader of the Rock Mechanics group. He has a PhD in Physics from Clemson University and has worked as a Geophysicist for the past 20 years (18 years at Saudi Aramco and 2 years at the Phillips Petroleum Research Center). William worked in the Saudi Aramco Exploration Geophysical Research Division before joining LR&DC in 1994. His current areas of research at LR&DC include measurement of in-situ stress using the Kaiser Effect and paleomagnetism.

Mohammed Al-Ghamdi is a Laboratory Scientist with the Saudi Aramco Laboratory Research and Development Center (LR&DC). He received his BS in Industrial Chemistry from King Fahd University of Petroleum and Minerals, Dhahran in 1982. He has worked in the Petrophysics Unit of the LR & DC Center since 1992 in the Special Core Analysis and Rock Mechanics groups where his research involved measurements of rock velocities. Mohammed is currently on a development assignment with the Drilling and Workover Department.

Saleh Al-Ruwaili works in the Saudi Aramco Reservoir Description Division (RDD) in the Gas Exploration and Petrophysics unit. He received his BS and MS in Physics from King Fahd University of Petroleum and Minerals, Dhahran in 1992. Prior to his RDD position, he worked in the Petroleum Engineering Research and Development Division and developed algorithms for reservoir simulation. Saleh is studying for a PhD in Computational and Applied Mathematics at Rice University.

Seismic Attribute-Based Small-Scale Fault Mapping in the Uthmaniyah Area, Saudi Arabia

Paul Lawrence and Khalid Al-Hawas
Saudi Aramco, Dhahran

In the Uthmaniyah area of the central Ghawar field, fault and fracture zones are responsible for an irregular water-flood advance in the Arab-D reservoir. Faults mapped by means of traditional 3-D seismic methods do not adequately explain the anomalous flood-front advance. However, seismic attributes provide a much more detailed view of faults. Fault throws as small as 15 feet that are difficult to detect using conventional interpretation methods (based on reflector offsets) can be observed as seismic attribute lineations. Small-scale extensions of larger 50-foot-throw faults can often be seen in the seismic attribute.

The attributes utilized, ranked in order of confidence, are coherency, dip-azimuth, dip-magnitude, and amplitude. Since the mapping of small-throw faults from seismic attributes extends the resolution limits of 3-D seismic, a detailed confidence ranking was applied. This was based on such factors as the spacial relationship of the small-scale faults to the higher confidence conventionally defined faults, and fault-throw magnitude. The statistical relationship between various fault families based on confidence factors and well-based observations of faulting and fracturing was used to confirm the seismic attribute-defined faults. The irregular water-flood advance in the Arab-D reservoir can largely be explained by means of the small-scale faults mapped from the seismic attributes. The results of this study are being used in Arab-D reservoir simulation and in the development plans for the Uthmaniyah field.
Paul Lawrence is a Geological Specialist with the Reservoir Characterization Department of Saudi Aramco. He is working on reservoir characterization and interpretation of 3-D seismic data for the Ghawar field. He has worked as a Seismic Interpreter for Atlantic Richfield Co., Terra Resources, and Marathon Petroleum Tunisia. Paul has a BS in Geology (1976) from Kent State University and a MS in Geology/Geophysics (1978) from Wright State University.

Khalid Al-Hawas is a Geophysicist with the Reservoir Characterization Department of Saudi Aramco. He is working on reservoir characterization and interpretation of 3-D seismic data for the Uthmaniyah field. Khalid has a BS in Geophysics (1980) from Tulsa University and a MS in Exploration Geophysics (1994) from Texas A&M University.

The Abu Mahara Group of Oman: Precambrian Diamictites and Dolomites in the Desert

Jonathan Leather, Philip Allen,
Trinity College Dublin
and Martin Brasier, University of Oxford

The oldest exposed sediments in Oman are of Neoproterozoic age and are named the Abu Mahara Group. The group outcrops both in the Huqf area and in the Oman Mountains. It is made up of the Ghadir Manqil Formation and the younger Masirah Bay Formation, separated by a dolomitic unit less than 10 meters thick termed the Hadash Dolomite.

In the Central Oman Mountains, the Ghadir Manqil Formation is less than one kilometers thick and is a dominantly siliciclastic formation made up of a series of glacimarine diamictites, turbidites, and siltstones that in places show soft-sediment deformation and rippling. In the lower part of the formation, volcanics and volcaniclastics are common. Rare carbonate units (less than one meter thick) also occur within the Ghadir Manqil and, in places, are interbedded with these volcanic units. The formation is capped by the Hadash Dolomite that in turn is overlain by about 100 meters of probable deep-water siltstones and argillaceous sandstones of the Masirah Bay Formation. No evidence for glaciation occurs above the Hadash Dolomite.

In the Huqf area the facies of the Abu Mahara Group are notably different. The Ghadir Manqil Formation is much thinner than in the Oman Mountains (less than 100 meters thick) and is represented by a series of felsic volcanics and volcaniclastics. These are only exposed at one locality where they overlie granitic basement. Overlying the Ghadir Manqil Formation (as in the Oman Mountains), is a dolomitic unit followed by the Masirah Bay Formation (more than 600 meters thick) composed of shallow-marine wave-rippled sandstones, coarse-grained trough cross-bedded sandstones, and deeper-water mudstones and siltstones.

One aspect of interest within the dominantly siliciclastic Abu Mahara Group is the dolomitic units, particularly the Hadash Dolomite. These units have been studied in some detail, both lithologically and by using stable isotopes. This was done for a number of reasons: (1) To better understand the formation of the dolomites. This is particularly important in the Oman Mountains where, at the top of the Ghadir Manqil Formation, the Hadash Dolomite directly overlies glacial deposits and marks the start of a distinct change in the style of deposition. (2) To achieve a more robust correlation between the Abu Mahara Group in the Huqf area and in the Central Oman Mountains. (3) To help correlate the Abu Mahara Group of Oman with other sections worldwide, where Neoproterozoic glacial successions are also capped by similar dolomitic units.

Jonathan Leather has a BA in Geology from Oxford University. He is a postgraduate student at Trinity College Dublin under the supervision of Philip Allen (Dublin) and Martin Brasier (Oxford). He is funded jointly by Enterprise Ireland and Petroleum Development Oman.

Philip Allen has held academic positions at the universities of Cardiff, Oxford, and currently, Dublin (Trinity College). He is particularly interested in basin analysis and the intersection of tectonics and Earth surface processes. He is part of a team investigating the Huqf Supergroup of Oman with the sponsorship of Petroleum Development Oman.

Martin Brasier biography not available.

Statistical Re-Positioning of 4-D Seismic for Noise Reduction

Richard Leggott, Mark Skinner and R. Gareth Williams, Veritas DGC

Residual noise can dominate the signal from differencing two 3-D datasets to produce a 4-D result. The amount of residual noise is very sensitive to small errors in the location of each survey. Using navigation data to regularise each
survey before differencing will reduce the noise but this is limited to the resolution and reliability of navigational information. Further improvements can be made using spatial and temporal statistical matching of the two datasets prior to differencing.

Systematic navigational differences between 3-D surveys can be described as the combination of a residual rotation, translation and time shift. Conventional methods for matching two 3-D surveys cannot measure these effects in isolation. This forces the quality of the result to be lowered as the effect of applying each residual shift becomes confused with each other.

The problem has been reformulated in a way that allows each residual shift to be measured in isolation. This reformulation uses powerful multi-dimensional statistics to calculate the absolute value of each shift, independently of each other. For example, the true orientation between two 3-D surveys can be computed in the presence of arbitrary translation and time-shift errors. In removing the confusion between different effects, residual errors in spatial navigation and time shifts are calculated to high accuracy and high resolution. Once known, these residual errors are used to correct the differences between the two surveys.

Results from both synthetic and real data show the power of the statistical techniques developed. Significantly, results from a real 4-D survey highlighted the existence of a translation error. Conventional matching techniques had insufficient resolution to detect this translation. Correcting for this error significantly reduced the residual noise on the 4-D result and improved its appearance.

Richard Leggott graduated in Theoretical Physics and gained his DPhil in Physics (1997) from the University of York. He is a Research Geophysicist with Veritas DGC Ltd. Richard’s current research interests include 4-D processing, migration algorithms, anisotropy modeling, and tomography as a procedure for velocity inversion.

Mark Skinner graduated in Geology from the University of Leicester in 1994. He has worked for Veritas DGC Ltd. since 1995 as a Processing Geophysicist and Processing Project Leader testing and processing 3-D proprietary and speculative marine surveys. Mark’s recent work has been with 4-D marine surveys.

R. Gareth Williams is Data Processing Marketing Manager and Research Geophysicist with Veritas DGC Ltd. He received his BSc in Physics, MSc in Theoretical Physics and Applied Mathematics, and PhD from Southampton University. He has 18 years experience in seismic research. Gareth’s professional interests include 4-D seismic and prestack time/depth migration.

Subsidence History of the Arabian Platform from Permian to Paleogene Times

Yves-Michel Le Nindre, Denis Vaslet, Joël Le Métour, Bureau de Recherches Géologiques et Minières, France
Mohammed Halawani, Saudi Arabian Deputy Ministry for Mineral Resources, Jeddah

The objective of this study was the modeling of sedimentary processes on the Arabian Platform, based on outcrop data from central Arabia and the Oman Mountains. This model was then integrated in a much larger geodynamic framework, covering the southern margin of the Tethys during the interval from Permian to Paleogene. The lithostratigraphic, biostratigraphic and sedimentologic data for this work were mostly collected during geologic mapping along the western border of the Central Arabian Platform and Oman Mountains. They cover formations with ages spanning the Late Permian to early Tertiary. Two boreholes in central Saudi Arabia were used for correlation with subsurface models. The dominant mechanisms that affected the Arabian Platform during the Late Permian to early Tertiary, combine tectonic and eustatic processes. Key events can be summarized as follows: Tectonic subsidence during the Murghabian corresponded to a lowstand or sea-level fall period. Eustatically controlled transgression took place during the Djulfian. The Scythian-Ladinian interval saw the formation of a closed intra-shelf basin. Eustatic transgression and tectonic subsidence acted together at the start of the Late Triassic, leading to the deposition of local sand bodies and diachronic facies. Tectonic subsidence dominated from the Bajocian to the early Bathonian. Rapid subsidence further accelerated during the middle/late Callovian, with retrograding deltaic deposits on the southern edge of the shelf and a build-up of reef limestone. During the Late Jurassic to Kimmeridgian, sea-level highstand sedimentation occurred under purely eustatic influences. A tectonically active period started at the end of the Jurassic. Its effect was weak in Saudi Arabia but very pronounced on the platform margin in Oman and Yemen. The Early Cretaceous saw the deposition of a well-differentiated succession in Saudi Arabia, but in Oman the start of this period witnessed a platform collapse, with deep outer shelf deposits overlain by rocks with a high terrigenous influx. Tilting or doming of the Central Arabian Platform started...
with the Late Cretaceous, when deep-sea conditions prevailed in Oman. A 2-D structural reconstruction along a north-south section between 27°N and 19°N, shows that a semi-permanent flexure zone at about latitude 24°N was a major tectonic feature. It had syn-sedimentary activity at least during Carnian, Toarcian, Bajocian, and Tithonian times. This long-lived structure, located close to the main Jurassic subsidence axis, was not recognized by earlier work.

Yves-Michel Le Nindre has more than 10 years of experience in the geological mapping of the Phanerozoic rocks of Saudi Arabia. He received his Doctorate of Sciences from the University of Paris in 1987, on sedimentation and geodynamics of Central Arabia from Permian to Cretaceous. Yves-Michel is currently working in the French Geological Survey on sedimentary basin analysis and modeling, particularly in hydrogeology. He is also involved in present-day littoral modeling.

Denis Vaslet see p. 94; Joël Le Métour and Mohammed Halawani see p. 95

Gharif Formation in Oman: an Integrated Geological Approach to Build Upon for the Future

Xavier Le Varlet and Peter Osterloff
Petroleum Development Oman, Muscat

For the past 20 years, the Early Permian shallow marine-continental Gharif Formation has been a primary target for both exploration and development activities. However, drilling on average some two exploration and 30 production wells per year has systematically seen all the big structures accounted for and decreasing production levels from mature fields.

To counter this decline, and rekindle new life into the Gharif, Petroleum Development Oman has, over the last two years, embarked on a multidisciplinary but highly integrated pan-Oman geological study of the formation. The key remit of the study was to better understand clastic facies geometries to develop a more robust geological framework suitable for 3-D reservoir modeling, which in turn, would optimize field-development strategy. Concurrently with exploration, the application of new sequence stratigraphic interpretations should generate new play concepts more reliant on stratigraphic trapping mechanisms than structure alone.

To facilitate this, two significant regional inventories have been compiled that are tangibly linked throughout their development. Firstly, some 2,000 meters of core have been consistently re-described, leading to the creation of a core-based facies catalog. Additionally, some 300 well sections have been analysed (including core data, electrofacies and 70 borehole image interpretations) to develop a pan-Oman temporal and spatial framework.

Integration of these datasets along with those derived from biostratigraphy, chemosтратigraphy and heavy minerals, the developing review of outcrop analogs, and the open dialogue with other Gulf operating companies, has yielded a unique dataset for the entire depositional system in Oman.

This dataset is being used by exploration to test a Gharif ‘noses’ play concept based on stratigraphic pinchout. In the Bahja-Rima area alone, improved 3-D models linked to enhanced water injection plans is already leading to the development of additional reserves. The development plan for the heavy-oil prone Mukhaizna field has also been based on 3-D static and dynamic modeling. The field will come on stream in 2000 and is expected to develop major reserves through 45 horizontal wells. Both water injection and development of heavy-oil fields are considered to be the mid to long-term future of the Bahja/Rima area.

Xavier Le Varlet is a graduate of the École Nationale Supérieure des Pétroles et Moteurs, Rueil Malmaison, France. He joined Shell as a Production Geologist in 1984. Following an initial assignment in Oman, he spent two years at KSEPL before joining the Production Geology section of NAM’s Business Unit Oil in 1991. He was posted back to Petroleum Development Oman in 1996 as a Production Geologist in Central Oman with an active participation in 3-D geological reservoir modeling studies. He is currently Production Geology Section Head of the Bahja/Rima Asset team.

Peter Osterloff received a BSc in 1981 and a PhD in 1993 in Carboniferous Palynostratigraphy from the University of Sheffield. He joined the Exploration Department of Shell Expro UK in 1982 and worked as a Carboniferous Palynostratigrapher in the Southern Gas Basin of the North Sea until 1992. He then switched to Stratigrapher for the Atlantic Margin (West of Shetlands) until 1995 and then to Central North Sea Tertiary plays. In 1997, he joined Petroleum Development Oman as a Senior Stratigrapher and currently heads the Biostratigraphy and Integrated Geology Studies Group. His interests in Carboniferous Palynostratigraphy remain and he is still active behind the microscope.
Key Elements for Cretaceous Carbonate Stratigraphic Trap Exploration in the Context of the Petroleum System

Anthony Lomando
Chevron Overseas Petroleum, La Habra, California

The major factors for carbonate stratigraphic trap exploration and risk assessment are; location, distribution and controls on reef and shoal distribution, the reservoir-seal pair relationships relative to structure that form the trap, and how the spatial relationships evolve through continued structural evolution and timing and migration of hydrocarbons. Along open shelf and ramp systems carbonate buildups tend to develop on the tops and upwind-upcurrent flanks of highs formed by salt domes, turtle structures and regional fault/fold systems. They may also form on the downwind-downcurrent rims of salt withdrawal sinks and intrashelf basins. Facies types forming windward and leeward of the buildup can have variable sealing capacity depending upon how the trap geometry evolves.

Of greatest significance is the concept of critical stratigraphic closure that controls the original fluid trapping capacity (column height and volume) and the trap integrity through post-entrapment structural evolution. Application of the concept involves defining and tracking the trap geometry elements through time. This aids in determining if the stratigraphic trap geometry existed at the time of migration, if it was on the migration pathway, and how the relationships among trap configuration, critical stratigraphic closure and fluid levels change through continued structural evolution.

Anthony (Tony) Lomando completed his graduate studies in 1979 at the City University of New York where he worked on the Jurassic ramp carbonates of the US Gulf Coast. The next eight years were spent in exploration and development in the Permian Basin and the Jurassic and Cretaceous systems of the Gulf Coast. For the past 13 years, Tony has been the Staff Carbonate Specialist for Chevron Overseas Petroleum assisting in the exploration and development, description and characterization of carbonate plays and reservoirs worldwide. Tony has conducted many Carbonate schools and seminars for Chevron, its partners and associates in Russia, Kazakhstan, Mexico, Congo, Angola, China, Kuwait, the UK and the USA. He has authored over 50 papers and abstracts dealing with all aspects of carbonate exploration and reservoir management.

Correction of Seismic Amplitude Maps to Validate Amplitude-Derived Porosity Inferences

Thomas Loretto, Saudi Aramco, Dhahran

A new technique is designed to remove the bias imparted to seismic amplitude maps by wavelet interference, or ‘tuning’. This is important because seismic amplitude maps are sometimes used to infer porosity changes on the assumption that the reflectivity along the mapped interface is not biased by wavelet interference between the mapped and adjacent interfaces. However, this assumption is frequently not met. In the northern part of the Ghawar field in Saudi Arabia, peak amplitude maps of the Arab-D reservoir are biased by tuning. This bias can lead to an incorrect inference from the amplitude map of the relative porosity change. Seismic inversion is one approach used to remove tuning bias but modeling conducted in this study shows that tuning effects are not necessarily removed by inversion. In order to generate amplitude-corrected maps, a correction-factor map is added to the amplitude map to account for thickness changes and velocity changes adjacent to the Arab-D reservoir. The extent to which this approach offers a robust porosity indicator depends on the following criteria: (1) Is the approach sufficient to construct a correction-factor map based on thickness and velocity considerations? (2) Does the approach offer more than the traditional approaches of porosity inference from (uncorrected) amplitude maps or seismic amplitude inversion? (3) Can it be quickly adapted to other fields and other formations?

Thomas Loretto is a Geophysicist with Saudi Aramco. His main interest is the integration of borehole seismic and surface seismic data. He has been employed by Saudi Aramco for three years. His previous assignments were in the Niger Delta (3 years) and the Gulf of Mexico (7 years). Tom has a BA (1980) and a MA (1984) both in Geology from Indiana University. He is a member of SEG and DGS.

Seismic Features Detection Using Generalized Hilbert Transform

Yi Luo, Saleh Al-Dossary and Maher Almarhoon
Saudi Aramco, Dhahran

A new Generalized Hilbert Transform (GHT) has been formulated where the traditional Hilbert Transform is a special case. As one application of this new formulation, a novel fault- and channel-detection processing algorithm (DETECT) has been developed.
The processing algorithm uses the GHT operator to transform the 3-D seismic cube into three imaginary cubes and combines the outputs to produce a detection cube. This new volume can then be viewed by itself, or together with any number of attributes derived from seismic on a high-end graphics workstation. Structural features such as faults, and stratigraphic features such as facies changes from reservoir-quality rock to non-reservoir quality rock, become clearer. The end result is a better understanding of the complexity of the reservoir through the visualization of attributes derived from the 3-D seismic volume. This new algorithm has been applied to numerous 3-D seismic surveys in Saudi Arabia. The DETECT algorithm significantly improves the signal-to-noise ratio, and reduces both the interpretation cycle time and the interpretation bias on the results.

Yi Luo is a Geophysicist with Saudi Aramco. He received his BSc in 1981 from the Chinese University of Science and Technology and his MSc in 1985 from the Chinese Geophysics Academy. He was awarded his PhD by the University of Utah in 1991. He is mainly interested in edge detection, signal processing, tomography and migration.

Saleh Al-Dossary is an Exploration Analyst in Saudi Aramco involved in writing geophysical code and supporting geophysical applications. He has a BS in Computer Science from the New Mexico Institute of Mining and Technology (1990) and a MSc (1997) in Geophysics from Stanford University.

Maher Almarhoon see p. 31

Costas Macrides joined the Geophysical Research and Development Division of Saudi Aramco in 1993. He received a BSc in Physics from the University of Athens in 1980, and a MSc (1983) and a PhD (1987) in Geophysics from the University of Alberta. He has been an Assistant Professor at the University of Manitoba and a Senior Research Geophysicist with Seis-Pro and Consultants in Calgary. He is interested in seismic tomography, refraction statics, AVO and multi-component seismology in oil exploration. Costas is a member of SEG and EAGE.

Panos Kelamis see p. 123; Martin (Marty) Rademakers see p. 167
Petroleum systems. Jurassic to Lower Cretaceous shales are proven source rocks for petroleum reserves discovered in the Cretaceous, Jurassic, and Paleozoic reservoir rocks. Fault-controlled blocks associated with Upper Jurassic extensional tectonics and sourced from Jurassic to Lower Cretaceous source rocks are considered to be future exploration targets. This exploration model would help increase the success ratio for the deep and under-explored pre-Cretaceous exploration plays in the Western Desert along with the frontier exploration areas in Upper Egypt.

The Gulf of Aqaba-Dead Sea fault system is a left-lateral transform that separates the Sinai microplate from the northwestern part of the Arabian plate. The Saudi Midyan field is the first commercial oil discovery in the northern coastal plain of the Red Sea. The Midyan discovery is 50 kilometers north of the offshore Burqan gas discovery. The reconstruction of the southern Gulf of Suez area during early Miocene times indicates that the Midyan-Burqan petroleum province formed a segment of the southeastern Gulf of Suez prior to the displacement of the Aqaba transform fault. Striking similarities between the Miocene sequences exposed in the southern Gulf of Suez and seismic sequences described in the Hurghada province suggest that the Egyptian northern Red Sea is an under-explored region with excellent potential of similar petroleum systems.

The Gulf of Aqaba is considered to be a succession of north-northeast trending pull-apart basins with potential sequences of organically rich source rocks. Similar narrow pull-apart grabens occur in eastern Sinai. Major left-lateral faults are exposed in Sinai and on the Saudi Arabian coastal plains along the Gulf of Aqaba. Analysis of Landsat images has shown that the 60-kilometer-wide deformed zone in the Saudi Midyan area narrows to the north. The floating asphalt blocks in the Dead Sea and the oil and gas shows reported in the Dead Sea pull-apart basin, together with the commercial oil and gas discoveries in onshore and offshore areas of the Saudi Midyan region indicate that the Gulf of Aqaba is a frontier exploration area with potential petroleum systems.

M. Dia Mahmoud is President of Geopex and Managing Director of Spectrum-Geopex Egypt Ltd. He completed his BSc in Applied Geology with Honors, in 1965 from Ain Shams University, Cairo. After two years as a Research Assistant at Ain Shams, he worked for eight years on exploration projects in the Gulf of Suez and Western Desert for GUPCO. From 1975 to 1993, Dia worked for Saudi Aramco as an Explorationist and Reservoir Geologist. In 1993, he returned to Egypt and founded Geopex. Dia is a Certified member of AAPG, and a member of SEG and EPEX.
Mohamed Taha is currently an Exploration Consultant (Geologist/Explorationist). His 35 years experience include working with Amoco, Egypt, GUPCO, Transword (a subsidiary of St. Joe Petroleum), Total, Conoco, and Repsol. In the last 20 years, he has held the positions of Chief Geologist, Exploration Operations Manager and Exploration Project Evaluation Manager. His professional experience includes regional geology and tectonics, new venture opportunities and prospect evaluation in both mature and frontier areas, covering Egypt, Libya, Tunisia, Algeria, Sudan, and the North Sea.

Ahmed Shahin has been the Exploration General Manager and Board Member of Suez Esso Petroleum Company, Egypt, since 1998. He has a BS (1964), MS (1968), and PhD (1972) from Cairo University. In 1975, he received a Postdoctoral Fellowship from the University of Missouri-Rolla. He was a faculty staff member at the universities of Cairo, Missouri-Rolla, and the Desert Institute between 1964 and 1976. Ahmed was a Regional Geologist and Petroleum Explorationist with Phillips Petroleum from 1976 to 1980) and with GUPCO from 1980 to 1990. He has been involved in basin analysis, the application of geochemistry to exploration, resource assessment, and concession evaluation. He taught courses in development geology, geochemistry, and integrated surface methods at Cairo, Ain Shams, Suez Canal, and Mansura universities in Egypt, and industry-tailored courses at Saudi Aramco, Kuwait Oil Company, FPC, and SPC. Ahmed is the author of numerous research papers and the editor and reviewer for several scientific publishers and periodicals. He has supervised several PhD and MS programs.

Palynofacies-Defined Cyclicity and the Recognition of Transgressive-Regressive Cycles Using Palynomorph Ratios: an Example from the Silurian of Saudi Arabia

John Marshall
School of Ocean and Earth Science, Southampton Oceanography Centre, UK

Preliminary studies of palynofacies carried out during Phase 1 of the CIMP/Saudi Aramco project revealed the existence in the Nuayyim-2 well of palynofacies-defined cycles with a repeat interval of some 50 to 70 feet. These are defined by the relative abundance of marine and terrestrial palynomorphs. These cycles are significant in that they indicate the presence of climatically driven Milankovitch forcing, which if present as a wireline log expression, will provide the basis for high-resolution correlation both within Saudi Arabia and ultimately to the Silurian stratotypes.

Further cycles have been investigated in well Berri-84. Here, three, cycles have been recognised within 170 feet of Upper Silurian core. These cycles were initially defined using a simple ratio of marine to terrestrial palynomorphs. However, such data suffers from being proportionate where changes in the absolute abundance of one component will alter the relative abundance of all other components. To mitigate this inherent problem, the palynofacies abundances were counted using a Lycopodium spike to give ‘absolute’ abundances. Although this method still contains a data closure through all values being per gram of rock, it allows greater comparison between the same component in successive samples. What this shows is that the changing marine to terrestrial ratio is parallel by significant cyclic changes in palynomorph abundance. Both the marine and terrestrial components increase and decrease synchronously, minor differences in abundance giving the changing ratio. Hence the ratio could be considered as an artifact, and resulting as equally from changes in organic matter productivity or preservation rather than any proximal / distal or sea-level change. Significantly these changes in palynomorph abundance are echoed by the TOC% (total organic carbon) content of the rock. In addition, the cross-plot of palynomorph abundance versus TOC% shows two distinct trends that relate to the amorphous organic matter content of the samples. Hence, it would appear that the changing ratio of marine to terrestrial palynomorphs reflects changes in marine productivity within the water column. The argument against a mechanism based on preservation through stratification is that it would not show a changing palynomorph ratio unless it was both more distal and stratified. In order to further explore this paradox an independent measure of proximality was sought. This was achieved by measuring size changes in the spore population that, with appropriate checks, appears to be a robust method of confirming cyclicity.

John Marshall is a Senior Lecturer in the School of Ocean and Earth Science at Southampton Oceano-graphy Centre. Prior to going to Southampton, he worked as a Palynologist in the Strat Lab at Gearhart Geodata in Aberdeen and in the Department of Geology, University of Newcastle upon Tyne. John’s research interests are Devonian palynology including high-latitude spore assemblages, recognition of large-scale climatic change in Devonian and Jurassic sediments, hydrocarbon source rocks.
and palynofacies, and thermal maturity determination, especially in pre-Carboniferous rock sequences. John received a BA from the University of Cambridge in 1976 and a PhD from the University of Bristol in 1981.

4-D Seismics: a Powerful but Sensitive Reservoir Tool

Roland Marschall
Schlumberger OFS, Geco-Prakla, Germany

4-D seismics represent an integration of the acquisition/processing/interpretation/reservoir simulation ‘boxes’ and aims to quantify fluid flow in the reservoir. All rules known for the individual boxes as well as some new ones for the integrated datasets apply. The main rules are reviewed and discussed.

Perhaps the most important rule here is (in terms of repeated 3-D data acquisition) that the 3-D geometry has to be the same for repeated surveys. However, additionally there exists a definite minimum requirement for the actual seismic coverage. Low-fold 3-D surveys have to be seen as purely structural 3-D seismic data that, due to the relatively high noise level in the differenced volume, in principle do not allow for reliable saturation mapping. Also, the so-called ‘Monitoring Quantity’ (usually Acoustic Impedance) needs to be defined. The key-quality parameter for 4-D is the S/N (signal-to-noise) ratio after differencing. Here the ‘signal’ is the Change in Acoustic Impedance due to local fluid substitution, while the ‘noise’ is given by the Non Repeatable Noise (NRN) component, which primarily is a function of the 3-D acquisition geometry and seismic coverage. Clearly, seismic amplitudes depend on offset, and as soon as the 3-D geometry changes, a different average amplitudes are different (due to a different 3-D geometry for each individual volume). In the case where the oil/water interface (which in principle represents a connected subvolume due to ongoing fluid-substitution within a certain timeframe) can be interpreted directly, one may derive from its actual dip-angle the front velocity as well as the thickness of the subvolume. This, if available, represents an extension of the structural model of the reservoir in terms of additional interfaces representing the top and base of this subvolume defined by fluid substitution over the timespan considered.

The main result is given by the final saturation map that is based on the monitoring quantity selected. It is normally Acoustic Impedance for which the seismic data have to be inverted before the differencing process. This requirement goes beyond the usual application of 4-D of being merely ‘drained/undrained compartment’ mapping that, only in the case of segregated flow-conditions represents saturation-mapping as well. The actual S/N-ratio of the differenced volume has to be determined with respect to the monitoring quantity. This is achieved by a technique called Sigma-Analysis that consists of two steps, firstly an analysis to give the NRN-component, followed by evaluation to give the saturation map. The extreme sensitivity of 4-D with respect to the actual S/N-ratio (that is, the amount of NRN present in the differenced volume) will also be discussed. For reliable mapping, a S/N-ratio >1 for the differenced volume is needed.

Roland Marschall has been with Geco-Prakla since 1967. He is currently the Chief Geophysicist Land Data Acquisition with Geco-Prakla in Hannover, Germany. Roland graduated from Montan University Leoben with a Diploma in Engineering in 1966 and a PhD in 1975. In 1990, he obtained full Professorship at Ruhr University, Bochum. He is a member of EAEG, SEG, and DGG and is interested in seismic data acquisition, processing, and interpretation.

Prediction of 3-D Seismic Acquisition Footprint


Land 3-D seismic survey results are frequently contaminated by spatially periodic interference that correlates exactly with the acquisition geometry. Such artifacts are commonly referred to as ‘footprints’ and can hamper seismic interpretation or even invalidate such aspects as inferences drawn from amplitude maps, amplitude-versus-offset (AVO) measurements and other attributes.
Conventional 3-D survey evaluation and design usually relies solely on analyses of various proposed geometries though fold maps, offset and azimuth distribution plots, and similar diagnostics. Although they provide useful indications of relative merit, they cannot predict quantitatively the level of footprint contamination that depends on the level and form of source-generated noise and acquisition geometry. Source-generated noise characteristics vary strongly from one area to another so that a design that is suitable for one area and objective may fail in other cases. Fortunately, information on the noise characteristics of a given area is almost always available from pre-existing 2-D data using appropriate methodologies.

In predicting 3-D acquisition footprints, both synthetic records and real 2-D data are processed using 3-D geometry. Stacked and migrated volumes for various acquisition geometries are correlated with noise characteristics of the input data and are compared with data from a 3-D survey acquired in the area. Advantages of using real 2-D data include more accurate simulation of the 3-D data, better ability to incorporate changes in conditions over the area, and no need to create a complicated synthetic model. Disadvantages include dependence on the quality of the 2-D data, and dependence on careful data processing. The advantages and disadvantages are demonstrated and discussed.

The main application of the work is in predicting data quality and the degree of footprint contamination that can be expected for different 3-D acquisition geometries in a given area. The data are also useful in understanding the response of processes such as dip moveout to different acquisition geometries. This work offers a new approach to prediction of 3-D seismic results by using previously acquired 2-D data. It is useful when deciding on an acquisition geometry and weighing economic considerations against geophysical objectives.

John Mathewson is an Area Geophysicist with Western Geophysical in the UK, assigned to EAME Data Processing. He is currently involved with work-in-depth imaging, tomography, multiple attenuation, and acquisition footprint analysis. During his 15-year career with Western, John has worked in both land seismic acquisition and processing in the UK and overseas. He has a BSc in Geophysics from the Colorado School of Mines.

John Savage has a first degree from Cambridge and a PhD in Geophysics from the University of Durham. Before joining BHP, he worked with oil companies (11 years with Shell, 2 years with Candecca) and service companies. John was heavily involved in early land, marine, and transition zone 3-D surveys with Shell in The Netherlands and Brunei. He has planned, operated and interpreted land 3-D surveys in the UK and is currently involved in designing and processing 3-D surveys for BHP in Algeria. He has also worked with land 3-D data from Pakistan, Abu Dhabi, and elsewhere.

Dual Wavefield Reinforcement of Ocean-Bottom Cable Data in Offshore Nile Delta: Methodology and Case History

John McCloy, Rick Sinno, Simon Barnes and Joel Starr
Petroleum Geo-Services, Cairo

In 1998, Petroleum Geo-Services acquired a 3-D multi-client seismic survey in offshore Nile Delta, Egypt. The survey consisted of 43 orthogonal patches of dual-sensor ocean-bottom cable and covered about 830 square kilometers of the Manzala concession. In an effort to improve the signal-to-noise ratio, the Dual Wavefield Reinforcement technique was implemented to create a reinforced stacked image. In this technique, pressure and velocity detectors on the water bottom are used to separate upward-traveling wavefields from polarity-reversed downward-traveling wavefields. Each wavefield had its components (hydrophone and geophone) summed and was processed individually, then summed together during stack to provide a higher signal-to-noise ratio and a better image. A comparison of 3-D conventional processing versus the dual wavefield processing will be presented. Both stack response as well as Amplitude Versus Offset response over a Pliocene bright spot will be examined.

John McCloy is the Ocean Bottom Seismic Project Leader for Petroleum Geo-Services (PGS) in Cairo. He began his career in 1994 on a vibrosis land acquisition crew in West Texas for Western Geophysical. In the following year, he relocated to Houston to join the land processing department. In 1997, he joined PGS, working in the Ocean Bottom Seismic Processing group. He has a BSc in Geology from Virginia Polytechnic Institute and State University.
Joel Starr is the Manager of Ocean Bottom Seismic Processing for Petroleum Geo-Services (PGS). He began his career in 1989 as a Processing Geophysicist for Halliburton Geophysical Services in New Orleans. He relocated to Houston in 1992 to the Ocean Bottom Cable technical group which developed and supported shallow-water seismic acquisition technology. In 1994, he joined Output Exploration exploring for hydrocarbons in Gulf Coast Mississippi, Alabama and South Texas. Currently, he is specializing in 3-D AVO and seismic attribute analysis. Joel has a BSc in Geology from Juniata College in Huntingdon, Pennsylvania (1985). After graduation, he worked for the Pennsylvania Department of Environmental Recources. In 1990, he received a MSc in Geophysics from the University of New Orleans. Joel has been an active member of SEG, SGS, and GSH.

W. Scott Meddaugh is a Senior Staff Scientist for Chevron Petroleum Technology Company in Houston. His areas of specialization are reservoir modeling, geostatistics, and software design/support. He has worked for Chevron’s various petroleum technology companies for 19 years. Scott has a BS and MS in Geology from the University of Wisconsin-Milwaukee and a PhD in Geology from Harvard University.

Robert Kirby is a Reservoir Geologist with Chevron Overseas Petroleum Technology Company in Kuwait. He has a degree in Geology from Georgia Southwestern College. Robert has worked over the past 19 years for A.P. Green Refractories Company, Trans Ocean Oil, Gulf Oil Corporation, Arabian Chevron (Saudia Aramco), and Chevron USA. He is a member of AAPG and SPE.

Jamal Al-Humoud, Avi Chatravati, Gerry Cook, James Wadowsky and Dawood Al-Matar biographies not available.

Risked Reservoir Development Planning Using Geostatistical Modeling and 3-D Streamline Simulation, Greater Burgan Field, Kuwait

A fundamental problem associated with reservoir modeling is the definition of an appropriate geostatistical distribution of reservoir properties to be carried forward into finite difference-based simulation. Often, project time constraints make unrealistic the simulation of significant numbers of geostatistical realizations that are required to achieve statistically meaningful results. In this presentation, we describe an approach that was used in the Greater Burgan field to limit the number of simulation models necessary for evaluating the probable outcomes from stochastic modeling. Development tactics for two reservoirs in the Lower Cretaceous Burgan Formation were evaluated using heterogeneity-risked geostatistical models. The models represent pessimistic, expected, and best-case realizations of reservoir variance. These realization cases were resolved by screening dynamic reservoir data against model fluid-flow characteristics using 3-D-streamline simulation. The objectives of the modeling were to investigate production and completion alternatives within a risked range of reservoir model uncertainty and to develop and evaluate different depletion plans within these limits.

Source Rock Assessment and Geochemical Processes Involved in the Formation of Heavy Oil (Kuh-e-Mund, Southwest Iran)

Mahmoud Memariani, Mohammad Kamali and Minoo Angajivand, Research Institute, National Iranian Oil Company, Tehran

The Kuh-e-Mund structure is a large northwest-trending anticline (90 kilometers by 16 kilometers) located to the southwest of Bushehr on the Gulf coast of Iran. It is a relatively symmetrical anticline whose axial plane is cut by numerous faults. The presence of two distinct heavy-oil reservoirs were confirmed by drilling well MD-6. The Eocene Jahr Um reservoirs contains immobile oil (6°–8°API) in highly fractured dolomite (upper section) and detrital dolomitic chert (lower section). The Cretaceous Sarvak reservoir is composed of highly fractured, marly, neritic and pelagic limestone with interbedded shales. It contains heavy oil of 14°–15°API.

In order to assess the source of the heavy oils, a total of 114 samples were collected for geochemical investigations from outcrops, cuttings, cores, and oils from the Kuh-e-Mund, Kaki, Zirreh, Kangan, Darang (onshore), and North Pars...
(offshore) fields. The samples cover almost the entire stratigraphic sequence from the Precambrian to the Miocene. It was found that candidate source rocks younger than the Paleozoic, such as the Gadvan (Cretaceous), Kazhdouni (Albian), Pabdeh (Paleocene) and Garu (Santonian-Campanian) formations, are incapable of producing commercial amounts of hydrocarbons because of their low maturity levels and insufficient organic content. Further investigations showed that oil accumulations in Tertiary and Cretaceous reservoirs are sourced from Paleozoic sediments. Similarities exist between the gas-chromatograms of the saturated fractions of organic matter extracted from the Permian Faraghan Formation and from the Late Cretaceous Ilam Formation. The results indicate that vertical migration of hydrocarbons took place from deeper source rock in the North Pars field, whereas in the Kuh-e-Mund, long-range lateral hydrocarbon migration from different source rocks is thought to have occurred.

**Mahmoud Memariani** received a BSc (1981), MSc (1983), and PhD (1988) in Organic Chemistry from Osmania University, India. He then joined NIOC's Research Institute of Petroleum Industry (RIPI) as Head of the Chemistry Section of the Geochemistry Department. Mahmoud has 11 years experience in petroleum geochemistry, particularly on biomarker analyses. He has published several papers in national and international scientific journals and has supervised 16 projects at RIPI.

**Mohammad Kamali** see p. 120; **Minoo Angajivand** see p. 122

---

**Jubaila Formation, Tuwaiq Mountain Escarpment, Saudi Arabia: Window to Lower Arab-D Reservoir Faunal Assemblages and Bedding Geometry**

**Franz Meyer, G. Wyn Hughes, and Ibrahim Al-Ghamdi**, Saudi Aramco, Dhahran

Stratigraphic mapping of an 82-foot-thick and kilometer-long road cut along the Riyadh-Makkah highway at Wadi Laban provides two-dimensional information about faunal assemblages and bedding geometry for the upper part of the Jubaila Formation. The map depicts major vertical and lateral stratigraphic variations along depositional strike as seen in a mosaic of 72 photos. A petrographic analysis of 195 samples revealed that the faunal, lithologic, and textural calibration for the mapped sequence resembles those of the cored lower Arab-D reservoir in Saudi Arabia. Semi-quantitative micropaleontological analysis shows that the representative samples from the exposure include species of polymorphinids, hispid calcispheres, sponge spicules, and strongly ribbed echinoid spines that represent the in-situ deeper marine forms typical of the lower Arab-D reservoir. Admixed with these faunas are a variety of allochthonous shallow marine forms such as *Kornubia palastiniensis* and *Nautiloculina oolithica*.

Stratification is even or wavy parallel, and bedding planes are non-parallel curved or wavy. Parallel stratification predominates in mud-dominated tabular units. Bounded by laterally extensive pause surfaces, these low permeability strata traverse the length of the outcrop. Non-parallel stratification outlines lenticular grain-supported accumulations enclosed by curved or wavy planes. These permeable units represent laterally discontinuous slump and channel deposits. A distinctive interval of slump structures as much as 3 feet thick occurs 15 feet above the base of the measured section and can be traced for more than 2 kilometers to adjacent road cuts. Coherent slump blocks with en echelon arrangement exhibit concave-upward shear planes and a backward rotation.

Porous channel deposits are as much as 8 feet thick, and up to 2,100 feet long. A conglomeratic coral-stromatoporoid fill distinguishes the largest channel complex located 50 to 60 feet above the base of the measured section. The environmental significance of faunal elements related to the two-dimensional geometry of various sedimentary units, together with the sedimentological processes that caused slump and channel-fill deposition, fashion a foundation for developing improved geologic models for the lower part of the Arab-D reservoir.

**Franz Meyer** has a BS in Geology from State University College of New York, New Palz and a MS and PhD from the University of Michigan. He joined Shell in 1979, initially as an Exploration Geologist and later as Carbonate Specialist at Shell's Belair Research Lab in Houston. Franz joined Saudi Aramco in 1991. He is currently a Geological Specialist engaged in various Jurassic carbonate reservoir and outcrop studies from eastern and central Saudi Arabia. His assignments include research in reservoir characterization, sequence stratigraphy, dolomite, and sedimentology, as well as teaching.

**G. Wyn Hughes** see p. 110; **Ibrahim Al-Ghamdi** see p. 22
Recent investigations on the development of Arab-D dolostones revealed new data about the development of porous dolomite rhombs. Porous crystal fabrics make up a significant component within certain dolomitized intervals in the Arab-D reservoir. The dolomite layers with porous rhombs are typically thin stratigraphic units, but rhombs with interval voids may account for up to 80% if the horizon is only partly dolomitized, or less than 10% if the stratigraphic interval is pure dolostone.

Intracrystal porosity varies from only a few percent to as much as 90%. The observed pore space generally exhibits highly irregular shapes and variable distribution patterns. However, some porous dolomite have crystals fabrics that mimic the micro-architecture of precursor grains. Curved crystal faces after thin-shelled grains, and crystals with internal pores that preserve foraminiferal chambers, offer compelling evidence that these porous dolomite fabrics have a constructional origin.

Such examples, plus the observation that many intracrystalline pore walls are planar rather than pitted surfaces, suggest that many porous dolomite rhombs may actually be a case of arrested crystal growth rather than selective leaching of unstable dolomite phases. If valid, the constructive crystal growth hypothesis holds two significant implications for the Arab-D. Firstly, the porous dolomites cannot be regarded as examples of dedolomitization. Secondly, the presence of porous dolomite is not unequivocal evidence for an intraformational exposure surface.

The methodology employed includes an integration of sedimentologic, micropaleontologic, diagenetic, and stable isotopic data. This approach requires closely spaced sampling across the unconformity that begins three to four feet below and extends one to two feet above the target surface. Sample collection is generally in half-foot increments in cores whereas on outcrops we collect rock at the base and top of each bed. Macroscopic features in core or outcrop are augmented by thin-section and stable isotope analyses.

This approach has been used successfully to distinguish seven significant formation and intra-formation unconformities from minor Jurassic and Cretaceous sedimentary discontinuities. Our initial work shows that all significant unconformities exhibit dramatic shifts in the biofacies and lithofacies components across the boundary.
expressed as gentle flexures. Tightly folded ‘slump balls’ of contorted or broken muddy strata occurs locally between the sedimentary bodies. The sheet slump documents a mass-wasting event in the upper part of the Jubaila Limestone. Its presence signifies that the Jubaila seafloor sloped at an angle sufficiently steep to allow for the event to take place.

Franz Meyer see p. 143

The Effect of Diagenetic Processes on Reservoir Parameters and Zonation of the Fahliyan Formation Reservoirs in the Kharg Oil Field, Offshore Iran

S. Ali Moallemi and Mohammad Kassaie
Research Institute,
National Iranian Oil Company, Tehran

The regionally extensive Neocomian Fahliyan Formation is the reservoir rock of several important oil fields in southern Iran and in the Iranian territorial water of the Gulf. In a study of the effect of diagenetic processes on its reservoir characteristics, the lithology, facies and porosity systems of a 880-foot core were investigated. Microscopic studies on 880 thin sections were carried out and the horizontal and vertical permeability and porosity of an equal number of samples were measured. In addition, the capillary pressure of 21 selected samples was measured. The size of particles, pores and pore throats was determined using a Scanning Electron Microscope.

The reservoir was divided into three zones on the basis of variations in fabric and cementation, and type and distribution of porosity and permeability. Subzones 1A and 1C and zone 3 demonstrated the best reservoir qualities as a result of good effective porosity, permeability and pore sorting.

Diagenetic investigations showed the presence of two porosity systems. That of zones 1 and 2 is mainly the result of fabric micritization due to recrystallization induced by green algae. The resulting chalky fabric is present throughout. The porosity is fine with pore diameters ranging from 2 to 5 microns. The average porosity and permeability were measured at 16% and 0.8 millidarcies respectively. In zone 3, in contrast, porosity consists of large vugs that developed due to solution by undersaturated waters. The average porosity and permeability in this zone were measured at 21% and 515 millidarcies respectively.

S. Ali Moallemi received his BS from the University of Baluchistan, Iran in 1987 and a MSc from Islamic Azad University, Tehran in 1992. He joined NIOC’s Research Institute of Petroleum Industry in 1990. Ali is a Senior Researcher in reservoir geology and fracture studies. He is a member of the Geological Society of Iran and SPE.

Mohammad Kassaie see p. 122

The Integration of 3-D Seismic, Reservoir and Basin Modeling to Better Define Static Model Uncertainties: a Carbonate Example from Abu Dhabi

Awad Mohammed, Peter Landmesser and Ahmed Khouri
Abu Dhabi Company for Onshore Oil Operations

Northeast Abu Dhabi is characterized by low-relief structures and poor quality, heterogeneous reservoirs that reflect a complex structural evolution and diagenetic history. The data sets of the field under investigation consist of 2-D and 3-D seismic surveys, logs, and whole cores from ten wells. The field under study is currently being evaluated through an early production scheme prior to implementing a full field development plan. The objectives of this work is to define the reservoir architecture and gage porosity and water saturation, and hence volumetric, before simulation work and field development.

3-D seismic data was optimally used to define and reduce the tops and the fault model uncertainties. Three different 3-D deterministic reservoir models reflecting the structural interpretation scenarios were constructed. The field discontinuity is supported by the reservoir fluid, gas and test analyses. Thirty-two layers were mapped. Four diagenetic facies bodies were mapped laterally using seismic attribute imprints. Multiphase structural tilt mapping helped define the diagenetic bodies. These facies bodies were further controlled by information on migration and remigration, extracted from the 2-D burial history model based on seismic and well data.

The seismic attribute data were correlated further with the porosity of the individual layers, and the resultant functions were used successfully to create high-resolution trend models. The structural frame, fault model, fine-layer sequence stratigraphic framework, diagenetic facies bodies, and seismic attribute trend models were all incorporated in the 3-D geological model to further control the porosity.
interpolation. The porosity dependency on the seismic attribute trend model was varied to reflect the uncertainty range. The saturation profile was controlled by the fault segment model. Using variogram models based on well data, a stochastic simulation was performed. The resultant ranges of oil reserves were then log-normally distributed. As a result of this 3-D integrated geological model, future well locations have been optimized. The uncertainties associated with volumetric and simulation input have been better defined and reduced.

Awad Mohammed is a Senior Staff Geologist with Abu Dhabi Company for Onshore Oil Operations (ADCO). Prior to joining ADCO in 1991, Mohammed was with UAE University (1990–91) and with Chevron from 1979 to 1989. He has a BSc (hons) in Geology and received his MSc and DIC in Petroleum Geology from Imperial College, London in 1983. Mohammed is a committee member and former General Secretary of SEE and a member of AAPG.

Peter Landmesser is a Senior Geophysicist/Geologist of Schlumberger GeoQuest in Abu Dhabi Company for Onshore Oil Operations. He has 20 years of worldwide experience in the petroleum industry in the field of seismic interpretation. Landmesser received a Dipl.-Geol. (MSc equivalent) in Geology in 1979 from the University of Hannover, Germany. His special interests are seismic stratigraphy, tectonics and reservoir characterization. He is a member of AAPG, SEE, EAGE, and DGG.

Ahmed Khouri is a Lead Review Geologist with Abu Dhabi Company for Onshore Oil Operations (ADCO). He has a BSc (1990) from UAE University in Geology with a minor in Chemistry. He has eight years oil industry experience covering wellsite geology, subsurface mapping and reservoir characterization. He has worked in the Exploration Team of the Petroleum Development Division of ADCO and is currently in the Undeveloped Fields Team. His interests include reservoir characterization and 3-D geological reservoir modeling. He is a member of AAPG, SPE, and SEE.

From Rock Physics to Rock Texture: a Case Study of Saudi Arabian Reservoir Rocks

Mohammed Mohiuddin, Gabor Korvin, Abdulazeem Abdulraheem, Mohammed Awal, Khaqan Khan and Mohammed Khan
King Fahd University of Petroleum and Minerals, Dhahran

The ultimate goal of inverting seismic and wireline-log data is to predict lithology, effective rock properties (such as porosity and permeability), and rock texture. As a step towards this ambitious goal, we carried out compressional (P) and shear (S) wave velocity, attenuation, porosity and permeability measurements on 50 reservoir rock samples from Saudi Arabia. This was for a wide range of confining pressures from 4 to 82 megapascals. We analytically related the results with rock texture.

We have found distinctly different porosity versus pressure (ø-p) behavior for sandstone and limestone. We have proved theoretically that the exponents in the ø-p relationship are related to the compressibility of the sandstone matrix, and to the fractal dimension of the pore space. However, the dependence of the ø-p relationship on pore geometry is more complicated for limestone.

The P-wave velocity in dry sandstone is a convex, monotonously increasing function of pressure in conformity with Gassmann’s theory. Limestone velocities change only slightly, and much more irregularly, with confining pressure. For both sandstone and limestone we have found a good overall correlation between permeability and porosity. P- and S-wave attenuation measurements were also conducted on the same set of sandstone and limestone samples, under similar pressure and saturation conditions. Preliminary results of these studies will be shown in the presentation.

A minimum entropy technique was proposed by Doyen to invert the crack geometry of igneous rocks from pressure-related rock physical data. We have applied a similar minimum entropy technique to invert pressure-dependent porosity. The result of the inversion splits the porosity into nodal and throat-related fractions and also gives an estimate of the shape distribution of the throats.

Mohammed Mohiuddin is a Research Engineer in the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a BS (1989) in Mechanical Engineering from Jawahar Lal Nehru Technological University, India. He was awarded a MS (1993) and PhD (1997) in...
Mechanical Engineering by KFUPM. From 1989 to 1990 he was a Drilling Engineer at Singareni Collieries, India. He joined the Research Institute of KFUPM in 1998 to do applied research in petrophysics. Mohammed is Task Leader in an industry-funded project investigating stress-dependent porosity and permeability. He is also working on inverting rock-texture properties from measured acoustic and transport properties of rocks. He is a member of SPE and ASME.

Gabor Korvin is an Associate Professor (Geophysics) at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a MSc from the University of National Sciences, Budapest, Hungary (1965) in Applied Mathematics and a PhD in Geophysics from the University of Heavy Industry, Muskole, Hungary (1982). From 1965 to 1985, he was Head of Seismic Theory Department, Hungarian Geophysical Institute. In 1985, he became Senior Lecturer in Geophysics at the University of Adelaide, Australia. He joined KFUPM in 1994. Gabor’s main professional interests are applied mathematics, statistical rock physics, and signal processing. He has more than 50 publications on these topics including the monograph, Fractal Models in the Earth Sciences.

Abdulazeez Abdulraheem is a Research Engineer in the Petroleum and Gas Division of the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He received a PhD in Civil Engineering (with specialization in Rock Mechanics) from the University of Oklahoma in 1994. His areas of research include theoretical and experimental rock mechanics, petrophysics, constitutive (material behavior) modeling, numerical simulation using finite element and finite difference, soil mechanics, structural dynamics, and in-situ stresses in hydrocarbon reservoirs.

Mohammed Awal is a Research Engineer in the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a B.Tech (1983) from the Indian School of Mines, Dhanbad, an MS (1988) from KFUPM, and a PhD (1991) from the University of Oklahoma. Mohammed’s degrees are in Petroleum Engineering, with specializations in Reservoir Simulation and Artificial Intelligence. His research interests include reservoir rock mechanics, drilling engineering, and hydraulic fracturing. He is a member of SPE.

Khaqan Khan is an Engineer in the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a MS in Civil Engineering from KFUPM. His main areas of interests are theoretical and experimental rock mechanics and petrophysics. He is a member of the Pakistan Engineering Society.

Safdar Khan is an Engineer in the Petroleum Engineering Section of the Research Institute of King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a MS (1995) in Civil Engineering (with specialization in Structural Engineering) from KFUPM. Safdar is involved in theoretical and experimental work, and data interpretation and analysis in the field of petroleum-related rock mechanics. His professional interests include structural mechanics of materials, computational mechanics, and numerical modeling using finite elements and boundary element methods.

High-Fidelity Vibratory Seismic in a Difficult Geologic Area

Nick Moldoveanu, Schlumberger, Houston

Gerrit Smeets, Schlumberger, Gatwick, UK

and Glen Tite, Schlumberger, Houston

High-Fidelity Vibratory Seismic (HFVS) is a method proposed and patented by Mobil and ARCO. It addresses the problem of limited resolution of vibroseismic surveys in oil exploration. The HFVS method requires the measurement and recording of the vibrator motion for each individual vibrator in the array. In addition, the transmitted sweeps for each vibrator must be designed such that the recorded geophone signal can be separated afterwards into the contribution of these individual vibrators.

This presentation is the result of HFVS experiments and 3-D HFVS seismic acquisition in the Delaware Basin, West Texas. The Delaware Basin is a notoriously difficult area for hydrocarbon seismic exploration due to a very poor signal-to-noise ratio. A high-velocity carbonate layer in the near-surface associated with karstic geologic phenomena causes a poor penetration of the compressional P-wave seismic energy and strong coherent and back-scattered noise. The rapid variation of the near-surface geology complicates the statics solution and this affects the final processed seismic data. Two 2-D HFVS experiments were performed to evaluate the HFVS versus conventional vibroseis in this type...
of geological environment and to determine the feasibility of HFVS for 3-D seismic in terms of data quality and production efficiency. A 3-D HFVS seismic survey was successfully acquired in Oak Lake, Delaware Basin and the results will be shown and discussed in the formal presentation.

Nick Moldoveanu is a Principal Geophysicist in the Marketing and Geophysical Support Department of Schlumberger in Houston. He has a MSc in Geophysics and a MSc in Mathematics from the University of Bucharest, Romania. He has worked for Schlumberger since 1989, in Calgary and Houston. He has been involved in data processing, seismic programming and geophysical support for acquisition, processing and new technology. Nick previously worked for Kelman Seismic in Calgary and for the National Geophysical Oil Prospecting Company in Romania. He is a member of SEG and EAGE and a Professional Geophysicist registered with AAPEGA.

Gerrit Smeets is the Domain Manager Land Sources for Schlumberger Geco-Prakla, based in Gatwick, UK. He has a MSc in Geophysics and Mining from Delft University of Technology, The Netherlands. He has been with Schlumberger since 1982 in Delft, Hannover, SugarLand, and Gatwick. Gerrit has been involved in data processing, programming, engineering, and geophysical support for acquisition and new source technologies. He is a member of EAGE and SEG.

Glen Tite is a Senior Geophysicist with Schlumberger in Houston.

Multiple Attenuation in the Middle East

Ian Moore
Western Geophysical, Middlesex, UK

Middle East seismic data typically suffer from severe multiple contamination. As such, multiple attenuation continues to play a prominent role in many, if not most, processing flows. The data processor’s tool box contains a variety of multiple attenuation algorithms, each of which finds favor in specific settings. Determination of the most appropriate tool or tools for a given setting can be a laborious and costly task.

This presentation reviews the range of multiple attenuation algorithms that are appropriate for Middle Eastern seismic data, placing emphasis on the applicability and optimal parameterization of each. Algorithms falling into the three broad categories of velocity discrimination (non-hyperbolic moveout correction, radon domain velocity mute), deconvolution (t-p deconvolution), and modeling are illustrated in both synthetic and real-data environments.

Considerable attention is paid to emerging multiple attenuation technology, especially that designed for interbed multiples. Such multiples may exhibit no significant velocity discrimination and the most promising attenuation algorithms are based on modeling and subtraction. Recent inclusions in this category are several methods that use primary information from the data themselves to predict interbed multiples, in a manner analogous to that used to predict surface multiples. The key to the success of such a method lies in its ability to produce a sufficiently accurate model with the minimum of effort. Several methods are compared and detailed results are presented from ongoing research into one such method.

Ian Moore joined Western Geophysical as a Research Geophysicist in 1996 after completing a degree in mathematics at Cambridge University and a PhD in the same subject at Leeds University. His main research interest is in multiple attenuation and as such he provides processing and R&D support to EAME regional centers. He is currently spending much of his time in the Abu Dhabi processing center concentrating on Middle Eastern multiple attenuation problems.

The Jurassic Hydrocarbon System in Kuwait: an Update

Leonard Moore, ExxonMobil and Mohamed Al-Ajmi, Kuwait Oil Company

Successful integration of a broad array of geological, geophysical and engineering data within a hydrocarbon system framework has allowed the Joint Technical Study team to identify the potential of this system in West Kuwait and develop exploitation strategies. Of particular interest to the team was the light (49° API) oil discovered at Kra Al-Maru. Burial history and thermal modeling of over 40 site-specific locations in Kuwait, along with migration modeling from the high maturity oil source areas, have defined closures with light oil potential. The tectonic setting of the Najmah hydrocarbon system has controlled key play element development including source richness, reservoir quality, top seal effectiveness, trap formation as well as timing of hydrocarbon generation and migration. Faults and fractures tied to periods of Arabian Plate tectonic stress, as well as localized fractures related to bed curvature, provide the
necessary permeability networks. The Najmah system, although characterized by both a world class oil-prone source rock and top seal, has generally poor matrix porosity development. Successful wells are dependent on encountering large open networks of long-lived stress related fractures that are fed by hydraulic microfractures and/or matrix porosity. Hydraulic fractures are created by hydrocarbon generation from Najmah source beds within a closed system that is already at or near lithostatic pressures. These micro-fractures may allow for the recovery of significant hydrocarbon volumes from the Najmah.

Leonard Moore is a Geological Associate with the Middle East Venture Development, Exxon Exploration Co. in Houston. He has over 25 years of geologic experience including postings to London, Singapore, Bangkok, and Dhahran. His fields of specialization include geological integration, source analyses, hydrocarbon systems, and the petroleum geology of the Middle East. Leonard has degrees in geology from the University of Connecticut and Southern Methodist University.

Mohamed Al-Ajmi is a Geologist with Kuwait Oil Company (KOC). Mohammed has a BSc in Geology from Kuwait University (1994). He joined KOC in 1995. He has worked in Field Development as a Wellsite Geologist for one year. Currently he is working as Exploration Geologist in the Exploration Group. Mohamed presented a paper at the AAPG Conference in Birmingham in 1999.

Depth Imaging on a Thrust-Fault Structure in Saudi Arabia: a Case Study

Roy Mueller
Saudi Aramco, Dhahran

Pre-stack depth migration was applied to better focus the 2-D seismic data over a complex thrust-faulted area. Some image enhancements were obtained primarily by applying pre-stack angle-domain depth migration after intermediate time and velocity updates were done through pre-stack time migration. After coherency interval velocity analysis and simple velocity modeling, pre-stack depth migration provided considerable image improvement over the standard post-stack time dip moveout-migration section. The improved modeling of the shallow and intermediate horizons provided better ray-bending and travel-time corrections. Pre-stack time migration was also used to improve the time picks and consequently further update the interval velocity section used for the final pre-stack angle-domain depth migration. Significant improvement was achieved by the pre-stack angle-domain depth migration’s ability to better focus through complicated overburden because the migration equation works in the plane wave domain. This is done by creating plane wave sections for each of the narrow ranged, reflection angles of entrance for the depth model and migrating each plane section. As a result, a much improved structural interpretation of complex geology was possible through pre-stack depth-migration imaging.

Roy Mueller is a Specialist Geophysicist who has been with Saudi Aramco since 1985. He worked for 11 years in Geophysical Processing and the past 3 years in the Geophysical Technology Division's Depthing/Imaging unit. He worked previously in Venezuela for 10 years with Teledyne Exploration and 2 years in the USA with Western Geophysical. He obtained a BSc in Geology in 1972 from the University of Missouri-Rolla. He is a member of SEG, EAGE, and DGS. Roy specializes in imaging seismic data through modeling velocity and depth domains.

Delineation of Potential By-Passed Oil Accumulations Through the Use of 3-D Seismic

Abdul Nabi Mukhtar and Anwar Khalaf
Bahrain Petroleum Company

The first 3-D survey of the Bahrain field was in 1998. Despite the long production history (about 68 years) and the dense well control (more than 600 wells) it is believed that the 3-D survey will substantially enhance the characterization models of the producing reservoirs. It will also help in delineating areas of by-passed accumulations outside the productive limit of the field. The preliminary interpretation of the 3-D data has already had a considerable impact on the understanding of the subsurface geology of the Bahrain field. This presentation will analyze the new structural interpretation based on the newly acquired 3-D data with the objective of delineating the most likely areas for potential by-passed reserves. It is interesting to note that such reserve realization can, on its own, justify the cost of the 3-D survey. Hydrodynamic flow in the targeted reservoirs and its influence on the entrapment of hydrocarbons in the mapped prospects must be studied in depth. Bahrain field is a model case for illustrating the critical role of hydrodynamic forces in trapping the potential by-passed oil accumulations. This will, most certainly, dictate the type and location of the wells planned for testing these potential reserve additions. This
presentation will address the initial results of the 3-D seismic survey and will highlight the positive impact of applying the new technology in a mature oil field such as the Bahrain field. The 3-D survey has paved the way for the delineation of bypassed oil accumulations within the Bahrain structure at comparatively low cost and risk.

Abdul Nabi Mukhtar is the Senior Geophysicist of the Bahrain Petroleum Company (BAPCO). He received his BSc in Geological Engineering/Petroleum Engineering from the University of Texas at Austin. He joined BAPCO in 1986 and has worked mainly in exploration and development geophysics. Abdul Nabi’s professional interests are structural geology and reservoir characterization using seismic information.

Anwar Khalaf is Manager of Exploration and Development at the Bahrain Petroleum Company (BAPCO). He graduated from Kuwait University with a BSc in Geology in 1976 and joined BAPCO as a trainee Development Geologist. He later spent two years with Chevron in Denver, Colorado working on the Green River field. He was promoted to his present position in BAPCO in 1994. Anwar’s professional interests are the application of hydrodynamic concepts in exploration and development projects and geological application of wireline logs. He is a member of AAPG and SPWLA.

Seismic ‘Facies’ Mapping Using Neural Networks in the Khuff-B Reservoir, Shedgum Area, Saudi Arabia

Edgardo Nebrija, Saudi Aramco, Dhahran
Denis Mougenot, ARGAS, Dhahran
and Charles Wagner, Saudi Aramco, Dhahran

The results of seismic facies mapping of the Upper Permian Khuff-B reservoir at Shedgum field in eastern Saudi Arabia are based on neural-network analysis of the 3-D seismic traces bracketing the reservoir. Six seismic facies relate to the following factors: (a) the impedance gradient of the overlying Khuff-A Member; (b) thickness of the gas-bearing Khuff-B reservoir; and (c) the nature of the base of the Khuff-B reservoir.

The 200-foot Upper Permian Khuff-B Member consists of an upper 60- to 80-foot gas-bearing porous zone, and a thicker, non-porous basal zone. A 3-D seismic survey over the field revealed a north-south-trending anticlinal structure for the reservoir. To calibrate the seismic data, sonic and density logs from all 16 wells drilled to the reservoir were used to generate synthetic seismograms. In two-way seismic time, the Khuff-B interval is about 50 milliseconds (msec) thick. Thus, in order to bracket the reservoir for seismic facies mapping, a 60-msec interval from 10 msec above to 50 msec below the Khuff-B seismic pick was extracted from the 3-D seismic volume. The neural-network application uses a Kohonen self-organizing approach and the number of expected classes is specified by the user. The resulting ‘model traces’ for each class were analyzed for similarity with other classes and, if necessary, the number of classes was reduced to suitably reflect distinct individual ‘model traces’. After several iterations, six model traces (or seismic ‘facies’) of the Khuff-B Reservoir were obtained. Each of the actual seismic traces was then correlated one by one with these model traces and assigned to the facies with which it had the maximum correlation coefficient. Reliability of the resulting facies distribution was judged from a cross-correlation map.

Most of the wells drilled to the reservoir fall within two of the facies, a few in two others, and none in the remainder. About 15% of the study area where the seismic data had poor signal-to-noise ratio failed to yield any seismic facies with high-enough correlation to be acceptable. Within each of the four facies with well penetrations, the acoustic impedance profiles derived from the sonic and density logs were consistent in the class to which they belong and uniquely different from those of the other facies. Differences among the class-impedance profiles lay in the gradient (either increasing, constant, or decreasing) of the overlying Khuff-A Member, the thickness of the gas-bearing Khuff-B reservoir, and the sharpness of its base (or blockiness of the reservoir).

Since acoustic impedance has been shown from the well logs to be inversely related to the porosity, the results provide an indication of the expected porosity profile at any location and serve to guide the placement of future development wells. Where core control is poor, they also provide ‘soft’ interwell data for regional depositional modeling and facies-based porosity modeling.

Edgardo Nebrija joined Aramco in 1992 as a staff member of the Northern Area Reservoir Geology Division. Since 1992, he has been responsible for the interpretation of the Shaybah 3-D seismic data in support of development drilling and reservoir characterization of the Shu’aiya reservoir. He has also worked in the Marjan field, offshore Arabian Gulf. Edgardo was awarded his PhD in Geophysics from the University of Wisconsin at Madison. From 1979 to...
A seismic amplitude inversion of the gas-bearing Upper Permian Khuff-B carbonate reservoir in the Shedgum area of the Ghawar field in eastern Saudi Arabia was made to assist placement of development wells and establish a framework for geologic modeling. Numerous qualitative and quantitative measures of confidence in the inversion results were developed to reflect their laterally varying reliability. The resulting acoustic impedance volume was transformed into a ‘reservoir quality factor’. This was converted from time to subsea depth using vertical seismic profiling surveys and sonic logs, and viewed as sections and horizontal or layer slices in assessing the reservoir that might be penetrated by a proposed development well.

Sixteen wells were used to generate synthetic seismograms. The seismic-to-well calibration within a 1,000-msec window containing the reservoir showed an average cross-correlation of 0.72 (maximum 0.83, minimum 0.50). The single low correlation came from a well located within a zone of poor seismic data. The derived wavelet was close to zero-phase and was fairly uniform throughout the field.

Crossplots of log and core porosity with log acoustic impedance show a fairly definite linear trend. As drill core has not been fully described, no lithofacies relationships were established. Reservoir- and non-reservoir-quality rocks were separated using a 3% porosity cut-off. The normalized ratio between the frequency of reservoir to non-reservoir samples at each impedance value was designated as a measure of the ‘reservoir quality factor’ and varied from 0 to 1.

The 3-D seismic data had variable coherence qualities. Several areas had poor signal to noise ratios or otherwise showed degraded reflection coherence and continuity. Analysis of satellite imagery indicated that many of them coincided with surface scree and debris deposits below the scarps delineating the field. Statistical measures such as mean amplitude, standard deviation of amplitude, mean energy, and dominant frequency of a 100-ms window about the reservoir, show that the bulk of the seismic data was of sufficient quality for inversion and that the acquisition and/or surface feature footprint was not significant. The inversion results were, in general, very good and stable. The match between log and seismic impedance profiles was excellent for the high-contrast events and variable for the low-contrast events depending on the location within the field. Several iterations with varying wavelet dominant frequency and normalization scalar yielded low (<10%) residual error and standard deviation. Areas of poor inversion coincided with the zones of poor seismic data.

The resulting acoustic impedance, transformed into reservoir quality and converted to subsea depth, was loaded as a seismic volume onto a conventional interpretation workstation. Deviated or horizontal well paths, logs, and engineering data may be loaded directly as the volume is in depth. The resulting high-spatial resolution from inversion enhances subtle stratigraphic features, such as unconformities and pinchouts, while the transformation of impedance into ‘reservoir quality factor’ serves as a reliable guide for the placement of a proposed well. For geologic modeling, the volume may be diced into arbitrary cross-sections, or sliced horizontally or parallel to a given horizon to obtain subcrop maps or templates for facies mapping.

Muhammad Saggaf is a staff member of the Northern Area Reservoir Geology Division of Saudi Aramco. He has a BSc in Mathematics (1989) from King Fahd University of Petroleum and Minerals, Dhahran and a MSc in Geophysics (1996) from the Massachusetts Institute of Technology. His areas of interest include signal analysis, fractal models, wave propagation, inversion, neural networks, fuzzy logic, microprocessor architecture, and parallel computing. Muhammad is a member of SEG.

Jung Kim see p. 25

Outcrop Equivalent of the Subsurface Precambrian-Cambrian Ara Group in Oman

Christopher Nicholas and Martin Brasier
University of Oxford

The Ara Group in the Oman salt basins provides important source rocks of Neoproterozoic-Cambrian age. Preliminary results are presented of a new study on the possibility of
latterly exposed equivalents in the Oman Mountains and Huqf areas.

In the Huqf area, new field evidence demonstrates a distinct stratigraphic unit between the Buah and Thumaylah/Nimr formations. This unit rests on a partly karstic top surface of the Buah Formation, but is eroded and truncated by the overlying Upper Cambrian Thumaylah Formation (equivalent to the Nimr Formation) disconformity in the Buah Dome area. Fenestral micrites and stromatolitic horizons characterize these peritidal carbonates, and several cyclical units of replaced gypsum are present between flooding surfaces. Particularly well preserved δ¹³C and δ¹⁸O signatures are consistent with carbonate precipitation from evaporitic waters in beds containing gypsum and anhydrite. The stratigraphic position, thickness, and original depositional environment of this unit suggests that it could be an extremely condensed lateral equivalent of the subsurface Ara Group.

In the Oman Mountains, the Fara Formation of Wadi Bani Awf is dominated by waterlain volcanic ash and tuff. Submarine pyroclastic flows from the middle of this formation have yielded a latest terminal Neoproterozoic age. In the south of Oman, even though the absolute age suggests that they may be age equivalent. However, early diagenetic concretions preserve stable isotopic signatures consistent with bacterial oxidation of organic matter derived from photosynthetic organisms, and these appear to be very similar to ‘silicilyte’ horizons in the Ara. Syn-depositional slumping in the Fara demonstrates that sedimentation took place on a slope deepening to the north-northeast at the onset of deposition. Thus, whilst the Fara Formation and Ara Group may at least be age equivalents, their depositional environments have striking differences.

Christopher (Chris) Nicholas received his PhD from Cambridge University in 1994. During the past six years he has developed wide-ranging experience in a variety of field-based and chemo-stratigraphic projects. These range from global environmental changes during the Cambrian ‘explosion’ of multicellular life to Paleogene sequence stratigraphy of southern coastal Tanzania and 3-D paleoenvironmental reconstructions of Early Cretaceous dinosaur-bearing fluvial systems in Japan. Chris is currently a Research Fellow at the University of Oxford.

Martin Brasier biography not available.

---

**Compressional Fault-Related Folds and Saudi Arabia’s Major Hydrocarbon Fields**

Paul Nicholson

Saudi Aramco, Dhahran

Broad, gentle to open anticlines typically 5 to 25 kilometers wide and 100 to 500 meters in amplitude are prominent within the Mesozoic sedimentary sequence of Saudi Arabia. Most of Saudi Arabia’s major hydrocarbon accumulations (and a significant percentage of the world’s oil reserves) are trapped within these structures. In this study, integrated analyses of seismic reflection data, gravity and magnetic data, regional tectonic history, and well control suggest that these structures are fault-tip folds (draped and fault propagation folds) formed by thick-skinned, compressional reactivation of deep-seated faults originating in the Proterozoic basement.

Anticlines are typically cored by a moderately to steeply dipping (45°–70°) master fault that displays reverse offset which terminates upward within the upper Paleozoic section. Asymmetrical folding in the overlying Mesozoic sediments is mainly located above the hanging walls of these master faults and appears to have formed in direct response to shortening caused by reverse dip-slip movement. Although some associated strike-slip displacement along master faults is likely, a strike-slip origin for most anticlines is not favored given that, along strike, fold axial surfaces display a constant vergence and their associated faults display consistent directions of dip and offset. The most significant phase of sedimentary folding in Saudi Arabia occurred during the Late Cretaceous in conjunction with a series of regional deformation events that produced southwest-vergent compression across the northeastern margin of the Arabian Shelf from Oman to Syria. Multiple regional unconformities associated with the Upper Cretaceous Aruma Formation indicate that, in Saudi Arabia, this compression commenced in the Turonian, continued into the Senonian, and was largely completed before the Maastrichtian.

Saudi Aramco is currently exploring for deep (non-associated) Paleozoic gas along the flanks of these major fault-related folds. Ongoing analyses of the structural style and timing of these folds will influence the delineation of deeper traps, the reconstruction of depositional fairways for Paleozoic reservoirs and source rocks, and the modeling of post-Paleozoic charge generation and migration scenarios.

Paul Nicholson is a Geophysical Specialist in Saudi Aramco’s Regional Exploration Team currently analyzing Saudi Arabia’s structural geology and Paleozoic plays. Paul had more than 10 years of industry experience, primarily as a seismic interpreter.
Integrated Fractured Reservoir Modeling Using Both Discrete and Continuum Approaches

Ahmed Ouenes, (RC)², Denver
Lee Hartley, AEA Technology, UK
and Udo Araktingi, (RC)², Denver

An innovative new approach that combines the use of continuum and discrete fracture modeling methods has been developed. It provides a unique opportunity to constrain the fractured models to all existing geologic, geophysical, and engineering data and hence derive conditioned discrete fracture models. Such models exhibit greater reality and reflect the fact that fracture planes are not randomly distributed between the wells, as has often been assumed in the past. There are two main areas where detailed discrete fracture models could be used: (1) upscaling of fracture properties (permeability and porosity) for input into reservoir simulators; and (2) optimization of well-design, completion and operation based on an understanding of the inter-well-scale flows.

The modeling process is initiated by constructing in ResFrac, continuous fractured models able to capture the underlying complex relationships that may exist between many geologic drivers (for example, structure, thickness, lithology, faults, seismic data) and fracture intensity defined through static data, such as the ones derived from image logs, or dynamic data such as hydrocarbon production. Artificial intelligence tools are used to correlate the multitude of geologic drivers to the desired fracture intensity. The resulting continuous fracture intensity models are then passed to NAPSAC to generate a discrete fracture network (DFN). In contrast to previous attempts in DFN modeling where the fracture planes are distributed randomly between the wells, this new approach determines the number of fractures in each grid-block based on the value of the fracture intensity provided by the continuous model. As a result, the discrete fracture models honor all the geologic conditions reflected in the continuous models and exhibit all the observed fracture features. The conditioned DFN models are used to build a realistic and detailed model of flow in discrete conduits.

For accurate results, the full permeability tensor is calculated for each grid-block based on flow calculations using generalized linear boundary conditions. Inter-well flows are analyzed in terms of the variability in flow paths, characterized by distance and time traveled through the fracture network connecting injectors and producers.

Ahmed Ouenes is Chief Reservoir Engineer at Reservoir Characterization Research and Consulting, Inc. (RC)². He is currently developing the fractured reservoir modeling activity within the company and he is the author and developer of ResFrac. Ahmed is a graduate of the École Centrale de Paris and was awarded a PhD in Petroleum Engineering by the New Mexico Institute of Mining and Technology. His interests include development of new reservoir description tools by use of inverse modeling, geostatistics, and artificial intelligence. Ahmed has published and presented more than 35 papers on reservoir modeling. He is currently a Technical Editor of SPE.

Lee Hartley is a Senior Hydrogeologist at AEA Technology, UK. He is also Software Manager for the established discrete fracture network software NAPSAC. Lee has worked in multi-disciplinary projects in the oil and gas, engineering, and radwaste industries. He graduated from Cambridge University and has a PhD in Fluid Dynamics from the University of Bristol. His current interests include development of realistic discrete fracture models, coupling of flow to stress and phase, and advanced visualization.

Udo Araktingi is a co-founder of Reservoir Characterization Research and Consulting, Inc. (RC)². Udo was awarded his PhD in Reservoir Engineering by Stanford University. He has 14 years of oil industry experience of which 6 were as a Reservoir Engineer for Mobil Oil in continental US and 4 as a Senior Researcher with Chevron in LaHabra, California. Udo has also taught at Amoco, Bechtel, Los Alamos National Laboratory, Occidental, Saudi Aramco, Unocal, and a graduate course at the University of Southern California. He has focused on the problem of data integration using geostatistical techniques, especially seismic data, with well logs and production information. He has also been working on the problem of upscaling for generating models for fluid-flow simulation. Udo is a recognized expert in the field of viscous fingering and particle-tracking flow simulation.
Palynological Event Stratigraphy in the Paleozoic of Saudi Arabia

Bernard Owens, University of Sheffield
Sa’id Al-Hajri, Saudi Aramco, Dhahran
and Janet Lines, British Geological Survey, Nottingham

The joint investigation undertaken by palynologists from Saudi Aramco and the Commission Internationale de Microflore du Paléozoïque has established important zonation patterns throughout the Paleozoic deposits of Saudi Arabia. Prior to this study, there was a sparse published regional database that had generated only a broad basis for the stratigraphical subdivision of the sequence and left a reliance on long-range comparisons to effect correlation.

Detailed taxonomic studies have now demonstrated the unique phytogeographical character of these assemblages and established the possibility of closer correlations with other locations on the northern margin of Gondwana. Formations that had been previously left with ill-defined age assignments (for example, the Abu Jifan Group) are now more precisely dated and, more importantly, it can be clearly demonstrated that the magnitude of specific hiatus may be shorter than anticipated. New stratigraphic intervals have been recognised for the first time and evidence discovered through the study of derived palynomorphs may suggest the existence of other intervals still awaiting discovery in the subsurface.

The achievements of the project are firstly to have expanded the biostratigraphical database in terms not only of the total amounts of section investigated but also by the detailed study of palynomorph groups previously poorly exploited (such as, cryptospores). Secondly, to have exploited that data to recognize a number of well-defined palynological events which appear to have widespread distribution and therefore allow reliable paleogeographical reconstructions to be attempted.

Bernard Owens is an Upper Paleozoic Palynologist who has recently retired after 33 years with the British Geological Survey, where he was also Manager of the Basin Analysis and Stratigraphy Group. During the past 18 years he has managed major research projects involving teams of European palynologists in both Libya and the Arabian Peninsula. He has recently been elected for a second time as President of the Commission Internationale de Microflore du Paléozoïque and is currently working with the University of Sheffield where he is Director of the Centre for Palynological Studies.

Sa’id Al-Hajri is Supervisor of the Regional Mapping and Special Projects Unit of Saudi Aramco. He has a BSc in Geology from the King Fahd University of Petroleum and Minerals, Dhahran and MSc in Geosciences from Penn State University. Sa’id is professionally interested in the early Paleozoic palynology and stratigraphy of northern Gondwana. He is a member of CIMP, AASP, BMS, and DGS, and has published several papers on geological and palynological subjects.

Janet Lines has acted as the Secretary for the joint Saudi Aramco / Commission Internationale de Microflore du Paléozoïque project for the past 10 years. She is employed in the Basin Analysis and Stratigraphy Group of the British Geological Survey. She has been a contributor to major review studies of Carboniferous palynology from the Arctic to North Africa and the Devonian/Carboniferous palynology of North Africa, the Middle East and the Gulf region.

Coherent Noise Attenuation by Multichannel Adaptive Filter Banks

Ali Ozbek
Schlumberger Cambridge Research

Adaptive signal processing techniques have been developed for attenuation of coherent noise in seismic data. Their objective is to attenuate dispersive, nonstationary and aliased coherent noise in the presence of phase and amplitude perturbations. The methods developed can be classified as multichannel adaptive interference cancelers.

Signal-free noise reference is not readily available in seismic data acquisition. Various preprocessing techniques are introduced to generate the coherent noise reference channels. These techniques are coherent noise attenuation methods in their own right, which seek to separate the data into the signal and noise components.

Methods have been developed for single- and multi-component data acquired using linear and areal arrays of receivers or sources. The arrays can be small or large. In the single-component version of the method, moveout (apparent velocity) and spatio-temporal coherence are used as the criteria for differentiating between the signal and the noise. In the multi-component version, polarization is used as an additional attribute for differentiation.
Once single or multiple noise reference channels are established, coherent noise in the primary channel is canceled using data-adaptive least-squares multichannel filter banks. The objective is to find a set of local multichannel filters that optimize a global optimality criterion. The global optimization problem leads to a large number of coupled matrix equations for the filters. Imposing certain constraints on the output windows allows a suitable approximation to be made that decouples the optimization problem. The resulting matrix equations are solved using the singular value decomposition. The number of principal components used controls the strength of filtering.

One of the most important applications of the new methods has been the attenuation of ground-roll in land seismic acquisition. Benefits of the methods are illustrated, based on several point receiver tests performed by Schlumberger in various parts of the world, including the Middle East.

**Ali Ozbek** is a Principal Research Scientist at Schlumberger Cambridge Research. He has a BSc (1980), MSc and EEng (1984), and PhD (1989), all from Massachusetts Institute of Technology in Electrical Engineering and Computer Science. He joined Schlumberger-Doll Research in the USA in 1989, working on signal and image processing for dielectric logging. Ali’s recent work at Schlumberger Cambridge Research includes research on seismic/sonic drift, wave propagation in finely layered media, acoustic emission monitoring, and noise attenuation in seismic data. He is a member of SEG, EAGE and IEEE.

---

**Ordovician and Silurian Chitinozoan Biostratigraphy in Central Saudi Arabia**

Florentin Paris, University of Rennes, France  
Sa’id Al-Hajri, Saudi Aramco, Dhahran  
and Jacques Verniers, University of Ghent, Belgium

Extensive palynological investigations have been carried out on subsurface material from central Saudi Arabia. They have demonstrated the occurrence of usually rich and well diversified Ordovician and Silurian chitinozoan assemblages mainly in the Qasim and Qalibah formations. Most of the recorded chitinozoan taxa are of northern Gondwana affinities that are already known from Libya, Algeria, Morocco, Spain, western France, and also from the Czech Republic or Turkey. Endemic forms are also present in the assemblages, together with a few more widely distributed taxa described either from Avalonia, Baltica, or even from the Laurentia or China paleocontinents. These species are used here for intercontinental correlation.

Local chitinozoan biozones have been established both for the Ordovician and the Silurian subsurface sequences of central Saudi Arabia. Accurate correlations are well documented between these local biozones and the chitinozoan assemblages previously described in northern Saudi Arabia. In addition, based on a few scattered pilot samples, these biozones seem directly utilizable in other Middle East countries. On a wider scale, correlations are proposed with the Ordovician chitinozoan Biozones of northern Gondwana and with the global Silurian chitinozoan biozones.

It must be noted that several northern Gondwana biozones have not yet been identified in Saudi Arabia. This is mainly due to the stratigraphic location of the available samples that are concentrated in some particular levels. However, hiatuses of various magnitude related to the latest Ordovician glacial event exist around the Ordovician ? Silurian boundary. An age assignment referring both to the global chronostratigraphy, and to the British regional chronostratigraphy is provided for the local chitinozoan biozones recorded in central Saudi Arabia.

Florentin Paris is Director of Research at CNRS at Géosciences-Rennes, France. He received his doctoral thesis from Rennes University in 1980. He works on Ordovician to Devonian biostratigraphy, Paleoenvironments and Paleogeography, using chitinozoans. Florentin recently began investigations on Early Paleozoic biodiversitition events (co-leader of IGCP no. 410). His research focuses on northern Gondwana, South America, China, and northern Europe. He is a member of the International Subcommission on Stratigraphy and is councilor of IFPS.

Florentin Paris is Director of Research at CNRS at Géosciences-Rennes, France. He received his doctoral thesis from Rennes University in 1980. He works on Ordovician to Devonian biostratigraphy, Paleoenvironments and Paleogeography, using chitinozoans. Florentin recently began investigations on Early Paleozoic biodiversitition events (co-leader of IGCP no. 410). His research focuses on northern Gondwana, South America, China, and northern Europe. He is a member of the International Subcommission on Stratigraphy and is councilor of IFPS.

**Florentin Paris** is Director of Research at CNRS at Géosciences-Rennes, France. He received his doctoral thesis from Rennes University in 1980. He works on Ordovician to Devonian biostratigraphy, Paleoenvironments and Paleogeography, using chitinozoans. Florentin recently began investigations on Early Paleozoic biodiversitition events (co-leader of IGCP no. 410). His research focuses on northern Gondwana, South America, China, and northern Europe. He is a member of the International Subcommission on Stratigraphy and is councilor of IFPS.

Sa’id Al-Hajri see p. 154

Jacques Verniers is Research Director in the field of Paleontology at the University of Ghent from where he obtained his first degree in 1971 and his PhD in 1976. Jacques has worked extensively on the Ordovician and Silurian in Belgium and also has experience of working on Permian and Triassic spores and pollen from the Mozambique coal basins.
High-Permeability Vertical Fracture Network in Carbonate Platforms Associated with Basin-Scale Reaction-Transport-Mechanical Processes

Anthony Park, Kagan Tuncay, and Peter Ortoleva
Indiana University, Bloomington, USA.

Many carbonate reservoirs worldwide are hosts to extensive vertical fracture networks that are characterized by sub-meter-scale fractured zones that may penetrate vertically across lithologic boundaries. Connected laterally, these fractures give rise to reservoir super-permeability. Such features have been studied extensively, but with a lack of consensus on the underlying geological mechanisms. Simulations using the CIRF.B program (a multiprocess 3-D simulator that implements Reaction-Transport-Mechanical phenomena) for carbonate platforms from the USA and the Arabian Peninsula show that the location and characteristics of the fracture networks are closely related to both the overall basin tectonics and the local rock rheology. CIRF.B predicts overpressuring, compartment and seal formation, organic matter maturation, heat flow, and fluid migration patterns, and their interaction with the evolving fracture network during a basin’s evolution. Its value in predicting the location and characteristics of fracture networks makes it an integral part of remote fracture-prediction strategy.

The program’s particular relevance to fractured carbonate systems is its ability to capture locally and temporally changing dynamic processes, such as rate of sediment compaction and fluid migration. These processes are responsible for, and accommodate, changing sediment properties. For example, changing depocenter locations during a basin’s evolution can cause the rate of compaction of the deeper sediments to be spatially non-uniform. Coupled to changing permeability and sediment viscosity, fracture zones can develop along the margins of the rapidly compacting part of the basin. These features are self-organizing, such that their occurrence is spatially patterned and can persist, or disappear, as basins evolve.

Anthony Park graduated in 1985 with a BSc in Geology from the University of Washington. Since then, he has been associated with the Department of Geology at Indiana University from where he obtained a MSc and PhD in Theoretical Geochemistry. He is currently a Research Associate at the Laboratory for Computational Geodynamics. While working for his graduate degrees, Anthony did extensive internship and contract work for Amoco and Mobil. From 1995 to 1996, he was a postdoctoral fellow at the Institut Français du Pétrole in Rueil-Malmaison, France.

Kagan Tuncay see p. 188

Peter Ortoleva has been analyzing reaction-transport systems for the past 28 years. During this time, he and his students have developed more than 20 numerical codes for simulating crystal growth, reaction-diffusion systems, mechanochemistry, reactive flow in porous media, and stochastic phenomena in reaction-transport systems. The main emphasis of his work over the past 16 years has been on geochemical phenomena, the synthesis and dynamics of compartments, and the development of geochemical exploration and engineering codes. Peter has written two monographs on geochemistry and chemical reaction theory and edited an AAPG Memoir on compartments. He recently completed a monograph on basin compartmentalization.

The Hydrocarbon Habitat of the Safiq/Ghudun (Ordovician and Silurian) of North Oman

Mark Partington, Redha Al-Lawatia, Paul Senycia, Paul Tricker and Angus McCoss
Petroleum Development Oman, Muscat

The Ordovician to Early Silurian sediments of North Oman consist of a thick (300–1,600 meter) interval of fine- to medium-grained, quartz arenites (Ghudun Formation) overlain by a series of shallow-marine mudstones and sandstones (Saih Nihaya Formation of the Safiq Group) deposited as part of a major glacio-deltaic (‘Safiq Delta’) complex that prograded from southwest to northeast along the axis of the Ghaba Salt Basin. More than 33% of the North Oman well penetrations have oil or gas shows in the ‘Safiq/Ghudun’. This data provided the impetus for a study to further understand the hydrocarbon habitat of the Ghudun/Safiq in North Oman by defining a predictive stratigraphic framework to further constrain the lateral and vertical distribution of reservoir, source, and seal.

The principal hydrocarbon play that can be recognized along many salt-pillow and salt-diapir flanks in the Ghaba Salt Basin consists of the Ghudun Formation sealed by Hasirah mudstones. The play is dependent on the development of differential accommodation space during the deposition of the Saih Nihayda Formation. The effective reservoir (Ghudun Formation) is continuous across North Oman whereas the seal (Hasirah mudstones) is best developed beyond the edge of the ‘Safiq Delta’. The critical issues are breaching by the overlying Al-Khala Formation and the development of a valid seal within the Safiq Group.

In late 1997, deepening of Saih Nihayda-3 (SN-3) into the Ghudun Formation tested and proved the commercial
viability of the play concept, yielding sustained flow rates of 350 cubic meters of oil a day. The adjacent structure to the north was followed up by drilling SN-35, which found extensive oil shows but with low saturations, and is interpreted as evidence for a breached trap. This was followed by Musallim Deep-1, with potential oil-in-place reserves of 500 million barrels of oil, although poor reservoir conditions at the well location prevented the booking of reserves for this accumulation.

This presentation will address the results of Petroleum Development Oman’s ‘Safiq/Ghudun’ exploration campaign, the lessons learnt and the risks associated with exploring for a new play in a mature basin.

Mark Partington is a Senior Seismic Interpreter with Petroleum Development Oman (PDO). He has a MSc from University College, London, and a PhD from the University of Aberdeen. Mark has worked as a petroleum geologist since 1981. Before joining PDO he was a Consultant Stratigrapher for Shell International in The Netherlands, and prior to that he was an Exploration Geologist and Palynologist with BP and Robertson Research International, working mainly on the UK and Norwegian North Sea. Mark has published several papers on exploration geology, stratigraphy, and paleontology.

Redha Al-Lawatia see p. 27; Paul Senycia see p. 30; Paul Tricker see p. 188

Angus McCoss is New Opportunities Team Leader in the Exploration Department at Petroleum Development Oman (PDO), Angus has a PhD in Structural Geology from Queens University, Belfast. Before joining PDO, Angus worked for New Opportunities in Shell China and Shell Research in The Netherlands.

A Dynamic Reservoir-Simulation Model of the Jurassic Najmah-Sargelu Formations of Kuwait: a Combination of Matrix Porosity and Fracture Permeability

Ralph Pauls, J. Paul Benkendorfer, R. Neil Aubuchon, Steven Webb, Christian Strohmenger and James DeGraff, ExxonMobil

A reservoir simulation model was constructed of the Najmah-Sargelu formations in western Kuwait to assess reservoir producibility and evaluate field development options. For the Najmah-Sargelu to be a viable play, both producible matrix porosity and an extensive fracture network are required to deliver fluids to the wellbore. The best fracture fairways were observed to occur near faults and in areas of relatively high formation curvature. Geologic models of facies occurrence, matrix porosity and permeability, and fracture properties were assembled into a 3-D geocellular model using a variety of geostatistical techniques. A statistical model was used to derive an empirical predictive model of fracture density and porosity by correlating fracture parameters measured in core with geologic attributes related to facies and structure. The fracture model consisted of two components: fracture density, which supplies connectivity to the hydrocarbons stored in the matrix system, and fracture aperture, which determines the production rate. The combination of these two components provided the basis for the flow prediction model used for reservoir simulation. A full-field reservoir simulation model was constructed to evaluate field development options. Well test and production data from the appraisal well were used to refine the calibration of the 3-D fracture model with simulated performance. Performance predictions from the reservoir model were used to forecast field-production profiles.

Ralph Pauls is a Senior Engineering Specialist with the Geologic and Engineering Studies Section, Exxon Production Research Co. in Houston. He received his BS (1978) and MS (1980), both in Mechanical Engineering, from Wichita State University, Kansas. Since graduating, he has worked as an Exxon Reservoir and Production Engineer on field studies in Abu Dhabi, Kuwait, and Saudi Arabia with specialization in reservoir management, reservoir simulation, and pilot design for gas injection projects. His Middle East experience includes a 5-year assignment with Saudi Aramco. Ralph is a member of the Kuwait team working the Kra Al-Maru Joint Technical Study in Western Kuwait.

J. Paul Benkendorfer is a Senior Engineering Specialist with the Reservoir Division, Exxon Production Research Co. in Houston. He received a BS in Mechanical Engineering in 1978 from the University of Texas at Austin. Since then, Paul has worked as an Exxon Reservoir Engineer on field studies in the Middle East specializing in reservoir simulation and reservoir management. He is currently a member of the Kuwait team working the Kra Al-Maru Joint Technical Study in Western Kuwait.
**GEO 2000 Abstracts**

**R. Neil Aubuchon** is a Senior Exploration Geologist at Exxon Exploration Co. assigned to the integrated reservoir interpretation group. 3-D geologic modeling. He received a BS in Geology from the University of Houston in 1981. He joined Exxon that same year as a Geologist working in the Gulf coast of Texas and Louisiana. He moved to Exxon Production Research in 1983 to work in regional sequence stratigraphy. In 1989, Neil transferred to Exxon Co. USA where his work has focused on detailed production scale stratigraphy, production geology and field studies.

**Steven Webb**, see p. 197; **Christian Strohmenger** see p. 183

**James DeGraff** received a BSc in Geology (1975) and a MSc in Geophysics from Michigan Technological University, and a PhD in Structural Geology from Purdue University (1987). After joining Exxon Production Research Co. in 1988, he worked on predicting fractured reservoir quality in a variety of reservoir types and structural settings around the world. His current assignment involves predicting fractured reservoir quality in Jurassic carbonate reservoirs of Kuwait. James has published numerous papers and abstracts on a variety of topics including fracture formation in fold-thrust belts and volcanic rocks, mechanical modeling of folds and faults, and fractured reservoir quality in carbonates, basement rocks, and tight sandstones.

**Palyno- and Sedimentary Facies of the Permo-Carboniferous Al-Khlata Formation, Eastern Flank Area, Oman**

**Randall Penney** and **Juma Al Belushi**

Petroleum Development Oman, Muscat

The Permo-Carboniferous Al-Khlata Formation reservoir produces significant quantities of ‘heavy’ (approximately 18°–28°API) oil mainly from the southern area of Oman. The complexity of these sediments is attributed to their deposition in glacial to periglacial environments, strongly influenced by halokinesis within the underlying Huqf Supergroup. Hence, correlation of these reservoirs is often problematical. The application of techniques such as heavy minerals, chemostratigraphy, and isotopic analyses has had limited success to date with glaciogenic sediments.

The present study investigates the paleoenvironmental interpretation of palynology and palynofacies in the understanding of these deposits, and the potential of palynofacies as an enhanced correlation tool on a production field-scale basis. The sedimentary facies have been well established based on outcrop and shallow borehole cores at the Wadi Al-Khlata ‘stratotype’ in the south Huqf area.

Palynological and palynofacies analyses was carried out on 10 of the shallow boreholes encompassing 8 of 15 common lithofacies types identified in the outcrop area. Results demonstrate that in addition to fingerprinting each unit, both palynofacies and palynology complement our understanding of the different depositional subenvironments involved. Examples of these subenvironments include glaciolacustrine, glaciiluvial and subaqueous glacial rainout through a subglacial water column. The most useful palynomacerals for typing the various units are a combination of optically dense woody detritus, carbonized material, sapropelic organic material and fragmented palynomorph debris. Other data such as the overall palynomorph content, particle size and preservational characteristics provide useful paleoenvironmental information. In all but one case (Upper Heterolithic lacustrine unit), the palynofloras indicate warmer conditions than suggested by sedimentology. Extensive cannibalization of interglacial or interstadial deposits is suggested as a cause. Although subsequent trials on interfield correlation did not validate palynofacies as a stand-alone correlation tool, when used together with quantitative palynology, correlations in certain lithofacies are enhanced on a production field-scale.

Further testing of this concept on a field-scale is required. It is anticipated that it should improve well correlation together with increasing our understanding of the subenvironments and thus reservoir prediction and modeling. Therefore, it should assist in locating production wells in order to maximise field exploitation, hence saving unnecessary drilling.

**Randall Penney** graduated in 1976 from Trinity College Dublin with a BA in Earth Sciences and completed an MSc from the University of Toronto in 1979. He worked with the Applied Geology Unit of the Department of Geology, Trinity College Dublin before joining Gearhart Geoconsultants (later Halliburton Reservoir Description Services) as a Senior Geoscientist in Aberdeen in 1988. Randall later worked as an independent Consultant specializing in stratigraphic palynology before joining Petroleum Development Oman in 1998 as a Palynological Consultant focusing in particular on Oman’s Al Khlata and Haima reservoirs.

**Juma Al Belushi** see p. 19
A study was undertaken to correlate and integrate subsurface seismic fault mapping with surface geological features across the Ghawar field. Surface lineaments taken from Landsat images, high-resolution topographic maps, and interpreted 3-D seismic, all reveal prominent northwesterly structural trends and secondary northeasterly trends. Data for the lineaments are presented in the form of maps and rose diagrams. The 3-D seismic-survey elevation data were used for surface structural interpretation of the Ghawar field. The Miocene surface structure, where seen on high-resolution topographic maps, is very similar to the structure of the top Arab-D reservoir. Seismic fault mapping in the northern part of the field shows that the axis of the north-south-trending anticline is shifted to the west in several places along the northwest-trending lineaments. West-shifting is consistent with left-lateral strike-slip movement.

This study indicated that the major northwest-trending topographic lineaments could be related to reactivated sinistral Najd faults. The Zagros stress regime, which acted in a northeasterly direction, may have had little effect on the structural elements within the Ghawar field. The east–west-trending Oman stress regime and the east-southeastern oblique obduction of the Masirah Ophiolite had a major impact in the region as seen by structures in the Harmalihya and Abqaiq fields. The other hand, reactivated sinistral Najd faults and the related east-west stress regime may have produced many of the structural features within the Ghawar field. Reactivated Najd faults appears to have controlled the thickness and distribution of the lower part of the Aruma Formation in the Late Cretaceous. The directions of the Najd and Oman principal horizontal stress regimes exerted a combined effect on the Ghawar field and surrounding regions. The structural grain of the pre-Permian basement has probably controlled the formation of structures since Carboniferous times.

Dogan Perincek was awarded his MSc (1972) in Geology and PhD in Petroleum Geology (1978) by the University of Istanbul. He worked for the Turkish Petroleum Corporation as a Structural Geologist and Petroleum Explorationist between 1975 and 1989. Dogan teaches at Kuwait University. He was previously a Research Scientist at the King Fahd University of Petroleum and Minerals (KFUPM). Dhahran, an Explorationist with Mobil Exploration and Huffco Turkey Inc., and a Geophysicist with the Geological Survey of Victoria, the Geological Survey of Western Australia, and World Geoscience Co. Ltd. He rejoined KFUPM in 1997. He is a member of AAPG, Australian Society of Exploration Geophysicists, Petroleum Exploration Society of Australia, and DGS.

Salih Saner is an Associate Professor at the Research Institute of the King Fahd University of Petroleum and Minerals (KFUPM). He received his PhD in Geology from the University of Istanbul in 1977. He was an Exploration Geologist with Turkish Petroleum Corporation before joining KFUPM’s Research Institute in 1981 where he is leader of the Geology and Well Logging Group. His interests are geological basin analysis, reservoir modeling, well logging, rock and pore characterization, and petrophysical studies. Salih is a member of AAPG, SPE, SPWA, Society of Core Analysts, Association of Turkish Petroleum Geologists, and the Chamber of Turkish Geological Engineers. Salih was awarded the Prince Mohammad Ibn Fahd Award for Scientific Excellence in 1990 and the OAPEC First Prize in the field of EOR in 1991. He was a co-author of, Shuttle Imaging Radar Views of Some Geological Features in the Arabian Peninsula, published in GeoArabia, v. 2, no. 2 (1997).

Ali Al-Ghamdi is an Assistant Professor in Geophysics and Manager of the Petroleum Geology and Geophysics Section of the Research Institute at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran. He has a BSc (1979) in Geology/Physics and a MSc (1985) in Geophysics from King Abdulaziz University, Jiddah, and a PhD in Geophysics from Texas A&M University (1996). He worked in the Ministry of Agriculture and Water for eight years supervising drilling and groundwater development projects. Ali joined KFUPM in 1987. After obtaining his PhD, he taught in the Department of Earth Sciences at KFUPM and became involved with projects in the Research Institute. His professional interests are seismic and sequence stratigraphy, depositional environment studies, well-log interpretation and correlation, tectonics and structural evolution, and petrophysics. Ali is a member of AAPG, SEG, AGU, and DGS.

John Cole see p. 72; Rami Kamal see p. 120
Controlled Wavelet Processing For Land Vibroseis Data

Colin Perkins, Compagnie Générale de Géophysique, Oman and Andrew McGinn, Petroleum Development Oman, Muscat

Recently, several authors have claimed that deterministic techniques can consistently produce zero-phase marine data. However, for land data the same degree of wavelet control has not been obtained. In this presentation, a new method is presented that attempts to reduce this gap between land and marine data.

The key to the success of the marine wavelet processing has been to use deterministic processes instead of statistical techniques such as spiking deconvolution. In the past, the estimation errors of these statistical techniques have resulted in a loss of wavelet control. However, for land processing a lack of knowledge of the near-surface makes statistical estimation unavoidable. In this presentation, a method is described that is partly deterministic and partly statistical. For the statistical part, the number of parameters estimated are kept to an absolute minimum, and very reliable estimation methods are used.

The method begins with a simple convolution wavelet model from which several of the deterministic components including the Q-filter are deconvolved. This process will be equivalent to current marine wavelet processing techniques. However, for land processing there is a residual wavelet component that can be observed in the resulting amplitude spectra. It is assumed the amplitude and phase of this residual wavelet inside the sweep band are the result of near-surface and reverberation effects.

To remove the residual wavelet, surface consistent deconvolution is used because this multi-channel technique produces very reliable estimates. Assuming the residual wavelet is minimum phase, the standard approach is to estimate its phase via the Hilbert transform. However, in this case the only reliable amplitude spectra are within the sweep band, and the Hilbert transform uses the entire amplitude spectrum. In the past, arbitrary slopes have been used to replace the values outside the sweep band. In this method, it is shown that the minimum phase spectrum within the sweep band can be accurately estimated from the amplitudes in the sweep band only.

Examples show that this method produces a more consistent wavelet. This is because statistical deconvolution has been kept to an absolute minimum, and estimation of the residual wavelet has been performed in a surface consistent fashion. It is not claimed that this method will produce perfect wavelet control at all times, however, it has a better chance of achieving this aim than standard land wavelet processing sequences.

Sirri A Field: a Pilot Development for the Ilam Reservoir

Jacques Pion, Michel Bois and Jacques Petitet
Total Sirri, Dubai

As a result of drilling by Sofiran between 1968 and 1975, it was concluded that the Ilam Reservoir of the Sirri A field could not be commercially developed with the technology then available. As part of the Sirri buy-back contract, Total Sirri (operating on behalf of IOOC), was requested to reconsider this conclusion.

The Sirri A Ilam Reservoir pilot development was in two phases. Phase 1 (July 1995 to April 1999) was in three parts: (1) acquisition of a 3-D seismic grid over the field; (2) installation of a wellhead platform in the southern part (connected to the neighbouring field Sirri D operated by IOOC); and (3) drilling of five horizontal wells. Based on the encouraging results of Phase 1, it was decided to proceed with Phase 2 that consisted of the installation of a second wellhead platform in the northern part of the field and the drilling of six additional horizontal wells.

Various tools were used in order to optimize the oil production from this very tight and heterogeneous reservoir while building a reliable reservoir model. Biostratigraphy was used to steer the horizontal drains. FMI logging, structural core analysis and curvature radius mapping helped detect and predict the presence of open fractures. The inversion of 3-D seismic to acoustic impedance, and the
use of geostatistics combining horizontal well logs and seismic data, yielded porosity maps.

Jacques Pion has been Geosciences and Planning Manager with Total Sirri since 1996. Between 1974 and 1990, Jacques was a Geophysicist with Shell working in The Netherlands, Oman, and Gabon. He joined Total in 1991 and became Head of Seismic Research and Technology before moving to his present assignment in Dubai. He is a member of SEG and EAGE.

Michel Bois is a Total Sirri Senior Reservoir Geologist in charge of Geological Reservoir Modeling for Sirri E and Sirri A. He joined Total in 1979 and has held various positions as a geologist at Total head office in Paris and Total Indonesia. He received his PhD in Earth Sciences from the University of Dijon in France.

Jacques Petitet is Senior Geophysicist with Total Sirri in charge of reservoir seismic interpretation for Sirri E and Sirri A. He has worked as a Geophysicist for Total since 1980. Jacques received a BSc in Physics from the Pierre and Marie Curie University of Paris, and graduated in Geophysics from the École Nationale Supérieur des Pétroles et Moteurs.

Comparison of Deterministic and Stochastic Methods of Distributing Reservoir Properties in a Complex Carbonate Reservoir: an Example from the Cretaceous Ratawi Oolite in the Kuwait-Saudi Arabia Partitioned Neutral Zone

Denise Pfeffer, Dennis Prezbindowski, Blake Sherman, Texaco, Houston, and Michael Waite, Saudi Arabian Texaco

Carbonate reservoirs commonly have complex porosity and permeability relationships that make it difficult to accurately predict and distribute reservoir properties in a static geological model. Measured reservoir properties can be distributed to nonsampled areas using deterministic or stochastic techniques. Deterministic techniques range from simple distance-weighted interpolation to linear and non-linear transformations of distributed properties. Geostatistical approaches utilize stochastic techniques such as Sequential Gaussian simulation and Cloud Transforms.

Comparisons of deterministic and stochastic approaches for predicting permeability and distributing reservoir properties were conducted in a Lower Cretaceous carbonate reservoir in the Partitioned Neutral Zone between Saudi Arabia and Kuwait. Cumulative density function graphs (CDFs) were used to compare permeability predicted from deterministic and stochastic techniques with measured values from core. This one-dimensional comparison using CDF plots demonstrated that the stochastic technique (Cloud Transform) more closely matched the permeability distribution derived from core measurements for individual wells, as well as regionally. In addition to more accurately reproducing the permeability distribution, the Cloud Transform provided the means of quantifying the inherent uncertainty associated with the reservoir’s complex porosity and permeability relationships. Quantitative and graphical comparisons of three-dimensional, deterministic and stochastic porosity and permeability models demonstrated that significant differences can be observed in fluid flow for areas associated with particular wells or for regional fluid flow. The stochastic technique was a more accurate method for distributing complex reservoir properties in the carbonate reservoir. It also produced more realistic geological models for use in reservoir performance evaluation and planning.

Denise Pfeffer is a Project Geoscientist with Texaco Upstream Technology in Houston, Texas. She is involved in the application and development of geostatistical techniques for reservoir characterization. Denise has a BSc and MSc in Geophysical Engineering from the Colorado School of Mines. She has world-wide experience in the geostatistical characterization of oil and gas reservoirs. Prior to joining Texaco Upstream Technology Department she was employed by Geomath Inc.

Dennis Prezbindowski see p. 164

Blake Sherman is a Senior Reservoir Engineer with Texaco Upstream Technology, Houston, Texas. He has 10 years reservoir and production engineering experience associated with reservoirs of the Gulf of Mexico and the Middle East. Blake has a BSc and MSc in Petroleum Engineering from Texas A&M University. He is a member of the Society of Petroleum Engineers.
Assessment of Undiscovered Oil and Gas Resources of the Greater Rub’ Al Khali Basin Province by Application of the Total Petroleum System-Assessment Unit concept: Part I. The Cretaceous and Jurassic Petroleum Systems

Richard Pollastro and Christopher Schenk
U.S. Geological Survey, Denver

The World Energy Project of the USGS has classified the Rub’ al Khali as one of 76 priority provinces selected for assessment of undiscovered conventional oil and gas resources and scheduled for completion in June 2000. On the basis of total discovered petroleum volumes, the greater Rub’ al Khali Basin (as defined here) ranks fifth globally.

In the World Energy Project, the Total Petroleum System (TPS) concept, modified from Magoon and Dow’s petroleum system, in conjunction with the assessment unit, was used to assess undiscovered oil and gas resources of the greater Rub’ al Khali Basin Province. The TPS refers to all genetically related petroleum generated by a pod (or pods) of mature source rock. The assessment unit is the basic unit of assessment and is a geologically defined, mapable volume of rock with similar exploration strategy and risk characteristics. Assessment units within the TPS are further defined by hydrocarbon type (oil, gas) and structural style (salt domes, horst blocks, anticlines, and so on). Specific fields and wells were assigned to each assessment unit. Using published geology, oil- and gas-field data, and analog datasets, a probability distribution was generated using a Monte Carlo approach to calculate sizes and numbers of undiscovered oil and gas accumulations within each assessment unit, to provide a 30-year forecast.

Three major petroleum systems, (Cretaceous, Jurassic, and Paleozoic), have been identified in the greater Rub’ al Khali Basin. Production in the northeast half of the greater Rub’ al Khali Basin province is from all three petroleum systems. The Cretaceous TPS is limited to the northeast half of the province where these source rocks are mature for oil along the basin’s axis and are within the gas window in the Falaha syncline, Abu Dhabi, and in the deeper (greater than 4000 meter) parts of the Oman Mountain foredeep. In the far northeast corner of the province, a north-south trend of Cretaceous gas fields is sourced from the Lower Cretaceous Thamama Group along the thrust front of the Oman Mountain foredeep. Source rocks of the Jurassic TPS, however, are mature for oil and gas in a large part of the province but limited to the southern extent of the Hanifa source facies. Moreover, because of termination of the Upper Jurassic Hith anhydrite seal, oil sourced from the Jurassic system mixes with oil from the Cretaceous system to the northeast to form a hybrid petroleum system. Jurassic Hanifa-sourced gas is produced from Saudi Arabian fields in the central part of the basin. Migration of hydrocarbons into accumulations beyond the areal extent of mature source rocks further extends the maximum geographic boundaries for the Cretaceous and Jurassic TPS.

Richard Pollastro is a Research Geologist with the USGS, Energy Resources Team. He has been a Principal Scientist for 21 years on a variety of petroleum basin studies. He is now a Province Geologist on both the USGS National and World Energy Oil and Gas Assessment Projects. Rich received an MA in Geology from SUNY at Buffalo in 1977.

Christopher Schenk see p. 175

Seismic Acquisition in Bahrain Island: a Case History

Jean-Jacques Postel
Compagnie Générale de Géophysique, France and Abdul Nabi Mukhtar, Bahrain Petroleum Company

Environmental constraints are becoming one of the most critical issues for land seismic operations, requiring the development of appropriate new equipment and methods. This study describes the acquisition of seamless seismic data of a complex field in Bahrain by Compagnie Générale de Géophysique (CGG) on behalf of the Bahrain Petroleum Company (BAPCO). The operation was run smoothly in a difficult context in regard to the great variety of environments involved; these included pipelines, wells, cliffs, sabkhas, urban areas, a zoo, golf course, race course, an oil refinery and other industrial and commercial facilities. The survey called for the deployment of a wide range of recording equipment including two sets of vibrators and a combination of radio and cable telemetry recording systems, and a fleet-management system.
The success was achieved thanks to several key elements: (1) Major efforts dedicated to collecting the correct baseline information. (2) Highly detailed planning of the operation (timeframe, human and material resources, adapted acquisition technique for different obstructions, health and safety plan, etc.). (3) Detailed and continuous monitoring of external conditions and impact of the operation, in consultation with the authorities. (4) Maximum flexibility (combination of sources, mixed radio-cable recording system, logistics, daily plans, etc.) to allow for changing conditions and unforeseen events. (5) Close partnership between CGG and BAPCO at all stages of the project (project planning, daily rate contract, daily co-ordination, etc.). The crew worked 350,000 man-hours in adverse conditions without any lost time due to injury. The recording of such an intensive up-hole survey has enabled the computation of a robust subsurface model that was used to derive a precise set of field statics. These contributed to the quality of the final data whose processing is presented in a complementary study (see Abstract, *Challenging Surface Conditions for the First 3-D Seismic Survey of Bahrain*, by Cremiere, Combe, and Radhi.)

Jean-Jacques Postel is Applied Technology Manager for the Land and Shallow Water Acquisition Strategic Business Unit of CGG. He graduated as a Civil Engineer from the École Centrale de Lyon in 1978. He joined CGG in 1980, spending five years in the field as Party Manager and Party Chief in the USA and Argentina. In 1986, he moved to processing and occupied several positions from Group Leader to Center Manager in China. In 1990, he joined the R&D team as Area Geophysicist and was appointed R&D Manager for Land Acquisition in 1995. Jean-Jacques’ interests are seismic acquisition equipment and seismic processing. He is a member of SEG, EAGE and AFTP.

Abdul Nabi Mukhtar see p. 150

Structural Control on the Development of Reservoir Facies in the Lower Cretaceous Ratawi Oolite, Kuwait-Saudi Arabia Partitioned Neutral Zone

Dennis Prezbindowski, Stewart Griest, Texaco, Houston
Jennifer Beall, University of Austin, Texas and Michael Waite, Saudi Arabian Texaco

Understanding the relationship of structure to carbonate reservoir facies development can enhance exploration success in the Lower Cretaceous Ratawi Oolite. The Ratawi Oolite is a prolific carbonate reservoir in the Partitioned Neutral Zone between Saudi Arabia and Kuwait. It is productive in the giant Wafra and South Umm Gudair fields with more than one billion barrels of cumulative oil production.

The Ratawi Oolite is composed of stacked, shallowing-upward cycles deposited on a broad, shallow carbonate platform. Reservoir porosity consists of primary and secondary pores developed in heterogeneous skeletal/peloidal grainstones, packstones and wackestones. Reservoir porosities and permeabilities range from 18 to 25% and from 10s of millidarcies to more than 1 darcy. Reservoir studies, 3-D and 2-D seismic interpretation, and exploration experiences indicate that the reservoir potential is dependent on the timing of structural development. The depositional facies patterns and secondary porosity overprints are related to paleotopography and relative sea-level changes. Grain-dominated (high primary porosity) facies were deposited in association with paleotopographic highs formed by anticlines. Sediments deposited off the flanks of structures are muddier and have little primary macro-porosity. These structures developed prior to Ratawi deposition, as demonstrated by the onlapping relationship of the Sulaiy and Ratawi sediments. The localization of grainy sediments associated with the highs placed them in an optimum position to undergo secondary porosity development and permeability enhancement by subaerial exposure. The same structural elements grew intermittently throughout the Mesozoic-Tertiary to form the prominent structures trapping hydrocarbons today in Wafra and South Umm Gudair fields. Drilling has corroborated the relationship of Ratawi reservoir development and paleostucture. Recognition of the dynamic relationship between carbonate deposition, relative changes in sea level, and structurally influenced paleotopography is important in enhancing exploration success in the Ratawi Oolite.

Dennis Prezbindowski is a Senior Research Associate with Texaco’s Upstream Technology Department. He is a member of the Partitioned Neutral Zone Team in Houston. He joined Texaco in 1998. Dennis has a BSc in Geology from Indiana University, a MSc in Geology from Michigan State University, and a PhD in Geology from The University of Texas at Austin. He is an AAPG Certified Petroleum Geologist. He has 20 years experience of world-wide exploration and reservoir development. His broad experience in the petroleum industry includes employment as a Research Geologist for Amoco Production Company, Associate Professor of Geology at Indiana University, geological consultant, and independent oil producer.
Stewart Griest is a Senior Geoscientist with Texaco's Upstream Technology Department as a member of the Partitioned Neutral Zone Team in Houston. He has worked with Texaco since 1980. Stewart has a BA in Geology from Albion College, Missouri, and a MA in Geology from Indiana University. His work has focused primarily on integration of 2-D and 3-D seismic and well-data for development of geologic models and reservoir characterization within producing reservoirs in the 'Second Eocene' and the Wafra Sandstone of the Wafra field, and on regional data syntheses for exploration evaluations. Stewart was involved in the 1998 Jurassic Marrat Limestone exploration discovery at Humma field in the southwestern Partitioned Neutral Zone.

Jennifer Beall received a BSc in Geological Sciences in 1995 from The University of Texas at Austin where she is currently completing a MSc researching Early Permian (Wolfcampian) carbonates of West Texas in outcrop and subsurface. Her interests are in sedimentology, invertebrate paleontology, and sequence stratigraphy. Industry experience includes geological internships with Conoco, Amoco, Arco and Texaco, working on projects from the CIS, Venezuela, West Texas, offshore Brazil, and the Partitioned Neutral Zone.

Michael Waite see p. 163

Petrographical, Mineralogical and Geochemical Studies of the Al-Khiran Quaternary Carbonates, Southern Coastal Kuwait and the Middle Part of the Lower Cretaceous Minagish Formation, South Kuwait

Suad Qabazard, Ali Al-Temeemi and Fowzia Abdullah University of Kuwait

This presentation gives the results of petrographical, mineralogical, and organic and inorganic geochemical studies of the Lower Cretaceous ‘Oolite member’ of the middle part of the Minagish Formation, one of the principal carbonate reservoirs in south Kuwait. These investigations are integrated with similar studies of Recent and Pleistocene oolitic sediments from the Quaternary carbonate complex of the Al-Khiran area on the southern coast of Kuwait, on the principal that ‘the present is the key to the past’. The study was undertaken in order to evaluate the physical and chemical conditions of the depositional environments of the sediments and to investigate their diagenesis. The Lower Cretaceous limestones and the Quaternary carbonates were analyzed petrographically by transmitted-light and scanning-electron microscopy, mineralogically by X-ray diffraction and an energy dispersive analyzer, and geochemically. Geochemical analyses were by means of an ICP-MS analyzer for major (Ca, Mg), trace (Sr, Fe and Mn) elements and trace metals (Cd, Cu, Co, Ni, Zn, Cr, V and Mo); total organic carbon content and kerogen elemental composition were determined by a LECO analyzer. In addition, the grain-size distribution of the Quaternary sediments was measured. The Quaternary analog provides insights into the depositional and postdepositional processes of the Lower Cretaceous carbonates.

The sediments of the middle part (Berriasian) of the Minagish Formation accumulated under shelf-lagoon and marine-shelf conditions, with restricted circulation and the local development of oolite shoals. The oolitic limestones consist of micrite and various skeletal grains such as foraminifera (textularins, miliolids, and rotaliids), echinoderms, calcareous algae, and shell fragments. The non-skeletal components are mainly peloids (micritized ooids), ooids, and intraclasts. These carbonates were affected by a range of diagenetic processes, among which dissolution led to the formation of secondary porosity. However, porosity was reduced by compaction, micritization, neomorphism, and cementation. The rocks are almost entirely composed of carbonates (>90%). The macro- and micro-fossil contents, the low concentrations of trace metals and the calculated V/Cr and V/(V+Ni) for the limestones of the middle part of the Minagish Formation reflect their deposition under oxic water conditions. As a result, part of their organic matter was consumed by early diagenetic aerobic degradation. However, carbon/nitrogen ratios, kerogen elemental analysis, and petrography show that the organic matter is mainly marine, amorphous, type-II kerogen. The dominance of this maceral type, typically derived from organic matter deposited in marine reducing environments in limestones of the middle Minagish, indicate that several factors were probably responsible for organic matter accumulation and preservation.

The Recent sediments represent shoreline carbonate sands, mainly composed of skeletal and oolitic particles with some aggregates, developed in a region of moderate to high wave energy. The Pleistocene oolitic limestones are elongate, cross-bedded, thinly-laminated ridges of carbonate sands, directed parallel to the strong tidal currents of the open Arabian Gulf and developed by sea-level fluctuations during glacial stages. The study of the diagenetic processes and porosity type in the Pleistocene carbonates shows that these
sediments exhibit excellent reservoir potential. Their overall low amounts of trace metals and organic matter, and relatively high oxygen/carbon atomic ratios indicate that they were laid down under highly oxygenated and bioturbated, open marine conditions. Current and wave actions led to the destruction of their organic matter contents and the generation of unpreserved, degraded, amorphous, organic matter, which is typical of an aerobic environment.

A comparison of the Quaternary oolitic sediments with the Lower Cretaceous oolitic rocks reveals similar lithological, mineralogical, inorganic geochemical, and diagenetic characteristics. In contrast, differences in organic matter type and quality indicate that factors other than the physical and chemical conditions of the depositional environments of the Lower Cretaceous oolites may contribute to the survival of organic matter in the carbonate facies. These factors may include primary biological productivity, the rate of sedimentation, and diagenesis of organic matter.

Suad Qabazard received her BSc in Geology from Kuwait University in 1994. Her minor field of study was in Computer Science. She is now a graduate student at Kuwait University. Her main field of interest is in petroleum geology, and especially organic geochemistry.

Ali Al-Temeemi is an Assistant Professor in the Geology Department of Kuwait University. He has a BSc in Geology from University of Redlands (1968) and a MSc in Sedimentology from Pennsylvania State University (1972). Ali obtained his PhD in 1977 from George Washington University. He was Head of the Geology Department of Kuwait University in 1981–82.

Fowzia Abdullah joined the Geology Department of Kuwait University as an Assistant Professor in 1993. She had worked previously as a Teaching Assistant for three years at the university and was a Researcher in Kuwait’s Environmental Protection Department for two years. She has a BSc in Geology and a MSc in Petroleum Geology from Kuwait University. Fowzia obtained her PhD and DIC in Organic Geochemistry in Petroleum Exploration from Imperial College, London in 1993.

Regional Seismic Stratigraphic Framework of the Unayzah Formation, Central Saudi Arabia

Martin Rademakers, Saudi Aramco, Dhahran

The Permian Unayzah Formation of central Saudi Arabia is characterized by a variety of facies ranging from basal conglomerates to sandstones, siltstones, and even paleosoil caliches. All facies were deposited in a complex meandering, fluvial-braid system, with later extensive reworking by eolian-dominated processes. Analysis of the available Formation Micro Imager log-dip data in the upper part of the Unayzah Formation indicates that a multilayered dune environment is present in many areas. An integrated 2-D and 3-D seismic stratigraphic interpretation shows the regional distribution of the fluvial-braid systems is largely controlled by Hercynian faulting and its associated paleotopography. The dominate structural style in the study area is mainly high-angle reverse faulting related to regional compressive forces. The Unayzah Formation is bound above and below by major unconformities. The regional Hercynian Unconformity is present at the base of the Unayzah and is easily identified in both open-hole well logs and cores. The contact between the Unayzah and the overlying Khuff Formation is a marked unconformity and acoustic impedance boundary, resulting in a good seismic reflection event. Based on seismic-sequence interpretation and isochron maps of the Unayzah Formation, the sand-dominated fluvial-braid systems were deposited in flank positions to fault-related paleohighs. This interplay between paleotopography and Unayzah sand deposition occurs throughout the Central Arabian Trend. Seismic stratigraphic modeling efforts of the regional 2-D and 3-D seismic data also provides further support to this depositional concept. The detailed seismic models help identify the stratigraphic boundary and depositional limits of the fluvial-braid systems and greatly aid in their mapping. A good potential exists for the discovery of stratigraphic traps in the Unayzah Formation using this new depositional model for the central Arabian region.
Deep Channels and Glaciotectonic Deformations in the Upper Ordovician Sediments of the Wajid Area, Southwestern Saudi Arabia

Riyadh Rahmani
Saudi Aramco, Dhahran

The Upper Ordovician (Ashgillian) glacial deposits are well preserved in both outcrop and subsurface of Saudi Arabia, and form part of a much wider belt of Upper Ordovician glacial deposits in the northern and northeastern parts of the Gondwanan Supercontinent. Their outcrop forms a discontinuous belt curved around the eastern perimeter of the Arabian Shield, dipping and disappearing into the subsurface toward the southeast, east and north. In a broad sense, the exposed Upper Ordovician glacial facies are of a proximal nature (coarse-grained, continental to shallow marine) to the west and southwest, becoming more distal (fine-grained, and deeper marine) in the subsurface to the east and northeast.

In the southwestern outcrop belt (the Wajid area) the glacial succession, here called the Sanamah Formation, consists of a complex facies association of subaerial and subaqueous ice contact, pro- and periglacial, current and gravity-flow deposited coarse clastics, interpreted as outwash deposits. The thickness of this succession is highly variable and can reach 150 meters or more. At many locations it shows severe deformation, including folding, faulting and fragmentation, whereas the adjacent older and younger units show little or no evidence of disturbance. In most of these locations, the glacial succession appears to fill channels incised in the underlying shallow-marine Dibsiyah Formation. These channels were incised into the underlying shelf sediments during glacial melting as tunnel valleys formed by the action of supercharged subglacial meltwater. The deformations shown by the glacial sediments are interpreted as the result of the lateral stress applied by the advancing glaciers on the recently deposited, un lithified but coherent (frozen) glacial outwash deposits, forming ‘push moraine’.

Riyadh Rahmani was awarded a PhD by the University of Alberta. Before joining Saudi Aramco he was a sedimentologist/stratigrapher with Shell Canada, Geological Survey of Canada, Kuwait Institute of Scientific Research, Alberta Research Council, Canadian Hunter Exploration, and Sirte Oil Co. (Libya). Riyadh’s interests are reservoir sedimentology, sequence stratigraphy, and ichnology of fluviatile, nearshore, and shallow-marine sediments. He is a member of AAPG, SEPM, IAS, and PESGB.

The Intra-Salt Carbonates of Oman: New Insights into Maturing an Unconventional Exploration Play

Joachim Reinhardt, Sultan Al Harthy, Folco Hoogendijk, Joachim Anthon, Mia Van Steenwinkel, Jack Woodward and Mohamed El Tonbary
Petroleum Development Oman, Muscat

Intra-salt carbonate ‘stringers’ of the Precambrian Ara Formation represent one of the more complex deep oil exploration plays of Petroleum Development Oman (PDO) and presently constitute a significant part of the undrilled prospect portfolio. The carbonate reservoirs consist of porous dolomite, stratigraphically trapped in salt at 3 to 5 kilometers depth, and hence commonly overpressured. These reservoirs have often been found to be prolific producers with flow rates exceeding 8,000 barrels of 30°API oil/day. The play was initially pursued during the late 1970s to early 80s, when PDO drilled seven commercial discoveries. However, the play was also found to be complex with respect to seismic imaging, reservoir prediction, and drilling and completion operations (resulting in prohibitively high drilling/completion costs). Therefore, in subsequent years, the play remained relatively dormant despite a large number of identified prospects.

In late 1996, a multidisciplinary Stringer Theme team was set up in PDO’s Exploration Directorate. It aims at fully assessing the potential of the play by addressing the critical play elements, applying key new concepts and drilling key strategic wells in order to commercially develop the play. A strong emphasis for the team approach was put on maintaining a very focused approach, flexibility, rapid data evaluation, integration, and maximizing value. The key critical success factor of the play has been, apart from seismic imaging, the understanding and prediction of reservoir facies in these unique Precambrian carbonates. Drawing on potential analogs from well-studied outcrops in Namibia and reviewing scores of cores, a new understanding of these reservoirs has emerged. Rather than dealing with stromatolites and an overall patchy reservoir development, it is now more likely that the typical reservoir represents sub- to peritidal laminites that were deposited in extensive sheets with rather homogeneous reservoir fabrics and lithofacies. The seismic ‘stringers’ are now thought to have originally been large carbonate platforms, growing during periods (TST to HST) of marine incursions into an overall evaporitic setting. Subsequent salt movement has deformed and in many cases even severely fragmented these original platforms.

Recent geochemical analyses and basin modeling studies have confirmed the earlier notion that the intra-salt stringers represent a self-charging hydrocarbon system. Due to the comparatively low ambient temperatures within the salt, the
oil window for the play extends far deeper than initially anticipated. Gas is only thought to occur at depths below 5,500 meters, or where stringer reservoirs have had access to the base of the salt and pre-salt kitchen areas. Since 1997, the team has drilled three oil discoveries in a row (Harweel Deep, Sarmad and Ghafeer), testing many of the new concepts (integrated seismo-geological play model) and technologies (improved well designs, PSI seismic processing, seismic inversion, and so on.).

Joachim Reinhardt is a Senior Seismic Interpreter in the South Oman Frontier Exploration Team of Petroleum Development Oman (PDO). He has been the Theme Leader of the Intra-salt Carbonate Stringer Theme since his arrival at PDO in late 1996. Joachim has a MSc (hons.) in Geology from Erlangen University, Germany. He joined Shell International in 1988 and has worked since for NAM in The Netherlands, Myanma Shell B.V. in Rangoon, and Shell China Petroleum Development in Beijing.

Sultan Al Harthy joined Petroleum Development Oman in 1985 as a Trainee and completed his Diploma in Electrical and Electronic Engineering in 1989 at Wigan College (UK). He worked in South Oman on power generation for four years before joining the Exploration Unit in 1992 as an Operations Team Assistant. In 1995, he moved to the South Oman Frontier Exploration Team, where he is now working as a Team Seismic Interpreter.

Folco Hoogendijk see p. 108; Joachim Amthor see p. 47; Mia Van Steenwinkel see p. 84; Jack Woodward see p. 109; Mohamed el Tonbary see p. 114

A Comparison Between Image Analysis and Mercury Injection Capillary Pressure Data: Applications for Reservoir Quality Evaluation

Mohammad Rezaee, University of Tehran, and Mohammad Kamali, Research Institute, National Iranian Oil Company, Tehran

Capillary pressure measurements can be made by injecting mercury into a sample, but the method has many disadvantages. In addition to the environmental hazards, it is expensive and time-consuming. In this study, a comparison was made between Image Analysis and Mercury Injection as a means of obtaining capillary pressure data. A set of sandstone samples with a high range of porosity and permeability was used for petrographic image analysis. The analysis was effected on coated polished sections using a Philips image analysis system in conjunction with a scanning electron microscope. The back-scattered electron images of coated polished sections were imported from the electron microscope in the form of gray-scale images using a video camera and the Windows-based software program, Image Analysis™. The gray back-scattered electron images were then converted to a binary image containing only grains (white) and pores (black). The calculation of pore parameters, such as pore-area sizes, pore-diameter sizes and pore-perimeter sizes, was accomplished by converting the analog output to a digital format. The cumulative curve from pore-area size data is very similar to the mercury saturation curve. This suggests that a photographic image analysis can be used in place of the mercury injection method to obtain capillary pressure data.

Mohammad Reza Rezaee is an Assistant Professor at the University of Tehran. He has a BSc and MSc in Geology from the University of Mashad and the Tehran Teacher Training University. He received his PhD from the National Center for Petroleum Geology and Geophysics, Adelaide in 1996. His field of study is reservoir characterization and integration of rock data with wire-line log information. He has published several papers in international journals.

Mohammad Kamali see p. 120

Al Ghubar Field, Qarn Alam Area, Central Oman, An Integrated Study to Optimize the Development of a Fractured Carbonate Reservoir

Pascal Richard, Peter Christman, Salah Al Dhabab, Dick Eikmans, Mark Fenton, Khalid Al Hashmi, Eilard Hoogerduijn-strating, Bettina Kampman, Jan-Henk vanKonijnenburg, Martin Kraaiveld, Jose-Luis Massarferro, Thomas Mauduit, Pascal Schoepfer, Manuel Willemsse, Krijn Wit, C. vanderZwan and Khalid Khabouri PDO-Shell International Al-Ghubar Virtual Global Team

This study presents the progress and results of an integrated study of the Al Ghubar field in central Oman. The study is aimed at helping to optimize field development strategy and the results will be disseminated as an example of how to deal with low-relief, low oil mobility, fractured carbonate reservoirs.
The Al Ghubar field is located in the Ghaba Salt Basin of central Oman on a low-relief dip closure developed on the northern side of a major normal fault. The field consists of stacked hydrocarbon accumulations in carbonate reservoirs of the Middle and Late Cretaceous Shu’aiba Formation (oil), Natih-E (oil), and Natih A/B (oil and gas) reservoirs. The reservoirs consist of a cyclic alternation of mudstones, wackestones, packstones, and grainstones, together with minor amounts of algal boundstones. The reservoirs are typically 50 to 60 meters thick and have oil columns of 30 to 50 meters. They are separated from each other by laterally continuous shaly seals. Al Ghubar field was discovered in 1974 and came on stream in 1985. Current gross production is about 680 cubic meters of oil per day (evenly split between the Shu’aiba and the Natih-E), with a watercut of up to 80%. Well-production history is characterized by an early water breakthrough that, so far, has been attributed to both the presence of open faults or fractures and, for some wells, to the proximity of the oil-water contact.

An integrated RTS-PDO project to optimize field development strategy for the Natih-E reservoir was begun early in 1999. The technical objective is to develop a static/dynamic reservoir model before the end of the year and to propose possible development options to enhance the ultimate recovery of the field. A strong interaction between, and integration, of disciplines such as geology, petrophysics, seismic interpretation, structural geology, reservoir engineering and production technology, and between PDO and RTS, is the key to success of this project. So far, several first-pass reservoir geological models have been built that are all consistent with the available subsurface data. Subsequently, these alternative models are compared with the actual reservoir performance to determine which model fits best. For example, the effects on production performance of high-permeability matrix streaks are compared to those of a high-permeability fracture network. These alternative scenarios are built upon integrated sedimentological and structural (fault and fractures) interpretations. We will present the final dynamic model by integrating all subsurface data and taking into account all production data.

Pascal Richard is a Structural Geologist with Petroleum Development Oman (PDO). He was awarded his PhD by the University of Rennes, France, in 1989. He joined Shell in 1991 and spent five years in KSEPL’s research laboratory in the Structural Geology group where he was involved in hydrocarbon migration studies and was responsible for structural sandbox modeling. Pascal is now the Structural Geology focal point in the Exploration Unit of PDO. He is particularly interested in strike-slip tectonics, sandbox modeling, and prospect evaluation. He is the co-author of, Generation and Retention of Hydrocarbon in the Haushii Play, North Oman, published in GeoArabia, v. 3, no. 3 (1998).

Peter Christman has been a Reservoir Engineer in the Carbonate Development Team of Shell International Exploration and Production in The Netherlands since July 1999 working on reservoir simulation of carbonate and fractured carbonate reservoirs. He has a BS in Chemistry and a MS in Chemical Engineering from the University of Wisconsin, and a PhD in Chemical Engineering from the University of Texas. Previously, he had assignments in the Belaire Technology Center and with Shell Western E&P where he worked on carbonate fields, fractured source rocks, and turbidite formations. He has taught training courses on Miscible Gas Flooding, Infill Drilling, and Phase Behaviour. He was Editor of the SPE Monograph, Phase Behaviour (1990–93), a member of the FMORP Technical Committee for the SPE Annual Meeting (1993–97), and a Review Chairman for SPHERE (1996–98).

Salah Al Dhahab has a BSc in Petroleum Geology from Aberdeen University (1995). He has worked for Petroleum Development Oman for two years as a Wellsite Engineer and for two years as an Operations and Production Geologist involved with fractured and matrix carbonates.

Dick Eikmans was awarded a PhD in Theoretical Physics by the University of Utrecht in 1991. He joined Shell Research in 1991 as a member of the Reservoir Simulator Development Team. Since 1996, he has been working as a Reservoir Engineer for Petroleum Development Oman on various major North Oman carbonate fields.

Mark Fenton has 15 years experience in Shell Group companies in Australia, The Hague, and Oman. He worked for Petroleum Development Oman (PDO) as a Senior Production Geologist, co-ordinating production geology efforts in the central Oman area and acting as focal point from the PDO side for the Al Ghubar study. He is currently working for Woodside Energy Ltd in Australia as Principal Geoscientist.

Khalid Al Hashmi joined Petroleum Development Oman after graduating with a BSc in Petroleum Engineering from University of Tulsa, Oklahoma. After two years as a Wellsite Operations Engineer, he was assigned to the Nimr Area Team as a...
Petrophysical Engineer for two years. He is currently assigned to the Qarn Alam Area Team as a Production Technologist.

Eilard Hoogerduijn-strating received his PhD in Structural Geology from Utrecht University, The Netherlands in 1991. He joined Shell in the same year and was posted to SIPM (later SIEP) in The Hague. Eilard was involved in the development of prospect evaluation software. Subsequently he joined a New Venture Exploration Team, looking at opportunities in the Middle East. After a year in a reorganization team, he got involved with fault-seal analysis research in Shell’s EP Research organization in Rijswijk, The Netherlands. Eilard joined Petroleum Development Oman’s Frontier Exploration Team in mid-1997 and from April 1998 onward he became involved in near-fields in central Oman.

Jan-Henk van Konijnenburg received his undergraduate degree from the Free University, Amsterdam and PhD in Carbonate Sedimentology from the Zurich University of Technology. He joined Shell in 1997 and is currently a Geologist in the Carbonate Development Team of Shell’s EP Technology Applications and Research (SEPTAR) centre in Rijswijk, The Netherlands.

Martin Kraaijveld has a MSc in Electrical Engineering and a PhD in Applied Physics, both from Delft University of Technology, The Netherlands. He joined Shell in 1993 to work in KSEPL’s General Research Department on pattern recognition, neural networks, and image analysis techniques for the interpretation of seismic and well data. In 1997, he began investigating the petrophysical and geological applications of quantitative borehole image analysis techniques.

Jose-Luis Massaferrro is a member of the Carbonate Development Team in Shell’s EP Technology Applications and Research (SEPTAR) centre in Rijswijk, The Netherlands. He obtained a Diploma in Geology at the University of La Plata (Argentina) in 1991, and a PhD from the University of Miami in 1997. His doctoral thesis focused on the interplay of carbonate sedimentation and tectonism in the Cuba/Bahama area. He then spent six months working on petrophysics of carbonate rocks. He joined Shell in January 1998, since when he has been working on 3-D seismic image processing and volume-based interpretation of carbonate fields, particularly in Oman and Malaysia.

Manuel Willemse received his PhD from Stanford University. His industry career started with five years at the Shell’s Research Lab, working as a Structural Geologist on naturally fractured reservoirs and fault sealing. Subsequently, he was seconded to Maersk Oil and Gas, Denmark. During his three years there, he was involved in operations and field development planning for chalk reservoirs. For the last two years, Manuel has worked as a Senior Petroleum Engineer to support opportunity evaluations and to improve recovery from carbonate reservoirs.

C. VanderZwan, Krijn Wit, Thomas Maudit, Bettina Kampman, Khalid Khabouri biographies not available; Pascal Schoepfer see p. 80

The Benefits of Acquiring 3-D Seismic Data Adapted to an Arabian Gulf Oil Field Reservoir

Patrick Rigolot, Guy Aurensan, B. Durand de Grossouvre, Jean-Marie Jourdan, Didier Rappin, Thierry Manivit, Henri Soudet Elf, France and Fabricio Bolondi, Agip, Milan

In the Arabian Gulf, outside areas of tectonic activity related to salt diapirism, the strata are often very flatlying. In the case of the oil field under discussion, the Mishrif reservoir dips gently eastward. A lateral change of reservoir porosity creates a stratigraphic trap.

Acquiring 3-D seismic data was not initially considered useful due to the flatness of the seismic horizons. The moderate changes in lateral reservoir characteristics observed in several appraisal wells also discouraged acquiring more-costly seismic data. A 2-D seismic grid was judged to be sufficient for locating the production wells in the first phase of development. The main uncertainty for this field was thought to be the production rate of wells.

After drilling several production wells, variable production behaviour was detected in the neighbouring wells. This
confirmed that reservoir heterogeneities were more important than previously thought. Consequently, for the second development phase, acquiring new seismic data was considered in order to obtain a more detailed reservoir description. In addition, the new seismic data would be used to optimize the location for future production wells.

Tests on amplitude inversion confirmed the use of acoustic impedance displays for reservoir characterization. The tests also confirmed the need to increase frequency content in order to improve the resolution for reservoir characterization. An adapted reservoir 3-D seismic survey was designed in order to meet the reservoir and production needs.

In our presentation, the reservoir will be described with the support of the sedimentological model built from the well data and regional knowledge. The reservoir behaviour will then be discussed. Comparison of images from the new seismic acquisition and the previous 2-D survey will demonstrate the benefits of the adapted 3-D reservoir seismic. Conclusions will be drawn on the expected improvements in reservoir description and the consequences on field-production management.

Patrick Rigolot is a Senior Geophysicist with Elf specializing in reservoir modeling. He is in charge of the Alkhalij Development Project (Qatar). His activities since joining Elf in 1990 focused initially on high-resolution seismic applied to production, then acquisition and processing for exploration and field development. He has a PhD in Geosciences from the University of Brest, France. Patrick is a member of SEG.

Guy Aurensan, B. Durand de Grossouvre, Jean-Marie Jourdan, Didier Rappin, Thierry Manivit, Fabricio Bolondi biographies not available; Henri Soudet see p. 59

Sequence Stratigraphy, Microfacies and Petroleum Potential of the Middle Cretaceous Mauddud Formation in the Arabian Gulf Basin

Fadhil Sadooni, University of Qatar and Abdulrahman Alsharhan, United Arab Emirates University, Al Ain

The Middle Cretaceous Mauddud Formation extends throughout much of the Arabian Gulf basin including North Iraq where it is equivalent to the Qamchuqa Formation. The Mauddud and its equivalents are major petroleum reservoirs in Oman, Kuwait, and some Iraqi fields. Shales of the Ahmadi Formation, or lagoonal limestones and anhydrites of the Jawan Formation, seal the Mauddud reservoir. Marly limestone of the Balambo Formation is probably the main source rock.

The Mauddud Formation in its type locality (Dukhan-1, Qatar) consists of basal lime mudstone that grades upward into pelletal, skeletal packstone and wackestone containing layers of Orbitolina- and Trocholina-bearing limestone. Local concentrations of rudists occur. It consists mainly of chalky limestone in the deeper parts of the basin along the southern Iran-Iraq border. It is extensively dolomitized in the northern part of the basin. Intergranular porosity occurs in foraminifera shoals and vuggy pores occur in rudist facies. Intergranular and moldic porosity values of up to 30% are present in the lower part of the Natih Formation (equivalent to the Mauddud) in Oman. Intercrystalline porosity is associated with dolomitization in Kuwait and northern Iraq with high porosities (10–22%) in Kuwaiti fields such as Bahara, Raudhatain, and Sabriya. Karstification is common in some units. Permeability values in Qatar range from 50 to 80 millidarcies.

Where the Formation is underlain by the Nahr Umr Formation and its equivalents, the contact between the two represents a type 1 sequence boundary that resulted from a stratigraphic discontinuity due to flooding of the clastic-dominated shelf by shallow-water carbonates. A climatic change was probably responsible for shutting off the supply of fine clastic sediments from the source area to the west. The upper contact of the Qamchuqa Formation also represents a type 1 sequence boundary where clastics of the Ahmadi Formation and its equivalents dominate the shelf. In northern Iraq, the Qamchuqa is overlain by oligosteginal marly limestone of the Dokan Formation and the contact may represent an eustatic sea level change at the start of a new transgressive sequence.

Fadhil Sadooni has been an Assistant Professor at the University of Qatar since 1998. He received his PhD from the University of Bristol in 1978. He worked as a Senior Exploration Geologist for 13 years with the Iraq National Oil Company, as an Assistant Professor in the University of Yarmouk, Jordan for 4 years, and as an independent Consultant Geologist for 3 years in Auckland, New Zealand. Fadhil is particularly interested in carbonate reservoir characterization and evaporites.
**Source Potential Evaluation of the Mobarak Formation (Lower Carboniferous) in the Central and Eastern Alborz Belts, North Iran**

**Fereydoun Sahabi**, Geological Survey of Iran, Tehran  
**Mohammad Kamali**, National Iranian Oil Company, Tehran  
**Alireza Mohammadzadeh**, Geological Survey of Iran, Tehran

The Lower Carboniferous Mobarak Formation in the Central and Eastern Alborz Belts of North Iran consists of alternating shale and carbonate facies. The lithostratigraphic sequence is cyclic and the cycles exhibit a shallowing-upward order. The carbonate rocks of the Formation were formed in shallow-marine to near-shore environments. They range from mud-supported to grain-supported lithofacies. The latter is characterized by considerable porosity and permeability and in many cases is saturated with dark-brown bituminous fluids that entered the rock in the later stage of diagenesis.

The shale facies are dark-gray to black and comprise 35 to 40 volume percent of the whole Formation. About 75 samples of shale from five stratigraphic columns were geochemically analyzed to determine soluble and non-soluble organic matter. The Total Organic Carbon content exceeds 3.1 weight percent. The extracted kerogens are types II and III. Both are thermally mature and had reached the oil window at the maximum temperature of 435°C. It was concluded from the results of the preliminary geological and geochemical exploration that hydrocarbon generation had occurred in the Mobarak Formation and that Lower Carboniferous sediments could be an attractive target for further exploration.

**Boosting Horizontal Well Performance in Carbonates by Selective Stimulation: Case Studies from Qatar**

**Yann Sannier**, Hubert de Lapasse, Elf France  
**Rune Kirkhus** and **Claude Richard**, Elf Petroleum Qatar

To enhance oil productivity in its Alkhalij field, offshore Qatar, Elf Petroleum Qatar took the decision in 1997 to complete the carbonate Mishrif reservoir through horizontal cemented-perforated liners. The vertical or subvertical wells in this field produced an average of 3,000 barrels of oil per day per well. The last five horizontal wells were put on stream at a flow rate of more than 8,000 barrels of oil per day per well.

To achieve maximum productivity from the horizontal drains, complete entry exposure had to be established along the entire length of the horizontal section. To meet this objective, the perforated sections of the drain were stimulated in these two stages: (1) opening the perforations in the toe of the horizontal section by pumping acid through coiled tubing; and (2) performing the main acid job by bull heading, through the drill-stem test string, a retarded triphase acid system (emulsified acid diesel solution with nitrogen) with ball sealers as the diverting agent.
This presentation documents the engineering methodology and the operational techniques employed in five horizontal wells to selectively stimulate producing intervals of between 600 to 1,200 meters. Case histories are presented to illustrate procedures, treatment designs, and productivity results.

Yann Sannier has worked for Elf for 18 years. He has been involved in stimulation projects world-wide specializing in horizontal wells in carbonate rocks. Before joining Elf, Yann had spent 15 years in the Schlumberger (Dowell) Group in various operational and management positions.

Hubert de Lapasse is a Senior Reservoir Engineer with Elf specializing in reservoir modeling and field development. He is Business Area Manager for Development Studies in Eastern Europe, the Middle East, and the Far East. He graduated in Petroleum Engineering from École Nationale Supérieure des Pétroles et Moteurs, Paris. He joined Elf in 1983, and his activities were focused initially on reservoir studies and reservoir developments in Africa. Later, he was involved in oil field re-engineering and was Reservoir Manager for fields in Iran and Qatar. Hubert is a member of SPE.

Claude Richard and Rune Kirkhus biographies not available.

Investigation of Reservoir Heterogeneity in Mishrif Carbonates Using Probe Permeametry

Ajay Sapru, Baker Atlas Geoscience, Aberdeen,
L. Charles Ways, Dubai Petroleum Company,
Stuart Buck and Graham Aplin, Baker Atlas Geoscience, Aberdeen

An automated probe permeameter was used to investigate permeability heterogeneity on a larger-scale than conventional core plug or whole-core analysis could capture. Vertical and lateral variations in the permeability of Middle Cretaceous carbonates from the Mishrif Formation were measured in three wells from offshore United Arab Emirates. Data for two high-resolution permeability profiles were collected at a 1-inch vertical sampling interval spaced 50 millimeters and 80 millimeters from the left-hand side of each core.

The permeability profiles show an overall upward increase in permeability, upon which smaller-scale trends of upward-increasing permeability on a 3- to 20-foot scale are often superimposed. The controls on permeability were investigated by macroscopic examination of the core. The Mishrif Formation is an overall upward-coarsening succession that in the upper part of the reservoir consists of a stacked series of upward-coarsening parasequences. Individual parasequences show a transition from low-energy, fine-grained lime mudstones and wackestones at the base to coarse-grained, high-energy grain-supported rudist packstones-grainstones with common moldic/vuggy porosity at the top.

The lithology is reflected in an upward increase in permeability. A thin karstic profile is present at the top of one well and the ingress of meteoric water there resulted in dissolution that generated moldic and vuggy porosity and karstic fissures that are most common in the coarse-grained rudist grainstones. Subsequently, some calcite cementation occurred as the fluids became saturated with calcium carbonate. The detailed probe permeametry has helped to provide a better understanding of the variations in vertical permeability and permeability heterogeneity in general.

Ajay Sapru is a Senior Geologist with Baker Atlas Geoscience based in Aberdeen. Prior to joining Baker Atlas Geoscience, Ajay worked with Schlumberger from 1985–97 as Divisional Geologist and Interpretation Development Geologist in South East Asia, India, and the Middle East. Ajay received his MSc in 1978 and PhD in 1982 from India. He is an active member of the AAPG, PSEGB, and GSI, and is interested in reservoir and structural geology.

L. Charles Ways received his BS in Geology from Sul Ross State University in 1977 and his MBA from Eastern New Mexico University in 1984. He worked as a Mudlogger for six months in West Texas. As a Development Geologist, Charles has worked in Southeastern New Mexico and West Texas for 18 years and in the Arabian Gulf for three years. The focus of the work in these areas has included all aspects of field development geology and the completion of numerous field studies.
Stuart Buck is a Sedimentologist with Baker Atlas Geoscience in Aberdeen. He received a BSc from Newcastle University in 1974 and a MSc and PhD from Reading University in 1978 and 1987, respectively. Stuart worked initially in the mining industry applying sedimentology concepts to gold and diamond exploration and production. Since completing his PhD, he has worked in the petroleum industry specializing in the interpretation of core and borehole image data.

Graham Aplin see p. 79

Assessment of Undiscovered Oil and Gas Resources of the Greater Rub’ al Khali Basin by Application of the Total Petroleum System-Assessment Unit Concept: Part II, the Qusaiba-Paleozoic Petroleum System

Christopher Schenk and Richard Pollastro
U.S. Geological Survey, Denver

The World Energy Project of the U.S. Geological Survey has classified the Rub’al Khali as one of 76 priority provinces selected for an assessment of undiscovered conventional oil and gas resources, and scheduled for completion in June 2000. On the basis of total discovered petroleum volumes, the greater Rub’al Khali Basin (as defined here) ranks fifth in the world.

The Qusaiba-Paleozoic is one of three major petroleum systems identified in the greater Rub’al Khali Basin. The distribution and the thermal maturation of the Silurian Qusaiba Shale Member of the Qalibah Formation has been mapped throughout the greater Rub’al Khali. The Qusaiba source rock currently is in the gas window throughout much of the basin, and is in the oil window in a band along the southern, western, and northwestern margins of the basin. Using existing fields to the north in central Saudi Arabia as an analog for the southern part of the basin, the reservoirs to the south may be mainly clastics of the Permian, whereas the reservoirs in the Qusaiba Petroleum System are mainly Permian carbonates in the northeast. Hydrocarbon traps are mainly associated with basement block faults and regional wrench-fault systems, but stratigraphic traps are also present. Migration was mainly from the Qusaiba along faults into Permian reservoirs.

The Qusaiba-Paleozoic Petroleum System has been divided into two assessment units: the Qusaiba Structural Oil Assessment Unit and the Qusaiba Structural Gas Assessment Unit. The Qusaiba Structural Oil Assessment Unit encompasses the margins of the basin where the Qusaiba source rock is in the oil window. The Qusaiba Structural Gas Assessment Unit encompasses most of the Rub’al Khali Basin, including gas production from fields in offshore Qatar. For each assessment unit a probability distribution was developed for the sizes and numbers of undiscovered oil and gas accumulations using published geology, oil and gas field data, and analog data sets, and a Monte Carlo approach was used to generate distributions of undiscovered resources.

Christopher Schenk has been a Research Geologist with the U.S. Geological Survey for 20 years. He is Oil and Gas Assessment Coordinator for the USA and Central and South America for the World Energy Project. He is also Province Assessment Specialist for several provinces in the Middle East. Chris has a MSc in Geology from the University of Michigan and a PhD in Geology from the University of Colorado.

Richard Pollastro see p. 163

Facies Interpretation Using Artificial Neural Networks as an Aid to Development: a Case Study from South Oman

Olaf Schoenicke, Schlumberger Oman, Randall Penney, Asya Al-Rawahi, Petroleum Development Oman, Saleh Al-Alawi and Ali Al-Bemani, Sultan Qaboos University, Muscat

The Rima field in South Oman contains 81 million cubic meters of recoverable reserves, 25% of which are contained in the Permo-Carboniferous glacigenic Al Khala Formation. The Formation contains some excellent reservoirs but exhibits rapid lateral and vertical changes in lithology. The field has reached an advanced stage of development and a study was initiated to optimize the remaining drilling opportunities. A key aspect of the study was the development of a robust application to identify facies and improve the understanding of reservoir architecture. A facies interpretation technique using Artificial Neural Network (ANN) models was developed which, once trained, is largely independent of experience and geological knowledge. Two models are proposed: Model-1 uses a selection of conventional log data from standard logging suites; and Model-2 uses, in addition, the internal organization of the formations (‘morphofacies’) provided by borehole images.
In a case study involving the reservoirs of the Al Khlata Formation in the Rima field, a series of correlation lines were constructed from available logs and palynological data. Within these lines, log-stacking patterns were combined with palynological data to generate a sequence stratigraphic framework for constraining input parameters and calibrating the ANN output. In practice, Model-1 can predict a set of six facies with an accuracy of 97% and Model-2, can predict 11 sedimentary facies with an accuracy exceeding 98%. Model-2 therefore provides an extremely reliable description of the very heterogeneous Al Khlata Formation. The facies framework will be used in targeting development wells and as input for 3-D geological modeling of reservoirs. Should the technique prove to be robust, it could be applied to other South Oman fields having Al Khlata reservoirs.

Olaf Schoenicke is Division Geologist (Oman and Pakistan Division) with Schlumberger based in Muscat, Oman. He is responsible for the introduction and development of new geological interpretation products, currently focusing on enhanced borehole image interpretations. Olaf is completing his PhD project on facies interpretations of the glacigenic Permo-Carboniferous Al Khlata Formation of South Oman. Before joining Schlumberger in 1996, he was a Geologist for Western Atlas based in Damascus, Syria. Olaf received his MSc in Geology from the Technical University of Clausthal, Germany in 1992.

Randall Penney see p. 158

Asya Al-Rawahi joined Petroleum Development Oman (PDO) in 1989 as a scholar. She obtained a BSc in Geology from Oxford Brookes University, UK, in 1995. From 1996 to 1997, she worked in Nederlandse Aardolie Maatschappij (NAM, Netherlands) as a Wellsite Petroleum Engineer, before rejoining PDO as an Operations Geologist. Asya is currently working as a Production Geologist in the Bahja-Rima Asset Team.

Saleh Al-Alawi is an Assistant Professor at Sultan Qaboos University, Muscat. He holds a BSc (Industrial Engineering) from the University of Portland, a MSc and MBA from Florida Institute of Technology, and a PhD from the University of Missouri-Rolla. His research interests include prediction and forecasting using expert systems and artificial neural networks, system integration and optimization. Saleh has several journal and international conference publications in the area of management and artificial intelligence.

Ali Al-Bemani is an Assistant Professor in the Department of Petroleum and Mineral Resources Engineering of Sultan Qaboos University, Muscat. He is currently Head of Department. He worked previously as a Production Technologist for Petroleum Development Oman. Ali has a BSc from the University of Texas at Austin, and a MSc and PhD from the University of Southern California, all in Petroleum Engineering. His areas of research include modeling and analysis of pressure transient testing, horizontal well application, reservoir characterization, and use of artificial neural networks in petroleum engineering.

Evaporites of the Ara Group, South Oman: an Essential Element of Stratigraphy in an Infracambrian Salt Basin

Stefan Schröder, Albert Matter
University of Berne, Switzerland,
B. Charlotte Schreiber
Appalachian State University, North Carolina
and Joachim Amthor
Petroleum Development Oman, Muscat

Ara Group intrasalt carbonate stringers have a high reservoir potential. In previous studies, sedimentology and geochemistry of the surrounding evaporites have received little detailed attention. However, a study of evaporites in cores from the Greater Birba Area (South Oman Salt Basin) demonstrates their potential for understanding Ara stratigraphy and facies evolution.

In the South Oman Salt Basin, the Ara Group comprises 5–6 third-order carbonate-evaporite cycles. Cycles are symmetric, with dolomitised carbonates sandwiched between anhydrite, halite, and some potash salts. In each cycle, a carbonate succession represents the initial flooding of the basin and subsequent progradation of a carbonate ramp system. Anhydrite is the only sulphate mineral today, but pseudomorphs after selenitic gypsum prove that it commonly replaced primary gypsum. Halite is strongly recrystallised because of important post-sedimentary halokinetics.

Sedimentary structures (for example, palmate gypsum morphologies and desiccation cracks) suggest a shallow subaqueous environment throughout evaporite deposition. Sabkha deposits represent only a minor fraction. Sedimentation occurred in shallow salinas with brine depth less than 5 meters during much of the sulphate precipitation. Brine depth shallowed even more when halite and potash
Evaporite geochemistry indicates a marine source with some minor contributions from continental or hydrothermal waters. The lack of major exposure surfaces suggests that the ramp slowly developed into a large evaporating sea, or a series of smaller lagoons that were partly connected. Potash salts mark the stage when the basin was almost completely desiccated. The subsequent return to carbonate deposition is highlighted by a series of corrosion surfaces separating older high-order evaporites from deposits of reduced salinity. Corrosion surfaces mark events of inflowing normal marine waters. Rising sea-level and high subsidence rates finally led to the re-establishment of an open-marine carbonate ramp.

**Stefan Schröder** received his MSc in Geology from Wurzburg University, Germany in 1997. He worked on Pliocene clastic sediments and neotectonics in Italy before joining Bern University. Stefan is currently working for his PhD on sedimentology and diagenesis of subsurface Proterozoic/Cambrian carbonates and evaporites of Oman.

**Albert Matter** see p. 125

**B. Charlotte Schreiber** was awarded a PhD in 1974 by Rensselaer Polytechnic University, the topic of which was the depositional environments and lithologies of the Messinian evaporites of the Mediterranean. Since then, she has studied modern evaporative environments, as well as numerous altered and deeply buried deposits. The gradual unraveling of the general depositional and diagenetic framework for evaporites, based on the original primary features has been the focus of her studies for the past 25 years. In addition to carrying out an active research program, she has been a Professor of Geology at Queens College (City University of New York) and a Research Associate at Lamont Doherty Earth Observatory (Columbia University, N.Y.). She is presently an Adjunct Professor at Appalachian State University, Boone, North Carolina. Charlotte has edited four books and authored over 60 papers on evaporites and related carbonates, as well as several experimental studies on the diagenesis of siliciclastic sediments.

**Joachim Amthor** see p. 47

**Unusual Hydrocarbon Reservoirs in Intrasalt Carbonate Stringers, Birba Area, Infracambrian Ara Group, South Oman**

Stefan Schröder, Albert Matter
University of Berne, Switzerland
and Joachim Amthor
Petroleum Development Oman, Muscat

Frontier exploration in South Oman presently focuses on intrasalt dolomite reservoirs (stringers) in the Infracambrian Ara Group. This study will present results from the Greater Birba Area. Carbonate stringers belong to a thick (3–4 kilometer) cyclic sequence of dolomites and evaporites reflecting recurrent changes in basin restriction. Dolomites combine characteristics of good reservoirs and source rocks. The dolomites are usually fully encased in evaporites, overpressured, and contain oil which is derived from within the Ara Group. Carbonate facies developed on a ramp system. Finely laminated organic-rich dolomites and some thrombolite buildups occupied an outer to middle ramp setting with conditions of low energy. They are overlain by shallow-water mudstones, packstones, and evaporites. Laminated carbonates provide the best reservoirs in the Ara Group, despite moderate initial porosities.

Fabric retentive dolomitisation was the major diagenetic process; carbonate and evaporite cements are rare. The system probably has been self-sourcing, with hydrocarbons being generated from the inherent organic matter. Porosity evolution contrasts with that of thrombolite buildups and shallow-water packstones where high porosities have been almost completely plugged by dolomite and evaporite cements. Several factors may explain the observed evolution of potential reservoir rocks: (1) Downward circulation of saline brines caused deterioration of reservoir characteristics in underlying carbonates. Any lithofacies close to overlying evaporites was likely to suffer from evaporite cementation, such as shallow-water carbonates at the top of stringers, as well as thin stringers. (2) Early maturation of organic matter may have flushed pore networks in laminites with hydrocarbons that prevented cementation by carbonates and evaporites. (3) Larger pores (such as in thrombolites) were more easily filled with evaporite cements than smaller pore networks (such as in laminated carbonates).
opportunities and risks. It is anticipated that this improved interpretation thus allows a better appreciation of subsurface their likely position in the sediment systems tract. The distribution of source, reservoir and seal lithologies, and possible controls (tectonics, eustasy, sediment supply) on the interpretation provides a better understanding of the chronostratigraphic framework.

Arabian Plate to be placed within a clear and robust reliance on sequence stratigraphic principles. Together these extensive CMFS have also been identified through a greater sedimentological, wireline log and other geological data has allowed the identification of over twenty plate-wide palaeogeographic maps, tectonic element maps, structural cross-sections and chronostratigraphic cross-sections. Eleven tectono-stratigraphic Megasequences bounded by unconformities have been identified which reflect major plate-wide reorganisations of accommodation space. Within these Megasequences the integration of biostratigraphic, sedimentological, biostratigraphic and geochemical aspects of the sedimentary succession through the construction of over fifty plate-wide palaeogeographic maps, tectonic element maps, structural cross-sections and chronostratigraphic cross-sections. Eleven tectono-stratigraphic Megasequences bounded by unconformities have been identified which reflect major plate-wide reorganisations of accommodation space. Within these Megasequences the integration of biostratigraphic, sedimentological, wireline log and other geological data has allowed the identification of over twenty plate-wide chronostratigraphically equivalent CMFS. Over forty less extensive CMFS have also been identified through a greater reliance on sequence stratigraphic principles. Together these CMFS provide an excellent framework of timelines, which allows the disparate lithostratigraphic units across the Arabian Plate to be placed within a clear and robust chronostratigraphic framework.

The interpretation provides a better understanding of the possible controls (tectonics, eustasy, sediment supply) on the distribution of source, reservoir and seal lithologies, and their likely position in the sediment systems tract. The interpretation thus allows a better appreciation of subsurface opportunities and risks. It is anticipated that this improved stratigraphic understanding will lead to the identification of new plays, new hydrocarbon discoveries and improved reservoir descriptions.

This paper presents the objectives, methodology and key results of a two-year geological study by LASMO to develop a sequence stratigraphic understanding of the petroleum resource potential of the Arabian Plate. The study was based on a thorough evaluation of the available literature, together with the study team’s extensive experience of the geology of the region. Although the Phanerozoic succession of the Arabian Plate covers more than 600 million years, and is the world’s largest petroleum resource, a published plate-wide sequence stratigraphic interpretation has yet to be developed. The new plate-wide sequence stratigraphic interpretation presented here is described using a proposed new nomenclature that subdivides or groups the previous lithostratigraphic descriptions into chronostratigraphically equivalent genetic stratigraphic sequences bounded by time-equivalent candidate maximum flooding surfaces (CMFS).

The interpretation has reviewed the tectonic, stratigraphic, sedimentological, biostratigraphic and geochemical aspects of the Phanerozoic succession of the Arabian Plate. The new plate-wide sequence stratigraphic interpretation presented here is described using a proposed new nomenclature that subdivides or groups the previous lithostratigraphic descriptions into chronostratigraphically equivalent genetic stratigraphic sequences bounded by time-equivalent candidate maximum flooding surfaces (CMFS). The interpretation provides a better understanding of the possible controls (tectonics, eustasy, sediment supply) on the distribution of source, reservoir and seal lithologies, and their likely position in the sediment systems tract. The interpretation thus allows a better appreciation of subsurface opportunities and risks. It is anticipated that this improved stratigraphic understanding will lead to the identification of new plays, new hydrocarbon discoveries and improved reservoir descriptions.


This paper presents the objectives, methodology and key results of a two-year geological study by LASMO to develop a sequence stratigraphic understanding of the petroleum resource potential of the Arabian Plate. The study was based on a thorough evaluation of the available literature, together with the study team’s extensive experience of the geology of the region.

Although the Phanerozoic succession of the Arabian Plate covers more than 600 million years, and is the world’s largest petroleum resource, a published plate-wide sequence stratigraphic interpretation has yet to be developed. The new plate-wide sequence stratigraphic interpretation presented here is described using a proposed new nomenclature that subdivides or groups the previous lithostratigraphic descriptions into chronostratigraphically equivalent genetic stratigraphic sequences bounded by time-equivalent candidate maximum flooding surfaces (CMFS).

The interpretation has reviewed the tectonic, stratigraphic, sedimentological, biostratigraphic and geochemical aspects of the sedimentary succession through the construction of over fifty plate-wide palaeogeographic maps, tectonic element maps, structural cross-sections and chronostratigraphic cross-sections. Eleven tectono-stratigraphic Megasequences bounded by unconformities have been identified which reflect major plate-wide reorganisations of accommodation space. Within these Megasequences the integration of biostratigraphic, sedimentological, wireline log and other geological data has allowed the identification of over twenty plate-wide chronostratigraphically equivalent CMFS. Over forty less extensive CMFS have also been identified through a greater reliance on sequence stratigraphic principles. Together these CMFS provide an excellent framework of timelines, which allows the disparate lithostratigraphic units across the Arabian Plate to be placed within a clear and robust chronostratigraphic framework.

The interpretation provides a better understanding of the possible controls (tectonics, eustasy, sediment supply) on the distribution of source, reservoir and seal lithologies, and their likely position in the sediment systems tract. The interpretation thus allows a better appreciation of subsurface opportunities and risks. It is anticipated that this improved stratigraphic understanding will lead to the identification of new plays, new hydrocarbon discoveries and improved reservoir descriptions.
Alaska. After receiving a BSc in Geology from Bristol University and a PhD from Southampton University, he spent 14 years with BP Exploration and for the past 5 years has been director of his own consultancy. His main interests are in the application of sedimentology and sequence stratigraphy to improve reservoir description.

Steve Hall currently works for StrucOil, a company specializing in structural geology interpretations for the oil and gas industry. He previously spent 11 years working for BP Exploration as an international Structural Geologist. He received a BSc in Geological Sciences from Leeds University and a PhD in Structural Geology from Imperial College, London. His main interest involves working on structural geological problems from the regional to fracture scale.

Alan Heward is a Subsurface Advisor in LASMO’s Technical Services Department, London. He obtained a BSc from London University and a PhD from Oxford University, both in Geology. He has worked in the oil industry for 18 years, mainly with Shell, including 7 years with Petroleum Development Oman. His interests lie in understanding hydrocarbon reservoirs, and optimizing the development of oil and gas fields.

Andrew Horbury has a BSc from Bristol University and a PhD in Carbonate Sedimentology from Manchester University. He joined BP Exploration in 1986 and worked on a variety of northern Arabia Plate projects. In 1992, he co-founded Cambridge Carbonates Ltd. His present interests include the sequence stratigraphic evolution, sedimentology and reservoir geology of northern Arabia, complex fractured carbonate and dolomite reservoirs in southern Italy, and Mesozoic play systems and reservoirs in Mexico. He is also involved in developing a system of quantifying poroperm and diagenetic evolution from thin-sections of carbonates via a project in conjunction with Royal Holloway College, London.

Michael Simmons is Head of the Department of Geology and Petroleum Geology, University of Aberdeen. He is also Brunei Shell Petroleum Senior Lecturer in Petroleum Geoscience. He worked for 11 years with BP Exploration as a Senior Geologist/Biostratigrapher, specializing in the Middle East and Former Soviet Union areas. Michael has a BSc and PhD from Plymouth University. He has research interests in applied biostratigraphy, the geology of the Tethyan region, and the use of outcrop analogs in understanding subsurface reservoirs.

Peter Sharland, LASMO, London, Ray Archer, Consultant, David Casey, Consultant, Roger Davies, Consultant, Steve Hall, StrucOil, Alan Heward, LASMO, London, Andrew Horbury, Cambridge Carbonates and Michael Simmons, University of Aberdeen

This poster presents the interpretation of the Infracambrian and Paleozoic sequence stratigraphy from the geological study of the Arabian Plate by LASMO. It illustrates the pre-Mesozoic development of the Arabian Plate from the consolidation of the basement in the late Precambrian to the breakup of Gondwana in the late Paleozoic.

A review of the Infracambrian to Recent tectonic history of the Arabian Plate allows recognition of eleven tectono-stratigraphic units, termed Megasequences, separated by widespread unconformities. Of these eleven Megasequences, the first 5 occur in the Infracambrian and Palaeozoic. Within the Megasequences, a large number of candidate maximum flooding surfaces (CMFS) are identified and correlated. These CMFS act as a framework of time lines, which allows the disparate lithostratigraphic units across the Arabian Plate to be placed within a chronostratigraphic framework.

The poster presents a proposed new sequence stratigraphy for the five Infracambrian and Paleozoic Megasequences recognized over the Arabian Plate. The correlations are illustrated using a series of chronostratigraphic charts following transects across the Plate. The charts also illustrate the petroleum play elements of source, reservoir and seal lithologies, together with periods of major trap formation.

Much of the early Palaeozoic rock record is represented by continental clastic sediments, and only in the marine clastic succession of the Late Ordovician to Early Silurian can plate-wide CMFS be readily recognized. Breakup of Gondwana in the late Palaeozoic, and subsidence of the new Neo-Tethys passive margin in the Late Permian, together with northward
drift of the Plate into more tropical climes, led to gradual onlap of the plate by marine carbonates. By the end of the Paleozoic the extensive Khuff carbonate-evaporite shelf was established over much of the Plate.

A Proposed Sequence Stratigraphy for the Phanerozoic Succession of the Arabian Plate: Mesozoic and Cenozoic Sequences


This poster presents the interpretation of the Mesozoic and Cenozoic sequence stratigraphy from the geological study of the Arabian Plate by LASMO. These carbonate-dominated successions contain the greatest accumulation of petroleum on earth. In consequence, there is a great volume of published material, and a much finer-scale sequence stratigraphic resolution has been achieved. The poster illustrates the ‘post-Hercynian’ development of the Arabian Plate from the development of a new passive margin with Neo-Tethys in the Late Permian to the eventual collision with Eurasia in the Late Tertiary to create the Zagros foldbelt. A review of the InfraCambrian to Recent tectonic history of the Arabian Plate allows recognition of eleven tectono-stratigraphic units, termed Megasequences, separated by widespread unconformities. Of these Megasequences, six lie in the Mesozoic and Cenozoic. Within the Arabian Plate Megasequences, a large number of candidate maximum flooding surfaces (CMFS) are identified and correlated. These CMFS act as a set of timelines, which allows the disparate lithostratigraphic units across the Arabian Plate to be placed within a chronostratigraphic framework.

The poster presents a proposed new sequence stratigraphy for the six Mesozoic and Cenozoic Megasequences recognized over the Arabian Plate. The correlations are illustrated using a series of chronostratigraphic charts following transects across the Plate. The charts also illustrate the petroleum play elements of source, reservoir and seal lithologies, together with periods of major trap formation.

Numerous high-order CMFS are recognisable in the Mesozoic and Tertiary stratigraphy of the Arabian Plate. These CMFS primarily record the interplay between eustatic sea level fluctuations and the tectonic evolution of the plate during the break-up of Gondwana, the northward drift of the Arabian Plate, and eventual collision with Eurasia in the Late Tertiary.

A Proposed Sequence Stratigraphy for the Phanerozoic Succession of the Arabian Plate: the Key Role of Biostratigraphy


This study presents some of the key biostratigraphic results of the two-year geological study by LASMO to develop a sequence stratigraphic understanding of the petroleum resource potential of the Arabian Plate. A reliable chronostratigraphic framework is a prerequisite to any sequence stratigraphic study. Not withstanding recent advances in chemical/isotope stratigraphy, biostratigraphy remains the most practical tool for identifying, characterizing and correlating reliable chronostratigraphic surfaces such as candidate maximum flooding surfaces (CMFS).

The Phanerozoic sediments of the Arabian Plate contain a wide variety of macrofossils and microfossils. Graptolites, ammonites and planktonic foraminifera (for example) are useful for correlation purposes, and the localized abundance of such open-marine indicators can point to the location of CMFS. Other fossils, such as bivalves, corals, benthonic foraminifera and calcareous algae, can be used to recognize trends in paleobathymetry within a succession and thus also locate CMFS.

Over 20 plate-wide CMFS have been recognized within the Phanerozoic succession. These include an Ordovician (Llanvirnian) surface recognizable from graptolite and acritarch faunas and florals, an early Turonian surface recognizable from planktonic foraminifera faunas, and a Middle Paleocene surface also recognizable from planktonic foraminiferal faunas. Over 40 other less extensive CMFS have also been recognized using more subtle biostratigraphic evidence augmented by sequence stratigraphic concepts, an example being the early Aptian surface typified by the Hawar Shale of the UAE.

Although biostratigraphy is not without its uncertainties, the identification, characterization and correlation of CMFS has enabled a robust sequence stratigraphy for the Phanerozoic succession of the Arabian Plate to be developed. This framework substantially clarifies the ambiguities that surround past lithostratigraphic correlations.

Peter Sharland, Ray Archer, David Casey, Roger Davies, Steve Hall, Alan Heward, Andrew Horbury and Michael Simmons see p. 179-180
**Analysis of Continental Palynomorphs from the Llandovery in Saudi Arabia**

Philippe Steemans, University of Liege, Belgium. Kenneth Higgs, University College Cork, Ireland and Charles Wellman, University of Sheffield, UK

Diversified assemblages of cryptospores and trilete miospores are reported from the Qalibah Formation in the Nuayyim-2 and Hawiyah-151 wells, Saudi Arabia. Four new genera and six new species are described. Independent biostratigraphical controls using chitinozoans and graptolites indicates that all the studied samples from Nuayyim-2 are Llandovery (Rhuddanian) in age. In contrast, independent dates from the Hawiyah-151 sections are rare. A new spore zonation scheme for strata near the Ashgill-Llandovery boundary is proposed, in which one assemblage biozone is divided into two interval biozones that are both further subdivided into two sub-biozones.

The criteria used to define these biozones are first occurrences of taxa (including the earliest trilete spores) and the relative abundance of envelope-enclosed cryptospores and of trilete spores. These data allow accurate dating and correlation of the Early Silurian stratigraphy of nearshore and continental sediments. Indeed, spores and cryptospores are the only fossils that are abundantly produced on the continents during this time. Quantitative analysis of the relative abundance of continentally derived and marine-derived palynomorphs has allowed an evaluation of the paleoenvironment, in particular, the distance of the sediments from the paleoshoreline.

The paleogeographically widespread distribution of similar spore assemblages during the Late Ordovician/Early Silurian may provide an explanation for the apparent lack of significant impoverishment in spore biodiversity during the Hirnantian glaciation. It is suggested that the parent plants were probably cosmopolitan and thrived in a variety of climatic conditions and were therefore little affected by climatic changes associated with the glaciation.

Philippe Steemans received his PhD degree in Geology from Liège University, Belgium, in 1986. He worked for two years in limestone quarries with the Carmeuse Society. Since 1990, Philippe has been employed by the National Fund for Scientific Research in Belgium as a Research Associate. He specializes in the palynology (miospores and cryptospores) of the Ordovician, Silurian and Devonian.

Kenneth Higgs is a Senior Lecturer in Geology at University College Cork, Ireland. He received his BSc in 1971 and his PhD in 1975 from the University of Sheffield. He then joined the Geological Survey of Ireland in 1975 as a Palynologist and Stratigrapher. In 1986, Kenneth was appointed as Lecturer in Paleontology and Stratigraphy in the Department of Geology at University College Cork, where he has established a research laboratory in Paleozoic and Mesozoic palynology.

Charles Wellman was awarded a BSc (hons) in Geology from the University of Southampton in 1987 and a PhD from Cardiff University in 1991. His PhD research was conducted jointly between the Natural History Museum (London) and Cardiff University and involved a study of spore assemblages from the Silurian-Devonian Old Red Sandstone deposits of Scotland. Charles subsequently worked on a number of postdoctoral research projects studying various aspects of Ordovician-Devonian terrestrial palynology and Paleobotany, as well as spending time in industry as a Petroleum Geologist and Environmental Geoscientist. In 1997 Charles was appointed Lecturer in Palynology in the Centre for Palynology of the University of Sheffield, where he teaches and continues his research.

**Integrated Fracture and Flow Modeling for the Jurassic Najmah-Sargelu Formations, Kuwait: A Follow-Up Evaluation Based on the KM-2 Appraisal Well**

Christian Strohmenger, James DeGraff, Steven Webb, R. Neil Aubuchon, Daniel Cassiani, Mark Tibold, Ralph Pauls, ExxonMobil and Mohamad Al-Ajmi, Kuwait Oil Company

Fractures are important to deliverability and for defining volumes in the Middle-Upper Jurassic carbonates of the Najmah and Sargelu formations in West Kuwait. From core measurements, six fracture generations were defined. Fracture density was tied to each of five facies assemblages. Reservoir units, their facies composition, and fracture properties were correlated and predicted throughout Kuwait. Seismically identified faults in the study area have variable density, with throws generally less than 25 feet. Fault density, throw, and orientation were used to predict fracture occurrence in the Kra Al-Maru 3-D volume and ultimately...
to select the KM-2 appraisal well location. Multivariate linear regression analysis of a large number of variables derived from core, wireline logs and 3-D seismic data were used to identify stratigraphic and structural elements controlling fracture density and aperture. While matrix porosity directly controls reservoir storage and thus sustainable production from the Najmah and Sargelu formations, fracture permeability dominates well deliverability. Matrix porosity combined with the distribution and lateral extent of fracturing defines the drainage volume for a given well. Fracture analyses indicate that KM-2 has one of the highest fracture densities of all wells evaluated in Kuwait, despite being located on perhaps the least structured closure drilled thus far. Performance, core, and well log data from KM-2 were used to verify and calibrate the OD fracture and reservoir porosity models derived from the earlier analysis.

**Christian Strohmenger** received a Diploma in Geology from the University of Giessen (1983) and a PhD in Mineralogy/Sedimentology (1988) from the University of Heidelberg, Germany. From 1989 to 1990, he was a Research Assistant in carbonate sedimentology and sequence stratigraphy at the University of Geneva. Christian joined BEB Erdgas und Erdöl GmbH, Hanover, Germany in 1990, working as a Carbonate Sedimentologist until 1994, and as a Seismic Interpreter until 1996. Since 1996, Christian has been on a foreign assignment with Exxon Exploration Co. in Houston where he is currently working on carbonate and sandstone reservoirs of Kuwait.

**Mark Tibold** is a Senior Engineering Specialist with the Geological Services/Well Testing division of Exxon Exploration Co. in Houston. He received his BS in Mechanical Engineering in 1985 from the University of Manitoba, Canada. Since then, he has worked as an Evaluation, Production and Reservoir Engineer in the Western Canadian Basin. His current assignment is as a Well Testing Specialist, which has involved projects in the Gulf of Mexico, Sakhalin Island, Niger, and the Middle East. Mark is a member of the Kuwait team working the Kra Al-Maru Joint Technical Study in Western Kuwait.

**James DeGraff. R. Neil Aubuchon, Ralph Pauls**, see p. 157-158; **Steven Webb** see p. 197; **Daniel Cassiani** see p. 66; **Mohamad Al-Ajmi**, see p. 149

---

**Sequence Stratigraphy of the Khuff Formation: Emphasis on the Exploration Potential in Kuwait**

**Christian Strohmenger, Harry Mueller, Paul Wagner, Donald Yurewicz, Daniel Cassiani, ExxonMobil Scott Ferguson and Adel Ebaid, Kuwait Oil Company**

Assessment of the exploration potential of the Late Permian Khuff Formation in Western Kuwait is based, in part, on data from the six Kuwait wells that penetrate the formation. In these wells, the Khuff is predominantly dolomite and anhydrite. One well has significant shale and siltstone. Six depositional sequences can be correlated throughout the Arabian Platform. The interval from top Khuff to base Middle Anhydrite (Tatarian) comprises sequences KS1 through KS4. Sequences KS5 and KS6 (Kazanian) make the interval between base Middle Anhydrite and the pre-Khuff Unconformity in structurally high areas in Kuwait and throughout onshore Saudi Arabia. An older Khuff sequence, KS7 (Kungurian), is interpreted to be present in structurally low areas in West Kuwait as well as offshore Saudi Arabia. The latter is time-equivalent to the Upper Unayzah-A reservoir in onshore Saudi Arabia. Reservoir quality of the dolomites encountered in the six Kuwait wells is very poor. These sediments are mostly low-energy, micritic, intertidal or lagoonal deposits although high-energy ooid grainstones also occur. Primary interparticle porosity has been lost due to intensive cementation. Studies on other interbedded grain-dominated/mud-dominated carbonates have shown that the higher the grainstone/mudstone ratio, the better the reservoir quality. In the case of the Khuff, the ratio is expected to be low, so early structuring and hydrocarbon emplacement is thought to be key to preserving suitable quality reservoir rock. Only sediments that experienced Early Triassic structuring are thought to have reservoir quality preserved in present-day structures. Intensive 2-D and 3-D seismic interpretation has helped identify Triassic structures by mapping the thickness of the interval from top Minjur carbonate to top Khuff.

**Christian Strohmenger see this page.**

**Harry Mueller** is a Senior Reservoir Geologist with Abu Dhabi Company for Onshore Oil Operations (ADCO). Since receiving his PhD in Geology from the University of Texas, he has spent 20 years in the oil industry, mostly at Exxon Production Research Company. He has been involved in service work and training in the application of carbonate sedimentology and sequences stratigraphy to exploration and production problems. Harry is a member of AAPG, SEPM, SPWLA, SPE, SEE, and HGS.
Paul Wagner is a Research Specialist at Exxon Production Research (EPR). Prior to joining EPR, he worked on clastic regional studies of the Gulf of Mexico with PGS Reservoir, and carbonate studies with Amoco. He obtained his PhD from Brown University in 1983. He is a member of AAPG, SEG, and HGS.

Donald Yurewicz has a BA in Geology from Rutgers University (1970) and a MS (1973) and PhD (1976) in Geology from the University of Wisconsin. He began his career as a Research Specialist in carbonate rocks at Exxon Production Research Company in 1977 and transferred to an exploration assignment in 1985. Since then, his assignments have varied from prospect and play identification, to regional studies focusing on hydrocarbon systems, reservoir characterization, stratigraphy and paleogeography, and resource assessment within North America, South America, and the Middle East.

Daniel Cassiani see p. 66; Scott Ferguson biography not available.

Adel Ebaid graduated from al Azhar University in 1981 with a BSc in Geology. Adel obtain a Diploma in Seismic Exploration Tools in 1987 from Cairo University. He joined the General Petroleum Company, Egypt in 1982 as a Geophysicist, since then his professional experience has been in seismic interpretation. Adel joined Kuwait Oil Company in 1998 as a Geophysicist. Currently, he is responsible for the regional seismic interpretation of the all-deep horizons from Triassic to the basement. Adel is a member of the prospect evaluation teams of the Khuff and pre-Khuff.

Petroleum Systems of Oman: Charge Timing and Risks

Jos Terken, Sarah Indrelid, and Neil Frewin
Petroleum Development Oman, Muscat

After 35 years of exploration, creaming the conventional plays in Oman is nearly complete and, consequently, the search is on for new, less obvious plays and more subtle trap-styles. Many of the new opportunities occur beyond the known hydrocarbon provinces and are considered to have significant charge risks. To define these risks and determine the remaining scope in our conventional plays, extensive basin modeling studies were carried out in recent years. Modeling and empirical data show that Mesozoic and Cenozoic kitchen areas are restricted to the Fahud Salt Basin and Foreland Basin in western North Oman, the only areas currently at their maximum temperature. Large parts of North and Central Oman depend on lateral migration from these kitchens for their charge. Lateral migration requires favorable structural dips and good seal integrity. In North Oman, progressive uplift of the eastern flank since the mid-Paleozoic, and Alpine-age graben inversion, combined with regional Khuff (Permian) and Nahr Umr (Albian) seals provide such conditions for the post-Haima interval. Charge risks increase in the deeper sequence, in which eastward-migrating hydrocarbons have to traverse the Ghaba Salt Basin, a pronounced syncline at depths greater than 3 kilometers. In Central Oman, a north-trending, reactivated basement grain has funneled charge from the Fahud Salt Basin up to 300 kilometers southward to the tilted eastern flank of the South Oman Salt Basin. In the South Oman Salt Basin, half-graben inversion and progressive uplift of the gentle eastern flank occurred since mid-Paleozoic times. As a result of insufficient re-burial and hydrodynamic fluid-flow activity since the late Cretaceous, the basin is cooler than its maximum temperature. The basin depends on an early, Cambrian to Ordovician charge, that was released in stages from carbonate and silicilyte stringers capped by and encased in the Ara salt sequence as the salt-edge retreated.

Source rocks in Oman are predominantly oil-prone (marine) and most of the gas found is thought to result from thermal cracking of oil trapped in deep reservoirs but also retained in source rocks. The chance of finding gas, therefore, increases significantly in reservoirs hotter than 130°C, which is interpreted as marking the onset of cracking. Basin modeling has outlined the extent of the different petroleum systems and provided us with risk maps to guide our next exploration phase. It has also revitalized some of the old plays such as the Gharif play, where oil exploration is now focused along Late Cretaceous and Tertiary migration paths, and deeper sections that are thought to have significant scope for gas.

Jos Terken received a MSc (cum laude) in Geology and Sedimentology from the University of Utrecht in 1982. He joined Shell in 1982 and worked in The Netherlands, Brunei, New Zealand, and Indonesia. In 1993 he joined Petroleum Development Oman (PDO) as a Senior Review Geologist/Basin Modeler in the Regional Studies Team. In close
cooperation with the Geochemistry Group, he modeled and mapped the Huqf, Q, Natih, and Tuwaiq petroleum systems in Oman. He also worked in the Commercialization Team of PDO and was involved in booking reserves from past and recent discoveries. He rejoined Shell in 1999.

Sarah Indrelid and Neil Frewin see p. 90

Makarem—Tighter Integration for Tighter Gas

Graham Tiley, Ian Billing, Roland Muggli, Saada Al-Rawahi, Junaid Ghulam and Alison Jones, Petroleum Development Oman, Muscat

Joerg Mattner, Jonathan Strauss, Ismail Ozkaya, and Volker Köchler, Baker Atlas, GEOScience Bahrain

Montri Rawanchaikul, Mark Sams, and Gordy Shanor, Jason Systems, Dubai

The Makarem gas field holds gas-initially-in-place estimated to be in excess of 20 trillion cubic feet in an approximately 2,000-square-kilometer structure in the Block 6 Concession, Oman. Three gas-bearing reservoirs have been proved by three wells drilled on the structure. They are the Cambrian-Ordovician Barik and Amin sandstones, and the Precambrian Buah dolomites. Two tests of the Buah produced gas at economic rates of up to 600,000 cubic meters/day, but the third penetrated unproducible reservoir. The Amin flowed at only 25,000 cubic meters/day after a hydraulic frac whilst the Barik failed to yield a sustained flow. The gas column in the Buah has also been demonstrated to be a ‘cellar’ volume to the Amin accumulation.

A multidisciplinary study team was established to produce an integrated field model that took into account all the available data, including well logs, core data, production test information, 3-D seismic, and outcrop studies.

Results so far include a constrained sparse-spike inversion that confirmed the correlation between zones of higher porosity and lower impedance seen from log data. The impedance data also allowed a more accurate correlation of intra-Buah seismic events, which, together with analog models derived from outcrop, enabled the construction of a sequence stratigraphic framework. Analysis of core, image log, and seismic fault data has yielded a fracture model for the Buah that indicates a connected network of fracture families that in turn connect more permeable vuggy layers. A key uncertainty for defining the recoverable gas volumes is whether the matrix contributes to production from the Buah or whether only the fracture system can be drained. This was addressed by a re-entry and test in 1999. A reservoir model will be constructed, constrained by the seismic inversion results, and used as the basis for booking the remaining scope in the Buah and Amin reservoirs. The Barik reserves were further appraised in 1999 for improved reservoir quality on the flank of the structure.

Graham Tiley is Team Leader for the Government Gas Exploration in Petroleum Development Oman (PDO). He has a MSc in Geophysics (Durham) and a PhD in Geological Sciences (Birmingham). He joined Shell in 1988 and worked in the Research & Technology Services Group in The Netherlands on seismic interpretation software development. In 1992, he was posted to Nigeria as a member of the Quantitative Seismology and Exploration Evaluation teams. Graham joined PDO in 1996 as a Seismic Interpreter.

Ian Billing is a Carbonate Sedimentologist. He joined Shell in 1991 with a PhD from Durham University and was a Regional Geologist for three years in the Russian Geology Team. He then transferred to the Carbonate Research Group of Shell’s Research & Technology Services in The Netherlands where he worked on carbonate fields, including Shu’aiba-age equivalents in Venezuela and the UAE. Ian was posted to Petroleum Development Oman in 1997 as a carbonate Focal Point in Frontier Exploration. In 1999, he moved to the Government Gas Exploration Team to work on the Makarem field. Ian left Shell in 1999.

Roland Muggli graduated in 1992 from ETH, Zurich, with a MSc in Geophysics. He joined Shell in 1993 and worked in Shell Expro’s Northern North Sea Mature Areas Asset Team in near-facilities prospect evaluation. In 1997, Roland moved to the Reservoir Characterization Team of the Geosolutions Department in Petroleum Development Oman. His focus of work lately has been on integrating seismic into reservoir-model building.

Saada Al-Rawahi is a Seismic Interpreter for Petroleum Development Oman in the Government Gas Exploration Team. Saada has a BSc in Geophysics (1995) from the University of Leeds and a MSc in Petroleum Geosciences from Aberdeen University (1997).
Junaid Ghulam joined Petroleum Development Oman (PDO) in 1995 with a BSc (hons) in Construction Management and Engineering from Reading University. For two years he was a Mechanical Construction Engineer and a Wellsite Petroleum Engineer. In 1997, he joined the Government Gas Team as a Reservoir Engineer. He focused initially on pressure monitoring and performance of producing dry-gas reservoirs and well testing. Junaid now provides reservoir engineering support to the Frontier Gas Exploration Team in deep-gas reserves booking exercises. He is also the contract holder for PDO’s reservoir fluid sampling and analyses contract.

Alison Jones has a BSc in Mathematics from the University of Bristol and a PhD in Applied Mathematics from the University of Leeds (in conjunction with Schlumberger). She joined Shell in 1992 as a Production Technologist in the Research & Technology Services Group in The Netherlands. Alison later joined Petroleum Development Oman’s Gas Team where her responsibilities have included designing the fracture treatments for deep-gas development wells, and testing and completion of gas exploration wells.

Jonathan Strauss has worked for Baker Atlas GEOScience in Bahrain as a Senior Reservoir Engineer since 1997. Prior to this, he worked for Soeker E and P (South African National Oil Company) and PGS Reservoir UK. He received his BSc (hons) in Physics from the University of Natal, South Africa, in 1986. His interests include reservoir simulation, probabilistic methods, pressure transient analysis, and fractured reservoirs.

Ismail Ozkaya holds a MSc in Computer Science, Mining Engineering and a PhD in Geology. His experiences include field geology and regional tectonics, statistical and computer studies in geology. He has developed computer software for various applications such as balanced cross-section construction, and finite element solution of fluid flow and stress. Ismail is working for Baker Atlas GEOScience on fractured reservoir characterization. He is interested in modeling fracture networks and simulation of fluid flow through fractures.

Montri Rawanchaikul is a Consultant Geophysicist of Jason Geosystems Middle East based in Dubai. He has a M.App.Sc (Exploration Geophysics) from the University of New South Wales, Australia (1991) and experience in engineering geophysics. He joined the Petroleum Authority of Thailand in 1991. Prior to joining Jason Geosystems in 1997, Montri was based in Kuala Lumpur in charge of offshore 3-D seismic acquisition and processing for a joint Thailand-Malaysia operating company. His work has focused on 3-D seismic interpretation, visualization, reservoir characterization, and stochastic modeling.

Mark Sams has been a Consultant Geoscientist for Jason Systems Asia since 1997. He has a PhD in Geophysics from Imperial College, London (1987) and was a Fellow of the Ocean Drilling Program and a Research Associate of Imperial College. He was a Senior Geophysicist with Petronas Research and Scientific Services from 1994 to 1997.

Gordy Shanor is Business Manager of Jason Geosystems Middle East, Dubai. He has a BSc in Geology from the University of Oklahoma (1976). He has 25 years of international hydrocarbon exploration and development experience in major oil and service companies. His work has focused on 3-D reservoir characterization and stochastic modeling. Before joining Jason Geosystems as Geoscience Advisor in 1997, Gordy worked for Schlumberger (10 years) and Smedvig Technologies (4 years) in Asia, the Middle East, and Europe.

A 35-m Oil Column and Still not Happy? Defining the Sweet Spots by Integrating Geology and Seismic following the Musallim Ghudun Discovery Well, North Oman

Paul Tricker, Paul Senycia and Mark Partington
Petroleum Development Oman

In 1997, the Musallim Deep-1 well in North Oman drilled to 4,006 meters and discovered a 35-meter column of 41°API oil on a 50 square kilometer structural dip closure.
beneath existing production facilities. Unfortunately, the quality of the lower Paleozoic Ghudun clastic reservoir was poor. Average log porosities were less than 10% and the reservoir was interpreted as being uncommercial. The challenge has been to define and predict the reservoir sweet spots in order to develop this significant discovery.

Accurate mapping of the top reservoir was not possible using the existing 1995 3-D short offset (4.3 kilometers) seismic dataset as acoustic modeling indicated that the reservoir-seal interface is only observed on long offset data (> 4 kilometers). Consequently, two dedicated seismic lines (10 kilometers offset, 400-fold) were acquired in 1999 to tie Musallim Deep-1 to Makarem-3, an off-structure well with improved Ghudun reservoir quality. Accurate mapping of the reservoir-seal interface was then possible and the data more readily allowed prediction of reservoir quality. Reservoir Scanning Electron Microscopy, X-ray Diffraction, and optical microscopy showed that feldspar dissolution, quartz overgrowths and pore-plugging clays are the main factors in reservoir quality. Geochemical techniques (FIS/RockEval) were used to reduce other reservoir risks, such as pyrobitumen plugging.

Geological models for the structural development of the accumulation were developed by utilizing the reservoir models and the new seismic interpretation. Integration of the geological controls on reservoir development with the full suite of seismically derived information has provided the key to understand and attempt to commercialize a difficult, marginal accumulation. An ongoing exploration and appraisal strategy for the Musallim Ghudun Reservoir has been developed from this work.

Paul Tricker joined Shell in 1991. After working on the Central North Sea, he was involved in North Sea regional play analysis and UK greenfield evaluation. Subsequently, he evaluated the offshore basins of Ireland. In 1997, he joined Petroleum Development Oman. After two years as Theme Leader for the Shu’aiba Reservoir in Frontier Exploration he moved into the Safiq-Ghudun Theme, exploring for Paleozoic clastic reservoirs. He is currently a Senior Explorer in the Frontier Gas Exploration team.

Paul Senycia see p. 30; Mark Partington see p. 157

Three-Dimensional Modeling of Salt Tectonics and Rock Deformation: Exploration and Production Implications

Kagan Tuncay and Peter Ortoleva
Indiana University, Bloomington, USA.

Salt migration and deformation is strongly coupled with that of neighboring formations, evolution of fluid pressure, sedimentation history, and overall basin subsidence and compression. The resulting feedback requires models based on the simultaneous solution of Reaction-Transport-Mechanical (RTM) equations. The RTM processes used in our model are multiphase flow, non-linear large-strain incremental stress rheology, heat flow, petroleum generation, and diagenesis.

The following results were obtained using three-dimensional simulations with multiple shale and sandstone layers below and above the salt body:

(1) Sediment layers below the salt layer affect the salt migration as much as the layers above it.

(2) Salt movement results in a complex but predictable network of fractures in the surrounding sediments.

(3) These fractures affect the fluid pressure and therefore rheology of surrounding rocks, creating a strong feedback between fracturing, stresses in the surrounding lithologies, and salt migration.

(4) The dynamics of the coupled salt-sediment system is shown to affect petroleum expulsion, migration, and trapping. Our model is thus an important new tool for exploration and production in salt-related petroleum systems.

Kagan Tuncay is a postdoctoral fellow in the Laboratory for Computational Geodynamics at Indiana University. He received his BS and MS from Middle East Technical University in Ankara, Turkey, and was awarded his PhD by Texas A&M in 1995. His current research interests include rock rheology, multiphase flow, fracture mechanics, and non-linear processes in geosciences.

Peter Ortoleva see p. 156
On the basis of outcrop and sub-surface data, a regional sequence stratigraphic model is proposed for the Kharaib and Shu’aiba formations, covering a transect of 650 kilometers in Oman and the United Arab Emirates. The transect connects the outcrops in northern Oman with the adjacent sub-surface, and ranges from the open ocean margin in Oman to the western side of the Bab Basin in Abu Dhabi. The model shows distinct variations in depositional facies and geometrical patterns in relation to the 3rd-order sequence evolution. The relative influence of eustatic sea-level and (local) tectonic control is demonstrated.

The sequence stratigraphic model is based on a revised sedimentological interpretation of the facies. New biostratigraphic and isotope stratigraphic data have provided time constraints, and the regional geometries are controlled by a well-log correlation that includes 30 wells in Oman and Abu Dhabi. Four 3rd-order sequences are defined as the lower Kharaib, upper Kharaib, Hawar/lower Shu’aiba, and upper Shu’aiba sequences. The main conclusions are:

1. The lower and upper Kharaib sequences double in thickness from Oman to Abu Dhabi, probably due to differential subsidence.

2. The lower Shu’aiba sequence shows the development of an intra-shelf basin during overall sea-level rise, with the contemporaneous accumulation of basinal source rocks (minor clays) and backstepping microbial platform deposits. During sea-level highstands, rudists accumulated and progradation occurred.
(3) An important thickness difference of the lower Shu’aiba deposits on both sides of the Bab Basin (the deposits on the western side are 50 meters thicker) is probably due to the combined effects of differential subsidence and active uplift in the Oman region at about the time of the early/late Aptian boundary.

(4) The upper Shu’aiba sequence is entirely restricted to the Bab Basin, and represents a clay-rich infill phase in two main cycles. At that time, the platforms at both sides of the basin were exposed. Nannofossils date this major relative drop in sea-level in the late Aptian, to the boundary of the late Aptian, to the boundary of nannoconid zones 6a and 6b.

Frans van Buchem is a Senior Research Scientist at the Geology and Geochemistry Department of the Institut Français du Pétrole. He has nine years experience in the petroleum industry, of which one was with Elf. His main fields of research are carbonate petroleum systems; including the sedimentology of carbonates and organic matter, sequence stratigraphy, and reservoir characterization. He has been involved in extensive research in the carbonate petroleum provinces of the Middle East, Western Canada, Western USA, and North Africa. Frans has Masters degrees in Biology and Geology from the University of Utrecht (1986), and a PhD in Geology (1990) from Cambridge University.

Bernard Pittet is a Lecturer in Sedimentology at the University of Lyon, France. His specialist field is high-resolution sequence stratigraphy and cyclostratigraphy of carbonate depositional systems. He spent one year with the IFP working on outcrop analogs of the Lower Cretaceous Kharaib and Shu’aiba platforms. Bernard has a PhD degree from the University of Fribourg, Switzerland (1996).

Heiko Hillgürter is Research Scientist at the University of Fribourg, Switzerland. His specialist field is high-resolution sequence stratigraphy and cyclostratigraphy of mixed carbonate/siliciclastic systems. Heiko spent one year with the IFP working on the quantification of Lower Cretaceous reservoir bodies. He has a PhD from the University of Fribourg, Switzerland (1998).

Jürgen Grötsch see p. 97

Abdullah Al-Mansouri is Reservoir Geologist with ADCO. His specialist field is reservoir characterisation studies in Cretaceous carbonate systems.

W. Heiko Oterdoom see p. 113

The Hydrocarbon Potential of the Misfar Formation, South Oman

Ivo Verstralen and Mark Partington
Petroleum Development Oman, Muscat

A new stratigraphic framework has been defined for the Misfar Formation, supported by palynofloral analyses. It impacts on the opening up of new plays in an old basin. The Misfar consists of a clastic sequence of Early to Middle Devonian age (early Eifelian—late Emsian), unconformably bounded by sediments of the underlying Mahatta Humaid Group and the overlying Al Khlate Formation. Ever since the first penetration in 1973 by well Misfar-1, the origin of the Misfar has been poorly understood. The results of a recent study have identified further exploration opportunities along the Eastern Margin and within the South Oman Salt Basin.

The study has proven a much wider distribution of the Misfar than previously assumed, with ambiguous Al Khlate, Mahwis and Amin sections being re-interpreted as Misfar. Stratigraphic correlation between over 21 wells along the Eastern Margin of the South Oman Salt Basin, has resulted in a subdivision into Lower Misfar Sandstone, Middle Misfar Sandstone and Upper Misfar Mudstone members. Laterally extensive marine mudstones identified in the Upper and Lower Misfar and to a lesser extent in the Middle Misfar, are interpreted as representing regional maximum flooding events, and provide reservoir seal pairs. These Devonian sediments are of a marine origin and are characterized by high net to gross, stacked aggradational shoreline-shoreface sandstones (up to 120 meters thick) passing vertically into deeper marine anoxic mudstones with oil-prone, algal amorphous kerogen. The sediments were deposited as a linear clastic shoreline (150 kilometers long and 40 kilometers wide) along the Eastern Flank of the South Oman Salt Basin, parallel to the Huqf High and are preferentially preserved within salt-withdrawal synclines, along the western margin of the Huqf High. The overlying Al Khlate (P9) glacio lacustrine mudstones, typically around 150–300 meters thick, provide the regional top seal, and are also preserved in these salt synclines.

Exploration wells on the Eastern Flank typically targeted Gharif and Al Khlate sandstones and commonly bottom in the first clean sandstone (Mahwis or Amin) below the base of the Al Khlate. Hydrocarbon-bearing Misfar sandstones, with porosities in excess of 20%, sealed by Al Khlate mudstones, were serendipitously discovered in the early 90s by wells Tharish-1 and Thurayah-1. The wells tested 40 cubic meters of 16°API oil (BSW 40%) and 5 cubic meters of 16°API oil (BSW 40%) respectively. Within the new framework, Mahwis and Amin sandstones have been re-evaluated as Misfar clastics, leaving one, or possibly two, reservoir-seal pairs undrilled. In the South Oman Salt Basin, there is potential for marine Misfar mudstones sealing a
variety of subcropping reservoirs, including Ghudun, Mahwis, Amin or Nimr sandstones. Critical exploration risks along the Eastern Flank of the salt basin comprise poor seismic imaging of the pre-Gharif reflectors on old 2-D data and heavy, biodegraded oil. Within the salt basin proper, the main risks are considered to be charge and the validity of structural mapping.

Ivo Verstralen biography not available; Mark Partington see p. 157

Prediction of Thief Zones/Barriers in the Mauddud limestone, North Kuwait from Logs Using Fuzzy-Logic Based Facies Prediction Model

Edwin Vervest, Hussain Al-Ajmi, Raja Mukherjee, and Waleed Al-Awadi, Kuwait Oil Company

Injection and production behavior of wells from two water flood pilots in the Mauddud carbonate reservoir in the Raudhatain and Sabiriyah fields of North Kuwait, demonstrated the detrimental impact that thief zones have on early water breakthrough and reservoir sweep efficiency. Core sedimentological studies indicated that facies control the vertical and areal occurrence of high permeability and barrier/baffle zones in the reservoir. A mathematical model using fuzzy logic was used to predict the carbonate facies after being calibrated to sedimentological facies in cored wells. Various other permeability methods were also used and tested against core data to provide additional control. An optimal perforation strategy was developed for both production and seawater injection wells being drilled to the Mauddud reservoir.

Integration of detailed geological descriptions with well performance data indicates that certain reservoir facies dominate flow behavior significantly. The facies prediction model built on fuzzy logic provides exceptionally good facies prediction from logs, specifically in the identification of thin thief zones and barrier horizons. Fuzzy-logic based facies were used along with permeability predictors from high-resolution resistivity curves and the sonic log Stoneley curve. NMR/CMR permeability where available, also provides improved control over perforation interval selection. A detailed guideline was established to avoid perforation of thief zones and barriers, and at the same time meet well production and injection indices. An improved fuzzy-logic based facies prediction from logs gives excellent control on fluid flow and therefore reservoir management of this carbonate reservoir under water flood. Such heterogeneity is often subtle in carbonates, and can only be resolved by the application of detailed reservoir description techniques. The fuzzy-logic derived facies prediction may minimize the cost of data acquisition by reducing the number of cores. A detailed perforation strategy can delay the early water breakthrough and improve the reservoir sweep, and also minimize well intervention.

Edwin Vervest is a Senior Petrophysicist with BP Amoco. He joined BP Amoco in 1990 as Petroleum Engineer in Aberdeen. He has held various assignments in London, Alaska and Australia before being seconded to Kuwait Oil Company in 1999. He has a MSc in Petroleum Engineering from Delft University of Technology (1988).

Hussain Al-Ajmi and Raja Mukherjee see p. 17-18

Waleed Al-Awadi is a Senior Petrophysicist with Kuwait Oil Company. He started as a Geologist in 1990 and has worked on various field developments in North Kuwait.

The Permian-Triassic Boundary: an Example from the South Pars Field, Iran

Aurélien Virgone and Philippe Lapointe, TOTALFINA, France. Elise Marro, University of Geneva

Gilbert Camoin, CEREGE, Aix-en-Provence, France

Christian Fraisse, TOTALFINA, France

A. Ghaemi, Tehran Energy Consultants and A. Khalili, Pars Oil and Gas Company, Iran

The Permian-Triassic (P/T) Boundary marks a world-wide biotic mass extinction. Unlike the Cretaceous-Tertiary boundary, the P/T boundary is characterized by a gradational change in the fauna and flora and no dramatic variation in sea level. Identification of this boundary from drill core is not straightforward; however, based on recently cored wells from the South Pars field, two sedimentological events are assumed to represent the boundary. One is a breccia-like layer and the other is a thrombolitic horizon. Both are present in different wells and are identifiable from electric logs.

As two sedimentological events are candidates for representing the P/T boundary, it is difficult to put in the golden spike using only macroscopic observations. Consequently, it is a combination of detailed analyses that will provide enough clues for final recognition of the definitive boundary. The two main methods used in identifying the P/T boundary were (1) detailed stratigraphic determinations using the extinction and appearance of foraminiferal groups, and (2) the stable isotopes of carbon and oxygen. A link between rock fabric changes and the evolution of the rocks in the South Pars reservoir is clearly defined. In particular, the thrombolitic horizon is interpreted as a condensed facies during a transgressive and anoxic event. A relationship between the potential anoxia in the Lower Triassic atmosphere and the H₂S concentration of the gas reservoir is proposed.
Aurélien Virgone is a Junior Geologist in the Carbonate Sedimentology Group at the TOTALFINA Technical and Scientific Center. He received his PhD in Carbonate Sedimentology in 1997 from Marseille University. Aurélien joined TOTALFINA in 1998 and works on geological evaluation of the Khuff reservoir for Total South Pars.

Philippe Lapointe is Head of Carbonate Sedimentology Group of TOTALFINA. He joined TOTALFINA in 1981. He has a PhD in Carbonate Sedimentology from Paris Sud University. Most of Philippe’s work has been as a Senior Carbonate Sedimentologist supporting international exploration and development projects. From 1989–1992 he was a Geological Specialist with Abu Dhabi Marine Operating Company.

Elise Marro is an Engineering Sedimentologist at the University of Geneva. Her research in the Swiss Alps led to studies of the sedimentology and microfauna of Upper Permian and Lower Triassic rocks in the north Tethyan area. Elise is participating with TOTALFINA in research projects devoted to the Permian/Triassic boundary in the South Pars field.

Gilbert Camoin is a Joint Director of the European Center for Research and Teaching of Environmental Geosciences, Aix-en-Provence, France. He is a carbonate sedimentologist and stable isotope specialist who has worked on Cretaceous rocks of North Africa and Italy, and Quaternary reefs of the Indian and Pacific oceans.

Christian Fraisse is Geoscience Manager of the Total South Pars team. He joined the TOTALFINA group in 1977. He has a Masters degree in Geology from Paris IV University and a degree in Engineering from École National Supérieure du Petrole (1974).

A. Ghaemi is Managing Director of Tehran Energy Consultants. He holds an Applied Scientist Degree and a MSc in Operations Research (with emphasis on energy systems and and mathematical programing) from George Washington University. From 1980 to 1992 he was Senior Reservoir Engineer for the Iranian Offshore Oil Company.

A. Khalili has been Geoscience and Technical Adviser for Pars Oil and Gas Company since 1995. He graduated in Geology from Tehran University. He joined the Geology and Reservoir Engineering Department of National Iranian Oil Company (NOIC) in 1961 and was in charge of the Geology and Petrophysics departments of the Iranian Offshore Oil Company, NOIC until his retirement in 1995.

Comprehensive Fracture Characterization for EOR Pilot Design and Implementation

Eugene Wadleigh, Jon Snell and Joan Tilden
Marathon Oil Company, Midland, Texas

The successful design and implementation of any improved oil recovery (EOR) project in a fractured reservoir depends on an accurate characterization of the fracture system. This is especially true in a steam pilot project currently underway in a massive carbonate formation at the Yates Field of West Texas. The character of this formation is similar to the Arab-D reservoir of the Middle East. From the conceptual phase of the project through implementation and monitoring, fracture characterization in the pilot area has been critical to pilot design and success. Key decisions have depended on an accurate assessment of fracture density, orientation, flow capacity and connectivity to other portions of the reservoir. Many geologic and engineering methods have been employed to understand the fracture system. Flexure mapping, tracer testing and pressure interference testing and reservoir simulation were employed in the design phase of the project. Fluid sampling, temperature logging and passive microseismic monitoring have been employed in the implementation phase of the project. This presentation will describe each of these methods, field results, and key decisions. Techniques applied in this study, and the resulting degree of fracture-network connectivity can be used to gauge the level of flow heterogeneity in Middle Eastern fields for primary, secondary, or tertiary oil recovery projects.
**Eugene Wadleigh** is an Advanced Senior Reservoir Engineer with Marathon Oil Company. He obtained his BSc in Geology (1973) and BSc in Geological Engineering (1979), both from the South Dakota School of Mines. Eugene's work has been focused on fractured formation oil recovery applications and research (including carbonates, sands, shales, and volcanics). His experience includes Gulf of Mexico unconsolidated sands, California turbidite formations, and mineral exploration.

**Jon Snell** is currently an Advanced Reservoir Engineer at Marathon Oil Company and a member of SPE. He received his BSc in Petroleum Engineering from the University of Texas at Austin in 1986. Prior to joining Marathon, he worked for 10 years for Exxon, USA. His experience includes work on waterfloods, miscible CO₂ floods and steam floods. He is currently working on the Yates field evaluating thermal applications to improve gravity drainage.

**Joan Tilden** works with Marathon Oil Company in the Production Technology Center. She has a BSc in Geology from the University of Waterloo, Canada (1980) and a MSc in Petroleum Engineering from the Colorado School of Mines (1996). Joan works in Reservoir and Well Performance. She specializes in reservoir characterization and simulation. She utilizes Stratamodel, water chemistry analysis techniques and upscaling programs to build fully integrated reservoir simulation models. Joan has worked extensively on West Texas fractured carbonate reservoirs, primarily with the Yates field.

**Flow Characterization: Applying Geologic Tools to Merge Static (Rock) and Dynamic (Flow) Data**

*Eugene Wadleigh*, Marathon Oil Company, Midland, Texas, **John Campanella**, and **James Gilman**, Marathon Oil Company, Littleton, Colorado

Middle Eastern oil fields producing from the Arab-D and other prolific formations would benefit greatly from improved methods of characterizing the heterogeneous formation flow properties (Super K). Production efficiency in highly heterogeneous (channelized or fractured) formations requires unique reservoir characterization methods. Classical reservoir characterization often is performed in sequence: (1) build the static 3-D geologic model; (2) generate the saturation governing inputs (capillary pressure, relative permeability curves and Pressure-Volume-Temperature data); (3) upscale, and (4) modify the upscaled model to ‘history match’ the dynamic performance data. There has been much recent emphasis on upscaling the static model to preserve appropriate heterogeneity within the simulator. However, during the history match, the upscaled static model may be substantially altered. This presentation describes an alternative approach of incorporating both static and dynamic information at the beginning of the reservoir characterization process. This approach decreases both the modifications to the geologic and saturation models and the time required for history matching.

This presentation provides examples from a field producing from a massive carbonate to demonstrate how information on fluid flow compiled by individual well, reservoir performance area, and total field was used to assess the large-scale ‘plumbing’ of the reservoir. Tools developed for 3-D geologic modeling have been employed to distribute the connected secondary-porosity flow features (caves, solution-enhanced fractures, connected vugs, etc.) and barriers. Static geological data from the well scale is honored along with deterministic large-scale flow features identified through production performance. Identified large-scale flow features and barriers were incorporated into field operational planning and simulator construction early in the characterization process. Characterization efforts have lead to improved workover success, avoiding millions of dollars in costs. Simulation and field examples demonstrating the value of simultaneous static and dynamic characterization are provided. This approach merges the geoscience and engineering interpretation.

**Eugene Wadleigh** see this page.

**John Campanella** is a senior reservoir engineer at Marathon Oil Company’s Petroleum Technology Center in Littleton, Colorado. He has held operations and reservoir engineering positions in the Big Horn Basin of Wyoming. John’s technical interest are reservoir characterization and simulation. He has a BSc in Chemical Engineering from Montana State University.

**James Gilman** is a Senior Technical Consultant at Marathon Oil Company’s Petroleum Technology Center, Littleton, Colorado. He has a MSc from Colorado School of Mines in Chemical and Petroleum Refining Engineering and a BSc
production profiles similar to those observed in field phenomena. The simulator has successfully generated simulation studies that deal with three-phase coning coning related phenomena has not been the focus of other This loss of oil mobility through phase connection and in effective fracture connection to the outlying oil column. As the fracture oil column depletes, oil mobility reduces with the decrease in effective fracture connection to the outlying oil column. This loss of oil mobility through phase connection and coning related phenomena has not been the focus of other simulation studies that deal with three-phase coning phenomena. The simulator has successfully generated production profiles similar to those observed in field performance data. This wellbore simulation has been used to determine completion placement for optimal performance. Results can be compared to various Middle Eastern fields to assess the level of fracture influence on well performance.

Eugene Wadleigh see p. 194

Paul Button is a Reservoir Engineer with Marathon Oil Company. Since joining the company in 1998, he has mainly been involved in eclipse simulation of discrete fracture networks with the goal of improving oil recovery and completion efficiency. He has a BS in Petroleum Engineering from the University of Montana (1997). Paul is a member of SPE.

The Kra Al-Maru Joint Technical Study: An Integrated KOC-ExxonMobil Geoscience and Engineering Evaluation

F. Dennis Walton, ExxonMobil and Khalid Al-Sumaiti, Kuwait Oil Company

In October 1995, Kuwait Oil Company (KOC) announced the discovery of light, 49°API oil in the Kra Al-Maru structure, located in the Gotnia Basin of Western Kuwait. The light oil flowed from fractured, overpressured carbonates of the Middle to Upper Jurassic Najmah-Sargelu formation.

In October 1996, KOC and ExxonMobil signed a Joint Technical Study Agreement, whereby the two parties agreed to jointly evaluate the discovery. An integrated geoscience, engineering and drilling team was set up. The joint study team had access to ExxonMobil’s worldwide knowledge and experience base, including extensive coverage of the Middle East, as well as KOC’s detailed knowledge within Kuwait. Regional studies provided the framework for geologic and engineering models calibrated to local information. Analogs were used for model-based predictions, including selection of the preferred appraisal drilling location. Geologic and reservoir engineering data needs provided the basis for the jointly developed drilling and evaluation plans and protocols. The plan that was put in place met the specific evaluation requirements of this uniquely complex reservoir. The well was successfully drilled, completed and tested.

A series of 5 presentations will document several years of joint geologic and engineering efforts. We will work from a regional scale, including discussions of the tectonostratigraphic evolution of the Gotnia Basin and the Jurassic hydrocarbon system of Kuwait, to a field-level dynamic reservoir simulation model of the discovery integrating the KM-2 appraisal well results. The engineering model we will show, incorporates the results of our seismic attribute evaluations as well as our integrated fracture and...
flow model. Performance predictions from the reservoir model were used to forecast field production profiles and to support field development planning.

**F. Dennis Walton** is a Senior Exploration Advisor with the Middle East Venture Development Group, Exxon Exploration in Houston. He has more than 29 years exploration experience, mostly international, with Exxon. Overseas assignments included Singapore, Malaysia, Australia, and Indonesia. His fields of specialization include play assessment and geoscience integration. Dennis has a BS in Geology from Rutgers University (1968) and an MS from Florida State University (1970). He is Technical Team Leader of the Kra Al-Maru Joint Technical Study.

**Khalid Al-Sumaiti** is a General Superintendent Exploration Department of Kuwait Oil Company (KOC). He graduated from Kuwait University in 1978 with BSc in Geology. Khaled joined KOC as a Geologist and held several management positions in the Exploration and Development Group. He also worked with international oil companies (Exxon, Shell, Chevron) in joint exploration and development projects.

---

**Tectonostratigraphic Evolution of the Gotnia Basin, Kuwait**

**Steven Webb, Daniel Cassiani, John Mariano, ExxonMobil**

and **Alaa Al-Ateeqi**, Kuwait Oil Company

The Jurassic age Gotnia Basin of Kuwait is one of the classic prolific hydrocarbon producing intraplatform basins of the Arabian Platform. During Early Jurassic times it began forming in response to several pulses of mild extensional faulting, load-induced isostatic sagging and relative sea-level rise, creating a gentle, low-relief depression with homoclinal ramp-style sedimentation. Its character is suggestive of fairly rigid, uncomplicated, plate response dominated by gentle flexures extending to the basement, but this turns out to be untrue. The Jurassic flexuring is simply a mild (albeit important) overprint atop complexly faulted basement elements extending back at least to Hercynian age and likely following Proterozoic lineaments.

Profound Paleozoic faulting, including a Hercynian age fault with a throw of 4,000 feet, is documented on the Kuwait Arch. Infracambrian halokinesis, possible magmatic intrusion, and major cycles of uplift and erosion add significantly to the complexity. These tectonic features not only dictate Jurassic intraplatform basin controls, but also control hydrocarbon play elements up to the present-day. The complexity and degree of variability provides a caution to using other seemingly simple intraplatformal basins, even within the Arabian Platform, as analogs.

**Steven Webb** is a Geological Associate with Middle East Venture Development group, Exxon Exploration in Houston. He received his BS (1973) and a MS (1975) both in Geology from Texas Tech University in Lubbock, Texas. Since then he has worked as an Exxon geoscientist in over 20 basins in a wide variety of exploration and production projects. His specialization is frontier exploration, sequence stratigraphy, and reservoir quality analysis. Steven has been working in the Middle East since 1994 with attention focused on Kuwait. He is a member of the Kuwait team working the Kra Al-Maru Joint Technical Study in Western Kuwait.

**Daniel Cassiani** see p. 66

**John Mariano** is a Gravity and Magnetics Specialist with the Technology Department of Exxon Exploration Company in Houston. He received a BS in Geology from the University of Chicago in 1985 and a PhD in Geophysics from Purdue University in 1992. From 1985 to 1988, he worked as a Geologist for the Potential Fields Section of the U.S. Geological Survey, and from 1992 to 1994, as a Potential Fields Geophysicist for the Geological Survey of Canada. John has been employed by Exxon for the past five years providing gravity and magnetics consultation on a variety of exploration projects around the world.

**Alaa Al Ateeqi** received his BSc in Geology from Kuwait University in 1993 and joined Kuwait Oil Company in September of the same year. Alaa worked as a Wellsite Geologist for one year before joining the Geophysics Division as a seismic interpreter, where he was initially seconded to Exxon working on exploration assignments. He is currently part of the West Kuwait Fields Seismic Interpretation Team, focusing on the Umm Gudair field.
Basement Structure and Escape Tectonics in the Eastern Arabian Peninsula: Applications to Early Paleozoic Hydrocarbon Prospectivity

Ian Webster
Phillips Petroleum Middle East Exploration, Woking, UK

A model is presented to account for basement structures in the eastern half of the Arabian subcontinent (eastern Saudi Arabia, Oman, Yemen, and the United Arab Emirates). The time period considered is from 750 to 530 million years ago (mid Neo-Proterozoic to Late Cambrian). The model charts the development and suturing of the island-arc suites and micro-continental units of proto-Arabia as they were driven together by the cratonic masses of East and West Gondwana. The Arabian subcontinent is seen as a by-product of the late Neo-Proterozoic shortening processes of the East African Orogeny. The model provides a context for the visible basement lineaments, and their subsequent re-activation in the Infra- to Mid Cambrian. For Oman in particular, this is proposed to have involved escape tectonics and a mixed transpressional-transtensional system that provided a mechanism for the localized development of the Abu Mahara and subsequent Ara basins, and the Angudan Uplift. The model helps to quantify the nature and extent of post-Huqf deformation. It has been used to predict the location and likely stratigraphy of lower Paleozoic basins northwest of the Ghudun-Khasfah High, and consequently to upgrade the hydrocarbon prospectivity of southwestern Oman. Block-specific work from the area is presented in a paper by M.F. Blood, ‘New Lower Paleozoic Exploration Plays in Southwest Oman’ (this issue, GeoArabia, v. 5, no. 1).

Ian Webster has worked as an Explorationist for 18 years, initially with Western Geophysical, and later with Agip and Phillips Petroleum. He has a BSc from Nottingham University, UK. Ian’s experience in exploration and development is from the Tethyan margins of Europe and the Middle East, and from the North Sea and Africa.

Exploration Using High-Resolution Aeromagnetic and Gravity Data

Susanne Witte
Shell, The Netherlands

Integrated interpretation results of high-resolution aeromagnetic and gravity surveys were acquired by Petroleum Development Oman in 1997 and various Shell Operating Units in 1998. As improvements on classical prospecting techniques, these surveys are cost-effective partial solutions to tough exploration problems.

In South and Central Oman, many hydrocarbon traps are related to the movement of thick mobile salt, salt withdrawal, and Infracambrian salt dissolution, overlain by clastic sediments. The very poor seismic data due to the presence of shallow carbonates, has made the task of mapping the Palaeozoic intervals difficult, if not impossible. However, thanks to the accuracy and resolution of aeromagnetic data, which has been significantly improved by ultra-high-sensitivity magnetometers and the Global Positioning System, some of the intra-sedimentary intervals can now be delineated.

Because of the low acoustic-impedance contrast, mapping of salt structures and prospects below salt remain unresolved seismic-processing challenges. In many areas in the Central North Sea and West Africa, high-resolution gravity data has been used to determine the depth and extent of salt structures. The combination of gravity interpretation and pre-stack depth migration has improved the velocity analysis of structures below, or at the flanks of such salt structures, which has an immediate impact on the economic prospect evaluation.

High-resolution data acquisition, careful processing and tight integration of all the available geological and geophysical information provides an improved knowledge of the subsurface that extends beyond the available seismic data coverage. High-resolution aeromagnetic and gravity data have the potential to improve shallow-fault mapping; aid the determination of the depth and thickness of sedimentary formations; map salt thickness variation and associated structures; determine porosity variation within prospective sediments; and highlight the extension of Mesozoic carbonate basins, which are associated with major hydrocarbon fields along the eastern flank of the South Oman Salt Basin.

To derive maximum benefit from such data, better interpretation and inversion capabilities are being developed by the Research and Technical Services division of Shell Technology Exploration and Production so as to improve the knowledge of rock density and magnetic susceptibilities.

Susanne Witte joined the Royal Dutch Shell Exploration and Production group in 1983. She was responsible for the development and implementation of gravity and magnetic data-interpretation software and database applications. From 1989, she was assigned to various hydrocarbon exploration projects worldwide, including Shell New Ventures, UK, Albania, Australia, Gabon, BEB, NAM.
High-resolution seismic sequence stratigraphic analysis was performed as part of a well-tie project of the Zaafarana (formerly Warda) field in the North Zaafarana Concession, Gulf of Suez. The analysis integrated the high-resolution biostratigraphy with well-log signatures and seismic reflection profiles. It improved the time correlations and permitted British Gas to better develop the field rather than relinquish the concession. We utilized a new interpretation of proprietary biostratigraphic data and subdivided the stratigraphic section into third-order depositional sequences, lowstand, transgressive, and highstand systems tracts, and loop-tied these chronostratigraphic intervals in all seven wells within the study area. Through this new technology, we supplemented well-log lithologic correlations of British Gas with a chronostratigraphic framework, thereby establishing more realistic time correlations in the reservoir intervals. This application of seismic sequence stratigraphic analysis proved to be an effective methodology in re-evaluating the stratigraphic framework of the Zaafarana field and the larger concession area. Subsequently, British Gas determined that the reservoir was of sufficient size to justify development. Strategic to these results were the identification of the following Sequence Boundaries: top of the Zeit Formation is at 6.3 million years (Ma); Belayim Formation at 12.5 Ma; Kareem Formation at 13.8 Ma; and the Rudeis Formation at 5.5 Ma. This was one of the first projects to demonstrate the significance of seismic sequence stratigraphic analysis as an effective risk-reduction technology in the search for hydrocarbons. The same technology has been used effectively in the Darag Block of the Gulf of Suez, in the Nile Delta, Albania, Bulgaria, the North Sea, Norway, and the Gulf of Mexico.

Walter Wornardt has a BS (1956) and MS (1958) from the University of Wisconsin, Madison, and a PhD (1958) from the University of California, Berkeley. From 1965 to 1967, he was a Research Geologist with Esso Production Research Co. in Houston. He then joined Union Oil Research of California as a Senior Research Geologist (1967–77). He was an Adjunct Professor at Rice University, Houston from 1988 to 1990. In 1983, Walter became President and Chief Geologist of MICRO-STRAT INC. which specializes in well-log seismic sequence stratigraphy. He is a California registered geologist and a member of AAPG, SEPM, and the Geological Society of London.

Jan Vargo is West Africa Manager for Burlington Resources International Inc. He has a BS from the University of Illinois (1968) and a MS in Geological Sciences from the University of Southern California (1971). Before joining Burlington Resources, he was employed by Tenneco Oil, Unocal, and Texaco in various technical and managerial capacities. He is a member of AAPG.

Source-Rock Evaluation and Geochemical Measurement of Thermal Maturity in Upper Triassic and Lower Jurassic Sediments, Central Alborz, Iran

Ziba Zamani, University of Tehran
Mohammad Kamali, Research Institute, National Iranian Oil Company, Tehran
and Hossein Rahimpour, University of Tehran

The Upper Triassic to Lower Jurassic Shemshak Formation in the Galandroud area consists of coal-bearing shales interbedded with sandstone. Geochemical investigations including RockEval pyrolysis and organic petrography indicate that these organic-rich beds are thermally mature (Tmax = 435°–450°C) and have generated commercial quantities of both liquid hydrocarbons and wet gas. Extracted kerogen studied under transmitted-light microscopy indicates that the organic matter is chiefly amorphous, herbaceous, woody, and coaly in nature. The extracted kerogen was also examined under reflected and ultraviolet light in order to identify different maceral groups and determine thermal maturity. Petrographic study suggests that the organic matter is mainly composed of vitrinite but that inertinite and liptinite occur as subordinate group of macerals. The measured vitrinite reflectance (Ro) ranges from 0.6 to 0.8% suggesting that the Shemshak Formation has already reached the oil generation window.

However, liptinite is abundant in samples with high hydrogen index values. The liptinite group of macerals in order of abundance are sporinite, cutinite, resinite, fluorinite, and alginitite. These macerals exhibit yellow to orange fluorescence under ultraviolet excitation. Thermal maturity data obtained from the thermal alteration index, Tmax, and Ro are consistent and reflect the onset of oil generation. In addition, petrographic microscopy, scanning electron microscopy, and X-ray diffraction analysis performed on interbedded sandstone layers indicate that the Shemshak...
Formation was deposited in a river-dominated delta. The diagenetic sequence is reflected by processes such as neomorphism, cementation, silicification, calcitization, and dolomitization.

**Ziba Zamani** received her BSc in Geology from Isfahan University (1987) and a MSc (1999) in Petroleum Geology from the University of Tehran. She has presented and published papers in the field of organic petrography. Her research interests are in petroleum geochemistry and sedimentology. Ziba is a member of the Geological Society of Iran.

**Mohammad Kamali** see p. 120

**Hossein Rahimpour** received his BSc and MSc (1990) from the University of Tehran, and a PhD (1997) in Geology from the University of Adelaide, Australia. He joined the University of Tehran in 1997 and is an Associate Professor in the Department of Geology. He has published several papers in international journals and continues his research on stable isotope geochemistry.

**Recent Advances in Multi-Component Processing**

**Xianhuai Zhu, Suat Altan** and **Jianchao Li**

PGS, Houston

3-D multi-component processing has evolved together with collection methods to offer additional information about reservoirs. Processing techniques now exist to generate a time or depth image of compressional (P) to shear (S) converted waves (or C-waves) using ocean-bottom sensors. These images can be used to enhance reservoir characterization, especially with shallow gas clouds that may inhibit P-wave propagation.

Three field-data examples are used to demonstrate the advanced C-wave processing technology. The first example shows C-wave prestack depth migration of North Sea salt domes, in which the data was collected using a ‘dragged array’ system. The second example illustrates the 3-D imaging capability of C-waves over the Valhall field in North Sea, where the data was acquired using a ‘dragged-draped-cable’ system. The third example shows one of the critical processing issues with orienting ocean-bottom multi-component receivers, using a 3-D C-wave data set collected with a ‘draped-cable’ system, in Matagorda Island in Gulf of Mexico. The key challenge in processing this combination of data sets is in deriving the velocity field consistent with the complex rock property variations affecting propagation of the wavefield through the subsurface. In areas where P-wave velocity is difficult to estimate, such as gas clouds in the Valhall field, we derived a direct measurement of the C-wave velocity through the prestack time imaging technique. This improves the C-wave images significantly.

Binning the C-wave data to a proper Dip Moveout-consistent common-conversion-point was relatively straightforward but there remain opportunities for further refinement. Correlation between P-wave and C-wave images in the time or depth domain is critical, and well log information is still necessary to correct for the possible miss ties. With rich (source-receiver) azimuth sampling, the P-wave and C-wave properties, which are a function of azimuthal and polar anisotropy, need to be exploited. This new information will need to be utilized before we can fully benefit from the vector interpretation techniques.

**Xianhuai Zhu** is currently Head of Converted Wave Imaging at PGS. He worked for the Research Institute of Geophysical Prospecting for Petroleum in China from 1977 to 1985 and Union Pacific Resources in the USA from 1991 to 1997. He received a PhD (1990) in Geoscience from the University of Texas at Dallas. Xianhuai joined PGS as R&D Manager of Reservoir Imaging Group in 1997. He was a Visiting Scientist with the COCORP project at Cornell University in 1985-86. He is a member of SEG and EAGE.

**Suat Altan** joined the PGS Reservoir Imaging Group as a Senior Geophysicist in 1996. He previously worked for Turkish Petroleum, Geosource, Halliburton Geophysical Service, and Western Geophysical Company. He has a BSc in Geophysics (1997) and Geophysical Engineering (1980) from the University of Istanbul.

**Jianchao Li** received his BSc (1982) and MSc (1985), both in Geophysics, from Changchun College of Geology, China. From 1985 to 1991, he was an Associate Professor of Geophysics and a Deputy Dean of the Department of Geophysics at China University of Geosciences in Beijing. During 1991–1992, he was a Visiting Associate Professor at the Center for Wave Phenomena, CSM. He worked for Lauren Geophysical, 1992–97 and CogniSeis Development in 1997. He joined PGS as a Principal Geophysicist in 1997. Jianchao received the Golden Hammer Medal of the Chinese Society of Geologists in 1989 for his contribution to teaching and research. He has authored and co-authored two books on seismic data migration. He is a member of SEG and EAGE.