ABBREVIATIONS

The names of Companies and Institutions to which authors and co-authors are affiliated, and the Professional Societies of which they are members, have been abbreviated. For convenience, all subsidiaries companies are listed as the parent company. The following is the list of abbreviations used in this issue of GeoArabia*:*

AAPG	American Association of Petroleum Geologists
AASP	American Association of Sedimentary Petrologists
ADCO	Abu Dhabi Company for Onshore Oil Operations
ADMA-OPCO	Abu Dhabi Marine Operating Company
ADNOC	Abu Dhabi National Oil Company
AGU	American Geophysical Union
APEGGA	Alberta Professional Engineers, Geologists and Geophysicists Association
ASEG	Australian Society of Exploration Geophysicists
BGS	British Geological Society
BMS	British Micropalaeontological Society
BRGM	Bureau de Recherches Géologiques et Minières
CASP	Cambridge Arctic Shelf Programme [Cambridge U.]
CGG	Companie Générale de Géophysique
CIMP	Commission Internationale de Microflore du Paléozoïque
CRC	Carbonate Research Center [Sultan Qaboos University, Muscat]
CSEG	Canadian Society of Exploration Geophysicists
DEG	Division of Environmental Geologists [AAPG]
DPC	Dubai Petroleum Company
EAGE	European Association of Geoscientists and Engineers
EPEX	Egyptian Petroleum Exploration Society
ETAP	Enterprise Tunisienne d'Activitiès Pétrolières
ETH	Eidgenössische Technische Hochschule [Zurich]
GNPOC	Greater Nile Petroleum Operating Co. Ltd.
GSA	Geological Society of America
GSI	Geological Survey of Iran
GSO	Geological Society of Oman
GUPCO	Gulf of Suez Petroleum Company
GX	GX Technology
IES	Integrated Exploration Systems
IFP	Institut Français du Pétrole
JNOC	Japan National Oil Company
JODCO	Japan Oil Development Company
KACST	King Abdulaziz City for Science and Technology [Riyadh]
KFUPM	King Fahd University of Petroleum and Minerals [Dhahran]
KISR	Kuwait Institute for Scientific Research
KOC	Kuwait Oil Company
MIT	Massachusetts Institute of Technology
MOG	Ministry of Oil and Gas [Oman]
NIOC	National Iranian Oil Company
NOC	National Oil Corporation [Libya]
OMV	Östereichische Mineraloel Vereinigung
OPI	Ontario Petroleum Institute
PDO	Petroleum Development Oman
PEPA	Petroleum Exploration and Production Authority [Yemen]
PESGB	Petroleum Exploration Society of Great Britain
Petrobel	Belayim Petroleum Co [Egypt]
PGS	Petroleum Geo-Services
RHC	Royal Holloway College [London University]
RRI	Robertson Research International
SEG	Society of Exploration Geophysicists
SEPM	Society of Economic Paleontologists and Mineralogists
SGS	Saudi Geological Survey
SPE	Society of Petroleum Engineers
U.	University
USGS	US Geological Survey
WTGS	West Texas Geological Society
ZADCO	Zakum Development Company

(#44-P) Improved tarmat visualization results in improved peripheral water-injection performance, Minagish field, Kuwait

Mohammad A. Abadah
and Hamad N. Al-Ajmi, **KOC**

The Minagish Oolite is a multi-billion-barrel carbonate reservoir located in West Kuwait. The reservoir was discovered in 1959. It has experienced rapid pressure depletion due to the presence of an extensive tarmat that significantly limited pressure support from the aquifer. In 1967, a gas-injection pressure-maintenance project was begun that successfully increased reservoir pressure. During the Gulf War, the gas-injection facilities were extensively damaged. Following the war, a field-redevelopment project was developed to increase oil production from the Minagish Oolite. To replace the loss of the gas-injection facilities, a peripheral water-injection plan was developed that would replace reservoir voidage while sweeping oil from the flanks to the crest.

The main challenge in implementing the peripheral water-injection project has been the location of injection wells. The optimum location for each well should be downdip to minimize trapped oil but must be far enough updip to have sufficient horizontal reservoir permeability above the tarmat to allow high injectivity.

Only limited information on the tarmat was available before 1998. Since then, an extensive data collection and interpretation program has been incorporated into the drilling programs of the mid-flank producers. Our presentation illustrates how a multidisciplinary team interpreted the newly acquired data and integrated geology, geochemistry, 3-D seismic, reservoir surveillance, and reservoir simulation into a visualization process for predicting the location of the tarmat and the optimum locations of the injection wells.

The poster will explain the work of the project team. It will highlight reservoir characterization using the Modified Lorenz method of tarmat identification from the following parameters: Spontaneous Potential log response; Iatrascan studies of core; acoustic impedance; Repeat Formation Tests; aquifer influx from reservoir simulation; overlay map of target layer and top of tarmat used in selecting well locations; and results from initial peripheral injection wells.

(#310-O) 3-D Basin modeling of the Abu Dhabi carbonate platform: a possible scenario for hydrocarbon charge history

Azhari A. Abdalla, **ADCO;** Joseph T. Westrich, **Shell;** Bjorn P. Wygrala, Christof Keuser and Michael Hertle, **IES**

Integrated geological and geochemical data were used to successfully construct the first 3-D petroleum systems model for the whole of Abu Dhabi. The model encompasses 32 layers selected to simulate the Mesozoic petroleum systems of the onshore and offshore Abu Dhabi carbonate platform. Evidence from geochemical analyses indicates that contributions from the lower Paleozoic petroleum system were negligible. The model reveals a complex hydrocarbon charge history for Abu Dhabi fields. A Tertiary northeast regional tilt triggered a reversed migration course that added to the complexity of the possible charge scenarios. This tilting followed the period of maximum hydrocarbon generation, thus giving it a major impact in shaping the current hydrocarbon distribution. Preliminary computations of restored richness values (total organic carbon) for the source rocks indicate that the Upper Jurassic hydrocarbon sources account for the bulk of the generated oil and gas in the area. Contributions from source intervals in the Lower and mid Cretaceous seem to be comparatively less significant. Depositional facies variations within three prolific reservoirs were taken into consideration in order to understand the possible impact on the observed distribution of hydrocarbons. Major wrench-fault trends were simulated as open or closed during critical geological times and the results were compared with actual field observations. The simulation was performed using a 'hybrid petroleum systems simulator' that allowed various petroleum migration methods, such as Darcy and Flowpath modeling, to be used within the same geologic model during the one simulation run.

(#109-O) Organic geochemical characterization of carbonate reservoirs and source rocks in the Upper Cretaceous Mauddud Formation of Kuwait

Fowzia H.A. Abdullah, **Kuwait U.;** Bernard Carpentier, Isabelle Kowalewski, Frans S. van Buchem and Alain-Yves Huc, **IFP**

The Upper Cretaceous Mauddud Formation is one of the major hydrocarbon-bearing stratigraphic intervals

in Kuwait. It consists of calcarenitic limestone interbedded with marl and glauconitic sands, and varies in thickness from almost zero in the south to about 99 m in the north. Organic geochemical analyses allowed us to distinguish source rocks, reservoir units, and non-productive zones in the Formation.

A total of 99 core samples were collected from six oil fields in Kuwait; they were the Raudhatain, Sabiriyah, and Bahra fields in the north, and the Burgan, Ahmadi, and Magwa fields in the south. Well logs from the oil fields were correlated. Analyses such as Rock-Eval 6 pyrolysis (reservoir mode), rock extraction (bulk composition, gas chromatography, gas chromatography mass spectrometry), and kerogen characterization (^{13}C elemental analyses), were performed on selected samples.

The results showed similarities in the nature and amount of organic matter in the southern and northern oil fields, with the composition controlled by lithology, porosity, and residual oil saturation. In carbonate reservoirs with high oil saturation, Total Organic Carbon (TOC) is about 2.5 weight percent, with highest values (up to 8.0 wt %) in the northern Sabiriyah field. In non-oil bearing reservoirs, TOC values are very low at about 0.07 weight percent. Insoluble organic material (kerogen) varies between type II-III and III with a low hydrogen index. Differences exist in the amount and composition of the $^{14}C+$ rock extracts that might be related to a mixture between migrated oil and in situ kerogen generation. In the oil-bearing reservoirs, no important variations in the composition of the organic material were detected, suggesting an absence of reservoir bitumen and the presence of an homogeneous fluid at the field scale.

(#138-P) Lithofacies and geometry of the Cretaceous fluvial/lacustrine sandstone of northern Sudan: outcrop analog for the Muglad rift basin reservoirs

Osman M. Abdullatif, **KFUPM**

In the Sudan, more than 25 structures have been recognized by geological and geophysical techniques as being rift-related basins that are regionally linked to the Central African Rift System. Several oil fields have been discovered within these basins and successful exploratory work is progressing in other sub-basinal areas. Complex tectonism and variable climatic conditions, in addition to other intrabasinal controls, appear to have played a major role in the vertical and lateral stacking patterns, geometry, and distribution of the fluvial and lacustrine facies in the various sub-basins.

A comprehensive geological study of outcrop facies and basinal architecture, together with petrograhic and mineralogical analyses, were carried out to define and characterize the Cretaceous sandstone reservoirs and their heterogeneity. Alluvial, braided and meandering streams, and lacustrine depositional environments were recognized; subenvironments included channel bases, abandoned channels, major and minor channel-fill and bar sequences, crevasse channels, and proximal and distal floodplains. Sandstone composition and type varied from arenite to arkosic arenite and lithic arenite, and appeared to have been controlled by factors such as the origin of the detrital sources, weathering, and the environmental and depositional history.

Reservoir heterogeneity was recognized at different scales from macro to micro. Sandstone connectivity, porosity, and permeability values varied from poor to good. They appeared to have been greatly influenced and controlled by facies architecture, microfabrics, silica cementation, clay infiltration, and selectively silicified fault surfaces. The assessment of the sandstone outcrop analog architecture and heterogeneity was critical to the understanding and prediction of the Muglad rift basin reservoirs and their development strategy.

(#239-P) Calibrating borehole images to core data using visible sedimentary structures in the image log of the Shu'aiba reservoir, Shaybah field, Saudi Arabia

Abdul-Jaleel A. Abu Bshait, G. Wyn Hughes and Dave L. Cantrell, **Saudi Aramco**

Borehole image logs have been used to characterize facies of the Shu'aiba reservoir of the Shaybah field by calibrating core-description data. The reservoir consists of highly heterogeneous Cretaceous carbonate rocks from which five main reservoir facies can be defined from core descriptions. Static and dynamic image logs were used to investigate our ability to recognize these reservoir facies in image logs. The facies can be traced to the images by using such features as texture aberrance, bioturbation, nature of bedding, biostratigraphy, and nodularity, that are visible in the image logs. Wireline logs were also included in the study. Shallowing-upward cycles were found to be one of the major geological parameters that are easily recognized in the borehole images. The objective was to define facies of similar geological character.

In order to evaluate the validity of the features visible in image logs and to further improve the use of image-log data, an integration of core data with image logs

was essential. Image logs from three wells in the Shaybah field have been included in the study, and the plan is to extend the recognized facies to horizontal wells and to uncored wells. Calibrating image logs to core would optimize the benefits of the logs and help reservoir characterization by extrapolating the interpretation into uncored wells. It would provide key data for reservoir development. Other potential benefits might include reducing the amount of core required to adequately characterize facies distribution and reservoir variation across the field.

(#297-O) 3-D petroleum systems modeling of the Paleozoic rocks of the Ghawar field and adjacent areas, Saudi Arabia

Mahdi A. Abu-Ali, **Saudi Aramco**; Christof Keuser, Bjorn P. Wygrala and Dietrich H. Welte, **IES**

Three-dimensional (3-D) Petroleum Systems Modeling (PSM) has recently become an integral part of modern exploration / production assessment workflows. This new technology equally considers all petroleum system elements; such as, source, reservoir, seal, trap, migration, and timing of all key processes. Whereas conventional basin modeling is mainly concerned with hydrocarbon generation within the source rock, the goal of 3-D PSM is to describe and model petroleum migration, dynamically and through geologic time, from source to trap. A 3-D model was constructed for the Ghawar area that described thermal and maturation histories of the Paleozoic geologic sequences. This model emphasized modeling hydrocarbon generation and migration histories from the Silurian Base Qusaiba source rock to the Devonian Jauf and Carboniferous-Permian Unayzah reservoirs.

Results suggest conclusively that the paleodrainage area must have been larger (with respect to the present-day drainage area of the Ghawar structure) because of the Tertiary tilting of the basin. To analyze the migration scenarios, a unique 3-D hybrid Darcy / Flowpath simulator was used, and took into account open and / or closed fault systems. For sensitivity testing, simulation results were compared with known present-day petroleum accumulations to test for different possible geological scenarios within the study area. A novel compositional generation scheme was used to model the hydrocarbon migration of the various compound classes. The results demonstrated that when 3-D PSM technology is combined with compositional modeling, it provides an excellent tool to predict quantity, quality, and distribution of petroleum occurrences within a basin. The application of such technology will open up a new era in petroleum exploration and field development.

(#47-O) Using oxygen activation from pulsed neutron logs to detect water flow and tubular problems inside the wellbore

Ahmad S. Addas and Mariam A. Al-Saeed, **KOC**

This presentation details the experiences of the Kuwait Oil Company in using the technique of oxygen activation from pulsed neutron logs to detect the upward flow of water inside the well bore and / or problems such as casing, tubing, or plug leaks. The technique depends on high- energy (14 MeV) neutrons to make the oxygen atoms within the water of the produced fluid radioactive. The detectors of the logging tool note the effect of the activation when the produced fluid moves upward and passes one of them. The operation may be done with stationary detectors or by running the log at a speed that is slower than the produced fluid.

The presentation will show several case studies where using this technique has generated cost savings by solving problems that otherwise would require separate production logs. In one example, we will identify cross-flow from a deep watered-out formation into a shallower oil-bearing formation to emphasize the advantage this method has in eliminating loss of oil during the production life of the reservoir. Identification of tubing / casing / plug / sliding side door leaks will be illustrated with examples from several wells.

(#293-O) Geophone density analysis

Wim J. Adolfs, **Saudi Aramco**; Julien J. Meunier, **CGG**

This presentation describes an experiment specifically designed to ascertain the optimal geophone density for a seismic survey. Seismic receiver arrays are used to attenuate both shot-generated and non-organized noise. Reduction of the latter is often described by the square root theory, which predicts attenuation proportional to the square root of the number of receivers. This theory assumes that noise is random. This assumption is valid when the distance between receivers is sufficiently large. However, if this distance is small, actual attenuation may be less than predicted. The need for improved seismic imaging has led to increased channel counts, which, in turn, have called for the deployment and maintenance of as many as 420,000 geophones by a single seismic crew. Clearly, if costs are to be controlled it is essential to determine the optimal geophone density.

A dense shot-point grid enabled the simulation of unaliased 3-D receivers for a true 3-D noise analysis. Extra seismic channels assigned to various receiver configurations were connected to the recording system as an auxiliary line. Test data could thus be acquired along with production data for only a marginal cost increase. It took between 8 and 10 days to record the 15,000 shot points necessary to make one complete test. The chosen combination of test and production channels allowed the comparison of six receiver densities and four array sizes. The tests were repeated six times at various locations over the survey. Despite a wide range of signal and noise conditions, they all pointed to the same optimal geophone density.

(#171-O) Viscoelastic modeling, 3-D dip moveout bin simulation, multiscenario 3-D ocean bottom design analysis, and 2-D/3-D ocean bottom test feasibility for an offshore carbonate field in Abu Dhabi

Ghiath Ajlani, Atef A. Ebed, Omar A. Suwaina, Musabah H. Al-Kabbi and Ali K. Al-Shamsi, **ADNOC**; Mike Hall, **GX**

An Ocean Bottom (OB) 3-D seismic survey was proposed for a large carbonate oil and gas field in offshore Abu Dhabi. The only seismic coverage was a few 2-D lines on the western flank that had high background noise levels which, it was thought, would get worse with OB cable seismic. In addition, hundreds of man-made surface and subsurface obstructions are present over the producing field. What impact would these obstacles pose to collecting seismic data of sufficient quality, and could a particular survey design be employed to minimize the effects of these obstacles? A multidisciplinary feasibility study was made in order address these reservoir management questions.

The presentation will focus on visco-elastic modeling, 2-D–2C OB acquisition tests, 3-D multiscenario design, and 3-D dip moveout and synthetic volume simulation segments, and the results of the subsequent 3-D OB test. All available seismic, well logs, geologic and reservoir (measured and simulated) data were used in the feasibility study. Its aim was to determine if a high-resolution 3-D OB seismic survey would contribute significantly to the following parameters: (1) Reservoir issues: (a) detect faults with more than 15 to 20 ft of throw; (b) identify the density and direction of fracture zones; (c) identify the distribution of stylolitic zones; and (d) identify the porosity distribution within reservoirs more than 20 ft thick. (2) Seismic issues: (a) estimate the nature and strength of source generated noise in the geophone and hydrophone data; (b) investigate the impact of P-wave to S-wave mode conversion; and (c) determine an optimum 3-D OB survey design to accomplish the above requirements. The integration of all measured and simulated data was an essential requirement. Appropriate well-log data were selected for the modeling segment, and data from the acquisition tests were used to optimize the 3-D OB survey design.

The feasibility study indicated that it was possible to image the target horizon. As a result, the OB 3-D high-resolution seismic survey is underway over the offshore producing field to better image its reservoir characteristics. The feasibility study provided valuable optimization parameters in survey design to fulfill the demanding reservoir characterization requirements. The high technical specifications were justified as a means of addressing geologic issues of fracture and porosity distributions that would provide accurate data for future 3-D time-lapse seismic studies.

(#227-O) Nahr Umr Carbonate Marker: a recent oil discovery in Abu Dhabi

Karim T. Akrawi and Steef J. Linthorst, **ADCO**

Well Q-8 was drilled as an appraisal well for the Lower Cretaceous reservoir zones in the center of the Q-field of southeastern Abu Dhabi. It was the first well to discover oil (26° API) in the regional Carbonate Marker of the Nahr Umr Formation. This was after 50 years of oil exploration in Abu Dhabi and the drilling of more than 1,600 wells. It follows that oil may be present in the same Formation in surrounding fields. Our presentation highlights this recent new oil discovery and the potential of the Carbonate Marker.

The Albian Nahr Umr Shale is the major effective seal for the Lower Cretaceous carbonate reservoirs in Abu Dhabi and nearby areas, the ductility of the shale having reduced the effects of faulting. The shale was deposited in a fairly deep basin and the thickness ranges from 200 to 800 ft. In general, the Formation is composed of subfissile gray shale with a thin regional porous carbonate marker in most Abu Dhabi fields, but in east Abu Dhabi and Oman it is a mixed shale / carbonate. The Carbonate Marker reservoir is 17 ft thick in the Nahr Umr Formation of the Q-field and increases in thickness toward the east. It consists of a porous packstone / wackestone with an average porosity of 20 percent. As most well logging started below the base of the Nahr Umr Shale to cover the Lower Cretaceous carbonate reservoir zones, the Nahr Umr Carbonate Marker has not been properly evaluated in the area.

(#153-O) Application of a Geographic Information System in fracture prediction for carbonate reservoirs in Kuwait

Mohammed D. Al-Ajmi, **KOC**

The aim of the study was to develop a process for analyzing and integrating fractured reservoir datasets in order to make predictive estimates of fracture density, and to develop it in sufficient detail to allow others to apply the techniques. Geographic Information System (GIS) software applications store, analyze, and display multiple layers of geographic information. GIS is made up from several interrelated and linked components with different functions. GIS have functional capabilities for data capture, input, manipulation, transformation, visualization, spatial query, combination, modeling, and output.

Fractures are the key component for hydrocarbon flow in low-porosity carbonate reservoirs, and fracture prediction is therefore a very important process. Rock deformation, such as folding and faulting, are the main causes of fracturing in carbonates. This presentation will explain the process for the prediction of the spatial distribution of fractured reservoirs using GIS tools. The model of the fracture prediction process was built by assigning the fault system to a fault classification and integrating with the structure map anyalysis (slope, curvature, etc). The technique has been used for predicting fracture-prone areas in low-matrix porosity carbonate reservoirs.

(#282-P) Microstructure governs calculated saturation

Talib A. Al-Ajmi, **PDO**

Electrical resistivity measurements on sandstone reservoirs from several wells in Oman indicated uncommonly low saturation of less than 50 percent. Despite the calculated low oil saturation, some of the completed wells produced dry oil at a low production rate of less than 10 cu m / day, whereas others produced dry oil at very reasonable production rates of more than 200 cu m / day. Sedimentological, petrographical, and mineralogical analyses of Amin-10 vertical and Irad-12 horizontal cores have explained this unusual behavior. Authigenic grain-coating smectite acts as a conductive path through the rocks, so lowering the resistivity. In addition, a combination of water bound in small pore throats caused by fine sand grains and the water contained in microporous authigenic clays, leads to high-calculated water saturation. Reservoirs that contain authigenic smectite are dominated by low productivity where smectite narrows the pore space between individual grains and reduces the matrix permeability. In the case of reservoirs with low oil saturation producing at unexpectedly high rates, this could be related to the existence of microporous authigenic clays that acts as a conductive medium within the rock matrix. Such microstructures have an enormous impact on the interpretation of the petrophysical data. Reservoir intervals that show low oil saturation have been calibrated to include the effect of these microstructures. Completion intervals in new wells have been designed to cover the reservoir section that includes zones with low oil saturation.

(#289-O) Conventional and sparse 3-D: what is in between?

Mustafa N. Al-Ali, Richard Hastings-James and Riyadh S. Al-Saad, **Saudi Aramco**

A major factor when exploring for deep, subtle structural traps in areas characterized by long- and medium-wavelength statics is shallow chrono-stratigraphic markers used for flattening or isochroning during interpretation. Failure to image these markers is inherent in sparse 3-D survey designs aimed at imaging deep targets. Furthermore, the relatively low fold of sparse 3-D data, especially at shallower horizons, makes initial processing steps—like velocity analysis and statics correction—difficult. Saudi Aramco has developed a composite sparse 3-D acquisition designed for these conditions by introducing additional source points along the receiver lines. Although the additional points increased the source density by about 30 percent, coverage rates dropped by only 15 percent compared to those achieved in a previous survey without extra source points. An example of a 2,600 sq km, full-fold survey will illustrate the advantages of the design that consists of two main components, orthogonal and parallel. The orthogonal part uses a cross-spread acquisition technique with full swath roll in the source-line direction, whereas the other has parallel source and receiver lines with source lines adjacent to the receiver lines occupied on one side only. Both use the same receiver spread but have separate source locations except at the intersection points.

The design produces evenly spaced high-fold 2-D lines near each receiver line in the active patch, with a complete offset range. These form a contiguous volume with rectangular bins where the longer side of the bin is determined by the receiver line separation. This should be adequate to map shallow horizons in

areas with relatively low geologic complexity. Because all the receiver lines are active when acquiring the parallel geometry component, some of the sampled common mid-point lines are well attended not only by inline fold components but also by cross-lines. This makes them very useful for velocity analysis. In addition, refraction statics can be computed with good multiplicity along each receiver line to build datum statics for the entire survey area.

(#86-O) Salt structures in the South Oman Salt Basin

Badar Al-Barwani, Ken McClay
and Chris Elders, **RHC**

The late-Proterozoic South Oman Salt Basin (SOSB) is oriented northeast. It is bounded to the east by the coastal Tertiary basin, to the west by the Ghudun-Khasfah high, and to the north by the Oman Central high. The SOSB is a half-graben thickening westward, with a southwesterly basement dip overlain by the Ara salt. Several salt diapirs and salt walls form minibasins and salt pods. Various models have been proposed for the evolution of the SOSB ranging from a half-graben basin and an oblique foreland basin, to a transpressional basin. None of these models focused on the evolution of the salt structures in the area.

The aim of this study was to determine the 3-D geometries of salt structures in the SOSB and its tectonic evolution in response to variable 3-D sedimentation patterns. The research involved detailed interpretation of 2-D regional lines, a 3-D seismic volume of the Ghafeer blocks, and analog modeling of salt tectonics. The 2-D regional lines show a clear relationship between the location of salt diapirs and basement faults.

In the 3-D seismic, the Ghafeer block consists of six sediment withdrawal zones, encircled by salt ridges. Most of these salt-withdrawal zones are oriented northeasterly perpendicular to the basement dip. The interpretation shows a shift in depocenter within the postsalt sequence corresponding to periods of salt withdrawal. The change in depocenter played a major role in the orientation of the salt ridges and diapirs.

Scaled analog modeling was carried out to investigate the effects of sediment progradation against a basement slope in the presence of a ductile layer. Two fundamental models were tested in terms of sediment progradation with or against the direction of the basement dip. The results showed that sediment progradation could trigger and drive salt tectonics in both cases, but with different styles of salt tectonics.

(#243-P) My name is calcium silicate

Waleed H. Al-Bazzaz, **KISR**

Characterization of carbonate reservoirs in Kuwait revealed an interesting new matrix component in the form of calcium silicate. This material was commonly found in large quantities adjacent to calcium carbonate grains. It was formed by the recrystalization of calcium carbonate rocks by the action of pressure and/or temperature caused by pore fluids. Detailed analysis at the pore level has examined the role of calcium silicate in characterizing carbonate reservoirs. Using X-ray Diffraction (XRD) and Electron Probe Microanalysis (EPMA) has revealed unique physical and chemical characteristics for this previously unstudied mineral. The calcium silicate is porous and favors illite clay minerals. From its chemistry, it was deduced that it is the source of clays in carbonate rocks as its silica content is a major component of aluminum silicate clays.

Four samples from tight carbonate reservoirs were examined (samples 4, 12, 19 and 24). XRD showed the presence of calcium silicate minerals, for what were previously listed as unidentified matrix minerals. From EPMA analysis, the mineral had a pore structure in the nanometer scale. This nanoporosity could account for almost 60 percent of the total porosity (samples 12 and 24). Because of such porosity, calcium silicate minerals can complicate pore morphology by increasing its anisotropy. It was noticed that clay minerals, such as illite and kaolinite, attach themselves to the calcium silicate more readily than to calcite or dolomite. Since the nanopores are smaller than the clay mineral particle size, calcium silicate will be a good candidate for enhancing formation damage. I consider that more investigations of calcium silicate are needed to understand its role in secondary porosity, its chemical relationship with clay minerals, and its physical role in determining carbonate reservoir heterogeneity and rock evaluations.

(#100-O) Improved seismic imaging of deeper Jurassic events through poststack seismic enhancement techniques

Khalid S. Al-Deen, Nikhil C. Banik
and Abdulaziz M. Al-Fares, **KOC**

The Jurassic Marrat Formation is one of the most prolific hydrocarbon producers in Kuwait. Most production from this Formation has been from southern Kuwait, where inner-ramp grainstone

carbonates offer excellent reservoir quality in the middle Marrat. To the north, however, more mud-prone facies were developed in an outer-ramp setting, which results in a deterioration of reservoir quality. Recent well tests have shown that the presence of fractures associated with matrix porosities enhances productivity.

2-D seismic data were acquired with exploration objectives down to the Jurassic, whereas, 3-D data were for development objectives primarily within the Cretaceous. A poor signal-to-noise ratio and multiple interference hindered the original interpretation of the Marrat Formation and several primary seismic events were obscured by these multiples.

The presentation focuses on the poststack processing that has been applied to the 3-D data volumes of two fields in north and west Kuwait. Though this attempt is not a substitute for prestack multiple attenuation and imaging techniques, it provides a simple, time saving and cost-effective approach. A sequence workflow of poststack processes, such as FK fan filter, dip-scan stack, and image enhancement, was applied to achieve this result. The data was first flattened at the Gotnia level and then, making use of dip difference of the primary reflector, coherent energy that fell outside the specified dip range was attenuated. The process was particularly effective around the Marrat structures where an obvious dip difference exists between the Gotnia and Marrat formations. The method has its limitation toward the flanks of the structures where the beds are conformable.

(#238-P) Late Jurassic foraminifera and their paleoenvironmental significance in the Arab-D reservoir of the Ghawar field, Saudi Arabia

Abdullah G. Al-Dhubeeb, **Saudi Aramco**

The lower Arab Formation is of Late Jurassic (Kimmeridgian-Tithonian) age and consists of carbonates and evaporites. The carbonates were deposited on an extensive shallow-marine platform with localized intrashelf basins. The biocomponents of the carbonates are foraminifera, together with calcareous algae, massive and branched stromatoporoids, ostracods, brachiopods, gastropods, and sponge spicules. Their distribution has been studied in cored exploration wells in the Ghawar oilfield of eastern Saudi Arabia.

The foraminifera have a consistent vertical order of appearance within the lower Arab and the underlying Jubaila Formation across the study area. This consistency is considered to be a response to regionally effective paleoenvironmental variations during the time of deposition of both formations. The overall paleobathymetric trend is of gradual shallowing from an early moderately deep environment below wave base, through a shallower stromatoporoid-dominated zone, into a shallow lagoonal setting dominated by wave energy. Only cerithid gastropods and phylloid algae could tolerate the hypersaline conditions at the end of the depositional succession.

As the levels of introduction or removal of the biocomponents varies from well to well, their lateral and vertical distributions should provide important clues to regional paleobathymetric variations, and thereby assist sedimentary sequence determination and reservoir layering.

(#267-P) Identifying and mapping key diagenetic lithotypes: a new approach in modeling carbonate reservoirs

Ghazi A. Al-Eid, Rami A. Kamal and John C. Cole, **Saudi Aramco;** Mahbub Hussain and Mohammad Badrul Imam, **KFUPM**; G. Wyn Hughes, **Saudi Aramco**

Thirteen key diagenetic lithotypes were identified from a study of thin sections taken at six-inch intervals from nearly 1,000 ft of rock core. The samples were taken from eight deep wells that penetrated a heterogeneous gas-bearing reservoir interval in Upper Permian shelf carbonates of the Khuff Formation in eastern Saudi Arabia. The 13 diagenetic lithologies were traced back to three parent rocks. The diagenetic pathways leading from the parent rocks were charted and relative volumetrics established. The presenters see the traditional complexities of diagenesis in ancient carbonates as becoming a user-friendly tool in facilitating the characterization of flow pathways in oil and gas reservoirs.

The diagenetic lithotypes were divided into two groups: non-reservoir lithologies (six) and reservoir lithologies (seven). The members in each group were then ranked as to their reservoir development properties—from best to absolute worse. Each lithotype was found to have its own characteristic porosity and permeability ranges. The lithotypes were color-coded and used to populate a high-resolution 3-D geocellular model (vertical cell dimension: six inches) incorporating the study wells across the study area. Resulting patterns revealed colorful user-friendly sets of flow pathways, stratal relationships, and ancient depositional regimes. Potential is seen for using the system for more precise pore-volume calculations.

(#66-P) An application of pulsed neutron logs for water-movement tracking and other changes in West Kuwait reservoirs.

Abdulaziz M.H. Al-Failakawi, **KOC**;
Charles R. Smart, **BP**

This presentation demonstrates forward modeling techniques that integrate pulsed neutron-derived capture cross-section, matrix and fluid properties, and porosity to solve production problems. Nuclear forward-modeling techniques simplified the complex physical interactions between the high-energy neutrons emitted from the tool and their surroundings, by characterizing the capture cross-section as a function of matrix composition, pore space, and fluid properties. These techniques were used to develop accurate saturation profiles necessary for waterflood management in the Minagish Oolite reservoirs of the Umm Gudair and Minagish fields, West Kuwait. Both fields show complex conformance behavior under waterflood due to heterogeneous flow-unit architecture. The 400-ft-thick producing interval consists of a series of interbedded grainstones, packstones, and wackestones with porosities ranging from 15 to 25 percent, and permeabilities from less than 1 mD to more than 1,000 mD. The integration of dynamic time-lapse saturation profiles from the nuclear forward-modeling approach, together with open-hole logs, production logs and the static flow-unit description has enhanced our ability to monitor and predict water movements within the Minagish Oolite reservoirs. Examples of various production issues will be documented to illustrate the utility of this approach.

(#96-O) Well logs: the link between geology and reservoir performance

Omar U. Al-Farisi and Adel A. Belgaied, **ADMA-OPCO;** Hesham T. Shebl, **ZADCO**; Ghassan M. Al-Jefri and Abdel Naser S. Barkawi, **ADMA-OPCO**

In an offshore Abu Dhabi Lower Cretaceous carbonate reservoir, well-log data link a petrographical-based rock classification system in cored wells to uncored wells. This presentation describes the process of building a reservoir model using well logs to link geology to reservoir performance. The objective was to help construct a 3-D-geocellular model that could be upscaled to a dynamic simulation model and used as a reservoir management tool. Petrographic analysis grouped the reservoir lithofacies into nine rock types that were validated by mercury-injection capillary-pressure experiments. The definition of a rock type as used in the study was 'a rock of a texture and mineral composition that ties in to unique static and dynamic physical properties'. An electrofacies model with a log-derived permeability estimator and log-rock classifier was linked and compared to thin section descriptions. A correlation was evident. Subsequently, dynamic data from formation and well tests were incorporated to define reservoir flow units.

(#35-P) Evaluation of seismic anomalies of the Upper Jurassic oolitic gas reservoirs in central Abu Dhabi

Ali H. Al-Habshi, Omar M. Ashour, Thanaa E. Hamdy and Abdel Rahman R. Darwish, **ADNOC**

The Upper Jurassic (Kimmeridgian to Tithonian) oolite section in central Abu Dhabi is an elongated belt trending northeast parallel to, and east of, the Hith Anhydrite. It consists of oolitic grainstones and dolomites that range in thickness from 90 to 282 ft. Commercial gas has been discovered within the oolitic reservoir and in surrounding areas. This presentation provides information on the development, entrapment mechanisms, reservoir characteristics, and gas-prospect potential of the oolitic facies.

The Upper Jurassic oolite section is unconformably overlain by the Hith Anhydrite in the south and is underlain by the Arab Formation. It was deposited in a high-energy environment over an extensive carbonate ramp platform. 3-D seismic interpretation has indicated several elongated NW-trending anomalies that form attractive targets for gas accumulation. Sequence stratigraphic analysis, lithofacies description, and 3-D geological modeling were used to evaluate the seismic anomalies. Their high potential commercial value has been confirmed.

(#95-O) A new approach to using geostatistical modeling in a large clastic field

Fahad A. Al-Humam
and Abdulaziz A. Al-Gaoud, **Saudi Aramco**

Variograms play an essential role in constructing geostatistical models, but in some cases do not fit. This is either due to a nugget effect in data or to insufficient data in displaying the actual spatial correlation. Variations in the lithofacies unit, which are less than the well spacing, also commonly cause problems. These problems were apparent in a variogram model

used recently on a giant clastic reservoir with a dense well spacing. In this case, no matter what kind of variogram model was used, the lithofacies variations would not show a perfect fit. A new approach had to be adopted to capture small features that are less than the well spacing. The best method was to use net-sand maps for each geological layer and calculate the percentages of lithofacies from the well control for each layer. By doing this, proportion maps could be generated for each lithofacies from the net-sand maps and the well control to produce a proportion map of each lithofacies and each geological layer. Lithofacies proportion maps incorporated as proportion maps in Indicator Krigging could then be used in a probability model algorithm to simulate the different lithofacies into a single final-product lithofacies. In this method, the proportion maps honor the well control and statistically distribute the lithofacies evenly throughout the whole layer. whether between wells or in the outside sector away from well control. At the same time, the geological trend in the net-sand maps can be captured to reflect the overall trend.

(#48-O) Water encroachment in the Burgan reservoir, greater Burgan field, Kuwait

Jamal A. Al-Humoud, Kristian N. Pedersen and Peter T. Janele, **KOC**

The objective of the Burgan Water Encroachment Study was to establish the current stratigraphic locations of water intrusions in the Burgan Formation throughout the greater Burgan field by means of 3-D modeling. The current GOCAD Geostatistical Model built in 2000 for the Burgan Formation covered an area of 320 sq miles, and contains a total of 45 million cells. The Formation was divided vertically into four main reservoirs, each containing 100 vertical layers. Each areal grid cell was 100 x 100 m. Porosity, permeability, and water saturation properties were geostatistically distributed using a Reservoir Quality (Sand / Shale) Index, created from more than 800 wells in the greater Burgan field. A water database was created for 649 wells containing pulse neutron capture data from 1992 to 2001 and consisted of well-by-well data interpretation, data analyses, and contoured data quality.

Distributing the water in the Full Field Geostatistical Model was difficult as many techniques had to be evaluated in order to get the best data fit. The chosen method was to create the 2001 water data as point sets and geostatistically distribute the percentage of water to oil into the model with the guides of the Rock Quality Index. This ensured that the water was distributed only in the reservoir rocks where water encroachment occurs. In this technique, the water point set was treated as a binary set. Variograms were used to guide the distribution of data in the spatial area between the hard data. Multibinary sequential indicator simulation was used to distribute the water in each interval. The model was further evaluated using various geostatistical algorithms, cross-validation of well data, and a wide spread of variorum ranges. The 3-D Geostatistical Burgan Water Encroachment Model, 2-D maps, 3-D cross-sections, and GOCAD focused 3-D submodels, were customized to fit the need of customers, such as production and reservoir engineers. This data set will allow for an integrated team evaluation using 3-D visualization in workover decisions or in locating new drilling prospect locations.

(#251-P) Abqaiq field: integrated interpretation and reservoir modeling

Mohammad A. Al-Jadani, Roger R. Sung and Arthur E. Gregory, **Saudi Aramco**

A workflow was designed to prepare and integrate data from a variety of disciplines in order to perform integrated interpretations and seismic reservoir modeling. Various types of data were loaded and integrated to aid in seismic reservoir modeling, horizontal well-bore planning, and reservoir geostatistical modeling. As part of the work, seismic sensitivity to the existing reservoir fluids and geologic features, such as faults and fractures, was investigated to evaluate the predicted effects of these features on the seismic response. The investigation required fluid substitutions (for reservoir fluids) and the integration of image logs, 3-D seismic and flow meter data (for faults and fractures). These tests showed encouraging results for seismic sensitivity to reservoir rock properties. Various kinds of seismic volumes were generated to aid interpretation of structural features, such as faults, by means of Saudi Aramco's DETECT coherency processing, and to aid lithofacies determination through sonic and density volumes derived from the seismic impedance volume. Arab-D reservoir-stacked seismic traces were allocated to eight classes. Interpretation included the correlation of the seismic trace classes to modeled traces. Well-bore planning of new horizontal wells has used an integrated depth model, which was interactively inspected and interpreted along the well trajectory by the development and engineering team within a 3-D visualization environment. The predicted response curves of various types of well logs were extracted along the well path for planning purposes. Having all well, seismic, and production data combined in the

depth domain greatly facilitated evaluation efforts for monitoring-while-drilling, and provided postdrill updates of the seismic reservoir model.

(#142-O) Estimation of fracture orientation from azimuthal, compressional-wave amplitude versus offset data, offshore Abu Dhabi

Musabbah H. Al-Kaabi, Ali Al-Shamsi, Omar Suwaina, Ghiath Ajlani and Atef Ebed, **ADNOC**; Graham Roberts, Richard Wombell and David Gray, **Veritas**

Several recent studies have used variations in azimuthal P-wave Amplitude versus Offset (AVO) to estimate subsurface fracture orientations. Typically, the method assumes that the predominant fracture distribution can be modeled by a series of vertically aligned parallel fractures and cracks. Such a fracture distribution can arise from the impact of the prevailing stresses, as cracks and fractures tend to be preferentially opened parallel to the direction of the maximum compressive stress and closed perpendicular to it. The AVO gradient in such a medium varies as a function of source-to-receiver azimuth, and this variation is exploited in order to estimate fracture orientation.

We describe an investigation where we used azimuthal P-wave AVO to estimate fracture orientation in offshore Abu Dhabi, a region dominated by fractured carbonates. The study was carried out on a 3-D ocean-bottom cable data set. The acquisition geometry of the survey provided data that was well sampled with respect to azimuth and offset range. Data processing was designed to preserve offset-azimuth amplitude variations. Sensitivity analysis based on acquisition geometry and signal-to-noise ratio demonstrated that this data set was suitable for azimuthal P-wave analysis. The results suggested that there was a uniform trend of open fractures within the study volume. Also, the estimated fracture orientations proved to be consistent with fracture orientation inferred from azimuthal velocity analysis in one of the target zones.

(#203-O) Thermal model of Kuwait

Awatif F. Al-Khamis and Swapan K. Bhattacharya, **KOC**; Patrick Barnard and Alan Collins, **RRI**

A regional thermal model of Kuwait shows that the heat flow remained high (at about 80 to 85 mWm^{-2}) during the Paleozoic and gradually decreased to the present-day values of 50 to 60 mWm^{-2}. These values correlate with a probable riftogenic episode that prevailed in Kuwait during the Paleozoic and is now in a cooling phase. Inversion events range in age from Hercynian to end-Eocene. The oldest erosion event was modeled at 310 to 345 Ma; the amount of erosion could not be calculated due to paucity of data but an average of 1,000 ft of erosion was estimated from the rate of sedimentation. For similar reasons, the erosive events during the unconformities at the base and top of the Aruma Formation have been modeled with a constant amount of erosion of 50 ft and 250 ft, respectively. Erosion at Top Dammam was calculated from the maturity profiles, and varied from 2,500 ft over the Burgan Arch to about 250 ft on its flanks. The development of the Arch at this time, coupled with the timing and kitchen location of oil generation in Jurassic source rocks, has had profound consequences for exploration in the area. The present-day geothermal gradient in Kuwait is estimated to be low at between 18° and 22°C/km. However, some anomalies were observed over structures as well as near faults. It has also been noted that bottom-hole temperature corrections are not needed for those sections drilled with oil base mud, as the temperature equilibrium is attained more quickly than with water base mud.

1-D maturation history suggests that a lower Paleozoic source rock, if present, contributed significantly to oil generation during the Late Jurassic. The Late Jurassic Najmah Formation attained peak oil maturity in the early Tertiary to Holocene, whereas the Makhul Formation did not reach peak oil maturity in Kuwait. The 2-D (IES Petromod™) model revealed that the possible lower Paleozoic source rock became oil mature from 143 Ma, and by 115 Ma had become entirely gas mature. The Najmah Formation entered the oil window (about 100°C) by 91 Ma that by 15 Ma had reached its peak. The overpressure values simulated by interactive 2-D modeling were compared with present-day (measured) overpressure and showed that breaching of the Gotnia/Hith Formation probably occurred to allow oils to migrate into Cretaceous reservoirs.

(#65-P) The Integrated Reservoir Characterization process—a tool for improved reservoir characterization

Eman A. Al-Mayyas, **KOC**; Charles R. Smart, Chris Natenstedt and Marco Martines, **BP**

The Integrated Reservoir Characterization (IRC) Process is an enhancement of the Petrophysics Integration Process Model (PIPM). As implemented

for West Kuwait fields, the process consisted of five stages designed to integrate the diverse types and scales of static and dynamic information. Stage 1 established the reservoir framework based on the regional context, internal structural, and the sequence architecture of the reservoir. Stage 2 defined the petrophysical rock types at the core scale using probabilistic formation evaluation techniques, then up-scaled to the well-log scale. In addition to porosity and permeability characterization, Stage 2 produced petrophysical models of fluid-storage distribution and flow behavior. In the West Kuwait case study, the Modified Leverett J Method was used to validate permeability predictions and log-derived water saturation. Stage 3 linked petrophysical rock types to correlative geological elements such as lithology, depositional facies, and diagenetic trends. It was used to guide the assignment of rock types away from wells and represents an important addition to the original PIPM Process. Stage 4 created a reservoir volume distribution of porosity, permeability, and saturation within reservoir flow units as functions of rock type and geological elements. Stage 5 integrated dynamic data and simulation to validate and refine the static description of reservoir architecture and properties. The IRC Process is iterative and can start at any of the five stages depending on data availability and study objectives. West Kuwait results indicated that this approach provided a robust workflow for improved description of the static properties that control flow behavior.

(#133-O) Challenges and solutions in reservoir characterization and 3-D geological modeling: part 1

Yousuf S. Al-Mehairi, Bashir B. Garea, Ahmed Al-Shaikh, Naji S. Binbrek and Tawic A. Obaida, **ADCO**; S. Duffy Russel, **ExxonMobil**

The Lower Cretaceous (early Aptian) carbonate buildup in one of ADCO's giant oilfields is the most prolific and geologically complex reservoir in the UAE. The complexity of this Shu'aiba Formation reservoir stems from the interplay of the diverse fauna and the mixed depositional paleoenvironments, and less significant subsequent effects of meteoric diagenesis. Together, they give a unique rock fabric and textural heterogeneity represented by 17 reservoir rock types. Their study provided the basis for detailed reservoir characterization that shed light on the nature, scale, and correlation of geological heterogeneity. Primary mud-supported depositional fabrics and textures with poor macrofauna have poor reservoir quality due to matrix microporosity, whereas grain-supported sediments—particularly rudist rock types—have excellent reservoir qualities, dominated by intergranular and leached porosity.

A new approach to 3-D modeling was introduced by dividing the reservoir into three separate models: North, South, and AB models. The rock types within the AB Model correlated laterally across the field and could easily be traced for over 30 km, from south to north. The North Model exhibited significant rock-type variability within the rudistid buildup and the reef-front corelatable clinoforms. The South Model encompassed the buildup and back-reef sediments. It is basically a layered reservoir with the exception of the rudistid buildup unit that contains several reservoir rock types. In all three models, stochastic modeling of geobodies was conducted on the rudist rock types and dense units, and deterministic modeling on the remainder of the reservoir rock types. The three models of the Shu'aiba Formation have been successfully integrated into one full-field model having 31 million cells that was later upscalled to 1.4 million cells for reservoir simulation modeling.

(378-O) The Asab Pilot Project: geomechanical fracture modeling and permeability prediction from logs

Khalil Al-Mehsin, **ADCO**; Stephen J. Bourne and Anna Dombrowski, **Shell**; Gregor P. Eberli, **Miami U.**; Carlos Fonseca, Martin Kraiijveld, Henne Lammers, Jose-Luis Massaferro, Elena Morettini, Pascal D. Richard, Roeland C. Roeterdink and Ben J. Stephenson, **Shell.**

The Asab Pilot Project was a joint study between the Abu Dhabi National Oil Company (ADNOC), Shell Abu Dhabi, and the Shell Carbonate Development Team (CDT). The main objectives of the study were (1) to help technology development in collaboration with ADNOC, and (2) to transfer technology to ADNOC staff through close collaboration. The CDT chose the Asab field from other potential candidates during the Carbonate Workshop in 1999. Its choice was guided by the availability of a large amount of data, the good quality of the 3-D seismic, the 'potentially' highly faulted and fractured character of the reservoir, and the compressional nature of the anticline. The key technical objectives were to develop and test geomechanical fracture prediction tools, and to extend core-based matrix permeability relationships to uncored wells.

Detailed seismic interpretation was the basis for the conceptual fracture models. New fracture technology was developed by the CDT to assess the impact of folding in the presence of pre-existing faults on subseismic fracture development. The results of this

geomechanical modeling were compared with the production data for 30 years and showed potential links between fracture development and production performance that could be pursued in further detailed studies. A high-resolution sequence stratigraphic framework was defined that provided a solid base for flow unit definition. Within this framework, formation micro-imager logs were successfully used to predict small-scale, high-permeability streaks. The use of this valuable data set has enabled the development of new technology and improved the understanding of fractured carbonate reservoirs. This development was directly linked to the research effort by CDT on flow-unit and geomechanical-fracture modeling. The outcome of the study is not only applicable to the Asab field but is being implemented in other fractured carbonate fields.

(#116-P) Comparison of modern eolian sheet sand deposits with core and image-log data from the Unayzah Formation, Saudi Arabia

Yasir A. Al-Mubarak, Yousuf H. Mousa, Hassan N. Al-Subaikhy and Christian J. Heine, **Saudi Aramco**

'The Present is the Key to the Past'. This poster relates the observations made in a recently excavated construction-sand borrow pit 30 km west of Dhahran, to a similar thickness of Carboniferous-Permian eolian sheet sand interpreted from core and image logs from the Hawtah field, central Saudi Arabia. The pit cuts into a modern sheet-sand deposit to expose the internal stratigraphic features in three dimensions. The pit faces are 10 m high and are oriented 25 m parallel to the major southward wind-transport direction and 350 m east-west. In the exposure parallel to the dominant wind-transport direction, very low-angle (1°–5°) dipping bed sets were deposited unconformabily on a similar low-angle bed set, in the direction of the northerly 'Shammal' winds. The trailing edge of the underlying set is wind eroded. In the wall perpendicular to the Shammal wind direction, similar observations were made, except that the apparent dip of the bedding was flat as the exposed sand face is parallel to the axis of the major sand-transport direction. In detail, very long and thin sand lenses 1 to 3 m thick in the center thin upward and outward to zero but were difficult to see because of the horizontal nature of the bedding contacts and the low angle of the side contacts at the unconformity. All the relationships seen in profile became clear after inspecting the present-day surface. Areas devoid of vegetation are where active deposition is taking place, whereas vegetated surface are currently being deflated to form the low-relief angular unconformity.

The image-log data showed all the features observed in the modern dune exposure. Preserved bed sets ranging from 1 to 3 m thick had a constant dip of from 1° to 4°, and a constant dip direction. An unconformity (truncation) occurred at the top of each bed set, and was overlain by another set that differed by only a few degrees in the transport direction. Other features recognized in core and the modern sheet sands included well-sorted, near-spherical, uniformly frosted sand grains, bi-modal grain distribution, root scars in the sheet-sand facies, and reverse graded bedding in the preserved example of an avalanche face.

(#89-O) Gas exploration in Block-6, Oman: the Amin play revitalized by the Kauther discovery

Mohamed N. Al-Mugheiry and Pieter O. Spaak, **PDO**; Paul G. Senycia, **Woodside Australia**; Paul M. Tricker and Richard Knight, **Shell**; Abdullah Al-Shanfari, **MOG, Oman**; Mohamed S.S. Al-Lamki, Colin H. Boynton and Basma A.S. Al-Riyami, **PDO**; Lori A. Hathon, **Shell**

The Cambrian-Ordovician Amin Formation (equivalent to the Siq Formation in Saudi Arabia) is one of the main gas reservoirs within the Haima Supergroup and is sealed by lower Miqrat mudstones. The Amin consists of three main depositional facies: alluvial / fluvial; playa lake; and eolian. Dry-gas volumes have been booked in good reservoirs of aeolian facies in the Burhaan and Saih Nihayda fields, within the Ghaba Salt Basin, and from tight playa-lake facies within the Makarem structure. Nevertheless, the Amin has long been considered a high-risk gas play due to its depth and marginal reservoir characteristics. However, Kauther-1, drilled in the Afar region south of Adam—an area largely untested for deep plays—discovered an Amin wet-gas accumulation. Estimated reserves are of the order of 1 TCF (porosity of about 9% and permeability of 16 mD), at 4,200 m depth. Based on core and image-log data, the Amin sandstone was interpreted an erg-complex of mixed eolian and sheetflood sands.

The success of the Kauther-1 has significantly reduced charge and reservoir risks in the Afar region and will also have an impact on unlocking some of the volumes in other areas of fallow acreage, such as the Fahud Salt Basin. Further success in this play will, to some extent, depend on the ability to predict reservoir quality before drilling. The current work focuses on two areas. One is a petrographic review combined with forward-modeling of mechanical and chemical compaction processes. The other is a seismic rock-properties review to identify the feasibility of using seismic

attributes (for example, amplitude versus offset) as a predictive tool. Initial results show that the Amin aeolian facies can be divided into three petrofacies based on the degree of chemical compaction, which in turn captures a range of behaviors observed in the log data set.

(#43-P) Impact of renewed gas injection into a large reservoir in West Kuwait to minimize gas flaring

Salman A. Al-Qabandi and Fahed A. Al-Medhadi, **KOC;** Dave L. Meadows, **BP**

As a result of Kuwait's increasing oil production, associated gas production is expected to increase and exceed countrywide gas demand. To avoid flaring the surplus gas, renewed gas-injection into the Minagish Oolite reservoir was identified as a potential solution, so preserving the gas for future domestic consumption and enhancing oil recovery. Prior to the 1990 invasion of Kuwait, gas re-injection into the Minagsih Oolite reservoir was used to maintain reservoir pressure and store surplus gas production from West Kuwait.

This presentation documents the impact of restarting gas-injection on the current peripheral water-injection project and determines the optimum gas-injection scenarios for maintaining oil production rates and minimizing gas cycling. Various technical considerations were taken into account. (1) Identification of important parameters that effect re-injection of the surplus gas, such as, well density, well type (horizontal versus vertical), gas-injection rates, and total gas injected. (2) History matching of gas diffusion through the undersaturated oil column and the creation of a secondary gas cap using a coarse-grid reservoir simulator. (3) Evaluation of development scenarios that would optimize gas retention in the reservoir.

The results of full-field reservoir simulation concluded that although it would be technically feasible to re-inject surplus gas, doing so would have a major negative impact on oil production due to early gas breakthrough at producers, and to gas cycling. This in turn would force reduction in oil production rates to control the level of gas recycling. The presentation illustrates the difficult choices facing management when balancing the need for increasing oil production for revenue and the desire to minimize emissions from flaring.

(#154-O) Seismic stratigraphic interpretation of the Minagish Oolite reservoir from reprocessed 3-D seismic data, Umm Gudair field, West Kuwait

Hanadi B. Al-Qallaf, **KOC**; Dave G. Foster, **BP**

3-D seismic data were acquired in 1997 over the Umm Gudair field. During the initial interpretation it became apparent that reliable interpretation and characterization of the Minagish Oolite reservoir was being impaired by interfering surface and interbed multiples. The seismic data was successfully reprocessed during 2000 using multiple attenuation techniques based on moveout discrimination (apparent anisotropic moveout, frequency / wave number domain demultiple, inner trace mute) and deconvolution (in the tau-p [intercept-slope] domain) to produce a new data volume with significantly reduced multiple interference within the reservoir. More accurate mapping of the top and bottom of the reservoir from the reprocessed data was strongly supported by the excellent tie between seismic, vertical seismic profiling, and synthetic seismograms. For the first time, it has been possible to see evidence of the main reservoir progradation from south to north and a late-stage retrogradational phase of deposition with a rotated north to south depositional strike. The reprocessed seismic data will provide invaluable input into reservoir and acquifer characterization, and the drilling of flank water-injection wells. The successful interpretation of the reprocessed data together with rock physics analysis, suggested that 4-D seismic will also be worth testing to monitor the anticipated waterflood. This will lead to optimized recovery and reservoir management in this important Middle East field.

(#314-P) Using high-resolution seismic reflection to image shallow near-surface anomalies: a case study

Abdullah A. Al-Ramadhan and Hashim A. Hussein, **Saudi Aramco**

High-resolution seismic reflection data, when used correctly, can be a very effective tool in delineating the near surface, and can provide a better understanding of the geology of shallow anomalies. In this presentation, a comparison between high-resolution data and conventional data acquired for the same area

will be illustrated. The results show that the quality of imaging in the near surface using the high-resolution data has improved, hence enabling a more accurate static solution throughout, and improving confidence in deep-data imaging.

In order to reduce spatial aliasing of coherent noise and to produce effective temporal resolution of the near surface, data were collected using a vibroseis source with a linear upsweep between 10 and 120 Hz and a 2 msec sampling rate. The source and the receiver group intervals were 5 m, which resulted in a 2.5-m separation between consecutive common mid points. Simple but effective data processing and imaging operations maximized the frequency content and reduced coherent noise level. As a means of boosting the signal-to-noice ratio of the reflections, an adaptive linear noise elimination technique was applied to suppress the organized noise, in particular the surface waves that were dominating in amplitude. Variable coupling of the sources and receivers to the ground, and changeable near-surface conditions, substantiated the use of 'surface consistent' processing strategies. After identifying several shallow coherent reflectors with relatively strong impendence, a Horizon Velocity Analysis (HVA) was used to accurately determine the spatial velocity variations. Velocity information from velocity wells and up-hole data for shallow reflectors were used to constrain the HVA results.

(#339-P) A geophysical study of deep geologic structures of southern Iraq

Fitian Al-Rawi, **Sana'a U.**;
Ali M. Al-Raheem, **Baghdad U.**

Analyzing the gravity and aeromagnetic field by a variety of techniques has identified the concealed geology and structures of southern Iraq and their tectonic implications. Negative gravity and positive magnetic anomalies characterize granitic intrusions in the central part of the area and the Hormuz Salt is present in the south. The main structural and tectonic trends were clearly defined as northerly and northwesterly through the use of fan-filtering techniques. Deep regional trends from both gravity and magnetic data coincide, whereas shallow trends are variable. The deep trends acted as zones of weakness that affected the sedimentary cover through the various phases of the Alpine Orogeny and created shallow structures due to the influence of wrench-fault deformations. Three N-trending and one NW-trending zones of weakness have been outlined. The shallow structures are located along these zones and can be considered as promising areas for future oil exploration.

(#303-O) Prestack depth imaging as a tool of accurate structure delineation in the presence of complex surface topography

Turki Z. Al-Rowaili, **Saudi Aramco**;
Alex L. Litvin, **Paradigm**

In Saudi Arabia, complex surface topographic features, in particular sand dunes, lead to distortion of target horizons on seismic time images. In turn, these distortions can lead to incorrect time- and final-depth maps unless corrections are made during processing. In this presentation, we will show the benefits of a prestack depth-imaging workflow that includes tomographic iterative velocity modeling. The workflow is for 2-D data, but it can be applied with minor modifications to 3-D data.

Our initial velocity modeling used common mid point gathers on a floating datum to derive layer velocities from a ray-tracing-based approach coherency inversion. Ray tracing was performed from a floating datum representing a smoothed version of the topography. An initial velocity-depth model was used for the first pass of prestack depth migration. This process generated a depth section and depth-image gathers in each bin location. Residual moveouts on depth-image gathers were analyzed along the model horizons and the initial interval velocity-depth model was used to update the tomographic model. As the low effective offset for shallow reflectors did not allow a direct update of the shallow velocity model, we introduced a tomographic procedure that used better quality deeper reflections, as well as shallow reflections, to update the model. The updated model was used for the next iteration of prestack depth migration. At this stage, tomography was used to update the velocity in deeper layers of the model. In this way, we generated a final velocity model and final depth image free from artificial distortions observed on time images.

(#301-P) Facies distribution in the upper Qusaiba Member (Qalibah Formation), central Saudi Arabia

Mansour H. Al-Ruwaili
and Merrell A. Miller, **Saudi Aramco**

A transgressive event in the upper part of the Qusaiba Member of the Qalibah Formation in the Ghawar field, and to the south, is characterized by a distinctive newly discovered acritarch, *Fractoricornula* n. sp. It was recovered from core and cuttings samples and its occurrence is within, or at the top of, the Llandoverian

Angochitina macclurei chitinozoan Zone. Lithostratigraphically, this interval is between the informal middle Qusaiba sandstone and the Sharawra Member. The section represented by the transgressive event and characterized by *Fractoricornula*, apparently thins southwestward until excluded by coeval near-shore to nonmarine depositional environments. It can be used to identify approximately the relative position of the shoreline in the upper part of the Qusaiba. The section characterized by *Fractoricornula* in northern Ghawar is thicker, and this indicates that marine conditions were more persistent in that area. The distribution and thickness variation of the section in which this species occurs is an expression of the geography of this upper Qusaiba trangressive event. *Fractoricornula* is usually accompanied by an increase in palynomorph diversity. In one case, more than 80 palynomorph taxa (acritarchs, chitinozoans, cryptospores, fresh-water algae, and spores) were present in core samples. The new species was previously recorded as *Veryhachium* cf. *checkleyensis* Dorning 1981 in Arabia. In Libya, it was recovered from cores that have been dated as Aeronian and Telychian and called *?Dateriocradus monterrosae* (Cramer) Dorning 1981.

(#315-P) A general reconstruction scheme for sparse 3-D land seismic data

Riyadh S. Al-Saad and Panos G. Kelamis, **Saudi Aramco**; Remco Romjin and Dirk Verschuur, **Delft U. of Technology**

Seismic data are typically irregularly sampled along spatial coordinates. This can be caused by the presence of, for example, obstacles, inaccessible areas, and dead traces. Economic constraints impose further conditions related to irregularity and sparseness of seismic data. In practice, however, most multitrace processing algorithms cannot adequately handle sparse and irregular sampling intervals. The conventional technique of binning and stacking does not take into account the exact spatial positions. Moreover, methods for the removal of noise, based on single common mid-point gather processing, often suffer from aliasing in the offset direction. Therefore, irregularly sampled seismic data will lead to suboptimal processing and imaging results.

In this presentation, we propose a general regularization method applicable for seismic data. It consists of reposting along receiver lines to exact crossline positions, followed by least squares reconstruction in the midpoint-offset domain along crosslines and after normal moveout correction. The azimuth dependency of the data within the acquisition geometry is neglected. Therefore, three spatial coordinates remain that are in general irregularly sampled: the two midpoint coordinates and the absolute offset. The core of the procedure is the least squares reconstruction technique applied as a double Fourier transform, or a mixed Fourier-parabolic Radon transform. This reconstruction was applied to a 3-D land dataset. Various aspects and applications of reconstruction were investigated and will be demonstrated with examples from this dataset. In particular, the regularization of the offset coordinate will be shown to improve the stack response and enhance the spatial resolution. The success of the reconstruction depends on the spatial sampling, spatial bandwidth, and the choice of parameters.

(#272-P) Paradox of Shu'aiba karst: taking advantage of loss of circulation in the South Umm Gudair field, Kuwait-Saudi Arabia Partitioned Neutral Zone

Osama A. Al-Shaarawy, **KOC-Joint Operations**: James D. Ming, **Texaco-Joint Operations**; Mohammad R. Rajab, **KOC-Joint Operations**; Musa'ad S. Al-Harbi, **SAT-Joint Operations**

The South Umm Gudair (SUG) field is located in the northwest of the Partitioned Neutral Zone between Kuwait and Saudi Arabia on the southern plunge of the Kuwaiti Umm Gudair field. It was discovered in 1966 as a Ratawi Oolite oil producer. The Oolite is stratigraphically overlain by the Zubair, Shu'aiba, and Burgan formations. The carbonate Shu'aiba Formation is positioned between the massive sand bodies of the Zubair and Burgan. Its average thickness in the SUG field is 160 ft and several wells drilled into it have had difficulties due to loss of circulation.

Since 1966, increasingly high water cuts associated with oil production from the Ratawi Oolite have resulted in large amounts of produced water. The excess water is expected to double in volume in the near future. An integrated study was carried out to investigate the drilling of water disposal wells to handle the expected increase in produced water. 3-D seismic over the SUG field indicated that the Shu'aiba is characterized by karst features—sinkholes and dissolution channels, and karst towers—to which the circulation problems can be attributed. The genesis of the karst features was studied. The integration of 3-D seismic interpretation, attribute maps, geologic open-hole logs, and drilling and engineering data, delineated 'sweet spots' suitable for water disposal. These are likely to be highly fractured areas (especially along the margins of the karst features) and to be porous; hence,

loss of circulation can be expected. Several possible locations for vertical and horizontal water disposal wells were identified in the Shu'aiba carbonates. These areas are expected to have high injection rates and will probably be able to absorb most, if not all, of the produced water.

The extreme permeability of the Shu'aiba Formation has produced a paradox. On the one hand is the danger of uncontrollable circulation loss—on the other the attraction of incredibly efficient water injection. This has resulted in a paradigm shift from the perception of the Shu'aiba as a danger zone to being a sweet spot for water injection.

(#117-P) Enhancing permeability prediction through geological interpretation of a gasflood pilot, offshore Abu Dhabi

Abdullah Hussain Al-Shemsi and Yuki Y. Sugawara, **ADMA–OPCO**; Cathy E. Hollis*, **Badley Ashton**

In order to plan for a full field gasflood within a carbonate reservoir in offshore Abu Dhabi, two gasflood pilot studies are underway. Ten wells have been drilled and significant amounts of log and core data acquired with the key objective of identifying the vertical and lateral distribution of flow-controlling layers. Understanding the distribution of these layers is crucial to good reservoir management and also to the interpretation of the gas injection pilots, the results of which will be extended to the full field.

The reservoir can be considered as a single, low-order transgressive cycle consisting of three reservoir units that each defines high-order transgressive / regressive packages. Significant variations in permeability occur over short vertical distances, typically reflecting high-frequency cyclicity, although a significant diagenetic overprint has resulted in the decoupling of porosity and permeability. Consequently, porosity cannot easily be used to predict permeability in this reservoir.

Each reservoir zone consists of several decimeter- to meter-scale flow-controlling layers that are differentiated by using key-correlatable surfaces in order to enhance predictability in the subsurface. Correlation of these layers, and their integration with interwell communication tests, indicated that they could be laterally discontinuous, even over short interwell distances. Geological interpretation and the integration of all data sets has been the key to enhancing predictability and updating the existing simulation model so as to maximize our understanding of the gasflood pilot behavior.

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(#257-O) Evaluation of high-permeability zones in the Ratawi reservoir of the Marjan field, offshore Saudi Arabia

Yousif M. Al-Shobaili, Abdul-Jaleel Abu Bshait, David M. Bacchus, Ian M. Billing, E.A. Clerke, G. Wyn Hughes and Dave L. Cantrell, **Saudi Aramco**

Characterization of high-permeability zones within the Lower Cretaceous Ratawi reservoirs involved the definition of their lateral and vertical trends by calibrating core-based data and correlating these trends with non-cored Ratawi wells. This presentation is of an integrated approach taken in delineating permeability classes and lateral trends within a geologically consistent model.

Sedimentological and micropaleontological analysis of cored Yamama and Sulaiy formations revealed that the upper and lower Ratawi reservoirs are probably related to shallow, highstand systems tracts of two successive Sulaiy and Yamama sequences of earliest Cretaceous age. Mudstones, wackestones, and packstones of the transgressive systems tracts of both sequences contain moderately high diverse and moderately shallow-marine microfaunas, whereas the depleted microfaunas of the predominantly grainstone facies represent shallow, high-energy conditions associated with the highstand. The best reservoir facies are within the high-energy grainstones and mud-lean packstones of the lower Ratawi, just below the sequence boundary at the top of the Sulaiy Formation. Here, secondary leaching has created zones of enhanced permeability, possibly related to a major sea-level fall at the end of the Berriasian. The lowstand and transgressive system tract mudstones, wackestones, and mud-rich packstones constitute a poorer reservoir facies. However, their permeability was probably not low enough to act as an intrareservoir seal.

Though the reservoirs appear to be homogeneous over a large vertical interval on conventional wireline log displays, they have permeability variations of several orders of magnitude. Petrophysical integration of core and log data indicated a high-permeability zone within the reservoir below the upper / lower Ratawi boundary, delineated by the higher gamma-ray upper Ratawi beds, and a field-wide dolomite marker bed within the lower Ratawi. The permeability in the zone increases from essentially zero at the dolomite marker to over 1,000 mD near the top-bounding gamma-ray marker. The identification and evaluation of this zone, including modeling of its lateral extent, is critical for the efficient development of the field.

(#79-O) Fault seals in carbonates: integration of well data and outcrop studies

Hamad S. Al-Shuaily and Jacek B. Filbrandt, **PDO**

For over 25 years, the focus of studies into fault seals has been on siliciclastic reservoirs. Much of the effort has been targeted at the quantification of sealing capacity and uncertainties in clay smear, shale gouge, and cataclasis. It is now possible, in a probabilistic way, to predict maximum trapped column heights for a given stratigraphic interval or net-to-gross ratio and fault throw. However, investigations of the parameters that control fault-seal capacity in carbonates have begun more recently. A substantial amount of poroperm data exists for carbonate reservoirs but a systematic analysis of fault rock in carbonates does not. Similarly, although the impact of faults and fractures in carbonates on production and on mud losses whilst drilling, is widely recognized, a systematic review in the exploration realm of carbonate-carbonate fault seals is not available. We present results of a detailed analysis of field and dry-hole data in the Natih and Shu'aiba reservoirs of northern Oman, and describe carbonate fault-rock textures. The statistical data have been compiled into a risk matrix for application to newly delineated fault traps in this region. It is clear from this analysis that recent reactivation has had an important impact on the seal integrity of faults in carbonates, even in the case of shale-carbonate juxtaposition. The statistical database is small at present, but further analysis of drilled prospects and fields and integration with outcrop data is planned to reduce the uncertainties in our predictive capacity.

(#68-O) A new look at an old play: an integrated evaluation approach targeting Natih stratigraphic opportunities

Hisham A. Al-Siyabi and Abdullah H. Al-Habsi, **PDO**; Mark Partington, **Shell**

The late Albian to early Turonian Natih Formation is a prolific hydrocarbon producer in North Oman. All the commercial accumulations occur in structural traps. Although the potential for stratigraphic trapping in the shallow-marine platform carbonates of the Natih was recognized in the past, few opportunities were tested. Our assessment of the potential for stratigraphic trapping was through an integrated evaluation effort that used 2-D and 3-D seismic data, recorded hydrocarbon shows and accumulations, and the existing basin modeling studies and fieldwork. The integrated evaluation approach and use of state-of-the-art visualization and modeling techniques are expected to revive the Natih play.

Three stratigraphic exploration opportunities were identified. (1) Natih-A closures are sealed laterally or in an up-dip direction by mud-filled channels of the deeper marine lower Shargi Member of the Fiqa Formation (Coniacian to early Campanian)—deeply incised wide Shargi channels are restricted to the Ghaba Salt Basin. (2) Reefal buildups and mounds occur along the prograding platform edges of a Natih-E intrashelf basin between the Fahud and Ghaba Salt basins. These carbonate structures are potentially trapped by non-reservoir, intrashelf slope, and basinal facies that can act as top and lateral seals. (3) Truncated Natih intervals, formed as a consequence of Late Cretaceous platform uplift, are recognized in the Lekhwair/Dhulaima area of northwestern Oman. Potential reservoir intervals occur as truncated carbonate wedges, with intraformational lime mudstone and shales acting as seat seals and the basal Tertiary Shammar shale being the top seal.

(#70-P) New exploration opportunities associated with the Natih-E intrashelf basin

Hisham A. Al-Siyabi, Omar S. Al-Jaaidi, Hilal Al-Rashdi and Yaqoob M. Al-Sadi, **PDO**

The architecture of the Cenomanian shallow-marine Natih-E carbonate platform in North Oman was influenced by the development of an associated intrashelf basin. The accommodation space created by its development, coupled with high sedimentation rates, led to platform progradation that occurred from sites preferentially located on paleohighs toward the center of the basin. On 3-D seismic, mounded features were recognized seaward of the platform edge that showed downlap and/or onlap reflection terminations. Two interpretations are considered to explain the origin of these untested exploration opportunities.

(1) The mounds are carbonate buildups. Accordingly, the prograding Natih-E platform is part of a highstand systems tract capped by a sequence boundary that was not downlapped by lowstand wedges. Nucleation of the mounds is thought to have occurred during the transgression that followed. Reservoir facies within these mounds probably consist of rudist boundstones. Lime mudstones and shales of the transgressive lower part of the Natih-D provide top and lateral seals.

(2) Highstand deposits of the Natih-E platform are capped by a sequence boundary that is downlapped by mounded features representing lowstand deposits. These deposits are probably carbonate breccias and grainstones delivered to the slope as sediment gravity flows. The lower part of the Natih-D provides the top and lateral seals.

A dedicated exploration well was planned for the fourth quarter of 2001 to test one of the most attractive mounded features mapped from the seismic.

(#107-O) Hydrocarbon source-rock evaluation of the Middle-Upper Jurassic sediments in the Wadi al Jawf-Marib basin, Yemen

Khalid A. Al-Thour, **Sana'a U.**; Rafie A. Shinaq, **Yarmouk U.**; Abdullah A. Al-Atesh, **PEPA**

The Wadi Al Jawf-Marib basin in north-central Yemen is about 300 km long and 20 to 80 km wide. It contains hydrocarbon reservoirs that were intersected in several exploration wells, including Himyar-1, Sirwah-1, Baraqish-1, Sinwan-1, and Jebel Samadan-4. The reservoirs are within a 2,384-m-thick sequence of carbonates and siliciclastics of the Amran and Sabatay groups. The upper part of the Sabatayn Group, the Naifa Formation, has been completely eroded in the wells listed above. Uplift and erosion toward the northwest and subsidence and sedimentation toward the southeast characterize the sediments. Thirty-two microfacies type have been recognized, generally deposited under shallow-marine conditions in shelf lagoons with open-marine circulation (open-marine platforms, bays, and open lagoons), shelf and tidal flats (restricted circulation), and sabkhas with evaporites.

Various geochemical analyses carried out on samples from the basin indicated that their total organic carbon content ranged from poor to very good. The S1 (bitumen) and S2 (kerogen) values showed poor hydrocarbon generation potential for the Amran Group and for the Safer Formation of the Sabatayn Group. The evaluation of the extractable organic matter results indicated poor to good source-rock potential with the exception of the Safer Formation that was characterized as excellent. The Production Index, Hydrocarbon Index, Pyrolyzed Carbon, Pyrolysis Temperature, and Thermal Alteration Index, together with microscopic identification of kerogen, and bitumen analysis, all showed that kerogen-II (exinite), kerogen-III (vitrinite), and traces of amorphous kerogen (mainly of continental origin) were present. The kerogen types are characteristic of mature to post-mature stages of hydrocarbon generation with the possibility to producing only small amounts of oil and gas.

(#120-O) Tau-migration and velocity analysis applied to data from the Midyan region of the Red Sea

Tariq A. Alkhalifah, **KACST**

Imaging the presalt reflections of data acquired from the Midyan coastal region of the Red Sea requires prestack migration-velocity analysis. Conventional poststack time processing lacks the lateral inhomogeneity capability needed for such a problem. Prestack migration-velocity analysis in the vertical time domain reduces the velocity-depth ambiguity that usually hampers the performance of prestack depth-migration velocity analysis. In prestack tau migration-velocity analysis, the interval velocity model and the output images are kept in time. This avoids placing reflectors at erroneous depths during the velocity analysis process, and so avoids inaccurately altering the shape of the velocity model, which, in turn, would slow down its convergence to the true model. Using a 1-D velocity update scheme, the prestack tau migration-velocity analysis produced good images of data from two 2-D seismic lines in the Midyan region. For the first seismic line, only three prestack tau migration velocity-analysis iterations were required to focus presalt reflections in time. However, the other line, which crosses the first line, was more complicated and required five iterations to approach the final, reasonably focused, time image. After mapping both images to depth using the final velocity models, the placement of reflectors in the two lines were consistent at their crossing point. Some errors occurred due to the influence of out-of-plane reflections on 2-D imaging but were identifiable and generally small. The results compared favorably with images obtained for the same two lines using the common-focus-point imaging technique, developed recently at Delft University.

(#63-O) A look into the petroleum systems and plays of Iraq

Hashim F. Alkhersan, **Pioneer**

Iraq was located on the passive margin of Gondwana. The Tethys Ocean covered the area during the Paleozoic and Mesozoic. Silurian shale blanketed the area and is an excellent hydrocarbon source for Paleozoic reservoirs. The area was emergent during the Caledonian and Hercynian orogenies. Good source rocks were deposited in several Jurassic and Cretaceous intrashelf basins. Clastic influxes from the Arabian Shield during the Cretaceous led to the deposition of fluvial to shallow-marine sands. These sandstones, together with shallow-marine limestones,

provided reservoirs for Jurassic and Cretaceous hydrocarbon charges. Evaporite and terrigenous sediments that filled the basins during the Neogene formed effective seals and facilitated maturation and hydrocarbon migration. Five major petroleum systems are recognized. Exploration started early in the twentieth century, but has been limited to the younger hydrocarbon petroleum systems and plays of the Tertiary and Cretaceous. Of the 200 exploration wells drilled in an area of 453,500 sq km, only a few have penetrated as deep as the Jurassic and Triassic intervals and just two wells have intersected lower Paleozoic rocks.

Iraq's hydrocarbon reserves are 149 billion barrels oil equivalent (BBOE). These accumulations, although distributed in 10 plays, are mainly found in five Cretaceous and one Tertiary plays, with very little being in the Jurassic, Triassic, and lower Paleozoic plays. It is thought that the same young plays host most of the estimated 54 BBOE of future potential reserves. The tectonic framework and play distribution makes it possible to divide the country into exploration regions. For example, the area to the north and east of the Euphrates River subsided most during the Mesozoic and received thicker sediments and more favorable play fairway conditions. As a result, a large number of plays are stacked over the southwestern flank of the Mesopotamian foredeep.

(#143-P) Unmasking the subsurface: the Gulf of Suez demultiple project

Norman C. Allegar and Ian M. Threadgold, **BP**

The most significant barrier to discovering more oil and gas in the Gulf of Suez is the poor quality of the seismic data, as key target horizons are masked by the presence of free-surface and interbed multiples. In 2000, BP established the Gulf of Suez Demultiple Project in Cairo to identify, evaluate, develop, and apply techniques to significantly improve the quality of seismic data, and to assure the continued development of a high-quality prospect portfolio. Work was initially focused on better understanding the technical fundamentals of data-quality issues and the testing of existing methods of multiple removal. This is leading to research and development into new techniques. The investigation included 1-D, 2-D, and 2.5-D models being generated from a high-graded rock-properties database to better quantify the imaging problems. Additionally, a 2-D seismic program, tied to both 2-D models and risk-challenged prospects, was acquired to provide the optimal dataset to evaluate existing 2-D demultiple techniques. Results will be presented that indicate substantial improvements in imaging through the optimized application of Surface-Related, Multiple-Elimination (SRME) software on this recently acquired 2-D data. Preliminary results will also address interbed demultiple techniques, the extension of 2-D code to 3-D, and the testing of 3-D acquisition schemes.

(#167-O) Pliocene-Quaternary reorganization of the Arabia-Eurasia collision

Mark B. Allen, **CASP**; James A. Jackson, **Cambridge U.**

Evidence for a major reorganization in the Arabia-Eurasia collision zone in the last 5 million years is increasing. It is shown, for example, by deformation or the acceleration of strain rates in many parts of the broad collision zone that started during this time. Deformation in the 'Simple Folded Zone' of the Zagros began synchronously with deposition of molasse of the Bakhtyari Formation, dated as Late Pliocene. Slip rates on the Dead Sea Fault System doubled in the early Pliocene-Quaternary interval, to about 10 mm/yr. Offshore folding in the South Caspian Basin is dated as Late Pliocene, although onshore folding at the margins of the eastern Greater Caucasus may have begun about 2 million years earlier. Provenance data show an increase of Greater Caucasus sediment input into the South Caspian Basin in the Early Pliocene. Extrusion of Anatolia between the North and East Anatolian faults began at about 5 Ma. Much of Cyprus became emergent during the Pliocene for the first time. Three explanations are possible for this reorganization. (1) Arabia accelerated from Africa at about 5 Ma, as oceanic spreading began in the Red Sea. (2) Prior to 5 Ma, strain may have been taken up in more northern parts of the Arabian margin, now imbricated within the High Zagros. (3) Earlier Tertiary convergence between Arabia and Eurasia may have closed minor ocean basins within Iran, now represented by ophiolite zones. Recognition and quantification of this tectonic reorganization is important in understanding the evolution of hydrocarbon systems on the Arabian Plate and in southwest Eurasia.

(#8-O) The role of 3-D seismic data in defining fractures: a case study

Maher I. Almarhoon and Martin F. Dickens, **Saudi Aramco**

Seismic 3-D data provide higher lateral resolution than do 2-D data. This enhances the ability to detect fracture density and direction, both of which control fluid flow in tight reservoirs. In the case of the lower Unayzah

reservoir in South Haradh, the reservoir is very tight (porosity about 3%, interval velocity 16,000 ft/sec, density 2.2 g/cc). Its thickness ranged from 30 to 350 ft, which is less than the seismic wavelength and complicated the amplitude variation study. Using the seismic data, we defined fracture zones and fracture directions, in order to optimize well location. Previous exploration strategy had located wells in the vicinity of major faults on the assumption that they would penetrate a higher density of fractures in such areas. However, the 3-D survey affords us the opportunity of locating other intensely fractured areas with much greater precision. Faults were highlighted in the seismic data by using the Generalized Hilbert Transform (GHT) algorithm, which is very robust in detecting subtle changes in the seismic data. The application of edge-preserved smoothing before GHT helped to minimize random noise without sacrificing sharp edges. Attenuation trends were mapped by frequency analysis, and the frequency band ratio was computed to test the high-frequency content at different data levels. High-frequency attenuation was detected, mapped, and integrated with the fracture mapping.

The maximum stress direction in the area is approximately east-west. In a compressional tectonic system under these conditions, fractures would be open and parallel to the maximum stress direction. In order to intersect as many open fractures as possible, we designed a northerly directed and highly deviated, horizontal (80°) exploratory well, orthogonal to the open fractures. It penetrated almost 800 m of the reservoir and the production rate, pressure build-up, logs, and penetration rate supported the seismic interpretation. The well intersected an area of high fracture density that contributed to the fast pressure build-up. The resultant pressure was amongst the highest in the reservoir in this field, and the well flowed the highest rate of condensate.

(#19-O) Mapping reservoir potential of the upper Unayzah clastics using seismic attributes

Hafiz J. Alshammery
and Martin F. Dickens, **Saudi Aramco**

The upper Unayzah sands are a gas reservoir in the South Haradh region. This part of the Unayzah reservoir was deposited as incised channel-fill clastics in a shallow- to marginal-marine environment with facies varying from siltstone to reservoir-quality sandstones. Mapping the reservoir sands of the upper Unayzah posed an exploration/delineation challenge that we investigated by applying a variety of seismic attributes.

The existing well control indicated that acoustic impedance could discriminate between reservoir and non-reservoir facies. Inverting high-quality 3-D seismic data to acoustic impedance was the initial basis on which the reservoir was mapped. 1-D modeling was used to study the effect of the reservoir presence on the surface seismic signature. It was seen that reservoir development caused detectable stretching in the seismic reflections. These features were displayed areally to identify good reservoir development by means of neural networks and second-norm similarity attributes. Both methods showed a similar reservoir distribution to that mapped by acoustic impedance. Increasing the bandwidth during processing transformed the stretched wavelet to a doublet, which was mapped by attributes as elementary as the mean amplitude of the seismic data. Modeling also showed that the reservoir presence and the subsequent waveform change caused reduction in the frequency content, which was displayed using frequency attributes such as the centroid frequency. The various attributes converged, when viewed on a common reservoir distribution map, so verifying the presence of high-fidelity seismic data and increasing the confidence in identifying the Unayzah reservoir distribution.

(#20-P) Eustatic overprints on the diagenetic evolution of some Mesozoic platform carbonates from the Arabian basin

Abdulrahman S. Alsharhan
and Fadhil N. Sadooni, **UAE U.**

Eustatic, climatic, and tectonic factors have contributed significantly to the configuration of the early diagenetic evolution of the Mesozoic platform carbonates of the Arabian basin. Geologic data on these sediments, recently obtained from various parts of Arabia, has made it possible to trace some of the eustatic influences, such as, evaporite dissolution, pedogenesis, and paleokarst development, on their diagenetic evolution. An example of evaporite dissolution occurs in the Jawan evaporitic facies—equivalent to the Mauddud Formation in the north of the Arabian Plate and to the Hith anhydrite of eastern Arabia. Pedogenesis was associated with regional erosion, such as the development of caliche layers between the Triassic Kurra Chine and the Upper Cretaceous Hartha Formation in the Western Desert of Iraq. The development of paleokarst was associated with regional unconformities, as in the Najmah Formation, and with widespread cementation and regional

dolomitization fronts, as in the Mauddud Formation of the Arabian basin.

These processes were investigated within the context of six major settings resulting from the combination of Milankovitch low- to high-amplitude eustatic sea-level and climatic changes. The settings included early diagenesis associated to either arid or humid climatic changes and attributed to low-, medium- or high-amplitude sea-level changes. Early diagenesis associated with arid climatic conditions and low-amplitude sea-level changes, can be traced in meter-sized evaporite-carbonate cycles of the Upper Triassic of northern Iraq and northeastern Syria, and the Upper Jurassic Arab Formation of Arabia. These sediments contrast with the Lower Cretaceous cycles of the Yamama Formation in southern Iraq that were developed under humid climatic conditions and low-amplitude sea-level changes. The results of high-amplitude sea-level changes associated with humid climatic variations may be seen within the Upper Cretaceous Hartha-Shiranish and Simsima formations.

(#362-O) New biostratigraphic and sequence stratigraphic constraints on Miocene synrift sequences from the northern Red Sea

Robert H. Alway, Andrei Tudoran,
Keith A. Knabe, Chengjie Liu
and Christian J. Strohmenger, **ExxonMobil**

New biostratigraphic and radiometric dating results from offshore Egypt, together with published data, have been used to establish a sequence stratigraphic framework for the Miocene synrift succession. Age and paleoenvironmental constraints have been established for each of these second-order depositional sequences. Our new age determinations suggest a younger age for the South Gharib / Mensiyah formations as compared to published data. This implies a greater amount of time for deposition of potential Middle Miocene reservoir facies and hydrocarbon generation in the northern Red Sea.

The earliest fluvial, marginal marine, and marine synrift sediments are Early Miocene. Although present in the Gulf of Suez and offshore Saudi Arabian wells, older deposits such as the Nukhul Formation / Tayran group were not present in four offshore Egyptian wells examined. The Early Miocene, Rudeis / Burqan second-order sequence consists of deep-marine sandstone, shale, and carbonate that were deposited during a period of high subsidence, and unconformably overlie crystalline Precambrian basement or the Nukhul Formation / Tayran group. An unconformity or correlative conformity separates this second-order sequence from one characterized by interbedded evaporites, siliciclastics, and carbonates of the late Early and Middle Miocene Kareem / Jebel Kibrit, and Belayim / Kial formations. Core data showed that sandstones of the Rudeis / Burqan, the Kareem / Jebel Kibrit, and the Belayim / Kial formations are potential reservoir rocks. During the late Middle to Late Miocene, a regional hypersaline episode caused the deposition of marine gypsum and halite of the South Gharib / Mensiyah formations. The overlying, progradational siliciclastics with scattered anhydrite beds of the Zeit / Ghawwas formations were deposited during the late Late Miocene within a fluvial to marginal marine environment. Open-marine conditions were re-established in the latest Miocene or the Early Pliocene due to rifting of the Red Sea.

(#307-O) New findings on the fracture characterization of the Arab-D and Khuff from core, Ghawar field, Saudi Arabia

Mohammed S. Ameen
and James Breninger, **Saudi Aramco**

A comprehensive, specialized study has been conducted for the first time on fractures in core from the Arab-D reservoir (Upper Jurassic) of the Ghawar field. This led to new findings concerning the modes of fractures and their implications for reservoir performance. It also challenged essential aspects of the conventionally accepted model of Ghawar being a drape fold over a horst structure in the basement that was controled by steep and vertical dip-slip faults. Although the study concentrated on the Arab-D, new observations on core from the deeper Khuff gas reservoir (Permian) and from outcrop observations were integrated, together with seismic and other data. They demonstrated that the Arab-D and the Permian Khuff sequences show multiphase, complex microtectonics (strike-slip, extensional, and thrust). These microtectonic regimes manifest themselves in a variety of modes and scales of fractures that include cracks, joints, faults, and tectonic stylolites. The main differences between the Arab-D and the Khuff are the important role of bedding, parallel and low-angle thrusts, and the apparently more common mineral occlusion of fractures in the Khuff compared to the Arab-D. The Arab-D sequences are 'welded' by frequent medium- to high-amplitude bedding stylolites. This has resulted in the Arab-D largely behaving as one thick, but heterogeneous layer, with gradual rock mechanical variations that affected the level of fracturing in the various zones.

(#366-O) Comparison between deterministic and geostatistical permeability prediction methods in carbonate reservoirs: a case study

Mostafa H. Amine, **ADCO**; Jean-Marc Chautru, **IFP**

Permeability prediction is a cornerstone of static and dynamic modeling. In carbonate reservoirs, many approaches have been made in order to predict permeability for non-cored wells by integrating the core and log data. It is a difficult task, as correlation between core permeability and log data is usually poor and/or complex in carbonates. This presentation discusses a case study in a carbonate reservoir in Abu Dhabi where various permeability prediction methods—such as, multidimensional histograms, linear regression analysis, neural networks, and 3-D geostatistical modeling—have been tested and compared. The focus was on the evaluation of the various methods and their implications in dynamic modeling, rather than on the theory behind them. This evaluation took into account the accuracy and robustness of the results for each method.

(#69-P) The Namibia connection: outcrop analogs for exploration and development of Neoproterozic intrasalt carbonate reservoirs of the South Oman Salt Basin

Joachim E. Amthor, **PDO**; John P. Grotzinger, **MIT**; David S. McCormick, **Schlumberger**; Hisham A. Al-Siyabi, Rashid A. Al-Hashimi and Omar S. Al-Jaaidi, **PDO**; Stefan Schröder and Erwin Adams, **MIT**

Intrasalt carbonates of the latest Neoproterozoic to Early Cambrian Ara Group in the South Oman Salt Basin (SOSB) are one of the complex deep-oil exploration plays in Oman. The total-in-place proven oil reserves exceed 300 million barrels and constitute a significant part of Petroleum Development Oman's (PDO) undrilled prospect portfolio. A cluster of five recent discoveries is being brought toward commercialization.

Well-studied and documented latest Proterozoic to earliest Cambrian Nama Group carbonates in Namibia are time-equivalents of the Ara carbonates. The outcrops in Namibia are a close analogy of PDO's intrasalt carbonate play in terms of tectonic setting, stratigraphic architecture, and facies distribution. They contain the abundant index fossil *Cloudina* associated with thrombolite reefs, similar to those seen in wells in the SOSB. As a reservoir facies analog, abundant thrombolitic reefs with excellent primary porosity were formed in shallow- to deeper-ramp settings. Other potential up-dip reservoirs are high-energy grainstones with primary and moldic porosity. Source-rock facies analogs are deeper-water microbially dominated carbonate mudstones and sapropelic laminites.

In Namibia, novel digital geological survey technologies—real-time global positioning system receivers with a 2-cm accuracy, total station, and reflectorless laser rangefinder—were used to map key stratigraphic surfaces, faults, and stratigraphic sections. They captured the hierarchy and length-scale variations of the outcrop analogs for conditioning the subsurface facies and reservoir models. Photogrammetry extracted a digital elevation model onto which the aerial imagery was draped to provide key geological textural information. The 3-D digital data from the Nama outcrops allowed visualization of stratigraphic relationships not apparent on conventional maps and cross-sections. Furthermore, key geological features could be directly measured or calculated. The 3-D digital dataset has improved the understanding of the spatial distribution of the heterogeneity of reservoir and source-rock facies, and has provided a mechanism for directly comparing outcrop data to the subsurface Ara intrasalt carbonates.

(#236-O) Structural analysis of the Mengharak transcurrent fault system in Zagros, Iran

Mehran Arian, **Shahid Beheshti U.**; Abdolhossein Ahmadnia, **NIOC**; Manochechr Qoreshi, **GSI**; Mohsen Pourkermani, **Shahid Beheshti U.**

The N-trending Mengharak (Kareh Bas) Transcurrent Fault System (MTFS) is situated about 80 km east of the Barazjan segment of the Kazerun fault zone and 40 km west of Shiraz. It has a total length of 200 km and cuts the northern margin of the continental basement of the Arabian Plate. It is a right-lateral linked, strike-slip fault system that has displaced several anticlinal axes. The effect on the anticlines was to create a non-gas-bearing trend in the Fars area. Isopach and facies maps indicate surface ruptures related to post-folding Zagros events. The fault system consists of six structural segments with relay and anastomosing fault arrays. Most segments have been smoothed-out by abrasion and shortcut faults as displacement has taken place, so producing continuous fault traces. As a result, hard-linkages and shear lenses were formed by the development of acognate horses. Seven Hormuz salt plugs intrude the

MTFS. Various models have been proposed for their emplacement, and it would seem from detailed studies on fault geometry and depth-to-basement that there are several mechanisms for the salt intrusion. An important feature of the MTFS is a strike separation of 109 km on the Zagros 'Mountain Front' fault / flexure. In the study area, the 'Mountain Front' consists of growth faults that separate the deep-basinal Padbeh Formation in the northeast from shallow-water carbonates of the Jahrun Formation in the southwest. Positive inversion tectonism was triggered by the Zagros orogeny. This was followed by orogenic fold-filling in the compressional structures of the simply folded belt where Hormuz salt, interposed between the basement and the overlying Phanerozoic sequence, filled the cores of the anticlines. Elsewhere, differential shortening of the Zagros foreland fold and thrust belt was the result of variable rheological properties of the sedimentary cover, and of basement tectonics controlled by deep-seated transcurrent fault systems, such as the MTFS.

(#332-O) The petroleum systems of the central Muglad basin, Sudan

Mohamed Z. Awad, **Greater Nile Petroleum**;
Kamil M. Idris, Pan Xiaohua,
and Lawrence Bernstein, **Talisman Energy**

The Mesozoic-Cenozoic Muglad basin of west-central Sudan is part of the Central African Rift System. The NW-oriented basin contains more than 15,000 m of clastic fluviolacustrine sediments deposited during three rift-tectonic cycles dating from 140 to 30 Ma. It is mainly extensional and includes tilted fault blocks, faulted anticlines, and hanging-wall rollovers. In the Greater Nile Petroleum contract area, tilted fault-block traps account for nearly 70 percent of the oil accumulation. Extensive exploration and development since 1997 has led to the discovery of 1.66 billion barrels original oil in place. Total reserves found so far are 975 million barrels of medium to light, sweet oil.

Two large petroleum systems have been identified—the eastern Bamboo-Unity, and the central-western Kaikang. Exploration in the Bamboo-Unity system is at a semimature level. It contains seven major fields and most of the oil found so far. Reservoirs are in Cretaceous (Albian-Aptian to early Maastrichtian) fluvial-alluvial sandstones. The Bentiu Formation is the main reservoir unit, and the overlying Aradeiba Formation floodplain shale and intra-Bentiu shales provide top and cross-fault seals. The Kaikang system is largely unexplored and includes the deepest part of the rift basin (Kaikang trough), and the western margin (Abyei high). Toward the center and the eastern step-fault zone of the Kaikang trough, oil accumulations have been confirmed in Tertiary sandstones. Intra-Tendi and Nayil Formation shales act as top and cross-fault seals.

The main source rock is the Lower Cretaceous lacustrine shale of the Abu Gabra Formation. However, some wells in the Kaikang trough have intersected Upper Cretaceous and Tertiary rocks that have high levels of total organic carbon. Thermal maturity modeling showed that hydrocarbon generation from the Abu Gabra occurred during Aptian (110 Ma) to Maastrichtian (70 Ma) times. Planispastic restorations and geochemical modeling suggest that the second rift phase (95–65 Ma) provided the best timing for trap formation when compared with timing of the generation and expulsion of hydrocarbons.

(#233-P) The role of strike-slip faulting in the control of sedimentation and deformation patterns in the Zagros Mountains, Iran: a case study of the Qatar-Kazerun fault

Mehran Azizzadeh, **NIOC**

The Zagros fold and thrust belt of southwest Iran consists of NW- to W-trending anticlinal folds. In many parts of the Zagros Mountains, fold-axes are deformed or ruptured by transverse strike-slip fault zones. One of these major fault zones is the Qatar-Kazerun lineament in central Zagros. The right-lateral strike-slip movements of the Qatar-Kazerun lineament and its geometrical relationship to the main trend of the Zagros Mountains, have caused many authors to consider it as a tear fault or lateral ramp that bears a genetic relationship to the Alpine folding of the Zagros. They believe that this fault accommodated differential displacement of various parts of the Zagros Mountains. However, the evaluation of morphotectonic and seisemotectonic data, structural geology, and sedimentary basin analyses suggest that the Qatar-Kazerun lineament is the surface expression of a major paleofault in the Zagros basement that does not have a genetic relationship to the Zagros Orogeny. Indeed, throughout the history of the Zagros basin, it seems that the geometry and renewed movements of the Qatar-Kazerun fault—together with other basement structures—have affected the sedimentation and deformation patterns. The recognition of surface lineaments related to basement structures, and the understanding of their implication in the control and modification of geological processes, is an important approach to reservoir evaluation and the search for accumulations of hydrocarbons in the Zagros Mountains.

(#187-O) Integrated seismic analysis of carbonate reservoirs: a look back, a leap forward

Steven L. Bachtel and J.F. (Rick) Sarg, **ExxonMobil**

Seismic analysis of carbonate strata has most recently concentrated on the generation of more accurate and robust stratigraphic frameworks using sequence stratigraphic methods. Seismic stratigraphy has provided the means to study large-scale carbonate-platform architecture and reservoir distribution. Development of seismic stratigraphy has influenced an entire generation of outcrop studies that have described geometric and facies relationships at and below the seismic scale. Sequence stratigraphic studies of platforms have shown that carbonate systems are dynamic and react rapidly to global changes in sea level, and to local structural subsidence. The sequence framework has provided constraints for geologic modeling in exploration and production settings. Integration of well logs, petrophysics, outcrop-facies dimensions, and geostatistics have been used to internally populate these geometrically constrained models.

Future breakthroughs in seismic analysis of carbonate strata will focus on methods to populate geologic and flow-simulation models with seismically derived rock-property data. Volume interpretation techniques using seismic attributes, coherency, impedance, and image attributes will assist in the prediction of pore systems in carbonate reservoirs. Calibration of seismic attributes with reservoir rock properties will provide a more quantitative approach to geologic and flow-simulation modeling in carbonate reservoirs. The visualization 3-D seismic may also provide intangible insights into carbonate systems by providing constraints for diagenetic and 3-D numerical modeling, and better predictions of fractures in carbonate reservoirs.

(#145-O) Solving imaging problems of the offshore Middle East reservoirs using a single-sensor recording system

Mohammed A. Badri
and Morten Svendsen, **WesternGeco**

Most of the offshore Middle East reservoirs are mature fields in which many production wells have been drilled. However, the use of high-quality 3-D seismic data can still enhance reservoir production and management. Although conventional 3-D surface seismic data have significantly improved our understanding of the reservoirs, there are still serious challenges to be considered. The effects of noise, lack of sufficient resolution, multiples, and deep imaging are limiting factors for optimum reservoir characterization. High-resolution imaging, mapping of minor faults, fracture-density distribution, and detection of by-passed oil, are required information for optimizing reservoir performance and improving the recovery factor of oil and gas.

To address these challenges, a revolutionary technology based on single-sensor recordings has been developed. This new technology is called 'Q' Marine and is designed to bring a new level of precision to seismic reservoir characterization and evaluation. The new acquisition system records individual sensors rather than the grouped arrays in conventional seismic acquisition systems. It delivers a real-time recording channel count of 80,000 channels, well beyond the capacity of conventional systems. The single-sensor recording method allows perturbations and noise to be removed, so bringing enhanced imaging quality and resolution that is invaluable in assisting production and reservoir management. We will show examples of this new technology from 3-D data recently acquired in marine basins. The seismic images provide high-resolution data that enabled the monitoring of fluid movement across the reservoir.

(#59-P) Aquifer influx tracking in the Minagish Oolite reservoir of the Umm Gudair field, Kuwait

Tapan K. Banerjee and Abdulaziz M.H. Al-Failakawi, **KOC**; Chris J. Natenstedt and Charles R. Smart, **BP**

This presentation documents patterns of water influx and the use of thermal decay-time and open-hole logs for water tracking in the Umm Gudair oil field of west Kuwait. The Cretaceous Minagish Oolite carbonate reservoir is under primary recovery with over 150 wells producing through electrical submersible pumps. Production is supported by bottom- and edge-water drive that will be supplemented by a future peripheral waterflood. Aquifer influx has swept the deeper productive intervals and created water fingers in some of the wells that have resulted in increased water cuts and more frequent workovers. Water movements must be closely monitored to properly design water shut-off treatments and guide the water-management strategy. For example, edge-water fingers, sourced from the aquifer, follow high-permeability flow units and lead to bypassed oil and reduced sweep efficiency. Analysis of historical open-hole logs and time-lapse thermal decay-time saturation profiles has identified several important water fingers

and focused attention on the development of effective shut-off techniques. Similarly, large-scale rock heterogeneities control patterns of water influx. Regions without laterally extensive low-permeability flow units have a gradual bottom-up rise in the oil-water contact and may show coning. In other regions, low-permeability baffles restrict vertical water movement and delay water-cut development. Analysis of the water-rise rate, interpreted from logs and single well modeling, provides a useful diagnostic tool for the recognition of normal bottom-up rise, coning, delayed rise due to baffles, and anomalous flows behind pipe.

(#360-O) Demultiple and prestack migration techniques applied to vintage seismic data highlight challenges and strategies for developing Saudi Arabian Red Sea plays

Charles R. Beeman, Jesse I. Shaw, D. Mark Steinhauff and Mark V. Wood, **ExxonMobil**

Vintage 1970s Red Sea seismic data present both opportunities and challenges where deep water and thick Miocene salt sequences cause severe imaging problems. Modern seismic reprocessing techniques, such as demultiple and prestack migration, are providing key insights into planning future seismic programs and focusing exploration strategies. The vintage data are Esso Egyptian Red Sea (ERS) and Esso Saudi Red Sea (SRS) stacked seismic. The ERS data had 48 channels with a 2.6-km maximum offset and the SRS data 66 channels and 3.2 km maximum offset. Depth-migrated images and analysis of these data are helping in the modeling, planning, and designing of future Red Sea seismic acquisition programs.

The demultiple methods used were wave equation algorithms to remove simple water bottom multiples and Radon transforms to remove residual multiples. Prestack time and depth migration have reduced noise and improved presalt reflection continuity and the positioning of reflectors. They have provided confidence that modern acquisition and processing techniques can yield improved seismic imaging. The combined techniques have improved the imaging of salt structures and dipping stratal reflectors below the salt, and sharpened fault-plane events. Pliocene-Pleistocene faults that sole out into Miocene salt layers can now be distinguished from older synrift basement block faults. Exploration targets will be more easily identified due to improved interpretations of fault-plane geometry, salt kinematics, sequence stratigraphy, and structural growth history.

(#16-O) Cenozoic carbonate platform development in NE offshore Tunisia

Abderrazak Belhaiza and Fraj Hammouda, **ETAP**

The study area consisted of the Cenozoic carbonate platforms of Bou Dabbous, Halk El Menzel, Ketatna, Ain Grab, Oued Belkhedim, and Melquart.

The extensive Lower Eocene open-marine platform of Bou Dabbous consists of *Globigerina*-rich mudstone-wackestone. The deposits increase in thickness northward and southward from a central eroded high. The fractured Bou Dabbous section flowed up to 20,000 barrels of oil per day in Belli-1 and, recently, more than 3,000 barrels of oil per day from Al Manzah-1.

During the Middle to Late Eocene, a minor compressional phase occurred, as shown by the locally developed base-Halk El Menzel unconformity. The shallow-marine Halk El Menzel platform developed to the west of the uplifted area and the equivalent deep-marine Souar shale was deposited to the east. The carbonate section was deposited in a shallow-marine to inner-neritic environment. Post-Eocene uplift induced dolomitization, mostly in the central gulf of Hammamet. Reservoir properties are good (porosity about 25%; permeability >700 mD) but only traces of dead oil have been found in the Oudna-2 and Tazerk-3 wells.

During the Late Oligocene to Early Miocene, a N140° compressional phase occurred, new areas were uplifted, and the Late Eocene central highs became elongated northward. At this time on the Ketatna platform to the west of the central NE-elongated high, wackestones-packstones rich in fossil debris were partly recrystallized into slightly dolomitized microspar. The presence of *Lepidocyclina* and *Coelenterites* indicate a shallow-marine upslope environment with local bioconstructions. Porosity of up to 30 percent in Halk El Manzel-1 was associated with good permeability that was improved by the close-spaced fracture system and diagenesis. The late Langhian Mahmoud shales are the top seal. The Ketatna reservoir tested 2,200 barrels of oil per day in Halk El Manzel-4.

The transgression that began in the early Langhian led to the flooding of most of the previously uplifted areas. It produced the Ain Grab carbonate platform composed of packstone-grainstone that grade upward into shaly wackestone and shale. Three depositional environments are (1) a gypsiferous carbonate facies (inner-shelf) in the Cap Bon peninsula, (2) a sandy limestone facies (middle-shelf) to the south, and (3) a shaly limestone facies (open-marine shelf) to the north. A N140° compressional phase in the late Tortonian caused local tectonic inversions. The eastern part of the Gulf of Hammamet continued to shallow and

gypsum deposits are indicative of lagoonal environments. A restricted gypsiferous carbonate platform (Oued Belkhedim) formed to the north and east and an open-marine carbonate platform (Melquart) developed to the south.

(#173-P) What is the benefit of using prestack attributes?

Charles Bertrand, **Beicip-Franlab**; Thierry Tonellot and Frédérique Fournier, **IFP**

It is becoming common practice to perform 3-D prestack inversion of iso-offset or iso-angles cubes, in order to estimate elastic parameters such as P- and S-impedances at the reservoir level. In particular, S-attributes should provide information on the reservoir parameters complementary to the information derived from P-attributes.

In the context of prestack attributes, four questions arise. (1) What is the amount of non-redundant information provided by the S-attributes? (2) What are the best parameters (such as impedances and Lame parameters) for interpreting prestack attributes in terms of reservoir properties? (3) How to define reservoir properties that are significantly related to the P- or S-information? (4) What is the impact of the limited bandwidth of the prestack seismic attributes on the reservoir property estimation?

These questions will be examined in this presentation through a deep-water case study. A general workflow has been proposed to quantitatively exploit the pertinent prestack attributes in relation to the reservoir properties, while assessing the uncertainties of such an interpretation. The workflow involved segmentation algorithms and estimation techniques in a probabilistic frame. It allowed for the derivation of maps or cubes of average reservoir properties, such as porosity or shale volume, and their associated uncertainties. It was an efficient tool for quantifying the benefits of prestack attributes.

(#322-P) July/Ramadan: 3-D imaging of six merged surveys

Frédéric J. Billette and Jim Mika, **BP**; John Garing, Jay Thorseth, Gary M. Mercado, Hatem Farouk and Norman C. Allegar, **GUPCO**

'July/Ramadan' is a 3-D seismic imaging project located in the central Gulf of Suez, Egypt. Amoco, and now BP, has been very active in this area. For this application, we unified six different surveys of various vintages in order to improve the data coverage around individual acquisition boundaries. A phase-matching filter was estimated by comparing each survey to a reference one. This allowed us to continuously image the whole area. The size of the project area was approximately 30 x 30 km. Multiple reflections were a major problem that is partially addressed in this presentation. The geological regime is quite complex and previous time or poststack processing did not provide sufficiently accurate images. To image subsalt targets, a 3-D prestack depth-imaging sequence has proved advantageous. The velocity model was estimated using migration-based 3-D tomography and salt flooding. The non-regular geometry of the unified dataset did not allow us to take advantage of common-azimuth types of migrations. Thus, we used a general Kirchhoff algorithm. Intensive computer usage allowed 3-D imaging to be completed within a few weeks. Subsalt high-angle faults and dipping layers that had not been seen clearly before were better imaged. Well control indicated a depth and dip-tie within expected margins. Since delivery, the dataset has been used in the appraisal and development program of a discovery well and in the development of two major exploration prospects scheduled to be drilled soon. This dataset is to be used in the upcoming field study of the giant Ramadan oil field.

(#207-O) Identification of non-reservoir facies within a giant Cretaceous reservoir using 3-D seismic data: onshore Abu Dhabi

Naji S. Binbrek, Khaled A. Al-Amari, Yousuf S. Al-Mehairi, Andrew M. Gombos and Ahmad A.W. Al-Shaikh, **ADCO**

The giant field is an onshore structure in central Abu Dhabi. The Cretaceous rudist-rich carbonate reservoir contains inclusions of non-reservoir facies in the southern part of the field (designated as 'I-Dense'). The I-Dense originated as carbonate mud deposited in a lagoonal environment and was compacted into hard mudstone. The inclusions are from 10 to 100 ft thick and have porosity values of from 0 to 8 percent. Twenty-eight wells have penetrated the I-Dense inclusions.

A recent field study was made to identify these non-reservoir facies. Mapping their distribution was required in order to correctly discount the Stock-tank Oil Initially In Place (STOIIP) and assess the potential of the inclusions as flow barriers. A significant factor in the field study was the acquisition of recent 3-D seismic data. This showed that I-Dense could be detected from seismic amplitudes but that it was not possible to unscramble the effect of porosity from thickness changes

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on seismic amplitudes. Nevertheless, by combining the RMS amplitude attribute and isochron anomalies within the Shu'aiba reservoir, it was possible to capture the distribution of I-Dense from the 3-D seismic data. The data indicated that I-Dense occurs as discrete bodies rather than as continuous layers and that they do not act as significant flow barriers. By knowing the location of the I-Dense inclusions it will be possible to avoid drilling into them with the consequent loss of well productivity. Infill drilling has successfully used the 3-D seismic to avoid penetrating the non-reservoir inclusions. STOIIP reduction in the southern part of the field is about 2 to 4 percent, but these results will be refined by the use of the acoustic impedance inversion of the 3-D seismic cube.

(#94-O) Palynostratigraphy and paleobiogeography of Late Devonian strata in central Iran, NE of Yazd

Bijan Biranvand, **NIOC**

In order to determine more precisely the age and paleogeographical relationships of the Devonian strata north of Yazd, a stratigraphic section was measured and sampled. A total of 72 surface samples were collected and the palynomorph content studied. All samples contained well-preserved and abundant miospore, scolecodont, chitinozoa, and acritarch taxa. The microscopic study identified 87 palynomorph species (38 acritarch and 49 miospore). These were arranged into four biostratigraphic zones. As a result of comparisons with palynomorph taxa and bizones elsewhere, a Late Devonian (Frasnian-Famennian) age was assigned to the Devonian rocks north of Yazd. The palynological and lithological data indicated that the area was located in tropical paleolatitudes and that a shallow-marine environment prevailed.

The study also identified two hiatuses in the Paleozoic sequence. The first occured between the Shirgesht and Shishtu (member 1) formations and had a duration of Late Ordovician to Early or Middle Devonian, possibly corresponding to the Caledonian Orogeny. The second hiatus was between the Shishtu (member 1) and Jamal formations.

(#357-P) Petrophysical modeling and simulation of carbonate outcrop analogs

Wolfgang Blendinger
and Lutz Stecken, **Clausthal Technical U.**

Many outcrop analogs of hydrocarbon-bearing carbonate formations have completely lost porosity and permeability as a result of diagenesis. In contrast, adjacent subsurface equivalents have commonly retained economic properties, often due to early charge. This is particularly so for Middle East carbonates, whose outcrops are generally suitable only as stratigraphic analogs.

In order to map and quantify the distribution of petrophysical properties at the interwell scale (hundreds of meters), we selected Permian patch reefs in Thuringia in central Germany. They served as analogs for interpreted subsurface patch reefs with dimensions of up to 1 km, such as in the Cretaceous Shu'aiba Formation or the carbonate stringers in the Infracambrian evaporites of Oman. The Permian patch reefs are perfectly exhumed. They consist of early diagenetic dolomite 40 to 100 m thick with high (20–30%) residual primary and moldic porosities, and permeabilities of about 100 mD. Reef flank, reef flat, and offreef facies have variable petrophysical properties. A sampling program on a grid of about 10 x 10 m in abandoned quarries allowed detailed modeling of the 3-D distribution of petrophysical properties, and the subsequent simulation of flow properties in a dynamic simulator.

(#271-O) Twenty years of 3-D seismic in ADCO: a review.

Gérard Bloch, Abu Baker Al-Jeelani, Erik B.J. Kleiss, Abdulsalam M. Bin Ishaq, Patrick Fouchard, Peter D. Melville and Ahmed A.W. Al-Shaikh, **ADCO**

Abu Dhabi Company for Onshore Oil Operations (ADCO) acquired its first 3-D survey in 1984 at a time when 3-D was an emerging technology. Due to high costs and limited recording channels, the fold was low (typically 16 to 24) resulting in relatively poor quality data, partly offset by the benefits of having a continuous volume of seismic data when compared to 2-D. ADCO's second 3-D survey was in 1992, and since then it has acquired 3-D data at the rate of about 750 sq km per year, mainly over difficult terrains, such as sand dunes and transition zones. Data quality improved slightly, but 3-D volumes were still mainly used for structural information and it was not until the later part of the 1990s that the era of 3-D seismic for carbonate reservoir characterization truly began. From 1994 to 1997, ADCO acquired two large surveys covering 1,780 sq km. For the first time, it was possible to map complex en echelon fault zones and produce accurate depth maps. Inversion techniques also allowed average reservoir porosity prediction away from well control with a higher degree of confidence.

Recent 3-D surveys aimed at reservoir characterization have shown a marked improvement in data quality.

Fold coverage is now typically above 100 (reaching 600) but, thanks to improved acquisition techniques, costs have been controlled. The frequency content has expanded from about 40 Hz in the mid-1990s to about 80 Hz today at depths of around 9,000 ft (1.5 sec TWT), so increasing the vertical resolution by a factor of two. ADCO has covered almost 8,000 sq km of its acreage with 3-D, and the last survey of its giant fields is in progress.

The costs of 3-D seismic data can be offset against better producer locations by targeting sweet spots in the reservoir, and by fewer drilling problems. Nowadays, 3-D seismic is an invaluable tool in constraining static reservoir modeling down to the log-scale by using stochastic techniques. This has resulted in more confidence in drilling locations (accurate geosteering) and reserve evaluations, ultimately reducing the financial risks of exploration and development. Nevertheless, two major challenges remain—the vertical seismic resolution and multiple attenuation—both factors limiting inversion and quantitative reservoir studies.

(#287-P) One step beyond fractured-reservoir management: a multiscale integrated approach

Marie-Odile T. Bockel-Rebelle, Yann Lagalaye and Sylvie O. Delisle, **TotalFinaElf**

What is the optimum way of implementing our latest research improvements within an operational workflow for fractured-reservoir characterization and dynamic modeling, in order to enhance field productivity and recovery? Our approach enables us to define the ranking of the various fracture types and to focus on the adapted type of dynamic modeling (single medium, dual medium, conductive faults).

Fracturing occurs at various scales from the microfracture to the fault, and implies different mechanisms of generation. Several types of fracturing can therefore coexist in the same reservoir and should be approached and modeled in different ways. Thus, the first question that should be asked when dealing with a new field, whatever the state of its maturity (development stage) may be, is this: Is there suspicion that the fracturing has an effect on the dynamic behavior of the field? Secondly, what is the type of fracturing concerned?

Through examples from the Middle East, we will illustrate three scales of fracturing and their static and dynamic characteristics. (1) Small-scale or diffuse fracturing usually modeled through its equivalent parameters (permeability tensor and block size). (2) Fractured corridors and 'conductive faults' that can be explicitly modeled thanks to new research. (3) Large-scale faults in which the modeling focuses on the two main components; namely, the damaged zone and the core zone, each with their proper characteristics. A diagnostic is then performed in order to estimate their sealing potential based on the geological and dynamic understanding.

(#367-O) Direct hydrocarbon indicators in Cretaceous and Jurassic carbonate reservoirs, onshore Abu Dhabi

Martin P. Boekholt, **ADCO**; Mohamed N. Luheshi, **BP;** Rafael M. Rosell, Jean-François Dervieux, Abu Baker Al-Jeelani, Suleiman Ali, Abdullah A. Al-Aidarous, Abd El-Fatah El-Agrab, Azhari A. Abdalla, Fatema Al-Shekaili and Naema Al-Zaabi, **ADCO**; Steve Smith, **BP**; Bernard J. Pierson, **Shell**

Oil and gas reserves of the Abu Dhabi Company for Onshore Oil Operations (ADCO) are contained within Upper Jurassic and Cretaceous carbonate reservoirs. Seismic amplitudes and inversion studies have provided convincing evidence for Direct Hydrocarbon Indicators (DHI) in several major ADCO fields. Amplitude brightening conformable to structure was observed in four Cretaceous and Jurassic reservoirs, as the seismic amplitudes reflect the better porosity in the hydrocarbon-filled reservoirs compared with water-wet rocks. The porosity in the pay zones was preserved due to hydrocarbon fill very shortly after structure formation, which itself occurred soon after deposition of the sediments. Hence, the diagenesis of the hydrocarbon-filled carbonates was significantly slowed down compared with hydrocarbon-free rocks.

Well-calibration studies on the carbonate reservoirs, and the forward modeling of synthetic seismic sections, have quantitatively assessed the rock and fluid properties. In the four carbonate reservoirs, the hydrocarbon-filled rocks had a higher porosity (6–10 units) than the water-wet rocks. The change was independent of the depth of the reservoir and the type of the hydrocarbon phase (gas or oil). Hence, the hydrocarbon phase is of secondary importance to the seismic response; the major influencing factor is the porosity preservation in hydrocarbon-filled rocks.

The key for the confident detection of DHIs was the integration of data from nine 3-D surveys totaling about 6,000 sq km, 700 2-D lines, and 150 exploration wells. It was aided by the excellent quality of newly acquired 3-D seismic and the high-quality regional interpretations of 11 key Permian to Eocene horizons. The horizon and fault interpretations unraveled the structural style and helped in timing the formation of

structures. The information was input to a 3-D basin model that indicated the migration pathways and the time of maximum hydrocarbon expulsion.

(#7-O) Is wetter better? The impact of paleoclimate on vadose diagenesis and its implications for reservoir characterization

Richard D. Bray, **Saudi Aramco**;
Eugene C. Rankey, **Iowa State U.**

Recognition of subaerial exposure features is important in defining surfaces of stratigraphic and diagenetic significance. Their character and level of development are strongly related to paleoclimate. In this presentation we will compare and contrast subaerial exposure features from humid and arid paleoclimatic settings, and discuss the possible implications for early diagenesis and reservoir characteristics.

The Arab-D reservoir (Upper Jurassic) of eastern Saudi Arabia and the Holocene of Abu Dhabi contain numerous examples of subtle vadose diagenesis developed in arid settings. Diagnostic features include micritic meniscus cements (volumetrically the most common), calcite pendant cements, calcite meniscus cements, and circumgranular cracking. These definitive vadose features are commonly associated with less-diagnostic features such as reddened (hematitic) grains and surfaces, patchy distribution of vadose cement, blackened surfaces and grains, perched sediments, dedolomite, quartz silt, clays (kaolinite), and micropelopids. Early marine cements are noticeably absent in these arid examples. In contrast, the Pleistocene of south Florida and the Pennsylvanian-Permian of the Permian and Mid-Continent basins of the USA have abundant, very strongly developed subaerial exposure features that formed in humid settings. In these rocks, karst phenomena, rhizoliths, root tubules, and laminated crusts are conspicuous macroscopic features, and pendant and meniscus cements, alveolar structure, and circumgranular cracks are common microscopic elements.

In general, the early, meteoric stage in the more arid climate favors less pronounced dissolution, less vertically extensive moldic porosity, and more retention of primary porosity. As a result, the porosity and permeability remain similar to those of the depositional facies. In the absence of later diagenesis (perhaps limited by early migration of hydrocarbons), flow units, barriers, and baffles follow depositional patterns. In contrast, in more humid settings, diagenesis results in an early redistribution and occlusion of porosity, and depositional facies may no longer represent flow units, barriers, and baffles.

(#340-O) Tectonic and geologic evolution of Syria

Graham E. Brew*, **ChevronTexaco**; Muawia Barazangi, **Cornell U.**; Ahmed K. Al-Maleh, **Damascus U.**; Tarif Sawaf, **Al-Furat Oil Company**

Syrian hydrocarbon plays are critically dependent on aspects of the regional tectonic evolution. We have detailed this evolution through the interpretation of extensive surface and subsurface data. Products of this research include several subsurface structure maps and a new tectonic map of Syria. Our interpretations show that Syrian tectonic deformation is focused in four major zones that have been repeatedly reactivated in response to activity on nearby plate boundaries. These diverse zones are the Palmyride Mountains and Abd el Aziz / Sinjar uplifts (both inverted basins), the Euphrates Fault System (a failed rift), and the Dead Sea Fault System (a transform fault). The first three zones contain major reserves of hydrocarbons.

Our synthesis shows how specific deformation episodes within Syria were penecontemporaneous with regional-scale plate tectonic events. After a relatively quiescent early Paleozoic shelf environment, the NE-trending Palmyride / Sinjar trough formed across central Syria in response to regional compression followed by Permian-Triassic opening of the Neo-Tethys Ocean and the eastern Mediterranean. This continued with carbonate deposition in the Mesozoic. Late Cretaceous tectonism was dominated by extension in the Euphrates Fault System and the Abd el Aziz / Sinjar graben in eastern Syria, associated with the closing of the Neo-Tethys. Repeated collisions along the northern Arabian margin from Late Cretaceous to Late Miocene caused platform-wide compression. This led to the structural inversion and shortening of the Palmyride trough and Abd el Aziz / Sinjar graben. Each element in this evolution has controlled different aspects of the hydrocarbon plays.

* This work was done while the primary author was at Cornell University

(#14-P) Incorporating uncertainty in porosity estimates from seismic plus well data as applied to a Middle East field

Michael K. Broadhead, **Saudi Aramco**

A method of estimating spatially distributed mean porosity together with uncertainty bounds was developed and applied to the carbonate reservoir of a field in Saudi Arabia as a means of refining reserve estimates. Seismically derived acoustic impedance and

borehole data from wells were used, the latter consisting of core and log data related to porosity and impedance. Major problems were how to represent the various types of uncertainties and how to combine them for the final estimate of mean porosity with a meaningful confidence interval.

Representation of the uncertainties was based on the geological variability (for example, minerals, fluids, porosity type/pore shape, and depositional environment), and the seismic variability (for example, data quality, processing, inversion, and well-tie issues). Marginal and conditional Probability Density Functions (PDFs) were estimated from the data. These were used to model the joint PDF, from which the PDF for porosity could be computed by direct integration (this last step can also be done by the Monte Carlo method). The conditional PDFs were provided by regression analyses. However, estimating those that represent the seismic inversion between well control was difficult. Hence, several strategies were investigated. Details of the algorithm will be given, as well as application to the data set, and the relative contribution of major sources of uncertainty will be assessed. Seismic data adds information but also uncertainty: this trade-off will be discussed.

(#215-P) Mixed Late Permian floras and related paleoenvironments in the upper Khuff Formation of central Saudi Arabia

Jean Broutin and Martine Berthelin, **U. Pierre et Marie Curie;** Mohammed Halawani, **SGS**; Denis Vaslet and Yves-Michel Le Nindre, **BRGM**

Mixed Late Permian paleofloras related to the Gondwana, Eurameria, and Cathaysia paleocontinents are found in the uppermost part of the Midhnab Member of the upper Khuff Formation in Qasim Province, central Saudi Arabia. Numerous new taxa have been discovered in three new fossil localities between Al Wahta (east of Buraydah) and Midhnab (southeast of Unayzah).

Sandy or clayey deposits reflect the paleoenvironment-dependence of the various macrofloral associations. A sphenophyte association, mainly of Cathaysian species like *Lobatannularia*, was associated with floated trunks of gymnosperm affinity and characterizes a sandy deltaic environment. A dominantly pteridophyte association, with abundant pecopterids, occurred in clayey swampy deposits. Lateral facies variations showed both associations to be at the same stratigraphic level. The microfloral associations, dominated by gymnosperm bisaccate pollen, accord well with a Late Permian age and were very similar in composition to the coeval palynological assemblages described in the Salt Range (Pakistan) and Australia. Macrofloras in the clayey lower part of the overlying Khartam Member included typical vegetation, leaves, and fructifications of Gondwanian glossopterids intermingled with Euramerian coniferous leafy shoots. Floras and microfloras both confirm a Late Permian age for this part of the Khuff Formation.

The occurrence of mixed Permian paleofloras, the intermingling of Gondwanian, Cathaysian, and Euramerian floral elements, and the discovery of numerous glossopterid remains (including well-preserved fructifications and fertile leaves) are of primary importance for constraining major plant-cover changes. Moreover, they can be linked to the geographic and climatic evolution throughout southern Pangea during Permian times.

(#181-P) 3-D seismic reservoir characterization: an original application of a neural network in the UAE

Dominique F. Chenot, **TotalFinaElf**; Abu Baker Al-Jeelani and Antonio Valle, **ADCO**; Jean-Luc Piazza and Nirina Haller, **TotalFinaElf**

This presentation describes how 3-D seismic reservoir characterization contributed to the management of a main reservoir unit in a major Abu Dhabi field. The challenge was to detect dense units that seemed, despite numerous well intersections, to be randomly distributed. The field is covered by a very high-quality 3-D seismic survey. The definition in terms of spatial distribution and porosity variations of these dense units used the most advanced tools for seismic reservoir characterization.

The dense units vary in position, thickness, and porosity within the reservoir. An appraisal of their origin, which is still not fully understood, required geological evaluation of well data. It provided key elements for the 3-D seismic reservoir characterization. Based on well data, synthetic seismic modeling was performed to obtain a set of seismic model traces corresponding to the dense unit in the reservoir. A multiwell approach was implemented in order to estimate the optimum seismic wavelet characterized in terms of frequency content and phase rotation, as well as by the signal-to-noise ratio. Different classification approaches were then performed, taking into account the various seismic attributes derived from the 3-D seismic cube and the inverted impedance cube. The classification results were correlated first against the dense unit occurrences in the well data, and secondly against the modeling results in order to derive a detailed description of the dense unit.

(#71-O) Re-appraisal of a mature carbonate reservoir in North Kuwait and integration into the development plan

Hom B. Chetri, Ravula V. Chakravarthy, Bader Al-Matar and Mubarak M. Al-Hajeri, **KOC**; Bill Hill, John Isby and Alan J. Clark, **BP**

The Mauddud reservoir in North Kuwait's Sabiriyah field is a giant multilayered carbonate reservoir of about 250 sq km that has produced oil since the 1950s. It is undergoing a phased waterflood development. Phase1 developed the crestal area (50 sq km) of the structure, with the second phase developing the remaining peripheral acreage (200 sq km). Most wells are in the crestal area and account for 83 percent of production. In contrast, little was known about the Phase 2 area due to few well penetrations and minimal production. A review of the areal distribution of wells, logs, core, and test data emphasized reservoir property uncertainties and showed large data gaps. It identified five reservoir segments—one crestal segment (Phase 1) to be appraised through the evaluation of ongoing waterflood performance, and four Phase 2 segments with sparse well control needing further appraisal prior to Phase 2 drilling. Three new appraisal wells were drilled within three Phase 2 segments, and data on fluid contacts, rock quality, and fluid quality were collected. In addition to the available open-hole logs, a series of repeat formation tests, core and zonal fluid sampling, pressure-volume-temperature studies, and productivity injectivity tests were conducted in all appraisal wells. Opportunistic reservoir data were collected during workover operations on the few wells of the Phase 2 area. The dynamic performance of the producers and injectors on the outskirts of the Phase 1 area further enhanced the understanding of the reservoir dynamics. Geochemistry on cores from the appraisal wells and on zonal oil samples have provided insights into the filling process.

It was concluded that a large segment within the Phase 2 area, originally considered to contain light oil, actually contains viscous oil. The appraisal also helped the ongoing dynamic modeling and development planning for this multibillion-barrel reservoir.

(#99-P) Prediction of waterflood residual oil saturation in the carbonate reservoirs of North Kuwait

Alan J. Clark and Edwin Vervest, **BP**; Hom B. Chetri, **KOC**

The Mauddud carbonate reservoirs in the Sabiriyah and Raudhatain fields of North Kuwait are being developed with large (800–1,000 acre) inverted 9-Spot patterns. In preparation for waterflood startup, pilots were run from mid-1997 until late-1999 in both fields. Examination of oil saturation in water-swept zones, obtained from pulsed neutron logs in the Waterflood Pilot (WFP) wells, suggests that Residual Oil Saturation to Water Displacement (Sorw) can be predicted as a linear function of initial water saturation, log permeability, and porosity. The reservoir is interpreted to be intermediate to oil wet.

A simple procedure will be presented for developing linear correlation of Sorw, using the LINEST feature in EXCEL to process steady-state Special Core Analysis data and combinations of log/core data. The predictions of Sorw for Mauddud WFP wells, were compared with observed saturations in water-swept zones and production logging tool results. Continuation of the Sabiriyah WFP will be discussed, including the requirement that the capture cross-section of the injected water be maintained, if thermal decay-time logs are to be used to track saturations. Recent experience with through-tubing carbon-oxygen logging will also be discussed in relation to the observed sweep in a WFP observation well.

(#188-O) Stellar™: the ExxonMobil integrated basin-modeling system

William S. Clendenen, W.A. Symington, S.L. Lyons and J.C. Sempéré, **ExxonMobil**

Hydrocarbon systems analysis is an integral part of ExxonMobil's worldwide exploration effort. Both Mobil and Exxon had independently developed innovative proprietary technologies that put them at the forefront of the basin-modeling field. ExxonMobil has aggressively pursued the integration of these leading technologies and mined the expert knowledge of the two heritage companies to create a powerful new basin modeling system, Stellar™, that influences exploration decisions across the company.

Stellar™ consists of both proven work processes and state-of-the-art software that allows rapid, complete, and fully integrated evaluation of the hydrocarbon system at basin and prospect scales. The Stellar™ system integrates analyses of source-rock maturity, hydrocarbon yields, hydrocarbon migration, fluid pressure, reservoir quality, top-seal integrity, and fluid properties; and it contains proprietary technologies for rigorous calibration of the basin model. The system predicts hydrocarbon-charge history, the pressure-volume-temperature evolution of hydrocarbons, and overpressure by using accurate 3-D thermal and fluid-flow calculations. Ray-tracing, seismic-volume interpretation techniques, and fluid-flow calculations

are used to analyze potential hydrocarbon migration routes to a prospect. Reservoir quality is addressed by quantifying the reduction in reservoir porosity due to compaction and quartz cementation. Stellar™ propagates uncertainties in the basin model and provides quantitative estimates of risk in charge, fluid properties, and reservoir quality, for use in business decisions. In response to new business challenges, Stellar™ is continuously being improved through an aggressive research program.

(#356-P) Petrologic controls on reservoir quality in the Devonian Jauf Formation sandstones of Saudi Arabia

Joshua D. Cocker, **Saudi Aramco**; Robert W. Knox, Graham K. Lott and Tony A. Milodowski, **BGS**

In the Jauf reservoir, pore-lining illite cement is essential to the preservation of the primary intergranular porosity and permeability. In the absence of illite, the sandstones have undergone near-total cementation by quartz overgrowths. In this study, the primary objective was to determine the petrological controls that lie behind this diagenetic differentiation.

Five key stages were recognized in the diagenetic evolution of the Jauf sandstones. (1) Grain coating of mud pellicles was an early development in all but beach-facies sandstones. (2) Nucleation of illite on mud pellicles: fine-grained mud pellicles hosted densely nucleated isopachous-illite fringe cements, whereas coarse-grained mud pellicles host sparsely nucleated pore-filling fibrous illite cements. (3) Illite cementation ended with the development of pervasive pore-filling illite cements. (4) Onset of quartz cementation: normal quartz overgrowth cements developed, in the absence of illite, at relatively high temperatures (120°–160°C) and from low- to high-salinity fluids based on fluid inclusion data. (5) In sandstones with pore-lining illite cements, quartz cement developed through the rupturing of the illite rim caused mainly by compactional fracturing at grain contacts.

Although mud pellicles have exerted a fundamental control on reservoir quality in the Jauf sandstones, their mode of formation is poorly understood. However, the absence of pellicles in beach-facies sandstones indicates that pellicle formation was confined to estuarine environments. In estuaries, tidal pumping may have led to a repeated flow of mud-laden waters into and along beds of permeable sand. This link between the sedimentary environment and the preservation of pore space is the key to predicting reservoir quality.

(#364-P) Heavy-mineral provenance signatures from Paleozoic sandstones of Saudi Arabia

Joshua D. Cocker, **Saudi Aramco**; Robert W. Knox, **BGS**; John Filatoff, **Saudi Aramco**

Heavy-mineral analysis has been carried out on Cambrian to Permian sandstones from three sections in northern Ghawar, southern Ghawar, and the Hawtah field. The primary aim was to assess the potential of the technique in the correlation of sand units and the reconstruction of sand-dispersal systems.

Mineral assemblages had low diversity throughout, reflecting derivation from source rocks of restricted lithological variation. As a consequence, the range of provenance-sensitive mineral signatures was limited and the potential for unique mineral signatures was low. Despite this, it was possible to demonstrate that the Paleozoic sandstones display marked geographical variations in mineral signature, especially in the Cambrian to Devonian sections. This indicated that the sands were derived from relatively local sources, with limited mixing between sands of different dispersal systems.

The greatest potential for stratigraphic correlation was found in the distribution of apatite. Apatite is a common constituent in most metamorphic and igneous rocks, but is highly sensitive to dissolution by acid meteoric waters. Variation in the abundance of apatite is therefore most commonly related to variation in the intensity / duration of weathering, both at outcrop and at shallow depths within alluvial floodplains. In the Cambrian to Devonian successions, apatite was generally absent, so that where it did occur it was useful both as an indicator of long-term climatic change and as a correlation tool. The greatest potential for correlation at the reservoir scale appeared to be in the Permian sandstones, where apatite abundance showed marked stratigraphic variations in some sections.

(#265-O) Mixed Reality Virtual Centers: the next step in geoscience data visualization

Daniel H. Cooper
and Mohammed A. Tayyib, **Saudi Aramco**

No topic in geoscience Information Technology has generated more excitement or anticipation than the integration of virtual reality into collaborative workgroup activities. Hailed as the new paradigm for

data visualization and manipulation, virtual reality offers the geoscience professional the ability to interact with digital information in a simulated 'real world' environment. Mixed Reality, achieved through the full integration of Immersive Virtual Reality and Telepresence, extends the application of virtual reality beyond the limits of the physical visualization facility and introduces the concept of Virtual Centers.

In recent years, the oil and gas industry has invested heavily in the development and installation of Virtual Reality Centers. Most operate as Physical Virtual Reality Centers (PVRC) in which all participants are present at the facility for a common purpose. This approach to centralized collaborative interaction has represented the industry's first attempts in support of multidisciplinary asset-team management.

The Mixed Reality Virtual Center (MRVC) model proposed in this presentation is intended to extend the concept of the PVRC by moving outside the confines of a fixed location. By employing recent advancements in interactive 3-D computer graphics and communications technology, the MRVC will give professionals common multi-user access to 'virtual worlds'. These will reside on MRVC server sites, accessible from the user's desktop workstation. The MRVC will significantly enhance the collaborative benefits of the PVRC by incorporating many of the more advanced concepts of mixed reality graphics processing. Through LAN / Internet communications, users will be able to enter a project environment independently and communicate with others in the same virtual space. The use of advanced virtual reality graphics architectures will expand the user's sensation of real-world interaction beyond that currently experienced in the PVRC.

In this presentation we will explore the MRVC model and compare it with current PVRC implementations. A synopsis of the MRVC architecture will be presented, together with suggested implementation strategies for the oil and gas industry.

(#197-O) Source rocks of the Middle East and North Africa: the integration of a Geographic Information System with geoscience

Mark Cowgill, Colin Darlington, Heather Clegg and Mike J. Goodrich, **RRI**

Data illustrating the source-rock facies distribution of the laterally extensive Early Silurian source rocks of North Africa and the Middle East (Tanezzuft and Qusaiba formations and equivalents) have been compiled and mapped. The data were incorporated as a Spatial Database Engine (SDE) layer using ArcInfo and can be viewed and manipulated using ArcView. The paleogeographic evolution of the region will be illustrated and suggests that the presence of an uplifted area centered over the Sinai Peninsula during the Silurian was responsible for the absence of source rocks in that area. 1-D modeling within each sedimentary basin enabled the assessment and definition of the depths at which the source rock was likely produce hydrocarbons. This information was combined with the facies distribution maps to create oil and gas kitchen maps for the region.

The distributions of oil and gas kitchens were stored as a separate SDE layer. Migration distances from these kitchens and likely migration pathways were determined from the analysis of regional structure, reservoir, and seal data. The storage of such data combined with field and well data as additional SDE layers and comparison with petroleum system events charts, will enable exploration geologists to determine the prospectivity of open acreage and farm-in opportunities. Thus, using a Geographic Information System, the main risks of any element of the petroleum system can be rapidly assessed at any scale.

(#81-O) Pass the salt: the terminal-Proterozoic presalt Buah play in Oman

Andrea Cozzi, Hisham A. Al-Siyabi and Rashid Al-Hashimi, **PDO**; John P. Grotzinger, **MIT**

Intrasalt carbonates, showing heavy 'stringer' dependence and little diversification, dominate Petroleum Development Oman's (PDO) Exploration Prospect portfolio. The need for new plays (and the recent success in presalt reservoirs) has rejuvenated the interest in Oman's presalt stratigraphy. The presalt Huqf Supergroup consists of five formations. The terminal-Proterozoic Buah carbonates are the youngest of these and represent the most promising presalt exploration target.

To assess the prospectivity of the Buah in PDO's concession area, an integrated outcrop-subsurface study was initiated. High-resolution chemostratigraphy and field gamma-ray surveys were used to correlate outcrop data with PDO's subsurface database. This allowed the reconstruction, at unprecedented accuracy, of the distribution of Buah depositional environments throughout Oman. The results indicated that the Buah Formation was deposited on a slowly deepening shallow-water carbonate ramp in an intracratonic basin during a highstand systems tract, as a shallowing and upward-coarsening cycle. Good reservoir facies (peloid-

ooid grainstones) are ubiquitous in the shallow-water deposits.

The Buah Formation forms continuous sheets that extend for tens of kilometers. Karst and fracture developments at the top Buah may improve the reservoir quality, as shown already in the Makarem field. The Ara salt generally caps Buah reservoirs, except on structural highs where the top seal is provided by mudstones of the middle Haima Group. The Buah off-ramp basinal facies represent potential source rocks with total organic carbon contents ranging from 2.5 percent to 3.5 percent. Combined Buah risk maps delineate areas with good potential for both oil and gas exploration.

(#291-P) Determination of permissible wind-induced noise during seismic data acquisition for assured poststack success

Peter A. Crisi, **Saudi Aramco**; Timothy J. Perrin, **WesternGeco**

Seismic acquisition parameters are designed to account for a wide range of factors including target geology, surface geology, and the normal ambient noise conditions. Exceptional conditions, such as earthquakes, low-flying military aircraft, and strong wind, all produce high-amplitude noise. This results in data-quality degradation to the extent that data must be omitted or reacquired, or production halted until conditions improve.

Halting production or reacquiring data both have an associated cost. Finding out after stacking that recording noise levels were too high to achieve the survey objectives would be disastrous. Normal procedures to avoid problems are to halt production when noise levels exceed an arbitrary level, or when 'gut feelings' suggest poor results. These procedures lead to lost production for the client and lost revenue for the contractor, with no guarantee of success.

By recording noise under various surface geology and wind speed conditions, and relating these records to recording-truck spread noise measurements, we can characterize the noise for the different wind conditions. Taking a benchmark section of line in a new prospect, and adding noise to the raw data to represent different noise conditions, simulates recording the line under controlled wind conditions. Analyzing and interpreting data sets created in this way defines target-oriented noise thresholds that can be applied in the field in real time.

(#141-O) Exploration of Mesozoic rift basins in the central Yemen North Hoowarim Block-44.

Enrique A. Cuervo and Rick Schmitt, **Occidental**

Yemen's exploration potential extends beyond the established productive areas. The two main discoveries, by Hunt in 1984 in the Marib-Al Jawf basin and by Nexen (formerly Canadian Occidental) in 1990 in the Sayun-Masila basin, triggered exploration throughout the region. A subsequent lack of significant success reduced interest over much of the country and refocused exploration activity in proven areas. However, improved technology and refined geological concepts are now yielding exploration success farther afield. Recent discoveries north of the Masila oil fields include Tassour that was drilled by Clyde in 1997 and Sharyoof, drilled by Dove in 2000.

Occidental, in partnership with Ansan Wikfs, is explorating in an area believed to contain key elements of the prolific Sayun-Masila basin. This exploration venture is in the 6,335 sq km North Hoowarim Block (Block-44) located in the Ardah subbasin, in the northern part of Sayun-Masila basin. This Mesozoic rift basin consists of discrete depocenters with rich organic source rocks overlain by widespread siliciclastic reservoirs. Poor-quality seismic data have previously made it difficult to unravel the geologic history and define traps but the Sayun-Masila hydrocarbon province may well extend into Block-44. Occidental is therefore focussing its efforts on improving seismic data quality in order to understand the geologic evolution of the basins and advance the exploration of this region.

(#296-O) Integration of multiple permeability indicators to provide an effective permeability model in carbonate reservoirs

Colin Daly, **Roxar**; Mohamed N. Bushara, **ZADCO**

It is often possible to recognize that fractures are contributing to flow in a well by comparing the well-test interpreted permeability with that from core measurements. The latter do not usually reflect the contribution to permeability from fractures. Therefore, a large difference between the test permeability (assuming that this is a good indicator of the true effective permeability near the well) and the core permeability may indicate a contribution to the effective permeability, and hence to flow, from fractures. This is the case in many fields.

A method to provide an integrated effective-permeability model was developed for an offshore field using matrix permeability, models of the strain field, and dynamic data. These three variables were combined in a probability model that was designed to ensure that the well-test permeability was honored at the wells. The probability model was sampled using a metropolis-hastings algorithm.

A 3-D fine-detailed model of the horizontal permeability matrix for the field was based on detailed lithotype mapping. This provided the desired trends within which the permeability for each lithotype was simulated, and constituted one component of the effective permeability model. The other component was the fracture permeability. To account for this fracture permeability it was first necessary to predict the location of the fractures. For this, we used a strain model of the field as an indicator for the location of fractures. The next step was to combine the matrix permeability model and the fracture attribute model in a way that was consistent with the effective permeability. Moreover, we wanted to make use of potentially important secondary variables that are available from wells, such as Production Logging Tools or Repeat Formation Tester data. A new geostatistical algorithm was developed to allow this simultaneous conditioning of the various permeability indicators.

(#365-O) Exploiting drill-bit energy as a seismic source: a seismic-while-drilling case study, Ghawar field, Saudi Arabia

Shiv N. Dasgupta and David W. Alexander, **Saudi Aramco**

Seismic-While-Drilling (SWD) is a relatively new technology that uses drill-bit energy as a seismic source. Vibration of the rotating drill bit generates P-wave energy that is recorded at the surface using geophone arrays. Saudi Aramco recently evaluated the application of SWD for imaging the subsurface in the Ghawar field. Drilling through the competent carbonate rocks in Ghawar generated sufficient acoustic energy to be a reliable seismic imaging source in the borehole. Results from the experiment have been promising. In this case study, results will be presented from SWD surveys in four development wells. The SWD data will be compared with conventional VSP and synthetic seismogram data from the same wells.

SWD provides an opportunity to measure the velocity (or time-depth) continuously, which allows for the accurate positioning of the drill bit on surface seismic data volume in real time as drilling progresses. This may be critical in determining optimal casing or coring points. Unlike well logs and vertical seismic profiling acquired after the well has been drilled, SWD data are acquired while the well is being drilled; this provides the opportunity for drilling optimization and has the potential for significant cost savings.

The principal advantages of SWD are as follows: (1) No loss in rig time and no interference with drilling operations; (2) No down-hole instruments deployed; therefore, no risk of borehole damage or tool loss in hole; (3) Real-time Time-to-Depth relationship; (4) Drill-bit positioned in time enabling monitoring of the drill bit with respect to the 3-D seismic section; (5) Predicting ahead of the bit—reflection energy can be used to look ahead for drilling hazards; and (6) Early detection of possible drilling problems.

(#313-P) Mid-Cretaceous mixed clastic-carbonate shelf systems: sequence stratigraphic models and examples from the Arabian Plate

Roger B. Davies and David M. Casey, **Neftex**; Andrew D. Horbury, **Cambridge Carbonates**; Peter R. Sharland, **Neftex**; Michael D. Simmons, **CASP**

Sharland et al. (2001)* have proposed a sequence stratigraphic scheme for the Arabian Plate based on identification and correlation of Maximum Flooding Surfaces (MFS) and Sequence Boundaries. This poster discusses the identification and correlation of MFS in the mid-Cretaceous mixed carbonate-clastic shelfal systems of the Arabian Plate, from the northern Gulf to Oman and Yemen. Dependent on systems tract position, MFS are located either at the base of clean highstand carbonates, or in deeper water marls and shales deposited below the most efficient window for carbonate production. The former generally overlie more proximal Transgressive System Tract (TST) mixed clastics and carbonate successions, whilst the latter generally overlie more basinal TST limestones.

The rapid lateral migration of prodelta shales, and the associated diachronous contraction and expansion of the down-systems-tract carbonate ramps of the Burgan-Nahr Umr-Kazhdumi-Sarvak and Zubair-Biyadh-Gadvan-Kharaib complexes of mid-Cretaceous age, suggests that the relatively deeper water prodelta shale areas cannot be regarded as typical intrashelf basins. We prefer to regard them as ‘migratory carbonate-suppressed belts’ whose lateral extent and bathymetry is likely to have been primarily controlled by the interaction of clastic supply, marine opacity, freshwater run-off, nutrient excess, and carbonate productivity.

These issues are of major economic importance at the reservoir scale (e.g., in the control of vertical permeability profiles within reservoir models), as well as at the regional play fairway scale (e.g., in the geometric distribution of seals and their potential influence on petroleum migration pathways).

* Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. GeoArabia Special Publication 2. Gulf PetroLink, Bahrain, 371 p.

(#334-O) Shell Geoscience Services experience with 4-D

Jan W. de Maag, Jos van der Veeken, Linzey Cartwright, Michael Muerz, Rob Staples and Karel Maron, **Shell**

The recent time-lapse-seismic successes in the North Sea (where 4-D seems to have become a fully proven technique) together with the accompanying technical push and market pull, have spawned a flurry of activity in the 4-D seismic field worldwide. As a result, Shell Geoscience Services (in close cooperation with the SEPTAR global 4-D implementation team) has created a global 4-D processing team to provide the latest technology. Working on 4-D on-shore and offshore projects for Nigeria, New Zealand, Syria, and Malaysia, this tight cooperation has ensured a steep-learning curve and the rapid dissemination of current knowledge and experience. At the same time, customers benefit from the special processing that Shell Geoscience Services can offer; in particular, advanced multiple attenuation, surface consistent deconvolution, and true-amplitude depth imaging.

(#105-P) Integrating reservoir modeling and seismic simulation for efficient interpretation of 4-D seismic data

Jean-Paul M. Diet, Olivier Colnard, Jean-Luc A. Formento and Luis F. Guerreiro, **CGG**

Intensive seismic simulation of several reservoir geological and production hypotheses is essential when analyzing the feasibility of time-lapse seismic monitoring and the qualitative and quantitative interpretation of 4-D data. Using a Middle East water flood pilot as an example, we will show how an integrated 3-D geo-modeling platform was used in a 4-D study, from preliminary sensitivity analysis to quantitative estimation of saturation changes.

(1) A sensitivity analysis was carried out to select the best approach for modeling the reservoir, calculating the seismic response, and interpreting the time-lapse results. Building a 3-D conceptual model made up of a large number of pseudo-wells allowed a rapid analysis of the key parameters affecting the time-lapse seismic response. Several fluid substitution scenarios were tested on this model with respect to time-lapse seismic simulation, as well as several petrophysical relationships, such as seismic bandwidths and noise levels. A search for the most relevant seismic 4-D attributes was made at this stage.

(2) A seismic simulation exercise was made on the reservoir model. The numerical model had to be integrated with geological and petrophysical information and re-scaled into a geophysical model that was appropriate for seismic simulation, using the findings from the previous step. The expected time-lapse response was quantified so that the feasibility of seismic monitoring could be assessed.

(3) The geo-modeling platform was used to calibrate the actual time-lapse attributes, simulate saturation changes, and integrate the time-lapse seismic information with well data and production data.

(#33-P) Sequence stratigraphic distribution and biostratigraphic zonation of the Permian-Triassic section in Kuwait

Adel F. Douban and Ghaida Al-Sahlan, **KOC**; James P.G. Fenton, **RRI**

Despite the generally limited biostratigraphic data available for the Permian-Triassic section, new palynofloral data have been used to establish a zonation scheme specific to Kuwait. Microfaunal data are sparse due to the prevalence of non-marine/marginal-marine facies throughout much of the section, and the consequent absence of the marine microfaunas required for biozonation. Palynofloral zonations for the Permian-Triassic of the Arabian Peninsula and adjacent areas were applied to strata of relevant ages found in Kuwait. The Permian-Triassic stratigraphic sequences were subdivided with regard to the lithological composition, depositional environment, age, and stratigraphic relationship with the underlying and overlying units.

A major unconformity representing the Hercynian Orogeny separates the pre-Permian rocks from the overlying Unayzah Formation. The palynoflora suggests that the lower Unayzah is of Early Permian age (Asselian-Sakmarian) and that the upper Unayzah is Early to Late Permian (Artinskian-Ufimian). The Upper Permian Khuff Formation rests with a major facies change on the underlying Unayzah Formation

that almost certainly reflects a major Late Permian (Tatarian) sequence boundary. The Triassic-Jurassic boundary is located in the Minjur Formation, the upper part of which may be either of Late Triassic or Early Jurassic age. A major unconformity at the base of the overlying Lower Jurassic Marrat Formation encompasses possibly part of the Hettangian and some or all of the Sinemurian stages.

(#250-P) Stratigraphic architecture of Cretaceous interior-platform carbonates: impact on flow-unit geometry and continuity

Henk H.J. Droste, **CRC, Sultan Qaboos U.**

Interior-platform carbonate deposits hold more than 50 percent of the oil reserves in Oman, but recovery efficiencies are relatively low. A proper understanding of the stratal geometries and definition of flow units within these carbonate systems are essential in order to improve production and recovery. A seismostratigraphic study of several 3-D data sets of the interior-platform carbonates of the Albian-Turonian Natih Formation showed a complex internal architecture with clinoform belts and intraplatform basins. Based on this study, facies belts and flow-unit geometries, and the controls on their distribution in space and time, were determined.

The Natih is the uppermost interior-platform carbonate sequence of an extensive Lower to mid-Cretaceous carbonate platform. During Natih times, the main area of carbonate deposition was along the edges of the platform in the north and east. Southward, carbonate growth was limited by the influx of fine-grained clastics from a positive-relief area around the Arabian craton. Repeated cycles of southward expansion and retreat of the interior-platform carbonates were controlled, either by variations in clastic influx as a result of changes in climate, or by relative changes in sea level.

The southward expansion of the interior-platform carbonates started from isolated platforms separated by intraplatform basins. The platform nuclei appear to have been structurally controlled, and clinoform belts (clearly recognizable on seismic) show that they expanded by lateral accretion. Angles of the clinoforms vary from less than 0.5° up to 35° and reflect the composition of the slope sediments. Individual platforms may have merged into larger complexes to form one carbonate layer.

The geometries of the Natih interior-platform carbonate system have important implications for field-scale lateral correlation of reservoir units and at the inter-field scale. The integration of high-quality 3-D seismic and well data is of crucial importance in meaningful reservoir modeling. Field performances can be better understood, and history matches improved, when flow units in dynamic models are based upon geological reservoir models that take the geometries described above into account.

(#132-O) The sequence stratigraphic framework of a Maastrichtian reservoir in the Wafra field, Kuwait-Saudi Arabia Partitioned Neutral Zone: a key to geostatistical modeling and reservoir development

Dennis W. Dull and Byron B. Sherman,
ChevronTexaco

The Maastrichtian reservoir is one of five prolific oil reservoirs (four carbonate and one sandstone) in the giant Wafra oil field located in the Partitioned Neutral Zone between Kuwait and Saudi Arabia. Production is from subtidal dolomites at an average depth of 2,500 ft. The reservoir is in an early stage of development even though production started in 1959. Development was delayed because of the low oil gravity, high sulfur content, and high water-cut. The purpose of the modeling described in this presentation was to investigate these problems and evaluate the potential of the Maastrichtian reservoir. The key was to construct a sequence stratigraphic framework with data from five cored wells and 123 wells with synthetic lithofacies curves.

The first requirement for modeling was to develop a depositional model from core descriptions. The descriptions and the correlation of the Maastrichtian well-log data showed the presence of 10 High-Frequency Sequences (HFS) that could act as barriers and baffles to vertical fluid migration. The next step was to build a 3-D sequence stratigraphic framework. This involved constructing 22 cross-sections that correlated the HFS to all the wells. The correlation was verified with isochore and structure maps for each HFS.

The geostatistical modeling of the Maastrichtian reservoir revealed a highly layered and compartmentalized reservoir. The 10 HFS act as barriers and baffles to flow. As determined by the model, the location of the reservoir facies within the Maastrichtian was controlled by the original depositional fabric and subsequent dolomitization, both of which have had been influenced by the

paleotopography. The geostatistical modeling of the Maastrichtian has quantified a multibillion-barrel oil resource and the model is being used to evaluate and maximize the oil production potential of the reservoir.

(#134-P) Synthetic facies curves from well logs for a shallow ramp-carbonate Maastrichtian reservoir, Wafra field, Kuwait-Saudi Arabia Partitioned Neutral Zone

Dennis W. Dull, **ChevronTexaco**

The Maastrichtian reservoir has a cumulative production of 17 million barrels of oil from 36 wells with oil-in-place estimated at several billion barrels. It is one of four prolific carbonate reservoirs in the giant Wafra oil field located in the Partitioned Neutral Zone between Kuwait and Saudi Arabia**.** The development of a 3-D sequence stratigraphic framework and lithofacies model has been hampered by a lack of core. This has necessitated the use of well logs for the development of the facies model. The Maastrichtian deposition took place on a shallow ramp in an arid and restricted environment. The reservoir is an overall regressive sequence that is composed of 10 High-Frequency Sequences (HFS). It is highly layered, with evidence of subaerial exposure that defines the tops of many of the HFS.

The first step in constructing a lithofacies model was to develop a relationship between lithofacies from the five available cores and the reservoir quality. The second was to correct the well gamma-ray and porosity logs for the apparent shale content due to uranium contained in the dolomite. This was necessary so that the logs more closely matched the lithology and porosity observed in the cores. The third step was to develop a correlation between lithofacies and well-log response to predict lithofacies in non-cored wells. A multiple crossplot, non-linear method predicted lithofacies in non-cored wells.

The prediction process consisted of a modeling phase and a prediction phase. The first used the five well-log curves and the lithofacies from the five cored wells. The curves were chosen because of their correlation to the lithofacies, both depositionally and petrophysically. The prediction phase generated a synthetic lithofacies curve for the cored wells that had good correlation with the core lithofacies. The multiple crossplot, non-linear equation was applied to 123 non-cored wells, thereby greatly improving the development of the 3-D sequence stratigraphic framework of the Maastrichtian reservoir.

(#235-O) Overpressure prediction from 3-D seismic data: a rock-model-based approach

Nader C. Dutta,**WesternGeco**

The ability to predict subsurface pressure regimes prior to drilling can significantly influence a drilling program, from safety issues to well planning and control. The prime mechanism for developing overpressure is compaction disequilibrium. The overpressure influences seismic velocity and density by differences in porosity between normal and overpressured shales, and is acoustically measurable. Similar acoustic responses can be observed in overpressured carbonates given certain conditions. Carbonate environments, such as those in the Middle East, present a more complex response than clastic depositional environments, and parameters such as lithology, burial, and fracture history need to be better understood in the pressure- to acoustic-measurement calibrations.

Before a well is drilled, especially in frontier areas, seismic may be the only information available. Normal moveout seismic velocities, however, suffer from poor temporal resolution and are optimized for stacking and not rock properties. WesternGeco has developed a seismic procedure that adds more temporal and lateral resolution by using various velocity and amplitude inversion techniques. These techniques allow for velocity analyses at every common mid point and time sample along every coherent and spatially continuous event on a seismic section, and are especially suitable for large-scale 3-D survey. By combining velocities with a rock model that transfers velocities to effective and overburden stresses, we can obtain a very detailed image of subsurface pore pressure image before drilling. This is then updated in real time using drilling data.

In this presentation, I will illustrate how the procedure works by first outlining the method and then presenting Middle East case histories.

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(#222-P) Integrated saturation monitoring with cased-hole formation resistivity and reservoir saturation tools

Mosleh K. Ebrahim, **ADCO**; Paolo Ferraris, **Schlumberger**

This presentation describes an innovative, integrated approach combining recently available Resistivity Behind Casing with traditional Pulse Neutron Sigma measurements to better describe the near and far wellbore saturation in a vertical monitoring well. The combined approach integrated core analysis with vertical pressure profile and open-hole and cased logs to make a coherent interpretation. The application of this technique in other monitoring studies has potential for removing the typical limitations of individual approaches.

The subject was a pilot observation well drilled in an onshore Abu Dhabi field and located 100 m away from a horizontal water injector. While drilling this well, some deep invasion was experienced and consequently open-hole interpretation was made difficult. After completing the well with a 7-ft steel casing, the injector well was kept shut for nine months in order to let invasion dissipate from close to the wellbore. During this period two combined runs of Cased Hole Formation Resistivity (CHFR) and Reservoir Saturation Tool (RST) were made. The two tools have different depths of investigation: RST reads up to one foot from the wellbore and CHFR approximately one order of magnitude greater. Independent analyses of CHFR and RST had initially contrasting results. CHFR showed a progressive hydrocarbon re-saturation, whereas RST confirmed the presence of an invaded zone close to the wellbore that took longer than expected to dissipate due to possible formation damage and reduced permeability. Using the ELAN integrated approach, the shallow RST Sigma measurement was converted into an equivalent Resistivity of Flushed Zone (RXO). The CHFR calibrated output the RXO fed a 2-D inversion algorithm solving for True Formation Resistivity and the diameter of invasion. This approach was successful in simultaneously describing (1) invasion characterization and evolution with time, (2) shoulder-bed effect and relative correction on CHFR laterolog measurement, (3) identification of damaged and permeable zones, and (4) homogenization of results, increasing absolute confidence in the method used.

Injection was started in the horizontal well after completing the second survey. For two years, additional monitoring runs were recorded every six months. Using the same approach as described, it was possible to follow and quantify mud-filtrate invasion behavior simultaneously with saturation evolution far from the wellbore. This provided a degree of understanding not previously available.

(#280-O) The judicious application of oil-base mud imaging logs and inverse geological modeling to assist the geosteering of a horizontal well: a case study from an Abu Dhabi carbonate reservoir

Mosleh K. Ebrahim, Mohammed R. Ayoub and Jorge S. Gomes, **ADCO**; Mahmoud M. Akbar and Sandeep S. Chakravorty, **Schlumberger**

In this presentation the authors discuss technical matters associated with Oil-Base Mud Imaging (OBMI) logs, inverse geologic modeling using Logging While Drilling (LWD) data, geosteering, geomechanics, and structural analysis.

A horizontal well was planned for a carbonate reservoir located northeast of Abu Dhabi. According to the plan, the well had to cross a body of shale during the buildup section before the landing point. To avoid problems associated with borehole instability, it was decided to drill the curved section with oil-base mud. On the basis of seismic data and structural information from other wells in the area, complex faulting and dip changes were expected in the vicinity of the well. Because of the low quality of the acoustic imaging, electrical imaging was preferred. Hence, OBMI was run that gave good-quality images for structural characterization. The images revealed a fault, several fractures, and clearly developed bedding. The results were used to develop a structural model around the well. The model was validated through inverse modeling of LWD data that helped to compute the throw of the fault and the apparent dip along the trajectory of the well. Based on the modeling results, the trajectory was adjusted to achieve the required targets and meet the reservoir objectives.

(#363-O) Geostatistical modeling of permeability in a giant carbonate field in the Middle East

Mohamed R. Efnik, Abi A. Modavi, **ADCO**; Jean-Marc Chatrue, **IFP**

This presentation is a case study of estimating permeability from well logs using core data from a heterogeneous carbonate reservoir in the Middle East.

It was based on a variety of geostatistical techniques. The purpose of the study was to use the existing core data to better predict thin, high-permeability streaks not detectable by log data alone. It was important to locate the streaks as they have a major impact on reservoir fluid flow.

The method was based on a multivariate analysis carried out on core porosity, core permeability, and logs from each stratigraphic unit. Analysis had shown that the core permeability could be considered as two components—a smooth trend, easy to correlate from well to well, and a high-frequency component. The trend was estimated either from core data using a factorial kriging method or by regression from the Neutron Porosity Index (NPHI) log. The high-frequency component was modeled either by stochastic simulation or by cokriging using neighboring core data and a curve having the same variogram (obtained from NPHI log after deconvolution and filtering by kriging). The estimated trend and the estimated high-frequency component were combined to produce the final permeability estimates in all the wells.

Satisfactory results were obtained and blind tests on cored wells proved the prediction of permeability streaks to be good. This new permeability model has led to a significant improvement in the reservoir simulation history match.

(#159-O) A feasibility study to determine if the surface seismic method can detect thin channels in the presence of statics and noise

Mark S. Egan, **WesternGeco**

Exploratory wells found oil-bearing sand channels in a field in Oman. Although these reservoirs were less than 5 m thick, they were considered to be economic. Conventional 2-D and 3-D surface seismic programs were unsuccessful in detecting the reservoirs. Consequently, interest waned until the development of high channel-count systems was announced. This study investigated if such high channel-count systems could detect the sands.

The chief tool used was modeling. In addition to handling signal, all major noise components were comprehended. These included multiples, scattered ground roll, air waves and ambient interference. The effects of inelastic attenuation and intra-array statics were also considered. Results showed that high channel-count systems could indeed provide significantly better results than conventional systems. However, it was also found that direct detection of the sand channels would still be difficult unless tuning effects could be correctly exploited during the interpretation.

(#64-O) Early Paleozoic glacioeustatic and tectonic event-stratigraphy of western Libya: a reservoir/source rock scenario.

Ahmed S. El-Hawat, **Garyounis U**; Abdul-Afiz M. Bezan, **NOC;** Adel Ali Obiedi, **Schlumberger;** Hassan El-Bargathi, **TotalFinaElf**

The Upper Ordovician to Lower Silurian succession of western Libya consists of two glacioeustatic depositional sequences. The lower sequence starts with a Transgressive Systems Tract (TST) of basal sandstone followed by a laminated marine shale containing glacial dropstones of reworked pebbles derived from older rocks. It is overlain by a regionally extensive condensed section of sandy coquina-hardground that changes southward in the Murzuq basin to an iron-oxide horizon, and northward in the subsurface of the Ghadamis basin, into cold-water carbonates. A Highstand Systems Tract (HST) consists of interbedded sandstone and shale grading upward into fine-grained, shallow-marine and nearshore sandstone association. These clastics show evidence of pervasive, multiscale soft-sediment deformation and turbidite sedimentation, attributed to tectonic seismic activity that overprinted HST sedimentation. In northern Ghadamis basin, it grades laterally into carbonate bryozoan bank build-up. The second sequence starts with a Lowstand Systems Tract (LST) of deeply incised channel systems, attributed to a major glacioeustatic sea level fall, and followed by coarse-grained fluvial infill of the second deglaciation event. These fluvial channels followed the northwesterly trend of the inherited structural troughs of the mid-Ordovician rift system, and form the main reservoir facies in western Libya. The following TST deposits consist of basal nearshore sandstone grading into graptolitic shale that ends a condensed section (an organic-rich, radioactive marker) throughout the Murzuq and Ghadamis basins and beyond.

Similarly, two glacioeustatic depositional sequences constitute the same stratigraphic succession in Morocco and Arabia. However, whereas periglacial marine and fluvial sedimentation dominated sedimentation in western Libya, deposition in the other areas was relatively close to the glaciation centers.

(#110-P) Utilization of the mud-logging unit in geosteering horizontal wells in thin reservoirs

Mohamed E. Elsaid
and Saeed M. Dama, **ADMA-OPCO**

In offshore Abu Dhabi, the development of Middle Jurassic carbonate grainstone thin-reservoir layers having minimum target thicknesses, is a challenge that can be overcome using horizontal drilling. Because of the risk of failure in placing the horizontal well on target (due to tool configurations, bottom-hole assembly performance, and geological uncertainty) geosteering is the most appropriate technique to use, particularly in thin and dipping reservoirs.

Sensors collecting data for geosteering need to be as close as possible to the bit so as to promptly detect and respond to variations in geology and structure. Most 6-inch-hole sensors are located at least 40 ft behind the bit, which might result in non-effective drilling—as in the case study—away from the reservoir sweet spot. However, data from the mud-logging unit allows earlier detection and faster response to bed boundaries in relatively thin and dipping reservoir layers, as compared with conventional Measuring While Drilling and Logging While Drilling techniques.

In the case study, hydrocarbon gas detection and chromatographic analysis provided an effective geosteering tool while landing, and also in the reservoir navigation phase of the horizontal section. This improved the real-time geosteering decisions and formation evaluation. It also enhanced well placement and optimized drilling control and efficiency.

(#225-O) Redatuming of reflection seismic data in a complex near surface, based on common focus point technology

Kevin E. Erickson and Panos G. Kelamis,
Saudi Aramco; Kees Hindriks
and Eric Verschuur, **Delft U. of Technology**

A complex near surface can prevent proper imaging of even the most straightforward geology. In recent years, the use of Common Focus Point (CFP) technology has made possible a wave-equation redatuming of reflection shot gathers to a level below a complex near surface. This is the case even without explicit knowledge of the velocity macromodel of the geology above. Furthermore, updating of the CFP operators inherently incorporates the propagation effects of the media above the redatuming level. At the end of the process, the CFP operators have fully described the kinematics of one-way propagation from the redatuming horizon to the surface.

In synthetic and real-data examples, a tomographic inversion technique using CFP operator travel times and first-break pick times extracts an equivalent media velocity for the strata above the redatuming level, and an estimate of the depth of the datum. As the CFP redatuming process is data driven, the results are entirely dependent on the quality of the input data. Areas where the near surface is very complex, or the signal to noise ratio is poor, makes the picking of corrections to the CFP operators difficult. These problems can be overcome by reorganizing the CFP operators into a domain that best exploits the wave front healing principle, thus simplifying the operator update process.

(#156-O) Zagros minor detachment horizons

Mohammad D. Fakhari, **NIOC**

Field observations and detailed structural studies of the Zagros fold belt show that the geometry of the surface exposures of the compound anticlines is different from those of the deeper horizons. This geometric variation was created by deformation of the incompetent layers within the Permian to Miocene multilayer sequence. Dashtak and Hith evaporites, Neyriz, Gadvan, Kazhdumi, and Pabdeh-Gurpi shales are the incompetent formations of the sequence, and host the minor detachment horizons. Parallel concentric folding is dominant but, due to room problem and geometric deformations of the incompetent layers, there is no geometric similarity between competent formations above and below the incompetent layers within the folded sequence.

The study has three main conclusions. (1) Many of the auxiliary folds in Ilam-Sarvak, Asmari-Jahrum or younger exposures in the Fars province, do not correspond with the anticlinal geometry at deeper horizons. In some cases, there is a major anticline beneath the adjoined minor folds (for example, Sefid-Baghun and Gavbandi-Tarakemeh anticlines). (2) Shallow saddles of the en echelon adjoined elongated anticlines with Agha-Jari or Asmari whaleback exposures change to deep synclines beneath the incompetent layers. They separate long, major anticlines from several small culminations at depth. Examples include Asaluyeh-Dehnow and Kuh-e-Mand anticlines. Such geometrical variations in the structure will increase or decrease the expected

reservoir volumes and hydrocarbon reserves of the study area. (3) Hydrocarbon potential of dry-tested elongated anticlines, such as Khalafani-Madar, could be increased and other new prospects made available for further exploration drilling.

(#17-O) Lowstand systems tract identification and prospectivity in southwestern Saudi Arabia

Mohammad I. Faqira, **Saudi Aramco**

Seismic characters of the Early to Middle Miocene Maqna2 Formation show lowstand systems tract geometries in southwestern Saudi Arabia that have significant structural and stratigraphic exploration potential. Several seismic criteria, such as geometries, patterns, and attributes are seen within the seismic facies.

The slope-fan seismic facies is a textbook example in this area and deep-marine fan and lowstand wedge were interpreted relative to it. The seismic facies were characterized in the strike direction by five factors. (1) Mounded, convex-upward reflection patterns with bi-directional downlap. (2) Common occurrence of high-amplitude reflection on the upper surfaces due to the velocity contrast between the basinal shale-prone sediments and the underlying middle and/or lower fan sand-prone sediments. (3) Their three-dimensional fan shape. (4) Velocity pull-up for the underlying sediments due to the difference in velocity between the slope fan sands and in between shale-prone lowstand wedge. (5) Differential compaction between sand-prone mounds and the adjacent the shale-prone sediments that causes drape of the overlying sediments across the fan edges.

The low-stand wedge showed onlap relations onto the older slope fan in the intervening areas. In the dip direction, the lowstand submarine fans demonstrated shingled progradational clinoform patterns due to a shallow-water prograding system. Deep-marine fans formed a low-relief bi-directional mound basinward from the slope fan that downlaps onto it, and a lowstand wedge onlapped the slope fan with a retrogradational pattern. Thin turbidity sands, with poor reservoir properties characterized the slope fans.

The Maqna2 seismic data showed leveed channel development on the top of the slope fan. Sands within the leveed channels are commonly of excellent reservoir quality. Although the deep-marine fans are not as evident in the seismic data as the slope fans, they are recognizable relative to the overlying slope fans and the lowstand wedge.

(#18-O) Prospectivity of the pre-Khuff section in West Ghawar: a new interpretation approach

Mohammad I. Faqira, **Saudi Aramco**

The seismic reflections of the Base Qusaiba-Base Tawil (Qalibah Formation) show a clear erosional truncation in the northern part of the Ghawar-Fadhili trend. This truncation is also seen on the Ghawar structure in several wells. The Khuff Formation overlies the Qalibah Formation in several crestal wells along the Ghawar-Fadhili trend. These observations, in addition to the relatively consistent thickness of the sedimentary package over a broad area and the lack of any seismic sequence stratigraphic geometry, indicate that the sediments were deposited in a ramp basin with a broad shelf. The possible ramp-setting model indicates that drastic changes in depositional environments should not be expected over a short distance, especially as the presence of the Qusaiba Hot Shale in these crestal wells represents a condensed section. The equivalent high-energy facies of the Qusaiba Hot Shale in such a ramp setting can be expected to have developed hundreds of kilometers form the crestal wells. The missing Silurian-Devonian section over the Ghawar-Fadhili trend most probably resulted from subsequent tectonic uplift as a result of compressional stress or thermal uplift during the Hercynian Orogeny. This interpretation was supported by new, reprocessed 2-D seismic data from west of Fadhili that showed a pre-Khuff erosional truncation controlled by the Hercynian paleohigh of the central block. The new interpretation will make the area between Ghawar and Khurais (West Ghawar) more attractive for pre-Khuff gas exploration.

(#148-O) Integration of 3-D seismic, reservoir, and production data to revitalize assets: Thamama case study, Rashid field, Dubai

Xavier Faugeras, Philip J. Rorison and Jeffrey W. Yeaton, **DPC**

The Rashid field is located in the Arabian Gulf, offshore Dubai, on a low-relief salt-induced dome. Production is from two carbonate reservoirs. This presentation concentrates on the subsurface team's approach to re-evaluating the Thamama reservoir. The integrated study has provided a better understanding of the reservoir as well as a solid base for recommending a new well to be drilled on the structure as a first step toward possible redevelopment of the asset.

Production from the Thamama reservoir began in 1979. Since then, it has produced continuously under natural

depletion without significant water production. In 1999, a 3-D seismic survey provided an improved image of the reservoir's 3-D geometry and fault architecture. The data were interpreted and, together with reservoir property data, were integrated into a fine-scale geocellular model. Finally, a dynamic model was constructed. At each stage of the study, structural, static and dynamic information (as well as uncertainties) was confronted. For example, when the static model was reconciled with the dynamic data, it became clear that there was a strong correlation between fault proximity, reservoir quality, and performance. Additionally, pressure and production data indicated that certain wells were in communication but that other areas were partly compartmentalized. The history match highlighted such areas that were then verified using seismic.

In conclusion, in addition to gaining a better understanding of the reservoir and the methods to be used in its interpretation, this study has led to the planning of the first development well in the field for the last 18 years.

(#92-O) The North Oman Common Earth Model: regional mapping at a prospect scale providing a framework for 3-D portfolio analysis

Jack B. Filbrandt, Safia A.S. Al-Mazrui, Liping Sha, Hendrik R.H. Rebel and Roland Muggli, **PDO**

Most of the hydrocarbon concession areas in Oman have been covered by 2-D and increasingly by 3-D seismic. In the northern half of Block-6, seismic data, vertical seismic profiles, and check shots have been acquired since 1997 at a common seismic reference datum of 150 m a.m.s.l. Legacy data were aligned with the new datum. A Common Earth Model was created within GeoFrame to bring together all seismic data, with borehole, check shot and synthetic seismic information in a 50,000-sq-km area. We present an overview of the status of the model, the forward plan, and pitfalls associated with its creation and implementation.

The North Oman Common Earth Model is the framework for consistent regional geological evaluation and play and prospect definition, as well as systematic technology implementation. This regional approach has allowed identification of new play concepts and re-invigorated sequence stratigraphy, paleogeography, and facies mapping. Prospects are consistently risked and play information properly reconciled with field data. For example, as all the large four-way dip closures and fault traps have been drilled, the remaining potential lies within subtle, low-relief structures and stratigraphic traps. Uncertainties in depth prognosis at 1,000 to 1,500 m in wildcat drilling are as much as 25 to 35 m—equivalent to potential column heights of structures currently being delineated. In order to rank leads and prospects appropriately and deploy resources in the most economical way, depth conversion is performed using a single harmonized velocity cube derived from stacking velocities, and calibrated to wells. Continuous velocity analysis, poststack depth migration are applied to reduce the depth and positioning uncertainty at prospect scale.

The model also provides the framework for full 3-D charge and migration modeling. The focus extends beyond burial histories of source rocks and reservoir / seal pairs, and included migration and remigration along carrier beds and faults that may act both as conduits or seals.

(#190-O) Impact of volume visualization technologies on upstream business activities

Tom J. Frantes, J.E. Holl and Steve R. May, **ExxonMobil**

Volume interpretation and visualization technologies are having a significant impact on upstream geoscience and engineering activities at ExxonMobil. From regional exploration to mature field development, from seismic interpretation to detailed well planning, from macroscopic to microscopic scales, volume interpretation and visualization technologies can improve business results.

Volume interpretation includes the methods and tools for efficient interpretation and analysis of 3-D data using such techniques as geologic feature extraction, volumetric multi-attribute integration and analysis, and interactive well-path planning. Visualization technologies facilitate the rapid comprehension of 3-D data through the interactive rendering of volumes, surfaces, lines, and points. We will use the term 'volume visualization' to include both interpretation and visualization technologies.

ExxonMobil's volume visualization capabilities are derived from the integration of powerful computers, advanced display technology, commercial and proprietary software, and specialized geoscience and engineering methods. The value of ExxonMobil's combined volume interpretation and visualization techniques is measured in terms of (1) exploration and development cycle time, (2) technical quality, (3) improved communication and collaboration, (4) reserve additions, (5) reservoir management,

(6) cost savings, and (7) next-generation technology development. Appropriate application of state-of-the-art volume interpretation technologies have helped ExxonMobil to manage a large portfolio of geoscience projects across a range of business stages.

(#91-O) Gas exploration in Block 6, Oman: gas families and gas petroleum systems

Neil L. Frewin, **Shell**; Juma D. Al-Belushi and Nashwa M.M. Al-Ruwehy, **PDO**; Francois Gelin, **Shell**; Mark J. Newall, **PDO**; Jan Kleingeld, **Shell**; Graham J. Tiley, **PDO**

Oman is finding new prosperity through the exploitation of its gas reserves. However, despite an ambitious reserve requirement, the gas-charge system of north Oman is poorly understood with most of the reserves being creamed from successful Ghaba Basin gas plays. Moreover, a substantial part of the exploration portfolio is defined for south Oman, a province that is critically under-explored for gas. A thorough evaluation of empirical data, coupled with 1-D and limited 3-D charge modeling, has enabled the extent of genetically linked gas systems to be mapped in north Oman and for the more accurate risking of gas prospectivity in the south.

Specific isotope fingerprints indicate four distinct north Oman gas families. Additional comparative information has been obtained from other reservoir phases, such as oil, condensate, bitumen, and pyrobitumen. Most of the gas families were sourced from Precambrian-Cambrian Huqf rocks. However, differences in signatures can be related to either generation from late-mature source rocks or to oil-to-gas cracking mechanisms that occurred during the deep burial of the Paleozoic Haima reservoirs in the Ghaba and Fahud salt basins. Charge modeling suggests that most of this charge and oil-to-gas cracking occurred since about 150 Ma.

South Oman is more complex in terms of its gas system since there is little unassociated-gas data available for interpretation or for calibration of basin models. Oil generation, although prolific, occurred relatively early within complex intrasalt Huqf source rock-reservoir sequences. Charge modeling suggests that the time of maximum burial of the central and eastern areas of the South Oman Salt Basin was at about 420 Ma. Since retention over such a long residence time could be an issue, deep reservoirs with relatively recent conditions for gas formation should be sought. Pre-Ara Salt source rocks may still hold the key to south Oman gas exploration.

(#279-P) 3-D geometry for demultiple and noise cancellation

Mike Galbraith, **Seismic Image Software**

The simple process of Common Mid Point (CMP) stacking is a powerful mechanism for the suppression of multiples and the attenuation of linear shot noises such as airwaves, ground roll, and backscatter. In 3-D acquisition geometry, each CMP bin will have a variety of traces from different shot-receiver offsets and azimuths. The traces will be processed through algorithms such as scaling, normal moveout, statics corrections, prior to summing them into CMP stack traces. The act of summing or stacking will increase the coherent signal content and reduce incoherent noise, such as linear shot noise and multiples, whether surface or interbed.

The offset and azimuth distribution of the traces in a CMP bin plays a critical role in determining the effectiveness of attenuating multiples and other noise. Different geometries lead to different attenuation characteristics. The key factors in the 3-D geometries in relation to noise attenuation are (1) aspect ratio (width versus length of the recording patch), (2) ratio of shot line interval to receiver line interval, (3) angle of shot lines to receiver lines (slanted geometries), and (4) choice of minimum and maximum offsets, and hence the range of offsets to use in CMP stacking at each depth; that is, the choice of 'inside' and 'outside' mute functions.

Synthetic linear noise and multiples can be generated to investigate the effects of these key factors. Knowing the levels of input noise, the level of output noise can be established through CMP stacking at various points throughout the CMP bins of a particular 3-D geometry. Hence, a range of noise attenuation may be assigned to various 3-D geometries. The key factors listed above can be used to create a series of geometries, each of which is measured for its range of noise attenuation. The results indicate which are the most important factors to determine prior to designing a 3-D geometry for noise attenuation.

(#139-P) Seismic inversion results from a mature carbonate reservoir, Fateh SW field, offshore Dubai: a case history.

Geoffrey S. Galvan, **DPC**; Aline Besson-Hurlimann, **Jason Geosystems**

The Fateh SW field is a low-relief structure influenced structurally by gentle deep-seated salt movement. The

main reservoir targets are the Cretaceous carbonates of the Mishrif and Thamama formations. Within the Thamama Formation, seismic resolution of the 3-D seismic data is insufficient to map thin, porous reservoirs that are separated by dense zones. The top of the Thamama reservoir has large lateral variations in seismic amplitude due to a combination of multiple interference, tuning effects, and lateral changes within the carbonate units. It is therefore difficult to correlate changes in seismic amplitude to changes in the reservoir parameters.

To address these problems, a seismic inversion pilot study was carried out over part of the field using Jason Geosystems' Constrained Sparse Spike Inversion (CSSI) technique. An acoustic impedance volume was generated over a selected area where future wells are planned. The workflow included seismic well calibration, wavelet estimation, solid-earth model generation, 3-D seismic CSSI inversion to obtain an acoustic impedance cube, detailed interpretation and mapping of reservoir units, and estimation of reservoir parameters. Preliminary results indicated (1) improved resolution on the acoustic impedance volume compared to the seismic data, (2) increased accuracy of horizon picking for key seismic markers, and (3) detailed interpretation of Thamama Zone 1B and Zone 2 reservoir layers can now be carried out in some parts of the field. As more wells are drilled in the Thamama reservoir, drilling results will be compared with the acoustic impedance data to validate the seismic inversion results.

(#385-O) Jurassic and Lower Cretaceous sedimentation patterns in the Dezful embayment and Fars area, SW Iran

Fabrice Gaumet and Frans S. van Buchem, **IFP**;
Darioush Baghbani, Reza Ashrafzadeh,
Hossein Assilian and Forooz Keyvani, **NIOC**

The Jurassic and Lower Cretaceous in the Fars province and the Dezful embayment that are currently a target for gas exploration, are the subjects of this presentation. Based on three outcrop sections, and about 60 wireline logs and paleologs, a sequence stratigraphic framework will be presented, predictive geological models (geometries and facies distribution) proposed, and the geodynamical basin evolution (paleo-geographical and isopach maps) analyzed.

In general, the Fars region was a subsiding platform on the margin of the paleohigh of the Qatar Arch for most of the time, whereas the Dezful embayment was a transition zone where major facies and thickness changes occurred. Five tectonosedimentary phases have been distinguished based on changes in depocenter location, nature of the depositional system, and nature of the tectonic control. Phase I (Early Jurassic Neyriz Formation) was characterized by attached ramp systems, with some local platform shoals. During phase II (Middle to Late Jurassic Surmeh and Sargelu formations), vast normal-marine and lagoonal platforms existed in Fars, whereas a starved basin was present in the Dezful embayment and Lurestan. During Phase III (latest Jurassic) the Gotnia, Hith, and upper Surmeh formations were deposited in rimmed hypersaline platforms and adjacent salina basins. Phase IV (earliest Cretaceous Garau Formation) was characterized by narrow radiolarian-rich seaways that cut the emerged Zagros Platform. Phase V (Early Cretaceous Garau, Fahliyan, and Gadvan formations) consisted of rimmed carbonate platforms on which was deposited a mixed carbonate-siliciclastic regional-scale ramp system.

The dominant-controlling factor on the sedimentation pattern was the tectonic control that defined a changing mosaic of subsiding domains and paleohighs.

(#377-O) Basin analysis and source evaluation of the Upper Jurassic succession of northern Iraq

Ali D. Gayara and Bassim F. Al-Kubaisi, **Baghdad U.**

The Upper Jurassic succession was deposited within a ramp setting in a passive margin basin. The Najmah Formation was deposited in restricted marine, shallow open-marine and shoal environments. The Naokelekan Formation on the other hand represents deposition within restricted secondary basins to the east. The evaporitic Gotnia Formation was formed during a major regression and is correlated with the evaporitic and restricted marine Barsarine facies to the east. The deep marine and basinal Chia Gara facies represent the effect of a major sea level rise at the end of Late Jurassic.

Five third-order cycles were recognized, each consisting of transgressive and highstand systems tracts. The cycles reflect successive episodes of transgression and stillstand related to relative changes in sea level. The deviation of the relative sea-level curve from the global curve at the beginning and the end of the Late Jurassic, as well as in the early Kimmeridgian, shows the effect of local tectonism.

Burial history analysis reflects changes in basin geometry through the Upper Jurassic due to variations in local tectonic activity. This caused the development of several secondary basins whose subsidence rates reached a maximum in the Kirkuk area. The

subsidence rates lessened westward. Three initial geothermal gradients were constructed for three depth intervals. The geochemical indices of the Sargelu, Naokelekan, and Chia Gara formations reflect their high potential as source rocks as well as their thermal maturation. The quantity evaluation model showed that a sufficient amount of hydrocarbons was able to migrate from the studied succession to provide charge for the overlying reservoirs. Multiphase vertical migration took place as well as early lateral migration from mid-Cretaceous source rocks in the central and eastern parts of the basin toward Iran.

(#342-O) Biostratigraphy and paleobiogeography of chitinozan taxa in the Lower Silurian Niur Formation of the eastern Alborz Range, Kopet-Dagh region, NE Iran

Mohammad Ghavidel-Syooki, **NIOC**

The Silurian Niur Formation is well developed in the Kopet-Dagh region of the eastern Alborz Range about 55 km southeast of the Caspian Sea. It has a thickness of 750 m and is made up of two members. Member 1 is 500 m thick and is composed mainly of black shales with subordinate thin-bedded limestones. The overlying 250-m-thick Member 2 consists of basal conglomeratic sandstone that passes upward into red shales with a few olive-gray shale beds. The lower and upper contacts of the Formation are conformable with the underlying Upper Ordovician strata and the overlying Upper Padeha Formation. A total of 200 surface samples were selected for paleontological study, in order to establish a biostratigraphic zonation and to determine the paleogeographic relationship of the Kopet-Dagh region.

Member 1 contained well-preserved and abundant chitinozoans, acritarchs, cryptospores, graptolite remains, and scolecodonts. Member 2 was mostly barren. Thirty-five chitinozoan taxa were recorded and arranged in seven biozones, consisting of *Spinachitina fragilis*, *Belonechitina postrobusta*, *Lagenochitima nuayyimensis*, *Ancyrochitina qusaibaensis*, *Plectochitina paraguayensis*, *Angochitina hemeri* and *Angochitina macelurei* biozones. Based on these biozones, Member 1 was assigned an Early Silurian age. The chitinozoan species from the Niur Formation show a broad similarity with those of the same age from Algeria, Libya, Morocco, Saudi Arabia, and Spain, suggesting the eastern Alborz Range has been part of a pre-Gondwana supercontinent.

With regards to acritarchs, Member 1 contains *Dactylofusa maranhensis*, *Daclylofusa estills*, *Geron guerillerus*. *Eupoikilofusa* sp., *Domasia trispinosa*. *Dilatispaera* sp., *Elektoriskos* sp., *Visbysphaera* spp. and *Multiplicisphaeridtum neaghae*. They suggest an Early Silurian age for Member 1 consistent with the chitinozoan age. Member 2 contains only a few acritarch species such as *Baltisphaerdium diabolicum*, *Anomaloplaisium* sp., and *Elektoriskos aurora*. They indicate a Middle Silurian (Wenlockian) age for this part of the Niur Formation.

(#98-O) Upscaling of a multimillion-cell geological model to a practical dynamic simulation model of a major carbonate oil reservoir, offshore Abu Dhabi

Shawket G. Ghedan and Tom W. Gunningham, **ADMA-OPCO**; Bassam M. Ehmaid, **ADNOC**; Samir R. Azer, **ADMA-OPCO**

Careful design of the simulation model areal grids, fine reservoir layering, and quality controlled up-scaling processes, are vital to retaining the static model's main structure and heterogeneity features of a carbonate reservoir. This presentation is of the methods to construct a 0.7-million-cell dynamic model out of a 25-million-cell static model, together with the required quality checks, as applied to a major carbonate oil reservoir in offshore Abu Dhabi.

Mechanistic simulation modeling was employed to evaluate the optimum (largest) areal cell size that would still retain the features of the geological model, while keeping a reasonable number of grid blocks between producers for future infill wells and sidetrack workovers. Control lines were digitized on a base map in order to assign areas of different cell size, such as gas cap, oil rim, and aquifer zone. The grid cells were mapped exactly over the geological model cells to reduce the uncertainty of the upscaling process. Major faults were modeled as slanted faults, keeping the grid cells next to the fault surfaces as orthogonal as possible. The simulation layers were made as detailed as possible so as to retain identified key geological features such as barriers, high-permeability streaks, and pinchouts. Mechanistic simulation modeling, together with permeability variance maps and profile graphs of the permeability of the geological fine layers, were used to check the adequacy of the initially proposed reservoir layering system. New simulation layers were introduced as required.

Good simulation grid design is an essential step in the success of the upscaling process. Rock properties may not have the biggest effect on fluid displacement relative to layering, faults, or other structural features. Various upscaling techniques were utilized as needed. The upscaling process was then quality checked to ensure minimum errors.

The successful application of these three important aspects of dynamic simulation construction produced a quality simulation model ready to be initialized and history matched.

(#281-O) Enhancing reservoir structure through heliportable 3-D seismic acquisition in rough terrain, Yemen

Marc J. Girard, Pascal Nicodeme
and Patrick Grivot, **TotalFinaElf**

3-D dynamite survey at the end of 2000 was a step forward in the development of the Kharir and Atuf fields in the East Shabwa Block-10 of onshore Yemen. This presentation focuses first on the decision-making process for acquiring costly 3-D seismic data over oil fields that have been in production since 1997 and were already imaged through several 2-D surveys. It also describes the optimization of the 3-D survey design and acquisition as a means of improving knowledge of the reservoir through the expected seismic image enhancement.

Block-10 is an eroded limestone plateau at an elevation of 1,000 m. An intricate network of deep wadis produces relief differences of as much as 300 m. The 3-D survey required the use of heavy seismic crews with fully heliportable logistics. The main challenge was to optimize final data quality at reasonable costs, knowing that previous 2-D surveys had been characterized by low signal-to-noise ratio and narrow frequency bandwidth, mainly due to unfavorable surface conditions. Prior to acquisition, TotalFinaElf carried out a comprehensive seismic feasibility study, including several 3-D dip moveout cube simulations built with 2-D data correctly sampled spatially. It provided a global set of parameters that were adjusted according to budget and operational constraints. Results are promising, as their impact on reservoir characterization and structural frame has been very positive for the next field development phase, having confirmed several anticipated targets in attic positions for horizontal drilling.

(#178-P) Faults and faulting in a large oil field, onshore Abu Dhabi

Andrew M. Gombos, Khalid A. Al-Amari,
Naji S. Binbrek, Ahmad A.W. Al-Shaikh
and Bashir B. Garea, **ADCO**

Two clusters of faults that trend N55°W and N67°W are present in the field. They have small amounts of throw and seem to die out below the main reservoir. In map view they appear as discrete en echelon segments. It is probable that these larger segments represent amalgamations of much smaller en echelon segments that are below seismic resolution. The faults are thought to result from contractional forces that deformed the field in the Tertiary. Dip-slip faults with minor oblique offset developed above the neutral surface. The resulting fault pattern is one of discrete, discontinuous, minor-throw faults forming a zone, rather than a single planar surface. Many minor intraformational faults occur in the reservoir zone but they have minor throws and are not significant impediments to fluid flow.

(#62-O) Depositional framework of the Ara Group carbonate successions in the South Oman Salt Basin

Imelda Gorman Johnson, **Badley Ashton**; Joachim E. Amthor, **PDO**; John P. Grotzinger, **MIT**;
Cathy E. Hollis*, **Badley Ashton**

The Neoproterozoic to Early Cambrian Ara Group of the South Oman Salt Basin consists of at least six third-order evaporite / carbonate depositional sequences (A1 to A6) that contain prolific hydrocarbon reservoirs of the intrasalt carbonate stringer play. Carbonate rocks comprise key lithofacies associations that imply deposition in a shallow-water platform to offshore slope / deep-water basinal setting. This is illustrated by the following sequences:

The A2 carbonate was the lowest intrasalt carbonate succession studied in detail. It consists of an inner-ramp thrombolitic to grainstone-dominated succession, with a broad regressive signature. Correlation indicated that lithofacies belts were laterally extensive, probably a function of the low accommodation regime, low-relief depositional profile, and resultant aggradational architecture. In contrast, the overlying A3 carbonate consists of a lower section that is commonly dominated by outer ramp breccias and remobilized mudstones and grainstones, and an upper section of inner-ramp thrombolites and grainstones. Correlation within the A3 carbonates suggested a more complex proximal to distal lithofacies distribution with kilometer-scale lateral lithofacies changes. This, together with the abundance of breccias, suggested that steeper depositional profiles existed at this time, and that fault-related differential subsidence may have played a role in controlling relative sea level. Carbonates of the A5 sequence are low energy outer ramp and turbiditic carbonate mudstones alternating with organic matter; hence they are more representative of source-rock stringers and form only marginally productive reservoirs.

The increasing component of outer ramp lithofacies within the A5 carbonates compared to the A3 and A2 stratigraphic sequences suggests that deposition had been within a long-term transgressive regime. This has important implications for reservoir distribution, and has resulted in an overall reduction in reservoir potential and increased risk in younger stringers.

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(#382-P) The 'Hercynian event' in Arabia and North Africa: timing, distribution, and possible controls

George J. Grabowski, Michael A. Sullivan, John W. Steritz, Robert J. Ferderer and Steven Creaney, **ExxonMobil**

Across North Africa and Arabia, the 'Hercynian' unconformity is diachronous. In Algeria and westernmost Libya, the main unconformity is Early Permian (Sakmarian) and overlies Autunian-Stephanian clastic sediments. In eastern Libya and Egypt, two discrete unconformities exist of Early Permian and Late Carboniferous age. In Arabia, Westphalian to Artinskian clastic sediments of the Haushi and Unayzah formations unconformably overlie Carboniferous and older strata. This general younging of uplift and erosion to the east is inconsistent with the well-constrained timing of Hercynian compressional deformation in Europe and northwestern Africa. Deformational intensity and style also diminishes across the region, with the Trans-Saharan Fault Zone (TSFZ), defining a critical strain-partition boundary. To the west of the TSFZ, fold and thrust belt deformation typical of orogenic forelands is observed, whereas to the east in Libya and Egypt, gentle folding and warping is the dominant style.

Paleozoic facies patterns in northern Egypt also illustrate progressive uplift that began in the Ordovician and culminated in the Late Carboniferous. It is this uplift, and not far-afield 'Hercynian' compression that was responsible for unconformities in eastern North Africa and westernmost Arabia. One potential driving mechanism behind this uplift was the progressive development of the long-lived alkaline magmatic provinces of eastern Egypt and northern Sudan. This uplift may also have been an early abortive attempt at rifting in this location. In Arabia, the Central Arabian Arch appears compressional in nature and may have resulted from orogenic deformation along the pre-break-up northern margin of Arabia (present-day Iran).

(#160-P) Structural elements in the Arabian Gulf from satellite gravity data

Harald Granser, **OMV**

Satellite altimetry has revolutionized the knowledge of the tectonic structures in offshore areas where other geophysical data are either sparse or not easily available. A Bouguer and Isostatic Anomaly Map of the Gulf region was derived from satellite altimetry and bathymetric and onshore topographic data. The satellite data were collected during the Geosat Geodetic Mission and the ERS-1 Geodetic Phase as dense profiles of about 7 km spacing, to yield a free air gravity anomaly grid with a reported accuracy of about 5 mGals.

Although the low-pass effect of the radar footprint has to be considered, the easily available altimetry data can provide a regional dataset of valuable information on the tectonic and structural framework, especially when further processing (such as shading) is applied and derivative maps produced. In the Arabian Gulf, the main structural elements, such as the N-trending highs of the Qatar Arch, the offshore extension of the En Nala (Ghawar) anticline, and the Safaniya-Hout-Dora-Nowruz trend, can be identified. Also a N-trending anomaly zone associated with Bahrain-Abu Sa'fah is discernible. Because the mainly carbonate rocks of the region have relatively high bulk densities, basement highs or lows do not necessarily correlate with gravity highs and lows. Due to salt doming, many oilfields in the Gulf—Bul Hanine, Idd El-Shagri, Balal, and others—relate to negative gravity features. Also, the giant North Field has a negative gravity anomaly. In the Iranian area of the Gulf, NW-trending lineaments, roughly parallel to the coastline, were identified from the available seismic data as being related to an extensive fault system.

(#254-P) Abqaiq field: redatuming and scaling of 3-D seismic volumes

Arthur E. Gregory, Roger R. Sung and Mohammad A. Al-Jadani, **Saudi Aramco**

3-D seismic data has been redatumed and scaled to depth to enable integrated interpretation and seismic reservoir modeling of the Abqaiq field. Redatuming of the seismic data from a sloping mapped surface to sea level was performed to minimize shallow inaccuracies in the depth cube, to simplify interval velocity and related depth-scaling calculations, and to facilitate integrated analysis and quality control. Layered velocity models were generated, using cross-plot and geostatistical techniques. Various velocity and

depthing scenarios were generated and analyzed, to arrive at the optimum depth-scaling velocity for each of five layers. Sequential Gausian Simulation and Cross-validation techniques were also used to estimate and map the depth uncertainty for key areas of the volume. Discrete (instantaneous) velocity volume models were also generated and used to scale various seismic volumes to depth. These velocity and seismic volumes have provided the framework for subsequent integrated interpretation, drill-well-path planning, and reservoir development.

(#276-O) Uncertainty assessment in reservoir modeling: the Jacta integrated approach

Emmanuel Gringarten
and Taoufik Ait Ettajer, **T-Surf**

With the emergence of asset teams and the advances in visualization and immersive and collaborative technologies, shared earth models are increasingly providing the basis for reservoir management decisions. In the process, they are forcing an overlap in the work performed by traditional disciplines and a consistency between geophysical, geological, and engineering models. Each element of the earth model has not only a separate influence but also a combined impact on the end result, and particularly on the estimation of uncertainties, which drives economic and engineering decisions.

Uncertainty exists at all levels of the construction and exploitation of the earth model, starting with measurements of raw data and their interpretation. For instance, uncertainty in seismic interpretation and in the velocity model affects time-to-depth conversion in the structural model. For the petrophysical model, uncertainty is due to poor sampling of the complex and heterogeneous subsurface. Finally, there is uncertainty on the specifications of the flow model. The combination of these uncertainties affects one's ability to understand and predict reservoir behavior and to reliably forecast reservoir production.

Assessing the cumulative effect of all these sources of uncertainty with stochastic modeling and multiple scenarios can rapidly become overwhelming, yet it must be done. This requires tools that are able to do the following: (1) account for the complete range of uncertainties, from time-to-depth conversion and structural modeling, to property modeling and flow simulation; (2) identify the critical sources of uncertainty; (3) assess the impact of key uncertainties on specific reservoir management decisions; and (4) assess the best course of action to reduce these critical uncertainties by refining the interpretation models or gathering new data. In addition, storing thousands of stochastic realizations is usually impractical, so it must be possible to recreate a limited number of ranked realizations that are most representative of the uncertainty affecting the reservoir management decision.

JACTA is a tool that provides such functionality by capturing and integrating all possible uncertainties related to the construction of a full 3-D model. The seamless integration of commercial streamline-based simulators, enable JACTA to also capture uncertainties in the dynamic model.

(#101-O) The Upper Jurassic Arab Formation in UAE: sequence stratigraphy, reservoir architecture, and integrated subsurface modeling

Jürgen Grötsch, **Shell**; Reyad A. El-Khassawneh, **ADNOC**; Ray F. Staller, Erik van der Weerd, Shehadeh K. Masalmeh and Johan J. van Dorp, **Shell**

A 3-D geological model was prepared for the Manifa, Hith, Arab-ABC, Arab-D upper, Arab-D lower, and upper Diyab formations. It is based on a newly established sequence stratigraphic, sedimentologic, and diagenetic model for the Upper Jurassic (Kimmeridgian-Tithonian) of onshore Abu Dhabi. The modeling exercise has demonstrated the complexity of the Arab reservoir that is controlled by a set of fourth-order aggradational and progradational cycles that are themselves composed of fifth-order, small-scale shallowing-upward cycles, mostly capped by anhydrite in the Arab-ABC.

The Arab sequence was identified as having prograded toward the east-northeast, essentially filling an intrashelf basin that occupied the accommodation space generated during the Kimmeridgian. High-energy oolitic/bioclastic grainstones of the Arab-D upper and the Asab Oolite mark the prograding coastline. The Arab-ABC, Hith, and Manifa formations pinch out toward the northeastern part of the field. The strongly bioturbated sediments of the lower Arab-D are an intrashelf basinal deposit that is time-equivalent to the Arab-ABC and part of a gently dipping ramp within the Arabian Plate. The Manifa Formation is part of a drowning succession that indicates a major backstepping event of the shallow-water platform deposits before the onset of a renewed Lower Cretaceous intrashelf basin infill cycle. Petrographic and regional analysis indicated that dolomitic streaks in the Arab-ABC cycles are of early diagenetic origin, resulting in a good overall preservation of properties. The stratiform dolomite

streaks in the bioturbated oolitic / bioclastic grainstones of the Arab-D upper, on the other hand, show a greater deterioration of properties with depth due to burial diagenesis. A rock-type scheme was established for all lithostratigraphic units as the depositional facies scheme could not be directly related to petrophysical properties because of diagenetic overprinting. Standard core-analysis data acquisition and attribution of saturation functions to the static and dynamic model were performed on a cell-by-cell basis using the established rock types.

After ongoing data acquisition in the field, iterative feedback looping and updating was applied between the static and dynamic model. Upscaling was performed with emphasis on preserving the cyclicity and the thin streaks of increased permeability in the dynamic model. A series of extracted dynamic simulation models allowed definition of the development requirements in the sour-gas reservoir. The appraisal-drilling results confirmed that well productivity in the Arab-ABC is predominantly controlled by the development of thin permeable dolomitic streaks within fifth-order shallowing-upward cycles. This is considered a key finding with respect to reservoir management, well completion, stimulation strategy, and development planning.

(#375-O) New model for tectonic evolution of Neoproterozoic-Cambrian Huqf Supergroup basins, Oman

John P. Grotzinger, **MIT**; Hisham A. Al-Siyabi and Rashid A. Al-Hashimi, **PDO**; Andrea Cozzi, **ETH-Zurich**

New U-Pb ages have constrained the deposition of the rift-related Ghadir Manquil Formation and Mirbat Sandstone to between 730 and 700 Ma, about 150 my older than previous estimates. Shelf facies of the overlying Nafun Group were deposited between 600 and 550 Ma, based on chemostratigraphic profiles. This 100 my unconformity precludes a simple relationship between Abu Mahara crustal extension and Nafun regional subsidence due to thermal decay. The Nafun Group is temporally continuous into the Ara Group based on U-Pb zircon dating of volcanic ash beds in A0 (basal Ara) and A4 (middle Ara) carbonates. The onset of Ara subsidence at about 550 to 548 Ma was accompanied by a shift to arid climate and the uplift of basement blocks to form smaller basins in which salt and carbonates accumulated. Ara strata younger than A4, including volcanics of the Fara Formation, are of earliest Cambrian age. Ghadir Manquil-Mirbat subsidence was related to the extension at about 725 Ma of a composite basement terrain. This consisted of Archean basement blocks stitched by older Pan-African (about 800 Ma) arcs, which was sutured to the younger terranes of the Arabian Shield at about 625 Ma. Nafun regional subsidence started at this time and is here considered to relate to dynamic depression of the lithosphere associated with subduction of oceanic lithosphere beneath the Arabian Plate. Subduction is inferred to have occurred from the northeastern margin of Gondwana (eastern Oman) where an Andean margin resulted in orographic retroarc desiccation. Uplift of basement blocks where the subduction dip was gentle, was analogous to the Bolivian segment of the Andes. Volcanic ashes within the Ara Group record this arc activity, and volcanic centers such as the Abu Butabul caldera in North Oman record subduction-related melting of the crust in a retroarc setting.

(#350-P) Rock-type simulation constrained to geological features, Awali field, Bahrain

Luis F. Guerriro, Jose Antonio and Amilcar Soares, **CGG**; Yahya Al-Ansari, **Bapco**

Defining rock types is one of the first steps in reservoir characterization and modeling. They are characterized by a consistent set of petrophysical properties, which implies that they may have similar hydraulic behaviors. Since rock types summarize a suite of petrophysical properties, they represent a powerful way of characterizing reservoirs. Theoretically each rock type should have a characteristic porosity and permeability range, and a specific porosity / permeability relationship. Although it is difficult to meet both objectives most of the time—especially the second one—rock types remain a powerful tool.

Several methods based on the geological model and well data (from logs and cores) can be used to define the rock types. Simple log, core, or facies associations offer alternatives and multivariate data analysis (or more recent techniques such as Neural Networks) can also be used. However, the appropriate rock-type definition is not enough if the main goal is to obtain a 3-D model of the petrophysical properties. The simulation of porosity and permeability should be constrained by the rock-type model for the entire reservoir if it is to reflect lateral and vertical variations in reservoir quality. Special care is required during the rock-type simulation, because the resulting model will guide the porosity and permeability simulations.

Where the rock types are dispersed spatially according to a non-stationary pattern characterized by local trends of rock types, the standard Sequential Indicator Simulation (SIS) usually fails to reproduce those

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trends. A modified version of the SIS algorithm is needed to ensure that the final images honor the local means and spatial trends of different categories, such as rock types. The modification was a progressive correction of the estimated local proportions of various categories during the sequential simulation process. In practical terms, this non-stationary version of SIS is useful wherever the geology indicates a stable depositional environment and well-defined layers. The presentation will describe the method applied to two Bahrain reservoirs and show that, by combining a set of rock type simulations, the final model honors the main geological constraints.

(#352-O) A multidisciplinary approach for optimizing reservoir performance: a case study

Luis F. Guerriro, **CGG**; A. Nabi Mukhtar, **Bapco**; R. Patrick MacDaniel, **CGG**

The Bahrain field is a mature asset having been producing since 1932. There are 11 major reservoirs. The Rubble Zone (Upper Cretaceous) is the shallowest and the pre-Khuff (Lower Permian) is the deepest. Most reservoirs are oil-bearing, but gas is present in the Arab-A and Arab-C, the Khuff, and the pre-Khuff (Unayzah). The Khuff and Unayzah are the main gas reservoirs. The field is heavily faulted, which has created compartments that allow for cross-flow along the faults and between some reservoirs. An integrated reservoir study is underway in order to improve the asset management of this resource. This involves static and dynamic modeling. An integrated approach that involves geological, geophysical, petrophysical, and engineering data sets was implemented for the reservoir characterization. The interpretation of new 3-D seismic and stochastic reservoir modeling provided a framework to assess ways of optimizing the exploitation of the remaining oil and gas reserves. The stochastic techniques included Neural Network methods and discrete fracture modeling. The models were upscaled for the numerical simulation. Some geostatistic algorithms—for example, Sequential Indicator Simulation—were tailored to couple with specific geological and technical constraints during the simulation of stochastic petrophysical properties.

This case study is an example of how different disciplines can be integrated in order to obtain a reservoir model that honors the geologic model and matches the production data. The multidisciplinary approach was essential in order to obtain reservoir models that could be easily matched with the production data during the dynamic simulation.

(#210-O) Balal field, upper Arab reservoir: core-based microstructural model and impact on permeability field definition

Laurent Guy, **TotalFinaElf**; Mohammad J. Mashayekhi, **NIOC**; Christian Staffelbach, **CORIAS/ CORPRO**; Abdel-Hamid Anis, **CORPRO**

The Balal field in offshore Iran, is being developed for oil production from the Upper Arab reservoir by Elf Petroleum Iran in association with Bow Valley Energy and AGIP Iran BV, through a buy-back contract signed in April 1999 with the NIOC.

The Upper Arab reservoir has a complex behavior with fractures and vugs having enhanced the reservoir productivity. Indeed, the average permeability derived from the well-test interpretation is an order of magnitude higher than the matrix permeability obtained by conventional petrophysical core measurements. A continuous coring of the reservoir on the first producer well, and an extensive micro-structural core analysis has been performed to qualify and quantify the fractures.

The characteristics of the core-based micro-structural model have enabled the fracture component of the permeability network to be assessed in detail. It was deduced that the reservoir should not act as a simple 'matrix-plus-fracture' model. Instead, the fracturing model consisted of diffuse fractures occurring all along the cores, together with some fracture corridors. As a consequence, fluids could flow both through the diffuse fracture framework (acting as an enhanced matrix permeability field) and the fracture corridors (acting as very high permeable drains). The N30° to N40° direction, which is parallel to the regional Zagros related stress direction, seems most favorable for fluid flow. However, the N120° to N140° partially open fractures could also remain open under any in-place stress conditions due to partial filling acting as a bridge and preventing the sealing of the fractures.

(#241-P) Dynamic data for dynamic models: upscaling static models using monitoring data from production tests and pilots

Asbjorn Gyllensten and Medhat K. Abdou, **ADCO**

This presentation will discuss how to extract maximum information from various types of dynamic data by presenting examples from a large carbonate reservoir in onshore Abu Dhabi. It will also illustrate how such

data can be used with static data to improve and history-match dynamic simulation models.

The ultimate objective of reservoir characterization by reservoir rock typing is to generate models that allow accurate prediction of future recovery, in order to optimize field development and production management. For carbonate reservoirs, it is possible to build several geological models, all honoring the available core and log data and incorporating the latest geological ideas. The 'right' static geological model can only be selected (after upscaling) through flow simulation. Dynamic reservoir simulation models are expected to match pressure, gas-to-oil rates, and water-cut trends over time. In new field developments, dynamic data may be limited to production tests and pilots. Production logs, monitoring logs, tracers, and time-lapse formation pressure data respond to flow units rather than rock types and often have coarser vertical resolution than do the static data. For example, production logs in vertical wells with barefoot completions will show inflow profiles that reflect the combined flow characteristics of several rock types within a geologically heterogeneous hydraulic flow unit. On the other hand, production logs across barefoot completions have no adverse effects from limited perforations or partial stimulation, which may complicate the interpretation of such logs in cased holes.

In clean carbonate reservoirs with high porosity, and high-salinity formation- and injection-waters, pulsed neutron capture logs generally provide reliable data. To avoid the effects of acid-stimulation and local, near-wellbore effects like water coning or water slumping into producer perforations, we prefer to monitor wells penetrating the target reservoir, but completed on deeper zones.

(#194-O) Surface-related multiple elimination to mitigate multiples in marine 3-D data

Mohamed T. Hadidi, Anatoly I. Baumstein, Young C. Kim and Warren S. Ross, **ExxonMobil**

In many parts of the world, marine seismic data are corrupted by multiple reflections that obscure target horizons of geologic interest in hydrocarbon exploitation. Geophysical methods of suppressing such multiples have a long history, from the simplest trace-by-trace deconvolution approach developed in the 1960s to the more sophisticated wave-equation methods developed in the 1980s and 1990s. The Surface-Related Multiple Elimination method (SRME), which uses the data itself to predict the multiples, has been effective in suppressing multiples in 2-D data where the lines are shot dip-to-structure, so generating multiples.

The extension of SRME to 3-D follows two lines of development. These are (1) applying the 2-D method to 3-D data (multistreamer data), where the multiple-generating mechanism is predominantly 2-D; and (2) a full extension to 3-D, where the multiple-generating mechanism is truly three-dimensional. The full extension to 3-D is under development.

We will show an application of 2-D SRME to multistreamer data in an area with an uneven sea floor and a consequent data-quality problem due to complex multiples. An entire sail line (all streamers) was processed using our proprietary implementation of SRME. We will present a comparison of the processed innermost and outermost streamers, demonstrating good multiple suppression on both. We will also compare the final processed data with previously processed data from this area. SRME improves on the earlier data by identifying interpretable horizons at the target level.

(#127-O) North Field Bravo: Qatargas well-log database

Khaled Hamam, **Qatargas**

North Field (NF) is the World's largest non-associated gas field. It is about 80 km offshore Qatar and about 8,300 ft below sea level. Reservoir studies estimate the gas-initially-in-place at 504 trillion cu ft in four main producing reservoirs (Khuff-K1 to -K4). Qatargas acreage (North Field Bravo) is an area 10 by 10 km that has 20 gas-producing wells. The three companies operating the North Field—Qatar Petroleum, Qatargas, and Rasgas—have established a NF Technical Master Database Project (NF MDDB) to safeguard the NF data in a consolidated database on Finder and to put it to optimum use.

This presentation will describe the creation for Qatargas of a Well-Log Database (WLDB). The database will record all logs and tapes in digital formats that are easy to access and update, and will make retrieval of data possible from a user-friendly cross index. A total of 400 records and 130 tapes were verified. The data, inherited from the former Drilling Department, included hard copies of an incomplete records set that was full of repetitions, inconsistencies, and mistakes.

The NF MDDB Project began in December 1999. It consists of several modules and took the Corporate Well Log Database as a starting module. To put

Qatargas' log data in order, the IT Department in February 2000 devised the Well Log Tracking System (WLTS) using MS Access. The System gives a unique number for each log. The tape data were recorded in MS Excel. All logs (films, prints, and tapes) are physically checked and verified before they are entered on the WLTS. Repetitions were removed, inconsistencies and mistakes put right, and all the 'left-out' logs were entered to make log records complete. The WLDB forms a solid contribution to safeguarding Qatargas' invaluable log data, and to the NF MDDB Project as a whole.

(#196-O) Modern demultiple techniques applied to Arabian Gulf data

Neil D. Hargreaves and Helmut Jakubowicz, **Veritas**

Arabian Gulf multiples are often resistant to conventional multiple-removal techniques, partly because of their geological setting and partly because of the nature of the multiple-generating mechanisms. Internal multiples generated by different interbed reverberation sequences, for example, will be non-stationary with a mixture of different periods and with limited differential moveout between primaries and multiples. Predictive deconvolution will struggle to remove such events, whilst Radon and similar methods may also be ineffective. Surface multiple prediction may not be relevant to the multiple-generating mechanism, and is also not easily applied to land acquisition geometries.

In this presentation, we will give the results from some new multiple-attenuation techniques that have the potential to address limitations of the more-conventional approaches. We will show results from a high-resolution Radon transform that by applying constraints to the least-squares solution, increases the separation between primary and multiple in the Radon domain as compared to the standard approach. This allows us to obtain a more complete multiple removal than with the conventional transform for events with limited differential moveout. A better primary amplitude preservation is also possible.

We will also show results from wave-equation internal multiple prediction, in which interbed multiples are calculated directly from the surface-recorded wave-field components. We have incorporated this into a targeted pattern-recognition approach to multiple subtraction, which discriminates between multiples and nearby primaries using the lateral amplitude and phase behavior of those events.

(#74-O) Regionally tilted oil-water contacts or sealing faults in oil fields of northwestern Oman

Kester D. Harris, **PDO**

The Late Cretaceous Lekhwair East oilfield is in northwestern Oman, close to the borders with UAE and Saudi Arabia. The field is characterized by low permeability, chalky reservoirs with long entry heights (5–40 m) and long transition zones (5–20 m). In 1999, a downdip exploration well found unexpectedly high oil saturations, and raised aquifer pressures in the water-leg. This suggested that the field was compartmentalized by sealing faults, with differing free-water levels in the various blocks. The presence of sealing faults upgraded the prospectivity of the area. A follow-up well was drilled in 2000 but found only marginal saturations.

Careful analysis of the structural history of the field has now revealed that a large part of the present-day 'transitional' oil is in fact the remains of an early (pre-Eocene) oil-fill that was breached and then recently tilted. The paleo-oil-water contact has accordingly also been tilted, and the present-day oil saturations are controlled by imbibition processes, rather than by drainage. The mapping of geochemical oil-typing data supports this model.

The post-Eocene tilt was a significant regional event, and several other oil-fields in the region show the same anomalous 'transition' zones that are symptomatic of the re-migration of hydrocarbons. This has consequences for petrophysical and reservoir modeling, and implications for reservoir properties, production behavior, and prospectivity.

(#124-P) Controls on cementation of fractures, Lekhwair field, Oman

Kester D. Harris, **PDO**; Sait I. Ozkaya, **Baker Hughes**; Wilhelm H. Kolkman, **PDO**

Lekhwair is one of the north Oman fields that produces from fractured Cretaceous Shu'aiba carbonates. Fractures are mostly fault-related and occur in dominant WNW-, NNW-, and occasional NE-trending corridors. The mapped distribution shows that fracture corridors are fluid conductive at the crest of the Lekhwair structure, but cemented on the flanks. All three sets of fractures and faults obey this general principle. Faults may also change character along the fault trace and fluid-conductive faults become cemented away from the crest of the Lekhwair structure toward its flanks. The boundary of cemented

and fluid-conductive fractures is coincident with the oil-water contact.

Multiple phases of fracturing, cementation, and dissolution took place in the Lekhwair field during the Late Cretaceous and Tertiary. Fractures were cemented or re-cemented soon after each generation or reactivation episode. Only fractures that were generated within the oil leg, and after oil emplacement in the early Tertiary, escaped cementation.

Within the water leg, cementation sealed the small fractures first and then gradually filled larger fractures. Some major fractures near faults escaped complete sealing owing to their wide apertures.

(#226-P) The effect of stylolites on rock geochemistry, porosity, and mini-permeability of the Khuff reservoir in Saudi Arabia

Hassan M. Hassan, **KFUPM**

Stylolites are common in reservoir rocks of the Late Permian to Early Triassic Khuff Formation in Saudi Arabia. In some cases, they are present at a frequency of one stylolite per foot of core. This presentation is of their effects on the rock geochemistry, porosity, and horizontal minipermeability of the Khuff reservoir. Inductively coupled plasma mass spectrometry, X-ray line scan and X-ray mapping were used in the geochemical studies, whereas the porosity and the horizontal minipermeability were measured using a conventional porosimeter and a Temco gas minipermeameter. Results showed that stylolitization was accompanied by the depletion of some original rock (chemical) elements and the introduction of others. Stylolites are known to be barriers to the vertical minipermeability. However, in this study it was found that this is not necessarily the case where horizontal minipermeability is concerned. Stylolites could reduce the permeability in dolomite rocks with intercrystalline pore systems but may enhance it in limestones that had a moldic pore system by creating intercrystalline pore systems that could be conduits as well as hosts for natural gas.

(#327-P) The tectonic setting of the Rutbah uplift area in Iraq.

B.R. Hijab and E.N. Baban, **Baghdad U.**

Surface and subsurface geological data were used to investigate the tectonic setting of the Rutbah uplift in the western desert of Iraq. As a result, this area—which for the past few decades had been considered as an uplift—may have a different tectonic setting.

Borehole data do not show any signs of uplift but rather indicate a N-trending longitudinal basin that was filled by mainly clastic rocks of the Carboniferous-Permian Gaara Formation. The clastics were derived from the erosion of exposed areas in Saudi Arabia and deposition may have continued as far as Syria. Thin beds of clastics and carbonates of Mesozoic age overlie the Gaara Formation. In addition, the middle and lower Paleozoic reflectors that were deduced from seismic reflection data to a depth of 8 km, clearly show that the Rutbah area formed a broad depression between two major paleohighs. One paleohigh is the Risha uplift, the crest of which is located about 6 km west of the Iraq-Jordan border. It is believed to have been formed in the Late Devonian to Early Carboniferous. The other paleohigh is the Anbar uplift located to the east of Rutbah. It was possibly formed during the Late Silurian to Early Devonian. Results of a residual and second-vertical derivative analysis of Bouguer and total magnetic data from the Rutbah area indicate a sequence of positive and negative anomalies that form a ring feature with of diameter about 130 km around Rutbah. This could be due to lateral variations in the sedimentary cover, or it may be related to a deep-source anomaly within the upper mantle.

(#383-P) Implementation of fault-trap analysis best practices into the exploration and development cycle

Susan J. Hippler
and Francesco V. Corona, **ExxonMobil**

ExxonMobil's fault-trap analysis best practices are a set of integrated technical workflows for evaluating trap and seal in specific business environments. This integrated approach to fault trap analysis has affected ExxonMobil's business decisions throughout the exploration and development cycle. Workflows have been applied to frontier and mature basin exploration and to development plans for new and mature fields. Examples and applications of best practice workflow technologies will be presented.

The workflows contain recommendations for the application of the latest tools and technologies in fault interpretation, seal evaluation, and volumetric assessment of faulted traps. Implementation of these best practices has three results. (1) Improved efficiency and quality in fault interpretation and structural mapping. (2) Application of appropriate fault seal analysis technologies involving trap and seal definition, analysis of historical drilling results, fault

juxtaposition analysis (includes proprietary technology dealing with multiple faults and stratigraphic realizations), and examination of other controls on seal. (3) Improved linkage of trap and seal analysis with volumetric assessment.

The best practices have been designed for use by a broad range of geoscience customers. For example, inexperienced geoscientists can use the workflows as a resource for seismic cube interpretation and structural mapping. Fault seal experts use the best practices to ensure traps are risked and sized consistently throughout the upstream. Technical advisors use them to evaluate the applicability of technology in various business and geologic settings, and managers use the workflows in project planning.

(#61-O) Pore-system analysis of Ara Group carbonates, South Oman Salt Basin

Cathy E. Hollis*, **Badley Ashton**; Joachim E. Amthor, **PDO**; John P. Grotzinger, **MIT**; Imelda Gorman Johnson, **Badley Ashton**; Edwin E. Lamers, **PDO**

The Neoproterozoic to Early Cambrian intrasalt Ara Group carbonates in the South Oman Salt Basin constitute hydrocarbon reservoirs in pervasively dolomitized ooid/peloidal grainstones, thrombolite reefs, and organic-rich laminated mudstones. Dolomitization occurred early in the depositional history, in an open system dominated by brine reflux that modified the primary depositional textures of the reservoir facies. Intercrystalline macropores, dolomolds, and vugs dominate the resultant pore types. The vugs may be up to several millimeters in diameter, and have commonly been generated by the dissolution enhancement of primary macropores, such as fenestrae and intrafabric cavities. Matrix permeabilities are highest where vugs are connected via the intercrystalline macropore network. Fractures are important locally, but are not considered to be of significance in controlling production.

A petrophysical rock fabric scheme is being developed for the reservoirs. Rock-types are defined based upon combined petrographically defined rock-fabric (including dolomite texture and pore types), and porosity and permeability characteristics, each characterized by a distinctive capillary pressure and pore-size distribution curve. Full consideration was given to the sedimentological character of each rock-type in order to enhance the predictability of its distribution. As a result, integration of core sedimentological and open-hole log data with the petrographically and petrophysically defined rock-types has permitted upscaling to define flow units within the cored and uncored intervals. This has enhanced our understanding of the distribution of potential flow units within the intrasalt carbonate successions, thereby reducing uncertainty in permeability estimation and prediction within uncored and inter-well areas.

* Now with Shell International Exploration and Production B.V.

(#104-O) Prestack depth migration: land-data examples

Leon L.Z. Hu and Jung J. Kim, **Saudi Aramco**

Prestack depth migration (PSDM) has been successfully applied in the past decade to image complex earth structures such as subsalt, subbasalt, overthrust faults, and gas-cloud, where conventional time or poststack procedures achieved only marginal success. To apply PSDM successfully to land data acquired in the Arabian Gulf area, additional steps are needed.

Here, we demonstrate some valid approaches using Saudi Aramco's in-house PSDM software. Examples are (1) migration from survey surface, (2) migration from a redatumed surface, (3) various data preconditioning filtering, (4) migration with a gridded model, (5) iterative migration velocity analysis, (6) imaging condition for turning-wave energy, (7) postmigration signal enhancement, (8) velocity model smoothing, and (9) amplitude compensation. Both synthetic and real data were applied through time and depth domains for illustration and comparison.

(#246-P) The stratigraphic significance of microbiofacies to selected Saudi Arabian reservoirs

G. Wyn Hughes, **Saudi Aramco**

Paleoenvironmental reconstruction is a routine contribution of industrial micropaleontology. The intraformational application of this technique is, however, less well established but can illustrate bioevents of considerable significance, especially when integrated with sedimentological and wireline log data. Careful interpretation of biofacies should permit the confident reconstruction of primary paleoenvironment variations. In Saudi Arabia, the use of semiquantitative holomicropaleontology has enabled the bioecostratigraphy of several economically significant carbonate and siliciclastic reservoirs, ranging in age from Late Permian to Middle Miocene, to be established.

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For example, marginal marine and hypersaline to shallow-marine normal-salinity-tolerant foraminifera, ostracods, and calcareous algae display variations in population density in the Upper Permian to Lower Triassic Khuff carbonate reservoirs. A series of field-wide depositional cycles, of variable significance have been established in a pioneer study using microbiofacies. The results showed that shallow to deep, normal-salinity carbonate platform environments supported a wide range of depth, hydraulic energy, and turbidity-sensitive calcareous benthonic and planktonic micro and macrofaunas and floras. This has enabled paleoenvironmental partitioning of Jurassic to Cretaceous carbonate reservoirs from the Tuwaiq Mountain Limestone (Fadhili reservoirs), Hanifa Formation (Hanifa reservoir), Jubaila and Arab formations (Arab-D reservoir), Sulaiy and Yamama formations (Ratawi reservoirs) and Shu'aiba Formation (Shu'aiba reservoir).

In the northern Red Sea region, the Lower Miocene deep-marine mudstones of the Burqan Formation (Burqan reservoir) contain complex-walled foraminifera associated with deepening events that have enabled correlation of the interstratified turbidite sands. Combined outcrop and subsurface studies of the Jabal Kibrit Formation carbonates (Wadi Waqb reservoir), revealed a transition from basement-flanking lagoonal carbonates to debris-flow equivalents within planktonic foraminiferal-bearing slope sediments.

(#248-P) Lithostratigraphy of the Saudi Arabian Red Sea region

G. Wyn Hughes
and Robert S. Johnson, **Saudi Aramco**

The Red Sea has a complex structural history in response to the anticlockwise rotation of the Arabian Plate away from Africa. A transition occurred from an Oligocene-Miocene Red Sea extensional regime to the Aqaba Fault Zone left-lateral transtensional regime, which began during the latest Miocene. As a result, the onshore and offshore Red Sea region of Saudi Arabia has lithological variations not previously described. The proposed lithostratigraphy is the result of an intensive study of the succession, and has integrated biostratigraphic, sedimentological, seismic and field studies from Midyan in the north to Jizan in the south.

The entire Phanerozoic sedimentary succession was deposited during the Late Cretaceous to Pleistocene. In Midyan, the oldest rocks are Upper Cretaceous shales unconformable on the Precambrian basement, whereas Paleogene sands and shales, with thin limestones occur in the south. The Al Wajh, Musayr, and Yanbu formations of Midyan make up the Lower Miocene Tayran group. The first marine siliciclastics of the Al Wajh represent rift-associated sediments deposited during the earliest Miocene. Lower Miocene shallow-marine carbonates of the Musayr conformably overlie the Al Wajh. In central Red Sea onshore basins, sometimes-thick Lower Miocene submarine evaporites of the Yanbu formation were deposited under locally restricted conditions. Rapid subsidence during the Early Miocene in Midyan caused the deposition of deep-marine, planktonic-foraminiferal mudstones and thick submarine-fan sandstones of the Burqan formation. Carbonates, marine mudstones, and submarine evaporites of the Maqna group (Jabal Kibrit and Kial formations) unconformably overlie the Burqan, and were deposited during latest Early Miocene to earliest Middle Miocene. The Jabal Kibrit formation in Midyan is an anhydrite-carbonate facies of which the carbonates form the Wadi Waqb member; siliciclastic facies elsewhere are the Umm Luj member. Interbedded anhydrite and carbonate typify the Kial formation. Within the Midyan region, thick anhydrite of the Mansiyah formation was deposited during the Middle Miocene and is overlain by poorly exposed sands, shales, and thin anhydrite of the Middle to Upper Miocene Ghawwas formation. The Lisan formation unconformably overlies the Ghawwas and consists of coarse alluvial sand and gravel of possible Pliocene to Recent age.

(#119-O) A high-resolution 3-D seismic inversion-based geologic model of the Wara reservoir, Burgan field, Kuwait

Thekriat J. Hussain, **KOC**; Richard R. Terres, **ChevronTexaco**; Jamal A. Al-Humoud, **KOC**; Joon Y. Kim**, ChevronTexaco**

High-resolution 3-D stratigraphic seismic inversion and geostatistical modeling have been applied to build a more accurate geologic model for Kuwait's Burgan field Wara reservoir.

The Upper Cretaceous Wara Formation hosts a significant proportion of the original-oil-in-place of the Burgan field. It has been a prolific producer and still has a considerable future recovery potential. The Wara Formation is an interbedded sand / shale sequence that is fluviodeltaic in origin. It is a geologically complex system with a strongly heterogeneous sand distribution. The reservoir flow units have limited lateral extent and interconnectivity, and building an accurate geologic model is the key to successful reservoir simulation and management of the Wara.

However, we recognize that this task has been very difficult to achieve through conventional methods that rely only on well data.

A new, more detailed, initial geologic model was built using 3-D poststack seismic inversion. Geostatistical well-based modeling was then applied to improve the lateral and vertical resolution of the model. A comparison of results to a previous well-only geostatistical model demonstrated significant improvements in lateral resolution of flow units and definition of reservoir continuity. This new geologic model better defined the reservoir character and should provide a more robust simulation, so allowing for better prediction of reservoir flow characteristics and drive mechanisms.

(#172-O) Tectonic evolution of the Zagros orogenic belt: regional- and reservoir-scale implications of new interpretations.

Simon Inger and Mark B. Allen, **CASP**; Hossein Hassani, **Amirkabir U., Tehran**; Eric J.-P. Blanc, **CASP**

The Zagros orogenic belt is dominated by spectacular compressional structures, including the periclines that provide the major hydrocarbon traps. Exploration strategies therefore require not only a sound regional tectonic framework but also a detailed understanding of structural histories at the reservoir scale. This can only be achieved by understanding the variations in fold structure, the origin of different fold types, and their evolution in time and space.

A modern interpretation of the Zagros structure permits both cover detachments and basement-involved thrust structure at depth, with consequent variations in deep structure and implications for constructing balanced cross-sections. A single detachment on top of the basement is not a reasonable interpretation in most parts of the belt, as seismicity strongly suggests basement-involved faulting. It is likely that pre-existing fabrics localized basement deformation, and that shallower tectonic features are partly controlled by the geometry of basement steps.

Distinguishing between fault-related folds and detachment folds is a crucial stage in evaluating potential plays because they are associated with different fracture distributions in the reservoir units. The growth mechanism of folds also has a profound influence on fracture distribution and can be assessed by detailed studies of well-exposed structures. In three dimensions, Zagros fold structures were seen to have different styles of lateral continuity and interactions with strike-slip zones. Lateral propagation of underlying detachments produced relay zones with distinctive strain patterns. These lateral variations in fracture and fault evolution, together with local longitudinal extension, are key factors in assessing reservoir continuity and compartmentalization.

(#12-O) Balanced cross-sections and oil-field structures from the Himalayas to the Middle East

Ishtiaq A.K. Jadoon, **Schlumberger**

Most of the world's hydrocarbon production comes from structural traps along the northern margin of the Arabian Plate. The geometry and evolution of these structures is of concern in reservoir management and in the recognition and relationships of faults and fractures. Similar structures are better understood through kinematically viable and admissible balanced cross-sections across the Himalayan foreland in Pakistan. Balanced cross-sections with integrated geological (surface geology and Landsat) and geophysical (borehole and seismic reflection) data identify a thin-skinned mechanism of deformation with a weak decollement (subhorizontal thrust) in ductile Eocambrian evaporites in northern Pakistan.

A 120-km-long balanced structural cross-section across the Himalayan foreland in north Pakistan (Salt Range and Potwar Plateau) shows an exposed thrust with about 20 km of shortening at the mountain front. The trailing edge of 90-km-long thrust sheet was imbricated to form oil-field structures as fault-related folds, a triangle zone, and pop-up structures. In contrast, the balanced cross-section across the Himalayan foreland in western Pakistan (Sulaiman fold belt) has no exposed thrust at the mountain front. Instead, structural features are (1) low-amplitude, broad concentric (detachment) folds (Sui and Loti gas fields) at the tip of the decollement, (2) development of ramp and duplex structures, (3) out-of-sequence thrusting, and (4) tear and extensional normal faults in the overthrust wedge.

Preliminary structural cross-sections across several oil fields in the Zagros fold belt, such as Ahwaz, Masjid-i-Sulaiman, Gachsaran, and Kangan, show fault-related anticlines, and imbricate and duplex structures with decollement, possibly in Hormuz salt. Similarly, several oil field structures, such as Dammam, Awali, and Dukhan along the northern margin of the Arabian Plate, may be interpreted as detachment and / or fault-propagation folds. Balanced cross-sections are required to resolve oil field structures for reservoir evaluation, characterization, and management in the Middle East and Iran.

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(#198-O) Basin evaluation and tectonic development of Libya

Saad Z. Jassim, Ian W. Somerton
and Simon J. Campbell, **GETECH**

Data from over 800 wells and from countrywide gravity and magnetic surveys have been used to investigate and evaluate the basin geometry and tectonic development of Libya. Detailed stratigraphic analysis of the wells, and enhanced processing and inversion of the gravity and magnetic data, provided material for a series of geological horizon maps, a depth-to-Precambrian basement map, and the regional tectonic framework. The basement map outlines the major known basins and, in addition, suggests other less well-known areas of Libya that may have a thick sedimentary sequence.

Arching played an important role in the development of the basins in Libya, the most important of which is the Late Silurian ENE-trending Gargaf arch that appears to continue beneath the Sirte basin and the Cyrenaica platform. This Silurian event has complementary NNW-trending minor arches that influenced the southwestern part of Libya. Minor Late Devonian arching was restricted to the Thambuka high in southwest Libya. Late Carboniferous and Early Permian arching seems to have been the most significant event and resulted in the removal of most of the Paleozoic sequence from the Sirte basin. It affected the Tibesti high and the Kufra basin, and extended northwestward toward the Sirte basin, the Naffusa high, and into Tunisia. Triassic, Jurassic and Early Cretaceous tectonic evolution was characterized by an E-W arch that affected the central parts of Libya. Deep trough-development in the Cyrenaica and Pelagian basins seems to have been a result of the opening of the Tethys, which started in the Late Permian and became strongly pronounced in the Tithonian and Berriasian.

(#349-P) Paleozoic Unayzah and Jauf hydrocarbon potential in Bahrain

Waleed A. Jawad and Naji A.Qassim, **Bapco**

The Awali field is a giant structural trap and Bahrain Island is the surface expression of the deep-seated tectonic activity. The field produces from six intervals; the Cretaceous Wasia Group (Ahmadi, Wara, Mauddud, and Nahr Umr formations—also known as the Bahrain Zone) and the Jurassic Arab and the Permian Khuff. No detailed depositional modeling of the Paleozoic section had been done previously. Our presentation shows the influences of deposition and structure on the potential Paleozoic Jauf (Lower Devonian) and Unayzah (Lower Permian) reservoirs.

The study used recent 3-D seismic surveys of onshore Bahrain. Data quality was good on the flanks of the Awali anticline but fair to poor in the central part. The Awali structure at the Permian level is asymmetrically elongated north-south. The 3-D interpretation showed a detailed fault pattern with maximum throws of 200 to 300 ft with a predominant northerly orientation. This complex fault zone consists of numerous fault blocks and a younger NW-trending fault system offsets the N-S faults. Primary rock properties were determined from cores, thin sections, and well logs. Porosity and permeability were correlated with composition, texture, and borehole-logs so that reservoir characters could be determined from well logs in uncored intervals.

The Paleozoic in Bahrain is subdivided into two major sequences. The lower is correlatable with the Paleozoic of Saudi Arabia, and its reservoirs (Saq, Khafah, and Quwarah) have poor to moderate reservoir characteristics. The upper sequence is difficult to correlate regionally due to variations in thickness, depositional setting, tectonic activity, and erosion. It consists of the Qalibah Formation, a shale unit that is a regional source rock, and the Tawil, Jauf, Jubah, and Unayzah formations. The Jauf and Unayzah are potential reservoirs. The thickness of the Lower Devonian Jauf Formation in the Awali field is 350 ft, and the reservoir facies consist of deltaic and middle shoreface sands and point-bar and braided channel deposits. The overlying Jubah Formation is an alternation of silty / shaly sandstones and shales in the lower part and massive sandstone in the upper part; the massive sandstone is traceable across the field. The Lower Permian Unayzah Formation unconformably overlies the Jubah. The thickness of the Unayzah Formation increases in the down-dip wells and part of the unit wedges-out against the pre-Unayzah unconformity. It consists of sandstone and shale alternations deposited in a braided stream and flood-plain environment; lateral facies and reservoir-thickness variations occur.

(#191-O) High-fidelity vibratory Seismic: a new concept in land seismic acquisition

Marvin L. Johnson
and Christine E. Krohn, **ExxonMobil**

ExxonMobil has developed the High-Fidelity Vibratory Seismic (HFVS) method for seismic data acquisition. This new method can improve data quality and decrease costs, particularly in areas with large variations in surface conditions, such as sand dunes or limestone outcrops. Data examples will be used to demonstrate the theory of the method and show the improvements in data quality. A specific example will also demonstrate the improvement in resolution in an area of dunes and sabkhas. HFVS can be used worldwide with current contractor equipment.

During acquisition, the ground-force signals for multiple vibrators are separately recorded and used to derive separation operators that extract the reflection data from each vibrator as if it had been individually recorded. By measuring the output of each vibrator, the harmonic distortion and coupling variations are minimized and, as a result, stable minimum phase wavelets are obtained. Field data confirm that the separation between signals extracted from individual vibrators recorded simultaneously is in the range of 40 to 60 dB.

When multiple vibrators are at different elevations and ground conditions, the ability to process them individually significantly improves data quality. With traditional acquisition, the signals of each vibrator are automatically combined, and near-surface variations result in a decrease in resolution. With HFVS, source statics can be derived for each vibrator before stacking. In addition, HFVS usually results in higher fold, which allows better mitigation of coherent noise. If signal-to-noise conditions are appropriate, HFVS can also improve production rates by recording multiple shot points simultaneously.

(#380-P) Large structures on the Arabian platform: inverted late-Proterozoic grabens?

Christopher A. Johnson, Barbara A. Rassman, Barry L. Sauve, Lawrence E. Wender, Leonard V. Moore, Charles Beeman and Caleb J. Pollock, **ExxonMobil**

We propose that a class of large traps on the Arabian Platform was created through repeated Phanerozoic structural inversion of late Proterozoic grabens. Individual structures vary, but most of the relief on the base Phanerozoic surface can generally be attributed to three major events: 'Hercynian' (60 percent relief), Late Cretaceous (30 percent), and 'Zagros' (less than 10 percent). Documented Late Cretaceous compression, combined with evidence that structural relief, sense of asymmetry, uplift, and erosion were repeatedly focused along the same structural axes, strongly imply 'Hercynian' deformation was also compressional. Mild, basement-involved, contractional inversion of older extensional structures offers a model consistent with all available data. Inverted structures often mimic rift-related doglegs and trap doors in plan view because of the control exerted by ancestral extensional faults. The total accumulated contractional strain across the largest structures, such as Ghawar, is probably less than a few percent. Late Proterozoic stratigraphy and radiometric dates point to a multiphase origin for the original N-trending extensional fabric across Arabia.

The Amar (Pan-African) orogenesis resulted in late Proterozoic northward escape, extensional collapse, and shearing (Najd/Assyntic) of the Arabian accretionary crust. The grabens and half-grabens that were formed during collapse imparted an extensional basement fabric that was later inverted during Phanerozoic events. Contractional inversion has important exploration and production implications with regard to the early development, geometry, and timing of the structures, as well as on map patterns of Paleozoic subcrops and subunconformity truncations. It also has implications for maturation modeling, fluid migration pathways, and field compartmentalization.

(#304-O) The artistic science of reservoir quality prediction of the Khuff Formation gas reservoirs in the subsurface of eastern Saudi Arabia

Rami A. Kamal, **Saudi Aramco**

Within eastern Saudi Arabia, Late Permian Khuff sediments were cyclically and aggradationally deposited on the very broad, shallow-marine, low-

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gradient, Arabian Shelf. It will be demonstrated sedimentologically that today's structural highs correspond closely to Late Permian topographic highs. Optimal reservoir development was contingent on the paleotopographic highs that enabled early porosity-enhancing diagenetic mechanisms to kick in. Different types of reservoir development occurred on and around these topographic highs. Strings of diversely shaped topographic highs are irregularly strewn, archipelago-style, along today's Ghawar substructures. Regional and even subregional reservoir predictability is contingent on finding the original topographic highs (including partially subaerial 'islands'). In addition, throughout the history of Khuff deposition, water depth changed and the nature of the sedimentary depositional components was a function of relative sea depth. The consequence of this added dimension is that the products of diagenesis—the reservoir facies—vary in the vertically stacked Khuff-A, -B and -C reservoirs.

Traditional sequence stratigraphy does not have much bearing on the prediction of reservoir quality development in any of the three Khuff reservoirs. This is chiefly because the reservoirs are shelf, not shelf-edge, deposits, and seismically identifiable clinoforms are indiscernible. The trick is to map the ancient topographic highs that are now relief features on irregular structures. The surviving ancient topographic highs are identifiable through depositional sedimentology and the reservoir facies that they carry. They and their surrounding topographic lows can be initially mapped through well control. Acoustic impedance maps are the best hope for defining the interwell extensions of previously identified reservoir facies. Improved seismic imaging and seismic resolution will have a direct impact on improving the ability to predictively map reservoir facies in the Khuff Formation.

(#49-O) Paleozoic hydrocarbon potential of the Fars area, Iran

Mohammad R. Kamali, **NIOC**; Mohammad R. Rezaee, **U. of Tehran**; Arsalan Zeinalzadeh, **NIOC**

Silurian shales are known to have generated commercial quantities of oil and gas in the Middle East. These organic-rich source rocks have not been adequately studied in Iran and their hydrocarbon-source potential needs to be investigated in detail. Lower Paleozoic strata are not continuous in the Fars region and, due to deep burial, these rocks have been drilled in only few wells and rarely crop out. These limitations have made the understanding of their lateral and vertical distribution ambiguous. New geochemical data based chiefly on stable carbon isotopes suggest that the Silurian shales are the major source for gas that has accumulated in the Dalan and Kangan (Khuff Formation equivalent) giant commercial gas reservoirs. In addition, detailed source-rock analyses, including pyrolysis, organic petrography and geohistory modeling, indicated that the Silurian shales are not at the graphitic stage in the hinterlands of Bandar Abbas, as previously thought. Instead, their maturity changes regionally from oil to wet- and dry-gas generative windows. It is concluded that the lower Paleozoic rocks are less mature to the southeast but become oil to gas mature to the northwest. Thin intraformational beds of shale and carbonaceous shale within the Dalan and Kangan formations are rich in organic matter and had the potential to generate gas in situ.

(#244-P) Influences of depositional fabrics, diagenesis, and structural controls on Arab-D production, Ghawar field, Saudi Arabia

Thomas H. Keith and Dave L. Cantrell, **Saudi Aramco**; Peter K. Swart, **U. of Miami**; C. Robertson Handford, **Strata-Search**; Sait I. Ozkaya, **Baker Hughes**

Ghawar Arab-D production behavior is the result of a complex interaction of depositional, diagenetic, and structural events occurring through geologic time.

They produced a pattern of porosity and permeability that is sometimes dominated by one factor but, more often, is the result of the interaction of all three. It is the lack of recognition of this interaction of primary depositional fabrics, dolomite textures, and fractures on a variety of scales that made many production phenomena difficult to explain.

New technologies employed at Saudi Aramco and new, integrated workflows have contributed to a quantum leap in our understanding of this behavior, and of our ability to predict reservoir architecture and its resulting flow pattern. Sequence stratigraphic analysis of depositional processes has significantly improved prediction of original rock textures and their permeability between wells. Recent isotope studies have suggested a complex history of diagenesis resulting in predictable reservoir parameters and distributions for various types of dolomite. 3-D seismic surveys, together with image logging, have suggested a multiscale interaction of fractures and matrix.

Examples of production dominated by each of the three geological processes will be presented together with their characteristics. Key studies devoted to sequence stratigraphy, diagenesis, and fracture distribution will be summarized and examples of their impact on production patterns illustrated. Also shown will be areas in which all aspects of reservoir architecture must be invoked in order to understand and predict reservoir performance.

(#1-P) A web-based solution for submitting, managing, and evaluating abstracts for GEO 2002

Anna M. Kelly, **Gulf PetroLink**; Heather M. Pattison, **PetroLink Consultants**; Nestor A. Buhay II, **Gulf PetroLink**; Joerg E. Mattner, **GeoTech**; Moujahed I. Al-Husseini, **Gulf PetroLink**

Since its launch in 1994, the technology for organizing the biennial Middle East Geoscience Conference (GEO) has undergone a rapid evolution from abstract submission by post, fax, and courier, to an Internet solution. For GEO 2002, a team from Gulf PetroLink (the Bahrain-based Conference Secretariat), GeoTech, and programmers from Bahrain's Arabian Network Information Systems, developed a user-friendly, step-by-step, web-based interface for the submission of abstracts and authors' biographic and contact information. The completion of an online abstract submission to the Conference Secretariat using 'copy and paste' commands from pre-prepared Word document files takes just a few minutes. Before launching the online submission 'e-form', all interface components were tested internationally using various browsers and different operating systems (e.g., MAC OS, DOS, Windows NT, and Unix).

The Secretariat's Webmaster used an online database to manage the submitted abstracts and authors' information. Once an abstract was considered appropriate for GEO, the Webmaster posted it on the Website where GEO surfers and the GEO 2002 Program Committee (PC) members could read it. The 18-member technical PC individually evaluated each abstract as 'Very Good', 'Good', 'Exclude' or 'No Comment', and sent their ratings on customized spreadsheets to the Secretariat. The PC's ratings were merged and converted to a quantitative score from 0 percent (all voted to Exclude) to 100 percent (all voted as Very Good) for each abstract. Reasons for excluding an abstract were stored by the Secretariat.

The database allowed (1) 'force-ranking' of the abstracts according to their evaluation grading, and (2) rapid sorting by session, oral-versus-poster, author's affiliation, and so on, thereby allowing for the development of a flexible final conference program. The program, together with the abstracts and the authors' biographic data and photographs, have been featured on the Website for many months before the event. The early program presentation—in conjunction with web-based information packages on short courses, field trips, Bahrain's hotels and tourist attractions—provided the conference delegates with all the necessary information to make their GEO 2002 visit as effective as possible.

(#72-O) Bypassed oil tracking in the lower Burgan sandstone of the Sabiriyah field, North Kuwait

Ali N. Khan, **KOC**; Martin H. Smith, **BP**; Mubarak M. Al-Hajeri, **KOC**

The Burgan Formation of Kuwait forms one of the largest oil reservoirs in the world. The Albian Burgan clastics were deposited in a paralic setting and have been informally subdivided into the Lower, Middle, and Upper Burgan in Kuwait. In the Sabiriyah field of North Kuwait, the Lower Burgan is the most prolific of the multiple reservoirs. Based on detailed sedimentological and pressure studies, it has been subdivided into the M and L members. The M-Member is the lower unit and is composed of high-quality, massive sands deposited mainly in amalgamated braided channels. The overlying L-Member has comparatively thin-layered sands, deposited in more marine-influenced channels and associated estuarine environments.

The M-Member has produced most of the Lower Burgan oil in the Sabiriyah field and is supported by a very active bottom-water drive. The thinner, interbedded L sands, are less prolific but contain most of the remaining reserves in the Lower Burgan, and are supported by down-dip edge-water drive. The

water movement in the L-Member was interpreted by integrating sand geometry mapping and dynamic reservoir data. Open-hole logs, cased-hole logs [Thermal (neutron) Decay Time and Production Logging Tool], water cut behavior and Repeat Formation Tester pressure distribution were analyzed.

The L-Member reservoir was studied to (1) identify bypassed pockets of dry oil, (2) ascertain the tortuous path of water movement in the major sand bodies, (3) establish the flow direction within the aquifer, and (4) identify the degree of heterogeneity important to fluid flow. The results have reshaped the future development of the L-Member sands. A revised development plan designed to enhance sweep efficiency and boost oil recovery has already resulted in the drilling of four successful infill wells.

(#192-O) Improving 3-D land-seismic images by mitigating near-surface effects

Young C. Kim, **ExxonMobil**

Three-dimensional seismic surveys are fundamental to reservoir identification and characterization. Preserving seismic character and structural integrity of the final image leads to a better assessment of reservoir volume and quality. In most land areas, source-generated surface waves travel in the near surface and are recorded as high-amplitude, low-frequency dispersive wave trains called ground roll. Furthermore, the heterogeneity of the near surface introduces static shifts that can degrade the structural integrity of the image. This presentation will demonstrate how to improve the quality of a 3-D land seismic image by mitigating these adverse effects of the near surface.

Since the amplitude of ground-roll noise is often very high, it obscures reflections, so making it difficult to obtain a high-quality 3-D seismic image suitable for reservoir analysis. A combination of phase matching and spatial low-pass filtering was used to remove the noise. With the noise suppressed, it was possible to accurately determine velocities and short-period static corrections that are critical for obtaining high-quality subsurface images from land 3-D seismic data. In addition, the ability to attenuate ground-roll noise provides flexibility in optimally designing the 3-D survey geometry for target reservoirs.

Refraction-based approaches have often been used to remove the long-period structural distortion caused by near-surface heterogeneities. Recently, static corrections using first-arrival tomography have become more popular, particularly in areas where the near surface is not layered. First arrivals sample the background vertical velocity gradients in the near surface. By inverting these first-arrival times, shallow velocities can be determined. Comparisons with uphole times suggest that first-arrival tomography generates reliable near-surface velocities for static corrections. The combination of ground-roll attenuation and tomography-based static corrections provides a significantly improved reflector continuity and structural integrity.

(#144-O) Seismic data quality for reservoir characterization of Abu Dhabi onshore oil fields

Erik B. Kleiss, Abu Baker Al-Jeelani, Samer Marmash, Abdulsalam M. Bin Ishaq, Jean-Michel L. Dawans, Raymond King and Ahmed A.W. Al-Shaikh, **ADCO**

Since 1998, ADCO has been acquiring a series of high-quality 3-D vibroseis seismic surveys over their main oil fields. One of the main objectives of these surveys is the structural mapping of the complex faulting of the reservoirs and the identification of optimum well locations for field development. Despite the fairly deep reservoirs and the difficult surface conditions such as high sand dunes, the quality of the seismic data has become good enough to bring quantitative reservoir characterization (mapping of porosity distribution, subtle faulting, identifying reservoir subzones, and time-lapse seismic) within reach.

These important seismic data-quality improvements have been based on comprehensive field tests (including the shooting of sizeable 3-D test cubes), careful analysis of new and existing data, and optimization of the existing field practices. Significant improvements in data quality and resolution have been achieved but acquisition costs have been kept at an acceptable level.

In this presentation, we will review with examples the impact of various acquisition parameters (e.g. fold, group size, and source/receiver effort) on the data quality and cost. Where possible, we will quantify the effect of these parameters on the signal-to-noise ratios and the achieved temporal resolution. Seismic data processing issues that affect the resolution and noise and multiple contamination will be discussed. The impact of the various acquisition and processing

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parameters on the mapping of reservoir properties, such as porosity, resolution, and seismic attributes, will be demonstrated using the results of seismic inversions. The achieved seismic quality will be compared with modeled data that specify the minimum requirements to meet the seismic survey objectives.

(#302-O) Use of real-time azimuthal logging-while-drilling measurements and image logs for geosteering and reservoir characterization of the Shu'aiba Formation, Idd El Shargi South Dome field, offshore Qatar

Jack Klotz, **Occidental**; Paolo Ferraris, **Schlumberger**; Spence Gustav, **Occidental**

Idd El Shargi South Dome (ISSD) is located in the Arabian Gulf approximately 90 km east of Doha, Qatar. ISSD is the southern culmination of a large N-trending faulted anticline. The primary development target in the field is the Cretaceous Shu'aiba Formation composed of high-porosity, low-permeability chalky carbonates and intraformational shales. Because of the low permeability of the Shu'aiba in ISSD, economic production rates have been achieved only when wells intersect fluid-conductive faults and fracture zones. From a reservoir performance perspective, the Shu'aiba reservoir at ISSD should be considered a type-2 fractured reservoir. In this type of reservoir, hydrocarbon storage is within the matrix porosity but permeability is provided by fractures.

Azimuthal Logging-While-Drilling (LWD) tools were used for the pre-full field development of ISSD. Effective use of these tools aided geosteering and contributed valuable information that improved the structural description of the field. Image logs processed from the LWD data were used extensively to develop an accurate description of the ISSD Shu'aiba reservoir.

In this presentation, we will demonstrate how the real-time azimuthal measurements were used to improve structural understanding and take appropriate steering decisions. We will present and demonstrate an analytical and a graphical technique to compute dips along the well axis by means of the relative displacement of up / down curves and well deviation. Examples of LWD high-resolution azimuthal images for identification and characterization of faults and fractures will be presented and compared with real-time evaluations.

(#174-O) Improving seismic data: an example from the Sab'atayn basin of central Yemen

Matthias Koerbe, Sybille E. Aust and Paul J. Krajewski, **Preussag Energie**; Carsten Geiger, **OMV**; Hashim Al-Sakkaf, **Yemen Oil and Gas Corp**

The potential for significant improvements in seismic data can be demonstrated from Exploration Block-S2 in the Sab'atayn basin of central Yemen. Preussag Energie reprocessed 1,100 km of 2-D vibroseis seismic of 1991 vintage and achieved clear improvements over the previous processing. Frequency content, continuity of seismic events, and fault-plane definitions were significantly improved. This resulted, among others, in a new statics solution that was calculated without a subsurface model but tied to the upholes. A distinct enhancement of the seismic signals was achieved by applying surface deconvolution to the data. Additionally, the use of prestack time migration led to a more accurate estimation of the stacking velocity and improved the seismic imaging. A 3-D velocity model was created to allow for depth migration. As sonic velocities and vertical seismic profiling results failed to produce a coherent velocity field, stacking velocities and prestack depth migration velocities on selected lines were used and geostatistically integrated into a model that could give different weights to selected information. Depth maps for six horizons were generated.

(#123-O) Fault control on jointing in the Natih carbonate reservoir, Fahud field, Oman

Wilhelm H. Kolkman, **PDO**; Sait I. Ozkaya, **Baker Atlas**; Kester D. Harris, **PDO**

The Fahud field of North Oman provides an opportunity to study layer-bound joints and the interaction of faults and joints in a fractured carbonate reservoir. The fractured Natih reservoir units have been producing under Gas Oil Gravity Drainage (GOGD), whereas the less-fractured units are currently developed by matrix waterflood. Both waterflood and GOGD production require a high degree of control on fractures. A wealth of fracture information has, therefore, been acquired from borehole image logs as well as indirect fracture-flow indicators, such as mud loss occurrences and well performance histories.

The vertical distribution of fractures is largely controlled by stratigraphy, and lateral distribution is

controlled by structure-mainly by faults. Widely spaced large, open fractures are present in thick-bedded porous units, whereas closely spaced, small layer-bound fracturing is more common in thinly bedded units. Fine-grained muddy carbonates such as Natih-B and Natih-D are not fractured. Fractures occur either as pervasive jointing or as fracture corridors (subvertical, narrow, elongate, tabular fracture clusters). Fracture corridors occur mostly within 1- to 2-km-wide fracture fairways. Most fairways are coincident with fault zones, but a few—including the most prominent fracture fairway—are not associated with visible faults. Once calibrated using borehole image logs, stratigraphy and production behaviour, the identification of these subtle fault zones is the key step in defining an integrated and predictive 3-D fractured-reservoir model.

(#369-O) Characterization of unconventional organic matter in South Oman: effects on gas-oil generation.

Isabelle Kowalewski, Bernard Carpentier and Alain-Yves Huc, **IFP**; Jean-Michel Gaulier and Patrick Wojciak, **Beicip-Franlab**; Neil L. Frewin, **Shell**; Nashwa M.M. Al-Ruwehy, **PDO**

The properties of organic matter associated with the Infracambrian Ara intrasalt hydrocarbon system in south Oman were investigated. The intrasalt hydrocarbon system consists of silicilyte and carbonate stringers encased in salt. In the case of the silicilyte system, the slabs clearly act both as source-rock and reservoir. However, in the carbonate stringers, the association is not so evident. A set of rock and oil samples located at various depths was selected for organic matter analysis from different wells. For the stringers, two types of source rocks have been proposed: shaly intervals (similar to those in Harwell Deep-1) and / or carbonate Nitrogen / Sulfur / Oxygen-rich (NSO) (resins and asphaltenes) intervals. The silicilyte system probably only reached the beginning of the secondary cracking stage affecting only the NSO compounds. The organic matter studied in the stringers is apparently less mature.

The organic matter present in both intervals is associated with a hypersaline depositional environment and shows very similar chemical (bulk composition, elemental analysis, and biomarker content) and isotopic (^{13}C, ^{34}S) signatures characterized by an unusual 'asphaltenic' nature. Compared to classical organic matter at an equivalent maturity level, the organic matter found in the silicilyte, shales, or carbonates is highly soluble with a high NSO content. This leads us to consider that the Infracambrian 'kerogen' in South Oman is composed of both insoluble and unconventional soluble (NSO compounds) organic matter. Independent geochemical parameters (Rock-Eval analysis, artificial maturation, and kinetic parameters) seem to be consistent with this hypothesis. Specific kinetic parameters for the Infracambrian kerogen was used in a compositional 2-D basin model (TemisPack) of a transect through the South Oman Salt Basin. The model provided improved gas / oil-ratio prediction within the silicilyte when compared with results obtained using classical type-IIS kerogen.

(#41-O) Seismic @ccess: the management of propagating and pervasive seismic volumes

Jess B. Kozman, **GeoQuest**

Managing the volumes of geophysical data created by new exploration technologies requires effective and integrated data-management solutions. Proper data management can be used to create added value for organizations, and this value can be quantified with industry-standard metrics. Site assessments document an exponential increase in the volumes of seismic data in application projects. This increase is being driven by the delivery of multiple versions of seismic surveys, and applications that allow processing, attribute analysis, and visualization. The result is pressure on disk storage, backup, and delivery infrastructures, and a rise in the total cost of ownership for large data-storage environments. The volumes persist well past the value-added lifetime of the projects that they are used to evaluate. However, center-based service providers provide innovative solutions for seismic data management.

Case histories of these solutions will be presented that highlight map-based spatial inventories, automated loading to applications from standard-format delivered data, and workflows for insuring the integrity of spatial information. These solutions also utilize hierarchical storage management systems and integrated nearline tape robotics. Business rules for disk / tape management are determined from the analysis of user-access patterns for seismic volumes. Large seismic volumes are taken out of traditional workstation backup schemes and those that have not been accessed in a predetermined time period are released from online disk and moved to nearline tape. Project archiving products using the same nearline data stores complete a solution that allows the seamless management of propagating and pervasive data volumes in the decision-making environment.

(#319-O) Application of image and multicomponent induction log data to characterize fault zones in the Marmul field, Oman

Gerald J. Kuecher, Gulamabbas A. Merchant, Otto N. Fanini, Inga Matthews, and Tsili Wang, **Baker Hughes**

This presentation will examine an approach to fracture-fill modeling that uses new logging technologies to estimate vertical and horizontal reservoir properties within and adjacent to two faulted zones in a well from the Marmul field, Oman. The faulted zones include natural fractures of high angle (± 75º), and lower angle (± 65º) as well as very high angle (± 85º) drilling-induced fractures. These three fracture sets influence the bulk resistivity of each faulted zone. Natural fractures are variously mineralized or open and drilling-induced fractures are always open.

The fault zones were characterized by integrating image logs, multicomponent induction logs, and conventional log data. Image logs were used primarily to provide high-resolution ground truth for the deeper-reading multicomponent induction tool.

The results of this modeling effort indicated that this type of integrated approach was successful in the Oman test case in 'detecting' the fault zone made known by the image tool. Especially promising was the method developed to extract a single representative button curve from the image log and to model open and mineralized fractures as dipole behavior deviating from matrix resistivity. This approach may prove successful elsewhere.

(#351-O) Integrated evaluation of 3-D seismic and geological data for delineation of the Wara sands in the Awali field, Bahrain.

Nagaraju Kusampudi, Habib Al-Alawi and Lana Al-Hashimi, **Bapco**

The Wara Formation is an early Cenomanian clastic sequence, 60 to 120 ft thick in the southern part of the Awali field, Bahrain. The sandstone member of the formation is a prolific oil producer due to its excellent porosity and permeability; entrapment is stratigraphic due to lateral and updip pinch out. The Wara sands range in thickness from a few feet to 60 ft and occur as apparently discrete, elongated sand bodies with sharp lateral edges and abrupt terminations along their length. Two sand trends, northeast and north, are recognized. The thickness of the Wara Formation increases with increasing sand thickness. Wara sands are inferred to have been deposited as strike-valley sands in pre-existing fault grabens through transportation by currents in a near-shore or shallow-marine environment. The additive relationship of sand to formation thickness is due to the partial wedging of sands against flanking escarpments. Rapid lateral variations in sand thickness constrain precise mapping of the sand geometry from well data alone.

The sand distribution model has been substantially improved by an integrated interpretation using recently acquired 3-D seismic data. The isochron map of the Formation broadly imitates the isopach trends mapped from well data. However, conversion of the isochron to an isopach map by means of detailed velocity analysis resulted in a closer agreement with well data. Horizon amplitude, instantaneous frequency, and phase data provided circumstantial support to the more reliable relationship between isopachs and sand thickness. The sand distribution obtained by integrating these results with inferred geological controls on sand deposition indicated that the known sand bodies extend beyond the drilled area and are part of more persistent, interconnected trends. This enhances their exploration and development potential. The study has underscored the potential of simple seismic attributes in providing high-resolution subsurface solutions when rigorously integrated with well data.

(#348-O) 3-D seismic characterization of Permian Khuff II gas reservoir in the Awali field, Bahrain

Nagaraju Kusampudi, C. Bapu Reddy, Rajasekhar V. Kommaraju* and Waleed A. Jawad, **Bapco**

The Khuff formation in the Awali field of Bahrain is a Middle to Late Permian sequence that consists of dolomitized carbonate rocks with thin anhydrite intervals. It is about 2100 ft thick and is divided into zones K0, KI, KII, and KIII (from top to bottom) based primarily on porosity. The two main productive intervals in the upper part of zones KI and KII are composed of grainstones and secondary dolomite. The top of Permian Khuff II (KII)—the target zone of the current study—has a depth range of 8,800 to 11,300 ft. Its average net and gross thicknesses are 270 ft and 330 ft, respectively. Porosity varies between 5 and 15 percent and is mainly intercrystaline to intergranular with some moldic, vuggy, and fracture porosity. The lower part of KII is a tight dolomite, 150 to 200 ft thick. Sonic and density values of KII range from 45 to 69 µsec/ft and 2.19 to 2.95 g/cc respectively; high sonic

and low density values represent gas reservoir intervals.

Impedance contrasts at the top of the KII gas reservoir are strong enough to generate a negative reflection at the interface, and the resultant amplitude can be directly related to reservoir pore thickness. This was confirmed by evaluating 1-D forward-modeling (synthetic seismogram) results from several wells in the study area. The reflection response was validated in 3-D seismic data by a sharp negative reflection at the top of the KII reservoir, with good correspondence between reflection intensity and reservoir quality as observed in well penetrations. The X-plot between amplitude and reservoir thickness gave good correlations and indicated that medium-to-high reflection amplitudes relate to better reservoir development. Computed regression functions enabled interpretation of horizon seismic amplitude in terms of reservoir pore thickness for the entire 3-D area by statistically integrating petrophysical and geological information. Resultant maps in combination with seismic-guided depth-contours for the KII reservoir, identified areas with good reservoir development downdip from where most wells are located.

The study provided a reasonably dependable basis for identifying areas of better reservoir development in the field area, and supported ongoing exploration efforts in surrounding offshore areas for similar gas prospects.

* Now with Petroleum Development Oman.

(#278-O) Conductive-fault dynamic modeling and history-match improvements on a fractured carbonate field

Yann Lagalaye, **TotalFinaElf**;
Christophe Gerard, **Beicip-Franlab**

TotalFinaElf operates fractured carbonate fields where the production behavior in terms of water or gas breakthrough could not easily be matched with classical dual-medium modeling. It appeared to TotalFinaElf that the modeling of the heterogeneity was not correctly handled. The field discussed in this presentation is an example of where a sudden and unpredicted massive water breakthrough occurred in a particular part of the field. Diffuse fracturing could not explain such a rapid water breakthrough and conductive faults were the most likely geological scenario that could explain this phenomenon. IFP and Beicip-Franlab have recently worked on a new method to dynamically take into account conductive faults in dual-medium simulations (half-explicit modeling). TotalFinaElf also financed research on explicit modeling of conductive faults.

A comparison of the two dynamic modeling methods was made using a field example. It led to three important conclusions. (1) The explicit modeling of conductive faults gave a good match of the water breakthrough. (2) The half-explicit method is a quick and easy-to-use approach that provided a history-match improvement, but the conductive-fault systems have to be of a particular density for it to be used. (3) The explicit modeling was less computer-time consuming as it treated the physics more correctly.

The positive results from this study have improved our knowledge of conductive faults and fracture corridors. These improvements will help us to make better choices and to evaluate risks more properly.

(80-O) Permeability assessment in intrasalt carbonate reservoirs, south Oman

Edwin Lamers, **PDO**;
Jonathan Strauss, **Baker Hughes**

Since 1997, a cluster of seven oil fields has been discovered in the South Oman Salt Basin. The oil is contained in slabs of carbonate within Neoproterozoic Ara salt. The reservoirs are typically 100 to 150 m thick and consist of interbedded dolomite and limestone with anhydrite intercalations at the top and base. Porosity tends to be mediocre at about 5 to 15 percent and horizontal permeabilities are typically quite low (generally 1-10 mD). Reservoir quality is mainly related to lithology and depositional facies.

In spite of overall low permeabilities, the reservoirs were very prolific on short-term production tests (often in excess of 1,000 cu m / day), partly due to very high overpressures. An important phenomenon in all reservoirs is pervasive salt plugging of fractures and faults, and local plugging of the matrix.

A permeability dataset from the 12 exploration and appraisal wells in the cluster was based on core plugs, nuclear magnetic resonance logging, Stoneley acoustic logging, wireline formation testing, and well testing (flow meter and pressure-transient analysis). Differences of up to two orders of magnitude occur between permeabilities obtained from the various sources. Well tests showed that the dynamic pressure behavior was complex and varied. A combination of well-test modeling and analysis placed constraints on permeability and has important implications for recovery efficiency under various recovery schemes.

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It provided a basis for testing alternative geological models. For example, the presence of flow restrictions or barriers and their distance away from the well allowed conclusions about the significance of salt plugging along, and away from, faults. A generic model was developed that accommodates the results of all tests to date.

The analysis of wireline formation tests was important in providing permeability information on a scale intermediate between well tests and measurements from core plugs and wireline logs. Integration of the permeability data with all available information was essential in understanding the test responses. Given the often-contradicting core and logging data, well-test evaluations were used as the main constraining data source in determining the reservoir quality distribution used in static and dynamic reservoir modeling.

(#85-O) Fast creaming of the intrasalt carbonate stringer play in Oman

Jean-Michel Larroque, Folco F. Hoogendijk, Radha M.M. Al-Lawatia, Mohamed El-Tonbary, Tahani J. Al-Awaira, Joachim Amthor, Sultan S.A. Al-Harthy, Masoud Al-Mahrazi, Khairan K.J.H. Al-Mauly and Fahar Al-Rabeei, **PDO**

The Neoproterozoic to Early Cambrian intrasalt Ara Group Carbonate Stringer Play is developed over a large part of the South Oman Salt Basin. Since the revival of the play in 1997, Petroleum Development of Oman (PDO) frontier deep oil exploration has focused on the Southern Platform stringers, resulting in five oil discoveries in the Harweel cluster (Harweel Deep, Sarmad, Ghafeer, Sakhiya and Zalzala). Nine exploratory wells were drilled to find these five commercial accumulations (commercial success rate: 55 percent). The discoveries have yielded 25 million cu m of oil reserves (primary recovery), and a development team has recently been formed to bring these discoveries to production by 2004. Gas-injection could significantly increase the reserves.

Meanwhile, carbonate stringer exploration continues in the existing Harweel cluster to maximize reserves for early development possibilities. In addition, PDO is exploring to extend the proven fairway and to open a new stringer cluster in the northern region of the South Oman Salt Basin. The Carbonate Stringer play constitutes a significant amount of PDO exploration potential. The defined prospect portfolio has been fairly well constrained by the large amounts of 3-D seismic shot in South Oman.

Four to six deep exploration wells (4,000 m to 5,500 m) will be drilled annually in the future and will quickly drill away a significant part of the portfolio potential. The challenge will be to replenish the prospect portfolio that has been built so far by Possibility-of-Success polarization and the acquisition / reprocessing of 3-D seismic.

(#221-O) Sequence stratigraphy and paleoenvironments of the Biyadh-Wasia interval at outcrop: implications for potential reservoirs

Yves M. Le Nindre and Denis Vaslet, **BRGM**; Sami Maddah, **Ma'aden**

The Lower Cretaceous Biyadh Sandstone and the basal Majma Member of the Wasia Formation are exposed in central Saudi Arabia between lat 20°30'N and 28°30'N. Separated by a major unconformity, these clastic units have complex geometric relationships that, due to rapid lithological variations and poor biostratigraphic control, are difficult to correlate between outcrop and the subsurface. Recent fieldwork by the Saudi Arabian Deputy Ministry for Mineral Resources and Bureau de Recherches Géologiques et Minières (BRGM) has provided new data on the sequence stratigraphy, age, and paleoenvironments of these formations. As a result, it is possible that surface and subsurface correlations could be updated for a better understanding of the reservoir geometry.

In the Riyadh area, the Biyadh Sandstone consists of three members of which the middle Sallah Member is marine. Near lat 24°15'N it contains the ammonite *Hypacanthoplites* cf. *millesianus* of late Aptian age. Between lat 27°N and 28°N, detailed mapping has shown the presence of the Biyadh Sandstone unconformably overlying Lower to Middle Jurassic deposits. Analysis of the nannoflora, palynoflora, and bedforms, indicated a tidal influence and a Valanginian to late Aptian age. This marine transgression was followed by a lowstand with the formation of bauxite from lateritic paleosols. The basal truncation extends to the southern edge of the shelf, near lat 21°30'N, where the Biyadh Sandstone overlies the Hanifa Formation.

The Majma Member of the Wasia Formation includes sediments from fluvially incised valleys and recurrent tidal flats that were deposited prior to a maximum flooding event and the extensive deposition of shelf carbonates containing the ammonites *Neolobites vibrayeanus* and *N.* cf. *fourtaui* of late Cenomanian age.

(#169-O) Sequence stratigraphy and sedimentology of the Cretaceous Qishn clastics, Masila Block-14, Yemen: tide-dominated sedimentation in a paleogulf

Dale A. Leckie and Tom Rumpel, **Nexen**

Lower Cretaceous Qishn clastics of the Masila Block-14 in the Hadhramaut region of Yemen have reserve estimates of 1.0 billion barrels of recoverable oil. Clastic sedimentation took place in the elongate paleogulf of the Say'un-Masila basin, open to marine carbonates to the east. The lower Qishn unconformably overlies mixed carbonates and clastics of the upper Saar clastics. Lower Qishn onlap resulted in the deposition of brackish and tidal (probably macrotidal) estuarine to bay facies. The middle Lower Qishn shows evidence of arid non-marine sedimentation—debris flows, red beds, and shale-clast conglomerates—in turn, overlain by interfingering coastal and non-marine facies. The lower Qishn was truncated by a sequence boundary at the base of the informal S3 unit that consists of extensive sandstone deposited within a low-accommodation braidplain close to the shoreline. A flooding surface occurs at the top of the S3, over which progradational, tide-dominated deltaic deposits of S2 were emplaced. Delta progradation culminated in shallow-water clastic dolomitic deposition on a coastal plain. With subsequent transgression, deposits of the S1C show evidence of a rising water table (lakes and lacustrine delta) and a non-marine flooding surface, overlain by tidal-flat deposits. Ongoing transgression resulted in wave-ravinement overlain by shallow-shelf clastics and then slightly deeper shelf carbonates of the S1B. The overlying S1A consists of bioturbated, clastic shelf deposits related to a drop in sea level. Throughout the Qishn interval, accommodation was relatively high, except for low accommodation associated with regional sheet sandstone of the S3. Virtually all marine and brackish deposits show evidence of tidal sedimentation.

(#240-O) Thin-sand prediction for an oil field in Sudan

Miles Leggett, **Jason Geosystems**; Foo W. Yang, Ahmad F. Jubralla and Paramaswaran Suppiah, **GNPOC**; Hamadelnil M. Abdalla, **Sudapet**

One of the biggest challenges to discovering additional reserves and producing from thin-sand reservoirs in Sudan is the characterization of the spatial distribution of their reservoir properties (porosity and permeability), their continuity, and lateral connectivity. Using leading-edge technology to detect and characterize these thin sands can result in optimized field development.

The Aradeiba is an example of a thin-sand reservoir. Its sands were deposited in a meandering depositional system and were extensively faulted due to multiphased tectonic rifting of the Muglad basin. They are complex, laterally variable and only 4 to 10 m thick. Because of their complex depositional nature, the sands are discontinuous and very difficult to interpret from seismic data alone. To image them, a high-resolution reservoir characterization study was made that provided multiple equiprobable models of sand and rock-property distribution.

Phase 1 used seismic inversion to provide acoustic impedance to aid in the reinterpretation of the bounding reservoir surfaces and the faults. Phase 2 used geostatistical inversion—combining seismic, well logs, and statistics—to produce high-resolution volumes of lithology, acoustic impedance, and porosity. These volumes match all the available data and offered a means of reducing the uncertainties that exist when developing oil fields such as these, and for planning producer and injector locations. With multiple rock-property models, the range of volumetrics was easily calculated and ranked to provide an estimate of the uncertainty in the reservoir. Final deliverables of the P50 porosity and lithology volumes may be used directly as input to upscaling and to the reservoir simulator.

(#370-O) A regional structural interpretation of the Zagros mountain belt in northern Fars and High Zagros, SW Iran

Jean Letouzey, **IFP**; Shahram Sherkati, **NIOC**; Jean-Marie Mengus, **IFP**; Homayon Motiei, M. Ehsani and Abdolhossein Ahmadnia, **NIOC**; Jean-Luc Rudkiewicz, **IFP**

Based on field observations and the interpretation of 120 seismic lines and data from over 60 wells, a regional northeasterly transect across northern Fars was constructed and balanced with Locace software. It starts at the Gulf, crosses northern Fars and the High Zagros east of the Kazerun tear fault, and ends at the Imbricate Zone—a total of 300 km.

The structural style was controlled by the stratigraphic position of the decollement levels that vary with depth in different parts of the transect. Within the sedimentary pile, the main decollement level is the

Hormuz salt. In places, this decollement level (as well as pre-Hormuz sedimentary basins) can be clearly seen on seismic lines, and Paleozoic formations are involved in the main structures. The second decollement and disharmonic level is the evaporitic Triassic Dashtak Formation. The difference in the tectonic style between northern Fars in the southern part of the transect and the High Zagros in the north, is partly due to the lateral facies changes from evaporite to dolomite in the Triassic rocks. The shaly layers of the Kazhdumi (Cretaceous) and Pabdeh/Gurpi formations (Upper Cretaceous/lower Tertiary), as well as the Gachsaran (Upper Miocene) evaporitic layer, can locally act as secondary decollement levels.

The disharmonic levels have produced a complex structural picture and shifted the various reservoir culminations from surface to depth. Later involvement of the basement (below the Hormuz salt) has uplifted the whole sedimentary sequence in the area stepwise from southwest to northeast. Locally, the basement is still seismically active. The Zagros follows the classical build-up of a thrust belt with thin-skinned tectonics propagating ahead of thick-skinned deformation. This has induced basement shift and large, folded structures higher in the sedimentary pile.

(#333-O) Onshore seismic data processing in the Middle East: multiple problems, multiple solutions, multiple challenges

Maarten H.P. Ligtendag, Yomi Adejonwo and Jan Biersteker, **Shell**

Geophysics is ever increasing its impact by supplying ever higher-fidelity images of the subsurface. Onshore seismic data, however, does seem to lag behind marine seismic data in this context. One of the major challenges, especially in the Middle East, is the presence of strong multiple energy in the seismic data, that are often difficult, if not impossible, to distinguish from primary energy on the final processed data. This, combined with other well-known onshore seismic problems, for example, shot-generated (side-scattered) noise or the resolution of very low-relief structures in combination with near-surface low-velocity anomalies, poses a continued challenge.

This presentation will give an overview of recent experiences of Shell Geoscience Services, including the results of seismic reprocessing projects from an integrated project team approach. The main focus of the presentation is on multiple-attenuation and its applicability to onshore seismic data. It will also stress the importance of the close interaction with the evaluation team so as to successfully identify multiple events and evaluate the processing results.

Various multiple-attenuation methods have been successfully applied to many marine seismic data sets. However, they fail when applied to onshore seismic data. The latest available methods and their limitations are presented and illustrated by examples from the Middle East. As part of the challenge also involves the successful recognition of multiple events, results of a multiple modeling study will be presented. This showed the limitation of a vintage data set and the potential of newly acquired data in terms of multiple attenuation. In conclusion, the way ahead for multiple attenuation will be highlighted. As this mainly involves (still) costly 3-D prediction of multiples, support will be needed from the evaluation teams in order to achieve the same breakthroughs with land seismic data as have been demonstrated recently for marine seismic.

(#51-P) SUSTAIN: focused exploration through hyperspectral technology for sustainable development in desert terrains

Mark G. Little, Olaf Podlaha and Hong Yang, **Shell**

Hyperspectral remote sensing is at the frontier of space-borne satellite hydrocarbon detection in onshore rocky and desert terrains. Hydrocarbon seepages have distinctive hyperspectral fingerprints that remain invisible to conventional sensors. Hyperspectral sensors mark a step-change in the way we visualize and integrate subsurface information to quickly and accurately assess and high-grade large acreage. In focused exploration, they can be used to reduce major risks and cycle time in exploration, to identify potential prospects at lower cost, and to increase efficiency in targeting successful wells. This technology, combined with a regional geological understanding allows for a fully integrated approach to identify 'hot spots' and so reduce exploration time and expenditure.

Progress in using hyperspectral technology will be illustrated by means of a three-phase study. Phase 1: A collaborative research project used Probe-1 airborne data from Santa Barbara, California to demonstrate the proof of the concept and the technical capability of hyperspectral data sets in identifying hydrocarbons. Phase 2: A proprietary Shell follow-up study demonstrated that the identified seeps had characteristic spectral signatures that could be detected by airborne sensors. Phase 3: Implementation of a

'Shell case study' in the Oman desert on seeps, source rock, and pipelines provided a 'true' proof that the concept was applicable to Middle Eastern desert terrain for acreage evaluation in an integrated and focused exploration framework. This phase incorporated ground truthing, subsurface data-integration, and the latest airborne hyperspectral acquisition.

The next step will be to deliver a tool that supports focused exploration and production in large parts of the Middle East and which will also provide advantages for future opportunities and developments within a sustainable development framework.

(#216-O) Depth conversion using seismic velocities: a case history from offshore Abu Dhabi

Alex L. Litvin, **Paradigm**;
Omar A. Suwaina, **ADNOC**

Depth conversion is most often performed using well-velocity data. In areas of sparse well control, regional trends between well velocity and marker depth are used to generate layer-interval velocity maps. Alternatively, simple analytical functions derived from logs and check-shot data may be used for depth conversion.

Seismic data provide a valuable additional source of velocity information. In this presentation we will assess the value of seismic velocities for depth conversion. We will show the limitations in the direct use of processing seismic velocities aimed at optimizing the quality of the final image. As an alternative, seismic velocities can be derived from dip-moveout gathers using horizon-based velocity analysis. Seismic velocity maps derived from the interpretation of horizontal semblance spectra have a much better correlation with the structure and can be used in depth conversion.

For the Thamama level where several well-control points are available in the project area, we could assess the accuracy of the depth prediction by analyzing depth misties obtained using seismic velocities. These were compared with depth misties obtained from depth prediction based on a regional well-based velocity trend. For the deeper Khuff structure where only one well-control point was available, comparing depth maps based on seismic velocities with those based on well-based velocity trends, assessed the uncertainty of depth conversion.

We can also assess uncertainty in depth conversion related to different velocity model representations (midpoint depth conversion versus conversion with vertical velocity gradient), and the uncertainty related to lateral ray displacement due to refraction in the overburden.

(#157-P) A detailed sedimentological and petrographic study of the Arab Formation, onshore Abu Dhabi

Stephen W. Lokier, **Badley Ashton**; Reyad A. El-Khassawneh and Jürgen Grötsch, **ADNOC**; Gordon Coy and Cathy E. Hollis*, **Badley Ashton**

The Late Jurassic Arab Formation forms an important sour-gas reservoir in the studied onshore field of Abu Dhabi. This poster will show the results of the detailed description and interpretation of four new cored wells that had been drilled to generate sedimentological interpretations and reservoir quality data for conditioning a 3-D model of the reservoir. The study constrained the depositional environment of the Arab Formation. The resulting sedimentological model was populated with petrophysically based rock types that have facilitated accurate reservoir characterization and prediction.

The four wells recorded a prolonged transgressive phase (Arab-D) culminating in a highstand (uppermost Arab-D, Arab-A to C and Hith Formation) that was terminated by rapid transgression (Manifa Formation) reflected in temporary back stepping of the platform. Within this context, the following six distinct paleoenvironments were identified: (1) a supratidal sabkha setting with localized salinas; (2) an intertidal environment; (3) a low-energy subtidal setting; (4) a high-energy inner-ramp environment; (5) a moderate-energy mid-ramp setting; and (6) a low-energy outer-ramp setting. The distribution of paleoenvironments across the field was constrained by correlation within a sequence stratigraphic framework.

A direct relationship between primary depositional facies and rock properties was not seen. This was because of the diagenetic modification of the sediments by processes such as syndepositional dolomitization, displacive anhydrite formation, non-ferroan calcite burial cementation, and leaching. Consequently, a petrophysical rock-type scheme that took account of this diagenetic overprint was developed. Five rock-types with distinctive petrophysical characteristics were defined and upscaled to allow prediction from open-hole logs and the population of the sedimentological model.

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(#309-P) Reservoir architecture and characterization of the Early Jurassic Marrat reservoir, greater Burgan field, Kuwait

Anthony J. Lomando, **ChevronTexaco;** Saleh F. Al-Azmi, **KOC**; Randall D. Hobbet, **ChevronTexaco**

The key to a successful reservoir characterization study is making the transition from a geologic model to a geoengineering earth model for simulation. In the Middle Marrat reservoir of the Burgan field, constructing the geologic model began where it should, with the rocks. Facies and cycle characteristics from cores and logs were used to revise an existing layer model and demonstrated a prograding sigmoidal geometry within the main shoal reservoir, and the distribution of associated facies suites. This revision of the older, simple layer model clearly reveals a NE-trending shoal system that advanced northwestward into a depositional basin during Middle Marrat times.

Plug-based Mercury Injection Capillary Pressure tests, Nuclear Magnetic Resonance, petrography, and standard Phi and K data were used to characterize the pore system. Wackestones and mud-rich packstones had unimodal and small pore-throat and pore-size distributions, whereas mud-lean packstones and grainstones were bimodal with large interparticle pore throats and intraparticle microporosity.

The new stratigraphic framework and pore system characterizations were combined to provide greater detail, which was carried forward into the geostatistical model. Variograms, used to distribute properties in the reservoir model, contained much subjectivity. To compensate for this, various variograms were applied to produce P10-P50-P90 flow versions to model the increased and decreased connectivity. This, combined with a three-fold increase in the number of layers, provided a model ready for upscale and simulation.

(#208-P) On the feasibility of geopressure detection from seismic data in Saudi Arabia

Thomas Loretto and James J. Funk, **Saudi Aramco**

Laboratory measurements of Compressional Velocity (Vp) as a function of Effective Pressure (Pe) were used to determine the feasibility of geopressure detection from seismic data in Saudi Arabia. These measurements were used to calibrate the response of two seismic attributes—Stacking Velocity (Vstk) and acoustic impedance—that are generally considered to be possible indicators of changes in formation pressure. Current laboratory results allowed us to establish a Vp-Pe relation that can be used to calculate RMS velocity (Vrms) for normally pressured to highly overpressured section. This quantity was used to model the expected change in stacking velocity along a 2-D seismic traverse that extended from a normally pressured to an overpressured section in Saudi Arabia. A comparison of the expected change in Vstk (due to geopressure) with estimates of Vstk from the seismic traverse (using coherence plots) showed that the expected change in Vstk was not resolved by the seismic data. These laboratory tests defined velocity as a function of effective pressure for one lithology, one pore fluid, one porosity, and ultrasonic frequencies. Subsequent experiments will broaden the Vp-Pe definition to cover a greater range of lithology and porosity, and the impact of frequency on the Vp-Pe definition will be addressed. They will help to quantify the relative contributions of porosity and effective pressure to changes in velocity. Given a traditional relationship between porosity and impedance, the value of impedance as a geopressure indicator can then be assessed.

(#111-O) Detection of shear-wave splitting and fracture orientation from PS converted waves (C-waves) for carbonate reservoirs

Min Lou, Yaohui Zhang and Long D. Pham, **PGS**

Shear-wave splitting from PS converted waves (or C-waves) contains information on subsurface fractures and azimuthal anisotropy. The fracture orientation is determined from the particle motion direction of the fast shear wave (S1), whereas the fracture density is estimated from the delay time between the S1 and S2 waves. Shear-wave splitting has been applied in detecting azimuthal anisotropy and fractures from marine multicomponent PS wave seismic data. Shear-wave splitting and its implied fracture orientation were identified by examining PS wave amplitude and its azimuthal polarity variation on the transverse component, or by calculating the ratio of radial to transverse energy for a range of azimuth stacks in a 3-D seismic survey.

We will present a two-component rotation/cross-correlation method to detect shear-wave splitting and its implied fracture information from PS waves. Compared to other methods, the cross-correlation method is straightforward and can be applied to both 2-D and 3-D PS wave data sets. The method is also robust to random noise since it uses as input a whole PS waveform train instead of amplitudes alone. We

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will demonstrate the effectiveness of our cross-correlation method through the analysis of a synthetic and a real 2-D-4-C ocean bottom cable data set recorded over a carbonate field. Our results have demonstrated that the two-component rotation / cross-correlation method is robust in detecting shear-wave splitting and its implied fracture orientation and density from PS waves.

Finally, we will show that the decoupling of PS waves into fast (S1) and slow (S2) shear-wave components improves the temporal resolution of PS waves in the presence of shear-wave splitting. This method can be applied with similar success to the carbonate reservoirs of the Arabian Gulf and the Arabian Peninsula.

(#223-P) Time-frequency analysis with a phase-corrected wavelet transform

Yi X. Luo and Maher I. Almarhoon, **Saudi Aramco**;
Javier Sabadell, **WesternGeco**

Wavelet analysis is a powerful tool for analyzing non-stationary data. We have introduced the S-transform, a mathematically derived extension of the continuous wavelet transform. The major differences were the addition of a phase correction and a novel view of the weighting factor, linearly proportional to the frequency instead of the usual inversely proportional scale in the wavelet transform. These features provided independent localization of spectral components in seismic data, thus making available frequency-dependent resolutions and a direct relationship with the Fourier spectrum.

The window used in the transform is gaussian. As a result, it minimized the uncertainty inherent to this type of analysis, but it could be changed to accomplish various trends on the steady-state behavior of the signal, such as asymmetries or fast decays. When the S-transform is applied to seismic processing, the frequency content of the uncorrelated signals can be used to examine and enhance significant features in prestack depth migration and prestack time migration data sets. Also, it permits retrieval of the local phase of the signal. This property allows the decomposition of the seismic traces in a more accurate way than do techniques based on the analytic signal or on conventional multiresolution analysis (discrete wavelet transform).

Results produced with synthetic and real data revealed the advantages of the transform in detecting edges, seismic channels, and strong variations of soil structures, as well as various scale-dependent features.

(#321-O) A feasibility study for a 3-D–4-C seabed seismic survey in the Arabian Gulf

Costas G. Macrides, **Saudi Aramco**;
Paul Ras, **WesternGeco**

We present a feasibility study, designed to investigate whether 3-D seabed, multicomponent (4-C) seismic recordings over the Zuluf field would improve the structural and stratigraphic interpretation. A primary objective of the study was to determine which of the potential benefits of 4-C recording would materialize into tangible benefits in the case of the Zuluf field. Surface seismic data sets consisting of towed streamer and ocean bottom cable (2-C) data from a neighboring field, were analyzed and compared. Multicomponent vertical seismic profiling data were also used, both to evaluate the amount of shear wave energy generated by mode conversion and to predict the achievable bandwidth. Earth models built from the P (compressional wave) and S (shear wave) logs were used to model P and S offset reflectivity and create realistic synthetics.

We have been able to predict those aspects of a 4-C survey that would provide additional new insights and those aspects that are less likely to succeed. For instance, whereas the use of S-waves for imaging low P-impedance contrasts does not seem promising for the Khafji Main Sand (the main producer to date), converted S-waves are expected to improved imaging for the overlying Khafji and Safaniya stringer sands. The stringers are where most of the remaining reserves are located. There is also scope for S-wave data to provide additional constraints on the interpretation through the use of seismic velocity analysis (Vp / Vs). Combined interpretation of the two data volumes (PP and PS) could provide both a reservoir-quality indicator and a means for lithological and fluid discrimination.

(#368-O) Attenuation of a 3-D acquisition footprint via alternate-trace FX/FY deconvolution, onshore Qatar

James R. Magill, Alan L. Edmonson,
Elena M. Fischer, Christopher W. Hollister
and Kent M. Mangold, **ChevronTexaco**

Chevron, in partnership with Qatar Petroleum, acquired a vibroseis 3-D survey of onshore Qatar during January through March 2000. Subsequent processing and preliminary interpretation of this data set revealed a significant 'acquisition footprint' within the stack volume. This type of artifact is commonly

observed to varying degrees on 3-D data sets worldwide. It is expressed as a spatial variation in amplitude and phase that is related to acquisition geometry, typically seen on amplitude or structure maps as regular 'stripes' or 'egg-crate' patterns. These variations are thought to be due to the interaction of an irregular offset distribution across the survey with coherent noise, random noise, and normal moveout/dip moveout effects.

Our efforts to attenuate this acquisition footprint were motivated by the desire to derive detailed stratigraphic information from the survey interpretation. Plans for poststack inversion and attribute mapping required aggressive noise reduction on the stack volume. As a result of testing several possible noise-reduction techniques, we found that an alternate-trace fxdecon (applied in two passes) was particularly well suited to the challenges presented by the Qatar data set. This method, to our knowledge, is not widely used in the industry. However, it may have broader applications to 3-D surveys that are affected not only from acquisition footprint artifacts but also from cross-line noise problems of a more general nature.

(#193-O) The impact of exploitation geochemistry on production and development strategies

Paul J. Mankiewicz, Cara L. Davis, Robert J. Pottorf, Mark Richardson, Lloyd M. Wenger and Jim R. Gormly, **ExxonMobil**

Petroleum geochemistry, integrated with geologic and engineering data, can play an important role in optimizing field development and long-term production strategies. Geochemical information can be collected from a variety of samples, including downhole or separator gas, oil, and water, and fluids adsorbed to or included in rock cements. Sample analyses are relatively quick to do and inexpensive and the results directly affect issues related to reservoir segmentation, fluid types and contacts, oil and gas quality and producibility, migration and fill history, and potential production problems.

Understanding the complete hydrocarbon system (source, maturation, migration, emplacement, and alteration of hydrocarbons) is critical in optimizing the future development of discovered fields. Variations in source and maturity of reservoir fluids, as resolved by high-resolution geochemical techniques, can suggest migration pathways and fill-timing for individual reservoir compartments. These techniques can detect subtle chemical differences arising from secondary processes, such as hydrocarbon-rock-water interactions, biodegradation, leakage, or migration effects. The measurement of fluid-inclusion volatiles (organic and inorganic compounds trapped in cements) allows for nearly continuous stratigraphic mapping of present or paleofluids in the subsurface. Combined with optical fluid-inclusion petrography and microthermometry, this technique can determine the pressure, temperature, and timing of hydrocarbon migration and trap-filling events. It can thus locate bypassed pay zones, identify fluid types (gas, oil, water) and contacts, and estimate seal quality.

The integration of geochemical data into both regional and field-scale geologic and development frameworks allow a better understanding of the hydrocarbon system responsible for the economic accumulation. This can result in the addition of significant reserves, lowered production costs, increased production rates, and accelerated earnings.

(#22-O) Influence of structural evolution and in situ stress on early waterflood response in the Minagish Oolite, Minagish field, Kuwait

Marco Martines, **BP**; Mohammad M. Abbas, Khaled M. Al-Mutairi and Naveen K. Verma, **KOC**; Dave G. Foster, **BP**; Hamad N. Al-Ajmi, **KOC**

Knowledge of the in situ stress field is highly beneficial when designing the drilling direction of horizontal or deviated wells, programming hydraulic fracturing, and water flooding a reservoir. All of these operations are influenced by its direction. In particular, as supported by statistical field data and numerical modeling performed by some authors, the analysis of waterfloods shows strong correlation between the direction of the waterflood and the present-day principal stress. Our work has successfully integrated various types of information (field structural history, borehole breakouts, surveillance data, time-lapse (4-D) seismic, and early waterflood response) in order to assess some of the controlling factors on water movements in the Minagish Oolite of the carbonate Minagish field.

The Minagish structure is formed by a N-trending anticline, resulting in structural closure on the Lower Cretaceous section. This structure has been growing since the Jurassic with quiescent periods alternating with uniform or asymmetric growth. The structural growth has been in line with a regional compression vector oriented northeast. Borehole breakout data analysis has indicated a NE-orientation of the present-day maximum horizontal stress. A recent pilot time-lapse seismic survey shot over the field has supported the movement of water from an injector to a producer as indicated by seismic anomalies. Those anomalies

are not isotropically distributed around the injector but are aligned according to two preferential directions. The stronger has a northeasterly trend whereas the weaker one is aligned in a north-northwesterly direction. The strong seismic anomaly and the surveillance data support a water movement parallel (or nearly parallel) to the orientation of the Minagish maximum horizontal stress, and the weaker one indicates the local influence of secondary shears on the water movement.

(#165-P) Calibration of $^{87}Sr/^{86}Sr$ and $^{13}C/^{12}C$ data on a well-constrained biostratigraphic section of the Cenomanian carbonate platform in the Middle East

Pierre J.L. Masse, **TotalFinaElf**

The chronostratigraphic use of isotopic geochemistry is a recent development. Changes in the $^{87}Sr/^{86}Sr$ ratio provide age definitions within a previously known time-slice across the Tethys and $^{13}C/^{12}C$ ratios reveal further chronostratigraphic events. We have established a Cenomanian reference scale to identify isotopic ratios usable at a reservoir scale by means of a biostratigraphically constrained section in Tunisia. Rotaliporidae ($^{13}C/^{12}C$) and Calcisphaerulidae ($^{87}Sr/^{86}Sr$) provide the isotopic data.

A middle Cenomanian $^{13}C/^{12}C$ positive event was correlated with a similar-aged event in Spain and the UK. Two low-value events were identified in the $^{87}Sr/^{86}Sr$ signal, tied to plankton and ammonite biozones at the top lower Cenomanian, and at the top middle Cenomanian. The $^{13}C/^{12}C$ event is located between them. The reference section was tested on core samples from the Mishrif Formation of a Middle East well. Benthic biozones are difficult to calibrate chronostratigraphically; thus, an estimation of the duration of discontinuities within the succession had not been previously possible. An analysis of bulk rock samples used cemented bioclasts: the $^{87}Sr/^{86}Sr$ signal showed two peaks of low values, as in the reference section, with the $^{13}C/^{12}C$ event located between them.

The following conclusions were made. (1) The cored Mishrif section is of late early to early late Cenomanian age. (2) The lower part of the middle Cenomanian is missing, or is strongly reduced; this hiatus could be represented in sediments laterally. (3) Isotopic data can be used for chronostratigraphic interpretation when microfossils are rare, but prior biostratigraphic calibration is necessary. (4) High-frequency variations of $^{87}Sr/^{86}Sr$ are difficult to interpret because of diagenesis and the oceanographic distribution of $^{87}Sr/^{86}Sr$.

(#184-P) How much is fracture intensity controlled by petrography in carbonate reservoirs of the Natih Formation, Oman?

Gérard J. Massonnat, **TotalFinaElf**;
Stéphanie Eyssautier-Chuine
and Francis Odonne, **U. Paul Sabatier**

In naturally fractured reservoirs, early water breakthroughs are usually related to fracture clustering in particular parts of the field. The organization of these highly fractured zones in space can be laterally heterogeneous when driven by large-scale deformation (such as folding, faults, and fracture corridors), or vertically heterogeneous when controlled by stratigraphy. The controlling parameters of fracture development have been studied intensively in recent years. However, the influence of carbonate petrography is poorly documented in the literature. An intensive study performed on outcrops of the Natih Formation in Oman has enabled us to identify and quantify the relationship between the bedding parameters and the fracture density.

In several exposures on Jebel Madar and Jebel Madmar, the fracture network was evaluated in terms of the density per fracture set or by type of fracture (joint or vein) for many beds and compared with parameters such as thickness, texture, and porosity. Continuous relationships illustrated the decrease of fracture density when the grain proportion (micritic grains or bioclasts) increased and the proportion of micritic matrix decreased. On Jebel Madmar, about 50 percent of the whole variance of the fracture density could be explained by the textural parameters alone, and this increased to more than 70 percent for some parts of the fracture network. The same relationships were seen with fractures in thin sections, so allowing similar studies on core data. Fracture models built using these constraints provide much more realistic images of the Natih reservoir.

(#201-O) A new method for constraining stochastic modeling of sedimentary facies by genetic processes

Gérard J. Massonnat, Enrico Pernarcic
and Henri J. Soudet, **TotalFinaElf**

When building reservoir models for flow simulations, the key issue is generating realistic images of the reservoir heterogeneity that drives flow behavior in the field. The development of stochastic modeling techniques is a response to this quest, as far as reservoir heterogeneity is generated consistent with the hard

data. However, some input parameters, not directly related to the data, influence the level of ability of stochastic models to represent in a realistic way the actual distribution of heterogeneity. Among these parameters, the 3-D block of facies proportions plays a leading role as it mostly controls facies distribution.

A new method has been developed to build this 3-D block of facies proportions coherently with sequence stratigraphy and knowledge of the sedimentary processes. It is based on the realization that in carbonates, depositional facies are mostly dependent on the paleobathymetry of sedimentation, the level of hydrodynamism, and on the type of systems tract in which the facies is generated. The method is in 12 parts and enables the calculation of accommodation potential at each well, the building of a precise stratigraphic grid, the identification at field scale of common factors and residuals of accommodation potential, and the building of 3-D guides of accommodation, hydrodynamism, and paleobathymetry. Combining these grids with computed matrixes of facies occurrence builds the facies proportion block and computes the probability for each facies to be affected by early diagenesis.

This method makes it possible to obtain significant advances in the realistic and predictive aspects of stochastic models. A field example, located in the Mishrif Formation, clearly illustrates this advance in carbonate reservoir modeling.

(#359-P) Sequence stratigraphic architecture of non-marine to fully marine Cretaceous strata of Kuwait: the Zubair Formation and Ratawi Shale Member of the Ratawi Formation

Glen G. McCrimmon, Robert W. Wellner and Penny E. Patterson, **ExxonMobil**; Adel F. Douban, Meshal A.H. Al-Wadi, Abdul Aziz Al-Fares and Mishari A. Al-Awadi, **KOC**

The integration of well logs, core and seismic data has provided a predictive chronostratigraphic framework for the Cretaceous Zubair Formation and the Ratawi Shale Member of the Ratawi Formation of Kuwait. The units form three composite low frequency sequences that are separated by major regional unconformities. The sequences are subdivided into lowstand, transgressive and highstand sequence sets composed of 31 high-frequency depositional sequences. Each of the high-frequency sequences contains units belonging to either lowstand or transgressive / highstand systems tracts. Each systems tract subdivision has distinct facies trends, thickness distributions, and variations in reservoir quality. The lowstand systems tracts consist primarily of sand-prone incised valley fills. These valleys become thinner, more laterally discontinuous, and more tidally influenced downdip toward the northeast but amalgamate into apparent sheet sands updip. The highstand and transgressive portions of these sequences are dominated downdip by marginal-marine sandstones and mudstones and updip by alluvial / coastal plain mudstones and sandstones. The paleoshorelines typically trend northwesterly, and are best developed in the northeastern part of Kuwait.

Due to similarities in depositional elements (lithofacies types and the geometry and orientation of the facies belts) strata from what has traditionally been called the Ratawi Shale Member and the lower part of the Zubair Formation have been grouped together to form a progradational highstand sequence set. This is overlain by a major angular unconformity that is interpreted here as a composite sequence boundary. Two additional composite sequences make up the remainder of the Zubair Formation. Strata interpreted as being marginal-marine dominate each composite sequence downdip to the northeast but become more non-marine dominated updip to the southwest.

(#323-O) Central Arabian Paleozoic stratigraphic targets

Ronan McElroy, **Saudi Aramco**

Upper Paleozoic clastic gas reservoirs in Saudi Arabia are variable in terms porosity, permeability, age, stratigraphic relationships, facies and diagenesis. It is not uncommon that gas accumulations appear to be hosted in structural closures with relief that is less than the column height of the pool. A strong stratigraphic component to the reservoir and its trapping potential is common.

A key to understanding the distribution of high-quality reservoir sands lies in the configuration of regional unconformities within the Carboniferous-Permian Unayzah sequence. These are of two genetic types (1) intraformational (sequence-boundary) surfaces related to base-level changes, and (2) late post-tectonic erosional boundaries. The two are fundamentally different in terms of their exploration potential. The first type is invariably associated with a complex and locally variable sand-fairway distribution and the unconformity configuration plays a relatively limited predictive role. In contrast, the predictive potential of the second type of unconformity is greater because the post-tectonic unconformity requires that the structural geometry of the older layers be different from that of the younger beds. Large and predictable sand fairways

can be generated if the appropriate lithologies are preserved in paleolows (synclinal cores) beneath the unconformity. Their absence along the crest of regional paleoanticlines therefore sets up large-scale regional stratigraphic trap potentials within the Carboniferous-Permian succession.

The presentation will demonstrate that the pre-unconformity structure at about 255 Ma accounts for the preservation of some of the better Unayzah reservoirs, and that its recognition unlocks hidden exploration potential across the region.

(#224-P) Glacially tectonized and glaciomarine deposits of Late Ordovician (Ashgill) age in a shallow core from west-central Saudi Arabia

John Melvin and Merrell A. Miller, **Saudi Aramco**

A distinctive succession of glaciomarine facies is recognized in core from a shallow velocity survey well in west-central Saudi Arabia. Sedimentological facies analysis identified, from the base of the core upwards: (1) coarse-grained to gravelly, cross-bedded sandstone sets with rare, thin bioturbated mudstone, (2) sandy diamictite, (3) medium- to coarse-grained, cross-bedded and rippled sandstone, (4) thin-bedded (6–9 inches), sharp-based, graded, locally contorted sandstone, (5) polychromatic mudstone with scattered, floating grains of coarse sand, (6) thin-bedded (5–6 inches), upward-coarsening muddy diamictite, with interbedded thin sandstone and mudstone, (7) red claystone, and (8) highly contorted and sheared red / gray mudstone with 'inclusions' of sandy diamictite. These sediments represent, respectively: (1) subaqueous glacial-retreat sands and gravels, (2) glacial readvance subglacial tillite, (3) proglacial subaqueous 'delta' outwash sands, (4) proglacial outwash turbidites, (5) restricted proglacial clays possibly chemically affected by dense subglacial brines, (6) proglacial ice-rafted diamictites, (7) proglacial clays, and (8) proglacial clays tectonized by glacial readvance. Palynologically and sedimentologically, this succession is correlatable with that from the Late Ordovician (Ashgill) lower Hawban Member of the Sarah Formation, at outcrop.

Within the glacial succession, the polychromatic mudstone is radioactive with a strong gamma ray response that is similar to the one commonly used to identify the base of the Silurian organic-rich 'hot shale' on the Arabian Plate. In the subject well, the Silurian 'hot shale' has been identified about 85 ft above the Late Ordovician radioactive polychromatic mudstones. The presence of this anomalous radioactive zone in the Late Ordovician glacial sediments demonstrates that caution should be exercised when picking the base of the Silurian from wireline logs only.

(#183-O) Microfossil assemblages, sequence stratigraphy, and tectonic control in Cretaceous carbonates: should we expect eustasy to be recognized?

Alessandra Menegatti, **Aberdeen U.**;
Michael D. Simmons, **CASP**

Biostratigraphic, sedimentologic, and sequence stratigraphic techniques were applied to an interpretation of the middle to late Cenomanian Mishrif Formation of Dubai. Fourteen wells were analyzed in core and thin-section. Microfossil assemblages and sedimentary features revealed that 13 biofacies are suggestive of different paleo-environments. Trends in the biofacies indicated paleowater-depth changes that permitted us to identify parasequences. Most of the analyzed cores indicated an overall middle-shelf to inner-shelf habitat, whereas some embodied outer-ramp to basinal sediments. The major stacking patterns of parasequences could be interpreted as thick highstand systems tracts with thin transgressive systems tracts. Beneath the top of the mid-Cenomanian a maximum flooding surface was recognized. Several erosional surfaces were also present below the base Laffan unconformity (top Mishrif).

Local paleogeography played an important role within the Gulf region. In the middle to late Cenomanian the platform was prograding toward the central Abu Dhabi basin. However, it was rhythmically exposed and eroded in the northwestern part of the Dubai area as the formation of intrashelf basins, commonly anoxic, characterizes the southeastern part. In this context, observations were made of the base Laffan and of the Mishrif-Khatiyah depositional transition. This study focused on a better understanding of the geometry of these surfaces in relation to the depositional model of the Mishrif.

(#292-O) Dip estimation from array induction measurements

Gulamabbas A. Merchant, Bill Corley, Otto Fanini and Ingo M. Geldmacher, **Baker Hughes**;
Jiaqi Xiao, **Sperry Sun**

In array induction measurements, the relative dip angle between the formation bedding plane and the tool axis has been successfully estimated by a method

that is fast enough for well-site processing. This method makes it possible to apply an automatic and self-contained dip correction to array induction logs. This in turn is a pre-requisite for accurately processing array and multicomponent induction measurements in horizontal and deviated wells. Relative dip angle is an input parameter in the data-processing sequence of array and multicomponent induction measurements in deviated wells. Although it can be obtained from dipmeter or image logs, in practice a trial-and-error method is typically applied to estimate the angle. Inversion offers an alternative approach, but it is time-consuming and requires an expert user input; therefore, it is not suited for well-site processing. From the resemblance between the different array measurements of an array induction tool, it is possible to predict one measurement from another within a certain accuracy range. This prediction is, among other factors, a function of the relative dip angle. Knowing this dependence, a prediction algorithm can be applied to measurements from a well of unknown relative dip using a series of discrete angles. The correlation coefficients calculated between the actual acquired data and the predicted data will peak at the most likely relative dip angle. The width of the correlation coefficient curve indicates the uncertainty of the estimated dip angle.

This presentation will describe the dip estimation method, and the High Definition Induction Logging instrument illustrates its implementation. The method achieves the desired accuracy, efficiency, and robustness and will be demonstrated through field examples.

(#237-P) Application of high-resolution sequence stratigraphy in defining Khuff-reservoir facies partitioning, Uthmaniyah area, Ghawar field, Saudi Arabia

Franz O. Meyer*
and G. Wyn Hughes, **Saudi Aramco**

The Upper Permian to Lower Triassic Khuff-C and Khuff-B reservoirs are composite sequences that show major depositional facies changes vertically and laterally on a kilometer scale in the Uthmaniyah area of the Ghawar field. A total of 3,200 ft of core, 5,914 core plugs, and 3,200 thin sections from 11 wells defined the depositional model, the internal facies architecture, and chronostratigraphy on the basis of an integrated sedimentologic, micropaleontologic, and petrophysical analysis.

The Upper Permian Khuff C reservoir has two composite sequences. Skeletal-pelletoid-dominated grainstone cycles with tidal-flat cycle caps characterize the lower part of a Transgressive Systems Tract (TST). The overlying TST cycles below a Maximum Flooding Surface (MFS), and Highstand Systems Tract (HST) cycles above it, had unfilled accommodation space, and are characterized by thick skeletal grainstone deposits. A shift to mud-dominated, restricted lagoonal sedimentation started half way through and gave way to tidal-flat deposition in the upper third of the HST.

The stratigraphically higher Khuff-B reservoir has Upper Permian and Lower Triassic composite sequences. The Upper Permian sequence is only 17 ft thick and was erosionally truncated down to skeletal-pelletoid-dominated grainstone cycles of the TST. The Lower Triassic sequence has a retrogradational cycle stack below, and strongly progradational cycle stack above, an MFS. Major grainstone deposition and a turnaround in the facies and cycle stack took place above the MFS. An abrupt shift to restricted lagoonal and tidal-flat sedimentation occurred toward the upper part of the HST.

* Now CEO of Carbonate Research International Inc.

(#234-O) Significant new biostratigraphic horizons in the Qusaiba member of the Silurian Qalibah Formation of central Saudi Arabia, and their sedimentologic expression in a sequence stratigraphic context

Merrell A. Miller and John Melvin, **Saudi Aramco**

Detailed biostratigraphic analysis of 25 wells from central and southern Saudi Arabia has led to the discovery of new Silurian palynomorph taxa that allow previously unrealized biostratigraphic resolution within the middle Llandovery. The biostratigraphic markers augment published acritarch and chitinozoan zonations.

In particular, within the base of the informally designated mid-Qusaiba sandstone (lower part of the *Angochitina hemeri* Interval Zone), and above the Last Appearance Datum of *Sphaerochitina solitudina*, two palynologically distinct, unconformity-bounded parasequences are recognized. Clusters of a distinctive cryptospore species define the stratigraphically higher parasequence; the lower one is characterized by the consistent occurrence of the acritarch *Tylotopalla caelamenicutis*. The palynomorph assemblages for these packages are similar, consisting of angochitinids, conochitinids, cryptospores, and a low-diversity acritarch assemblage. The resulting resolution has allowed the identification of at least two

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unconformities representing falls in relative sea level, and these are reflected in distinctive lowstand sedimentary facies associations within the sandstones. The facies associations consist of several storm-generated sedimentary facies of shelfal affinities as well as enigmatic 'turbiditic' sandstones.

In addition, two new commonly co-occurring acritarchs, an easily identifiable recurved granulate *Eupoikilofusa* species and a new bipolar acritarch genus, are present within the *Conochitina alargada/Plectochitina paraguayensis* Concurrent Range Zone. Their distribution to date is in the northern part of the Rub' Al-Khali and the southern margin of Ghawar. The cryptospore and acritarchs used here are robust enough to be preserved in areas of elevated thermal maturity, so making them useful for regional correlations.

(#88-O) Gas exploration in Block-6 Khazzan Oman: defining scope in a Haima stratigraphic trap

John A. Millson, Mohamed H. Al-Lawati,
Graham J. Tiley and Jean-Michel Larroque, **PDO**

The central Oman gas fields (Saih Rawl, Barik, and Saih Nihayda) in the Ghaba Salt Basin exploit gas condensate from thick clastic reservoirs in salt-cored structures of the lower Paleozoic Barik Sandstone Member (Haima Supergroup). Deep exploration wells to the northwest of the Basin on the Makarem High (Musallim Ridge), discovered substantial volumes of gas in the older Amin and Buah formations, but found poor reservoir development in the Barik Sandstone Member. A review of well data indicated a possible northward stratigraphic pinch-out of the reservoir, away from the Salt Basin onto the High. A recent exploratory appraisal well (Khazzan-1), on the flank of the High, has confirmed this model and proved a major new gas field in the Barik.

The 'Khazzan' field has an area that is possibly in excess of 1,200 sq km, with a vertical closure of some 450 m. Scope volumes for the field are of the order of several trillion cubic feet of gas. Barik reservoir quality is problematical (net-to-gross 11% to 35%, horizontal permeability 2 to 20 mD) and recovery is dependent on 'dry' gas inferred from pressure and fluid sample data. A test in 2000 of the Barik in Makarem-3 demonstrated that economic flow rates could be achieved with this combination of reservoir and fluid.

Primary Khazzan appraisal activities are focused on the definition of areas of Barik reservoir thickening and economic sand pinch-out and well design will be tailored to optimize the productivity of more marginal reservoirs. Secondary objectives include targeting exploratory appraisal scope for recovery in the deeper formations.

(#125-O) Reservoir alteration at the mid- to late-Cenomanian unconformity, Falah field, offshore Dubai

Raymond W. Mitchell,
Kenneth J. Fredricks and Peter D. Bowser, **DPC**;
Alessandra Menegatti, **U. of Aberdeen**

The Falah field, discovered in 1978, produces from middle- to late-Cenomanian Mishrif limestones. The Mishrif was deposited on the ramp of the Rub' Al-Khali basin and conformably overlies the deep-shelf Khatiyah organic-rich limestone. The Mishrif top is eroded, marked by a cemented and pyritic limestone about 1 ft thick overlain by marine shale of the Turonian Laffan Formation. In places, a marginal-marine to non-marine carbonaceous unit ('coal') occurs at the unconformity. Detailed biostratigraphic correlations indicated structural growth during and immediately following deposition of the Mishrif, localized by movement of the late Precambrian Hormuz salt. Domal uplift resulted in the erosion of as much as 450 ft of the Mishrif, representing about 5 my of missing section.

The coal has not been cored but it has been identified by high gamma-ray and low density log signatures and confirmed by drill cuttings. It is up to 8 ft thick, and similar material has been intersected in vertically oriented 'dikes' penetrated by horizontal laterals at the top of the Mishrif. A seismic anomaly has been mapped that spatially correlates with the presence of coal in the wells. Where coal is present, the Mishrif limestone is characterized by a saturation-versus-height profile indicative of larger pore throats. We believe that during deposition of the coal, the pore structure of the fine-grained Mishrif grainstones were altered by corrosive groundwater. This alteration has been preserved through later diagenesis and oil emplacement, and is a controlling factor for the saturation profiles observed in some wells.

(#82-O) High-resolution sequence biostratigraphy of the upper Haima Supergroup, central Oman

Stewart G. Molyneux, **BGS**; Peter Osterloff, **PDO;**
Randall R.A. Penney, **Reservoir Laboratories**;
Pieter P. Spaak, **PDO**

Over the past decade or so, significant gas / condensate reserves have been found in the Haima Supergroup

of Central Oman. These discoveries highlight a need to understand the stratigraphic architecture of the Supergroup so as to identify stratigraphic traps and determine the relationships between reservoirs and seals. Biostratigraphy has a role to play in determining Haima stratigraphy. However, until now biostratigraphic schemes have been imprecise with individual zones commonly spanning one or more lithostratigraphic units and chronostratigraphic divisions.

New palynological studies hold the promise of higher biostratigraphic resolution. At their heart lies the recognition that unique assemblages of marine palynomorphs characterize marine flooding events in the Haima Supergroup. In the upper Haima (Mahatta Humaid and Safiq groups), distinct and often diverse marine palynomorph assemblages occur in the Upper Cambrian, Lower Ordovician (upper Tremadoc), Middle Ordovician (Llanvirn), Upper Ordovician (separate Caradoc and Ashgill assemblages) and Lower Silurian (Llandovery). The intervening strata commonly yield sparse, low diversity palynomorph assemblages that indicate marginal marine and non-marine environments.

Recognition of distinct marine assemblages has led to a more precise correlation between sections in the Haima Supergroup, and to a better understanding of stratigraphic relationships, including lateral facies trends. Furthermore, the discrete assemblages provide data to test the sequence stratigraphic models developed for the Arabian Plate, as they should show a spatial relationship to candidate maximum flooding surfaces. Viewed in the context of sequence stratigraphy, the biostratigraphy being developed for Central Oman may have wider applications to the Arabian Plate as a whole.

(#384-P) Early Silurian Qusaiba source maturation modeling on the Arabian Plate: a multidisciplinary approach

Leonard V. Moore
and Christopher A. Johnson, **ExxonMobil**

Early Silurian Qusaiba source rocks were deposited over much of the Arabian Platform. The Qusaiba is the probable source for reserves in excess of one quadrillion cu ft of discovered gas in the Permian-Triassic Khuff, as well as the significant discoveries of sweeter gas in a suite of pre-Khuff clastic plays. An integrated team approach that incorporates plate reconstruction, timing of regional structural events, basement terrain maps, heat-flow models, biostratigraphy, sequence stratigraphy, seismic datuming, geochemical fingerprinting, backtracking and activation energy profiles of the Qusaiba, has been used to better quantify the Qusaiba source rock.

Four key groups of data collectively control the quantity, quality, and timing of hydrocarbon generation from the Qusaiba. (1) Heat flow through time is a function of basal heat flow and the basement terrain, as well as rock and fluid conductivity. (2) Post-Qusaiba depositional and erosional histories at both on- and off-structure modeling sites are critical to maturation timing. (3) The quality and quantity of hydrocarbons generated by the Qusaiba is a function of organic matter type, thermal maturity and source rock expulsion status. (4) The original total organic carbon content and the original hydrocarbon index of the 'immature' Qusaiba can be reconstructed from present-day values by using thermal maturity, visual kerogen, pyrolysis, and activation profile data.

Site-specific (1-D) models provide the assessment team with quantified uncertainty ranges. They also feed into 3-D modeling of volumes, timing, and drainage at the basin, play, and prospect levels.

(#253-O) A heuristic approach to decision making based on multiple attributes: Haradh gas field development drilling, Saudi Arabia

Edgardo L. Nebrija
and Muhammad M. Saggaf, **Saudi Aramco**

Development drilling decisions are best made based on an integrated model of the reservoir, but commonly, time and logistical constraints preclude this ideal situation. Typically, only separate geologic, seismic, or engineering data are available.

This presentation is a heuristic approach to development drilling decisions based on the combined analyses of all pertinent reservoir attributes. It follows the actual decision process and systematizes it. Each attribute must be related to a reservoir property. If its value points to a good reservoir then it makes a large, positive contribution to the decision; otherwise, it contributes little or nothing. Since attributes have different magnitudes, their effects must be normalized to a common range, of say 0 to 10. The decision-maker inserts his bias when he determines the significance of each attribute by assigning a weight to it. His decision preference is expressed as the weighted, linear combination of the various normalized attributes. The outcome is a 'score' that defines the relative desirability of a given proposed drill location. In short, this method calculates his 'decision'. All he has to do is decide how to decide. This holds true for one decision maker or a group.

This approach was applied to an actual gas development-drilling program in the Haradh area of the Ghawar field, Saudi Arabia. The target reservoir was the basal Khuff clastics, a Lower Permian sandstone reservoir. Five delineation wells were used for the analysis. They sampled what is believed to be the whole spectrum of the reservoir, from thin, silty marginal reservoirs to massive, porous sandstones. Several attributes are used; acoustic impedance from seismic inversion by two different techniques, average frequency, reservoir isopachs, porosity, and gas saturation. Since the seismic data quality varies laterally, confidence attributes, such as the mean error in inversion and trace-to-trace seismic correlation, were used to modulate the decision outcomes.

To date, four new wells have been drilled based on this analysis. All successfully matched the predicted average porosity. However, one well was water bearing, not gas-filled, indicating that the effect of fluid on the analysis is subtle. Analysis of the drilling results showed a close relationship between decision 'score' and reservoir quality.

(#217-O) A 700-million-year tectonic framework for hydrocarbon exploration and production in Saudi Arabia

Paul G. Nicholson, **Saudi Aramco**

Hydrocarbons are produced from Cenozoic, Mesozoic, and Paleozoic traps in Saudi Arabia, whereas the Neoproterozoic represents an unexplored but prospective exploration target. The tectonic history for exploration and production in Saudi Arabia spans 700 million years, and can be simplified into a framework of seven major events based on regional seismic mapping, potential field data, field studies, and well results:

(1) Late Proterozoic amalgamation of basement terranes occurred along predominantly N-S oriented sutures in east-central Saudi Arabia. Reactivation of these basement sutures throughout the Phanerozoic played a key role in hydrocarbon trap formation.

(2) Neoproterozoic extension along pre-existing basement sutures in east-central Arabia opened major N-trending grabens that now underlie the Phanerozoic basins of the west and east Rub' Al-Khali.

(3) Regional compression during the Early to Mid Carboniferous (the 'Hercynian' event) ended a lengthy period of early Paleozoic passive subsidence. Erosion of uplifted fault blocks, followed by plate-wide deposition of Permian-Carboniferous terrigenous clastics and then shallow-water carbonates, formed combination structural / stratigraphical traps that are primary exploration targets for non-associated gas.

(4) Accelerated differential subsidence due to regional extension occurred through the Late Permian and Triassic, driven by the opening of Neo-Tethys along the eastern Arabian Plate margin.

(5) Rifting in northwestern Saudi Arabia commenced in the Early Cretaceous, opening the NW-trending Al Jawf graben and creating numerous tilted footwall blocks in this area that are potential traps.

(6) SW-vergent regional compression in the Late Cretaceous (initial closure of Neo-Tethys) reactivated N-S basement sutures and formed broad, fault-tip folds across east-central Arabia. Most of Saudi Arabia's oil reserves are trapped in the hanging-wall anticlines of these structures.

(7) Red Sea rifting through the Oligocene and Miocene created traps in tilted fault blocks and their overlying drape anticlines. This event uplifted and eroded the now exposed Arabian-Nubian Shield and, together with the Zagros collision and foredeep development (final closure of Neo-Tethys), tilted the Arabian Plate northeastward.

New tectonic interpretations from this integrated regional study will be highlighted.

(#126-O) Spectral attribute analysis of wireline log data applied to synrift sequences of the Gulf of Suez rift, Egypt

Djin S. Nio, **Enres International**;
Mohamed D.M. Salem and Nazih Tewfik,
Earth Resources Exploration

Spectral attribute analysis is a new approach that uses facies-sensitive wireline log data in near-synchronous detailed stratigraphic well correlation. The basic concept is the presence of climate-forced cycles in the sedimentary successions that can be detected by facies-sensitive wireline log measurements. Spectral analyses of these log data result in several unique functions that include spectral images and attributes. The down-hole presence of cyclic depositional patterns in the rock record is displayed as cyclic repetition of the log curves modeled in the spectral analysis. The spectral images show the downhole hierarchical pattern of cycles, changes of wavelengths, and the presence of vertical cycle discontinuities. Spectral change analysis detects cycle discontinuities, and the spectral trend analysis evaluates the trends of long- and short-term cycles.

The spectral trend analysis of wells from the Gulf of Suez shows a time-related development of the rift, synrift depositional patterns, and the spatial distribution of potential reservoirs. Cyclostratigraphic correlation between wells from the Gulf and outcrops

along the Sinai margin, shows that the opening of the Gulf of Suez occurred mainly by a northerly drifting of Sinai and the staged fragmentation of the African margin. The Southern Province of the Gulf reached its present shape first, followed by the Central and Northern Provinces. The Central Province has a higher degree of fragmentation, which was probably caused by the absence of near-surface basement due to thick pre-rift sediments and pre-existing structures. Oil fields are developed in relationship with the continuous shifting of depositional centers during the stage-wise opening of the Gulf. Ten tectono-stratigraphic events are recognized as lateral correlation markers concomitant with the evolution of the successive rift stages.

(#286-O) Challenges and solutions in reservoir characterization and 3-D geological modeling: part II

Tawfic A. Obeida and Yousuf S. Al-Mehairi, **ADCO**

The 3-D geological modeling of the Lower Cretaceous (early Aptian) carbonate buildup in one of ADCO's giant oil fields is very complex. It consists of 31 million cells that account for the detailed heterogeneity of the reservoir's 17 Reservoir Rock Types (RRT). This makes the upscaling of the resulting geological model into only 1.4 million cells prior to dynamic modeling very challenging. Various realizations of simulation grids were built to preserve most of the geological heterogeneity and petrophysical properties. The upscaled grid was oriented at N35°E parallel to the original depositional trend of the reservoir units, particularly in the northern part of the field. This was found to preserve the petrophysical properties, especially permeability, better than the non-oriented grid.

Capillary pressure data based on RRTs were used to generate saturation functions for the dynamic model initialization. The results of the dynamic model initialization indicated good agreement between the dynamic and geological model initial water-saturation results.

(#60-P) The Eastern Mediterranean: natural oil seeps and spec seismic help identify exciting new lead areas

David G. Peace, **Infoterra**;
Mike P. Johnson, **Spectrum EIT**

The offshore Eastern Mediterranean region from Egypt to southern Turkey is emerging as an exciting new exploration province. Recent large gas discoveries in Egypt, the Levant, and Gaza, together with some condensate and modest oil discoveries, have sparked a new interest in the area.

To help evaluate the Eastern Mediterranean region, Infoterra and Spectrum have for the last two years carried out a combined natural oil-seep study and spec seismic program that correlates the natural seep data with structural information from seismic. This program has proved the occurrence of significant seepage in the region and has helped identify an interesting range of new seismic leads ready for new exploration programs.

This presentation will give details of the study and will highlight some of the new lead areas that have seismic and natural seep data.

(#75-O) An improved palynostratigraphic zonation for the glacigenic Al-Khlata Formation: refinements and applications

Randall R.A. Penney, **Reservoir Laboratories**;
Peter L. Osterloff, **PDO**

A significant proportion of South Oman's heavy (about 18°–28° API) oil production comes from the Carboniferous-Permian glacigenic Al-Khlata Formation reservoirs. Their constituent palynofloral assemblages have enabled stratigraphic subdivision of these complex sediments. Recent studies have provided a refinement from the existing 4-fold scheme to a higher resolution 10-fold zonation. These improvements are based primarily upon quantitative counts of the major taxonomic groupings. The stratigraphical variation in the proportion of these components is a reflection of the changing paleoenvironmental conditions through time, induced both by the changing latitudinal position of Oman and the overall warming trend as the Carboniferous-Permian glaciation came to an end. The greater refinement of the palynostratigraphy has improved the correlation with other Gondwanan sections, enabling better chronostratigraphic calibration of this interval.

On the exploration scale, this has been particularly useful in inferring the lower age limit of the Al-Khlata Formation, and in distinguishing it from older sequences such as the Devonian Misfar Formation and its variants. At its upper stratigraphic limits, the improved zonation has helped recognition of reservoir architecture through paleoenvironmental inferences that resulted from the final phases of Carboniferous-Permian Gondwanan glaciation and the relationship with the overlying Permian marginal-marine Gharif Formation.

On the reservoir scale, this improved palyno-stratigraphic scheme has successfully constrained wireline log-based correlations within the productive Al-Khlata fields. Further to this, the establishment of a more detailed sidewall and core-sample based palynostratigraphic framework has facilitated the application of palynological dating to horizontal well sections, even where palynomorph recovery has been extremely limited. Examples of its application will be drawn from case studies in the Marmul, Nimr, and Rima fields, with commercial implications consequent on our increased understanding of their reservoir architecture.

(#113-O) A new approach for velocity estimation and depth imaging of converted waves

Long D. Pham, Weizhong Wang,
Yaohui Zhang and Sheng Lee, **PGS**

We present a new approach for the velocity estimation and depth imaging of converted-waves (C-waves). Though prestack depth migration is the most advanced method for C-wave imaging, it requires an accurate initial velocity model. Without such a model, depth migration can produce inferior results compared to time migration. We designed an approach that provides a more accurate initial estimate of the velocity than do conventional approaches and at the same time simplifies the processing flow. This approach consisted of prestack time imaging and a poststack joint P-P and P-S velocity inversion.

Converted-wave processing is more difficult than pure-mode processing. A simple common conversion point stack requires an input trace to be grouped to different conversion-point locations that vary laterally with increasing time. To compute these conversion points, we need the Vp / Vs ratio. In practice, we often assume that the velocity of the P-wave is known in order to estimate the S-wave velocity. This requirement makes the processing of C-wave data cumbersome. Pseudo-offset migration overcomes this limitation by enabling P-wave and C-wave data to be processed in parallel. As a consequence, we performed time-focusing for both P-waves and C-waves, independently. The strength of this technique is that prestack time migration is less sensitive to velocity errors than prestack depth migration. This is particularly important in areas where the P-wave velocity is difficult to estimate, for example, gas clouds. We could then correlate the time-migrated images (where signal-to-noise has been improved, diffractions collapsed, and dips partially corrected for) and invert for P-wave and S-wave interval velocities by constraining the mapped depths to be the same. The combination of the prestack imaging technology with a joint P and S wave field inversion has produced a robust estimation of the velocity-depth macro model that will also assist in the structural and stratigraphic interpretation of the Arabian Gulf reservoirs.

(#255-O) The use of volume-based visualization and interpretation to identify, define, and rank prospects in a frontier exploration play: deepwater, western Nile Delta

David W. Phelps and John Bedingfield, **Apache**;
Robert M. Bond, **Paradigm**

Over the past 35 years, approximately 3.8 billion barrels of oil equivalent has been discovered in the Nile Delta, primarily as gas and condensate. With the discovery of multi-trillion cubic feet of gas in the western Nile Delta and an industry success rate exceeding 80 percent, interest in the deepwater Pliocene play has increased significantly in recent years. A 1,500 sq km 3-D seismic survey was acquired in 2000 in the deepwater-part of Apache's West Mediterranean Concession in the western Nile Delta. Volume-based interpretation and visualization is being used to reveal the stratigraphic and structural architecture of this lightly explored lobe of the delta system.

Direct hydrocarbon indicators are common within the Concession. Gas chimneys have pronounced sea-floor expressions and hydrocarbons are also inferred from seismic characteristics that include flat spots, phase changes, Class II and III amplitude-versus-offset responses, and structurally conformable amplitude anomalies. As is common in deltaic environments, many channel deposits show up as bright seismic anomalies. The evolution and organization of the channel systems can be traced through time, regionally and locally. Similar features in nearby concessions are associated with commercial gas and are primary exploration targets.

Stratigraphic visualization coupled with structural and seismic-attribute analysis was used to locate several possible exploration targets within the concession. This presentation will discuss the interpretation techniques used to better delineate, quantify, and risk these leads and prospects. They include opacity stacking to better image the individual channel architectures; horizon flattening to determine the relative ages of the various anastomosing channel sets

and faults; and anomaly extraction to isolate and rank the prospects generated. Examples of channel systems showing gradual changes in sinuosity through time and abrupt avulsions resulting in abandonment will be shown. The presentation will be illustrated by animated, three-dimensional displays.

(#361-O) Structural controls for preferential deposition and preservation of source intervals and synrift reservoirs for the northeastern Red Sea and Gulf of Suez

Stephen R. Polis, Michael T. Angelich, Charles R. Beeman, Will B. Maze, David J. Reynolds, D. Mark Steinhauff, Mark V. Wood and Andrei Tudoran, **ExxonMobil**

An integrated GIS-based play evaluation that incorporates restorations of the northeastern Red Sea and Gulf of Suez has helped to identify potential prospective areas associated with thick, high net-gross, syn-rift reservoirs juxtaposed to extensive source-kitchens. The two largest synrift Gulf of Suez fields are Morgan and Belayim-Marine (>1,800 and >1,700 million barrels oil equivalent originally-in-place, respectively). They are recognized as being located along major fault transfer zones that have optimized the conditions for the deposition and preservation of thick high net-to-gross sands. These fields are also ideally positioned up dip of large migration areas. Restorations indicate that the northeastern Red Sea should have had comparable reservoir facies deposited in similar structural positions with preservation being the significant risk due to additional crustal extension. Although crestal block erosion remains a great concern, initial seismic mapping indicates that block sizes along the coastal region and inboard areas are similar to the Gulf of Suez. This suggests that most of the strain was accommodated along the warmer axial portion of the rift where weaker crustal rheology exists.

Reconnaissance mapping of the northeastern Red Sea border fault system has identified a high degree of variability in structural styles that highlights certain regions for further evaluation. The southern Yanbu-Jiddah and Umluj-Al Wajh subbasins are bounded by curvilinear, down to the west-southwest border faults separated by suture-controlled accommodation zones. To the north, the Midyan-Ifal sub-basin is located along the flexural margin bounded by NNW-trending Najd planar faults overprinted by a strong northeasterly (Aqaba) trend such that transpressional and transtensional features exist. Of these areas, the northern flexural margin, offshore of Wadi Azlam, has been identified to have the potential for localized, thick second-generation, synrift sediments similar to that of Gulf of Suez.

(#347-P) Imaging of Permian fault systems: a 3-D seismic case study in onshore Bahrain

Naji Ahmed Qassim and C. Bapu Reddy, **Bapco**

The presentation is based on the interactive data interpretation of a recently acquired 3-D seismic survey of a Bahrain onshore area. The work focused on the effectiveness of 3-D seismic data for imaging faults in a Permian sequence. The interpretation used standard horizon- and fault-correlation tools on vertical displays, and the generation and interpretation of time slices and horizon seismic attributes such as dip and azimuth displays. It afforded a quick and conclusive alignment of the lineaments. The study reaffirmed the undisputed imaging capabilities of 3-D techniques.

The 3-D interpretation imaged a detailed fault pattern. Though the observed faults were predominantly oriented N-S in agreement with previous work, the 3-D data demonstrated that this complex fault zone actually consists of numerous fault blocks. In addition, a NW-trending younger fault system that offsets the N-S fault system was identified, mainly by the capabilities of horizon attribute analysis. This younger fault system had not been observed in earlier studies. Such enhanced fault-pattern imaging has helped in appreciating the regional and local stress-field orientations and supplemented the previous understanding of fault tectonics at the field scale. It will also be useful in planning the development of the Permian gas reservoirs in the Khuff and pre-Khuff formations.

(#220-O) Permian basal-Khuff clastic channels in central Saudi Arabia

Martin J. Rademakers, Patric M. Rutty and Gregory S. Douglas, **Saudi Aramco**

Seismic attributes from nine 3-D seismic surveys in central Saudi Arabia covering approximately 3,800 sq km, were used to map the areal distribution of channels within the Upper Permian basal-Khuff clastic section. The Khuff Formation overlies the Permian Unayzah Formation and has a major transgressive marine clastic sequence at its base. Numerous meander belts and incised channels characterize this basal Khuff clastic sequence and are clearly identified in 3-D seismic

detect coherency volumes. This presentation documents a study of the spatial distribution, frequency, and flow direction of the channel systems.

The study found two types of channel systems: type-1 one had excellent reservoir potential, and type-2 was non-prospective. Each channel type has distinctive geologic and seismic characteristics. Type-1 channels are found in meander belts and are sand-filled, hard to distinguish seismically, and typically highly productive when found under closure. Type-2 channels are shale-filled incised valleys—easily mapped seismically—but, unfortunately, they are non-productive.

(#38-O) High-resolution sequence stratigraphy of the Devonian Jauf gas reservoir: a shoreface and estuarine embayment succession, greater Ghawar area, eastern Saudi Arabia

Riyadh A. Rahmani, **Saudi Aramco**;
Ronald J. Steel, **U. of Wyoming**;
Abdulaziz A. Al-Duaiji, **Saudi Aramco**

The informally redefined Devonian (Praghian to Frasnian) Jauf Formation in the Ghawar field and adjacent areas of eastern Saudi Arabia thickens from 650 ft in the west to 1,100 ft thick in the east, and comprises a marginal- to shallow-marine siliciclastic succession. It consists of a lower third-order sequence S1, here called the Lower Jauf, which is dominated by a sand-prone progradational Falling Stage Systems Tract that lacks overlying coastal-plain deposits. The upper third-order S2 sequence consists of the informal Middle and Upper Jauf. The Middle Jauf is a mud-prone, estuarine Transgressive Systems Tract (TST) that forms the Jauf Embayment; the Upper Jauf is a Highstand Systems Tract (HST) composed of progradational shoreface and overlying coastal-plain deposits. The D3B biozone is an extensive stratigraphic marker of mainly dark-colored shale at the top of the TST in S2 that marks its Maximum Flooding Surface. A key aspect of the succession, and a critical point in making a predictive regional model, is that the third-order sequences can be subdivided into a series of fourth-order depositional transgressive-to-regressive sequences. Sequence S1 consists of 16 fourth-order sequences and S2 contains 15; three types of fourth-order sequences with different systems tract architecture have been recognized.

The detailed stacking patterns of the high-frequency (fourth-order) sequences and an understanding of their well-to-well architecture will provide a powerful tool for the prediction of sand- and shale-dominated areas away from the data set. A notable feature of the fourth-order sequences seen in the sequence array is that the TST tends to thicken significantly landward whereas the HST thickens basinward. This trend is important in extending prediction into unknown areas.

The exploration implication of the model is that in the S1 and S2 sequences, the high reservoir-potential third-order Lowstand Systems Tract (not present in the study area), may occur further east—possibly in the eastern Arabian Gulf or thrust into Iran.

(#258-O) Silurian shelf-margin to slope deposition: a predictive model for the exploration of Mid-Qusaiba Sand reservoirs, east-central Saudi Arabia

Riyadh A. Rahmani
and Muhittin Senalp, **Saudi Aramco**

In central and eastern Saudi Arabia, the Qusaiba Member is the lowest unit of the Silurian Qalibah Formation. Sedimentological evidence and depositional styles suggest that deposition in the Qusaiba Member was dominated by slope mudstones and episodes characterized by introduction of slope and basin-toe / floor sandy turbidites (the Mid-Qusaiba Sand reservoir) during and following episodes of sea-level lowstands. These slope clinoforms prograded by downlapping onto the Qusaiba Hot Shale, a rich hydrocarbon source rock representing single to stacked maximum flooding surfaces. The overlying shallower water parasequences of the Sharawra Member were deposited on a low-lying coastal plain and the adjacent gently sloping marine shelf. It is probable that during lowstands, the Sharawra shoreface reached the shelf edge in the form of shelf-edge deltas. As a result, sediments spilled over the shelf break as gravity flows to deposit the Mid-Qusaiba Sand amongst Qusaiba mudstones on the shelf slope. In northern and northwestern Saudi Arabia, the Mid-Qusaiba Sand has not been reported in the Qusaiba Member, therefore suggesting the absence of a shelf-slope break in these areas. However, a significant conglomerate-marked disconformity was recently recognized in north-central Saudi Arabia, about 100 to 120 ft above base Qusaiba and was interpreted to have been caused by the same relative drop in sea level that caused the progradation of Sharawra deltas to the shelf margin. It is probably, therefore, that basins with shelf-slope breaks formed locally in areas that underwent faster subsidence. This was most likely in areas that were bounded by major fault lineaments and periodically activated to influence regional sedimentation.

This shelf-to-basin-slope relationship is an important tool in predicting potential reservoirs of Mid-Qusaiba Sand accumulations in unknown areas. It implies that locating thick Sharawra deltaic lobes that had been deposited during sea-level lowstands could lead to the discovery of Mid-Qusaiba Sand turbidites in deeper offshore locations.

(#379-O) Bringing together fracture characterization, seismic and sequence stratigraphy into a fully integrated reservoir model of the Fahud field, Oman

Keith D. Rawnsley, Elena Morettini, Anthony R. Thompson, Peter Christman, Jan-Henk van Konijnenburg, Wenche H. Asyee and Tony Cortis, **Shell**; Gregor P. Eborli, **U. of Miami**; Victor H. Hitchings and Karen Foster, **Shell**; Wilhelm H. Kolkman, **PDO**

Fahud is the largest oil field in Oman. This presentation describes work carried out on the thick Natih-E layer, on which a waterflood development is being implemented. The waterflood aims to improve recovery factors and accelerate recovery when compared to the existing gas-oil-gravity-drainage process. The main objective of our study was to predict unfractured areas, in an otherwise fractured reservoir, that would allow optimal waterflood development. The Fahud data set consisting of core, borehole images, seismic, tracers, and production data was analyzed to determine the main geological elements. A relationship between fracturing and the depositional and diagenetic architecture of the strata was proposed to explain the heterogeneous distribution of well performance. Larger elements of the fracture system, as detected primarily from analysis of production data, corresponded closely to faint attribute lineaments in the seismic data. Lineament trends in neighboring fields and outcrops supported this interpretation. Extensive reservoir simulation modeling was used to tie down the geological components and determine flow properties. The key geological controls determined from the simulation were preferentially fractured fourth-order regressive layers, large-scale NE-trending fracture lineaments, disconnection between the fracture layers, and the fracture lineaments. The combination of these elements in a 3-D, dual porosity, three-phase simulation model provided a best fit to the performance history of the field. The predictive capability of the fracture model was successfully tested against well data from several new wells. The new model has reduced uncertainty in the reserve numbers, and the method used is now being integrated and expanded by Petroleum Development Oman for the reserve bookings of 2001 and 2002.

(#131-O) Geostatistical seismic inversion for reservoir characterization of an undeveloped field, onshore Abu Dhabi

Maria T. Ribeiro, Salem M. Al-Bakr and Patrick Fouchard, **ADCO**; Aline Besson-Hurlimann, **Jason Geosystems**

The use of 3-D geostatistical algorithms coupled with 3-D seismic inversion data has proved to be a useful approach in the characterization of carbonate reservoirs by constraining the modeling of reservoir properties. Because of the very limited well data available during the delineation of undeveloped fields, assessing uncertainties is an important issue that has a strong impact on volumetrics and field development options. This presentation describes an integrated project where the constraints of 3-D geological modeling by geostatistical seismic inversion considerably increased the understanding of a reservoir in an undeveloped field.

The method that was used honors seismic, petrophysical and geological data. The generation of multiple equiprobable models allows uncertainties to be addressed. Although Deterministic Acoustic Impedance inversion honors seismic and well data, the result consists of a single volume at seismic resolution that cannot resolve very thin reservoir units. A geostatistical inversion pilot covering a small area of the field was launched in late 2000 and the encouraging results allowed the extension to the whole field. Emphasis was placed on performing the geostatistical seismic inversion within the same framework as that used in the geological model so as to preserve the reliability of the spatial correlation.

A 3-D geological model derived without the seismic constraints was compared with those that integrated either deterministic or stochastic inversion. The results highlighted the improvement and showed that the new geostatistical technique of acoustic impedance inversion clearly improved the vertical and lateral resolution of rock-property distribution. It therefore provided a better way of quantifying uncertainties and produced a more reliable geological model. The high-quality deliverables were the result of an integrated team effort by petrophysical, geological, geophysical, and reservoir-engineering specialists to provide input data, follow up the process, and assess the results.

(#204-O) Rejuvenating a mature reservoir with 3-D, modeling, and horizontal drilling: the Fateh SW, Mishrif case study, Dubai

Philip J. Rorison, **DPC**; John Bruner, **Conoco**;
Xavier Faugeras, Slamet P. Hartono
and Jeffrey W. Yeaton, **DPC**

The Fateh SW field in the Arabian Gulf, offshore Dubai, is located on a salt-induced dome. Production is from three different carbonate reservoirs. This presentation is a case history showing how a changing multidisciplinary team created a step change in the asset's production profile.

The Mishrif reservoir produced under natural depletion from 1972 until 1975 and since then has been under full water injection. Logged contrasts in rock characteristics showed that the water sweep was effective in the better-quality Upper Mishrif reservoir. Logs also indicated that the parts of the Lower Mishrif reservoir were unswept and overlain by water; they were 'override' areas. A series of horizontal wells drilled since 1996 in 'override' areas has made a major contribution to the actual production profile and the expected final recovery. The positioning of the horizontal wells was based on the integration of 3-D seismic, geological model, dynamic reservoir modeling, and a static reservoir model.

The presentation describes successes and surprises from the horizontal drilling program and the technology used by the team to manage the reservoir. The current challenge is to re-evaluate all static and dynamic reservoir data in order to predict remaining areas of unswept oil. This is not a trivial task after 30 years of production and water-injection by more than 120 wells.

(#371-O) Thermal and maturity reconstructions in northern Fars and the Zagros mountain belt, southwestern Iran

Jean-Luc Rudkiewicz, **IFP**; Shahran Sherkati, **NIOC**;
Jean Letouzey and Jean-Marie Mengus, **IFP**;
Abdolhossein Ahmadnia
and Mohamad Ali Ashkan, **NIOC**

The history of temperature variations and of hydrocarbon generation and expulsion in the Zagros mountain belt and its foreland has been modeled through geological time. At the same time, the history of folding and thrusting allows us to investigate which structures existed at the time of peak expulsion. Based on a regional 300-km-long balanced cross-section, coupled structural and geochemical computations were performed using the Thrustpack software. The transect began in the least-deformed part of the foreland near the Gulf and crossed the fold belt perpendicular to the main structural trend as far as the ophiolites of the imbricate zone.

Silurian and / or hypothetical Ordovician source rocks generated and expelled liquid hydrocarbons during the Late Cretaceous and early Cenozoic, that is, before the start of the Zagros folding. At present, only gas from the Paleozoic charge structures formed during the Zagros orogeny.

The Mesozoic source rocks have contrasting behaviors depending on their burial and thermal history. When present, Jurassic source rocks might have been in the peak oil window in the deepest synclines before the Zagros folding but only in the condensate or wet gas zone after the development of Zagros structures. They are dependent on the stratigraphic position of the source rocks and the depth of the kitchen. The Cretaceous Kazhdumi source rock was not present everywhere along the transect. However, when present it was in the peak oil-expulsion phase in the deepest synclines during the peak time of folding, whereas it was not mature or only early mature in the shallowest anticlines. It contributed to the major oil charge of Tertiary reservoirs. The Tertiary Pabdeh is a potential source rock only in the northern part of the transect; it is immature in anticlines and early mature in the deepest synclines.

Key factors in the efficient exploration of an area are the interpretation and prediction of source rocks in the sedimentary sequence. Coupled structural, thermal, and expulsion modeling then highlight the major factors that influenced the charge history of the reservoirs.

(#130-P) Delineation of an Upper Cretaceous prospect in Kuwait using seismic attributes

David J. Russell and Saifullah K. Tanoli, **KOC**

The Maastrichtian Tayarat Formation in Kuwait is a 900- to 1,300-ft-thick carbonate unit consisting of limestone, dolomitic limestone, and dolomite deposited in shallow-marine environments. The Formation holds large reserves of relatively heavy oil. Trapping mechanisms for the reservoirs have been difficult to establish. Various combinations of stratigraphy, structure, and a hydrodynamic gradient tended to control the oil accumulations in the southern part of Kuwait, including the greater Burgan field. This complexity makes it difficult to predict present-day variable oil-water contacts.

In the sparsely drilled West Kuwait area, it was recognized from log evaluation that the Tayarat Formation contains oil in some wells while adjacent, structurally similar, wells are water bearing. This presentation will show that the porosity within the Upper Tayarat zone can be related to the seismic reflection amplitude. Another more or less independent approach is to relate the frequency content of the seismic data (in the reservoir zone) to the porosity as determined from log analysis. This frequency correlation, although somewhat vague, was found to indicate a similar reservoir outline as that outlined by the seismic reflection amplitude. Although the prospect is delineated by a relatively high 12 percent porosity cutoff, it was assumed that this porosity was impermeable to the relatively heavy oils trapped in the Tayarat, yet allows formation water to migrate into these areas. The Tayarat Formation is immature, and it is postulated that the trapped oil has migrated upward along minor fault planes that extend into the deeper Cretaceous source rocks.

(#78-P) Saudi Arabian Silurian and Devonian sequence stratigraphy, paleogeography and play concepts

Patrick M. Rutty, Riyadh A. Rahmani, Ronald J. Steel, Michael Hulver, Robert S. Johnson and Randall G. Demaree, **Saudi Aramco**

A third-order sequence stratigraphic model of the Silurian and Devonian systems in Saudi Arabia has been constructed, using detailed sedimentologic, lithostratigraphic and biostratigraphic data from 50 wells and approximately 10,000 feet of core from Paleozoic basins. Eight third-order sequences were identified and correlated from the base of the Silurian Qusaiba Member to the Devonian Jubah Formation. The following six depositional systems tracts were recognized in the section: (1) offshore marine highstand; (2) offshore marine lowstand; (3) offshore marine transgressive; (4) tide-dominated transgressive; (5) fluvial-deltaic forced regressive; and (6) wave-dominated forced regressive.

Mapping of the systems tracts highlighted the following five key features: (1) the ongoing influence of Infracambrian basins on Silurian and Devonian paleogeography; (2) a clear second-order basinward progradation of the shoreline during the Devonian; (3) a persistent clastic depocenter on the eastern side of Ghawar; (4) development in the northwest of a broad shelf with local carbonate sedimentation; and (5) periodic Devonian exposure of the Qatar Arch. The exposed arch, together with the stable eastern edge of Ghawar and the Niban arch to the south, formed a recurrent embayment in which were deposited restricted marine facies, including the reservoir units of the Jauf Formation.

As a result of this new sequence stratigraphic interpretation, an analysis of trap elements has enabled better risk assessment of various existing play types, and has helped identify new play concepts.

(#146-O) Integrated characterization of fractures and faults of the Shu'aiba reservoir, Shaybah field, southeastern Saudi Arabia

R. Kumbe Sadler, **Saudi Aramco**

Microresistivity image logs, 3-D seismic, and dynamic data from the Shaybah field of southeastern Saudi Arabia provided an unusual opportunity to define the parameters of the fracture and fault network of the Aptian Shu'aiba reservoir. Fractures picked at the millimeter resolution of the image log were correlated to faults and tectonized zones picked from 3-D seismic, and the link was validated by dynamic data.

The Shaybah field is a doubly plunging anticline slightly asymmetric to the west, oriented N30°E. Saudi Aramco has drilled 25 vertical wells and 149 horizontal wells since 1996 and logged Schlumberger's FMI(TM) and UBI(TM) tools in 19 of the vertical wells and 63 of the horizontal for a total of 238,000 ft of image data. Image analysis showed the Shu'aiba reservoir to be fractured and faulted into four well-defined vertical sets. They are organized into clusters 15 to 25 m wide and swarms 150 to 200 m wide, with the latter spaced 300 to 400 m apart. Seismic lineations from 300 to 5,000 m long as defined from curvature analysis of the Biyadh reflector at the base of the reservoir, corroborated the orientation and distribution of image-defined fault / fracture sets.

Dynamic data tied the fractures visible at image scale to those picked at seismic and reservoir scales. Zones having total lost circulation in horizontal wells or production surges incident to flow-meter logs could be tied directly to fractured zones picked from the images. Simultaneous posting of dynamic data and image-derived fracture data onto a map of seismic lineations validated the close tie between these features picked at various scales and from different and independent sources. Seismic lineations on a reflector at the base of the reservoir and tied to fracture clusters and swarms found in horizontal wells drilled close to its top, confirmed that the faults and tectonized zones were potentially deep rooted and cut the entire reservoir.

This method of integrating image logs with seismic and dynamic data yielded a consistent and confident characterization of stress-induced fracturing and the

interpretation of their affects on reservoir behavior. It therefore has implications on reservoir management decisions.

(#15-P) Chronostratigraphic evolution of the Cretaceous basin-margin rudist buildups in the Arabian basin

Fadhil N. Sadooni
and Abdulrahman S. Alsharhan, **UAE U.**

Rudist buildups characterized the tropical-subtropical belt of the Tethys Ocean from the present-day Gulf of Mexico to Japan. They form many major oil reservoirs. In the south of the Arabian Platform, rudist-bearing carbonates occur within the Early Cretaceous Thamama Group. The most prominent buildups are in the Aptian Shu'aiba Formation of the major oil fields of the Arabian Gulf, such as Bu Hasa, Idd El Shargi, Al Huwaisah and Shaybah. However, the Shu'aiba in Iraq contains no significant rudist material. The Albian-Cenomanian Mishrif Formation also contains rudist reefs in the southern Arabian Gulf (Fateh, Umm Ad Dalkh, Fahud) and southern Iraq (Majnoon) but none in central Iraq (e.g. East Baghdad) or in its equivalent, the Gir Bir Formation in northern Iraq.

Rudists, however, became important rock-forming organisms during the Campanian-Maastrichtian (Late Cretaceous) in the northern parts of the Arabian Platform. Their development was associated with the decline of corals as reef builders. Rudist buildups are described from the Aqra and Bekhme formations (Upper Senonian) in northern Iraq, the Hartha Formation (Campanian-Maastrichtian) in central and western Iraq and from Wadi Sir Formation (Turonian) in eastern Jordan. Rudists also continued to be important within the Maastrichtian Simsima Formation in the southern parts of the basin (Shah field).

Published data on oxygen isotopes of belemnites and other fossils from Europe, and extrapolated to include northern Iraq, indicated that the Early Cretaceous started with a cool period, particularly during the Hauterivian to Aptian. The climate warmed during the later Albian and the Turonian-Campanian. Hence, the northward migration of rudists may have been associated with specific climatic conditions in southern Arabia during the Early Cretaceous and these conditions may have changed during the Late Cretaceous to include present-day northern Iraq and eastern Jordan. It is therefore probable that the development of rudists was related to a relatively warm climate. As a result, it may be possible to use rudist buildups to trace gradual paleoclimatic changes during the Cretaceous across the Arabian Platform.

(#34-O) A fuzzy-logic approach to the estimation of facies from wireline logs

Muhammad M. Saggaf
and Ed L. Nebrija, **Saudi Aramco**

We propose a method based on fuzzy logic inference to identify lithological and depositional facies from wireline logs. Fuzzy logic is inherently well suited for characterizing vague and imperfectly defined knowledge, a situation encountered in most geological data. Thus, it can yield models that are simpler and more robust than those based on crisp logic.

Moreover, quantitative confidence measures are ascribed to the results of the analysis that describe how well the procedure can identify the facies, given uncertainties in the data. These measures represent an integral part of the solution, as they convey vital information about range of applicability of the solution. Also, the method is enhanced by incorporating human experience and geologic principles into the inference process in the form of formulated static and dynamic constraints that guide that inference process. Therefore, prior knowledge and existing geological models can be easily utilized and incorporated into the analysis.

We tested the method by applying it to a prediction of the depositional facies of a cored well in a marine carbonate environment in southeast Saudi Arabia, and compared the output with the facies derived from core analysis. The two showed considerable agreement, and indicated that the method can be an effective means of predicting the facies of uncored wells from their logs. We contrasted our method with other techniques that relied on multivariate statistics and neural networks. Compared to those techniques, our method is simpler, easier to retrain, more reproducible, non-iterative, and more computer efficient.

(#318-O) Enhanced imaging using well-log data and seafloor multicomponent seismic technology: an offshore UAE case study

Surinder K. Sahai, **Conoco**; Santi C. Randazzo,
Joe I. Sanders and Eric A. Madtson, **PGS**

Several tests of an evolutionary multicomponent (4-C) marine-seismic cable survey were conducted by PGS in offshore UAE during June and July 1998. This presentation is a case study of one of the test lines over a large carbonate dome structure. The acquisition, processing, interpretation, and reconciliation with borehole data will be discussed.

The objectives of the 4-C survey were enhanced structural interpretation, lithological characterization, and fracture analysis. The major impediments to structural and lithological interpretation from seismic data in the study area have been surface and interbed multiples. Whereas dual-sensor technology has aided in attenuating surface multiples, it does little for interbed multiples generated by the lower Fars Formation that is present in the area. However, the converted wave data seem to be less affected by interbed multiples. Another use of multicomponent data has been in fracture analysis, and in this presentation we will expand on preliminary work that has been done in the study area.

In order to understand the converted wave data better, synthetic models for both P-P and P-S waves were generated from available well data. The models were generated using Zoeppritz's equations and a finite-difference modeling scheme. The modeling confirmed that the converted wave data were not affected by interbed multiples to the same extent as the P-P data, and tied in quite well with the synthetic data. Ultimately, this type of modeling may be useful in selecting processing parameters that will attenuate interbed multiples in the P-P data.

(#355-O) The quantitative interpretation method from feasibility to reservoir model: the Ramlat Rawl Gharif reservoir

Dhiya Said, **PDO**;
Montri Rawanchaikul, **Jason Geosystems**

Quantitative interpretation (QI) plays a considerable role in Petroleum Development Oman's Exploration and Field Development planning activities. The reservoir characterization team uses leading industry software in addition to Shell's proprietary applications. Services and solutions are offered that are appropriate to the business needs of clients. As a result, various workflows have been developed to tackle particular tasks. The workflow described here is illustrated by a case study of a fluvial sand / shale reservoir sequence.

For the Ramlat Rawl field, the three main seismic volumes are Poststack Migrated, Prestack Depth Migration, and Prestack Inversion (PSI) volumes. A combination of factors, including wavelet stability, seismic attributes, and well-tie quality identified the PSI volume as being most suitable for QI study. Examining the quality of deterministic sparse-spike inversion of the three volumes supported this conclusion. However, the inversion highlighted two problems with the current PSI dataset. Low frequencies up to 17 Hz were absent from the seismic data, and the match of the inverted traces at the well locations was severely limited by the cyclic nature of geology.

A notable feature of the well data from the reservoir was the separation of acoustic impedance values according to lithology. Hence, geostatistical modeling of the data was carried out using the Jason Geoscience Workbench. Modeling at a sample interval of 1 msec captured the cyclic nature of the reservoir. Ten acoustic impedance realizations were produced that honored the seismic data; each of which matched the well-impedance traces. From these realizations, thirty porosity models were co-simulated, ranked, and the P15, P50, and P85 models identified. These were output to a reservoir-modeling package, together with their associated lithology and acoustic impedance models, to be used by production geologists in building a static reservoir model. In the field-development context, they can be used to optimally locate development wells. Stacking the lithology models provided a probability of sand occurrence volume that captured the variations in the models.

(#341-P) Pore geometry and its impact on waterflooding performance: Sidri Member, Belayim Land field, Gulf of Suez

Ahmed Salah, Raafat Rizk
and Saad Hassan, **Petrobel**

The Sidri Member is one of the major producing oil zones in the Belayim Land field. A waterflooding project was aimed at supporting the reservoir pressure but the injection rate was found to be very low and was not enough to support the depletion in reservoir pressure.

Core samples from three wells were studied to investigate the problem. The selected samples were subjected to flooding tests with seawater to simulate the field case. Petrographic and Scanning Electron Microscope analyses were evaluated before and after flooding the samples. In addition, mercury injection capillary pressure tests were performed in order to obtain the pore-throat size distribution. The flooding results indicated that water injectivity gradually decreased during the sample flooding. The petrographic analyses showed that dolomite rhomb aggregates in the pore spaces had been moved and had blocked the pore throats that are of smaller diameter than the dolomite aggregates. The pore-throat size distribution was also used to select the optimum filter size to control solids in the injected water.

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The investigation found that the water-injection performance was severely affected by aspects of pore geometry; pore-size distribution, pore-throat distribution and pore interconnectivity, which in turn were affected by depositional and diagenetic processes.

(#42-O) Integrated reservoir characterization and earth modeling: case study of a Cretaceous carbonate reservoir, Kuwait

Ajay Samantray, Salem H. Al-Sabea
and Hamdah Al-Enezi, **KOC**

The 400-ft-thick Lower Cretaceous Minagish Oolite reservoir is productive over the crestal portion of the Burgan structure in Kuwait, and is an important development target below the clastic reservoirs of the Greater Burgan field. A major update of the Minagish Oolite reservoir description and geological model has been made to validate reserves and provide input to simulation and development planning activities.

Recently acquired 3-D seismic shows that the reservoir is more faulted than previously mapped from 2-D data and highlights the need for a thorough understanding of compartmentalization. Reservoir characterization focused on improvements to the stratigraphic framework, new facies groupings, pay definition, and an optimized model-layering scheme. A new method was used to assemble rock types and stratigraphic grids to honor the sequence stratigraphy in a quantitative sense. Flooding surfaces within the progradational carbonate shoal deposits were mapped as distinct single-layer boundaries within the earth model. Porosity-permeability relationships were investigated by facies and layer. A combination of mercury injection capillary pressure and conventional plug analyses helped to characterize the rock types and group related facies with distinct porosity-permeability transforms. The broad rock-type assemblages captured by the main reservoir layers helped guide the selection of an optimal layering scheme for upscaling. Property population was carried out using anisotropic variograms controlled by the interpreted facies trends.

A geostatistical approach was used to capture the perceived reservoir heterogeneity and integrate all characterization elements. The final 6-million-cell GOCAD earth model represented the integration of 3-D seismic data, regional well control, sequence stratigraphy, reprocessed petrophysics, core petrography, and geostatistics.

(#263-P) Assessment of the Silurian Qusaiba Total Petroleum System of the Arabian Peninsula

Christopher J. Schenk, Richard M. Pollastro
and Thomas S. Ahlbrandt, **USGS**

The Qusaiba Member of the Silurian Qalibah Formation was deposited over the northern and eastern part of the Paleozoic passive margin that now forms part of the Arabian Peninsula. The Qusaiba Member is recognized as a significant hydrocarbon source rock from the Wadi Sirhan basin in the north to the Rub' Al-Khali basin in the south. The potential source rock interval in these basins is up to 75 m thick, with total organic carbon values of up to 20 percent (average 4%). Qusaiba source rocks are generally in or beyond the gas-generative window in the central parts of the basins whereas it is commonly in a narrow oil-generative window along their margins. Six assessment units defined within the Silurian Qusaiba Total Petroleum System in the Arabian Peninsula were assessed for undiscovered resources, providing total mean estimates of 808 TCF gas, 37 billion barrels oil, and 51 billion barrels natural gas liquids. Nearly all of the hydrocarbons discovered and produced so far from the Qusaiba Total Petroleum System have been from the Qatar Arch and its extension in Iran. This indicates that significant potential may exist for more Silurian Qusaiba-derived hydrocarbons outside of this area; for example, in the Rub' Al-Khali basin.

(#324-P) Application of an exploration method using biological, isotopical and geochemical parameters from shallow sediments

Manfred W. Schmitt, **Geochemische Analysen**;
Khalid A. Al-Thour, **Sana'a U.**

Many classical oil provinces were discovered by searching for oil and gas seeps. These hydrocarbon outflows are either the result of leakage from subsurface accumulations through fractures and faults, or they occur as subcropping, updip truncations of permeable carrier beds. Exploration for oil and gas today can rely on much more subtle expressions, albeit of the same geological features. The sensitivity and precision of modern analytical equipment and methods, in conjunction with recent scientific advancements and the introduction of information technology allow the detection in shallow sediments of trace amounts of hydrocarbons and of

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microorganisms indicative of oil and gas. These could indicate the presence of microseeps and represent ample evidence for hydrocarbon accumulation and/or migration. The recently developed Biological Isotopic Geochemical (BIG) system is an example of a multidisciplinary detection technique.

BIG determines the growth and activity of hydrocarbon-consuming bacteria, characterizes the genesis of absorbed gases by isotopic analysis, applies molecular analysis of adsorbed gases, and examines sediments by UV-fluorescence for traces of oil. BIG combines at least four different, independent underground signals. The information acquired allows for the assessment of basin prospectivity, determination of the quality, presence and type of source rocks and migration pathways, evaluation of the underground hydrocarbon type and maturity, detection of seal efficiency, and the lateral extent of accumulations. A prospect-ranking order applied before drilling can provide information on where or where not to drill, regardless of structure.

In the last five years, the BIG system has been applied to offshore and onshore surveys in Oman, Yemen, and the North Sea. The results showed that the BIG system is a valuable and effective supplemental tool that should be applied before the application of conventional exploration methods. It will improve the success rate of exploration ventures and distinguish between oil and gas, and is an extremely cost- and time-effective method.

(#264-P) Geographic Information Systems within the petroleum industry: an enterprise-wide integrated approach

Jerald D. Schultz
and Mohammed A. Tayyib, **Saudi Aramco**

The Exploration and Production cycle within the petroleum industry is greatly hampered by the lack of an integrated approach to spatial data. Data are commonly collected by many departments, stored in multiple formats, and seldom shared. Quick access to reliable, accurate spatial data is the weakest link in the most important aspect of Exploration and Production decision-making processes.

Petroleum companies tend to be large with many departments and business lines. These subdivisions have allowed large tasks to be subdivided and responsibilities to be determined and mandated within these subdivisions. This model was adequate in the past, but now hinders solutions to problems that require access to multiple spatial data sets from throughout the enterprise. The lack of an integrated approach is a common and clearly evident serious problem throughout the industry.

Three different approaches to the problem have been taken to date. (1) Keep things as they are, ignore them, and hope that the problem goes away. This is not a solution but is a common practice throughout the industry. (2) By using a command and control approach, a single organization takes control of all spatial data and their applications and dictates how data will be collected, maintained, and disseminated. This can work if the organization is small or is willing to undergo radical surgery with a significant short-term negative impact. It also suffers from significant morale problems within departments as mandates are handed down. (3) The collaborative control approach requires a centralized organization that is empowered to set standards for spatial data throughout the company. It chairs a committee formed from each of the major spatial data providers as well as the major users. This committee is empowered to turn the company away from the multiple island-based model toward a more integrated approach. It's mandate is to set standards for data quality and to develop an overall data model for each data management group

In this presentation, each of these approaches will be discussed in terms of their advantages and disadvantage. It concludes that (1) The highest levels of management can play a key role by being aware of the seriousness of the problem and, most importantly, of the benefits that a solution will bring to the company. (2) The mandate for the integration of spatial data must be implemented using a top-down approach. (3) The solution will be difficult and costly but it will become more costly in the future. Isolated data-capture, data-maintenance, and data-providing without an integrated, quality-controlled spatial data model will fail in the long run. (4) Now is the time to empower users and organizations to use their valuable spatial data assets more effectively by allowing easy access to up-to-date, well-modeled, accurate, and integrated spatial data.

(#52-O) New evidence on the stratigraphy of the Ordovician-Silurian boundary in Saudi Arabia

Muhittin Senalp, Mansour H. Al-Ruwaili
and Merrell A. Miller, **Saudi Aramco**

The Hawban Member was defined near Baq'a in the Ha'il region of northern Saudi Arabia as the upper member of the Sarah Formation of the Late Ordovician glacial/periglacial Zarqa/Sarah formations. In the Baq'a area, the Sarah has extensive grooved and striated pavements that prove its glacial origins. The

Hawban Member underlies the Early Silurian Qalibah Formation. Recently, Late Ordovician (Ashgill) palynomorphs have been found for the first time in Hawban outcrops. The new palynological, stratigraphic, and sedimentological studies of the type area call for a re-evaluation and subdivision of the Member.

The revised Hawban Member in this presentation is restricted to a succession of interstratified olive-green, massive, silty and partly sandy shale, and tillite. The boulders in the tillite are strongly folded, fractured, and sheared and were eroded from the underlying red- to light-brown Sarah sandstone and transported by ice during the Late Ordovician glaciation. The upper 27 m of the original Hawban Member, here named the Baq'a Member, differs strongly from the lower glacigenic section. It is a continuous and complete thickening- and coarsening-upward beach parasequence. Its lower part consists of 8.5 m of gray shale and thin, very fine-grained, wave-rippled sandstone beds representing offshore marine facies. This interval is conformably overlain by 7.5 m of very fine-grained, hummocky cross-stratified, and wave-rippled sandstones of the lower shoreface environment. They gradually grade into 9 m of upper fine-grained, trough cross-bedded (polymodal) sandstones of the upper shoreface. The foreshore facies is represented by 2 m of upper fine-grained, planar-bedded sandstones with abundant tracefossils. The foreshore facies is silica cemented, iron stained, and covers a large area indicating a major flooding surface below the Qalibah Formation. The proposed Baq'a Member is important in understanding Late Ordovician and Silurian climatology and eustacy.

(#84-O) Downthown fault traps in Gharif clastics: new exploration potential

Liping Sha and Safia A.S. Al-Mazrui, **PDO**

Gharif clastics of Permian age have been a prolific play for hydrocarbons since the early days of Oman's petroleum industry in 1957. Exploration has traditionally focused on anticlinal and faulted dip closures, with multiple stacked reservoirs of fluvial to shallow-marine origin having intraformational seals and the tight Khuff limestone as top seal. Charge came from Neoproterozoic and Cambrian Q and Huqf source rocks.

The exploration potential of conventional traps will decline as the play matures. However, traps in downthown fault blocks have not been explored systematically and may provide significant unidentified potential. Merging of 2-D and 3-D seismic data, regional mapping, and volume interpretation as a part of the North Oman Common Earth Model project during 2001, provided evidence for this emerging play and several leads and prospects were identified for further investigation. The sealing mechanism is expected to be clay smear or shale-sand juxtaposition along the fault plane. Only two field analogs occur in north Oman (Mabrouk and Saih Nihayda SE), but they show that hydrocarbon columns of up to 60 m can be found in downthown fault traps.

As the fault-sealing potential is the critical risk, detailed fault analysis and interpretation is being carried out on the key prospects using state-of-art technologies, in addition to conventional tools such as shale-gouge ratio (Quasar). The new technologies include volume interpretation techniques, depth processing (prestack depth migration / prestack imaging) and continuous velocity analysis to improve fault imaging and reduce uncertainties in depth conversion. Fault seal statistics from producing fields were collected systematically to further reduce the risk. Although more risky than the proven upthrown play, it should be noted that downthown fault closures are more visible on 3-D seismic (and hence easier to evaluate, than other unidentified potential) such as stratigraphic traps, in the Gharif Formation. In 2002, it is planned to drill a dedicated exploration 'play-opener' well. If successful, a string of related Gharif prospects will be developed for follow-up drilling.

(#23-O) Geological controls on water movement in a mature reservoir: a case study of better reservoir management in the lower Burgan reservoir, Raudhatain field, North Kuwait

Abdul Azim Shaikh and Tahani A. Al-Saig, **KOC**

The Aptian Lower Burgan clastic reservoir in Raudhatain field in North Kuwait, is one of the giant reservoirs of the world. It has been the main producer in north Kuwait for the past 40 years. Highly complex water encroachment occurs in different parts of the field. Tracking water encroachment and integrating dynamic data with the main structural and depositional events are the key to understand the factors controlling water movement.

The main massive sand unit (LBM) was deposited as a braided river / braid delta complex during a sea-level lowstand and individual channels amalgamated to form the 400-ft-thick reservoir. The upper part of the reservoir consists of interbedded channel sandstone and shale. Water movement in the reservoir is a function of rate of production due to bottom-water

drive. The original oil-water contact has risen by 275 ft during the life of the field. Edge-water encroachment also occurs in the upper part of the reservoir. The overlying shallow-marine sequence acts as a field-wide hydrodynamic barrier.

Estuarine channels (LBL) are the main reservoirs above the shallow-marine sequence. Water movement in this unit is controlled by geological features such as channel orientation, faults acting as lateral barriers or as vertical conduits, and cross-flow through erosional holes. Cross-flow of oil / water from LBM to the overlying LBL is due to differential depletion. It occurs in wells with poor cement behind casing and through opened perforations in shut-in wells with commingled flow.

Identification of geological and well-integrity factors controlling water movement, together with precise mapping of the encroachment with time, has enabled better reservoir management in this mature reservoir. The improvement has been achieved by calibrating dynamic models, and by infill drilling and workover operations. The presentation describes in detail the methods used, the factors controlling water movement, and the use of models

(#170-P) The Kazerun deep-seated fault and its influence on sedimentary/ structural evolution of the Zagros fold and thrust belt, Iran

Shahram Sherkati and Ali Reza Rostami, **NIOC**

Basement faults and their influence on the sedimentary cover is an interesting subject for geologists, especially those engaged in hydrocarbon exploration. Recognition of such faults and the understanding of their geometry are often very difficult due to the changing relationship between cover and basement that have taken place during geological time.

The Kazerun fault is one of the most important deep-seated faults in the Zagros fold and thrust belt. It separates the two major structural-sedimentary basins of Fars and Dezful that are gas and oil provinces, respectively. The fault was deduced from physiographic features, variable depths of formations on either side of the fault, and from seismic data. According to recent work in the Borazjan area, it has a close relationship with the Zagros frontal fault and constitutes its lateral ramp.

Thickness variations in stratigraphic units determined from surface and borehole data and geophysical information imply that the Kazerun fault is located farther east than previously thought. It would appear that the major facies changes in the Albian Kazhdumi Formation coincide with the new location of the Kazerun fault, and that the exposed lateral ramp is the result of deep-seated faults penetrating the sedimentary cover.

(#312-O) The role of biostratigraphy in sequence definition on the Arabian Plate: examples from Permian sediments

Michael D. Simmons, **CASP**; Lucia Angiolini, **U. Milan**; David M. Casey and Roger B. Davies, **Neftex**; Andrew D. Horbury, **Cambridge Carbonates Ltd**; Peter R. Sharland, **Neftex**

Biostratigraphy played a pivotal role in the recently proposed sequence stratigraphic scheme of the Arabian Plate by Sharland et al. (2001)*. Paleontological trends were used in combination with other data to define maximum flooding surfaces at reference localities, and then, in the framework of biostratigraphy, to correlate them across the Plate. However, this task is far from simple, not least for Permian sediments in which a stratigraphic understanding is hindered by several factors. These are as follows: (1) complications from stratigraphic nomenclature; (2) conflicting information between fossil groups; (3) the coarse clastic nature of much of the succession; and (4) a real or apparent (i.e. lack of published data) absence of age-indicative fauna or flora in critical parts of the section.

This presentation describes the ongoing work to update the biostratigraphy of the Permian succession on the Arabian Plate and will demonstrate the procedures employed in the monograph of Sharland et al. (2001). Studies of macrofauna (brachiopods, ammonoids) and microfossils (palynomorphs, conodonts, foraminifera) have yielded new data on the stratigraphy of Permian successions in Oman, Saudi Arabia, and Iran. These will help in the production of the huge non-associated gas reserves in the carbonate succession and exploration for new hydrocarbon resources within the underlying clastic succession.

The Permian sediments of Arabia were deposited during a time of major global change—from the ice-house world of the Asselian glaciation to the hot-house world of Guadalupian-Lopingian carbonate deposition—coupled with the break-up of Gondwana and the birth of the Neo-Tethys ocean. Precise stratigraphic control is required to place depositional events in a global context.

* Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. GeoArabia Special Publication 2. Gulf PetroLink, Bahrain, 371 p.

(#97-O) Unconventional prospect evaluation: an approach for Jurassic source/ fractured carbonate reservoirs in Kuwait

Sunil K. Singh, Salah A. Abdulmalek,
Waleed A. Hameed and Menahi S. Al-Anzi, **KOC**

The Jurassic plays in Kuwait, particularly in the Middle to Upper Jurassic Najmah and Sargelu formations, are unconventional in that they are a very low porosity, fractured carbonate source-cum-reservoir system. A huge potential for hydrocarbons has been established. Although matrix porosity provides the essential storage capacity and the sustainable production, fracture permeability significantly dominates well deliverability. Conventional prospect evaluation processes led to a gross under valuation of the prospects in these reservoirs. The oil produced from such deep overpressured reservoirs is undersaturated, of moderate volatility and is free of water. Moreover, recent well tests support a dual porosity model as well as the replenishment of the fractures by the matrix.

The Kuwait Oil Company has made an innovative approach to the economic evaluation of these unconventional reservoirs in terms of profitability measures and reserve replacement strategy. In view of the absence of a reservoir aquifer, the limits of structural closure to be considered in volumetric evaluation may go beyond four-way closures. This would add to the possibility of off-structure potential but with an additional element of geological risk. The porosity of the entire thickness contributes to the Hydrocarbon Pore Volume (HCPV) but only selective fractured intervals contribute to the flow. This means that the considered net / gross ratio should be good for HCPV calculations but the same cannot be translated into reservoir deliverability as it is mainly controlled by fracture permeability across fractured intervals. The adopted approach has given due consideration to off-structure potential, HCPV, and reservoir deliverability aspects. It has led to a more logical and attractive economic evaluation of prospects of this huge unconventional source-reservoir combination, and has added considerable reserve growth. It has formed the basis for an aggressive exploration strategy including the drilling of high-angle wells.

(#185-P) The Habshan Formation of Jebel Akhdar, Oman: an analog model for the Yamama fields in the Middle East

Henri J. Soudet
and Gérard J. Massonnat, **TotalFinaElf**

Jebel Akhdar in northern Oman is a well-studied area. The excellent exposure has enabled an understanding in three dimensions of the sedimentary paleogeography and facies morphology. An intensive field study of the Hauterivian Habshan Formation in the northern and southern parts of Jebel Akhdar was made in order to develop an analog model for the Yamama fields of the Middle East. About 25 measured sections were described from which more than 1,000 thin sections were analyzed.

The evolution of the Habshan platform was in two main stages. (1) Sedimentary facies evolution showed that the filling of the available space on the platform took place during the deposition of the lower and middle Habshan. In the south, deposition began with mudstones containing benthic foraminifera, and ended with lag facies and grainstones containing proto-oolites. In the north, mudstones were deposited at the base and are overlain by wackestone-packstones with oncoides. These depositional environments evolved on an outer ramp that prograded from south to north. The top of this interval is marked by a major downward shift surface. (2) The upper Habshan occurs above this surface. At this time, the vertical evolution changed and the upper Habshan is a third-order sequence of stacked metric-sized shallow-marine parasequences.

During the transgressive stage (stage 1) zones of oncolite and oolite sedimentation elongated east-west occurred in the north, whereas grainstones with small oolites and lag facies were deposited in the south. In the regressive stage (stage 2), internal platform facies occurred throughout in the whole domain; for example, mudstones with rudists, *bacinella*, and pelletoidal grainstones. The filling ended with a general emergence of the zone to produce bird's-eye mudstones, and grainstones with keystone vugs. All of the upper Habshan appears to have been deposited in a locally barred platform, open to the west and east.

A new geological model of the Habshan Formation illustrates in a particularly realistic way the heterogeneity observed in the field. The model, combined with an understanding of the platform evolution, will be a key element in building realistic reservoir models for fields in the Yamama Formation.

(#90-O) Gas exploration in Block-6, Oman: sequence stratigraphy and play potential of the Haima Supergroup

Pieter P. Spaak, Mohammed H. Al-Lawati,
Bernard Durand de Grossouvre, Mohammed N. Al-Mugheiry and Peter L. Osterloff, **PDO**

The main gas accumulations in Oman are in the upper part of the Haima Supergroup. On the west flank of

the Ghaba Salt Basin, 375 billion cu m of proven gas reserves are contained in the Cambrian-Ordovician Barik, Miqrat, and Amin sandstones. In addition, considerable gas discoveries have been made in these reservoirs in the 'Afar' and 'Musallim Slope' areas. Oil is also produced from the Upper Ordovician Safiq and Ghudun sandstones and from various Haima reservoirs in southeast Oman.

The Angudan unconformity forms a major tectonostratigraphic boundary within the Haima Supergroup. Below the unconformity in south Oman, non-marine sandstones and conglomerates are present in small salt basins, whereas time-equivalent lacustrine and possibly marine shales (potential seals) occur in east and central Oman.

Based on marine flooding events, six major transgressive-regressive cycles have been recognized in central Oman above the Angudan unconformity, and they form the main reservoir-seal pairs in the Haima Supergroup. New biostratigraphic data and constraints provided by dipmeter data and cyclicity analysis underpin a more detailed sequence stratigraphic framework that allows the development of new play concepts. In particular, the presence of Upper Cambrian lowstand deltas and Upper Ordovician shelf canyons and associated lowstand deposits has become apparent.

(#106-O) The Yaser 3-D ocean bottom cable survey: a case history in multiple attenuation in the Arabian Gulf

Joel G. Starr, **PGS**; Francis Mila
and Franck Herbaux, **TotalFinaElf**; Rick Sinno, **PGS**

The Yaser 3-D seismic survey is a dual sensor Ocean Bottom Cable (OBC) survey located in waters offshore from Abu Dhabi. The survey covered approximately 120 sq km in water depths of between 12 and 34 m. The target horizons were the Mishrif, Thamama, and the Khuff.

Several characteristics of the area conspired to make multiple attenuation difficult. Water bottom conditions varied from very hard to very soft; therefore, water-trapped multiples were a great problem. Coherent noise contaminated the data and masked the underlying wavelet, so reducing the effectiveness of deconvolution. Interbed multiples had velocities similar to those of the primary events and this made traditional multiple removal techniques, such as parabolic radon demultiple, difficult to implement.

The processing of the Yaser survey employed some innovative techniques to overcome these difficulties. Although the techniques employed were developed specifically to meet the challenges of the Arabian Gulf, they were based on fundamentally sound geophysical concepts.

This presentation follows the processing flow of the Yaser 3-D OBC seismic survey from the initial 'brute' stack to the final migrated product. Particular attention is paid to the issues of dual sensor summation, radon demultiple, deconvolution, noise attenuation, and velocity analysis with respect to how these techniques affect the multiple attenuation.

(#135-O) New pool definition, delineation, and development: the P5 reservoir, Safah field, Oman.

Stanley W. Stearns
and Robert A. Dockweiler, **Occidental**

By 1998, a total of 159 wells had been drilled in the Upper Shu'aiba reservoir of the Safah field. The field contains 1,081 million barrels of stock-tank oil initially in place and has an Estimated Ultimate Recovery (EUR) of 356 million barrels; yet the updip limit of the field had still not been defined. A depositional limit on the porous limestone reservoir was interpreted from 3-D seismic amplitude data in 1998 that led to the drilling of the S-160 well. The success of S-160 extended the updip limit of the reservoir. Two additional multilateral wells were drilled within the same seismic amplitude anomaly and enlarged the productive area of the field.

Later in 1998, an exploration well drilled 11 km southwest of Safah found the same porous limestone unit, but wet. An updip stratigraphic limit of the field now seemed to be unlikely for such a laterally continuous unit. Re-interpretation of the Safah field well data led to the recognition that the thin reservoir unit in the western part of field was a separate accumulation, not connected to the main Safah field. Seismic continuity interpretation of a merged 3-D data set suggested that a through-going fault trend having a minimal vertical throw could provide the updip seal to this newly defined reservoir (named the P5 reservoir). S-165 drilled in 1999 confirmed the continuous nature of the fault system and the updip limit of the field.

Drilling multilateral horizontal wells in the newly defined area of the P5 reservoir began in 2000. Primary field development will be completed in 2002. The P-5 pool has a primary EUR of 18 million barrels of oil. A recommendation for a possible water flood will be made in 2002.

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(#73-O) High-resolution palynostratigraphy, paleoecology, and paleoclimatology of the deglaciation sequence represented by the Early Permian Rahab and lower Gharif members, Oman

Mike H. Stephenson, **BGS**; Peter L. Osterloff, **PDO**

A unique record of deglaciation following the Carboniferous-Permian Gondwanan glacial period is preserved in the oil-bearing Early Permian Rahab and Lower Gharif members of Oman. A large-scale study of closely sampled cored sections in wells across Oman revealed a sequence of paleoclimatic and paleoecological changes that are associated with climatic amelioration. In the upland areas, the paleoecology conditions changed from a periglacial monosaccate-producing flora to a warmer climate bisaccate-producing flora. In the lowlands, a parallel change occurred from a periglacial, typically Carboniferous-Permian Gondwanan, 'fern' flora to a warmer climate colpate-producing and lycopsid flora. The deposition of a layer, a few meters thick, that is marked by a new acritarch species *Ulanisphaeridium omanensis* sp. nov., followed and is believed to mark the first deglacial marine transgression of the sequence. The layer is present throughout Oman and is of considerable value in marking the middle part of the Lower Gharif member. A palynostratigraphic scheme has been developed for the sequences that is capable of resolving meter-scale changes and which represents a considerable improvement on other Permian palynostratigraphic schemes. Many of the events on which this scheme is built are thought to be associated with large-scale climatic change. Therefore, they are probably synchronous and of great significance for correlation across Gondwana.

This presentation is primarily a stratigraphic study and so only taxa of immediate stratigraphic value will be described and illustrated. Five new palynomorph taxa, *Indotriradites apiculatus* sp. nov. *Cyclogranisporites rex* sp. nov., *Cyclogranisporites pox* sp. nov., *Lundbladispora gracilis* sp. nov., and *Ulanisphaeridium omanensis* sp. nov., have been instituted and one new combination suggested. An extensive account of the taxa recorded in the study is to be published.

(#358-O) Regional sequence stratigraphic framework for the Burgan and Mauddud formations (Lower Cretaceous, Kuwait): implications for reservoir distribution and quality

Christian J. Strohmenger, Timothy M. Demko, John C. Mitchell, Patrick J. Lehmann and Howard R. Feldman, **ExxonMobil**; Adel F. Douban, Ahmed J. Al-Eidan, Ghaida Al-Sahlan and Hamdah Al-Enezi, **KOC**

Integrated sequence stratigraphic and biostratigraphic analyses indicate that the traditional lithostratigraphic Burgan-Mauddud contact is actually time-transgressive. Our improved understanding of this relationship is critical to regional-scale mapping and the prediction of reservoir facies. The Lower Cretaceous Burgan and Mauddud formations belong to two second-order composite sequences. The oldest consists of the lowstand, transgressive, and highstand sequence sets of the Burgan Formation. The Formation is characterized by marginal-marine deposits in northeast Kuwait but it becomes progressively more non-marine to the southwest. The lowstand sequence set of the uppermost Burgan and the transgressive and highstand sequence set of the overlying Mauddud form a second composite sequence. These deposits are dominantly siliciclastic in southwestern Kuwait but are carbonate-prone in the north-northeast. A major, second-order marine flooding surface at the top of the Burgan Formation in northern Kuwait is a regional chronostratigraphic boundary and can be correlated throughout the country. The Mauddud composite sequence is subdivided into seven high-frequency depositional sequences. The lower Mauddud transgressive sequence set shows a lateral change in lithology from limestone in north Kuwait to siliciclastics in the south, interfingering with what has traditionally been identified as the Burgan Formation. The upper Mauddud highstand sequence set is carbonate-prone and thins southward due to depositional thinning and significant erosion.

(#381-P) Sequence stratigraphy of Khuff analogs Bih, Hagil, and Ghail formations in the Musandam Peninsula, Ras Al-Khaimah, UAE

Christian J. Strohmenger, **ExxonMobil/ADCO**; Robert Alway, **ExxonMobil**; Richard F. Hulstrand, **ADCO**

Khuff analogs have been studied at Wadi Bih and Wadi Hagil in the Musandam Peninsula of Ras Al-Khaimah,

UAE and are compared to well data from Abu Dhabi. Outcropping carbonates of the Permian Bih Formation and the overlying Hagil Formation, together with the lower part of the Triassic Ghail Formation, are considered to be time-equivalent to hydrocarbon-bearing carbonates and siliciclastics of the subsurface Khuff of the Arabian Platform. The Khuff Formation is a second-order composite sequence. The transgressive sequence set consists of the Khuff third-order composite sequences KS7 to KS5 and the third-order lowstand/transgressive systems tract of KS4. The highstand sequence set is composed of the highstand systems tract of KS4 as well as third-order composite sequences KS3 to KS1. Major Khuff gas reservoirs are associated with the second-order highstand sequence set.

Sequence KS1 corresponds to the lower part of the Ghail Formation. The Hagil Formation is equivalent to Khuff sequences KS2 and KS3, and sequences KS4 to KS7 are interpreted as corresponding to the Bih Formation. At Wadi Bih the Permian-Triassic sequence boundary KSB1 at the base of the uppermost Khuff sequence KS1 is well exposed. It is marked by a karst breccia that overlies a shale-rich interval of the Hagil Formation. In Wadi Bih and in Wadi Hagil, Khuff sequence boundary KSB3 is interpreted as corresponding to an exposure surface showing mud-cracks and rain-drop imprints. This sequence boundary is also the boundary between the Bih (below) and the Hagil (above) formations.

In core from Abu Dhabi, the top Khuff sequence boundary is identified by a karstic horizon overlain by deeper-marine grain- to mud-rich carbonates. Above this sequence boundary, deepening-upward marine carbonates form the early transgressive systems tract are interpreted as onlapping westward onto the top Khuff sequence boundary. In cores, Khuff sequence boundaries KSB1, KSB5, and the pre-Khuff unconformity show erosive surfaces and are readily identified on wire-line logs.

(#108-O) Q-marine: 'true 4-D-ready seismic'

Morten Svendsen and Leif R. Larsen, **WesternGeco**

Seismic reservoir monitoring has demonstrated its effectiveness in understanding the dynamic behavior of a reservoir, and its value for reservoir management. The method has a yet unrealized potential that will be realized if higher repeatability can be obtained. Wider applications will include more quantitative interpretations, monitoring over shorter time intervals, and the use of the technology in smaller, tighter and more complex reservoirs.

Perturbations, (errors and differences), between different phases of a 4-D seismic study create noise when data sets acquired at various times are analyzed for change. It can mask the subtle variations in the seismic response of the reservoir that indicate changes in pore fluids. We can divide the perturbations into three types. (1) Those that affect the emitted source signature, such as shot-to-shot variations in the source output and the array directivity. (2) Those that affect the received signal, such as sensor sensitivity variations and ambient noise (swell). (3) Those that affect the positioning repeatability and accuracy, such as sea currents and the positioning system.

The effects of perturbations have been studied and their impact on seismic data quality quantified. The specification criteria for Q-Marine were set to consider the sources of perturbation both for high-resolution imaging and for repeatability in 4-D studies. Calibrated seismic through shot-to-shot source output monitoring, individual receiver-sensor calibration, horizontal and vertical streamer steering, and improved positioning accuracy minimizes the impact of the acquisition footprint in time-lapse interpretations. The amount of ambient noise in the data can be greatly reduced through the use of single-sensor recording and digital-group forming.

The presentation will describe the new technology and show examples of the ability to remove the perturbations experienced in conventional seismic data. It will describe results based on field examples from several case studies covering reservoirs with differing geology. It concludes that 4-D seismic which uses the new Q-Marine concept will be a cost-effective tool for accurate management during the lifetime of the oil reservoir.

(#29-O) Deep-water hydrocarbon prospectivity in the Gulf of Aden

Stuart S. Sweetman, **WesternGeco**

The analysis of a recent deep-water 2-D seismic data acquired in previously unexplored acreage in the Gulf of Aden together with the results of potential field modeling, indicated the presence of a prerift section in offshore Yemen. This prerift section is considered important for hydrocarbon prospectivity as it contains numerous oil discoveries that range from the onshore Masilah field (Cretaceous Qishn sandstones) to the offshore Sharmah-1 discovery (Eocene carbonates). Cretaceous source rocks are ubiquitous in this region and are composed mostly of type-II kerogen. Reservoirs in Nubian sandstones are developed throughout most of the stratigraphic sequence. The prerift section is probably 2 to 3 km thick in places

and demonstrates trapping mechanisms, such as rotated fault blocks associated with rifting. The postrift section is also well represented and is as much as 3,500 m thick in places; this thickness is sufficient for the maturation of any postrift source rocks that are present. The postrift is less heavily faulted than the prerift, and trapping mechanisms are likely to be slightly different in character to include rollover anticlines, amplitude anomalies, together with basin-floor and other sands. Additional hydrocarbon traps are associated with the highly conspicuous transpressional / flower structures located at the basin boundaries that could form low-risk fold closures. The presence of hydrocarbons in Eocene carbonates subcropping the breakup unconformity that separates the prerift from the postrift sequences, indicates the validity of stratigraphic trapping.

(#118-O) Reservoir characterization of the Kangan Formation, Salman field, offshore Iran.

Ali A. Taghavi, **NIOC**; Mohammad R. Rezaee, **U. of Tehran**; Siied Ali Moallemi, **NIOC**

The Kangan formation is a major gas reservoir in southern and offshore Iran. The Permian-Triassic Kangan / Dalan formations in Iran are equivalent to the Khuff Formation of the Arabian Platform. The thickness of the Kangan in the Salman field is about 190 m. Its average porosity is 12.85 percent and average permeability is 55.50 mD.

The goal of the study presented here was to evaluate the effective parameters that control the quality of the Kangan reservoir. More than 450 thin-sections were studied, and porosity and permeability were measured from 900 core plugs. Based on core and log analysis, the upper part of the reservoir is composed of dolomite and anhydrite layers, whereas the lower part consists of alternating dolomites and limestones. The Formation consists of tidal-flat (supratidal and intertidal), lagoonal, and shoal lithologies and a wide range of lithologies.

Dolomitization occurred during early to late diagenesis and was the most important diagenetic process. Coarsely euhedral and planar-e dolomite crystals have produced the best-quality reservoir conditions and the poorest quality reservoir zones are composed of xenotopic and fine-grained dolomite crystals. Anhydrite cement has reduced reservoir quality significantly in some intervals. Open fractures have a positive role in increasing permeability, and dissolution has enhanced both porosity and permeability.

Porosity types including interparticle, intercrystalline, dissolution porosities (vuggy, moldic), and microporosity. Intervals with interparticle and intercrystalline porosities have the best reservoir quality. In the Kangan Formation, diagenetic processes have a greater effect than other factors on the reservoir quality. The good reservoir quality of the Kangan Formation has in the Salman field is due to interparticle porosity in dolograinstones and intercrystalline porosity in crystalline dolostones.

(#320-P) Stratigraphic exploration potential of the Mishrif Formation in Abu Dhabi

Ahmed A.K. Taher and Ghiath Ajlani, **ADNOC**

The stratigraphic trap and hydrocarbon exploration potential of the Cenomanian Mishrif Formation of Abu Dhabi has been investigated by applying sequence stratigraphic concepts, detailed facies analysis, seismic interpretation, basin modeling, and impedance inversion. The Formation was deposited during a highstand system tract and consists of a carbonate platform complex that prograded toward the Shilaif basin. The combined seismic and geological investigations have revealed several Mishrif platform shelf margins, clearly influenced by sea-level fluctuations and an active local structural regime during deposition. Mounds and buildups developed along the shelf margins and created potential for the development of combined structural / stratigraphic closures at the Mishrif level.

On the platform margins, the best potential areas are where high porosity and local thickening occurred. Local Mishrif thickening can be seen on the seismic isopach map of Base Laffan to Top Shilaif formations. Seismic modeling and impedance inversion shows that the high-porosity values are consistent with geologic data and stratigraphic modeling prediction. In addition, mound / buildup features have been interpreted through seismic amplitude variations and by changes in the seismic character; strong amplitudes outside the feature become weak in the middle part of the buildup. The development of local buildups caused the deposition of other localized high-energy shelfal facies deposits, and later resulted in an early subaerial exposure that created much dissolution porosity.

The Mishrif structural / stratigraphic traps are highly prospective in areas that are located adjacent to mature Shilaif kitchens. The Shilaif source rock, which is time-equivalent to the Mishrif shelf facies, was deposited under restricted water-circulation and anoxic

AD

conditions. The maturation modeling indicated several localized mature kitchens in the West Bu Hasa and Falaaha synclines and in northeast Abu Dhabi. It suggested that the timing of the hydrocarbon charge from these synclines into the Mishrif reservoir started as early as Late Miocene. This prospective play requires a detailed and integrated evaluation, preferably with wider correlation of well data and the use of high-resolution 3-D seismic.

(#136-O) Fault characterization by seismic attributes and geomechanics in a Middle East oil field.

Yoshihiko Tamura, **JODCO**;
Futoshi Tsuneyama and Hitoshi Okamura, **JNOC**;
Keiichi Furuya, **JODCO**

Combining the attributes extracted from 3-D seismic data, especially those of similarity and dip, give clear images of small-displacement fault geometry and the orientation of subseismic faults and fractures. In the case of a faulted and fractured carbonate reservoir in a Middle East oil field, the new fault and geomechanical interpretations significantly reduced the uncertainty about the preferable fluid flow through the faults and fractures.

Two fault systems were recognized from similarity and dip analyses; a main NW-directed, fault system, and a NNE-trending secondary system that is parallel to the long axis of the elliptical domal structure of the field**.** Some of the main faults appeared to be composed of en echelon fault segments. Transfer displacement between the overlapping en echelon normal faults formed so-called 'relay ramps' and 'relay faults'. The fault systems recognized from the seismic were correlated with well logs (Formation Microimager) and core observations. The development of the fault systems was revealed by physical analog modeling experiments, computer simulation, and regional tectonics review.

In the study area, the impact of faults and fractures on fluid flow is considerable. The characteristics of the fault systems are controlled by the present-day stress regime with the maximum horizontal stress acting toward the north-northeast. Slip-tendency and dilation-tendency analyses under the regional stress conditions are an indicator of fault (and fracture) transmissibility. The secondary fault system, parallel to the maximum horizontal NNE-directed stress direction, was probably open or productive during the Cenozoic. It was concluded that the secondary fault system is a main conduit, consistent with interference well tests made in the field.

(#115-O) Structural and stratigraphic control on the Lower Cretaceous Zubair reservoir in northern Kuwait

Saifullah K. Tanoli, Abdulaziz M. Al-Fares
and Mishari A. Al-Awadi, **KOC**

The Barremian Zubair Formation is one of the major clastic units in Kuwait ranging in thickness from about 1,100 ft to more than 1,350 ft. It consists predominantly of sandstone in the west and southwest where fluvial environments prevailed, but the shale content increases toward the east and northeast. There, the basal part of the Formation consists of a predominantly shallow-marine facies, the middle part is fluvial and estuarine facies, and the upper part is a recurring marine-dominated facies. During the deposition of the Formation the overall basin slope was toward the east-northeast and the western and southern parts of Kuwait were proximal to the sediment source.

Thick fluvial-estuarine sands of the Middle Zubair make up the principal reservoir zone in northern Kuwait. The reservoir thickness is variable from field to field as it depends on the particular structural closure and on the location within the field. In the Upper and the Lower Zubair, in contrast, the pay zone in the relatively thin sand layers is largely structurally independent and is present in some wells that have no apparent structural closure at the Zubair level. These sandstones were mainly deposited in beach and shoreface environments with the enclosing shale being of offshore origin. The shale acted as a vertical and lateral transmissibility barrier to fluid movement and made the sandstones into stratigraphic traps. The shallow-marine sand bodies are preferentially oriented parallel to the paleoshoreline.

Because the Zubair reservoir is a combined structural and stratigraphic trap, its prospectivity on a regional scale requires the accurate modeling of these two elements.

(#294-O) Expert systems in hydrocarbon exploration programs

Mohammed A. Tayyib, **Saudi Aramco**

Searching for hydrocarbons is a very sophisticated scientific process. Over the years, a wealth of knowledge and experience has been accumulated and passed from one generation of explorationists to another. The advancements in computing technology have played a key role in automating these processes and capturing the exploration data. Similarly, advancements in application integration and visualization technology have enabled the explorationist to benefit more from the exploration

data. However, as the volume of data increases, the technology gets more and more sophisticated. As the active explorationist generation gets older, the need to capture their knowledge and experience in a systematic manner and make it accessible to future generations is critical. For many years, the oil industry has been attempting to use Expert System technology to capture the knowledge of their experts and make it accessible to the younger generation. Many success and failure stories have been reported in the literature. In this presentation, a survey of the attempts by industry in building Expert System applications will be given, together with some insights into each approach and the analysis of their success or failure. The highlights of some of the current research in this area will also be presented. The paper will be concluded with a recommendation of a new approach to tackle this old dream by using the latest advancements in computing technologies.

(#50-O) Clastic-carbonate transition in the Albian-Cenomanian of Kuwait: a case study from the Burgan and Mauddud formations

Sanjeev S. Thakur, Ahmed A.M. Manowar
and GhaidaA. Al-Sahlan, **KOC**

A clastic succession of the Upper Burgan Formation co-exists with the overlying Mauddud carbonates through a transition defined by short, yet laterally extensive periods of sedimentation. A range of depositional environments from fluvial, incised-valley fills with tidal influences, to shallow-marine, characterize the Burgan Formation. Transgressive sands and shallow-water carbonates in the basal part of the Mauddud were the products of the marine incursions. Fluvial to shallow-marine sedimentary packages are interbedded laterally with, and grade into, ramp-type limestones. Interplay of clastic influxes and shallow-marine carbonate deposition in relatively quiet conditions successively lapout the upsection cycles of Mauddud carbonates at various locations within Kuwait. Despite the lack of a faunal assemblage, the tracking of successive transgressive surfaces gives a meaningful expression to the nature of the transition. Consequently, thinning-thickening of both the sedimentary packages landward and basinward imposed relative depositional stress on the clastic-dominant or carbonate-dominant facies. In those cases where the vertical amplitude of the trapping structure was less than the thickness of transition or of the Mauddud, the resolution of this clastic-carbonate succession for stratigraphic-structural plays is important. Diagenesis in the mixed facies has had an impact on reservoir quality and continuity, but the clastic-dominant association remains a relatively good reservoir. Spatial and temporal variability in the mixing of the facies was explored by using subsurface data. Analyses of the data indicated that clastic-carbonate transitions in the stable Arabian Platform are mainly attributed to spatial variability.

(#219-P) The Central Arabian Arch: a key to Permian deposition?

Douglas E. Thomas
and Martin J. Rademakers, **Saudi Aramco**

Paleotopography and tectonism controlled the deposition and presence of the Lower Permian clastic Unayzah Formation in Saudi Arabia. There are indications that presence or absence of sand deposition was controlled by the local subcrop composition. Understanding the interaction is critical to successful exploration efforts in the area.

A prominent Central Arabian Arch began to develop in the Late Silurian, as shown by isopach analysis of the Silurian Qusaiba / Sharawra shale that is truncated by the locally unconformable Tawil Formation**.** The composition of this exposed surface, combined with later Hercynian erosion, has resulted in an alternating subcrop pattern of older sandstone and shale. The paleotopography with interpreted vertical relief caused by varying subcrop resistance influenced the local deposition of fluvial and eolian sands. Subcropping of the resistant Sharawra siltstone resulted in sand-poor deposits. Sandstone-rich subcrops such as the Devonian to Ordovician Tawil, Sarah, Zarqa and Qasim formations, or the Cambrian Saq, are commonly overlain by what are probably locally reworked and deposited sands. An alternative, and locally applicable interpretation, is the subsequent erosion of local paleohighs—although seismic and well analysis do not confirm this interpretation in all areas. Poor dating of barren zones and similar sand-source characteristics, preclude a definitive conclusion as to which is the most valid interpretation. Subsequent alteration and diagenesis is a factor in the exploration of these reservoir sandstones, but is not discussed here.

(#87-O) Gas exploration in Block-6, Oman: new discoveries and new petroleum systems in the Haima

Graham J. Tiley, Pieter P. Spaak, Mohammed N. Al-Mugheiry, Mohamed S.S. Al-Lamki, Mark Newall, Juma D. Al-Belushi
and Nashwa M.M. Al-Ruwehy, **PDO**

Gas exploration in Oman has been focused on the Haima Supergroup since the discovery of the Saih

Nihayda, Saih Rawl, and Barik 'LNG' fields at the start of the 1990s. Several small fields were subsequently added to the inventory, but the play appeared to have been creamed by the end of the decade. The proven plays are limited by a range of reservoir, charge, and seal issues that define a narrow fairway. Nevertheless, in 2001, back-to-back discoveries in Kauther-1 and Khazzan-1 demonstrated that exploration of the Haima is far from over. However, these discoveries represent new plays and petroleum systems.

Khazzan is an areally extensive stratigraphic trap on the margin of the Barik delta, draped across the southern flank of the Musallim ridge. The reservoir is thin in comparison to the LNG fields, but unlike those fields, the gas in the Barik is dry. This opens up the previously untapped stratigraphic plays in the Haima and illustrates the complex petroleum systems in Oman that place dry and wet gas in adjacent structures. Kauther is a crestally faulted anticline in the Afar region that is gas-bearing at the Amin level. Regionally, the Amin is thick, and has a high net-to-gross, but it is commonly of poor reservoir quality. However, Kauther has a relatively good reservoir despite deep burial. The gas charge is wet, but it is isotopically distinct from the gases in the LNG fields and hence part of a different petroleum system. Understanding the relationship of the Amin reservoir quality to the primary rock fabric and burial history, is the key to predicting further success in this play.

(#335-O) Integrated prestack depth migration—from geophysical research to interpreter: a case study of Petroleum Development Oman's Burhaan field

Timo Tjan, **Shell**; Jalila Al-Riyami, **PDO**;
Uwe Asmussen, **Shell**; Adrian Young, **PDO**

In recent years Prestack Depth Migration (PSDM) has been a crucial for imaging areas with a complex subsurface. It has become even more accessible due to a tremendous increase in the available computing power. Today, we can turnaround a PSDM project in shorter time, with better quality and more state-of-the-art migration options. Shorter turnaround times are demanded to bring reservoirs into production more quickly in order to maintain or increase production levels.

As the subsurface knowledge of these reservoirs resides in the operating company; a PSDM project requires close interaction with the interpreter or reservoir engineers in the operating company. Larger computing infrastructures also allow for more advanced, state-of-the-art-processing techniques, as a result of which, a constant interaction with the researchers is required.

Shell Geoscience Services (SGS) and Petroleum Development Oman (PDO) undertook an integrated PSDM project based in The Netherlands in which the processing team joined forces with the research group. PDO participated in the project through remote access to the large SGS computer infrastructure that allowed for simultaneous work on the data obtained from the Burhaan field. This presentation will provide an overview of the methods used in this integrated project. It will also highlight the value that the new PSDM technology will add to an improved understanding of the reservoir when integrated with geophysical research, and seismic processing and interpretation.

(#300-O) Mapping the occurrence and distribution of bitumen in the Uwainat reservoir, Dukhan field, Qatar

Ali M. Trabelsi and Mirza A. Beg, **Qatar Petroleum**

The Jurassic Uwainat consists of lime grainstones, packstones, and wackestones arranged in beds of consistent thickness and extent. They were deposited in an open-marine platform environment as overall regressive sequences. In the Dukhan field of Qatar, the hydrocarbon accumulations in the Uwainat reservoir occur as a relatively small, saturated oil pool in the Khatiyah sector, and as a small pool of non-associated gas in the Fahahil sector.

Integrated data from cores, thin sections, logs and repeat formation tests of 20 cored and 21 uncored wells were used to map the occurrence and distribution of bitumen in the Uwainat reservoirs. The results showed that the bitumen mostly occurs in grainstones, and to a lesser extent in a few bioclastic wackestones and packstones. It tended to fill interparticle and intraparticle pore spaces and stylolites and as minor fillings of a few hairline fractures. The amount of bitumen in some grainstones can be as high as 45 percent by volume. Petrographic examination showed that the bitumen is superimposed on the diagenetic cements, indicating that it is a late diagenetic phase that postdated the precipitation of the diagenetic minerals such as calcite and anhydrite, and that the hydrocarbon migration into the Uwainat reservoir occurred after the major overgrowth cementation.

Constructed cross-sections and thickness maps showed that the abundance and thickness of bitumen varies considerably between wells. It appears to be thick in crestal wells in the Khatiyah Sector but, in general, the bitumen layers are discontinuous and

lenticular and only rarely are they continuous for more than a few kilometers. The layers have a N-S trend. The thickest bitumen intervals are up to 45 ft thick.

The distribution of bitumen appears to be facies-controlled, as it is predominant in peloidal, bioclastic, and oncolitic grainstones that had good initial porosity and permeability. One explanation for this preferential occurrence is that the bitumen resulted from heavy hydrocarbons that migrated into the reservoir along highly permeable and porous layers. Another explanation is that bitumen developed preferentially in the highly porous and permeable grainstones as they allowed for the free mixing of oil and formation water, and hence increased the potential for non-microbial degradation of oil. One of the major byproducts of this reaction would be hydrogen sulfide gas, which is commonly detected in the Uwainat.

Bitumen influences the reservoir quality by reducing the total effective porosity. Permeability was significantly reduced by the restriction of pore throats and by migration of fines, even when the bitumen occurs in only moderate amounts. Mapping the spatial distribution of bitumen will help in optimizing well locations for infill drilling as well as any future enhanced recovery program for the Uwainat reservoir in Dukhan.

(#337-P) Estimates of lithospheric-stretching factors ('beta') for the carbonate platform of NE Oman

Carl G. Trowel, Alan G. Smith
and Nick J. White, **Cambridge U.**

Permian and Mesozoic sediments of northeastern Oman are excellent material on which to apply the lithospheric stretching model, facilitated by the large stratigraphic database of Petroleum Development Oman. Standard methods of decompaction and backstripping give water-loaded subsidence curves for the stratigraphic sections. A recently developed stratigraphic inversion model also allowed strain-rate variations during extension to be recovered from the subsidence data, and provided estimates of the magnitude and duration of the extensional episodes.

The lithospheric-stretching model suggests that the margin of northern Oman was created by extension that began in the Early Permian and lasted about 25 million years. Extension on the platform ceased at the end of the Permian and was succeeded by Early Triassic thermal subsidence. Regional uplift took place in the Late Triassic with thermal subsidence resuming in the Middle Jurassic. The margin developed a broad, shallow-water carbonate platform from 500 to 600 km wide produced by almost uniform stretching (beta = 1.1 to 1.15). The platform slope developed contemporaneously with the platform and was formed by Permian rifting at a slightly higher stretching factor of beta = 1.25. Minor extension (beta = 1.05) affected the platform during the Middle Jurassic and again in the Neocomian. The degree of stretching predicted by the model appears to be greater than the displacements inferred from the faulting seen in outcrop or in seismic profiles.

(#213-P) Modeling and interpretation of inversion results in the presence of multiples

Ching-Chang J. Tsai, **Saudi Aramco**

Poststack seismic inversion provides a tool by which impedance information can be obtained from the processed seismic data. As this information relates to porosity, seismic inversion can contribute to the knowledge of reservoir rocks and reservoir characterization. Most poststack seismic inversion is based on the 1-D convolution model. The seismogram represents the convolution result of a wavelet and an earth-reflectivity function. The aim of the inversion process is to recover the earth-reflectivity function (or impedance) from the input seismic data. In the presence of multiples caused by the strong impedance contrasts between carbonate rocks and clastic sediments, the inversion requires optimized parameters such that the results can be more easily interpreted. To complicate the process further, the lack of detailed information in the input model introduces uncertainty in the inversion results. I will present and discuss the inversion results by using actual and synthetic data with and without multiples. In addition, I will illustrate the effect of inaccurate source wavelet on seismic inversion results.

(#247-O) Anisotropy: who cares?

Constantine Tsingas, Long D. Pham,
Ruben Martinez and Maurice Gidlow, **PGS**

The reservoir characterization process increases the confidence level on the description of the rock and fluid properties that make up the constituents of reservoirs, both clastic and carbonate. With the increasing resolution of seismic observations and with the use of multicomponent acquisition and processing technologies, there is a growing awareness that the assumption of isotropy is often violated. Thus, methods that allow proper imaging and reservoir

characterization in the presence of anisotropy are highly desirable.

In the presentation we will show, by using synthetic and real data examples, various seismic data-processing technologies that incorporate anisotropic parameters, and which aim to correct the kinematics and dynamics of the seismic wave propagation in anisotropic media. Time-imaging algorithms operating in the prestack or poststack domain will show the effect of incorporating not only the normal moveout velocity for horizontal reflector ($V_{(o)}$NMO) but also the anellipticity coefficient η. Depth imaging algorithms, however, will indicate that these two parameters are not sufficient to properly position the structures at the correct spatial and depth locations. In this presentation, we will demonstrate that for a proper prestack depth migration methodology, one needs to incorporate Thomsen's parameters ε and δ in addition to V_o in order to obtain the correct travel times required during a prestack depth migration procedure. In addition, traditional Amplitude Versus Offset (AVO) theory breaks down in the presence of anisotropy. We will demonstrate the use of more sophisticated AVO algorithms in the description of anisotropic reservoirs, as well as isotropic reservoirs with anisotropic overburden.

(#137-O) Outcrop investigations and clay experiments for fault characterization: analogs for oil fields in the Middle East

Futoshi Tsuneyama, Hitoshi Okamura, **JNOC**; Yoshihiko Tamura, **JODCO**; David A. Ferrill and Darrell W. Sims, **Southwest Research Institute**; Alan P. Morris, **U. of Texas**

Hydrocarbon entrapment in the study area is dominated by a domal structure that was formed by deep-seated salt movements. A recent 3-D seismic survey showed that faults in the Cretaceous carbonate rocks of a particular domal structure had a dominant NW-trend. This work was aimed at predicting faulting and fracture mechanisms and patterns in carbonate rocks within domal structures and consisted of three phases. (1) The field investigation of analog outcrops to develop models of the style and character of small-displacement (less than 30 m) normal faults in carbonate strata. (2) Clay-cake modeling of fault and fracture patterns within domes, including domes that developed in anisotropic regional stress fields. (3) Integration of results from field-analog studies, clay-cake models, and 3-D seismic data interpretations to model the tectonic evolution of faulted carbonate reservoirs in the study area.

Results from the study of small-displacement faults in carbonate outcrop analogs gave a positive correlation between fault density and extension magnitude. Using an empirical power-law relationship between fault displacement and frequency, it was possible to predict the population of faults. Results from the clay-cake models suggested that the dominant NW-trending faults as well as smaller near-orthogonal faults are to be expected. Faults interpreted from the 3-D seismic data of a studied field correlated well with the power-law relationship determined from field examples. Clay-cake models indicated that the domes formed under conditions of regional northeast to southwest extension, or the equivalent stress regime, by E-trending right-lateral wrench faults during the Late Cretaceous.

(#256-O) Beowulf clusters for high-performance computing in the oil industry

Takis P. Tyraskis, Mohammad S. Khan, Mohammad H. Huwaidi and Yi X. Luo, **Saudi Aramco**

High-Performance Computing (HPC) systems have been used extensively in the oil industry for computing and input/output intensive seismic and reservoir simulation applications. Prestack time and depth migration and reservoir simulation are the most common examples of parallel applications that require HPC systems. To provide the required performance, such systems have used very expensive proprietary processors, high-performance memory, intelligent proprietary interconnects, and powerful input/output subsystems. Traditionally, HPC systems required supercomputers.

Beowulf clusters, constructed from commodity computer systems, are the fastest growing alternative for building high-performance parallel computing systems. Beowulf clusters originated from NASA and were first successfully demonstrated in 1996. The goal was to create a cost-effective parallel computing system from mass-market, off-the-shelf components to satisfy the specific computational requirements of the earth and space sciences community.

Seismic processing contractors first, and oil companies later, have begun to employ Beowulf clusters for their parallel seismic applications with unprecedented price and performance benefits. With the rapid advance and increasing availability of microprocessor technology, high-speed network interconnects and other related components, Beowulf clusters are expected to play an even more important role in our industry in the near

future. Most geophysical contractors have ported their complete software package into the Linux operating system and are moving to full-scale implementation using Beowulf clusters.

This presentation will provide an overview of the design of Beowulf clusters, the typical hardware and network architecture, and the required system software and cluster management tools. Design choices will be presented. In addition to cost-effectiveness, other benefits of this system will be discussed.

A year ago, Saudi Aramco evaluated a commercially available system consisting of a Beowulf cluster and a special processing package for Prestack Time Migration (PSTM) and decided to acquire a Beowulf cluster for a PSTM algorithm developed in house. The architecture of the Beowulf cluster and PSTM application was designed together in order to optimize the performance of the application on the cluster. Performance results will be presented and operational and support issues and future expansion plans will be discussed.

(#372-O) 3-D modeling of a fractured carbonate reservoir, Ghaba North field, Oman.

Volker C. Vahrenkamp, Salah H. Al-Dhahab, Rick L. Henning, Mehedi Hossain and Edward R. Telatovich, **PDO**; Pascal D. Richard, **Shell**

The Ghaba North oil field in the Ghaba Salt Basin of central Oman was discovered in 1972. Tested by 30 wells it was estimated to contain 118 million cu m stock-tank oil originally in place in the Cretaceous (Aptian) Shu'aiba Formation. The low-relief domal structure had a rapid production decline caused by water breakthrough by way of a connected fracture system. In order to support an increase in recovery by Gas-Oil-Gravity Drainage (GOGD) or thermal GOGD, the reservoir and its fracture system were modeled in 3-D.

The model frame was provided by the layer-cake architecture of the Shu'aiba Formation with two higher-order sequences of transgressive and regressive cycles identified in cores and logs, the lower transgressive hemicycle being the Hawar Member of the Kharaib Formation. The late highstand deposits are of lower porosity, more brittle, and believed to be fracture-prone.

A hierarchical fracture model was built. Major and minor faults were mapped from seismic and assumed to define fractured damage zones that cut the vertical extent of the reservoir. Smaller fracture swarms were derived from formation micro-imager data, are bed-bound, and thus related to the stratigraphic frame. Mapped fault damage zones and data from fracture orientation and frequency were used to build combined deterministic / probabilistic fracture models. These models can be reconciled or contrasted with fracture models derived from regional strain analysis or automated seismic visualization techniques. The models are used for visualization and as input to dynamic flow simulation and history matching. Ultimately the modeling process consists of iterative update loops between the static and dynamic models to optimize future development.

(#386-O) Middle and Upper Cretaceous sedimentation patterns in the Dezful embayment, SW Iran

Frans S. van Buchem and Fabrice Gaumet, **IFP**; Darioush Baghbani, Reza Ashrafzadeh, Hossein Assilian and Forooz Keyvani, **NIOC**

The middle and Upper Cretaceous sediments of the Dezful embayment form one of the richest petroleum systems in the Middle East, with the presence of the Khazdumi source rock, the Sarvak reservoirs, and the sealing Gurpi shales. This presentation is a sequence stratigraphic analysis of these rocks. It proposes predictive geological models, with respect to the geometries and heterogeneities of the depositional facies, and analyzes the geodynamical basin evolution with the help of paleogeographic and isopach maps.

Based on 10 outcrop sections and more than 50 wireline logs and paleologs, five tectonosedimentary phases have been distinguished, which group together third-order depositional sequences that are similar with respect to depositional system, sediment flux, and tectonic control. Phase 1, of Aptian age (Gadvan, Dariyan, and part of the Khazdumi), is characterized by the creation of a large, starved, organic-rich intrashelf basin surrounded by benthic foraminifera dominated ramps. Phase 2, of Albian age (Khazdumi), was a period of infill of the intrashelf basin, again with the concentration of large amounts of organic matter, and was surrounded by benthic foraminifera-dominated ramps. Phase 3, of Cenomanian age (Sarvak), is characterised by extensive and very thick rudist platforms, and only a small, starved intrashelf basin remained. Phase 4, of Turonian to Coniancian age (top Sarvak, Laffan, Ilam), shows sedimentation in small local basins with large exposed areas, controlled by the tectonic relict topography. In phase 5, of Santonian to Maastrichtian age (Gurpi, Tarbur), the sedimentation was entirely controlled by the creation of the foreland basin.

In summary, the sedimentation pattern was at first predominantly controlled by eustatically driven sea-level fluctuations, which during the Cenomanian/Turonian, were gradually superceded by an increasingly important tectonic control.

(#83-O) The Lower Cretaceous Habshan system as a new play in north Oman

Mia M. van Steenwinkel, **PDO**;
Henk H.J. Droste, **CRC, Sultan Qaboos U.**

Recent discoveries in the United Arab Emirates have led to a review of the Habshan as a new play in north Oman and to the screening for unconventional stratigraphic and subtle structural trapping potential. The Lower Cretaceous Habshan carbonate platform system progrades to the north and east, following a major uppermost Jurassic transgression. The diachronic nature of the intra-Habshan facies belts, highlighted on seismic by distinct clinoforms, provides scope for stratigraphic trapping in porous, platform-margin carbonates. The envisaged seat seal is formed by intraformational hardgrounds that reflect third-order sequence boundaries at the top of highstand packages. Transgressive, argillaceous limestones of the distal-slope Salil facies provide additional intraformational sealing potential. Basal Lekhwair lagoonal carbonates form the top seal. Low-relief structures, sealed by the same lagoonal carbonates, form another possible trap type. Although tight carbonates of the basal Lekhwair regionally cover the Habshan reservoir, fracturing and faulting of the brittle limestones is thought to be the main cause for trap failure.

Regional and prospect mapping will be focused on relatively high-chance areas identified from composite (charge, reservoir, seal) play-risk maps. Biostratigraphic analysis in selected wells is planned to constrain the sequence stratigraphic framework. The aim is to develop a viable drilling opportunity in 2002 to 2003 to test the Habshan play in an optimal structural and/or stratigraphic location.

(#21-O) Integrated petrophysical methods for characterizing reservoir flow units: a case study from the Minagish Oolite, Minagish field, Kuwait

Naveen K. Verma, Hamad N. Al-Ajmi, Khaled M. Al-Mutairi and Mohammad M. Abbas, **KOC**;
Marco Martines and Charles R. Smart, **BP**

The Minagish field is a multicomponent reservoir with hydrocarbon accumulation primarily in Cretaceous rocks. The Lower Cretaceous Minagish Oolite is the primary reservoir in the field and the presentation will concentrate on this interval. The Oolite is about 400 ft thick at a mean vertical depth of 9,600 ft below sea level. The reservoir is predominantly a grainstone carbonate that was deposited on a low-angle carbonate ramp. At the time of deposition, bathymetric variations controlled sedimentation energy, and hence rock quality. The highest energy deposits, the oolitic grainstones, make up the highest-quality part of the reservoir and occur in its middle third. Permeabilities in this zone are typically about 1,000 mD and porosities are about 18 percent. The upper third of the reservoir is of lower quality and heterogeneous, and will receive the bulk of the field's injected water. The lower third has the poorest quality with the permeability generally below 10 mD. Throughout the reservoir section, high-permeability streaks or barriers and baffles are present in particular layers.

Surveillance of waterflood and aquifer water movement in Minagish show clear signs that small-scale rock heterogeneities commonly break the reservoir into distinct flow units and control the behavior of water advance. Understanding the flow units character and distribution is of primary importance in interpreting surveillance data fully and in properly understanding the progress of water movement in the field. An integrated petrophysical method has been applied to provide a sound characterization of the reservoir for simulation studies

(#168-P) Biostratigraphy of the Ilam Formation, offshore Iran

Jean M. Villain, **TotalFinaElf**

A refined biostratigraphy of the Ilam Formation was needed, both to understand the geological model of potential reservoirs and to steer wells through specific horizons in the Sirri structure, offshore Iran. The boundaries of the Formation have been defined lithologically and by e-log criteria. The exact age of the beds remains uncertain, due to the facies conditions. Turonian to Santonian ages have been previously given for the Ilam, based on the Cenomanian age of the underlying Laffan Formation, as indicated by marker fossils. However, some of the Laffan Formation marker fossils extend into the Ilam.

A shallowing-upward trend was identified together with four biozones that can be recognized in four wells throughout the field. The biozones have been grouped into two sequences, each consisting of two biozones. A halokinesis episode during sedimentation might have been responsible for this paleobathymetrical evolution, in association with faulting. A

paleobathymetry of about 35 m is possible for the basal part of the sequence, but emergence might have occurred, especially at the end of the second regressive sequence. The muddy decanted sedimentation of the basal part was gradually replaced by a predominantly granular, tractive, and locally channeled style of sedimentation that produced prospective reservoirs.

About six regional biological markers are useful for the biofacies-steering of wells. However, most of the biota recorded regional environmental trends and particularly the changes in salinity that resulted from tidal exchanges between brackish nearshore water and normal open-marine seawater. Algae, *Dicyclina*, Alveolinidae, Miliolidae, and Rotaliidae provide either qualitative or quantitative indications for vertical trends and correlatable events.

(#202-P) An outcrop analog for Permian-Triassic reservoirs of the Kangan/Dalan formations (equivalent of the Arabian Khuff Formation) from the Zagros Mountains, southern Iran: Kuh-e-Surmeh and Kuh-e-Dena sections

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In order to improve our understanding of the architecture and geometry of the prolific Khuff-equivalent reservoir of the South Pars field, two Permian-Triassic outcrops were studied in the Zagros Mountains at Kuh-e-Surmeh (120 km south of Shiraz) and Kuh-e-Dena (70 km south of Isfahan). These outcrops, exposed over a distance of 2 km, are a good analog of Cambrian to Tertiary Middle East offshore reservoirs. The excellent quality of the outcrops allowed for precise sampling throughout the Permian-Triassic series (about 400 m in both areas). Special attention was paid to the description and explanation of the sedimentological evolution of the Upper Permian Dalan and Lower Triassic Kangan formations from shallow-marine (South Pars field) to deep-marine environments (Kuh-e-Surmeh and Kuh-e-Dena). Within these formations, the worldwide Permian-Triassic crisis was underlined by a microbialite (thrombolitic) event in the South Pars field and in outcrop. This was used to propose a reliable sequential framework.

This outcrop study led to an update of the stratigraphical and sedimentogical model already established for the South Pars field, and is relevant for a regional understanding throughout the Gulf. The geological succession is characterized by three major successions. (1) A thick Permian anhydrite equivalent of the Nar member in Kuh-e-Surmeh (South Zagros) passes laterally in the Kuh-e-Dena (North Zagros) into bauxite. They are overlain at both localities by the Dalan series that includes an oolitic shoal that has a well-preserved moldic porosity. (2) The Dalan / Kangan transition (the Permian / Triassic boundary) is marked at both localities by a gap corresponding to the uppermost Permian Dorashamian, as demonstrated in a recent micropaleontological study of the South Pars field. (3) The Lower Triassic Kangan Formation that is grain-dominated in the South Pars field, is mud-dominated in outcrop and is interpreted as having been deposited in a more distal environment. It has locally thick oolitic lobes.

(#40-O) Permian-Triassic second- and third-order sequence stratigraphy of the Arabian Platform and Neo-Tethys: controversy to the global signal?

Oliver Weidlich, **Technical U. Berlin**; Michaela Bernecker, **U. Erlangen**

Distinctive supersequence and composite sequence stratigraphic signals characterize Permian-Triassic carbonate platforms of the Arabian Peninsula and the Neo-Tethys. The carbonate succession of the Haushi and Akhdar groups of the Arabian Platform is composed of four Permian and three Triassic supersequences. Isolated platforms in the Hawasina basin are composed of two Permian supersequences and one Triassic supersequence. Carbonate platform growth on the Hawasina platforms was restricted to the Middle-Late Permian and Late Triassic and ceased after drowning.

Correlation of maximum flooding surfaces with published data suggests that supersequences 1 and 2 and 6 and 7 are present on the Arabian Platform and in the Neo-Tethys, whereas supersequences 3 to 5 resulted from local tectonic events on the margin of the Arabian Platform. The presented sea-level curve corresponds to the Tethyan sea-level curve during the Early Permian, but differs during the Middle and Late Permian owing to local rifting of the Arabian Platform margin. The Middle and Late Triassic curve is in good correlation except for a pronounced maximum flooding surface during the Rhaetian that postdates the global Carnian / Norian maximum of transgression. The Permian-Triassic sequence architecture was triggered by global warming, the initial rifting of the Neo-Tethys, and by sea-level changes on a global scale.

(#175-O) Processing and quality-control strategies for 4-D reservoir characterization

Martin T. Widmaier, Jorgen Moe
and John Brittan, **PGS**

Integrated 4-D geophysical technology is wide ranging from pre-survey modeling/feasibility analysis to acquisition, followed by processing, attribute generation, and interpretation. All stages of a 4-D project require quality control to ensure repeatability and enhancement of the 4-D signal. In the framework of this presentation, we will focus on the processing quality control of 4-D projects. The outlined procedures are relevant to Middle East reservoirs.

In the first part of the presentation, the 4-D performance of imaging operators will be evaluated. Imaging operators such as dip moveout and prestack time migration have been used to process seismic data from repeated seismic surveys on a common survey grid. Fourier regularization has been considered as part of the preprocessing to optimize the interpolation of the seismic traces to common bin centers. The various processing methods have been examined and the achieved 4-D repeatability has been quantified using statistical methods.

In the second part, tools developed for 4-D processing quality control in a high-end visualization system will be introduced. Volume-based cross-correlation analysis is performed in order to detect mismatches in time and phase between the 4-D data sets. The results are stored as attribute volumes. In addition, differences in energy level between the surveys are calculated. The direct link from the processing platform to the visualization system makes 4-D seismic quality control an integral part of reservoir characterization. Simultaneous analysis of 4-D seismic data sets and the attribute volumes is simple. These applications are not restricted to 4-D applications only but have also become a powerful quality control and interpretation tool in amplitude versus offset analysis.

(#176-O) Wide-angle towed-streamer acquisition: a cheaper alternative to multicomponent ocean-bottom cable surveys?

R. Gareth Williams, Graham Roberts
and Keith Hawkins, **Veritas**

Multicomponent, Ocean Bottom Cable (OBC) seismic surveys record both P-wave and S-wave data. A P-wave source is used and the recorded S-wave energy is converted from P-wave in the subsurface. Mode-converted processing typically assumes that the conversion from P-wave to S-wave occurs at the reflection point so that the energy travels downwards as a P-wave and upwards as an S-wave. The conversion from P-wave to S-wave depends on the rock properties above and below the reflection interface and also on the angle of incidence.

It is evident that conversion from P-wave to S-wave propagation not only creates S-wave energy but also reduces the amount of energy propagating as a P-wave. Since the conversion depends upon the rock properties and the angle of incidence, it is clear that the reduction in P-wave energy as a function of angle (Amplitude Versus Offset: AVO) contains the same rock property information as the mode-converted shear wave. Therefore, in principle, rock properties can be derived by either analyzing recorded mode converted energy or by analyzing the loss of energy in P-wave recordings.

Mode converted S-waves reach the surface at shorter offsets than the reflected P-wave. Therefore, it is necessary to use longer offsets for P-wave recording than for converted wave recording of the same information. Inversion of wide angle, or long offset, amplitude information cannot be done with conventional AVO methods based on approximations to the Zoeppritz equation. A non-linear method based on the exact Zoeppritz equation is shown to be a reliable estimator of shear wave and density information if a sufficient range of angles is recorded.

Both wide-angle AVO and multi-component OBC methods have practical problems and advantages that are discussed with examples in this presentation.

(#77-O) Structural style and growth history in Saudi Arabia

Hongbin Xiao, Abdullah A. Bokhari
and Randall G. Demaree, **Saudi Aramco**

Most of the hydrocarbon fields in Saudi Arabia are basement-cored uplifts. These structures are compressional, typically low relief, bounded by steep frontal fault, and backthrust in some cases. The most common trap type is a four-way closure, although subcrop-traps and fault-traps are becoming increasingly important.

We quantitatively assessed the growth history of each structure by adapting the concept of growth index, which is a numerical ratio of strata thickness in trough over crest. Every structure was given a set of four numbers (starting from 1 indicating no growth), each

indicating the severity of one of four phases of deformation: Carboniferous (Hercynian Orogeny), Early Triassic (Zagros rifting), Late Cretaceous (First Alpine Orogeny), and Tertiary (Second Alpine Orogeny) time, respectively. Maps of structural growth indicate that most of the structures have persisted from Carboniferous to Holocene. There is no clear relationship between structural orientation and the phase of deformation, although stronger deformation seems to have occurred along the Central Arabian Arch than in basins to the north and south.

(#195-P) Fractured carbonate reservoir characterization: a technique for early integration of production and performance data into 3-D geologic models

Lyndon A. Yose and Timothy L. Davis, **ExxonMobil**

Natural fractures are common to carbonate reservoirs and present significant reservoir characterization and modeling challenges. This study, focused on the Norman Wells field in northern Canada, highlights the value of using dynamic reservoir data, in combination with geologic information, to condition 3-D geologic models prior to scale-up for flow simulation. At Norman Wells, matrix and fracture properties were modeled separately using different information types and then combined into a total-permeability model. Fracture properties vary as a function of the mechanical stratigraphy and structural framework and were modeled using a two-stage approach. First, effective permeability data derived from well-test data were used in combination with matrix properties to isolate the fracture component of total permeability by reservoir zone for each well. Second, geometric fracture properties (orientations, sizes, densities) measured from core, image logs and outcrop data were used to construct discrete fracture-network models to assess flow anisotropy. Structural, stratigraphic, and facies information were incorporated into the 3-D model framework and used to guide the allocation of fracture properties away from well control. Modeling results showed that fracture influence was variable within the reservoir and that, locally, fracturing had a major impact on reservoir conformance. A significant benefit of incorporating dynamic reservoir data directly into the 3-D geologic models is that geologic information can be used to guide the distribution of the excess (fracture) permeability rather than ad-hoc adjustments in the flow simulator. The new static and dynamic models are being used for reserves and production forecasts, opportunity identification, and reservoir optimization.

(#295-O) Image enhancement below the pre-Khuff unconformity using prestack and poststack multiple attenuations

Mike A. Zinger, Khalid I. Hassan
and Richard G. Jerskey, **Saudi Aramco**

One of the principal processing challenges in Saudi Aramco is the attenuation of multiples. One source of multiples is the pegleg multiples generated between the Jilh and Khuff formations. This presentation will discuss several techniques used to minimize this energy, the effect on the final stack and, ultimately, the interpretation.

The attenuation of this energy is accomplished in the following ways: (1) the optimization of the velocity analysis by using demultipled input; (2) common depth point-based prestack demultiple algorithms; (3) an inner trace mute; and (4) an interpretation-driven poststack demultiple. No one process is adequate, but each provides incremental improvements in the attenuation of multiples. Taken together, the first three provided an optimized stack independent of the interpretation of the data, provided that the velocity analysis properly identified primary energy. The last step flattened the data on the Jilh horizon and assumed that the pegleg multiples would be parallel to this event. A very narrow, surgically applied FK filter was applied to the data below the Khuff, with the intent of removing only flat-lying energy.

The interpretation of the pre-Khuff data becomes crucial in the final process, as primary energy parallel to the Jilh, if it exists, is also removed. This process works when there is a difference between the dip of the primary energy and the multiple energy. The two examples shown in this presentation are (1) a dramatic subcrop beneath the pre-Khuff unconformity, and (2) the image of a deep Proterozoic graben that is barely visible on the non-demultipled data.