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GEO 2010 Abstracts Part IV

The following abstracts are a selection from those accepted for presentation at GEO 2010, the Ninth Middle East Geosciences Exhibition and Conference that was held in Bahrain on March 7–10, 2010. GEO 2010 was organized by Arabian Exhibition Management (AEM), the American Association of Petroleum Geologists (AAPG) in collaboration with the European Association of Geoscientists and Engineers (EAGE), and was supported by the Society of Exploration Geophysicists (SEG), Dhahran Geoscience Society (DGS), Bahrain Geoscience Society (BGS), Geological Society of Oman (GSO) and Emirates Society of Geoscience (ESG).

The abstracts that are published here by permission of the organizers represent the fourth group that primarily cover: (1) Structure and Tectonics; and (2) Applied Case Studies from the Middle East. The abstracts have been slightly edited and/or reworded so as to conform to a more common style and format; for example, capitalization of formal names for formations, geological periods and stages, etc. Some abstracts required rewording to clarify the scientific content or were submitted as short papers. Every effort was made to present these as concisely and accurately as possible. GeoArabia sent the pre-press version of all the abstracts to the primary authors for their approval, but regrettably some could not be reached or did not respond.

Throughout volume 16 of GeoArabia, four groups of GEO 2010 abstracts are now published so that a permanent record of these important studies is available to GeoArabia's readers and the international geoscience community.

(1) Structure and Tectonics

680888 Generation of *in-situ* stress map in Gulf of Suez and its impact from drilling high-angle wells, Egypt

A.M. Abuelfotoh and D.J. Dutta

The effect of magnitude and pattern of Earth's *in situ* stress is generally manifested on the shape of the boreholes. Stress around the wellbore induces deformation depending on several factors ranging from rock strength to the deviation of the well path. In the current study, a stress map is generated from borehole breakout information together with other wire-line logs from a reasonably large database. Both vertical and deviated wells covering a major part of the Gulf of Suez are considered for this study. The fact that stress-related breakout originates from the maximum tangential stress is the main criterion here. The tangential stress is a combination of forces such as the Earth's *in situ* stresses, drilled mud weight and pore pressure of the formation. Complimentary to the magnitude, breakout orientation indicates the direction of minimum *in situ* stress in the case of vertical wells. Stress evaluation in deviated wells requires multiple well input in a limited area to generate a stress tensor diagram that determines stress orientations with confidence. In a deviated well the breakout direction is controlled by *in situ* stress with respect to the trajectory of the well. The study reveals that the minimum horizontal stress (Sh) in the Gulf of Suez is aligned along two major trends. First, the main NNE-SSW trend, with an average orientation of 10°N exists in most of the region. The second trend is aligned NE-SW and has been observed locally at the central eastern and southwestern part of the Gulf of Suez, with an average orientation of 50°N. Most studies of the structural and tectonic history of the Gulf of Suez have concluded that two age-significant orientations prevail in this extensional rift. The Early to Middle Miocene rifting, yielded Sh direction of 55–60°N (rift-climax phase). The younger stress fields of the Late Miocene and Pliocene times rotated progressively counter-clockwise and yielded a 15–25°N direction that persisted into the Pleistocene time. The main trend therefore is mainly controlled by this

younger stress field of the Gulf of Suez rifting. *In situ* stress directions have strong impact in drilling high-angle wells in the Gulf of Suez. Proper placement of well trajectory with respect to *in situ* stress reduces instability in drilling; therefore, the need for realistic and accurate information of stress variation in this structurally complex terrain can be easily envisaged. This study presents an example of directional sensitivity of well trajectory and a successful drilling campaign based on the developed stress map.

665401 Integrated geophysical investigation of Al Hiyar area, eastern Abu Dhabi: Implications for structure of the frontal fold belts of Oman Mountains

S.A. Al Mesaabi, A.H. El Husseiny, A.A. Hassan and M. Ali

Gravity, magnetic and seismic surveys were conducted in Al Hiyar area, eastern Abu Dhabi, located on the border between the United Arab Emirates (UAE) and Oman on the western edge of the northern Oman Mountains, as part of a study to determine the subsurface structures and sedimentary sequences of the area. The interpretation of these new data was integrated with a new interpretation of reprocessed commercial seismic reflection profiles recorded close to the area.

We recognize five major tectono-stratigraphic sequences in the seismic profiles: (1) Mesozoic shelf carbonates, (2) Upper Cretaceous foreland (primarily Fiqa Formation), (3) Sumeini allochthon, (4) Upper Cretaceous to Lower Tertiary sequences, and (5) Upper Tertiary sequence. The seismic sections suggest a number of back-folded anticlines, which were probably initiated during Oligocene – Miocene times, corresponding to the beginning of the collision of Arabia and central Iran. In addition, the seismic sections reveal high-angle reverse faults that cut downward through the Mesozoic shelf carbonates and are interpreted to be related to the inversion of deep structures.

The residual gravity anomalies decline to the east of the study area. This is attributed to uplifted basement structures which probably resulted from a deep-seated, east-dipping reverse fault that was reactivated during the Late Cretaceous and Late Tertiary times. We modeled that the area contains a sequence of thick uplifted Mesozoic shelf carbonates to the west giving rise to high residual gravity anomalies. Magnetic anomalies are weak over most of the area suggesting no continuation of the Semail Ophiolite westward from its outcrop into the subsurface of the study area.

705381 4-D evolution of the Maradi Fault System, Oman

A. Al-Gahaffi and K. McClay

The 4-D evolution of multiphase strike-slip fault systems is generally poorly understood due to the structural complexities that develop along their strike, and their steep fault and stratal dips that are commonly poorly imaged in seismic surveys. The Maradi Fault System in Oman is an important more than 60 km long dextral strike-slip fault system that is poorly exposed. In the subsurface it is associated with a number of major hydrocarbon accumulations. In this study the main elements of the Maradi Fault System have been simulated using scaled analogue modelling. Both wet clay and dry sand analogue modelling experiments have been run to simulate deformation in a sedimentary cover sequence above releasing and restraining step-overs in a basement strike-slip fault system. The experiments were monitored by high-resolution, time-lapse photography, as well as digital laser scanning and by particle image velocimetry (PIV) monitoring. In this way the surface topographies were monitored (laser scanning) as well as detailed particle displacements and strain histories were measured (PIV monitoring). In the releasing step-over experiments an elongate rhomboidal pull-apart graben developed between the offset principal displacement zones (PDZs). Terraced oblique-slip extensional sidewall faults system developed along the boundary of the pull-apart basin. These sidewall faults changed kinematics along strike, from oblique-slip near the PDZs to extensional slip in the middle of the structure. A cross-basin fault system cut the flat bottom of the pull-apart basin and linked to the offset PDZs.

In the restraining step-over model a lozenge-shaped 'pop-up structure' developed. This was bounded by two sidewall, oblique-contractional faults that were arcuate in shape and curved inwards toward the main basement faults. At the end of the experiment, the retraining step-over offset PDZs were linked by a sinistral trans 'pop-up' strike-slip fault. Detailed displacement analyses and strain analyses are presented to illustrate the progressive evolution of the structures. The results of the scaled analogue modelling are compared to natural examples of strike-slip structures along the Maradi Fault System in Oman.

666001 Structural and tectonic history of the sedimentary basin in northern Iraq and the Kurdistan Region

M.B. Al-Gailani

The aim of this study is to address the main aspects of the structural and tectonic evolution of the sedimentary basin in northern Iraq and identify all the sedimentary cycles in detail from the Late Triassic period to Pliocene. The second part tackles the geohistory modelling of all the encountered source rocks in the basin and evaluates their maturation history and expulsion of hydrocarbons. The study of the structural and tectonic history of northern Iraq and the Kurdistan region describes in detail the evolution of the sedimentary basin. It involved constructing a series of isopach and facies maps accompanied by numerous schematic sedimentary cross sections covering the entire encountered sedimentary cycles from the Late Triassic to the Pliocene time.

The sedimentary sequence was subdivided into cycles defined by major unconformities with their corresponding conformity surfaces. Isopach and facies maps were constructed for each sedimentary cycle followed by detailed construction of lateral and vertical schematic sections identifying the various facies within each cycle and describing the transgression and regression episodes influencing the development of the various facies. The subsidence history during the development of each cycle was analysed and studied using a series of tectonic models and constructing several schematic cross sections showing the various tectonic and structural events affecting the development of each cycle.

The tectonic and structural evolution of the sedimentary basin was studied by constructing the thermal and subsidence history from 46 sites involving analysing 27 wells and 19 stratigraphic measured sections from the Kurdistan region and northern Iraq. Source maturation and expulsion history was achieved using a one-dimensional modelling programme with the results presented in a series of source rock transformation ratio (TR) maps constructed for each source rock sequence. The total amounts of expelled hydrocarbons are also presented in two regional maps covering the entire studied area showing the total expelled oil and the total expelled wet gas respectively. Finally, all the constructed maps presented and displayed in this study are displayed in geographic information system.

679668 Impact of South Oman salt halokinesis from fault interpretation

M.H. Al-Kindy and P.D. Richard

Since Precambrian time, the Oman region has been influenced by many tectonic regimes that resulted in different structural styles. The type and amount of tectonics vary significantly across Oman. As a result, a number of structural domains can be easily defined in South, Central and North Oman. The presence and thickness variation of the underlying Ara salt is one of the key parameters used to define these domains. In places where salt is absent or very thin, the effect and timing of far-field regional tectonics can be clearly demonstrated (e.g. Lekhwair High). However, in areas where the salt is very thick, the impact of far-field regional stresses is often difficult to distinguish from the local effect of salt withdrawal and salt dissolution.

In South Oman, salt halokinesis has dominated the deformation style and orientation of local stresses in Palaeozoic times. This resulted in a complex framework of salt domes, ridges and depressions, which have influenced any younger deformation events. Initially, sediments were deposited in local depo-centres (e.g. named as pods) and simultaneous differential loading and salt dissolution is interpreted to have been the main driving mechanisms of the deformation. It is important to note that the deformation happened without an external regional far-field driving stress regime. The final pod geometries are directly controlled by sediment supply, space accommodation and initial salt thicknesses. With ongoing thinning of the salt, the pods grounded progressively. Loci of depo-centres migrated following the salt availability. The most typical structures formed during this time are turtle-back anticlines, with extensional faults dipping away from the centre of the anticline. Surrounding these turtle back anticlines, narrow collapse graben structures have developed above salt ridges/domes (thick salt area) as a result of salt removal. Across South Oman, a number of depressions at the present surface topography formed above the deep thicker salt area, indicating that salt removal is still continuous today.

The presentation will concentrate on the early Palaeozoic halokinesis. We will illustrate the regional structural models with a series of key observations as well as demonstrate how the structural model can be used to help seismic fault interpretation, especially in areas of poor seismic quality.

680574 Tectonic effects on the hydrodynamics of the Arab-D reservoir in Eastern Arabia

M.J. Al-Mahmoud, M.H. Khalil and A.R. Moustafa

The Arab-D reservoir is exposed in Central Arabia and dips eastward into the Arabian Gulf. Late Jurassic extensional deformation, associated with opening of the Neo-Tethys Ocean and Late Cretaceous – Recent compressional deformation, related to convergence between the Arabian and Eurasian plates, affected the hydrodynamics of the Arab-D reservoir. The Late Jurassic extensional phase created the East Arabian basin which controlled the deposition of the Arab-D carbonates and anhydrites. The anhydrite at the top of the Arab-D is a seal for the underlying carbonates forming the regional flow unit of the Arab-D reservoir. The deeper parts of the East Arabian basin continued to exist in Eastern Saudi Arabia since it was created. This caused the groundwater to flow by gravity from Central to Eastern Arabia. The Late Cretaceous – Recent compressional deformation led to uplifting of the Zagros and Oman mountains, eastward tilting of the Arabian Plate, reactivation of pre-existing, NS-trending faults, and formation of the Central Arabian graben system. The uplifting of the Zagros and Oman mountains and eastward tilting of the Arabian Plate caused the groundwater to flow from structurally high areas in Central Arabia, the Zagros and Oman mountains to low areas in Eastern Arabia. The reactivation of pre-existing NS-trending faults created faults in the Arab-D, which include fault breccia or calcite-filled zones acting as barriers to fluid flow surrounded by damage zones that act as fluid flow conduits. This fault zone architecture caused deflections in groundwater flow and connectivity between reservoirs at regional and local scales. The Central Arabian graben system formed an EW-trending corridor of intensively fractured rocks which acts as a fast track for groundwater flow from the outcrops in Central Arabia to deep areas in the east.

669850 Characterization of the Hercynian Unconformity for prospect evaluation, Saudi Arabia

S.L. Al-Sulami, M. Ameen, M.M. Hariri and A. Osman

The Hercynian Unconformity in the Arabian Plate (Late Devonian to Early Carboniferous) impacts the hydrocarbon resources and therefore is an essential aspect of prospect evaluation and field development. We conducted a regional characterization of the unconformity using an integrated, multidisciplinary method, including borehole images, dipmeters, open-hole logs, cores, seismic data, vertical seismic profiles (VSP) and palynology. The study included 13 key wells with over 14,000 ft of borehole images (across the unconformity) and several hundred kilometers of seismic sections across key prospects and traps.

The study shows the unconformity is manifested in distinct modes in terms of: (1) unconformity facies: including conglomerate/breccia, paleosols, and disturbed zones due to soft sediments deformation; (2) angular discordance: including change in dip azimuth, or dip angle, or both; and (3) occurrence of tectonic faults. The above aspects of unconformity modes offer different hydrocarbon configurations. These include positive configurations that facilitate a sealing effect, potential reservoirs, or potential paths for hydrocarbon migration. In addition they include negative configurations that result in losses of potential resources, through weathering and erosion, of potential source rocks and reservoir rocks. Case studies of these configurations from mainland Saudi Arabia are presented and discussed in this study.

681975 Seismic evidence of strike-slip tectono-stratigraphy in the Hawtah Field

A.A. Al-Yahya

Hawtah Field is located in Central Saudi Arabia and constitutes a major structure within the Hawtah trend. The main objective here is to study the paleo-structures which existed during the deposition of the Lower Permian Unayzah Formation and how they affected both its depositional thickness and stratigraphy. Seismic impedance as well as seismic amplitude has been utilized to map the Unayzah two-way seismic time (TWT) structure of this complex field. The obtained TWT structure was then used to compute different seismic attributes to gain insight about the internal reservoir fabric. The TWT coherency map of the base Qusaiba hot shale indicates a clear presence of a dominating strike-slip tectonic regime characterized by steep faults that penetrates the Unayzah Formation at various levels depending on the location of the fault within the field structure. Visual comparison between the base Qusaiba coherency map and that of the reservoir suggests a possible link between the clearly observed strike-slip faulting at the Qusaiba level and the thickness and lithology changes observed at the reservoir level. The direct link between the two using seismic cross sections

is a subtle issue, due first to the complex reflectivity within the Qusaiba Member, and second, to the steep angle of the existing faults, even though it is possible to carry it out successfully at many locations.

The reservoir impedance map, using seismic inversion, is consistent with the available borehole image data at a number of wells within the area providing additional evidence of the link between the observed Qusaiba faults and the observed heterogeneity within the reservoir. The study concludes that the entire Hawtah Field is a large pop-up structure characterized by a strong strike-slip tectonic control on both the sedimentology and the stratigraphy of the Unayzah reservoir. This is suggested by the geometry of the bounding faults of the structure, and also the presence of intra-structure mixed faulting modes (i.e. both normal and reverse). Careful mapping of the observed faults leads to a better understanding of the reservoir heterogeneity and lithology, and therefore a more robust flow simulation models and the ability to plan more accurately future drilling operations.

680711 Paleobiogeography of the Permian Neo-Tethys shores

L. Angiolini, G. Muttoni, G. Crippa and V. Verna

The Permian was a period of marked climate change and plate-tectonic reconfiguration. Climate changed from glacial conditions at the dawn of the period to warm conditions in the Middle Permian. The Cimmerian terranes migrated from southern Gondwanan paleolatitudes in the Early Permian to subequatorial paleolatitudes by the Middle – Late Permian as the result of the opening of the Neo-Tethys Ocean. This opening was asymmetrical, with higher seafloor spreading rates for the central Cimmerian terranes (central Afghanistan, Pakistan and Karakoram) than for the western terranes (Iran), and it took place contemporaneously with the transformation of Pangea from an Irvingian B- to a Wegenerian A-type configuration. During this Early to Middle Permian tectono-climatic transition, bioprovincial patterns evolved rapidly across the southern and northern margins of the opening Neo-Tethys Ocean, as testified by the rich fossil record.

Here we place climate-sensitive biotic associations on paleomagnetically based paleogeographic reconstructions of the Gondwanan margin and the Cimmerian blocks for the Early and Middle Permian and use them to reconstruct the evolution of oceanic circulation patterns, latitudinal thermal gradients, and biogeography in this time interval. We show that, in the Early Permian, the tropical Gondwanan margin and the western Cimmerian terranes benefited from a warm subtropical surface current gyre, which was confined to low latitudes. At the same time at higher southern latitudes, the central Cimmerian terranes were affected by cold surface currents promoted by the Gondwanan ice caps that distributed cold biota toward the tropics. These results suggest that low-latitude, sea-surface temperature did not undergo significant cooling during the Gondwanan glaciation, and that there was a steep thermal gradient between the compressed tropical belt and the expanded cold high-latitude belt. This situation changed abruptly in the Middle Permian with the creation of current gyres in the newly opened Neo-Tethys Ocean that arranged biotic associations in distinct bioprovinces. Wordian brachiopods from the western Cimmerian terranes contain a significant proportion of Gondwanan taxa some of which are restricted to the Gondwanan margin (Tunisia, Turkey and Oman). Coeval brachiopods from central Cimmerian terranes are different and pertain to a separate, low-latitude bioprovince supporting the paleomagnetically derived differential drift of Cimmerian terranes.

680925 Fractures as indicators to 4-D fold development within the Zagros Fold-and-Thrust Belt, Iran

D. Brown, M. Oehlers and T. Rice

The Zagros Fold-and-Thrust Belt represents progressive deformation of Palaeozoic to Cenozoic sediments above a salt detachment, which in turn overlays inverted extensional faults in the metamorphic basement. The Cenozoic sediments of the Zagros contain some fine examples of exposed fractured carbonate sequences. Using Landsat 7 ETM+ imagery data, regional-scale fracture sets have been interpreted across the anticlines of Kuh-e Khurgu, Kuh-e Devin, Kuh-e Finu and Kuh-e Ginau in the Laristan domain, Southeast Zagros. Using Quickbird imagery data, field-scale fracture sets have also been interpreted across Kuh-e Khurgu. The results of the regional and field-scale fracture analysis show dominant fold axis-parallel, fold axis-orthogonal, and conjugate NW-SE and NE-SW fold axis-oblique orientations.

Utilising the 0.67 m resolution of the Quickbird data allows rapid, field-scale identification of fracture patterns. Mapping the fracture and joint sets alongside fold aspect ratio analysis illustrates

the deformation evolution of the folds, including the presence of, and disturbance by, reactivated basement faults. NW-orientated fracture patterns dominate anticlinal rose diagrams regardless of fold size, axial orientation or shape. This abundance confirms a local underlying basement trend striking roughly NW-SE. A balanced cross-section of the area was constructed, using the Landsat 7 ETM+ imagery and the newly released 30 m Global ASTER DEM data, showing salt-cored detachment folds above a series of reactivated basement thrusts that indicate both thin- and thick-skinned deformation.

The results of the satellite image interpretation are then integrated in 3-D Move and a geological model built. The restoration tools are used to validate the geological model and suggest alternatives where appropriate. Once a "best fit" structural history has been identified, the data are then used to capture the geometric strain history through time in 3-D Move. The strain information and other attributes (e.g. curvature) are used to generate a discrete fracture network that is controlled by the observed data. A multi-stage, 4-dimensional fracture model is proposed for all four folds of the area. This takes into account the incremental and progressive development of fractures as strain indicators within the fold.

705231 Petrogenesis and tectonic setting of island arc-metavolcanics from Um Samiuki area, southeastern desert, Egypt

M.M. El-Taky

The Um Samiuki area is located in the southeastern desert of Egypt. It is occupied by Neoproterozoic metavolcanics intruded by metadolerite and later by granitoid rocks. The metavolcanics of the investigated area underwent low-grade regional metamorphism related to green-schist facies during the Pan-African Orogeny. It has a low-K content and is distinguished into tholeiitic and calc-alkaline affinities, which range from basalt to rhyolite in composition. Trace elements and rare earth elements infer that Um Samiuki metavolcanics erupted in an island-arc setting and display typical island-arc geochemical signatures. It is characterized by large ion lithophile element (LILE) enrichments, low abundances of high field strength elements (HFSE) such as Ti, P, Zr, Hf and Ta with pronounced Nb anomalies and depleted heavy rare earth elements (HREE) relative to light rare earth elements (LREE); this refers to mantle-derived arc magma. Also, low Ti/V and high Ti/Zr ratios, low Nb/Y and Rb/Zr ratios, in addition to lower La/Yb < 5 indicate an intra-oceanic arc setting. The constant ratios of La/Yb *versus* La and Ta/Th *versus* SiO_2 through magma evolution refer to fractional crystallization of the felsic rocks through an island arc association. The presence of large amounts of pyroclastic and pillow lava infer that magma erupted in a submarine environment.

647377 Interpreted strike-slip fault elements in the First Eocene reservoir of Wafra Field, Partitioned Neutral Zone, Kuwait

N. Eloutefi, J. Smith and F. Al-Khaldi

The Wafra Field lies in the northwest part of Kuwait/Saudi Arabia Partitioned Neutral Zone (PNZ) and the First Eocene is the shallowest reservoir in the field. The structure of Wafra consists of two parallel anticlines, trending NW-SE. It is proposed that these anticlines are cut by NE-SW elements (strike-slip faults). Accordingly, structural compartmentalization has been created due to horizontal and vertical displacements, with some rotation in the horizontal plane especially in the southern area of the field. These elements are believed to play an important role in the development of structures in PNZ.

This structural domain represents the direct response to two major elements: the extension of the Red Sea to the west, and the compression of the Zagros crush zone to the east. Regionally, many observations have been detected suggesting the occurrence of these elements. These observations are: (1) Landsat images of Kuwait and Saudi Arabia; (2) sinuosity of the Kuwait coast line; and (3) structural offset of oil fields in PNZ area. i.e. Wafra, south Fawaris and Humma.

So far, micro-scanner image data has proved to be one of the best methods to provide evidence for the presence of these elements. Abrupt changes in bedding dip attitude, deviation azimuth, and facies plus the occurrence of intensive fractures are the main evidence for these elements (strike-slip faults). Structure and pressure maps have been integrated with image data to verify the regional distribution of these strike-slip faults in Wafra area. Current seismic data has insufficient quality to provide support for these interpretations.

680949 Basement characterization for Block 18, Yemen

R. Heinbockel and A. Al-Maktari

In the fractured basement play of Block 18 (Yemen) a granitic basement is expected to have the best reservoir potential and the basic igneous rocks (diorite/gabbro) the least reservoir potential. The basement lithologies of Block 18 may be divided into three reservoir facies: (1) granite; (2) metamorphic; and (3) basic igneous. These reservoir facies are likely to be lateral extensions of basement outcrops. Block 18 basement lineaments are expected to form complex networks and have developed over a number of phases. Local basement variations are influenced by a number of factors including basement lithology, the present-day stress field and tectonic factors associated with rifting in the basin.

2.5-D integrated gravity and magnetic modeling and enhancement techniques resulted in an improved definition of the basement. We identified basement blocks and fault zones and proved the heterogeneity of the basement in Block 18. We identified igneous bodies within the sedimentary section and highly magnetic structures within the basement. Based on the modelled densities and susceptibilities, we are able to classify the basement types as generally granitic in the south, as likely metamorphic in the central north and as partly basic igneous in the northwest. Based on the results from seismic, gravity and magnetics, existing wells and regional geological studies two new wells were drilled. The results from these wells fit with our studies and analyses in terms of structure and lithology as well as type and direction of fractures.

678782 Improved structural understanding of a complex anticline through advanced seismic processing: A case study from northern Iraq

J. Hoffmann, Ø. Engen, N. Bang, J. Nørgård and A. Harstad

The Tawke Anticline is situated in the Kurdistan region of northern Iraq in the folded zone of the Zagros Fold-and-Thrust belt. The region is characterized by folded Cenozoic carbonates and foreland basin siliciclastics, with considerable differences in mechanical properties. Rough terrain, narrow structures and strong velocity contrasts pose significant challenges to seismic imaging in the area. In 2006, DNO completed the first-ever 3-D seismic survey in Iraq with the objective of determining the subsurface structure of the Tawke oil field discovered in 2005. Since then, the seismic data have been processed three times with progressively more advanced techniques to meet geologists' and reservoir engineers' requirements for resolution and accuracy.

The first processing involved elevation statics and a fast-track time migration. The main purpose of this dataset was to perform early volume calculations and well planning. Despite several successful wells, the data showed clear limitations in imaging of complex thrust structures. The second processing project was initiated in 2007 using anisotropic pre-stack time migration based on the AutoImager velocity model building. This semi-automated method used the initially pre-processed data as input and provided significantly improved imaging of steeply dipping interfaces and faults. The key improvement factor was the AutoImager iterative migration velocity analysis producing a consistent seismic velocity model with anisotropy correction.

Seismic modelling and depth conversion tests were conducted in 2008 using 2-D image ray tracing techniques. Results showed significant ray path bending because of strong lateral velocity contrasts between Cenozoic carbonates and siliciclastics. This implies that time migration images are inaccurate and conventional depth conversion by vertical stretching is not applicable. To solve these problems, the Tawke 3-D data were reprocessed using pre-stack depth migration (PSDM) which migrates seismic events to their correct positions provided that the velocity model is correct. The PSDM results show better agreement between seismic events, well logs and vertical seismic profile (VSP) data and are consistent with the wider and gentler top reservoir geometry as predicted by ray trace modelling. Following the start-up of Tawke oil export on June 1, 2009, the PSDM data are used for reservoir management and infill well planning.

681941 Paleozoic volcanic reservoirs of Libya: A case study of the Cambrian – Ordovician Hofra (Gargaf) facies of Sirte Group reservoir, Tagrifit (Ora) oil field

M.I. Ibrahim

The Cambrian – Ordovician Hofra (Gargaf) reservoir of the Sirte Group at the Tagrifit (Ora) oil field in central Sirte Basin is a faulted and fractured NNE-trending pre-Upper Cretaceous buried hill. Production history of the reservoir reflects

a rapid oil production decline curve, early water encroachment or coning with spots of high peak oil production rate that overlaps with spots of high cumulative oil production. Such production pattern is common in fractured reservoirs.

The Sirte Group reservoir of the Tagrifit Field is lithologically composed in order of abundance of: (1) orthoquartzite-quartz-arenite; (2) volcanics which are composed of: porphyritic rhyolite, porphyritic rhyolite-dacite, and pyroclastic volcanic tuff and ash beds; and (3) orthoquartzite breccias in quartz arenite matrix. The reservoir is dissected by a major fracture system (probably striking northwest-southeast and dipping southwest) and secondary fracture system (probably striking northeast-southwest and dipping southeast) which provided essential permeability and porosity to produce the orthoquartzite quartz arenite facies and enhanced the permeability of porous-permeable white rhyolite-dacite volcanics.

The study integrated the production history with the available reservoir parameters and concluded that thickness of producing open-hole sections had no effect on the peak production rate and cumulative production of oil, and that the main controlling factors of Sirte Group high peak production rate and high cumulative production within the structural closure of Tagrifit oil field are: (1) the presence of matrix poro-permeable rhyolite-dacite volcanic facies; and (2) the presence of fracture poro-permeable orthoquartzite quartz-arenite facies. Volcanic rocks are reported in Cambrian – Ordovician sandstones reservoirs of the Paleozoic basins of Libya, their significance and contribution to the production pattern of these reservoirs can be predicted from the production pattern of analogous volcanic facies in Cambrian – Ordovician quartzitic reservoirs of Tagrifit, Amal, Augila and Nafoora oil fields.

728247 2-D Crustal seismic velocity structure beneath Quchan seismic network using inversion of local earthquake travel times

M. Javanmehri, M. Gheitanchi and S. Azhari

Quchan has been destroyed frequently from 1870 until now. This city which is located in central Kope Dagh region, northeastern Iran, has experienced four destructive earthquakes in 1851 (M 6.9), 1871-1872 (M 7.2), 1893 (M 7.1) and 1895 (M 6.8). These earthquakes caused widespread devastation and heavy human loss in Quchan and many surrounding villages. These events are the largest earthquakes which have occurred in the Kope Dagh in the past 160 years. What is responsible for these earthquakes is not yet clearly known. The Kope Dagh is a linear mountain range separating the shortening in Iran from the stable flat Turkmenistan platform. In its central part an array of active right-lateral strike-slip faults exists. These faults obliquely cut the range and produce offsets of several kilometres in the geomorphology and geological structure. The Quchan and Baghan faults are prominent faults of this area and are located north and northwest of Quchan. It is not known whether these faults continue to the town and south of it. In this study we attempt to answer this question with 2-D crustal seismic velocity structure beneath the Quchan seismic network and use inversion of local earthquake travel times. Finally we present and discuss evidence such as focal mechanism, topographic maps, and satellite maps.

680886 Structures of the Kirkuk embayment, northern Iraq: Foreland structures or Zagros Fold Belt structures?

W. Kent

Several anticlines in northern Iraq and Syria have been studied through the construction of balanced and restored cross sections. Based upon structural analysis each of the studied anticlines is a fault-propagation fold that developed due to Zagros related recent inversion of much older normal faults. Studies on the Iranian part of the Zagros fold belt have suggested that the regional variation in the character of the fold belt is related to weak detachment surfaces in the stratigraphic section, primarily the decollement developed near the top of the Hormuz salt where the salt is present. No evidence for Hormuz salt has been found within the Kirkuk Embayment, and although detachment surfaces contribute to the area's structural character, the prominent folds appear to originate mainly from basement involved faults.

Two distinct inversion structural trends exist; an E-W system and a NW system of inverted grabens. In Syria, several of the faults associated with the E-W trending system cut the basement on seismic data and have stratigraphic relationships suggesting that their displacement originated in the Neoproterozoic. In Iraq where a thicker sedimentary section is present, the available seismic data does not show the complete sedimentary section or fault systems' trajectories. While the NW fault system of inverted normal faults could be linked to the Zagros orogen by a

decollement surface in the sedimentary section, regional relationships and potential-field data suggest that this trend also is basement involved and has a Neoproterozoic origin.

677342 Tectonic escape (indentation) in Central Saudi Arabia: Possibility and exploration potential

M.H. Khalil, M.E. Muzaiyen, K.M. Hmoud and L.B. Ismail

Tectonic analysis indicates a high possibility of tectonic escape structures in Central Saudi Arabia which could bear significant hydrocarbon exploration potential. This study aims to introduce a new tectonic model that explains several surface and subsurface newly mapped structures in Central Saudi Arabia. Potential fields, seismic and surface geology data are integrated to accomplish this study.

Basement terrane analysis of the Arabian Shield and its eastern continuation beneath the sedimentary basin indicates the general north-south orientation with differences in width and composition. It shows that the maximum crust thickness is in the middle of the outcroping shield with a promontory extending 200 km towards the east in the subsurface (Central Arabian Arch) where Permian – Triassic (Khuff) marine carbonates directly overlay the basement. The crust shows gradual thinning eastward from this promontory till the offshore Arabian Gulf. Some terranes show wedging-out and others show narrowing against the eastern side of the basement outcrops. This pattern suggests the tectonic escape of the wedging out and narrowing terranes against the competent Afif Terrane since the infra-Cambrian accretion of Arabia. The terrane accretion occurred by westerly driven terranes collided against the thick promontory of the Afif Terrane causing dispersion towards the south and north through east-west accommodation zones. Long segments of unusual east-west surface structures (faults and strike of strata) over the boundaries of the subsurface basement promontory from north and south are thought to be a dragging of the dispersed terrane fragments at the promontory boundaries. West of these EW-trending zones, deformation is concentrated at the NS-trending terranes with curved hard link transfer zones. This infra-Cambrian tectonic setting is believed to have been reactivated during Phanerozoic tectonic phases to express its escape tectonics pattern further-up till outcrops. Re-distribution of the Phanerozoic stresses at that inherited basement fabric controlled the geometry of the sub-basins and their filling during extension phases. It also controlled the preferable locations of structural positive inversion during compression phases to form the fault-related fold traps. This approach explains the diversity of structural styles in the sedimentary cover (compression, transpression, and transtension) which formed simultaneously during Late Cretaceous compression but with different directions.

681129 Structural development interpretation of Idd El Shargi Field (Qatar) based on wide-azimuth 4C seismic data: New insights into salt-driven dome growth, timing, and implications for reservoir enhancement

E. Maili and R. Girbacea

This presentation shows the results of an integrated study addressing the structural evolution of the Idd El Shargi oil field, located offshore Qatar. By combining well and 4C wide-azimuth seismic data, we were able to build a model with a higher level of detail and genetically link the structure evolution in the context of the regional tectonic history. This project also allowed us to bring new insights into structural control of reservoir quality enhancement and compartmentalization, with implications for field development activities.

Idd-El Shargi oil field was discovered in 1960 and started producing in 1964. The hydrocarbons are mainly produced from stacked fractured carbonate reservoirs situated on a large NS-trending faulted anticline that has two salt-cored domes named Idd El Shargi North Dome (ISND) and Idd El Shargi South Dome (ISSD). Current production is sustained with an aggressive field development program through drilling of long-reach, multi-lateral horizontal producers and water injectors.

Our integrated seismic interpretation indicates that several regional tectonic- and salt-induced events have controlled the growth and faulting of Idd El Shargi. The main events and structural patterns can be summarized chronologically as follows. Early rifting extension caused NS-oriented basement faulting at the Khuff level. This event can be correlated with the regional continental extension during opening of the Neo-Tethys Ocean (Permian – Triassic). The basin deepening was marked by the deposition of the Sudair Formation (marine shales) and was followed by the Gulailah and Hamlah formations (with beds of silty marl, and anhydride streaks, graded with dolomites). At the same time regional extension induced salt

diapirism at ISND that was rapidly followed by salt withdrawal, causing a combination of dome growth and graben formation.

After the major top Triassic unconformity (top Gulailah - Hamlah), the whole region went through a period of carbonate deposition over a broad platform that extended across the Middle East. No major salt tectonic events are evidenced at ISND during deposition of Uwainat and Arab formations (Jurassic); however, NW-oriented faults, related to the ongoing regional Zagros rifting, are visible on the Arab D-Yamama isochron map. The regional dip at that time was towards the NE. The first signs of renewed salt activity can be seen on the Yamama-Kharaib isochron (Early – mid Cretaceous). Salt movement became more active after the deposition of the Shu'aiba Formation (Lower – mid Cretaceous), resulting in uplift and subaerial exposure, which generated localized enhancement of reservoir quality (i.e. permeability) due to carbonate leaching and dissolution. This event has major implications for field-development activities. The Nahr Umr deposition marks a major transgression and basin deepening; isochrones at this level suggest that no major salt activity/uplift of the ISND occurred.

Faulting was very active through Late Cretaceous, and predominantly NE-oriented faults developed across the entire ISND structure, especially on its crestal area. This event can be correlated with the Tethyan closure; i.e. Late Cretaceous – Paleocene Oman ophiolite obduction, followed by the Eocene – Holocene thrusting in the Zagros Mountains. As the younger NE-trending faults intersected the older NW-trending faults, fault-bound reservoir compartments were created. The fault intersection and cross-cutting relationships can be clearly imaged using max/min reflection curvature data from seismic. Detailed fault geometry mapping also suggests that overprinting of different faulting events, combined with changes in the stress field orientations, resulted in complex fault interaction patterns that can be best characterized as transpressional and/or transtensional tectonics.

706178 Mapping regional faults with geological, seismic and potential field data: A case study from Kuwait

R. Mulyono, R. Husain, A.H. Sajer, P. Singh, A. Prakash and N. Amar

The state of Kuwait is endowed with commercial hydrocarbon accumulations at Triassic, Jurassic, Cretaceous and Tertiary levels. These accumulations are dominantly structural entrapments affected by multiple sets of faults. The faults not only play a dominant role in structure formation but also control flow characteristics of the tight reservoirs by fracturing. In view of the above, a regional fault mapping initiative has been taken up.

In a synergistic approach gravity, magnetic, 2-D and 3-D seismic, image log and core data has been analysed to map the regional fault framework and to evaluate its role in hydrocarbon entrapment. Innovative visualization techniques such as 3-D curvature, spectral decomposition and semblance volume are employed for enhancing the subtle fault expressions. These faults mapped in the areas of 3-D coverage are linked to the regional framework brought out by the 2-D and potential field data.

The structural framework of Kuwait is broadly defined by two major elements. The NS-trending Kuwait Arch is the most conspicuous feature, which encompasses Burgan, Bahrah, Sabiriyah and Umm-Niqa structures. The NW-trending West Kuwait High encompasses Umm Gudair, Minagish, Kahlulah, Kra Al-Maru and Mutriba structures. These dominant trends are offset by dominantly EW-, ENE- and NE-trending cross faults. These faults and associated structures evolved at different times and as a result of different causative mechanisms. The Kuwait Arch represents basement-involved deformation with multiple phases of reactivation while West Kuwait High is located on gravity magnetic lows, indicating diapirism as the causative mechanism for structuration. The study established the usefulness of regional fault system mapping in deciphering the tectonic history and controls on hydrocarbon entrapment in Kuwait.

680239 The applicability of gravity gradiometry as exploration tool in east Dubai, United Arab Emirates

J.P. Protacio, J. Watson, F. van Kleef and D. Jackson

The east of the Emirate of Dubai is dominated by the geologically complex western thrust front of the northern Oman Mountains. This deformation front is the boundary between the western foredeep basin and the eastern Oman fold-and-thrust belt. Complex geology makes conventional exploration challenging. The reservoir (Thamama Group) structures are thrusted anticlines with the overlying Tertiary units, which show large-scale thrusting as well. The Lower Cretaceous Thamama Group limestone is one of the main hydrocarbon reservoirs in the Middle East. It forms a major

hydrocarbon-producing reservoir in the UAE, Iraq, Bahrain and Oman and has a high hydrocarbon potential in southeast Iraq, offshore Oman and offshore northeast Saudi Arabia. Due to the significant density contrast between the reservoir and the overlying sediments, Margham Dubai Establishment commissioned an airborne gravity gradiometry (GG) survey to improve the confidence in top reservoir location and identify potential exploration targets. GG, magnetic and LiDAR data were acquired followed by an integrated interpretation of these and other available datasets.

The survey is designed around the airborne GG technology known as the full tensor gravity gradiometer (FTG). GG measures the rate of change of the Earth's gravitational field while conventional gravity (CG) measures the vertical acceleration. Acquired from an aircraft, GG has a strategic advantage over CG due to the resolution limitation imposed by the differential global positioning system (DGPS). The DGPS limits airborne gravity resolution to > ca. 4,000 m wavelengths while GG can resolve wavelengths of > ca. 300 m. The shorter wavelengths are crucial to accurately model the geology above the reservoir.

In complex geology, multiple lithological units contribute to the GG signal. To map the reservoir, it is vital to isolate its response from the overlying geology. The high resolution GG data facilitated an accurate 3-D shallow earth model (SEM) to be built and thereby image the reservoir. Modelling of seismic sections constrained by GG and magnetic data exploits their complementary nature. Seismic data respond well to horizontal discontinuities while potential field data respond well to vertical discontinuities. This produced a geologically realistic SEM. Forward calculation of the GG signal from the 3-D SEM was performed and then subtracted from the observed signal. The SEM corrected data were then used to interpret the Thamama reservoir structure.

666097 North Oman fault geometries in outcrops: Analogues and subsurface

P.D. Richard and M. Al-Kindy

North Oman offers a rare opportunity for making outcrop observations of faults developed in formations that are also the producing reservoirs in the subsurface. It is possible to look in great detail at fault geometries and associated fault damage zones, both in map view and cross sections. From these observations it is possible to establish the geometrical rules that will help to build static models and interpret faults on seismic. It is also possible to illustrate the impact of the simplifications which are inherent to the static modelling process and assess whether they are acceptable or not to define the most suitable modelling strategy.

The main objective of this presentation is to share how we, in Petroleum Development Oman, are taking advantage of the outcrops, in combination with databases from sandbox models, to develop the structural geology skills and foundation of our geologists and seismic interpreters alike. We will first illustrate on a regional scale, the Oman structural domains and their specifics in term of structural styles and fault geometries, as well as the evidence for and the relative timing of the main deformation events. We will then take the learnings of the regional structural history into the seismic interpretation world to better constrain seismic interpretation. And finally, we will zoom-in to the field and bore-hole scale to illustrate the fundamental fault properties which can be quality controlled (QC'ed) to help build simplified but robust static models. This presentation is directly linked to the pre-conference field trip about North Oman fault geometries.

701313 Magnetically inferred basement structures in the central part of the Kuwait Arch

P. Singh, R. Husain and A.H. Sajer

Magnetic data over the Kuwait Arch concealed by overlying Phanerozoic strata, shows a broad circular magnetic high over the Kuwait Bay area and a conspicuous EW-trending associated magnetic low on the north over the Bahrah area of nearly comparable amplitude. The gravity and seismic data show a major high over the same area which is consistent with the tectonic events in the area. The present study is focused on the conspicuous magnetic low over the crestal part of the dominantly NS-trending Kuwait Arch where a comparatively complex Bahrah oil field is located. On the basis of magnetic signatures, it appears that shield elements (basic metavolcanics like basalt and rhyolite with high magnetic susceptibility) extend beneath Phanerozoic cover resulting in a dipole signature of magnetic anomaly. In order to infer the basement structures lying beneath the Bahrah and Kuwait Bay areas, magnetic anomaly data has been processed, filtered and integrated with the gravity and seismic data.

To locate the observed magnetic anomalies directly over the magnetic source bodies that caused these anomalies, the total magnetic intensity (TMI) data has been transformed into reduced-to-pole (RTP) map. The TMI data was also processed for 3-D analytic signal and produces a maxima over the magnetic contacts regardless of the direction of magnetization. The enhancement of magnetic anomalies associated with faults and other structural discontinuities was achieved by the application of bandpass filter (4–12 km) to the TMI-RTP data which defined the best continuity and resolution of the linear features.

Basement structures, faults and shear zones can easily be traced along linear features which prove the effectiveness in the interpretation. Faults and shear zones coincide with zones of significant changes in magnetic and structural characteristics. The NNE-SSW orientation of basement-involved structures over Bahrah and Kuwait Bay area are easily identified on band-pass filtered TMI-RTP data. The Bahrah oil and gas wells producing from Cretaceous and Jurassic levels are located on magnetically inferred basement highs. Basement structural highs control the structural development of the sedimentary cover. The magnetic data after integration with gravity, seismic, borehole and geologic data reveals the elements of basement structures over which the Bahrah oil field is located. This study can assist in effective placement of future wells in Kuwait Bay and Bahrah area.

680655 A tale of two glaciations

P. Spaak and M. Ross

Two major glacial events left their imprint on the Palaeozoic successions of Arabia. Glacial and post-glacial sediments of the Al Khlata and Unayzah 'formations' are the reservoirs of numerous Permian – Carboniferous fields in southern and Central Arabia. Latest Ordovician glacial deposits and erosional remnants form the target of wells and prospects in south and north Arabia. Moreover, the base Silurian post-glacial flood is the most significant (Qusaiba) source rock of the region. The extent of the Late Ordovician and Permian – Carboniferous 'ice-sheet' is tremendous, covering in both cases very large parts of Gondwana. In that context, it is remarkable that during the Devonian, ice-cover over Gondwana is limited, notwithstanding a 'very polar' position of the super-continent in that period. In this contribution, we will document the observations outlined above and will discuss the combination of plate configuration, polar position and the Hadley Circulation as a possible explanation for a relative ice-free Devonian compared to the preceding and subsequent periods.

(2) Applied Case Studies from the Middle East

680482 Mapping the internal structure of sand dunes in the Jafurah Desert of eastern Saudi Arabia using ground penetrating radar

A.A. Adetunji, A.A. Al-Shuhail and G. Korvin

Three-dimensional ground penetrating radar (GPR) surveys were conducted in two locations to map the internal structure of sand dunes in eastern Saudi Arabia. The 400 MHz antenna that was used achieved a 4 m to 6 m penetration depth. The excellent resolution of about 8 cm made it possible to identify the major internal features, such as cross-stratification and bounding surfaces. The recorded radargrams proved useful in understanding the dune's growth and migration in this area. Results suggest that GPR is an important tool in any study of recent sand dunes as analogues of hydrocarbon sandstone reservoirs of aeolian origin. Laboratory analyses showed the presence of elevated amounts of iron-oxide-bearing minerals in some dark layers of the sand in the study area. These elevated iron amounts might be the reason behind the strong electromagnetic impedance contrasts that ultimately generate reflections on the GPR images.

698758 Velocity modeling and static corrections for complex near-surface, Muglad Basin, Sudan

H.A. Ahmed

An important part of statics solution is the determination of the velocity and depth of the near-surface layer. This information can be obtained from an uphole survey, refraction first break methods and sometimes from shallow refraction reciprocal surveys. Uphole surveys provide the most reliable results but the spatial coverage of this method is always limited. Shallow refraction reciprocal surveys are only effective for certain geological situations. Refraction first break methods provide an attractive solution but the method depends heavily on the data quality of the refractor. By using first-break picks in a range of given common depth points (CDPs) for apparent

velocity and intercept time, the velocity and depth for the weathering and near-surface layers can be adequately estimated based on a local constant layer assumption. By repeating this process for all CDP ranges, a good refinement of a 2-D/3-D velocity model can be built. This method improves refraction statics solution.

This study presents uses of a sufficient amount of direct arrival and refraction picks data from 2-D and 3-D surveys in the Muglad Basin to extract the apparent velocity and intercept time from overall behavior of the picks. By replicating this process on multiple locations across the survey, an initial velocity depth model was built and used in calculating the velocity and depth of weathering layers accurately. This procedure provides an alternative way to solve one of the main challenges in static correction process.

680453 Practical implementation of wave-equation datuming for resolving near-surface problems

K. Al Dulaijan and S.M. Al-Saleh

Complicated near-surface geology and rugged topography can degrade the quality of seismic images. Time shifts or statics are still the work horse for resolving near-surface related problems. These shifts are usually computed from simple near-surface velocity models. More recently, refraction tomography was used to build more sophisticated models. The limitation of statics is that they are based on vertical ray-path assumption. When this assumption is violated, as in areas of complex geology, this solution fails to resolve the distortions caused by the lateral velocity variations. Wave-equation datuming (WED) is a powerful tool to resolve near-surface related problems. It was introduced about thirty years ago but still is not yet a production tool, due to its need for accurate velocity models. Unlike conventional near-surface solutions, WED does not fail for complex near-surface models, such as those of refraction tomography. In this presentation, the evolution of conventional near-surface solutions is reviewed, and then those solutions are compared to WED. Also, we discuss how WED can be practically implemented in a production environment by showing a processing workflow, which can handle the data regularization and interpolation as well as velocity model building. This is demonstrated using a 2-D seismic line acquired in an area with a challenging near-surface geology.

666804 Remote sensing in aid to geoscientists

A. Al Mawali, S.H. Al Balushi, I.S. Quseimi and A.S. Tabook

Over the years the use of remote sensing (RS) in Petroleum Development Oman (PDO) has evolved from being seen as providing general surface information images for seismic and engineering planning activities to an essential and cost-effective tool to support many other added value E&P activities. With the increase in the number of satellites and their spatial resolution and different type of sensors, accurate and detailed images can be acquired at a lower cost. This opened up new applications for oil industries including high-accuracy surface deformation monitoring. Satellite images /data and aerial photos are used to provide an overview of the regional geological setting, pre- and post-plan 2-D and 3-D seismic surveys, engineering construction activities, selection of exploration well sites, monitoring environmental impact and pipeline transfer of hydrocarbons. This study demonstrates the varied applications used in oil and gas activities including surface deformation monitoring and enhanced oil recovery (EOR) projects in support of reservoir surveillance and geological modelling.

679666 Prediction of apparent cohesion, angle of internal friction and Poisson's ratio of various types of rocks using laboratory measured unconfined (uniaxial) compressive strength

M. Al-Awad and B. Al-Anazi

The evaluation of Mohr-Coulomb failure criterion as well as other mechanical properties for reservoir rocks is essential for well planning, development and characterization of oil and gas reservoirs. This is because the understanding of the rock-stress relationship can solve many reservoir problems and avoid cost of remedial work. For example, a Mohr-Coulomb failure criterion may be used for borehole instability analysis, water-injection design, hydraulic-fracturing design, production-optimization techniques, compaction and sand-production prediction, etc. A Mohr-Coulomb failure criterion is a function of the apparent cohesion and the angle of internal friction. The evaluation of these two parameters requires testing of many rock samples using an expensive and time-consuming triaxial testing set-up.

In this study, a correlation between the apparent cohesion and the unconfined (uniaxial) compressive strength was developed. It is based on laboratory data of more than 282 rock samples of different types obtained from the literature. The correlation coefficient of the developed correlation equals to 0.88. Verification of the developed correlation using data from other references has shown an average error of estimation less than 10%. Unfortunately, some odd predictions were also noticed and can be attributed to measurement errors. Therefore, the Mohr-Coulomb failure criterion's parameters as well as Poisson's ratio can be estimated using the developed correlation based on fast and cheap measurements of the unconfined (uniaxial) compressive strength.

684096 Cost-effective, high density, wide-azimuth seismic sampling

T.M. Al-Ghamdi, P.I. Pecholcs and J.A. Musser

With most of the giant oil and gas four-way closure reservoirs discovered on land, we are now challenged with generating low-relief stratigraphic prospects from sparsely sampled spatial grids. To reduce risk, we propose a cost-efficient sampling scheme, which provides a full range of source and receiver offsets over a full range of azimuths within a square patch. This increase in source and receiver density is achieved by reducing the number of geophones per station, increasing the number of Vibroseis fleets, and using a combination of slip-sweep, independent simultaneous source (ISS), and distance separated simultaneous source (DS3) recording techniques to maintain high production levels and high trace density for improved seismic data quality at reservoir objectives.

Recent field tests have shown that a reduction in the number of sensors per receiver group combined with an increase in source/receiver sampling density has a minimal impact on seismic data quality. Such trade-offs shift the main focus of random and coherent noise attenuation from the field arrays to the processing center. With the increase in recording channels and the reduction in the number of geophones in the field (or the use of single digital sensors per station), the overall cost of a seismic crew is minimally impacted.

To achieve the optimum wide-azimuth square patch design, Vibroseis source points (VPs) can be positioned outside a dense receiver line patch. Although the source stations in such a design are typically reoccupied, the overall source productivity can be doubled (or better) by using two or more simultaneous Vibroseis sources separated by the width of the patch. This distance separation will also reduce interfering cross-talk and harmonic noise interference from the other Vibroseis sources. Equivalent sensor roll-rates can be easily achieved by reducing the source line interval (and increasing the resulting source density for better sampling). This balance between source and receiver effort provides a superior spatial sampling grid with minimal impact on existing seismic crew configurations. We show how this new seismic crew configuration and design provides superior reservoir characterization with only an incremental increase in survey cost.

680582 Fault detection using azimuthal coherence attribute: Case study, Central Saudi Arabia

F.M. Al-Qahtani, A.A. Al-Shuhail and S. Al-Dossary

Delineating faults is a challenging task, particularly if the faults run parallel to the strike azimuth. Normally, dip azimuth faults can be easily identified by traditional time slice methods. The coherence attribute is widely used for fault interpretation and determining orientation in addition to analysis of stratigraphic features. Chopra introduced a new method (Chopra, 2002) taking advantage of the azimuthal variation of seismic signature and coherence. Chopra's (2002) approach calculates the coherence between azimuthal data subset stack volumes. This study will produce four sub-volumes, sorted according to different azimuths plus the original volume. After that, we will apply the coherence attribute to all volumes and then compare coherency volumes having different azimuths with the original volume. The result of azimuthal coherence technique shows better fault mapping, especially those faults whose trends are perpendicular to the sorting azimuth. This study reports the occurrence of a system of discontinuity, trending northwest to southeast, which appears in the coherence time slice through the NE-SW azimuth-limited volume. In addition, the coherence time slice of the E-W azimuth-limited volume reveals more discontinuities where we expect faults and fractures to exist.

680490 Fractures detection using multi-azimuth diffractions focusing measure: A feasibility study from the Arab D reservoir

A.A. Aldajani and S. Fomel

3-D azimuthal P-wave post-stack seismic data has been analyzed to investigate the feasibility of using multi-azimuth scattering and diffractions focusing measure to detect azimuthal anisotropy anomalies at the Arab D carbonate reservoir; hence, assisting in the identification of potential fractures (i.e. sweet spots). Earlier studies and numerical examples demonstrated the azimuthal variations of scattering in vertically fractured media. Azimuthal variations of the focusing measure for the scattering energy and diffractions are estimated from stack data along a test 3-D multi-azimuth sub-line, after segmenting the data into four azimuthal sectors (stacks), each 45 degrees wide, and separating the diffractions and scattering from the reflections, using the plane-wave destruction technique. The analysis suggests the presence of azimuthal anisotropy anomalies in the focusing measure and they are generally oriented E-W (approximately N85°E). This conclusion is consistent with the results obtained by using an independent seismic technique which is based on a different but more accurate 3-D analysis using 3-D azimuthal pre-stack reflection moveout, to study the amplitude variations with offset and azimuth (AVOA) and the normal moveout (NMO) velocity. The intensity of the azimuthal anisotropy anomalies in the focusing measure (hence, potential fractures), along the seismic profile, is also consistent with the results obtained from 3-D pre-stack azimuthal anisotropy reflection moveout analysis. The structural geology of the area supports the results of this study. This is the first attempt to apply azimuthal scattering and diffraction focusing measure technology as a tool for fracture detection in Saudi Arabia. The technique is fast since it is applied on stack data, as opposed to 3-D pre-stack reflection moveout. This technology could be applied to fracture detection by complementing existing seismic methods; especially in cases where the 3-D seismic azimuthal data acquisition is rather challenged and the application of full 3-D pre-stack AVOA and NMO velocity analysis for the target reservoir is less adequate.

678477 The land-streamer acquisition system to map the sand dune base

H. Almalki, T. Alkhalifa, R.M. AlZayer and A. Alanezi

Complex near-surface structure is a major problem in land seismic data. This is more critical when acquisition takes place over sand dune surfaces, where the base of the sand acts like a trap for energy and depending on its shape can considerably distort conventionally acquired seismic data. Estimating the base of the sand dune surface can help model the sand dune and reduce its harmful influence on conventional seismic data. Among the current methods to do so is drilling upholes and using conventional seismic data to apply static correction. Both methods have their cost and limitations. For upholes, the cost factor and the inability of upholes to provide continuous model is well recognized. Meanwhile, conventional seismic data lack the resolution necessary to obtain accurate modeling of the sand's base. We have developed a method to estimate the sand base from land streamer seismic acquisition that is geared for sand surfaces. Land streamer acquisition not only provides a more efficient data acquisition system than the conventional spiked geophone approach, but in our case the land streamer provided better quality data, with broader frequency bandwidth. Such data enabled us to do proper near-surface velocity estimation that resulted in velocities that are very close to those measured using uphole methods. This fact is demonstrated on a couple of lines acquired near upholes, and the agreement between the seismic velocities and the upholes is high.

681055 Ocean-bottom seismic in the Arabian Gulf: Adapting acquisition parameters to the environment

K.A. Berteussen and Y. Sun

A summary of our analysis and modelling results from a study of a 2-D 4-Component (4C) Ocean-Bottom Seismic (OBS) dataset acquired in the shallow-water environment typical of the Arabian Gulf is presented. Our study illustrates both the challenges and opportunities of application of 4C OBS in such environments. The 2-D 4C OBS dataset was acquired with receiver spacing of 25 m in the Arabian Gulf in water depth of about 10 m and a hard bottom with P-wave velocity varying from 3 to 4.8 km/s. Because of the shallow water, the hard bottom, and relatively long seismic wavelengths,

the problem of energy partition and P-S wave conversion at the water/rock interface may not be adequately addressed using classical plane wave theory. We use numerical full waveform elastic modelling to understand the influence of shallow-water wave interactions between the air/water/rock interfaces on 4C seismic data. Comparative analysis of field records, logs and synthetic data is then used to investigate and assess the quality of existing 4C OBS data and their potential.

The preliminary results of this comparison are: (1) the quality of multi-component data is dictated by the geological conditions and follows the source physics and sediment physics. The 4C data could be quite reliable; i.e. the instrument response is basically good. (2) The shallow-water environment of the offshore United Arab Emirates (UAE) is unique and very different from other major offshore fields such as the North Sea and the Gulf of Mexico. This results in strong P-S wave conversion at the water/sediment interface. It also results in an efficient equivalent shear-wave source; i.e. this gives a better way to extract shear-wave information from 4C data, which again has important implications for waveform-based seismic processing and inversion. (3) Signal/Noise ratio seems low. This is partly due to inadequate acquisition design (aliasing), but also due to the inherent complexity of multi-component physics. (4) The C-wave at cap/reservoir interface is strong which is a good indication for reservoir description; i.e. bypassed hydrocarbons, permeability heterogeneity and resolution.

In summation we believe that 4C Ocean-Bottom Seismic is promising for the offshore UAE fields, but the acquisition parameters need to be adjusted for the special environment. This implies smaller shot/receiver spacing and longer time delay between shots, which obviously will have implications on the acquisition cost. Finally, more acquisition tests should be done.

680442 Land seismic data regularization: Overcoming urban acquisition limitations

R. Burnstad and A.A. Al-Mubarak

Prior to future reservoir development, Saudi Aramco embarked on an urban 3-D seismic data acquisition project over the Dammam oil field located in the Eastern Province of Saudi Arabia. As expected, the 250 sq km Vibroseis survey proved to be a processing challenge. Field data quality was impacted by: (1) an outcropping hard layer with extensive faulting and fracturing from reservoir to surface; (2) restricted source size and access within urban areas; (3) variable receiver array dimensions within urban areas; (4) high levels of source generated, scattered and cultural noise; and (5) complex near-surface geology. It soon became apparent that irregular positioning of source locations throughout urban areas meant noise suppression procedures could only be applied in two dimensions. To implement more powerful three-dimensional filtering, a solution for irregular source positioning became the central issue. Extensive testing resulted in an innovative data regularization workflow designed to proceed 3-D noise filtering.

Initial processing steps using standard noise removal techniques were unable to produce an interpretable volume. A number of pre-stack custom techniques, such as frequency-domain median filtering and frequency-distance deconvolution, were then implemented. Unfortunately, pre-stack time migration stacked images continued to be disappointing. A study was made to identify the underlying reasons for the failure of post-stack images when noise suppression appeared to work pre-stack. A data regularization workflow to allow 3-D noise suppression was identified as the best solution. Comparison of post-stack images proved fault details could be imaged, thus providing a usable 3-D volume for field development.

680439 Improved extraction and quality control of pre-stack seismic attributes

R. Burnstad and T. Keho

We present a procedure for improved extraction and quality control of pre-stack seismic attributes from wide-azimuth 3-D land surveys. Both the pre-processing and extraction stages of the procedure rely on a target-oriented, multi-term decomposition algorithm similar to that used in surface consistent processes; such as, statics, amplitude balancing and deconvolution. Quality control plots indicate that the decomposition procedure produces pre-stack attributes, which correlate better with porosity models derived from well logs. Decomposition allows consideration of other effects, such as anisotropy prior to Poisson reflectivity estimation from amplitude *versus* offset measurements. Our method utilizes normalization at two stages: (1) during processing, trace normalization factors are computed using a large time window defined by the target horizon; and (2) normalization is applied to the extracted attributes. During the first stage, a large background time window is selected

for normalization on a swath-by-swath basis in a source, receiver, offset and azimuth consistent manner. Both the offset and azimuth terms in this step do not vary significantly with spatial position. The second stage consists of four components: (1) swath-by-swath amplitude mode before noise removal; (2) swath-by-swath deconvolution mode; (3) swath-by-swath amplitude mode post-deconvolution; and (4) survey wide amplitude mode prior to AVO measurements. The second stage occurs after AVO analysis. Here we normalize target Poisson reflectivity measurements by an estimate taken across a large background time window. This stage is performed in a subsurface consistent manner with offset and azimuth terms allowed to vary spatially across the survey area. Application to a 3-D survey over a carbonate oil field in Saudi Arabia showed correlation of pre-stack attributes with the oil-water contact. Synthetic models indicate that the correlation is due to porosity variation, not fluid type.

670146 The role of non-seismic methods in near-surface solutions: Applications of seismic-gravity joint inversion and redatuming in South Rub' al-Khali, Saudi Arabia

D. Colombo, P. van Mastrigt, A. Al-Dulaijan, M. Mantovani, M. Sfolciaghi and T. Nafi

Onshore seismic data from the Middle East are adversely affected by near-surface and intermediate-depth velocity anomalies. The correct estimate of the near-surface velocity field is fundamental to obtain reliable seismic images. Conventional velocity model building workflows based on refracted arrivals (i.e. first breaks - FB) fail to appropriately reconstruct the shallow velocity complexities in the presence of large velocity inversions, sharp lateral velocity changes and noisy FB. In such cases, the integration of seismic with additional geophysical measurements (i.e. gravity-EM) can solve the shallow velocity modeling problem. Simultaneous joint inversion (JI) is an elegant and analytic method to address geophysical data integration. It is implemented in this presentation for velocity model building in South Rub' al-Khali by taking advantage of the availability of high-resolution gravity data coincident with the seismic acquisition. The analyzed 2-D seismic lines are sampling different near-surface geologic conditions such as dunes, sub-cropping carbonates and karsts. This corresponds to various degrees of complexity in the near-surface velocity field and related distortions introduced in the seismic image when a conventional "statics" approach is used. An alternative approach to statics solutions is then explored by simultaneous JI of FB and gravity data residuals for the shallow velocity and density fields. Pre-stack wave-equation redatuming (WED) is then used to model and remove the effects of complex velocity patterns from the seismic data. Various degrees of improvement are obtained with the discussed workflow depending on the severity of the near-surface velocity complexities and shallow geologic conditions. The analysis of the results identifies specific roles for non-seismic methods for the solution of near-surface problems in land seismic data processing.

703974 Acquisition and processing of 3-D dual-sensor towed marine streamer data

A. Day, T. Klüver, A. Long, M. Widmaier, B. Osnes and A. Burke

Traditionally, towed marine cables measure the seismic wave field using only pressure sensors (hydrophones). By contrast, in a dual-sensor streamer, independent measurements of the total pressure and particle velocity wave fields are obtained using collocated sensors. These two measurements of the seismic wave field can be combined in processing to separate the wave field into up- and down-going components. 2-D case examples have demonstrated that this procedure is both robust and accurate. This concept has now been extended to 3-D acquisition geometries. It has been shown that 3-D dual-sensor streamer acquisition avoids exposure to weather, sea-state and streamer spread control downtime by efficiently towing the entire 3-D streamer spread deep and at one common depth. Removal of the receiver ghost effects simultaneously boosts both low and high frequencies beyond any result achievable with conventional hydrophone-only streamers, and maximizes low-frequency signal-to-noise content required for accurate seismic inversion and reservoir description. These applications are illustrated using data examples from a number of 3-D dual-sensor streamer surveys.

680519 The main advantages to use the integration between geology and artificial intelligence techniques to interpret image logs: An example from Algeria

R. Di Cuia, D. Ferraretti, G. Gamberoni and E. Portier

Image logs hold important information about the subsurface sequences and they provide information about bedding and fault/fracture spatial distribution and characteristics. They can supply insight on the rock texture, textural organization and porosity types and distribution. To reduce the subjectivity of the interpretation and cut the interpretation time we developed and tested a new semi-automatic process for image log interpretation using a new software. This process led to the development of an expert system (called I2AM) that exploits image processing algorithms and clustering techniques, to analyze and classify borehole images. This system extrapolates the maximum amount of information from the image logs by considering not only the surfaces that cut the borehole but also the textural features of the images.

Once the image logs are analysed the application of clustering techniques to the values extracted from the borehole images supply a consistent classification of the images and the propagation of this classification along the logged section. In this way, we can automatically extract rock properties information with two main advantages: (1) avoid the subjectivity of the interpretation; and (2) reduce the interpretation time. The final result of this process is a set of "image facies" identified along the image log obtained by a largely automated log interpretation, although some level of human interaction and correction is still necessary. We define the clustering application as semi-automatic because the interpreter can decide, based on his geological background and on the geological characteristics of the logged section, to keep the clusters/classes proposed by the system or modify the number of clusters/classes. The clustering process and the propagation of the classes along the logged section is very fast (30 seconds) allowing an interactive approach, producing several scenarios with different number of classes and/or allowing a quick update of the image log interpretation once more data/knowledge is acquired. This approach was tested on 5 wells from North Africa where a previous image log interpretation was performed. The new interpretation based on this system made three years later (with more data and information) produced more refined results in very short time.

706271 Depth velocity model optimization using beam migration in a Mediterranean field, offshore Egypt

A. El Bassiony, B. Caselitz, V. Matsourak and C. Zeltser

Petroleum Geo-services (PGS) opted to use PGS Beam migration for depth velocity model building in a Mediterranean field, offshore Egypt. The multi-pathing capabilities of PGS Beam migration allow for improved images in proximity to high velocity contrasts or complex geologic regions, while the rapid turn-around time of migrations permits easy confirmation of models. Also the removal of random noise during the dip scanning process provides good signal-to-noise gather images suitable for estimating the moveout errors required for tomography updates. These are the characteristics that make the beam migration a suitable algorithm to build complex velocity models. In our case study, up to 13 iterations were computed within 12 weeks. During each iteration, most of the time was spent to interpret the results and no time was lost waiting for the migration to complete. The full-fold volume of 200 sq km was migrated in less than one hour enabling the interpretation of more than one possible velocity model. Once the final velocity model was obtained, the full suite of post-stack depth migration (PSDM) algorithms (Beam, Kirchhoff, one-way and two-way wave equation) could be applied to achieve the best possible image.

The depth velocity model started with a simple Dix-converted interval velocity from the available root mean square (RMS) pre-stack time migration (PSTM) velocity model. Down to the Messinian reflection, the model was updated using global tomography with two iterations. The top Messinian reflection was structurally updated through interpretation in depth. The Messinian shale/anhydrite layer was optimized by performing numerous velocity flooding tests to optimize the base of the Messinian reflection. The best flooded model was then subjected to global tomography to optimize the relatively higher velocity channels within the same layer. Five global tomography iterations were run until the intra-channels as well as the base of the Messinian were giving flat gathers. The base of the Messinian was then interpreted in depth, and the velocity model was built using the optimized shale layer with channel velocities determined by the tomography. The image quality for the pre-Messinian deposits was enhanced when compared to the PSTM images. The variable thickness of the shale layer along

with the channels embedded in the same layer had built complex ray paths that make the RMS velocity not suitable to image the structure below. The advantage of the fast Beam algorithm and the highly defined image was illustrated whereby the models were built and verified, at a speed that allows real time "processing and interpretation". It was then possible for the geologists to perform the interpretation based on the most geological reasonable model.

For the deeper targets between Base Messinian and the top unconformity we updated the initial model through 6 iterations while performing some lateral smoothing to the model and removing low velocity anomalies. Between the top unconformity till top carbonate we used a Vo map at the unconformity surface with a gradient of 0.2 to reach flat gathers at top carbonates. Below top carbonates we have updated the initial model through two tomography updates to reach the final model. This sums to a total of about 16 migration production runs to produce the final cube, besides the many migration runs to test the different velocity models and updates.

The final velocity model achieved after three months would not be possible using the conventional Kirchhoff migration algorithm. A comparison was made between the Beam algorithm and the Kirchhoff algorithm using the same velocity model to confirm the image quality. The Beam image was showing lower noise level when compared to the Kirchhoff image.

679675 Introducing *a priori* information in non-linear slope tomography: An application to Minagish seismic survey

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Slope tomography allows velocity model estimation from locally coherent events. These events can be picked in the migrated pre-stack depth or time domains, and then de-migrated into the observation space-time domain, providing us with kinematic invariant data. When locally coherent events are picked directly in the observation space-time domain, the kinematic invariants carry the exact acquisition geometry.

Kinematic invariants describe locally coherent events by their position and slopes in the un-migrated pre-stack time domain. Non-linear 3-D slope tomography based on the concept of kinematic invariants provides a powerful tool for velocity model building. Several iterations of residual moveout (RMO) picking, pre-stack depth migration and velocity updates are avoided, unlike conventional approaches based on a linear update where residual depth errors have to be re-picked several times. Because kinematic invariants do not relate to a particular depth velocity model, *a priori* information can be easily inserted into the initial tomography velocity model to assess different geological assumptions.

This capability is illustrated on land Minagish dataset in Kuwait for which RMO has been picked from pre-stack time migrated gathers. Tomography and imaging results have been produced for two different *a priori* velocity models. A first model was built by 1-D Dix inversion of time migration velocities while the second model was built using velocity information from wells. The updated "wells" model successfully combines two velocity components: the *a priori* high vertical resolution component that cannot be resolved by tomography and a lower vertical resolution component that maximizes the stack power of the depth migrated seismic data.

680713 Geophysical benefits of from improved seismic vibrator

M. Hall, J. Wei and T. Phillips

Vibroseis, a key source in land seismic exploration, has recently experienced many initiatives to increase productivity and seismic data quality. Most of these innovations deal with the signals used to generate the Vibroseis sweep and techniques for simultaneous acquisition. This presentation deals with physical modifications to the vibrator itself designed to enhance performance at both low and high ends of the frequency spectrum and also attempt to provide a more accurate measure of the ground force from the weighted sum.

Most of the recently introduced simultaneous Vibroseis techniques rely on the measured weighted sum as a good indicator of the actual ground force or the source signature for the vibrator. In reality it is common for there to be substantial differences between the weighted sum and the ground force, especially as a function of varying near-surface conditions. Modelling was undertaken to investigate how the physical properties of a hydraulic vibrator could be modified to improve this relationship while also extending

the useful bandwidth. As a result of this, modelling modifications were made to a production hydraulic vibrator, which was then tested against the production vibrator both on load cells and at a site in Texas with an instrumented well plus a 2-D surface line.

Analysis of these tests will be presented to confirm that the expected improvements were achieved. The implications of this are several fold. The bandwidth at the low-frequency end of the spectrum can be usefully extended below 5 Hz with considerably less harmonic distortion; this will aid in the exploration for deeper targets and also improve the accuracy of inverting seismic data to match well log data. The bandwidth at the high end can be similarly improved by about 6 dB at 150 Hz enabling improved resolution for quantitative analysis of shallower reservoirs. The overall reduced harmonic distortion means that more of the energy generated by the vibrator goes into the fundamental Vibroseis signal yielding a higher energy level of useful signal. The weighted sum is also closer to the ground force put into the earth by the vibrator. This, along with the reduced harmonic distortion will enable improved separation of overlapped source signals in simultaneous Vibroseis acquisition schemes. This improved seismic vibrator is complimentary to recent developments in improving Vibroseis productivity and will further improve the quality of the acquired Vibroseis data.

679764 Independent simultaneous sweeping in Libya: Full-scale implementation and new developments

D. Howe, A.J. Allen, M. Foster, I. Jack, D. Buddery, A. Choi, R. Abma, E. Manning and M. Pfister

At the 2008 and 2009 SEG conventions we reported on a proof of concept and initial production results of a new acquisition technique called ISS (independent simultaneous sweeping). This study describes the successful full-scale implementation of this method in Libya after it has been in use for more than one year acquiring a very large exploration land 3-D survey for a project with a seismic commitment in excess of 13,000 sq km. We will describe the advantages of this method, some of the challenges imposed by this new way of working and some developments being evaluated.

Recent advances in recording systems allow for a recording spread to be continually active, which we refer to as continuous recording, although it may be more accurately described as recording of a set of contiguous records. This removes the necessity for real time synchronization of sources and recording systems. As long as the continuously recorded data and the source initiation can both be linked to the same time standard (e.g. GPS time) the traditional shot records can be extracted from the continuous dataset at any later stage. We have used the benefit of continuous recording to operate a large number of sources simultaneously on a large recording spread thereby greatly improving the productivity of land acquisition.

In this method all vibrators work independently without any attempt to synchronize their activity, and the underlying principle is that the interference between sources can be treated as noise. In our simple and robust approach, there is no apparent limit to the number of sources that can be operated simultaneously, there is no waiting time for any vibrator and very little central control or communication is required. It is very well suited for work in many environments including difficult terrain, where vibrator maneuvering is slow, or where radio communication is challenged. We demonstrate that this technique can deliver very high fold data at high efficiencies, such that it enables exploration land 3-D to be acquired at costs comparable to marine exploration surveys. We also describe early results from a field trial of ISS and a cable-less node recording system. Taken together, these two technologies might have the potential to change the way land seismic crews are configured and operated.

680224 Seismic source parameters optimization in shallow-water area offshore Abu Dhabi, United Arab Emirates

T. Ishiyama, D. Painter, K. Belaid and T. Saleh

Seismic source parameters are one of the important specifications for a seismic survey. Conventional thinking is that larger sources produce higher energy, and thereby improve data quality. In shallow-water areas offshore Abu Dhabi, UAE, ocean-bottom cable (OBC) seismic survey is commonly acquired with air-gun array as the primary seismic source. However, the source size is limited due to operational constraints such as shallow water depth and scattered production facilities. Although several seismic surveys have been acquired in the region, the impact of source size on data quality is still open for discussion. In this regard, a 2-D 2C OBC pilot seismic survey was acquired in a shallow water area in the region.

In this seismic survey, several datasets were acquired with different source parameters, however using the same source vessel and air-gun array. The number of air-guns, total volume of air-guns in the array and shot-point interval (SPI) were varied among these datasets, while the same pressure, depth and synchronization of air-guns were maintained. During the processing, the same parameters and velocity were applied to all datasets to minimize any differences due to processing effects. Data quality for each dataset was evaluated at various processing stages. At pre- and post-noise attenuation stages, hydrophone, geophone and summed data were each analyzed to evaluate the amplitude levels of both signal and noise, the signal-to-noise ratio (S/N) and the signal frequency bandwidth (SFB). The same analysis was also performed on the final summed data at the final stage after signal processing, migration imaging and stack.

The main findings are: (1) higher source energy improves S/N of acquired data, however the improvement in S/N against source energy is little; (2) even the smallest source acquires data quality over the required S/N and SFB at the target two-way time window; (3) deeper two-way time window causes lower S/N and SFB, and the effect is larger on SFB; (4) shorter SPI leads to higher S/N of acquired data; and (5) processing itself greatly improves data quality in all cases of source parameters. Consequently, shorter SPI and appropriate processing could compensate for a lack of source energy, then even a small source could achieve the required data quality with the aid of suitable SPI and processing. The results will encourage investigation of even smaller sources, which are easier for the operations and friendlier to the environment.

702112 Next generation technologies for underbalanced coil tubing geosteering

A. Kozlov, S.A. Khamees, J.C. Guzman Munoz and S. Frantzen

Technology improvements continue to advance the capabilities of coiled tubing directional drilling (CTDD) worldwide. The recent global increase in CTDD activity and the need for precise wellbore placement and monitoring of downhole parameters in advance underbalanced re-entry applications has led to the development of bottom-hole assemblies (BHAs) with increasing functionalities. Saudi Aramco with its prevailing dedication to expanding the technological envelope has recently successfully completed the pilot phase of its first underbalanced coiled tubing drilling (UBCTD) project on the Haradh gas field. After the success of the pilot phase and with the project moving on to the next stage, impetus remains to further improve this economical re-entry technique through introduction of new coiled tubing tools and services.

Through the process of miniaturization and innovation, small-diameter rib steering system has been developed for CTDD and UBCTD. The introduction of this novel tool is aimed to help overcome the intrinsic hurdles of conventional CTDD and enhance geosteering capabilities of the CTDD BHAs. The rib-steering technology has been successfully tested on the North Slope of Alaska and North Texas and was most recently introduced to the UBCTD project in the Kingdom of Saudi Arabia. Straighter horizontal laterals and improved steering in open-hole sizes as small as 2 3/4-inch inside diameter (ID) have consequently allowed improved precision in geosteering within the narrowest of payzone and extended lateral step-out capability.

This presentation provides an overview of the Saudi Aramco UBCTD project, the new rib steering technology and the benefits realized on this project and potential benefits to other UBCTD projects. The presentation also gives an account of several most recent deployments of the rib steering technology worldwide, while focusing on the ongoing UBCTD project in the Kingdom of Saudi Arabia which provides the perfect testing ground for new UBCTD technologies. The advances that can be achieved on this current project, and new UBCTD down-hole technologies that can be developed through a close working relationship between the field operator and the service company, will be applicable in other mature gas and oil fields for the economical extraction of additional reserves.

680940 Resistivity borehole imaging in challenging borehole environments

R. Kuchinski

Until recently, the acquisition of resistivity borehole image data from wellbores less than 6 inches in diameter has been impossible, due to the size of conventional borehole imaging tools currently available on the market. In addition, conventional deployment methods limit efficient rig time utilization and ultimately lead to higher risk and costs associated with acquiring image

data. The introduction of new logging technology now allows operators to obtain excellent image logs in wells as slim as 3 inches in diameter, and in wells with challenging hole conditions. Image logs are required to properly understand formation properties and fractures details; and to help in future drilling and completion decisions. In Saudi Arabia, the cost savings that are possible by sidetracking existing wellbores makes the drilling and completion of ultra-slim lateral wells very desirable.

Access into these wells is achieved by employing numerous conveyance techniques including well tractors and drill pipe to push logging tools along the horizontal section to total depth. The borehole images can be acquired using small diameter imaging technology with acquisition in real time and in memory. The combination of conveyance and imaging technologies enable operators to make important decisions on where to place completion hardware in the well to enable the well to produce to its full potential. This presentation describes the new imaging technology and will discuss the image acquisition experience in the world's first ultra-slim hole and extended-reach horizontal sections in Saudi Arabia.

681115 Integrated approach to 3-D near-surface characterization

A. Laake, A. Cutts and C. Strobbia

Geophysical exploration and reservoir characterization mainly use surface sources to generate elastic or electro-magnetic waves which travel through the subsurface where they are reflected at the reservoir. Eventually, the reflected signals return to the surface where they are detected by surface receivers. The challenge these techniques face is to correct for the high degree of distortion which the near-surface layers inflict on the propagation of geophysical waves. Detection and correction, however, requires a certain degree of knowledge about these layers. We propose a multidisciplinary approach for the near-surface characterization since the strong vertical and lateral variations of the near-surface properties are hard to detect using one physical property alone.

An integrated approach to 3-D geologic and elastic characterization of the near-surface is presented. The integration of high spatial resolution, relatively low-confidence remote sensing, and geologic data with sparse spatial resolution, high-confidence geophysical data in a GIS database allows for cross-calibration of both types of datasets, thus providing calibrated near-surface models. The method comprises the generation of a 3-D near-surface geologic model, from which the input for a 3-D elastic model is obtained. The elastic model is then calibrated with seismic data to provide the final 3-D near-surface model. The method has been demonstrated at two case histories covering geomorphological features typical for desert areas in North Africa and the Middle East.

681110 An analysis of the near-surface using remote sensing for the prediction of logistics and data quality risk

A. Laake and A. Cutts

Remote sensing offers the unique ability to view the Earth's surface without actually being in contact with it. Using multi-spectral satellite data and digital elevation models (DEM) a workflow is presented to build a topography- and a lithology-based classification of the near-surface. This enables the creation of logistics and data quality (surface scatter and surface velocity) risk maps: (1) Logistics planning: areas that are rough, rocky, have uneven terrain or extreme soft ground will provide significant logistical issues. (2) Impact of the terrain on data quality: terrain edges and escarpments represent sources for scattering as do geomorphologic boundaries; areas of low surface velocity usually bear a high risk for attenuation of high frequencies and ringing of trapped modes.

The geomorphologic analysis based on DEM and multi-spectral remote sensing data extracts spatially dense information at a resolution of 15 m, which is sufficient for logistics, acquisition and data processing. The logistic risks represented by limitations for access and maneuver and the data quality risk from scattering, attenuation, coupling perturbation and reverberations can be mapped. Histograms for the risk categories can assist in risk assessment during seismic survey design and bidding. The technique has been validated successfully by surface geology sampling and photos as well as correlation with seismic data in the Western Desert of Egypt. The results demonstrate that the interpretation of remote sensing data allows the prediction of risks associated with land seismic acquisition.

681106 Tectonic mapping using geomorphologic characterization from remote sensing data

A. Laake, A. Cutts and S. Abbas

The joint interpretation of digital elevation models (DEM) and multispectral remote sensing data in connection with stratigraphic and geologic information reveals the geologic structure of the Earth's surface, particularly in desert terrain. The characterization and classification of the DEM using spatial statistics provides hints regarding formation tops, which are validated by mineral spectroscopy of multispectral remote sensing data. The idea behind this approach is that the Earth's surface topography is the result of geological processes such as deposition, erosion, and tectonics.

In the first step, the DEM is analyzed for geomorphologic terrain class such as table land. Also, terrain edges and escarpments are extracted using a spatial gradient filter. In hard rock areas, the escarpments often delineate valleys that follow fault lines. In the second step, individual bands of multispectral satellite images are combined to form a multiband RGB image that reveals the different rock types in certain areas. The rocks exposed as outcrops can be associated with their elevation using the digital elevation model. From the relative elevations, the deposition sequence can be obtained, and hence, a stratigraphic column. When combined with the tectonic lineaments extracted from the escarpments of the DEM, tectonic features can be identified.

We have applied the methodology to a pull-apart basin in the eastern Sinai Peninsula, Egypt. Fault lines parallel to the Gulf of Aqaba left-lateral fault were identified on the surface gradient. Lithology-focused processing of satellite imagery allows the distinction of Precambrian basement, Paleozoic metamorphic rocks and Mesozoic sandstone and limestone. Where the left-lateral fault system got stuck an S-shaped pull-apart basin developed. Using the geomorphologic analysis from DEM and multispectral satellite imagery the pre-erosion surface could be reconstructed and the amount of throw in the graben fault could be determined.

682882 A 32,000 channel 3-D Vibroseis field test: Where is the signal?

R.H. Lakeman, P.I. Pecholcs, N.N. Nakhla, M.A. Sannaa and T. Al-Ghamdi

With the dramatic increase in recording channels and improved productivity methods for Vibroseis surveys, we can effectively record the full signal and noise seismic wave field without aliasing. To evaluate the cost/operations/data quality benefit ratio for high source and receiver density acquisition designs, Saudi Aramco performed a field test with an effective 32,000 channel Vibroseis survey design over a known oil and gas development field. The source and receiver line intervals were 100 m (orthogonal) with 25 m source and receiver station intervals. Three vibrators were used per source point with a linear upsweep from 4 to 94 Hz to acquire well-sampled, wide-azimuth data with inline offsets up to 5,000 m and cross-line offsets up to 4,000 m.

The field test area was specifically selected to observe the benefits of dense spatial sampling over regions with high-amplitude surface waves and back-scattering caused by a complex near-surface. In addition, we analyzed the minimum signal-to-noise level required per trace or ensemble to balance and preserve the surface-consistent signal bandwidth for a range of decimation volumes. These volumes simulate either finer spatial sampling or some of our legacy seismic data volumes, and are referenced to our most recent vintage 4,000 channel survey design over the same area. In this presentation, we demonstrate the effects of variable spatial sampling on signal-to-noise, signal bandwidth, and interpreted reservoir properties at the oil target.

701316 Challenges experienced during processing of a transition zone 3-D seismic survey in Abu Dhabi

M.A. Mahgoub, J. Karwatowski, J. Witte, T. Hussein and A. Leveque

Acquisition of seismic data in Transition Zone (TZ) areas poses many challenges. Different sources and receivers are required to acquire data in the land, tidal flat, shallow water and marine environments. The diverse near-surface conditions and the differences between the various source and receiver types give rise to a complex cocktail of noises. Furthermore, poor first break picks in the transition zone can challenge traditional first

break refraction statics techniques. As a result, the processing of TZ data requires unconventional and creative processing techniques to address the data quality issues that are unique to these types of datasets.

In this project, a 3-D TZ seismic survey was acquired in three different, adjacent Abu Dhabi exploration areas utilizing nine different source and receiver combinations, each designed to accommodate specific requirements in sabkha, shore, shallow water and marine environments. Among numerous 3-D seismic data processing issues tackled were matching and optimization of phase and amplitude, bandwidth, dual sensor OBC PZ summation, wavelet processing, pre- and post-stack coherent and incoherent noise attenuation, statics solutions and imaging. The results led to a seamless final dataset with optimized resolution and continuity, suitable for refined structural interpretation and detailed stratigraphic analysis.

678197 "New Generation Seismic" acquisition with a land seismic super crew

S. Mahrooqi, S. Abri, S. Yarubi, A. Yahyai and P. Matheny

In 2008, Petroleum Development Oman (PDO) implemented New Generation Seismic to fulfill technical objectives while taking into account economical and efficiencies factors. The technical objectives are to obtain properly sampled and wide-azimuth (WAZ) seismic for both shallow and deep objectives in support of current and future exploration and development projects. The sampling requirements to meet these objectives translate into receiver grids of 12.5 to 25 m in-line by 200 m maximum cross-line and full-source VP grids no less than 400 VP/sq km (for example 50 x 50 m or 25 x 100 m). The WAZ requirement is to provide a minimum offset in all azimuths of at least the depth to deepest perceived target (typically 4 km or greater). When combined, these sampling and width requirements result in New Generation Seismic with a fold exceeding 4,000 in 25 x 25 m bins suitable for full common offset vector processing and full azimuth interpretation and quantification of azimuthally varying seismic attributes. Further, full top-to-bottom and high-quality imaging is realized for both very shallow and very deep targets.

In order to efficiently acquire large areas, 10,000+ sq km, with over 400 VP/sq km two super crews were introduced. One super crew with a capacity of 25,000 channels (12 geophones per station), and 16 vibrators, and the other with 16,500 channels (also 12 geophones) and 16 vibrators. These super crews enable efficient operations with block widths in the range of 30+ km (a 30% efficiency improvement), and also fully productize dual methods of short sweep length simultaneous sourcing using both slip-sweep and distance separation (a 300% productivity improvement). In addition, the super crews now operate 24 hours per day (another 50% productivity improvement) and are equipped with the latest high-channel count and high productivity SN428 recording system and VE464 vibrator electronics. While the throughput of these super-crews is improved by approximately a factor 6, the number of people needed in the field is a much more modest increase of approximately 50%. As fully implemented in 2008, these super crews are consistently meeting PDO expectations and are setting world record productivity numbers. Daily average VP rates exceeding 13,000 are common. Considering PDO's minimum VP density of 400 VP/sq km these productivity numbers translate into an average production of 30+ sq km surface area per day per crew.

680560 Innovative processing strategy for 3-D shallow-marine OBC seismic data over a giant offshore oil field in Abu Dhabi, United Arab Emirates

J. Reilly, A.P. Shatilo, Z.J. Shevchek, R. El-Awawdeh, N. Khouri and J. Zhang

At a giant oil-field offshore Abu Dhabi, UAE, an ocean-bottom cable (OBC) seismic survey was conducted to acquire seismic data in areas of shallow water and intensely developed production infrastructure. OBC data are acquired utilizing two types of detectors: hydrophones (fluid-pressure change detectors) and single- or multi-component geophones (particle-velocity or acceleration detectors). The conventional seismic processing strategy is to sum the two sensors very early in the processing sequence. However, due to numerous factors, the differences between the physical measurement characteristics of hydrophones and geophones, their data character (including noise levels, multiple content, coupling effects) can be very dissimilar.

In this project a strategy was employed which avoided summing of the separate sensor data until just prior to imaging. This allowed us to investigate the differences between the two data types, optimize the processing flow for the individual

sensors and then sum the sensor data in a manner which maximized the primary signal content in the dataset. Investigations of the raw field data clearly defined significantly different responses of the separate sensor data to the surface wave field. This was attenuated by the utilization of a "physics-based" 3-D surface wave mitigation algorithm applied to the separate sensor datasets. In addition, the separate sensors clearly demonstrated wavelet character changes beyond what would be predicted from conventional ghost filter modeling. As a result, different wavelet-shaping filters and surface-consistent, amplitude-compensation corrections were required to be applied to the two sensor types. In addition, the very small-scale (< 10 milliseconds) statics were observed to vary on the hydrophone and geophone data, again necessitating separate compensation for this phenomenon.

Finally, interpretive-driven deconvolution, residual-amplitude compensation, attribute validation and zero phasing were applied to the data in order to maximally condition it for subsequent quantitative and qualitative analysis. In this presentation, we show a step change in seismic imaging quality on a shallow-water Arabian Gulf dataset as a result of this processing strategy. We will compare our results with those obtained using more conventional approaches.

681749 Processing "New Generation Seismic" from unlimited in-house centre

R. Smith, P.M. Zwartjes, T. van Dijk, N. Benjamin, T. Wah hong, R. Cramp and V. Dhawan

Petroleum Development Oman (PDO) has upgraded its seismic crews to enable high channel count and high-productivity acquisition of wide-azimuth (WAZ), finely-sampled seismic data ("New Generation Seismic"). These crews operate 24 hours per day using simultaneous Vibroseis sourcing and are consistently setting world-class production records well in excess of 13,000 VPs per day. The typical PDO WAZ survey acquired by these crews is approximately 2,700 sq km of 4,000+ fold data in 25 x 25 m common midpoint bins. The resulting data volume per survey is approximately 25 billion seismic traces and 130 terrabytes.

As a result of these changes the volume of seismic data arriving at PDO's in-house seismic processing centre each month has increased by a factor in excess of 10 in the last year alone. Currently the processing centre receives over 20 terrabytes of field data per month from two crews. This data explosion has necessitated large-scale upgrades to the processing centre, including substantial increases in CPU capacity, network bandwidth and online and offline data storage. Total disk storage for ongoing project work, for instance, is set to rise to 2.8 petabytes. Despite upgrades, CPU demand will outstrip local capacity and external resources will be accessed to provide the in-house centre with "unlimited" CPU.

In addition to the hardware upgrades, geophysical software developments have been equally important. These developments include data-adaptive ground roll attenuation, software to facilitate azimuthal velocity analysis, a new 3-D radon multiple attenuation module and the implementation of common offset vector and 5-D interpolation. The transformation of PDO's in-house seismic data processing centre to accommodate and fully utilize New Generation Seismic will be described in this presentation.