Petroleum Geoscience Collboration

21-22 November 2007

The Petroleum Group would like to thank BP, ExxonMobil, StatoilHydro and Total for their support of this event:

Petroleum Geoscience Collaboration Conference

21-22 November 2007

Programme – Day 1

Wednesday 21 November 2007	
08:30	**Registration and coffee**
09:00	**Welcome and opening** ***Bernie Vining***
09:10	**KEYNOTE: Anthony Mallon (University of Durham)** The Petroleum Geoscience Database: A new knowledge transfer initiative.
Session 1: Sedimentology I - From Land to Deep Seas ***Session Chairs: Bernie Vining & Chris Jackson***	
09:40	**Margaret Stewart (Imperial College, London)** 3D seismic research: Multi-phase Pleistocene subglacial tunnel valleys in the Central North Sea.
10:00	**Jamie Vinnels (University of Leeds)** Sediment distribution and architecture around an intra-basinal structure: An example from the Eastern Champsaur Basin, Annot Turbidite System, SE France.
10:20	**Rachel Kieft (Imperial College, London)** Understanding reservoir character and distribution in and around the Dagny Field, South Viking Graben.
10:40	**Tom Praeger (University of Cardiff)** Characterisation of lithofacies from an exposed continental slope system, Taranaki Basin, New Zealand.
11:00	**Samantha Taggart (Imperial College, London)** Improved characterisation of marginal aeolian reservoirs, UK Southern North Sea, through modelling of outcrop analogues.
11:20	**Tea / Coffee**
Session 2: Structural Geology I – Extensional Settings ***Session Chairs: Bernie Vining & Chris Jackson***	
11:50	**Ulrike Freitag (Imperial College, London)** Migration of listric normal growth faults in the Columbus Basin, Trinidad.
12:10	**Etor Querendez (Trinity College, Dublin)** Using seismic reprocessing and interpretation to determine the thermal and temporal history of a deep water sedimentary basin. Case study: The Porcupine Basin, offshore Ireland.
12:30	**Trond Kristian Kalstø (Norwegian University of Technology and Science) and Gøril Tjetland (StatoilHydro)** Late Cretaceous - Paleocene exhumation of the Fennoscandian margin observed on the Utsira High and Finnmark Platform East.
12:50	**Paul Whipp (Imperial College, London)** Evolution of the Troll West Fault Array, Norwegian North Sea.
13:10	**Lunch**

Session 3: E & P Related Research ***Session Chairs: Jerry Chessell & Steve Veal***	
14:00	**KEYNOTE: Eirik Larsen (Statoil Hydro)** Industry-academia collaboration invigorates exploration in the South Viking Graben.
14:30	**Aggeliki Georgiopoulou (University of Cardiff)** Determining lateral and vertical seal integrity in channel-levee complexes .
15:00	**Lucky Imagbe (University of Jos)** Modelling void geometry in deepwater reservoirs 'x' field, offshore Niger Delta, Nigeria.
15:20	**Alex Finlay (University of Durham)** Re-Os Geochronology of oil source rocks: a viable tool for petroleum exploration?
15:40	**Julio Almeida (Universidade do Estado do Rio de Janeiro)** What is the role of crystalline basement geological mapping in the oil industry?
16:00	**Gordon Beattie (No Affiliation)** Hydrocarbon exploration in the archives.
16:20	**Tea / Coffee**
Session 4: Structural Geology II – Compressional Settings ***Session Chairs: Dorthe Hansen & Andrew McAndrew***	
16:50	**Caroline Burberry (Imperial College, London)** Combined remote sensing and field investigations of hydrocarbon trap analogue structures: Examples from the Zagros Simply Folded Belt, Iran and the Sawtooth Range, Montana.
17:10	**Ian Watkinson (Royal Holloway, London)** Strike-slip faulting in Peninsular Thailand: basin evolution and linkage to regional tectonics.
17:30	**Steven Sawyer (University of Edinburgh)** Influence of tectonic inversion and salt mobility on structural styles and reservoir quality in the Norwegian Central Trough.
17:50	**Seb Turner (Imperial College, London)** The role of pre-existing structures in the evolution of the Kepingtage fold-thrust belt, Tarim Basin, China.
18.10	**KEYNOTE: Tim Pharaoh (British Geological Survey)** The Atlas of the Southern Permian Basin Area (SPBA Project): Progress report and insights on the Permian to Cenozoic tectonic evolution of West Central Europe.
18:40	**Reception**

Petroleum Geoscience Collaboration Conference

21-22 November 2007
Programme – Day 2

Thursday 22 November 2007	
08:30	**Registration and coffee**
09.00	**KEYNOTE: Christopher Leppard (Statoil Hydro)** Summer internships: Interviewing the company.
Session 1: Controls on Deep Water Sedimentation ***Session Chairs: Howard Johnson & Alick Leslie***	
09:30	**Anna-Jayne Zachariah (University of Manchester)** Early post-rift basin development, early to mid-Cretaceous, North Viking Graben, Norwegian North Sea.
09:50	**Karla Kane (Imperial College, London)** Impacts of normal fault growth and salt tectonics on syn-rift play development in the Sleipner Basin, South Viking Graben, Norwegian North Sea.
10:10	**Ian Clark (University of Cardiff)** Structural controls affecting recent submarine channels in the Levant Basin, Eastern Mediterranean.
10:30	**Vicky Catterall (University of Manchester)** Controls on the 3D-seismic geomorphology of submarine channel systems: Nile Delta Slope, Egypt.
10:50	**Tea / Coffee**
Session 2: Carbonates ***Session Chairs: Howard Johnson & Alex Leslie***	
11:20	**KEYNOTE: Fiona Whitaker (University of Bristol)** Making sense of carbonate diagenesis: Understanding processes as a route to prediction.
11:50	**Ali Kadkhodaie Ilkhchi (University of Tehran)** A fuzzy logic approach for estimation of hydraulic flow units from well log data: A case study from Ahwaz Oil Field, South Iran.
12:10	**Rahmat-Allah Sadeghi (University of Bu-Ali)** A committee machine approach for predicting permeability: a case study from a heterogeneous carbonate reservoir, Balal field, Persian Gulf, South Iran.
12:30	**Peter Fitch (University of Leicester)** Petrophysical and image log facies of a carbonate dominated section of the Cap Mountain Limestone Member, Riley Formation, Blanco County, Texas.
12:50	**Gemma Bates (University of East Anglia)** Determining the origin and relative timing of formation of a sub-unconformity diagenetic caprock, Williston Basin, Canada.
13:10	**Lunch**

Session 3: Sedimentology II – Fluid Flow and Remobilisation ***Session Chairs: Richard Davies & Chris Jackson***	
14:00	**KEYNOTE: Olivier Dubrule (Total)** Multidisciplinary inversion of Earth models.
14:30	**William Vétel (University of Cardiff)** Statistics and scaling properties of the Panoche Injection Complex, California: Implications for sand intrusion mechanisms.
14:50	**David Meadows (University of Durham)** Predicting porosity using seismic data: A new approach.
15:10	**Jennifer Moss (University of Cardiff)** Giant fluid escape pipes imaged with 3D seismic data from the Namibian margin: implications for basin dewatering.
15:30	**Evelina Dmitrieva (Imperial College, London)** Distribution and large-scale soft-sediment deformation of deep-water depositional systems: a 3D seismic case study from the Palaeocene of the North Sea basin.
15:50	**Tea / Coffee**
16:20	**Suzanne Bull (University of Cardiff)** A liquefaction-propagation model for the development of submarine landslides.
16:40	**Joris Eggenhuisen (University of Leeds)** Reconstructing remobilisation of deepwater reservoir sequences from cored wells: A sedimentological case study from the Britannia Sandstone Formation, UK North Sea section.
17:00	**Gordon Lawrence (University of Cardiff)** A large frontally-confined slide offshore Norway, and implications for petroleum exploration on continental margins.
17:20	**Discussion and closure of meeting**

The Petroleum Geoscience Database- a new Knowledge Transfer Initiative

Anthony J Mallon and Richard E Davies, CeREES (Centre for Research into Earth Energy Systems), Department of Earth Sciences, Durham University

There is a large amount of research in the field of Petroleum Geoscience or that is funded by the hydrocarbon industry currently being undertaken by Universities and other academic institutions across the World. However there is currently no easy way for an oil company or researcher to access this resource. The Petroleum Geoscience Database (PGD) being developed at Durham University intends to address this issue.

The database contains publicly available information combined with data submitted by institutions, individuals and companies.

The database can be interrogated by a search function in which the user inputs a search term for which the results are displayed. The user can also browse the information through an interactive world map on which Geoscience institutions are displayed.

The data is interlinked so that the user can follow a thread combining institutions, individuals, research projects, research themes and funding bodies. The entries also contain links to university and company websites as well as individual researchers personal or project webpages.

The database will also incorporate a resources area highlighting Postgraduate courses of interest to the industry as well as numbers of MSc and PhD students at a given institution.

The database has a number of applications which are of benefit to both the academic researcher and the oil industry and foster increased collaboration between the two, these include,

For the Researcher:

- Showcasing an institution or individual
- Identifying which companies are funding particular research areas in order to allow a researcher to make targeted approaches for funding.
- Identifying potential “gaps in the market” and to ensure that new research ideas are novel and not being duplicated elsewhere.
- Identifying which institutions and individuals are carrying out research in similar areas in order to set up new collaborations.

For the Oil Company:

- Showcasing a particular companies research funding.
- Facilitating knowledge transfer from academia to the industry.
- Identifying experts for collaboration or consultation on new industry or research issues.
- Identifying institutions or individuals (students) that could be targeted for recruitment into the company.

NOTES

3D seismic research: Multi-phase Pleistocene subglacial tunnel valleys in the central North Sea.

Margaret Stewart, Lidia Lonergan, Gary Hampson, Department of Earth Sciences and Engineering, Imperial College, London, SW7 2AZ.*

Dense networks of tunnel valleys are imaged at a regional scale beneath the central North Sea using a number of overlapping 3D seismic reflection datasets. Detailed measurements for approximately 200 individual tunnel valleys indicate lengths greater than 150km, widths of up to 5km and depths up to 180m. Significantly, the tunnel valleys are separated into cross-cutting 'phases' – with each phase representing a generation of tunnel valleys on a relative age scale.

At the regional scale (150km x 100km), six confirmed tunnel valley phases are present. Locally, up to 10 tunnel valley phases are interpreted, with some tunnel valleys unassigned or attributed to phases with less confidence.

The majority of tunnel valleys show a distinctly undulating long profile, representing subglacial formation under pressure. Orientations are generally consistent within phase (±15°), but vary significantly between phases and regionally from north to south, indicating changes in the ice-sheet regime between glaciations and, contrary to most other work, a non-perpendicular relationship to a proximal ice sheet margin.

Many tunnel valleys display a bright chaotic basal reflector in their deepest parts, interpreted as either basal till or fluvioglacial sands and gravels deposited subglacially. Other common fill packages include a middle unit consisting of slightly dipping or opaque reflectors and a topmost draped unit, though to represent fluvioglacial or glacimarine/lacustrine deposition respectively. The largest tunnel valleys often show a complex deeper structure widening upwards to an apparent flooding surface, interpreted as a result of ponding within the tunnel valley boundary during fill, whether directly by meltwater or by shallow marine transgression.

Select tunnel valleys, particularly those in phase 4, display evidence of subaerial fluvial features present during fill, with braided channels and meanders present in-valley. Phase 4 tunnel valleys are also seen to contain mottled packages with circular features interpreted as large kettle holes, signifying rapid deglaciation, or as pockmarks, although vertical structure can not be resolved. Fill patterns in at least two phases suggest the reoccupation of tunnel valleys, indicating the importance of the larger tunnel valleys as relict landforms.

The presence of six distinct tunnel valley phases in the region suggest: 1) that the current model for three glacial episodes in the central North Sea during the Pleistocene is an underestimate or 2) that the tunnel valley phases preserve evidence of dynamic ice advance and retreat over the North Sea during these glaciations. In contrast to theories involving formation by catastrophic meltwater release, the tunnel valleys were formed subglacially and filled over time in varying environments, with the largest preserved in the landscape between ice episodes.

NOTES

Sediment distribution and architecture around an intra-basinal structure - an example from the Eastern Champsaur Basin, Annot Turbidite System, SE France

Jamie Vinnels, Rob Butler and Bill McCaffrey, Turbidites Research Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK (Contact e-mail: jamie@earth.leeds.ac.uk)

The Eocene to Oligocene deepwater sandstones of SE France are some of the most well documented turbidite deposits in the world, and have contributed greatly to the understanding of turbidite systems. The southern remnants, know collectively as the Annot Sandstones (i.e., the Annot, Grand Coyer, Sanguiniere and Trois Eveches sub-basins), are thought to represent perched, interconnected basins, characterised by channel and sheet-form architectural elements, with sediment distributing NW from a deltaic source fed from the Corsica-Sardinia Massif. However, little is know about the system in more distal areas. The Champsaur Sandstones (30 km N of Trois Eveches), which have resisted evaluation due to a strong tectonic overprint, are thought to represent the downstream continuation of the Annot Turbidite System. Presented here is an outcrop case study from the Eastern Champsaur Basin which describes how intra-basinal bathymetry within the receiving sub-basin controlled spatial and temporal flow behaviors, which have in turn driven quantifiable variations in sediment distribution patterns.

Within the Eastern Champsaur Basin is a well exposed onlap surface onto which a series of sheet-sandstone bodies were emplaced. These sandbodies are internally complex and are characterised by facies variations from thick granular deposits, thought to represent substantial, through-going turbidity current events, through to those that are most likely contained within the basin (surge type deposits), and those that interact with the surrounding substrate entraining material from these slopes. A workflow is described for firstly establishing the bathymetric template of the Eastern Champsaur Basin prior to turbidite deposition through analysis of the pre-turbidite section, and secondly resolving the extent to which successive onlapping turbidity currents were controlled by this bathymetry, and what, if any, subsequent remobilisation the resulting deposits underwent, i.e. slumping or entrainment into later flows. Both facies and hence net to gross variations are observed in association with an intra-basinal high, which is thought to have contained flows upstream (SE), allowing a relatively finer fraction of the flow to be striped downstream (NW). This approach demonstrates that not only is the sedimentological evaluation of deformed basin fills tractable, but that these sections aid in resolving the inferred extent and connectivity of the Annot Turbidite System. This study has direct application in aiding the understanding of sand emplacement processes at the fringes of turbidite basins, in particular in defining the genesis of stratigraphic trap geometries, and also in understanding connectivity issues between turbidite mini-basins.

NOTES

Understanding reservoir character and distribution in and around the Dagny Field, South Viking Graben

Rachel Kieft[1], Christopher Jackson[1], Gary Hampson[1], Eirik Larsen[2], Unni Sjursen[2]
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Sedimentology and sequence-stratigraphic analysis within salt basins is often complicated by syn-depositional halokinesis. Salt tectonics can modify basin-floor topography and sediment transport pathways, thus controlling facies character, distribution and architecture. Due to the dynamic behaviour of salt during burial, robust prediction of facies relationships requires reconstruction of the timing and distribution of salt movement to establish basin geometry at the time of deposition. Accordingly, it is important to integrate all available data (e.g. biostratigraphy, sedimentology and seismic interpretation) when attempting to understand halokinesis and its impact on facies relationships.

The Dagny Field is a gas and condensate accumulation reservoired within the Middle Jurassic Hugin Formation of the South Viking Graben. The Hugin Formation is shallow marine in origin and was deposited during an overall transgression, marking the southerly migration of the Brent Delta system. The formation overlies continental deposits of the Sleipner Formation and is capped by shelfal and offshore deposits of the Heather and Draupne formations. These units form the seal at Dagny where the hydrocarbons are trapped in a structural high cored by Zechstein salt. Deposition of these middle Jurassic units coincided with halokinesis, extension and normal faulting (related to the Upper Jurassic rift event) in the South Viking Graben and therefore their spatial inter-relationships are complicated.

Core logging of the Hugin Formation around the Dagny Field shows the unit to comprise a wave-dominated shoreface succession with some coarse-grained sediment input, inferred to be related to time-equivalent fluviodeltaic systems documented to the south in the Sleipner West Field. Correlation of lithostratigraphic units in the study area suggests that the Hugin Formation is isopachous, however, newly-acquired, high-resolution biostratigraphic data shows that the unit varies significantly in age. Seismic mapping over the Dagny structure is difficult, due to low seismic resolution and poor quality of data at this depth, but there is evidence of thickening into adjacent depocentres and basal onlap towards the salt-cored highs. It is therefore inferred that intra-basinal, salt-cored highs influenced the position of the shoreline and facies belts across the area during the Middle Jurassic. The coastline was not linear, but consisted of a series of shallow marine embayments and flanking salt-cored headlands and islands.

This study indicates that an improved understanding of syn-depositional salt movement within the Dagny Field area and related sedimentation is key to understanding reservoir architecture within the field and, as a result, has implications for field development. The challenge to predict reservoir distribution in this structurally complex area has implications for future near-field exploration, although the recent Middle Jurassic oil discovery at nearby Ermintrude is encouraging.

NOTES

Characterisation of lithofacies from an exposed continental slope system, Taranaki Basin, New Zealand

Tom Praeger [1]*, Joe Cartwright [1]& Andy Aplin [2]
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Fine grained continental slope sediments often provide the sealing lithologies to deep water hydrocarbon accumulations. These thick sequences of clay-rich hemipelagites typically display low porosities and permeabilities and provide high quality capillary seals. Cores recovered from many continental margins suggest that these fine-grained units are often polluted with thin horizons of coarser silt and sand material. These heterogeneities provide zones of anomalously high hydraulic conductivity and may severely reduce the sealing capacity of slope units. This textural variability is below the resolution of most exploration techniques and can easily go undetected.

Here we present a field study from an exposed Miocene slope sequence outcropping along the North Taranaki coast, New Zealand. The late Miocene sediments of the Urenui Formation represent deposition onto a prograding continental slope during the filling of the Taranaki Basin's eastern margin and record approximately 900m of stratigraphy (King et al, 1993). Sediments are dominated by weakly bedded muddy siltstones which are occasionally cut by sandy channel complexes. The Urenui Formation locally overlies the sand dominated Mt. Messenger Formation, giving a representative transect through a basin floor to upper slope succession.

The study aimed to map and characterise the nature and distribution of thin sand beds within a largely silt/clay dominated slope sequence. High resolution sedimentary logs and handheld gamma-ray spectrometry were used to give further insights into the distribution and resolvability of heterolithic units.

Our study indicates that hydraulic and sedimentological processes are largely responsible for textural heterogeneities at a range of scales within this classic slope sequence. Imaging these features during conventional hydrocarbon exploration has proven difficult (Theologou, 2001) and reinforces the need for a more comprehensive database in order to assign accurate seal risks to clastic slope sequences.

King P. R., Scott G. H., Robinson P. H., 1993: Description, correlation and depositional history of Miocene sediments outcropping along the North Taranaki coast. Institute of Geological & Nuclear Sciences Monograph 5

Theologou P., 2001: Petrophysical review of the Urenui and Mt. Messenger Sands. Ministry of Economic Development New Zealand Petroleum Report PR2751

NOTES

Improved characterisation of marginal aeolian reservoirs, UK Southern North Sea, through modelling of outcrop analogues

Samantha Taggart, Gary Hampson & Matthew Jackson, Department of Earth Science and Engineering, Imperial College London, UK

The Permian Rotliegend gas play of the UK Southern North Sea consists of aeolian sandstones that pass laterally northwards into evaporate-rich lacustrine claystones. Previous development of the Southern North Sea Basin has focused on the high quality aeolian sandstones. However, as these are now maturing, focus has shifted to exploring the potential of the more heterogeneous marginal reservoirs (so-called “feather-edge” play). Vertical and lateral heterogeneity within these marginal reservoirs pose high risks to their successful development.

The well exposed Page (aeolian/sabkha) and Cedar Mesa (aeolian/fluvial) Sandstones in southern Utah are analogous to elements of the marginal Rotliegend play and have been studied at outcrop to investigate sedimentological heterogeneity at reservoir and inter-well scales. Sedimentological logs and fence panels from the outcrop analogues have enabled the lateral extent and connectivity of different sandbodies to be mapped in three dimensions. 3D reservoir models of each outcrop analogue have been constructed to create an accurate realisation of facies architecture. Subsurface rock and fluid property data have then been used to populate these outcrop-based models. Fluid flow simulation of the resulting models will provide an improved understanding of the way in which heterogeneity affects fluid flow patterns, reservoir behaviour and potential development of Rotliegend “feather-edge” reservoirs.

NOTES

Migration of listric normal growth faults in the Columbus Basin, Trinidad

Ulrike A. Freitag, David J. Sanderson and Lidia Lonergan,* Department of Earth Science & Engineering, Imperial College London, London SW7 2AZ, UK.

The Columbus Basin off-shore Trinidad is situated on the South American shelf and within a complex structural setting close to the presently transtensional plate margin between the South American and Caribbean plates. The basin formed in the Miocene as a foreland basin and evolved into a thin-skinned pull-apart basin during Plio-Pleistocene times. The Miocene-Pleistocene basin fill is affected by extensional faulting, contractional folding and local thrusting (mainly limited to the northern parts) (GIBSON et al., in press).

The structural framework of the basin is dominated by a series of large-scale seaward-dipping listric normal faults of up to 50 km length and 2.5 km of displacement and a set of similarly sized landward-dipping counter-regional normal faults, which together significantly influence the distribution of sediment deposition and created large-scale rollover anticlines, which form at interference with the nearly perpendicular fold trend major hydrocarbon traps.

The biggest seaward-dipping growth faults have been shown by BP Trinidad & Tobago to initiate progressively seaward, taking over displacement from their landward neighbour and eventually leaving inactive landward faults behind before being replaced by the next seaward fault themselves by basin-wide seismic mapping and analysis of isopach maps (e.g. SYDOW et al., 2003).

This study uses high-resolution depth-converted seismic data to investigate a series of large- and medium-scale normal growth faults. This, together with the rapid sedimentation rates, good well control, a number of biostratigraphically dated marker horizons aged between ca. 2.5-0.27 Ma, and the application of corrections for sediment compaction enables us to determine fault throw on the major faults within the dataset and to constrain fault throw rate for individual horizon intervals, which reaches up to 5-6 mm/a over an interval of 0.15 Ma for the larges fault in the dataset. The breakdown of accumulated throw and throw rate to time intervals allows a much more detailed study of fault activity and evolution over time than an averaged throw rate over the total time of fault activity would provide. It reveals for example displacement transfer between soft-linked faults and lateral propagation of faults.

Our approach confirms the sequential seaward migration of active faulting and additionally provides quantitative measurement of the amount of fault throw and throw rate per time interval.

GIBSON RG, MEISLING KE & SYDOW JC (in press) *Columbus Basin, offshore Trinidad: A detached pull-apart basin in a transpressional foreland setting*. – In: BALLY AW & ROBERTS DG (eds): *Phanerozoic Regional Geology of the World*

SYDOW JC, FINNERAN J & BOWMAN AP (2003) *Stacked shelf-edge delta reservoirs of the Columbus Basin, Trinidad, West Indies*. – In: ROBERTS HH, ROSEN NC, FILLON RH & ANDERSON JB (eds.): Shelf margin deltas and linked down-slope petroleum systems: global significance and future exploration potential, Proceedings of the 23rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, 441-465.

NOTES

Using seismic reprocessing and interpretation to determine the thermal and temporal history of a deep water sedimentary basin. Case study: The Porcupine Basin, offshore Ireland.

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Deep water sedimentary basins are attracting increased attention from academia and the hydrocarbon industry as they remain one of the last frontiers still to be fully explored and understood. Poor geological and geophysical constraints in some parts of the basin, together with processing and imaging issues related to variations in water depth and data quality are among the issues that need to be addressed to derive better constrained geological models.

The Porcupine Basin is interesting both from hydrocarbon prospecting and academic point of views as it represents a good example of under-explored – extremely thinned – non-volcanic passive margin. By addressing some of the main issues concerning this basin we will shed some light into the understanding of the behaviour of this kind of passive margin, and will provide constraints on hydrocarbon maturation for the Porcupine Basin. Discrepancies about stretching factor estimates and nature of the Porcupine Volcanic Ridge System, apparent asymmetry of conjugated margins, and poor knowledge of the thermal and temporal history of the basin, particularly in its southern part have been identified as major sources of discrepancy among people working on the Porcupine Basin.

The approach used in this study for addressing these issues is to extract quantitative strain rate models from legacy seismic data coupled to well log information by inverting subsidence observations. Seismic data quality, depth image accuracy and interpretation uncertainties are some of the challenges to address to better constraint our subsidence history models.

We first tackle the issues related to seismic data quality by reprocessing chosen multi-channel seismic reflection lines with state-of-the-art processing techniques, and by careful interaction between interpretation and processing. Algorithms which modified relative amplitudes and frequency content were avoided and special care was taken during successive velocity analyses.

Kirchhoff pre-stack depth migration applied to reprocessed data shows considerable improvements in image quality, with cleaner and more accurate depth images which can be calibrated against borehole information and wide-angle seismic data and interpreted with more confidence.

Well constrained interpretation of the reprocessed key seismic sections is a crucial step in our approach to extract structural and thermal history from subsidence observations. Palaeo-bathymetry, lithology and age, as well as geometry of the basin need to be defined as accurately as possible as they are the main source of uncertainties in our modeling. In this two dimensional inverse modeling of the subsidence history, spatial and temporal variation of strain rate that best fit the subsidence observations are determined, from which basin extension/subsidence as well as thermal histories can be extracted.

Our final animated model shows a combined thermal, structural and stratigraphic evolution of the Porcupine Basin. The obtained results can help understand the evolution of extremely thinned non-volcanic passive margins, and can be used to estimate the hydrocarbon maturation history of the Porcupine Basin.

This publication uses data and survey results acquired during a project undertaken on behalf of the Irish Shelf Petroleum Studies Group (ISPSG) of the Irish Petroleum Infrastructure Programme. We are grateful to WesternGeco for provision of Omega software. Much of the processing was performed using the Seismic Unix package.

NOTES

Late Cretaceous - Paleocene exhumation of the Fennoscandian margin observed on the Utsira High and Finnmark Platform East

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The most prominent Upper Cretaceous - Lower Paleocene seismic reflectors are interpreted in the southeastern Barents Sea and the Utsira High from regional 2D data (southern Barents Sea) and by semi-regional seismic stratigrahpic 3D analysis (the Utsira High). A revised lithostratigrahpic description and subdivision have been introduced for parts of the lithostratigrahpic intervals based on sedimentological logging of cores from wells 25/11-16, 25/11-17 and 7323/12-U-01, recent revised lithostratigrahpic definitions (North Sea) and well logs.

Combined seismic interpretation and mapping together with stratigrahpic studies provide evidence of denudated Late Cretaceous platforms during the Late Cretaceous - Danian period. Two sequence boundaries developing during a combined eustatic sea level fall and tectonic uplift(?) are recognized. In the Utsira High the top Magne Fm. (Campanian) and top Tor Fm. (latest Maastrichtian) sequence boundaries are ascribed respectively transpressional stress along the Sorgenfrei-Tornquist Zone during the Campanian, and tectonic influence in the form of relaxation related to the Iceland Plume. Whether the denudation(s) of the Finnmark Platform East is due to rapid eustatic sea level drop or uplift of the sediment pile is a matter of discussion. The observed unconformities are probably a combined result of episodic thermal doming and one or more eustatic sea level drops during the Early Campanian(?) and later Danian.

On the Utsira High a large scale canyon morphology is interpreted in blocks 16/2 and 16/3. This feature is inferred to be the result of submarine current erosion during Late Cretaceous - Early Paleocene, later infilled by Paleocene sediments. The influence of strong bottom currents during chalk deposition stands in marked contrast to the conventional picture of a quiet pelagic deposition. The possibility of subaerial exposure and karst development is suggested based on well data. Numerous slide scars are interpreted on the top chalk surface as well as a turbidite mass flow generated in an unstable chalk slope, possibly induced by flexural uplift in the latest Maastrichtian. Isopach maps for Cretaceous - Lower Paleocene sediments show that the chalk depositional pattern changed during this time period due to the influence of tectonic uplift and infilling of existing relief.

On the Finnmark Platform East the Base Tertiary unconformity is observed as a prominent undulating reflector with a morphology of lateral alternating synforms and antiforms (generally 200-1000 m lateral and 40-120 m vertical extension), the latter in which angular collapse structures (10 x 100 x 2000 m) in the easternmost study area are observed in crests. The reflector suggests an unconformity of a subaerial erosive character (development of large scale karst) in the easternmost areas, whilst still undulating in places toward the Fennoscandinavian margin. The Base Tertiary reflector here represents Danian claystones lying conformable on Maastrichtian mudstones. Basinwards the antiforms might be both erosion and/or deposition related. Two major drainage channels (generally 1.3 - 2 km wide and > 40 km long) trending ENE-WSWand NW-SE, in addition to symmetric, semi-parallel and lateral extensive synforms, are interpreted along the sequence boundary on the Finnmark Platform East. The lack of sinuosity for the synforms in deeper areas may suggest a development as submarine canyons

in a narrow shelf slope, whilst the morphology and relative appearance of the features favor a deposition as storm or beach ridges during a stepwise regression and prolonged exposure of a paleo shoreline. An internal Upper Cretaceous reflector truncating underlying Upper Cretaceous reflectors is relatively dated to Early Campanian(?) and further truncated by the Base Tertiary reflector. Higher order sequence boundaries in the lower Upper Cretaceous package are inferred based on sedimentological core logging.

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Evolution of the Troll West Fault Array, Norwegian North Sea.

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Located on the Horda Platform, 80 km north-west of Bergen, the Troll Field spans an area of c.700 km^2 across blocks 31/2, 31/3, 31/5 & 31/6 of the Norwegian North Sea. Discovered in 1979, Troll represents one of the largest offshore gas fields in the world with GIIP of 59tcf and OIP 3.9bbl. The Upper Jurassic sandstones in large rotated fault-blocks represent the reservoir interval in Troll and these units are sealed by overlying Upper Jurassic, Cretaceous and Tertiary Shales.

Despite the area being covered by high-quality 3D seismic data and containing abundant well data, the Troll area has not been the subject of a detailed structural study. This study provides an insight into fault array evolution of the western part of the Troll Field and, in contrast to previous studies, suggests that rather than being a period of tectonic quiescence, the post-Late Jurassic to Tertiary was a period of intense tectonic activity.

Two major fault populations are identified; (i) a NW-SE trend possibly inherited from an earlier Permo-Triassic rift event, and (ii) a N-S trend formed during Upper Jurassic rifting. Isochores between key stratigraphic surfaces record five key stages in the spatio-temporal development of the fault array;

1) Lower to early-Middle Jurassic (203.6-175.6 ma); A period of basin wide thermal subsidence proceeding the Permo-Triassic rift event, with subtle evidence of localised growth across some possibly reactivated NW-SE trending Permo-Triassic faults;
2) Middle to early-Upper Jurassic (175.6 – 161.2 ma); A period of lacking both active faulting and differential subsidence;
3) Late-Upper Jurassic to Early-Cretaceous (161.2 – 140 ma); Initiation of extension along N-S orientated faults and eastward rotation of the major fault blocks and the formation of thick wedge-shaped stratal units;
4) Middle-early to Late Cretaceous (140 – 70 ma?); Protracted phase of activity on large N-S faults with subordinate growth on reactivated NW-SE faults. The synchronicity of displacement along these two fault trends led to segmentation of the evolving syn-rift depocentres. The exact duration of syn-rift deposition is unclear, with no wells penetrating the entire succession;
5) Tertiary (65.5 – 28.4 ma); Cessation of active faulting in the study area and migration of faulting 30 km eastwards onto the Øygarden Fault Complex.

In summary, this study has demonstrated that that overall fault activity migrated westwards across the Troll Field and that extension on the Horda Platform continued well into the Cretaceous, ~50 Myr after the cessation of rifting along the main axis of the North Viking Graben. This study also suggests there may be a component of interaction of reactivated Permo-Triassic and Upper Jurassic fault populations during the latter rift event. Comparisons with analogue models suggest how kinematics related to this interaction may work. Future work aims to look at fault scaling relationships in this area, evolution of individual fault zone, fault-propagation folding and the response of synrift systems to fault growth.

NOTES

Industry-academia collaboration invigorates exploration in the South Viking Graben

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The South Viking Graben (SVG) is a mature petroleum basin, with large fields exploiting Middle Jurassic and Palaeocene reservoirs on the Norwegian side of the basin. In addition to existing producing fields, including the Sleipner fields, there are promising discoveries, such as Gudrun, ready for development and numerous exploration targets within several diverse plays. As such, the SVG and Greater Sleipner area is a core commercial area for Statoil that still offers commercially significant exploration and field-development opportunities.

Although the Middle Jurassic and Palaeocene plays are now mature, recent exploration drilling has showed that promising discoveries such as Ermintrude and Biotitt can still be made in these reservoirs. Triassic, Cretaceous and Palaeogene reservoirs are less explored, and the Upper Jurassic in particular, can be considered grossly under-explored when compared to the UK side of the basin where the prolific Brae fields are located.

Within an extensional basin such as the SVG it is a major challenge to predict reservoir distribution and quality within the syn-rift interval. Although a large number of exploration and development wells are drilled in the area, only a handful of wells have proven Upper Jurassic reservoir rocks. Unlike the well explored pre-rift reservoirs that are commonly drilled on structural highs, syn-rift exploration needs to target stratigraphic traps involving higher uncertainty and risk with respect to reservoir presence and trap integrity.

To meet this challenge a multidisciplinary, regional geological study was initiated in 2005. This is an ongoing collaborative effort between Statoil, and Imperial College London. The research carried out at Imperial College is sponsored jointly by Statoil's Exploration R&D department and by the licence responsible for exploring the study area (production licence 303). This ensures close collaboration between academic staff at the university and exploration staff in the company.

Academic staff and students are provided a full subsurface dataset, including wells, seismic, various in-house specialist studies such as biostratigraphy, and also get access to company staff with detailed knowledge of the data and the challenges facing exploration and field development in the area. The company benefits from access to in-depth research results in various disciplines.

The main result of this collaborative effort is an improved understanding of the study area based on integration of various data types and research diciplines. Integrated use of biostratigraphy, sedimentology, sequence-stratigraphy, seismic-stratigraphy, structural geology, seismic inversion and analysis of fluid and pressure data has resulted in a revised regional geological framework for this mature basin. Close collaboration ensures that results are continually delivered and utilized in the prospect identification and evaluation tasks carried out in the company.

Geological predictions and risk evaluation have benefited greatly from the improved regional understanding gained from this research. Several exploration targets have been identified in the less-explored stratigraphic intervals in addition to the mature Middle Jurassic section. As such the project provides support for investment decisions related to both exploration and field-development.

This project demonstrates how industry/academia collaboration and an integrated multidisciplinary approach can generate new opportunities in a mature basin that has been explored for more than 30 years.

NOTES

Determining lateral and vertical seal integrity in channel-levee complexes

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CAPROCKS is a collaborative project aiming to improve seal risk prediction through better sedimentological and stratigraphic characterisation of sealing successions. Our focus for this project is to categorise slope systems using a process-based methodology, by defining key genetic units. The genetic units are: channel/levee complexes, mass transport complexes, contourites and hemipelagites. In this talk, we show our methodology for characterisation of channel/levee complexes. Channel fill deposits commonly form the main reservoirs in deep water settings and are therefore being extensively studied. However, their associated levees are usually overlooked despite their proximity to the channel fill deposits. The question we attempt to answer is under what circumstances levees have sealing potential or the capacity to transmit fluids.

In order to address this question, we combine seismic data and bed thickness and spacing data for permeable units within levee facies extracted from ODP cores of channel-levee successions and published outcrop data. The aims of this synthesis of published data are: (1) to establish diagnostic seismic characteristics of levees, (2) to compile a database of levee dimensions, and (3) to examine the length scales of lithological variations within the levee. These length scales are critical to any stochastic modeling of bulk flow properties. We find that net-to-gross values for levees range from 0-30% in a range of settings, and that there is no systematic variation in N/G with distance from the head of the channel. We also find that lateral N/G variation may have a significant control on levee geometry, and this opens a way for geometry to be used predictively in seal risking.

NOTES

Modelling void geometry in deepwater reservoirs 'X' Field, offshore Niger Delta, Nigeria

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A significant proportion of the world's undiscovered petroleum reserves are hidden in the deep oceanic waters surrounding the world's continents.

Over the last decade, advances in the geosciences, drilling and production technology are now making the exploitation of these vast reserves possible. Recent discoveries of the deepwater, Nigeria include Agbami, Bonga, Chota, Ngolo and Nnwa fields (Billoti and Shaw 2005).

As Deepwater offshore Nigeria enters a new phase as fields come into production, the enormous cost of finding and producing hydrocarbon reserves makes deepwater reservoir development strategies very challenging.

The challenges of describing connectivity of reservoir by either under estimating its complexity may have significant financial implications as initial drainage strategies might not produce the predicted recoverable reserves or overestimating complexity may as well lead to drilling too many wells in well connected reservoirs wasting valuable resources.

This research seeks to formulate a plan for the development of deep offshore reservoir units and provide the framework for the optimal placement of wells to maximize the architectural and facies controls on reservoir performance.

NOTES

Re-Os Geochronology of oil source rocks: a viable tool for petroleum exploration?

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Black shales rock units are the typical source for crude oil in many of the world's sedimentary basins. Establishing the absolute age of source rocks provides important chronologic constraints on the evolution of the petroleum system. To date, black shales have unequivocally been demonstrated to be viable for precise dating through application of the rhenium-osmium (Re-Os) geochronometer. The Re-Os systematics in black shales are not disturbed by hydrocarbon maturation, and therefore provides a geochronometer ideal for dating the depositional age of petroleum source rocks to further our understanding petroleum systems.

Previous studies have determined precise ages from outcrop and drill core samples, analysing powder aliquots (~1g) ground from 50-80g rock samples. Exploration companies rarely drill potential source units and in many cases only drill chippings are recovered. In sedimentary-petroleum systems of uncertain age Re-Os geochronology of drill chippings could provide meaningful dates, even if only to period uncertainty, and so critically establish the chronology of a petroleum system. We examine if source rock drill chippings can yield meaningful geochronology using the Kimmeridge Clay of the Miller oil field, North Sea.

Four drill core samples (70-80g) ranging from 4738.2-4737.3m from the Kimmeridge clay have been analysed. Pseudo drill chippings were created by breaking ~2-5g of sample from each core sample. Samples were cut and polished to expose fresh material, then powdered in a ceramic mill. Re and Os are purified form the rock powder through a selective digestion protocol, solvent extraction, micro-distillation and chromatography. NTIMS is used to determine Re-Os isotope compositions.

Four core samples yield an isochron age of 139.5 ± 3.5 Ma (2σ, MSWD = 0.18). This age is in good agreement with biostratigraphic constraints. The pseudo chippings yield an imprecise age of 159 ± 27 Ma (2σ, MSWD = 4) however, within uncertainty of the Re-Os core age. Evident is the difference in $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ values and Re-Os abundances between the core and chippings analyses. Though variable, the calculated initial $^{187}Os/^{188}Os$ value for the chipping samples (0.52 to 0.54) are broadly in agreement with the core samples (0.53). The variable $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ values and Re-Os abundances, and subsequently the imprecision in the age derived from the chippings is interpreted to be caused by the heterogeneous distribution of Re and Os, and different organic complexes for Re and Os in the black shale matrix. This '*nugget*' effect is further demonstrated by repeat analyses of a core sample prepared from powdering a large (~50 g) black shale sample. These analyses show very slight difference in $^{187}Re/^{188}Os$ values, which is positively coupled with $^{187}Os/^{188}Os$ values, such that the calculated Os initial values are very similar.

To first order this work shows the potential utility of Re-Os chipping analysis in petroleum exploration to establish the geochronology of sedimentary basins. Further, it demonstrates the natural Re-Os decoupling in the black shale matrix that can be overcome using rigorous sample preparation protocols. Follow-up work is currently underway on global Jurassic black shales to further establish this technique.

NOTES

What´s the role of crystalline basement geological mapping in the oil industry?

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The partnership between the University of Rio de Janeiro State (UERJ) and PETROBRAS was first established in 1999. Undergraduate and graduated students, and the company technical staff could broadly benefit from this 8-year integration, that resulted on more than 30 masters and PhD thesis, and the training of more than 200 newly hired Petrobras geologists. The knowledge acquired during the last 20 years of multidisciplinary work on basement evolution by the university researchers could, then, be added to decades of knowledge on the marginal basins evolution acquired by Petrobras. A remarkable achievement that arose from this collaborative work was the knowledge integration between the crystalline basement tectonic evolution, the adjacent Brazilian marginal basins studies, and their correlation with the counterpart basins on the African margin. Geological mapping and structural analyses, together with lithogeochemistry and isotopic geochronology data, geological processes modeling, geophysics and geomorphology on the basement rocks has been contributing for the understanding of the sedimentary processes, the stratigraphic record, the traps development and the oil maturation process in the Atlantic marginal basins. Some of those results are presented below.

On the basement of Santos, Campos and Espirito Santo basins, the Brasiliano compressive tectonic events (630-500 Ma) culminated with the Adamastor Ocean closing and Gondwana Supercontinent assembly. A remarkable anisotropy caused by lithologic boundaries, tectonic foliation, and ductile to brittle shear zones has established the main structural pattern followed by the mesozoic continental break-up processes.

The fissural tholeiitic magmatism that resulted from lithosphere extension was the first evidence of continental break-up. Dyke swarms interconnect and superimpose themselves in NW, N and NE directions, ranging in time from 190 to 130 Ma (Guedes *et al*., 2005). Structural data suggest an evolution due to interconnected triple junctions, with $_{Hmax}$ on a NNE direction, resulting on an extension of predominantly E-W to ESE-WNW direction. Oblique normal-sinistral NE striking faults corroborate this dynamic pattern.

The basement was, then, the onset of faulting and fracturing associated with an intense uplift of the Atlantic Rift border, giving birth to a younger rift system related to the campanian-maastrichtian alkaline magmatism. A conjugate system of E-NE and N-S faults was formed in association with breccias and cataclastic rocks cemented by silica-rich hydrothermal fluids. The paleotensors rotate slightly clockwise, positioning the $_{Hmax}$ between NE and ENE. The sediment infilling of the intracontinental basins was intense during the Eocene, passing then, to a period of tectonic quiescence and subsidence. At last, younger reactivations of the faults and dykes readjusted the crustal blocks, segmenting the internal basins and creating new topographic compartments.

Although seismic data could show some of the main fault zones, the detailed characterization of the geometry and kinematics of tectonic events in the basement rocks enrich the evolutive history of the marginal basins, specially when there are no outcrops of the sedimentary succession, as in southeastern Brazilian continental margin.

NOTES

Hydrocarbon exploration in the archives

Gordon Beattie

In view of apparent oncoming energy crisis may I suggest an area for further hydrocarbon exploration, the archives? The archives may prove to be fruitful with improvements in technology and reassessing prevailing bias of the time.

At this time in oil industry, there was frequently encountered, often at a surprisingly high level of management, the concept of the “Gusher”, and the widespread belief that if a well did not produce a gusher it was not productive.

There were several reasons why wells did not fulfil their potential, technical and personnel:

- During boom times, such as in the late 1970’s, many inexperienced staff were taken on, and many were promoted to positions of responsibility before their knowledge and experience warranted it. As this was a time when there was a considerable movement nationally and internationally of staff the effect could be seen on a global scale;
- Wells were drilled with an overbalanced drilling fluid, which obscured any hydrocarbons and lead to invasion of the surroundings. This was often the case after there has been an event at a well in the local area or within the experience of the operating staff. Hydrocarbons were hidden by the misunderstood incombustible light gas at the top of reservoirs.

This is a field where the basic skill of a geologist, the ability to read data and identify patterns, would come into their own. These are old skills which may have been lost somewhat in the current ardour for technology and systems.

NOTES

Combined remote sensing and field investigations of hydrocarbon trap analogue structures: Examples from the Zagros Simply Folded Belt, Iran and the Sawtooth Range, Montana

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Structures that outcrop at the surface in fold-thrust belts are frequently good analogues for hydrocarbon traps in compressional environments. Along-strike changes in structure and geometry have important implications for connectivity and fluid flow throughout the petroleum system, e.g. in the Zagros Simply Folded Belt, Iran, and in a surface reservoir analogue in the Sawtooth Range, Montana.

Using satellite images and remote mapping, the Zagros Simply Folded Belt is ideal for the study of along-strike change in structure at a convergent margin. Lines of anomalously long, high-aspect ratio folds, crossed by multiple wind gaps, are clearly linked to movement along basement thrusts and correlate with major steps in the landscape. The basement faults formed sequentially as the deformation front progressed SW towards the Persian Gulf. In the Zagros, brittle and ductile deformation processes interact. Movement along a ramping-up thrust creates a fault-bend fold. Compressive stresses build up, leading to serial folding in the cover behind the fault-bend fold. Eventually, deformation of the block requires stresses in excess of those required to form a new thrust. The original thrust is abandoned, the footwall collapses and the process repeats.

A field study of a fold pair in the frontal region of the Sawtooth Range, Montana indicates that individual folds may change considerably in geometry and deformation style along strike. The N-S trending Teton anticline and Little Teton Anticline are both incipient box folds with broad rounded hinges formed in the carbonates of the Mississippian Madison Group. The fold wavelength is determined by the depth of the detachment, which ramps up from the Cambrian shales in the hinterland, to Devonian shales and finally Cretaceous shales in the foreland. The Teton Anticline is a near symmetrical fold in the northern mapped section but becomes distinctly asymmetric when traced to the south.

The change in geometry of the Teton Anticline implies that there is increasing complexity in the sub-surface thrust faults to the south. This complexity may be related to the influence of pre-existing basement topography. Folds in a fold-thrust belt display a spectrum of different geometries between detachment folds and fault-related folds. These differences are determined by the relative amounts of brittle and ductile deformation and occur both along and across the strike of the fold-thrust belt, and along strike of individual folds.

NOTES

Strike-Slip Faulting in Peninsular Thailand, Basin Evolution, and Linkage to Regional Tectonics

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The Khlong Marui Fault (KMF) and Ranong Fault (RF) are major NNE trending strike-slip structures which dissect Peninsular Thailand. They crop out for 220 km and 420 km respectively, appear to pass into the Andaman Sea to the west and the Gulf of Thailand to the east, and are assumed to be conjugate to the NW trending Three Pagodas Fault (TPF) and Mae Ping Fault (MPF) in northern Thailand. According to models for the extrusion of Asian continental crust, a diachronous reversal in shear sense on the NW trending faults correlates to northward movement of India during the India – Eurasia collision. It follows that the KMF and RF are expected to show the opposite shear sense and an inversion at the same time as the MPF and TPF. Constraining the timing of movement on these faults, and their relationship to sedimentary basins in the Gulf of Thailand, is key to understanding basin formation in this important petroleum province.

Field mapping reveals that both the Ranong and Khlong Marui faults are defined by elongate cores of metamorphic rocks with dextral shear fabrics, bound by brittle sinistral strands. The cores are composed of amphibolite facies mylonites, migmatites, syn-kinematic granitoids, and lower grade sheared sediments. The RF has up to three parallel ductile strands, giving it a maximum width of 42 km. Two phases of ductile dextral shear – D1 and D2 - are separated by Campanian inter-kinematic magmatism. Palaeocene to Eocene post-kinematic granites constrain the end of D2, while D3, the brittle sinistral phase, deforms these granites. Minor dextral deformation, D4, occurred at shallow levels, and obliquely truncates the older fabrics.

A metamorphic core complex at the northern end of the RF lies near the southernmost strand of the TPF. West directed extension on a low angle ductile detachment exposes a core of granitic gneiss. Its geometry is consistent with E-W extension, associated with D3. Basins at the ends of the fault are also orientated so that they should open during D3. Both faults splay at their southern ends as they enter the Andaman Sea, and may die out entirely before they enter the Gulf of Thailand. It seems likely that the faults did not control or drive extension in the basins, but acted as accommodation structures. Syn-extension sedimentation on both sides of the peninsula occurred from Mid Eocene to the end of the Oligocene, during D3 and core complex unroofing. Basin inversion during the Miocene correlates to the onset of D4.

The D1/D2 to D3 inversion is consistent with the faults' hypothesised role as antithetic branches of the TPF. However, the sinistral phase on the TPF has previously been interpreted to occur 25 Ma after the equivalent D1/D2 interpreted here. This Upper Cretaceous – Palaeocene deformation is well before Himalayan continental collision, and may instead to be linked to the final assembly of Sundaland. The Eocene – Oligocene D3 phase is likely to represent reactivation of the D1/D2 fabrics at a shallower depth in response to locally driven basin extension.

NOTES

Influence of tectonic inversion and salt mobility on structural styles and reservoir quality in the Norwegian Central Trough

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The Norwegian sector of the North Sea Central Trough is a structurally complex region of economic importance due to hydrocarbon accumulations within traps containing Upper Cretaceous and Palaeocene Chalk Group reservoir (e.g. Ekofisk, Eldfisk, Valhall and Tor oilfields). New interpretations demonstrate that the structural traps were created through a combination of tectonic inversion and/or salt doming. This study examines the characteristics of and relationships between inversion and halokinesis in the Norwegian Central Trough.

A well-calibrated 3D seismic dataset covering a 5000km^2 area has been studied in accordance with standard seismic-stratigraphic principles. Horizon and isochron maps constrain the key geometries and stratigraphic intervals, from pre-Zechstein Permian units to Cenozoic strata. Zechstein Group evaporites became mobile during the Triassic, with the creation of minibasins adjacent to salt highs, and salt movements continued until Miocene times. Inversion occurred during comparatively discrete intervals: a Campanian episode is recognised (contemporaneous with Chalk deposition), as is a post-Palaeocene, pre-Miocene event.

The timing and extent of salt movement is a major control over the structural style associated with inversion and there are consistent and predictable differences between salt-free areas as opposed to salt-prone areas. Where there is no salt (or salt has been expelled), the structural styles are more asymmetric and localized over the site of a pre-existing structural trend. There are other important factors influencing the structural style associated with inversion, including the geometry of the basin undergoing compression and the orientation of the regional stress field.

Chalk Group reservoir quality (permeability and porosity) is variable and difficult to predict. It is influenced by the sedimentology of the depositional facies, by diagenesis, and by the physical characteristics of internal fracturing. However, subsurface salt movements and/or Campanian inversion clearly influenced Chalk Group thickness distribution and depositional facies type. Later salt movements and/or post-Palaeocene inversions may have directly affected and enhanced the fracture characteristics of the reservoir.

To test the possible influence of fold growth on fracture patterns, structural restoration software (3DMove by Midland Valley Ltd) has been used to model the strain associated with fold growth at the Eldfisk field. Strain measurements are derived from comparison of pre- and post-deformation states of the reservoir interval, and the resulting strain distribution maps provide direct insight into fracture patterns. These fracture predictions are calibrated against discrete fracture data from existing production activities.

Results from this study are valuable on account of their ability to explain the observed variability in structural styles and Chalk Group reservoir properties across the Norwegian Central Trough.

NOTES

The role of pre-existing structures in the evolution of the Kepingtage fold-thrust belt, Tarim Basin, China

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Pre-existing structures play an important role in the development of subsequent fold-thrust belts, and as such have important implications regarding the organisation of structures (folds and thrusts) and the distribution of hydrocarbons in compressional settings. The Kepingtage fold-thrust belt in the northwestern part of the Tarim Basin, adjacent to the Tien Shan orogenic belt, provides an exceptional example of active deformation in a foreland setting. A combination of field investigation, satellite image interpretation and digital elevation modelling has been used to examine the relationships between pre-existing structures, resultant sedimentary facies distribution and the architecture of a superimposed fold-thrust belt. The Kepingtage fold-thrust belt comprises a series of NE-SW trending thrusts that define an arcuate salient and expose a Cambrian through Neogene succession. The geometry and deformation style of the fold-thrust belt is variable along strike, allowing the belt to be divided into a number of structural domains. These domains appear to correlate with variations in stratigraphic thicknesses which in turn are associated with the presence of major, pre-existing structures. Perhaps the most prominent of these structures is the Piqiang Fault, a N-S trending fault which cuts across the fold-thrust belt. Previous studies have determined this fault to be the lateral continuation of a major pre-existing fault that extends into the interior of the Tarim Basin. The fault down-throws to the west and controlled the distribution of sedimentation prior to the evolution of the Kepingtage fold-thrust belt. As a result, the fault presently delineates two structural domains, with differences in deformation style, horizontal shortening and geometry. Understanding the controls of such faults on the evolution of the Kepingtage fold-thrust belt provides not only an insight into the active deformation of the hydrocarbon-rich Tarim Basin, but can be applied as an analogue for similar fold-thrust belts worldwide.

NOTES

The Atlas of the Southern Permian Basin Area (SPBA Project): Progress Report and insights on the Permian to Cenozoic Tectonic Evolution of West Central Europe

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The Southern Permian Basin Area (SPBA) project is a collaboration between the Geological Surveys of Belgium, Denmark, Germany, the Netherlands, Poland and the United Kingdom, together with a significant number of contributors from industry, licensing authorities, research institutes and academia. The aim of the atlas is to present a comprehensive and systematic overview of the results of over 150 years of petroleum exploration and research in the Southern Permian Basin Area, extending from eastern England to the Polish-Russian border. It will also celebrate the 50th anniversary of the discovery of the Groningen field which provided a major impetus to exploration of the region. Publication will be in both digital (CD) and paper (A2 atlas) formats, and is scheduled for 2009. The maps (print scale 1:3,000,000) will also be available in GIS format.

The project was launched in March 2005 and is managed by TNO with the assistance of a Steering Committee including representatives from industry. It has already attracted sponsorship of € 1,500,000. The project has developed through a series of meetings hosted by the national surveys. The participation of further E&P companies, both as sponsors and data-providers, is welcomed. Good progress has been made in the key areas of GIS mapping and chapter writing. The Atlas will address the geological evolution and hydrocarbon potential for each stratigraphic interval. Early chapters focus on the crustal and lithospheric structure of the region. The palaeogeographical and tectonic evolution will be covered within the framework of the principal stratigraphic intervals, from the Precambrian to the Holocene. The various structural and stratigraphic settings will be elucidated by studies of representative fields, overview maps and illustrations. Petroleum generation, migration, trapping and production, and the history of exploration and licensing in the basin will be covered, together with a summary of resource assessments. Other potential options for use of the deep subsurface, such as gas storage and geothermal aspects, will also be addressed.

The chapter on Tectonic Evolution has 9 participating authors. We will present a series of palaeogeographic reconstructions, orogenic and basin evolution syntheses and thematic studies on the subsidence, inversion and halokinetic history of the SPB. The morphology of the basin will be illustrated by interpreted regional seismic lines and long depth-converted transects from each country published at constant scale. The integration of these data with geophysical potential field, tectonic and stratigraphic mapping for the whole region is providing new insights into the initiation and evolution of the basin.

NOTES

Summer Internships: Interviewing the Company

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At present the employment market for recent graduates in geoscience related areas of the oil and gas industry is buoyant. In order to recruit, companies traditionally use a combination of panel interviews, one-on-one interviews, assessment centres and other forms of testing procedures to select candidates they feel are best suited to the positions on offer. One area that is often difficult to assess during the time restricted recruitment procedure is the personality of the candidate, and specifically how they as an individual will fit into the company and its general work culture. This question is however commonly high on the list of most candidates when applying for a position. With a buoyant job market and the 'package' offered by most companies being similar the candidates attention is now focused on trying to evaluate how well the company is suited to them as an individual. One way to address both the company's, and the individuals needs is through the use of an extended interview.

Summer internships for M.Sc. and Ph.D. candidates provide an excellent extended interview process for both parties involved. The internship should be planned in a way that it provides the internee with a structured project that is typical of the work performed by team they are placed in, it should also ideally require communication to be initiated by the internee both with their immediate team they and with colleagues located in other teams/disciplines within the company. This allows the company to assess both the technical competence of the candidate, and to observe their performance in a real-world situation. For the internee it enables them to 'interview the company' by gaining an insight into its working culture as well as the day-to day work of a typical employee and thereby evaluate how well the company is suited to them.

NOTES

Early post-rift basin development, early to mid-Cretaceous, North Viking Graben, Norwegian North Sea

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The transition from syn-rift to post-rift is often poorly constrained, and in contrast to syn-rift systems, the controls on the development of post-rift systems are poorly understood. This paper aims to document the timing of the onset of the post-rift interval and discuss the controls that affected the subsequent development of the post-rift infill of the North Viking Graben using an integration of seismic and well data. It is hoped that this study can further enhance the understanding of post-rift system development in general and thus be used as an analogue for other post-rift systems.

Within the early post-rift infill of the North Viking Graben five key seismic surfaces were mapped (Base Cretaceous Unconformity (BCU), Intra-Aptian, Top Albian, Top Cenomanian and Top Turonian), which divide the post-rift interval into 4 key seismic stratigraphic units (K1, K2, K3 and K4). The BCU was examined extensively in the well data and on the seismic as this surface is often believed to represent the transition from syn-rift to post-rift. The BCU has an intra-Volgian age on the basin slopes and shelfal and terrace areas and in conjunction with its appearance on seismic, which shows no evidence of vertical fault movement affecting it in these locations, it is interpreted that this marks the timing of the end of rifting in the study area. The interpreted BCU on the footwall crests adjacent to the graben and in the graben itself are interpreted to represent a complex composite unconformity from the syn-rift and post-rift combined and a conformable contact respectively and therefore could not be used to date the onset of the post-rift.

The thickness variations and age relationships between the underlying syn-rift stratigraphy and each K-unit reveal that the development of the early post-rift infill of the North Viking Graben was dominantly controlled by the strong local syn-rift topography that was inherited by the post-rift, especially in the K1 and K2 stages. The Cretaceous post-rift stratigraphy passively onlaps and infills the significantly uplifted and tilted fault-blocks and associated depositional lows left behind by the syn-rift interval. Development of the post-rift stratigraphy was also influenced by relative base level, which controlled the sediment source areas to the basin, the development of the basin geometry itself and subsequently the type of sediment deposition in the study area. An overall deep-marine depositional environment prevailed during the early to mid-Cretaceous and the key depositional and erosional elements identified in the North Viking Graben during this time are deep canyon-like incisions in the footwall crests of the uplifted fault blocks, margin-attached bodies adjacent to the footwall, and channel and fan systems within the basin. Regional variations are recognised in the post-rift stratigraphy although these signals are also strongly controlled by the local basin physiography.

NOTES

Impacts of normal fault growth and salt tectonics on syn-rift play development in the Sleipner Basin, South Viking Graben, Norwegian North Sea.

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As the Middle Jurassic, pre-rift play of the South Viking Graben becomes increasingly mature, exploration in the area is being regenerated through a collaborative project that focuses on the hydrocarbon potential of the Upper Jurassic syn-rift succession. Because previous exploration has targeted the proven Mid Jurassic reservoir across basin-bounding highs, the nature of the syn-rift interval within the Sleipner Basin study area is yet to be documented by well data. Here, 3D seismic data are used to reconstruct the structural and stratigraphic development of this salt-influenced extensional sub-basin for the purpose of predicting deep-water reservoir distribution.

Located on the hangingwall dipslope of the South Viking Graben, the N-S-trending, 30 km long by 8 km wide, Sleipner Basin was formed through a combination of Late Jurassic extensional faulting and halokinesis of the salt-rich Zechstein Group. The basin is bound to the east by a major extensional fault and to the west by a large salt-controlled high. Along-strike, it is compartmentalised into four discrete mini-basins by three smaller salt-cored highs.

Detailed seismic stratigraphic analysis reveals a complex interplay between normal fault growth and salt behaviour during the Late Jurassic rift event. The development of an asymmetric fault-parallel fold in the hangingwall of the basin-bounding fault can be explained by a mechanism of extensional forced folding, whereby the propagation of the fault was initially inhibited by the presence of the ductile salt layer. Post-Zechstein Group, pre-rift cover strata were folded ahead of the fault tip resulting in initial offset of the syn-rift sedimentary depocentre away from the fault. Upon breaching the salt and overlying cover strata, the fault was able to generate displacement at-surface. This led to subsidence of the fold structure and an eastward shift of the later syn-rift sedimentary depocentre toward the fault. Key seismic reflections were tied to available wells to establish a temporal framework for fold and fault development. Initiation of folding is constrained to end-Middle Jurassic times whilst breaching occurred during the Late Jurassic.

Isochron mapping enables pre-rift episodes of salt movement to be differentiated from those coeval with Late Jurassic faulting. Across major basin-bounding structures, substantial thickness variations of the Permo-Triassic succession indicate significant salt diapirism prior to rifting. However, the thinning of the Upper Jurassic succession across the intra-basinal salt-cored highs demonstrates the along-strike variation in the extent of syn-rift forced fold development. Initial results suggest that the distribution of the salt-cored highs and component minibasins is intimately associated with the segmentation and linkage history of the normal fault array.

The structural and stratigraphic reconstruction presented in this study has important implications for the distribution of syn-rift turbidite reservoirs. For example, due to the growth of the fault-propagation fold, early syn-rift, axially-fed turbidite systems would be offset westwards from the immediate hangingwall of the basin-bounding fault and restricted to the synclinal depocentre. During the late syn-rift, after breaching of the salt and folded cover strata, the turbidite system would migrate eastwards into the immediate hangingwall of the now surface-breaking fault.

NOTES

Structural controls affecting recent submarine channels in the Levant Basin, Eastern Mediterranean.

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The interaction between structural deformation in compressional deepwater fold and thrust belts, and submarine channel sedimentation is studied using a 3D seismic survey located in the Levant Basin, Eastern Mediterranean Sea. The later Neogene succession in this area is deformed by thrust related folds and a system of conjugate strike slip faults. This deformation is a result of the distal, gravity driven collapse of the Nile Delta and associated slope apron above a thick sequence of ductile evaporites deposited during the Messinian Salinity Crisis. Structurally-controlled seafloor topography strongly affects the flow pathways, morphology and depositional patterns of recent submarine channels in this area.

There are a number of end-member interactions between deformation and deposition in this area. Structures which pre-date the submarine channels create a complex slope bathymetry to which the submarine channels respond. Along strike variations in the geometry of thrust related folds and variation in vertical displacement along strike slip faults control the ability of these structures to confine submarine channels and their levees, and influence the location of changes in channel course and zones of increases overbank sedimentation. Where structural deformation occurs coevally with submarine channel deposition, channels can show a limited ability to maintain their course across growing folds. Other examples of fold growth orientated perpendicular to the axis of a submarine channel often results in deflection of the channel around the edge of the fold, channel avulsions, and in some cases complete blocking of the submarine channel against the growing fold. Channel avulsions and deflections are associated with formation of small scale depositional lobes which preferentially pond in the hanging wall and foot wall synclines of thrust related folds. The underlying structures which affect submarine channel morphology may also affect the distribution and development of any potential reservoir bodies by preventing, or enhancing the development of channel sinuosity. The results of this study improve our understanding of the structural controls on submarine channel morphology, particularly in deep water fold and thrust belts.

NOTES

Controls on the 3D seismic geomorphology of submarine channel systems: Nile Delta Slope, Egypt

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The Nile Delta is an active area of hydrocarbon exploration and in recent years submarine channel systems have become successful plays. Submarine channels are abundant in the study area and played a key role in the transport of sediment downslope from the Nile shelf to the deep-sea. Despite the importance of the channel systems for hydrocarbon exploration and the wealth of information they contain about climatic and tectonic processes, little is known about their evolution.

High resolution, 3D seismic data (provided by BG-Group) from the western Nile Delta, provide excellent coverage of the Plio-Pleistocene channel systems. The channel systems are imaged using volume-based maximum amplitude extractions and spectral decomposition techniques. At an individual channel scale, the architectural development of channels is qualitatively assessed and at basin scale, the spatial and temporal distributions of the channel systems are documented. In addition, the basal erosion surfaces bounding many of the channels are quantified.

The Pliocene channels are smaller, less incisional and levees are minor features compared with the Pleistocene channels. Pleistocene channels are up to 4 km wide, 500 m deep and are associated with levees up to ~ 250 m thick. In planform, the channels are tens of kilometres long and have variable orientations. Throughout the succession the location of channel head regions change. The head region of several of the channels is located between the Rosetta Fault System and the Nile Delta Offshore Anticline. In addition to changes of geomorphology between Pliocene and Pleistocene channels, the spatial and temporal locations of the channel systems change. In the Pleistocene there is an initial eastward migration of the channel-belt followed by a prominent westward shift.

The increase of channel size from the Pliocene to Pleistocene is controlled by decreasing distance of the study area from the shelf break related to Pliocene progradation of the delta. Channel location and orientation is influenced by slope topography which is controlled by structural deformation related to the Rosetta Fault System and Nile Delta Offshore Anticline. The temporal evolution of individual channel systems is influenced by changes in flow parameters associated with sea-level/climate change whereas the downslope evolution of individual channels is controlled by local structure.

The temporal and spatial migration of submarine channel systems described in this study shows the evolution of the Pleistocene depositional system. Understanding relationships between channel evolution, local structure, sea-level change and delta-top processes are essential to develop predictive models for channel inception and development.

NOTES

Making sense of carbonate diagenesis: Understanding processes as a route to prediction

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Traditional approaches to carbonate diagenesis focus on the nature and distribution of diagenetic products, such as cements. However interpretation of these data requires understanding of formative processes, which are controlled by the hydrology and biogeochemistry of diagenetic fluids, as well as the nature of precursor sediment. Here we present a case for focussing on understanding these processes as a route to improved prediction of water-rock interaction in any open system. This approach is illustrated with reference to early diagenetic processes, which can significantly modify porosity and permeability and also influence later deep-burial diagenesis.

A formidable suite of complementary tools is now available to predict carbonate diagenesis. Laboratory and field experiments offer insight into the controls on diagenesis, although to degree to which these replicate field conditions and can be spatially and temporally up-scaled is variable. Fluid chemistry is a very sensitive tracer of water rock interaction, can be used to elucidate the processes driving diagenesis and can be coupled with flux estimates to quantify rates. Increasingly sophisticated numerical models can be used to simulate individual components of the diagenetic system, such as fluid chemistry or hydrology, or to look at dynamic interactions via coupled reaction-transport models. Whilst sometimes challenging and cumbersome, these approaches enable investigation of diagenetic scenarios poorly represented in the modern.

We face a particular challenge in understanding diagenesis under non-steady state conditions, with temporal variations in boundary conditions such platform geometry, climate and relative sea-level. Coupled sedimentological-diagenetic models provide a route forward, but predictions are limited by our understanding of diagenetic processes. Hydrochemical studies of modern islands indicate that during minor sea-level falls, both soil-derived dissolutional potential and dissolved carbonate are transmitted rapidly to the water table. Petrographic evidence suggests that during major falls, diagenetic potential appears to become exhausted within the much thicker vadose zone. However, recent hydrochemical data from uplifted carbonates indicates that the phreatic zone remains diagenetically very active where recharge waters and surface-derived organic matter is routed rapidly to the water table via karstic flow routes. Given the extended duration of sea-level low-stands, resolving this uncertainty is critical to understanding early diagenesis in Icehouse carbonates.

NOTES

A fuzzy logic approach for estimation of hydraulic flow units from well log data: A case study from Ahwaz oil field, South Iran

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The porosity-permeability relationship in the framework of hydraulic flow units (*HFUs*) can be used as an instrumental way for characterization of heterogeneous reservoirs. Porosity is a volumetric parameter, whereas permeability is the measure of flow properties through the pores, which depends on porosity, and its geometric distribution and connectivity. Accordingly, zonation of the reservoir, using flow zone indicator (*FZI*) and identification of *HFUs,* is an efficient way for evaluation of the reservoir quality based on porosity-permeability relationship. The present study proposes an efficient and realistic approach to make a quantitative correlation between *HFUs* and well log responses using fuzzy possibility concept *(FPC)* in the mixed carbonate-clastic Asmari Formation of Ahwaz Oil Field, South Iran. A hybrid neuro-fuzzy approach was used to verify *FPC* calculated results. For this purpose, three wells in the study field, comprising well log and core data, were used for making an intelligent formulation between core derived flow units and well logs responses. Data from a separate well (test well) was used for evaluation and validity of the obtained techniques.

Results from this study demonstrate a good agreement between core derived and fuzzy logic estimated *HFUs*. The fuzzy logic was found successful in estimating *HFUs* from logs of the wells, from which there is no core data available.

NOTES

A committee machine approach for predicting permeability: a case study from a heterogeneous carbonate reservoir, Balal field, Persian Gulf, South Iran

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Permeability prediction problem has been examined using several methods such as empirical formulas, regression analysis and intelligent systems especially neural networks, and fuzzy logic. This study proposes an improved and novel model for predicting permeability from conventional well log data. The methodology is integration of empirical formulas, multiple regression, and neuro-fuzzy in a committee machine. A committee machine, a new type of neural network, has a parallel structure in which each of the applied methods (experts) has a weight coefficient showing its contribution in overall prediction. The optimal combination of the weights is obtained by a genetic algorithm. The method is illustrated using a case study from a heterogeneous carbonate reservoir in Persian Gulf, South Iran. For this purpose, one hundred fifty-one samples from the intervals comprising core and well log data were clustered into eighty-one training sets and seventy testing sets to evaluate the validity of the models developed. The results of this study show that the genetic algorithm optimized committee machine has provided more accurate results than each of individual experts used.

NOTES

Petrophysical and image log facies of a carbonate dominated section of the Cap Mountain Limestone Member, Riley Formation, Blanco County, Texas.

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The Cambrian sediments of the Riley Formation at the Johnson City Test Well, Blanco County, Texas, have been much studied and utilised in developing new tools for the oil and gas industry. The borehole was originally drilled by Shell in 1964, Baker Atlas now predominantly use it to test various wireline tools. The well flows fresh water with no hydrocarbon content. The lower clastic-dominated section of the Cap Mountain Limestone Member, and underlying Hickory Sandstone Member, are well documented, however the upper carbonate-dominated section is relatively poorly understood.

A full suite of petrophysical and electrical image logs were closely compared with core measurements and a sedimentary log through the carbonate interval. To calculate a more realistic porosity curve from the wireline log response, a variable matrix density curve was developed based on a density-PE-gamma relationship. Formation resistivity response was found to vary from 2000 to 100000 ohm-m, this combined with a “tap water” resistivity of 8.6 ohm.m meant that poor saturation estimates were obtained. Petrophysical log facies were defined based on the density-porosity, PE and gamma curves. Three separate groups of log facies are found to correlate well to the three main carbonate facies of the sedimentary log, with clear internal variation due to porosity. Image facies were manually picked from the electrical image log and relate to textural changes, the gamma curve was used to aid identification of shaley facies. Again downhole facies locations from images were found to correspond well with the petrophysical log-derived and sedimentary facies.

Calibration of log responses to core was proven to be essential for the complete understanding of the data, their reliability and to aid validation of any interpretations. Similar carbonate facies can be recognised and characterised using both image and wireline logs. Both the petrophysical and image texture facies can be characterised by similar rock properties, such as porosity and shale volume. Image facies can be obtained in a more time efficient method, therefore once analysis is completed for an individual well we should be able predict similar responses in subsequent sections. Core-log-image integration for an individual well enhances the understanding of formation geology and properties greatly.

NOTES

Determining the origin and relative timing of formation of a sub-unconformity diagenetic caprock, Williston Basin, Canada

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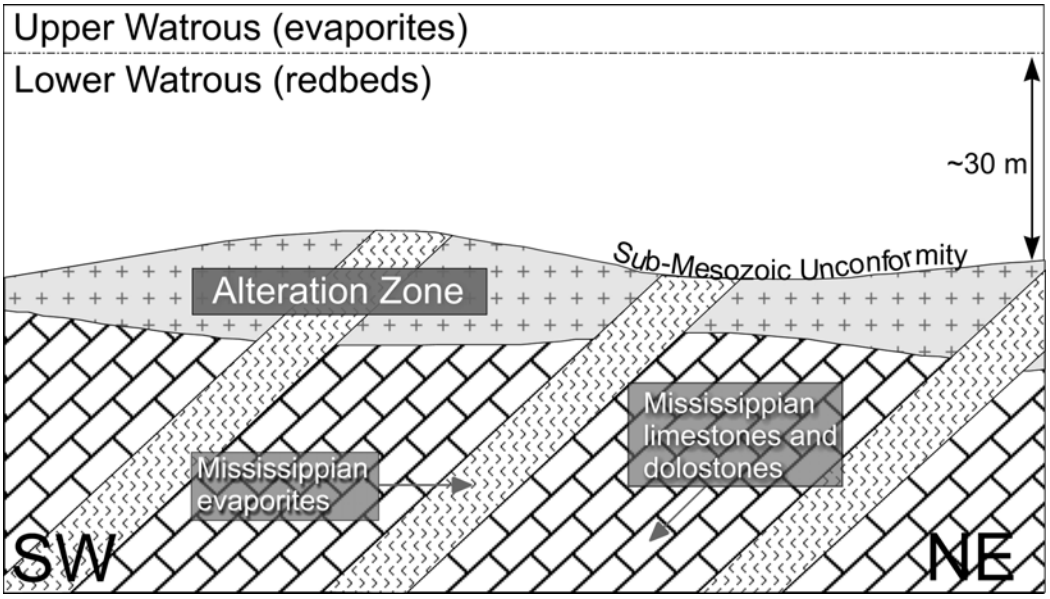
In the Williston Basin of southeastern Saskatchewan and Manitoba, western Canada, tilted and eroded Mississippian carbonates and evaporites are unconformably overlain by argillaceous siltstones and anhydritic mudstones of the Lower Watrous Formation (Fig. 1). Immediately beneath the sub-Mesozoic unconformity is a diagenetically altered zone consisting of typically 1-15 m of pervasively dolomitized carbonates, with secondary anhydrite present as void-fillings, partial replacement of dolomite, and as horizontal veins after gypsum 'satin-spar'. This diagenetic alteration has resulted in the occlusion of all porosity and permeability within the altered zone making it a regionally important caprock for numerous hydrocarbon fields within the area, and also a potentially suitable site for long-term geological storage of CO_2.



The origin and relative timing of the diagenetic alteration that generated this caprock are disputed. Numerous models have been proposed, including formation from meteoric waters prior to burial of the unconformity; from brines descending through the redbeds from the Upper Watrous evaporites; and from upward migrating deep basinal brines expelled from the centre of the subsiding Williston Basin, post-redbed deposition.

Local and sporadic absence of the alteration zone exists where either later dissolution of the porosity occluding anhydrite has occurred, or where it can be shown to have never formed. Some locations that lack this regional alteration have undergone late-diagenetic calcitization of Mississippian anhydrite nodules. Where the alteration zone did not form, the typically dolomitic redbeds have been lithified by primary calcite cement instead. This shows a genetic link between the dolomitized zone beneath the unconformity and the dolomitic cement of the immediately overlying redbeds. Hence the altered zone could not have formed pre-unconformity burial, but must have been contemporaneous with the deposition of the basal Lower Watrous.

Geochemical evidence has also been used to determine the source of formational waters. Strontium isotopes identify a strong radiogenic source for primary anhydrite blebs within the redbeds, and a Mississippian seawater source for early bedded evaporites. Anhydrite veins after gypsum satin-spar veins, which are diagnostic of the alteration zone, show the influence of a fluid with a more radiogenic $^{87}Sr/^{86}Sr$ value than if the sulphate was simply reworked from Mississippian evaporites. The strontium isotope values trend from typical redbed sulphate values near the unconformity surface with values becoming less radiogenic towards the base of the altered zone. This suggests that a mixing of waters from above and below the unconformity occurred which is consistent with the post-unconformity burial age of the alteration zone.

NOTES

Multidisciplinary inversion of Earth models

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Now that Earth Modelling tools are used routinely by most petroleum companies, efforts are under way to adapt multidisciplinary data inversion techniques to better constrain these models by geological, geophysical and dynamic data.

A new approach has emerged for building 3D geological models. This approach, known as Multi-Point Statistics (MPS), uses a radically new concept as compared to variogram-based techniques. The geologist first builds a “training image”, that is a representation (in 3D) of what he expects the geological architecture of the modelled field to look like. Then, MPS extracts the statistical patterns from this image and reproduces them when generating a 3D realisation of the reservoir, whilst matching well data and other constraints such as non-stationary trends. Stanford University has played a key role in the development of MPS.

Increasingly, the integration of seismic data is performed using stochastic approaches. Thanks to a technique known as geostatistical inversion, a large number of high-frequency acoustic impedance realisations are generated which all match the 3D seismic data. From these realisations, uncertainty figures can be obtained about the spatial distribution of high and low acoustic impedance streaks in the reservoir. Universities such as Edinburgh, Heriot-Watt, Trondheim or Stanford play a key role in these developments

The use of geostatistical realisations is also spreading to the generation of models constrained by dynamic data. One of the new approaches naturally linked to the multi-realisation concept is the Ensemble Kalman Filter (EnKF). EnKF has already given quite promising results on a number of case studies. It can be used to generate reservoir models matching production data with spatially continuous 3D fields like porosity and permeability constrained in each grid cell. We are working closely with Norwegian universities such as Trondheim, Bergen, Texas A&M or Oklahoma, who are progressing very rapidly on this topic.

The importance of rock physics is also becoming stronger and stronger, as it provides the link between the geological, the seismic and the dynamic domains. With many fields reaching maturity and hence a critical stress state, we should also expect geomechanics to play a growing role in Earth Modelling applications.

The benefits of such multidisciplinary integration can be measured in terms of more realistic models of the subsurface which are consistent with all available data and conceptual views in all domains, adding significant value to a large range of complex fields, including deeply buried high pressure and high temperature North Sea fields in the UK.

NOTES

Statistics and scaling properties of the Panoche Injection Complex, California: Implications for sand intrusion mechanisms.

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Because seismic resolution is a limiting factor in the interpretation of sand intrusion geometry and estimation of potential reservoir volume in petroleum basins, a statistical quantitative analysis is performed here for the first time on an exceptionally well-exposed clastic intruded system from the Panoche Giant Injection Complex (PGIC), California. The analysis is based on field mapping coupled with Quickbird high-resolution satellite imagery interpretation, to measure dimensional attributes of sub-seismic populations of injectites. The fundamental aim here is to develop a statistical rule set with which to populate statistic models. Key parameters presented in this study are: aperture (A), spacing (S), length (L) and geometry of the dykes.

The aperture and spacing distribution of the dykes are considered using cumulative frequency plots, allowing calculation of a coefficient of determination (R^2) for each sub-area in order to determine the best correlation to one of the classical statistical laws (Normal, Log-normal, Negative-exponential, Power-law). We find that the larger dykes have an aperture population (>1m wide) that subscribes to a power-law model whereas the smaller dykes conform to a negative exponential scaling distribution. The intrusive system thus comprises two mixed subsets: 1) a self-similar (fractal) system of large and steep dykes, also showing a preferential conjugate arrangement (NW-SE and NE-SW-trend), and 2) a randomly distributed system of small dykes both in terms of aperture and strike acting as bridges or apophyses, whose role is to provide connections between larger dyke swarms. Those latter are also often observed at the base of the PGIC, reflecting an inferred zone of intense hydraulic fracturing.

In addition, dyke spacing shows a good correlation to a power-law model, characterizing a mechanistic control on their spatial distribution. Plotting dyke aperture against minimum dyke spacing reveals that: 1) dyke emplacement controls and/or inhibits the distance of intrusion of an adjacent dyke and 2) they generally do not intrude in isolation. This relationship is ruled by a A/S factor ranging from 0.01 to 0.07. Plotting aperture against length also displays a good correlation for those two parameters governed by A/L ratios values of 0.008 to 0.03 allowing us to predict minimum lateral extent of dykes in areas of poor or sparse data quality.

This kind of statistical approach provides ratio estimations for the relation between fundamental dimensions of intruded sand systems that directly permit us to better constrain the geometry of sand intrusion, when present in subsurface oil-rich basins, through modelling or estimation of the under-sampled sub-seismic population.

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Predicting porosity using seismic data: A new approach

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Prediction of porosity in the subsurface is an important component of sedimentary basin analysis and an essential aspect of any exploration campaign. We consider a completely new method for predicting porosity reduction within siliceous successions that are to be found in extreme latitudes such as the Arctic, which are of importance in terms of current hydrocarbon exploration. A dramatic reduction in porosity, generally 25-35%, is frequently associated with the transition of biogenic silica (opal-A) to cryptocrystalline opal-CT (cristobalite and tridymite). The porosity drop together with other significant changes in the physical properties of siliceous sediments during the opal-A to opal-CT conversion can lead to these boundaries forming distinctive high-amplitude reflections on seismic data. Many of these silica diagenetic boundaries imaged on seismic reflection data, in several basins worldwide, show a variety of morphologies associated with the boundary. Some of these morphologies are thought to be the result of a combination of differential advancement of the boundary and the reduction in porosity associated with the reaction. Differential advancement leads to differential compaction and folding of the strata above the opal-A to opal-CT boundary. We use basin modelling software to try to associate the amplitude of the differential compactional folding with the amount of differential advancement and magnitude of the porosity drop at the diagenetic boundary.

These models are then adapted using parameters worked out from seismic reflection data for several case studies from the North Sakhalin Basin, Russian Far East and from the Faeroe-Shetland, Voring and More Basins from the Northeast Atlantic margin in order to try to predict the magnitude of the porosity drop associated with the opal-A to opal-CT conversion in these basins. This is the first documented case of using seismic data to try to predict porosity drop together with basin modelling to replicate the effects of differential compaction associated with silica diagenesis.

NOTES

Giant fluid escape pipes imaged with 3D seismic data from the Namibian margin: implications for basin dewatering

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Features indicative of focused fluid flow have been identified in the Namibe Basin, North Namibian continental shelf in 1000-2000m water depth using high resolution 3D seismic data. Located close to the Angolan margin north of the Walvis Ridge, the structural setting is characterised by a deep rifted topography, thick development of break-up related flood basalts, and a thick sequence of dominantly fine-grained slope sediments of the post-rift interval. A remarkably well imaged set of fluid escape pipes are seen to transect the later Neogene slope succession. These are typically ovoid in planform, tens of metres in diameter, and 200 to 1000m tall. Many of them can be linked to surface or palaeo-pockmark craters, testifying to their role in focused fluid escape. Pipes of this scale have only previously been observed in a small number of other basins, so this study area considerably expands the global database of these recently recognised features.

Integrating 3D seismic interpretation with Geographic Information Systems (GIS) the three dimensional spatial statistical significance of the pipes has been analysed. Detailed 3D seismic mapping of buried pockmarks, pipes and fluid sources was imported into a GIS environment combining spatial analysis with database functionality allowing for comprehensive feature cataloguing, morphometrical calculations and statistical spatial distribution analysis.

Several hundred pipes have been identified within the 500km^2 dataset. Preliminary observations suggest that the majority of pipes are randomly distributed, however the small scale distribution includes pockets of clustering and linearity. The pipes originate around the perimeter of an anticlinal structure at the level of a major reservoir, leaving the fold crest devoid of focused fluid flow features suggesting a fluid migration route that conflicts with predicted bleed-off positions based on standard models for seal failure. This suggests that the fluid escape mechanism was highly energetic, and did not rely on capillary leakage from the reservoir.

NOTES

Distribution and large-scale soft-sediment deformation of deep-water depositional systems: a 3D seismic case study from the Paleocene of the North Sea basin

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Large-scale soft-sediment deformation is an important process during burial in sedimentary basins and may have a major impact on reservoir architecture and connectivity. Previous studies have indicated that this is particularly true in the Palaeogene of the North Sea in the Outer Moray Firth, the South Viking Graben and the eastern margin of the North Viking Graben. This study investigates previously undocumented, large-scale soft sediment deformation along the eastern margin of the North Viking Graben. The present study is based on an integrated data set consisting of a 3D seismic reflection survey, partly covering North Sea exploration block 35/11, with a total areal extent of 580 km². Twelve exploration wells are also available, eight of which contain a full suite of wireline data. The good quality and coverage of both seismic and well data provide an opportunity to study the (i) origin and distribution of a large, remobilised sandbody, and (ii) the scale and geometry of the previously undocumented soft-sediment deformation which is dominated by large-scale sandstone intrusions. The study focuses on the Paleocene to lower Eocene interval on the Lomre Terrace which is bounded at its base by the top Shetland Group and top Balder Formation seismic horizons respectively. The unit varies in thickness between 188m in the NW to 620m in the SE and comprises variable thicknesses of turbidite sandstones interbedded with smectite-rich, hemipelagic mudstones. The lateral discontinuity of the sand bodies is observed in both seismic and well data with the sandstone interpreted as being deposited in a series of channels on a large submarine fan. The 3D seismic survey reveals that the deepwater sandstones have undergone major soft-sediment deformation in form of metre- to hectometre-scale clastic intrusions. The seismic expression of the remobilised sands is of bright amplitude reflection events which are discordant with the overlying, flat-lying reflection events. The sandstone intrusions form mainly ‘wing-like’ structures at the margins of channels and more rarely developed conical structures. The intrusions are up to 450 m in length and cross-cut up to 130 m of the overlying strata. In the central and southern regions, the top Balder Fm seismic horizon, which overlies the interval which is interpreted to have undergone major remobilisation, is deformed by a series of large bowl-shaped depression associated with polygonal faults. The faults which are preferentially-developed on ridges between the depressions are steeply dipping, have relatively small displacement, and are up to 4 km in length. The occurrence of large-scale sandstone intrusions in the study area is linked to the presence of thick, unconsolidated sands encased in low-permeability, smectite-rich mudstones. These may have been subjected to overpressure generation by disequilibrium compaction and which may have been heightened by an influx of hydrocarbons from source rocks at varying depths below. The enhanced lateral and vertical connectivity of the reservoir sandstone by porous, large-scale clastic intrusions over large distances, has an important control on reservoir geometry and fluid migration, and is, therefore, of great significance for hydrocarbon exploration and production.

NOTES

A liquefaction-propagation model for the development of submarine landslides

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Predicting the occurrence of major slope failure is important for the petroleum industry because of risks to subsea installations. A defining characteristic of submarine landslides is the development of a basal detachment due to progressive shear. Here, we describe a submarine landslide which exhibits a base defined by a weld formed due to the liquefaction and evacuation of a sensitive mobile layer. The slide is characterised by a deformed seismic facies unit consisting of closely spaced pyramidal blocks and ridges bound by small normal faults striking normal to the slope. The deformed region of the unit has thinned by c. 50 %, despite an extension value of only 4.5%, and in contrast to typical submarine landslides, the depleted region is not balanced by net accumulation downslope. The volume loss is explained by mobilisation of the lower part of the unit and its removal from beneath a thin overburden, which subsequently underwent extensional fragmentation. The remarkable pattern of deformation is directly comparable to that observed from the sites of onshore quick clay landslides. Recognition of the role of liquefaction in the development of a landslide in a subaqueous setting raises implications for the origins of large-scale submarine slides on glacially influenced margins worldwide, and the safe development of hydrocarbon reserves already discovered in such settings.

NOTES

Reconstructing remobilisation of deepwater reservoir sequences from cored wells:
A sedimentological case study from the Britannia Sandstone Formation, UK North Sea section.

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The Britannia gas-condensate field is located in the Outer Moray Firth, UK North Sea sector. Reservoir sands are thick turbiditic sandstones of the Lower Cretaceous Britannia Sandstone Formation.

The current correlation framework often fails when used as a predictive tool for the presence of reservoir sand intervals in the lower zones of the reservoir. The model is largely based on biostratigraphy and facies studies of the upper reservoir interval in which 'layer cake' stratigraphy makes correlation relatively straightforward. However, initial inspection of core samples has brought to light that the troubled lower intervals sometimes comprise an alteration between debrites and seemingly in-situ deepwater sandstones. Comparison between lithological sequences of a number of cores and the biostratigraphical model shows that some zonal boundaries are commonly located in or on the boundaries of debrite matrix intervals. The remobilised nature of shale blocks in debrites makes them especially unfit for biostratigraphic sampling. It is the under-representation of remobilisation facies and an over-reliance on problematic biostratigraphy that cause the problems in the lower half of the reservoir model.

The aim of the study presented here is to reconstruct and understand the nature and scale of remobilisation in the lower part of the Britannia reservoir interval, by performing a sedimentological re-evaluation of 2500ft of core from 14 wells covering a 9*5km area in the centre of the field, with emphasis on recognising remobilisation facies.

Due to the 1D nature of core data, two distinctly different interpretations fit a sequence of debris-flow matrix and apparently in-situ deposits: Model I): In-situ turbidite beds alternate with multiple debris flow deposits. Model II): Blocks of remobilised reservoir sandstone float in a larger scale mass transport deposit. Detailed 1:20 scale logging of the available core has led to recognition of intervals without any indication of remobilisation and intervals with common debris flow and deformed clast facies. Correlation of the logs yields a division of the study area in an undisturbed part with a coherent sand-shale sequence and a part where a pocket containing mass transport deposits totalling 45m in thickness is juxtaposed to those in-situ deposits. The total absence of any coherency in the pattern of sand and shale intervals between the remobilisation facies in different wells makes a model II interpretation, a deposit of a single mass transport event, most likely.

Spatial mapping of the remobilisation results in the recognition of a NE-SW debris flow axis or fairway with an in-situ bounding sequence in the NW. The map of the remobilisation front provides a predictive tool for risking low connectivity of reservoir sands.

This study gives a unique view of km-scale remobilisation in deepwater sequences and its expression in core. It can be expected to greatly enhance the predictive value of the reservoir model for future well targets inside the study area. And it provides a platform for development of remobilisation risking tools to be used outside the study area by integrating the core based results with other, more widely available, well based data-types.

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A large frontally confined slide offshore Norway, and implications for petroleum exploration on continental margins

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The Møre Basin offshore Norway is an important area of gas production in the North Sea, and there has been much recent activity due to the discovery of the Ormen Lange gas field in this basin. It is also an area that has seen repeated slope failures over the last two million years. Slope failure is a hazard to the petroleum industry, and it is important to understand the processes associated with submarine landslides in this area. Here Slide W, the first major slide to affect this area, is described. This will enable a greater understanding of slide initiation processes in the Møre Basin. This understanding may be applicable in other petroliferous continental margins.

Slide W occurred sometime between 2.7 and 1.6Ma, and that it covers a large area. However is has never been mapped and described in detail. It is shown here that Slide W is frontally confined, with translated material being buttressed against the Faeroe-Shetland escarpment. Slide W is mapped over an area of over 25,000km^2, measuring 220km long and around 120km wide, with a volume of 6,000km3. 3D images are presented of the basal shear plane of the slide, which show three separate glide planes, bounded by small steps. The boundaries between the different glide planes show evidence of small-scale slide failure and provide excellent kinematic constraints. Flow fabrics imaged in the 3D seismic data areas are complex. The main headwall area comprises of several segments, so it is likely that Slide W consisted of several discrete slide events affecting the same stratigraphic interval.

Our observations lead us to argue that Slide W was a retrogressive slide. Failure likely started at the bottom of the continental slope, and this may have destabilised the upper slope causing the headwall to move upslope. We argue that the Slide W process was not instantaneous, and it is likely that there were several pulses of slide activity. Slide W is likely to have been triggered by either an earthquake, a prolonged period of fluid release from an opal-A – opal-CT front below leading to a build-up of overpressure and reduction in shear strength on the basal shear plane; or a combination of both.

NOTES

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Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the main reception entrance.
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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly