VOL. 11, NO. 3 – 2014

GEOExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

geoexpro.com

COUNTRY PROFILE

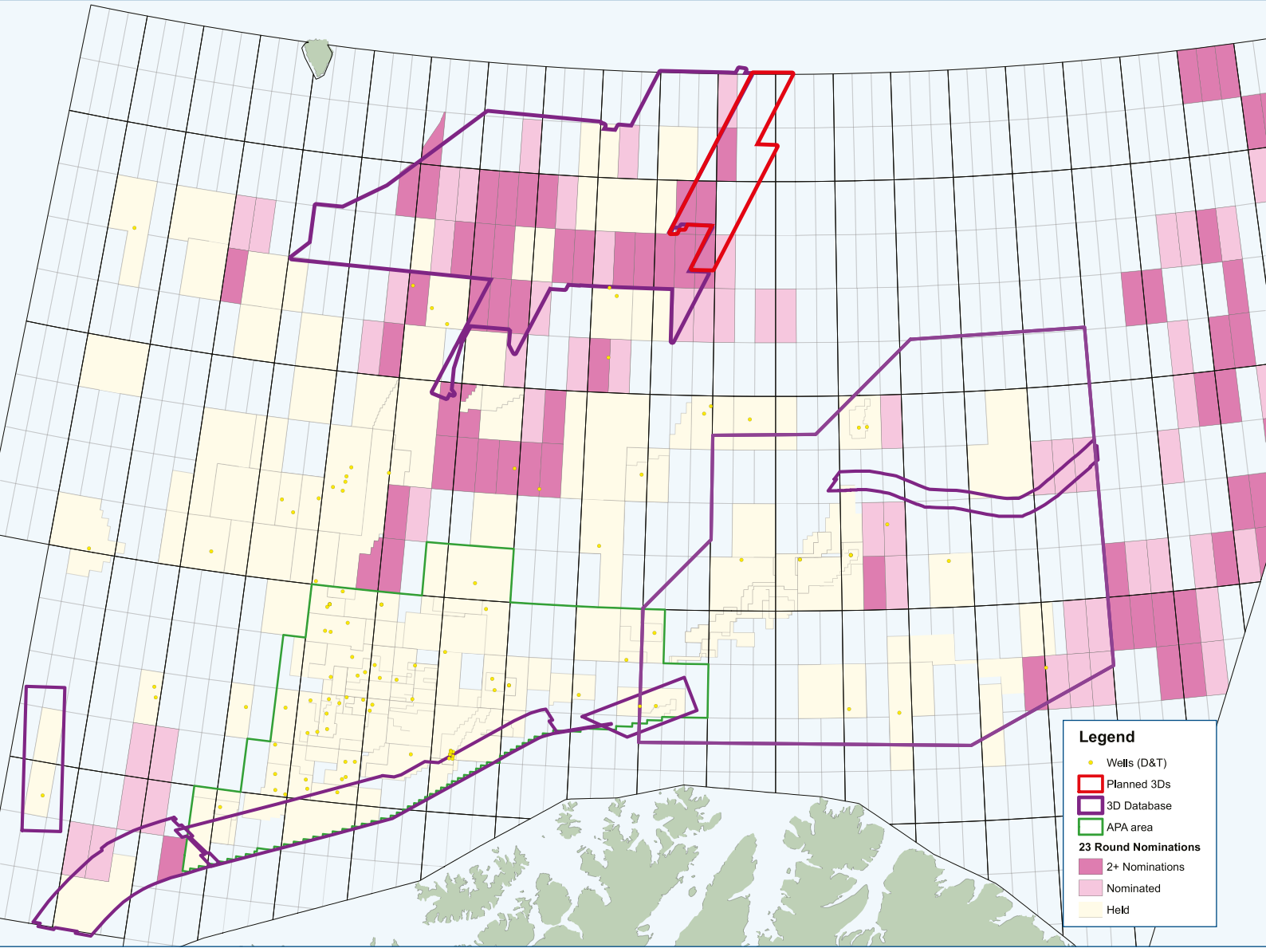
Ukraine's Gas-Fuelled Crisis

GEO EDUCATION

Fractures, Fractures Everywhere

TECHNOLOGY EXPLAINED

Polarising Pyrite



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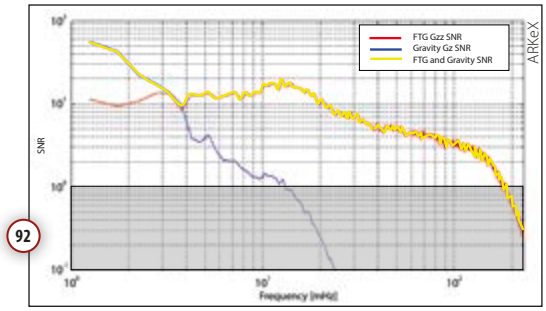
This edition of GEO ExPro Magazine focuses on Europe, and Unconventional Resources and Technologies



Full-tensor gravity gradiometry is a powerful tool for frontier exploration.

COLUMNS

FEATURES

The magnificent crater lake at the centre of Rinjani volcano, Indonesia.

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The Bigger Picture

Jane Whaley
Editor in Chief

GEO ExPro Magazine is 10 years old. And what better way to celebrate than with an edition full of – well, all the usual variety of articles you enjoy, designed to entertain, excite and educate.

We have a stimulating and thought-provoking piece on Ukraine, looking at just how much the supply of oil and gas to Europe is embroiled in the troubling situation there. We look back at the little-known history of the onshore UK oil industry, and forward to ways in which the use of water in the exploitation of unconventional resources can be controlled and monitored, and at some of the methods to assess these resources. Technology continues to advance, and new and more efficient techniques for identifying hidden reserves, such as induced polarisation and full-tensor gravity gradiometry, are explained. Knowledge of the mechanisms of rock fracturing is important, because the open fractures they provide are essential for fluid flow in reservoirs, so in our GEO Education series we take a fresh look at this topic.

And for a reminder of just how amazing and awesome our planet is, we take a trek up Rinjani, one of the highest volcanoes in Indonesia, to look down into the caldera at its crater lake and cinder cone and remember that the geological processes that created the world around us still continue.

The rationale behind this magazine has always been to educate people in and around the hydrocarbon industry about what is going on beyond their own sphere. I recently read Gregory Zuckerman's 'The Frackers' – reviewed on page 102 – a fascinating account of the rise and sometimes fall of the people and companies who made the shale energy revolution in the US. One of the most compelling aspects in this book is the realisation that no one at the time seemed to understand just what an effect a sudden glut of gas could have on their business, their country or the world market. All heads were down, beavering away at the individual challenges; no one seemed to look up and around and pause to think beyond the here and now.

This account teaches us all an important lesson: never lose sight of the bigger picture. As both Ukraine and the shale gas story show us, the hydrocarbon industry is a key part of the progress, politics and future of the whole world. It is our responsibility as citizens of that world to educate ourselves as much as possible, not just about what goes on in our own discipline, but about the ways in which what we do ripple throughout the industry and beyond, to affect the whole planet and everyone on it. ■

Drilling in the Bakken in North Dakota; who foresaw the effect of the shale gale on the markets?

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Internal OPEC Rivalry Ahead?

With the world's fifth-largest petroleum reserves, Iraq has – at least on paper – considerable potential for boosting production. If its goals are reached, it will bring the country's production to a level rivalling that of the world's largest oil exporters such as Saudi Arabia and Russia. At present the country produces around 3 MMbopd and the goal is to reach over 4 MMbopd by the end of the year, scaling up to 9 MMbopd before 2020, to help boost economic growth after many years of war and internal conflict. Iraq has started to plan for a possible return to OPEC's quota system, marking a change of political stance and reducing the likelihood of the market being flooded with oil. But how easy will it be for the member countries to agree on new production quotas without creating serious internal disputes, potentially leading to a collapse in oil prices?

OPEC's mission is to coordinate and unify the petroleum policies of its member countries and ensure the stabilisation of oil markets in order to secure an efficient, economic and regular supply of petroleum to consumers, a steady income to producers and a fair return on capital for those investing in the petroleum industry. Collaboration, however, is frequently tested by disagreements. In fact, OPEC's cooperation may soon be put to the test as, given the shale revolution in North America, non-OPEC oil production is forecast to expand by 1.5 MMbopd in 2014, whereas world oil demand is projected to grow at a somewhat lower pace, around 1.2 MMbopd. This means that demand for OPEC oil will be lower than the cartel's total production quota of 30 MMbopd, which could lead to falling oil prices – or OPEC must cut its production to stabilise the situation.

Pressure on Oil Price

If Iraq succeeds with its ambitious plans, OPEC members will intensify pressure to include it in their system, but renegotiations of quota allocations between member countries will increase the risk that the cartel's total production target is exceeded. And if negotiations with Iran on its nuclear programme proceed and sanctions are lifted, it will also step up its oil production. In addition, should political turmoil fade in countries like Nigeria, Libya and South Sudan, production there will pick up again; should this happen without other OPEC members cutting their production, a sharp oil price decline to around US$90/barrel may result.

If Iraq were to challenge Saudi Arabia's position as the world's swing producer by neglecting production quotas and pumping oil into the market, a prompt response from the cartel's de facto leader may be expected, similar to when it flooded the market at the end of the 1980s when cartel members did not adhere to their production quotas. Oil prices plummeted, which would be a considerable challenge for most of the OPEC members, as oil and gas account for a significant share of their export revenues, investments and sources of economic growth. A large oil price decline could test the economic position and stability of these countries. Both Iran and Iraq require oil prices of over US$100/barrel to balance their budgets, according to the International Monetary Fund.

So what are the chances of this short term? Iraq faces a number of major challenges which must be overcome to reach its ambitious production targets. Lack of infrastructure for increased exports, pipelines and refineries could act as a damper on capacity expansion efforts. The country has still not managed to agree on a hydrocarbon law to provide a framework for investments in the oil sector and the distribution of oil revenues, while growing political unrest increases the risk of production disruptions.

Thina Margrethe Saltvedt, Ph.D., Nordea

ABBREVIATIONS

Numbers
(US and scientific community)

M: thousand	= 1 x 10^3
MM: million	= 1 x 10^6
B: billion	= 1 x 10^9
T: trillion	= 1 x 10^{12}

Liquids
barrel = bbl = 159 litre

boe:	barrels of oil equivalent
bopd:	barrels (bbls) of oil per day
bcpd:	bbls of condensate per day
bwpd:	bbls of water per day

Gas

MMscfg:	million ft^3 gas
MMscmg:	million m^3 gas
Tcfg:	trillion cubic feet of gas
Ma:	Million years ago

LNG
Liquified Natural Gas (LNG) is natural gas (primarily methane) cooled to a temperature of approximately -260 °C.

NGL
Natural gas liquids (NGL) include propane, butane, pentane, hexane and heptane, but not methane and ethane.

Reserves and resources
P1 reserves:
Quantity of hydrocarbons believed recoverable with a 90% probability

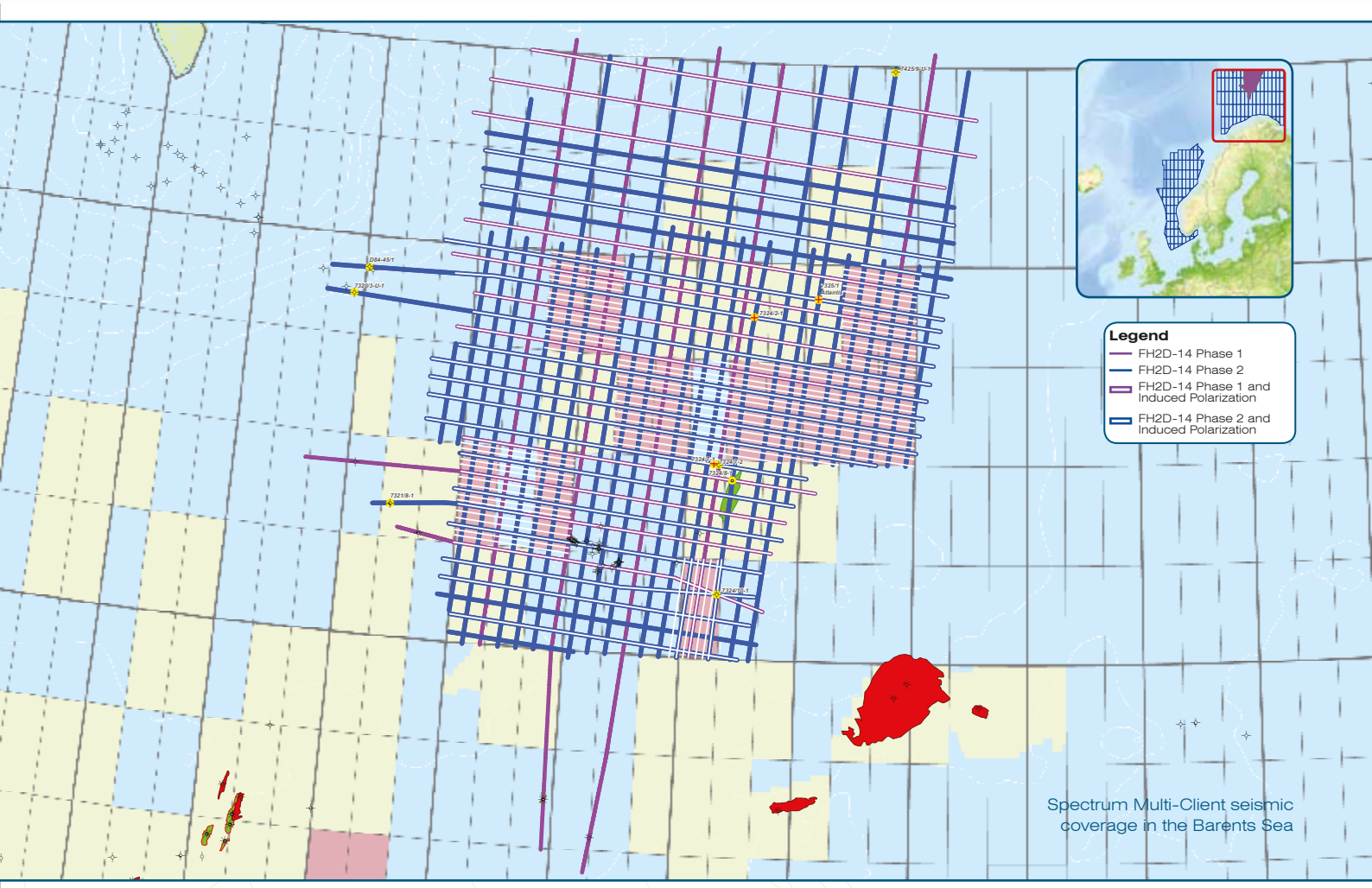
P2 reserves:
Quantity of hydrocarbons believed recoverable with a 50% probability

P3 reserves:
Quantity of hydrocarbons believed recoverable with a 10% probability

Oilfield glossary:
www.glossary.oilfield.slb.com

Barents Sea

New 2D Multi-Client Seismic and Induced Polarization



Spectrum Multi-Client seismic coverage in the Barents Sea

Spectrum has commenced the second phase of acquisition for a regional broadband 2D Multi-Client seismic survey in the Barents Sea, Fingerdjupet-Hoop area. Approximately 5,300 km of data will be acquired. This is a continuation of a 2,226 km survey acquired last year. Rock property products for lithology and fluid prediction will be provided for the entire survey to enhance prospect evaluation.

Additionally, Spectrum is collaborating with ORG Geophysical AS to acquire around 5,300 km of Induced Polarization measurements in the same area. This combined product, focused on nominated blocks, will provide oil companies with a unique dataset to evaluate prospectivity of the Fingerdjupet-Hoop area ahead of the 23rd licensing round.

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In association with Qeye Labs

Spectrum

Experiencing the Energy

Don't miss EAGE's annual meeting in Amsterdam!

On 16–19 June 2014, the 76th EAGE Annual Conference and Exhibition will be held in Amsterdam, The Netherlands. This year the theme of the event ponders the question of how can geoscientists best help the world to meet its future energy needs? The answer lies in the official title of the 76th EAGE Conference and Exhibition, which is 'Experiencing the Energy'. In other words we will be exploring how the multi-disciplinary approach to oil and gas exploration and production fostered by EAGE can contribute to meeting future energy needs.

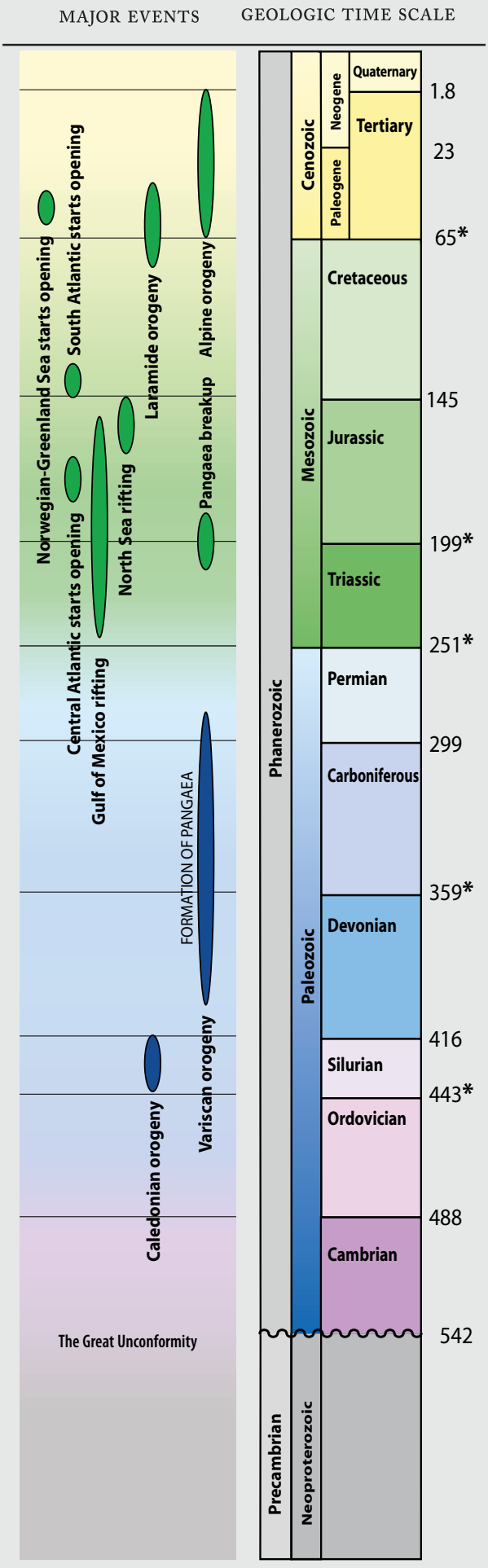
Amsterdam '14 is the largest multi-disciplinary geoscience event of its kind in the world. The full six-day programme (including pre- and post-event happenings) is probably the most ambitious yet. It includes a large conference, major technical exhibition, workshops, short courses, and field trips presenting the latest developments in geophysics, geology and reservoir/petroleum engineering, plus a comprehensive student programme.

Top-quality papers can be expected at the EAGE Annual Conference. The Technical Committee received a record-breaking submission of 1,308 valid abstracts which had to be reviewed and readied for selection, an indication of the importance of the EAGE Annual Meeting for the geoscience community. The technical programme has been organised with parallel sessions in 15 rooms and 13 poster boxes plus 15 student poster sessions. This year's delegates will be faced with agonising choices from this incredibly tasty menu, which consists of 48 oral and 24 poster geophysics sessions, 12 oral and 5 poster geology sessions, 12 oral and 2½ poster reservoir sessions, 8½ oral and 4 poster integration and general sessions and 1½ oral and one poster session on near surface. In addition there are the three dedicated sessions, two executive sessions and the forum.

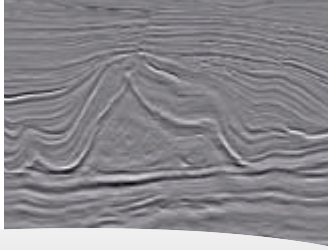
Meantime, for those interested in the exhibition there will be an impressive display of equipment and services with more than 300 companies over 10,000 m^2 of space already accounted for, including the increasingly popular Job Centre.

The student experience in Amsterdam will be cosmic! That's because astronaut André Kuipers will be touching down for the Student Evening on 17 June, sponsored by PGS. Kuipers is the first Dutchman to have undertaken two space missions, the second lasting over six months. Hopefully he will inspire students with some insight into some of his achievements and career. The full Student Programme offers technical poster presentations and the opportunity to attend a short course on geothermal energy and workshops on core evaluations and play-based exploration. A whole lot goes on in the Student Court area, such as the EAGE Geo-Quiz, the Student Challenge and two motivational speeches from Roel Snieder (Centre for Wave Phenomena, Colorado School of Mines) and Salomon Kroonenberg (professor emeritus, Department of Geotechnology, Delft University of Technology).

For more information and to register for Amsterdam '14, please visit www.eage.org/event/amsterdam-2014. ■

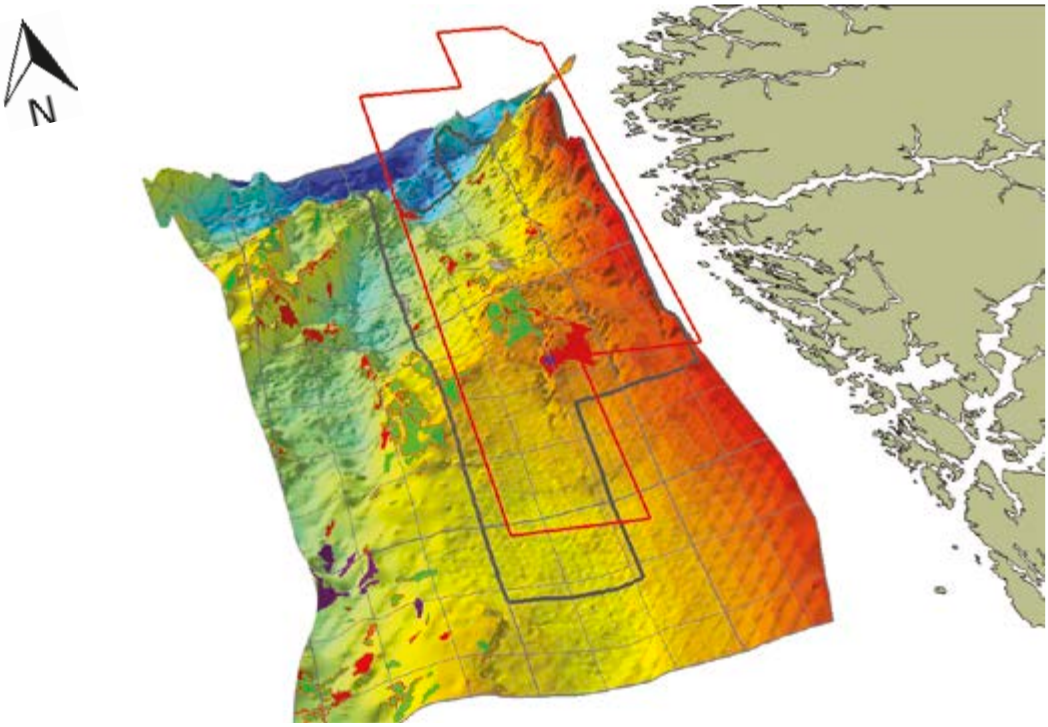




Horda - a broader view

19,000km² **BroadSeis**/**BroadSource**
6 octaves bandwidth



CGG has commenced the acquisition of the Horda multi-client survey. Covering 19,000km² of a highly prospective part of the Norwegian North Sea, this will be the largest **BroadSeis**™/**BroadSource**™ survey in the world. Combined with long offsets and a dense streamer configuration this survey will provide better imaging in this complex region.

The increased resolution delivered by CGG's 6-octave true-broadband technology will provide a platform for further activity in the area through all phases from exploration to production.

For further details, please email us at mcscandinavia@cgg.com or contact your CGG sales representative.

cgg.com/multi-client

CGG
Passion for Geoscience

Bakken's Billion Barrel Milestone

The Bakken shale means that North Dakota is now the second largest producing state in the US.

Late in 2013 the US Energy Information Administration (EIA) estimated crude oil production in the Bakken region of North Dakota and Montana would top 1 MMbopd. This meant that, at that time, the Bakken region contributed a little over 10% of total US oil production and became the fourth region (along with the Gulf of Mexico, Eagle Ford and the Permian Basin) producing more than 1 MMbopd in the country. At the same time, infrastructure improvements in the central part of the USA have allowed for more of this oil to reach central refineries, narrowing the price differential between Bakken and West Texas Intermediate crudes.

Now, the largest leaseholder and producer in the Bakken shale play – independent oil producer Continental Resources, based in Oklahoma City – has announced that the Bakken of North Dakota and Montana recently reached the milestone of producing a billion barrels of the light, sweet crude oil. According to Continental, data from IHS show that the Bakken's cumulative oil production reached this landmark in the first quarter of 2014.

"This milestone validates the immense potential of the Bakken field, and development is just beginning," said Jack Stark, Senior Vice President of Exploration for Continental. Going on to illustrate the remarkable ramp-up in production, Stark said, "Two-thirds of this oil was produced in the last three years. This is something our country can celebrate as the oil and natural gas industry continues to create jobs, grow our economy and secure America's energy future."

Rapid Development

Confirmation of the billion-barrel-milestone came with the publication of data showing that North Dakota has generated 852 MMb of Bakken crude, and Montana has produced about 151 MMb through to the first quarter of 2014. The remarkable speed of development has been possible due to the use of the widely publicised techniques of horizontal drilling and hydraulic fracturing, designed to recover the oil trapped in a thin layer of dense rock over three kilometres beneath the surface.

The Bakken encompasses some 65,000 km^2 in North Dakota, Montana, Saskatchewan and Manitoba with about two-thirds of the acreage in western North Dakota. Development and production have evolved at a rapid pace, as summarised by Thomas Smith in his excellent 2012 article in *GEO ExPro*, Vol.9, No.1. For example, in 2007 North Dakota produced 12,000 bopd (303 wells), rising to 106,000 bopd by 2009 (904 wells) and by 2012 was producing 443,425 bopd (3,118 wells), before reaching the 1 MMbopd landmark in 2013.

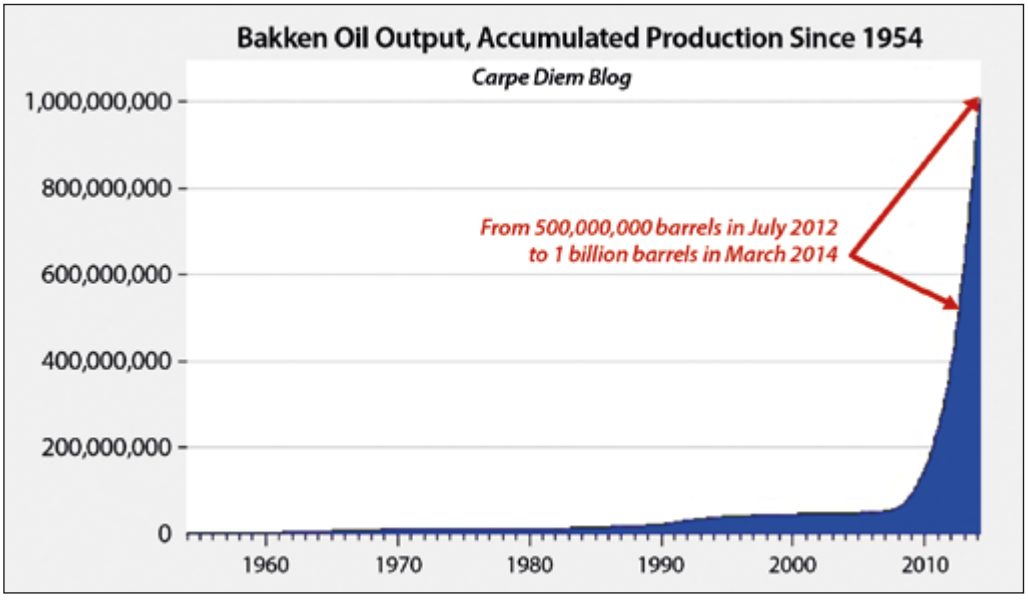
And, as we have seen, North Dakota is not the only area with Bakken production, with neighbouring Montana, where the present oil boom originated (see *GEO ExPro* Vol. 7, No. 2), and Canada adding significant production of their own. Unlocking the rich resources of the Bakken shale have propelled North Dakota from the nation's ninth-largest oil producer in 2006 to rank second in crude oil production in the United States, behind only Texas.

Devonian Formation

Deposited within the intracratonic Williston Basin, approximately 360 million years ago, the Bakken Formation is Devonian to Mississippian in age. The thickest portion of the Bakken (46m) is in north-western North Dakota and it thins evenly south-eastwards toward the margins of the Basin. The upper and lower members consist of hard, siliceous, black organic-rich shales. These form effective seals for the middle member, which consists of five highly variable lithologies, from several argillaceous siltstones to fine-grained sandstone and limestone, all with low primary permeability (0.04 mD average) and porosity (5% average). The other important reservoir target, the Three Forks Formation, consists of shales, dolostones, siltstones and sandstones with a maximum thickness of 76m.

Will Thornton

Chart showing that production in the Bakken shale formation in western North Dakota and eastern Montana has now exceeded 1 billion barrels of crude - and half of that oil has been produced in less than two years! Source: Mark J. Perry, 30 April 2014.



MultiClient

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MC3D-BYL2013 GeoStreamer® survey available for review and license in June 2014

This dataset covers 1,770 sq km and encompasses known fields, successfully producing from Triassic-Jurassic to Tertiary sediments.

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Looking Back to Predict the Future

Conventional exploration continues to be very successful, but 2014 is a make or break year for frontier deepwater exploration

One can learn a lot from looking at even the recent past. For that reason, Richmond Energy Partners annually measures the pulse of international conventional exploration outside North America by monitoring the performance of 40 mid- and large-cap E&P companies over the previous five years. From this analysis, published in the company's yearly *Exploration Performance* report, the conclusion is that it has been a very successful period for exploration for conventional hydrocarbons, particularly gas, and that 2013 was the best year for oil discoveries for five years. The study also reveals that commercial success rates are being maintained at around one in three globally, with a finding cost of $1 per barrel of oil equivalent over the last five years.

Gas discoveries in East Africa, Israel and Australia make up half of the 35 Bboe discovered by the companies analysed. However, although these discoveries are considered commercial, much of this gas will take decades to produce and monetise. In fact, the study finds 40% of recent discoveries have not yet started development six years after discovery.

A look at the key plays in East Africa and Iraq tells an interesting story for the future, as they appear to be maturing rapidly and delivering smaller discoveries. In addition, the dramatic increase in spending on frontier drilling in recent years has been largely disappointing, with a success rate of less than 10%.

Although the new pre-salt play in Angola has become the key emerging play globally, drilling in ever deeper waters does not always bring rewards, and its high cost, coupled with very little commercial success, can be a company breaker as much as a company maker. At $100m average cost per well, and with $2.9 billion budgeted in 2014 for deepwater frontier wells, 2014 may be literally a make or break year for several exploration companies.

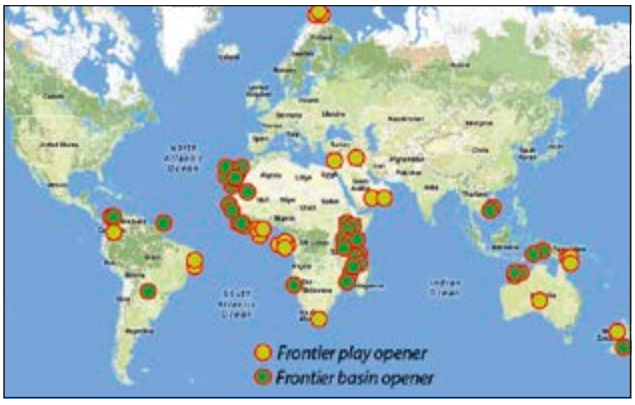
Benching Performance

Every exploration well drilled between 2009 and 2013 by the companies monitored for this report, including Cairn, Anadarko, Afren, Tullow and Lundin, has been recorded and analysed. The study assesses the likelihood of a commercial development for each successful well and estimates the most likely recoverable volumes. Resource estimates for pre-2013 wells have also been reviewed in the light of recent appraisal or development activity. Each company is assessed on gross and net wells drilled, commercial success rates, discovery sizes, net discovered volumes of oil and gas per well and finding costs.

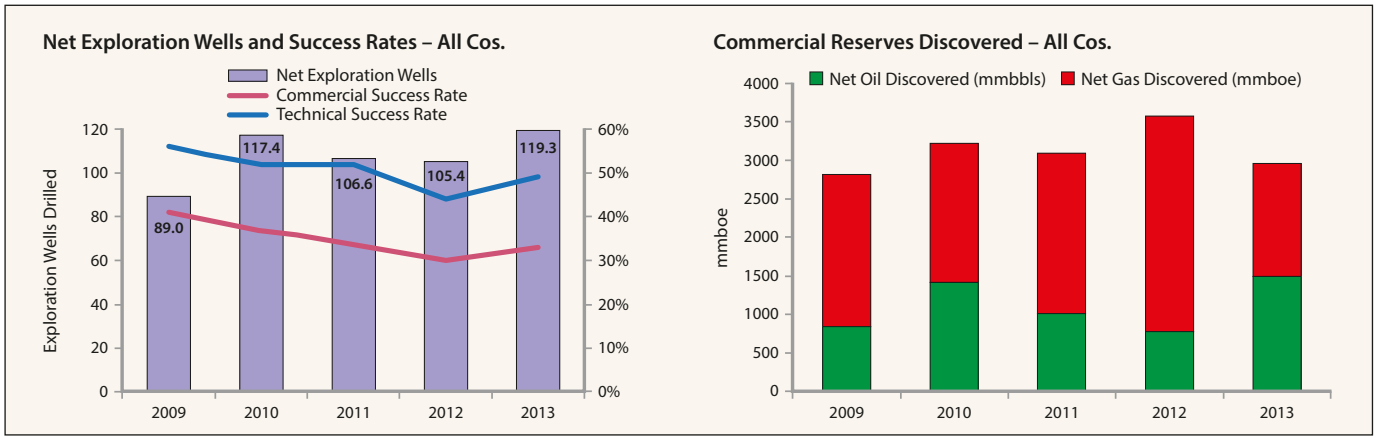
From this analysis a systematic benchmarking of company exploration performance can be developed, together with an analysis of global trends in conventional exploration and an understanding of where the industry is focusing geographically and geologically. This type of analysis helps gain an understanding of the reasons for failure of prospects in key plays and of the successful conversion of resources to reserves, plus an appreciation of what drives and leads a successful exploration strategy.

This analysis of the past five years can then be applied to planned wells, and the report includes a look at forward drilling plans for 200 wells in 46 countries, with forecasts of prospective resource volumes and exploration risks. ■

Frontier wells drilling and planned for 2014.



Exploration activity and discovered commercial reserves 2009–2013 for all 40 companies.



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Communicating Our Science: Building Trust and Openness

JEAN-MICHEL GATTI

This year saw the AAPG Annual Conference and Exhibition descend on the oil capital of the world, Houston. One focus of this year's conference was to discuss issues faced by those in the industry and beyond. Our own editor, Jane Whaley, was invited to sit on the panel for a forum that would debate the pressing issue of how science is communicated, to both scientists and the public.

The panel of highly respected individuals, each with their own angle on the science communication dialectic – from university professors to communications advisors at O&G multinationals, former astronauts to federal policy advisors, and naturally the Editor-in-Chief of an industry-leading earth sciences magazine fundamentally tasked with communicating science to everyone – set about raising and responding to some of the biggest issues facing us today.

In our rapidly developing world where communication methods have increased the speed at which information is shared, the nature of how and where we look to construct an opinion – or underpin our own existing beliefs – has changed dramatically. This rampant technological development has made science available and digestible to more people than ever before, yet we are experiencing a shift in interest away from science-based subjects to more vocational ones, at all levels of education. Geology and the earth sciences have suffered especially badly. With very little contact in schools and swathes of bad press circling the oil and gas industry, one begins to understand the struggle to get people engaged with the topics and key players.

Understandably, companies are wary of being misquoted by unscrupulous journalists looking for sensational sound bites, so choose to not engage unless they are forced. Academic freedoms have been similarly curtailed as universities rely more and more on private funding for research. All of a sudden, academics and industry specialists – the authorities on the subject – must be very careful of what they say as it could reflect badly on the faculty, company or their own reputation. This means fewer and fewer people we ought to hear speak on these things, to educate the public and redress the journalistic social bias, get the chance. The result is an inherent cultural suspicion of advocacy – a knee jerk reaction that assumes this accredited figure has been presented to con us and distract us from the truth.

Everyone's a Journalist

Social media has given a voice to those previously never able to be heard, helping to topple governments, spread hidden truths and get us all up to speed on most things at the click of a button. Now, anyone can be a journalist, report on what they feel is important and offer it up to the public, a fantastic achievement and exactly the kind of engaging attitude we need. However, this powerful tool is not without its 'Pandora's Box' quality. The loudest, the biased, the ill-informed and the powerful can usher in a thunderous presence that manipulates the consensus for personal or political gain, making what should be a rational and objective debate an entirely emotional one.

We all know bad news sells better than good news; one only has to turn on the television to hear a litany of global disasters. The question becomes: how do we use what we have to get people thinking and engaged in the matters at hand without the emotional hooks? I believe the answer lies in using cross-media platforms to speak directly to the public as often as possible, as rationally as possible, so as to alleviate the emotional burden. This means building institutional two-way trust and openness with the press, educating the public at all levels to spur the self-deterministic belief that social media has furthered, and to reward and protect the knowledgeable, trustworthy, courageous people who choose to stand against corporate interests or socially unfavourable practices for the sole reason of educating the public for the benefit of our planet, ourselves and the future generations that must learn to share global responsibility. ■

The AAPG 'Communicating our Science' forum panellists deep in discussion: (L to R) Michael Zehr, Jane Whaley, Iain Stewart, Heather Saucier, Jim Reilly and Don Paul.

Courtesy of AAPG

SeaBird Exploration

SeaBird Exploration

Marine Seismic Acquisition

SeaBird manages both Maritime and Seismic operations in-house providing for a unified crew and operation.

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Geo Pacific

4D/3D 8x 6,000m & 6 X 8,000m Sentinel Solid streamers.

Upgraded in May 2013 and with the latest navigation offerings from Sercel, Veripos and Satpos.

Voyager Explorer

4D/3D/2D 4 x 120m x 6,000m Sentinel ALS streamers.

Capable of operating in shallow or deep water programs. Wide Spread source arrays available.

Aquila Explorer

2D solid streamer long offset/Source vessel.

Equipped with 12,000m Sentinel Solid streamer and 6 Bolt 1900 LLXT gun strings and capable of dual source wide tow configuration.

Osprey Explorer

2D Solid streamer long offset/Source vessel.

Equipped with 10,050m of latest Sentinel RD Solid Streamer and 6 Bolt 1900 LLXT gun strings capable of dual source wide tow configuration.

Harrier Explorer

2D Solid streamer long offset/Source vessel.

Equipped with 12,000m of solid/Gel DigiSTREAMER and 6 Bolt 1900 LLXT gun strings capable dual source of wide tow configuration.

Northern Explorer

2D long offset/Source vessel.

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Croatia

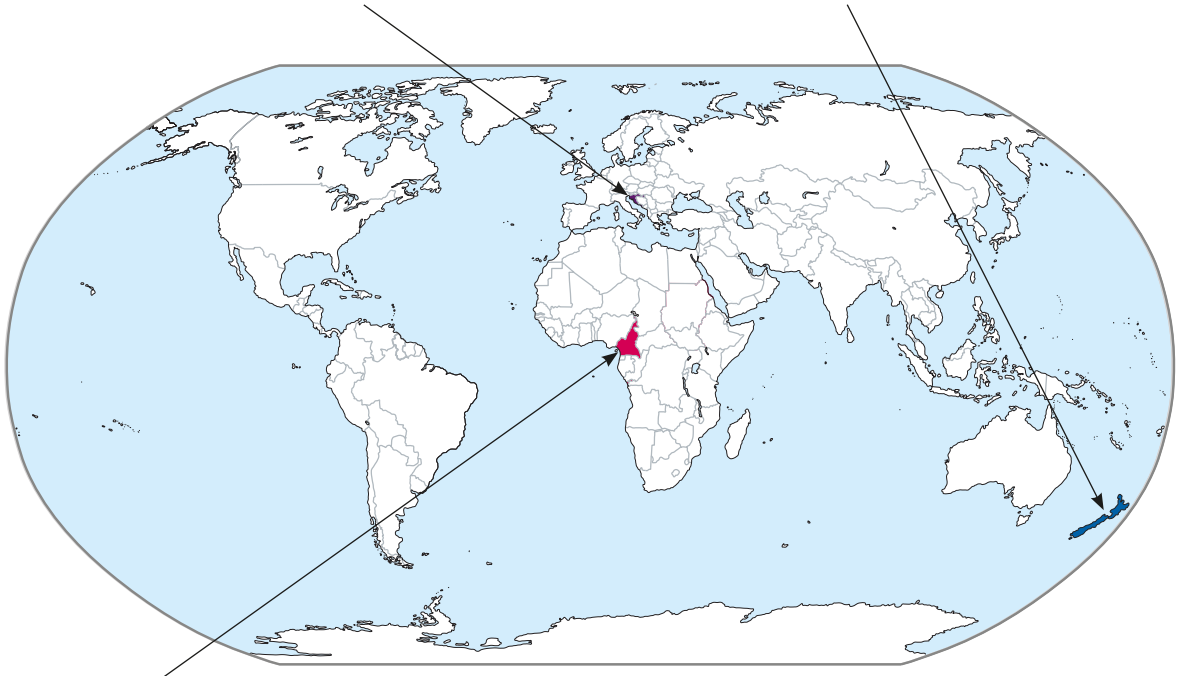
Almost one year after launching a new hydrocarbons law Croatia, boasting a strategic location and existing hydrocarbon potential, opened an offshore bid round on 2 April 2014. This comprises 29 blocks of between 1,000 and 1,600 km^2, eight of which are located in the northern Adriatic Sea, with the remaining 21 in the central and southern Adriatic. Production sharing agreements offered to bidders are with a five-year exploration phase, with no more than two six-month extensions and a 25-year production period. Offshore Croatia is largely unexplored although large but untested structures have been mapped. Ahead of the round Spectrum acquired 15,000m of 2D seismic which, according to Economy Minister Ivan Vrdoljak, shows there is "significant potential for finding oil and gas reserves along the side of the Croatian Adriatic." Applications close on 3 November 2014.

In addition to the new hydrocarbons law, Croatia enacted the Strategic Investment Act, new legislation to give preferential treatment to projects of national interest. These two Acts form the government's anti-recession strategy; both aim to attract new investment and facilitate economic recovery.

New Zealand

New Zealand Petroleum and Minerals (NZP&M) is inviting bids on five offshore and three onshore regions totalling 405,000 km^2, comprising a mix of well explored areas and frontier acreage. The offshore tracts are in the Reinga-Northland Basin, New Caledonia Basin, Taranaki Basin and the Pegasus-East Coast Basin, all off North Island, while the Great South and Canterbury Basin is off South Island. The onshore areas being tendered are in the East Coast Basin and Taranaki Basin on North Island and the West Coast Basin on South Island. In each case interested companies can outline their own blocks from the graticular grid. However, Taranaki blocks must not exceed 250 km^2 onshore or 2,500 km^2, while 1,000 km^2 is the limit for the other onshore and 10,000 km^2 for other offshore regions. The tender will close on 25 September 2014. Data packs, containing more than 239,000 km of 2D and 11,000 km^2 of 3D seismic data, can be ordered through the NZP&M website.

NZP&M has also opened nominations for Block Offer 2015. Interested parties are invited to suggest areas of interest (such as a basin or sub-basin) that they would like released for tender. Nominations should be on the basis of prospectivity and companies should provide some supporting evidence. Nominations close on 3 June 2014.



Cameroon

Société Nationale des Hydrocarbures (SNH) has opened four exploration blocks: Lungahe, Bomana and Ndian River in the Rio del Rey area of the eastern Niger Delta and the Manyu block in the Mamfe Basin. Bids must include a technical evaluation of the block, a work programme and budget for each exploration phase and documentation on the bidder. The work programmes during the initial exploration period have to include, for the Lungahe and Bomana blocks, at least one exploration well, plus seismic acquisition, processing and interpretation and geoscience studies. For the Ndian River and Manyu block they must involve one exploration well, seismic work and geoscience studies. The Bomana and Lungahe blocks lie close to existing production and have 3D seismic coverage, while Ndian River has 2D seismic, well data and identified leads in shallow water, near-shore and mangrove environments. The Manyu block is dominated by inland forest and has no seismic or well data. The bid round will close on 25 June 2014 and results will be announced on 16 July 2014.

SNH will be hoping for more interest this time around, with the Manyu, Bomana and Lungahe blocks having previously been offered in 2013 in a round that attracted just two bidders. Cameroon oil production has declined significantly to around 54,000 bopd in 2013 due to operational issues. New finds in the offshore Douala/Kribi-Campo Basin in the north-west and the Northern Logone-Birni Basin are helping to add new output growth. Cameroon's future upstream focus will likely be more on monetising gas reserves, as the country has an estimated 4.8–5.5 Tcf of natural gas resources that have yet to be utilised due to a lack of infrastructure.

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100 Great Geosites Sought

The UK and Ireland feature some of the most diverse and beautiful geology in the world, spanning most of geological time, from the oldest Pre-Cambrian rocks to the youngest Quarternary sediments. As part of Earth Science Week 2014 in October, the **Geological Society** and partner organisations are celebrating this unique geo-heritage by launching a list of **100 Great Geosites** across the UK and Ireland. A geosite could be a beautiful outcrop or a classic site; striking stones in a building or an important quarry or even a museum. The only requirement is that it is in the UK or Ireland and is open to the public.

A possible nomination? Old Red Sandstone of the Beara Peninsula, south-west Ireland.

So far, sites suggested include the 'Dinosaur Coast' of Dorset, Farringdon Station and 39 St. James's Street in London, the Lizard Peninsula in Cornwall and a host of sites in Scotland – over 250 nominations to date. Choosing just 100 out of that selection will be challenging for the organisers, and there is some time yet for more nominations to be received. You can join in by sending your favourite geosite via Twitter, using #100geosites, on the project's Facebook page at www.facebook.com/100geosites, or by emailing 100geosites@geolsoc.org.uk. ■

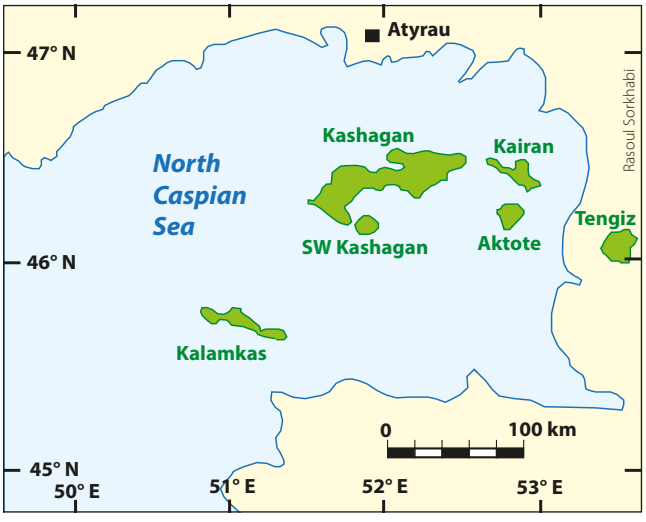
Ultra-Quiet Sensor

Sercel, a leading designer and manufacturer of innovative seismic equipment and reservoir monitoring instruments, recently unveiled a new, ultra-sensitive sensor which has an ultra-quiet performance of below 15ng/√Hz, resulting in a high dynamic range of 128dB. This extremely low noise level corresponds to the quietest ambient noise detectable anywhere on Earth and is more than three times lower than that of all other MEMS (Micro Electro-Mechancial System) sensors currently available on the market. The sensor, known as **QuietSeis**™ for obvious reasons, was demonstrated at the LSBB laboratory, a low-noise underground science and technology centre in the South of France, where tests were conducted in a silo at a depth of 500m below a mountain in a rural area with high acoustic shielding close to minimum Earth noise.

Applications for QuietSeis range from high-density single-sensor acquisitions to microseismic surveys, and the results are expected to enhance the resolution of subsurface images and provide more reliable reservoir properties. ■

Kashagan Remains Closed

The troubles at the **Kashagan** oil field, reportedly one of the largest discoveries in the last 40 years, continue. As reported in *GEO ExPro*, Vol. 10, No. 5, the giant field finally came on stream in September 2013, only to close in the same month after gas leaks were detected in its pipeline network. The operating company **NCOC** (North Caspian Operating Company), a consortium of partners which include ExxonMobil, Shell, Total, Eni, CNPC and KazMunaiGas, are contracted to deliver 75,000 bpd, but have to date failed to achieve this. The results of tests to investigate whether the high level of H_2S in the gas is responsible for the pipeline problems are now not expected until May or June this year. The development of the field, which is estimated to contain up to **13 Bbo** recoverable and cost nearly US$50 billion, is made particularly challenging by the harsh climatic conditions and delicate environmental balance of the region. ■



Pyrenean Reservoir Analogues

The **Pyrenees** are home to many excellent exposures, including those of the Axial Zone in **Andorra** between France and Spain, where exposed Palaeozoic sediments, granitic intrusives and layered metamorphic rocks can be used as analogues for Palaeozoic reservoirs around the world. These formations have low matrix k and would rely on fractures and alteration processes to create secondary porosity and host hydrocarbons.

A **field-based training course** is now running in the Axial Zone, using key exposures to describe and explain processes of secondary porosity generation and fracture development. Classroom presentations and discussions are used to reinforce the field-based work, the content of which includes the basics of structural geology for fracture characterisation, fracture modelling and case histories. Reservoir analogues in the outcrop include basement lithologies such as quartzites, folded and fractured Devonian carbonates, fractured metamorphic slates and gneiss. These provide analogues for producing reservoirs in the Cambro-Ordovician of North Africa, or the granites in locations such as the Yemen basement and offshore Vietnam. Please visit **GeoScience** Ltd (www.geoscience.co.uk) or **Geoplay** Ltd (www.geoplay.cat) for more details on the forthcoming trips in 2014. ■

Exposures in Andorra offer a superb resource to geologists.

Task Fronterra Group Formed

Two independent consultancies, **Task Geoscience** and **Fronterra Integrated Geosciences,** have joined forces to become a global geoscience consultancy – the **Task Fronterra Geoscience**, with help from a financial injection of growth capital investment from BGF, which will take a minority stake. Task Geoscience and Fronterra are both independent geological consultancies providing data processing, borehole image interpretation and reservoir modelling services to the oil and gas industry. The merger has created the largest independent geoscience company specialising in the use of borehole imaging and core integration, which allows it to improve clients' understanding of oil and gas reservoirs through analysis of the well bore geology and surrounding faults and fractures. Task Fronterra has a global footprint, with 10 offices across North and South America, Europe, the Middle East and Asia Pacific. The combined business benefits from the knowledge of more than 80 of the most experienced geoscientists in the field. ■

New Field Mapping App

"If only I'd had one of those as a student" is the most common reaction to **Midland Valley's** new digital compass clinometer app **FieldMove Clino**. As part of their on-going commitment to support the next generation of geoscientists and seismic interpreters, Midland Valley Exploration Ltd. have been developing a new range of products for digital field mapping. Used extensively by the Innsbruck University Summer School of Alpine Research during the 2013 field season, participants agreed it significantly sped up their data collection and saved time by not having to produce inked maps, allowing more time to think about geological relationships instead.

Midland Valley Exploration Ltd. will soon be launching FieldMove Clino Pro, providing even more functionality, with users able to plot their data on a stereonet and draw geo-referenced linework on their chosen basemap. To support the future of digital mapping, Midland Valley will continue the Academic Software Initiative, giving over 200 universities the ability to import their field data into Move, where further cross-section production, model building and analysis can be undertaken. ■

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GEO ExPro Turns Ten

Distributed to more than 60 countries, online readers in 183 – *GEO ExPro* has become a global magazine in just ten years.

"We want to assist those concerned with the subsurface to take part in the overwhelming flow of information on development in both geoscience and technology in the oil and gas industry. And we want to do so through simple explanations that will be easily understood by the broad range of geoscientists and engineers who study the subsurface by means of geological and geophysical methods."

Halfdan Carstens, Founding Editor in Chief , GEO ExPro Magazine, Vol.1, No. 1

Ten years ago in June 2004, at the 66th annual EAGE Conference and Exhibition in Paris, a new magazine was launched, with a concept unknown to the oil industry. The brainchild of Halfdan Carstens, the publication was designed to help geoscientists from different disciplines learn about each other's specialities, in an easy-to-read, informative, relaxed and entertaining manner. Crucially, each magazine and article was copiously illustrated with high-quality photos and images, making it very attractive to read and enhancing the learning experience.

GEO ExPro's target audience was geologists, geophysicists and reservoir engineers – but it soon became apparent that the appeal is much wider. There was an absence of information about developments in exploration geosciences written for people concerned with the hydrocarbon industry, but not necessarily working in a geological or technical sphere. With this new magazine, engineers, managers and production specialists could read and understand what was happening at the cutting edge of the petroleum geoscience world; so too could marketing executives, sales specialists and financial analysts, not just in E&P or service companies, but also those working on the periphery, such as analysts, bankers and recruitment specialists. The academic world also took to the magazine, with lecturers using it to educate their geoscience students about the many different facets of the oil industry.

As we are involved in an industry at the forefront of technological invention, it behoves us to similarly spearhead innovation. Since that first magazine, the publishing industry has moved apace, and we have moved with it, through our ground-breaking interactive iPad app and our multimedia website, which blend our usual must-read geoscience articles with interactive maps, superb illustrations, and other digital media features.

Worldwide Coverage

As well as providing important technical information, *GEO ExPro* has always believed that geology should be fun – and what better way of appreciating our wonderful planet than exploring it as a geotourist? Since the beginning, geotourism has been one of our most popular features, with photos, maps and geological explanations describing wonderful locations from every corner of the world. More than 1,000 copies were handed out at that EAGE conference in Paris. Since then, the *GEO ExPro* stand has become a firm feature at all major industry conferences worldwide, with Kirsti Karlsson, Marketing Director since the beginning, now a well-known and popular figure at the exhibitions.

GEO ExPro is truly a global magazine, distributed to over 60 countries, with thousands of online readers coming from 183 countries. Since 2004 there has barely been a corner of the world we have not covered with a story, and the number of contributors runs into several hundred, from every continent, with regular authors based in Europe, Australia, North America and the Middle East.

So, as the Editor in Chief, I would like to take this opportunity to extend a huge thank you to everyone involved in this magazine. To the founders, who had the vision and the tenacity to carry it through; the design, proof-reading and printing experts who consistently produce such a hugely attractive magazine; the many, many writers who endlessly delight me with their erudite and entertaining articles; all the photographers whose wonderful photos really make GEO ExPro what it is; our fantastic and endlessly patient digital team, continually pushing the boundaries; our stand representatives tirelessly handing out magazines; and especially our many, varied and loyal advertisers, without whom this could not happen.

But most of all, I would like to thank you, our readers, from across the globe and throughout and beyond the oil and gas industry. Because this really is for, and about, you!

Jane Whaley

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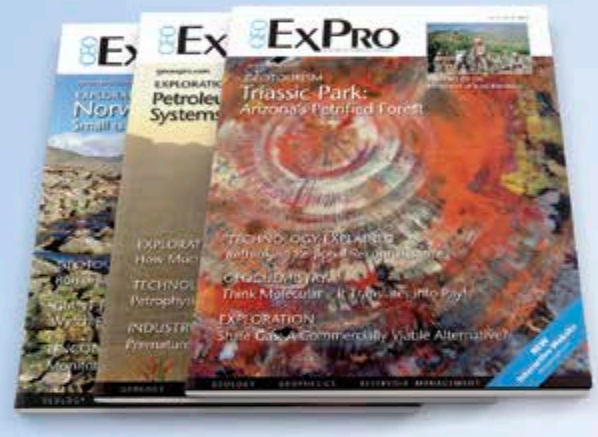

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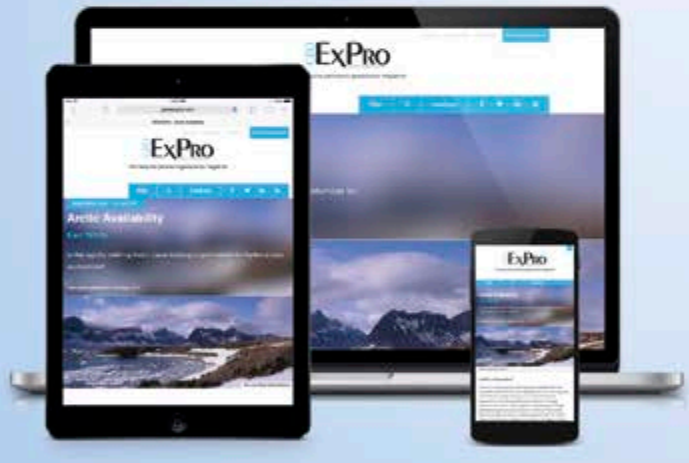

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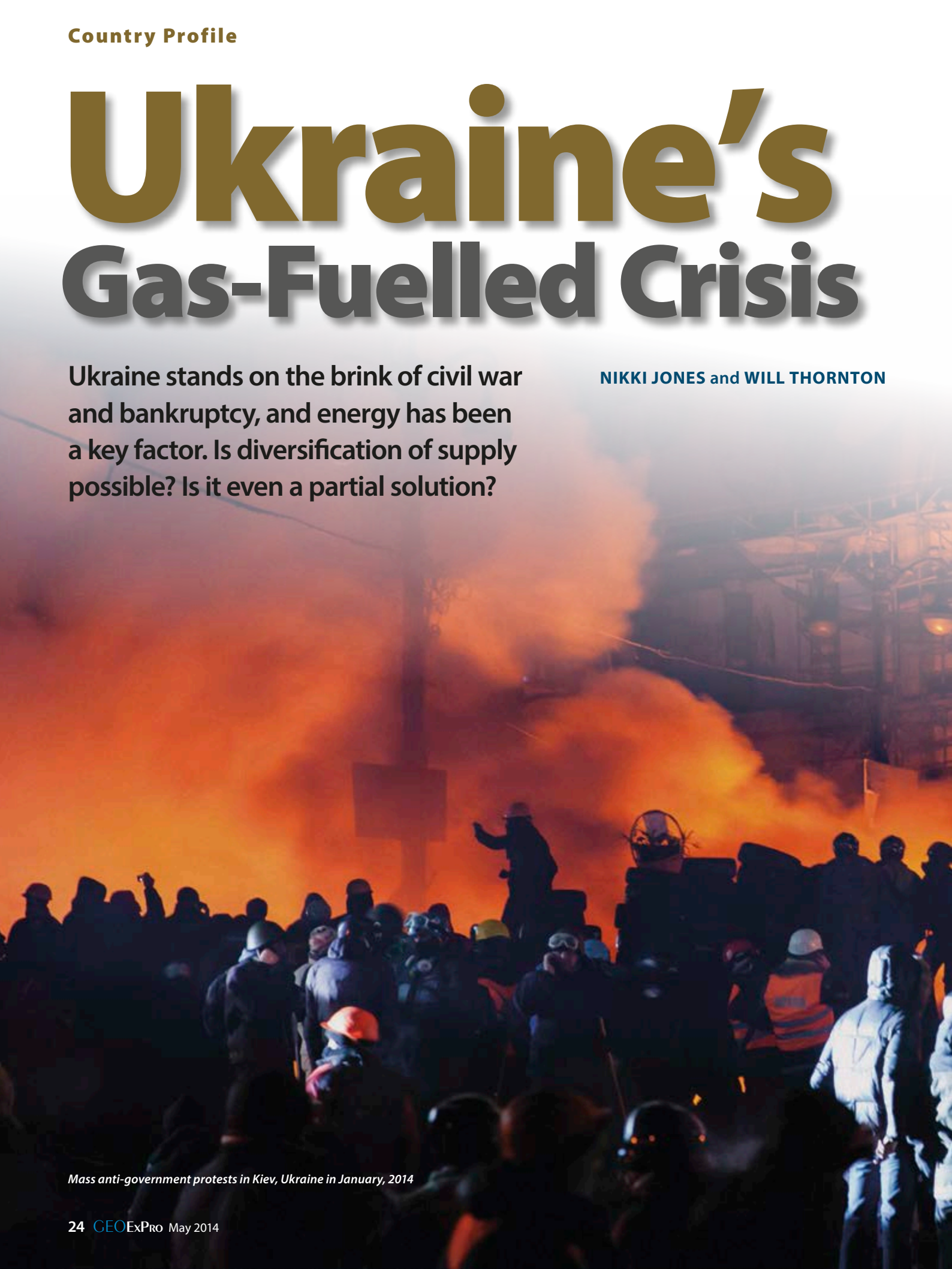
Ukraine's Gas-Fuelled Crisis

Ukraine stands on the brink of civil war and bankruptcy, and energy has been a key factor. Is diversification of supply possible? Is it even a partial solution?

NIKKI JONES and WILL THORNTON



Mass anti-government protests in Kiev, Ukraine in January, 2014

The questions of 'Why Ukraine?' and 'Why now?' have been much discussed over the last few months. The world has watched with shock and some disbelief as November's peaceful demonstrations in Kiev's Maidan square have slid uncontrollably into a formal Russian annexation of Crimea and a build-up of Russian troops on Ukraine's eastern border. The Ukrainian army has been attempting to clear Russian-speaking paramilitaries who have taken control of key buildings in eastern cities.

Ukraine has become the epicentre of a new cold – and possibly hot – war.

The role of energy – both Ukraine's reliance on Russia and its position as a conduit to the West – is critical among the causes of the crisis, although energy dependency has also helped dampen any East or West impulse for escalation. Just as Ukraine and Europe are reliant on Russian gas, Russia is reliant on revenues.

The immediate question is how to avoid a civil war with both East and West being drawn in. An integral issue is how to resolve Ukraine's gas debt to Russia, ensure continued supplies and avoid a sovereign default. Increasing the diversity of energy sources appears to be part of the long-term answer. Ukraine has both oil and shale gas potential, and could possibly import LNG and reverse the flows of its westward pipelines. Could these options provide some economic stability?

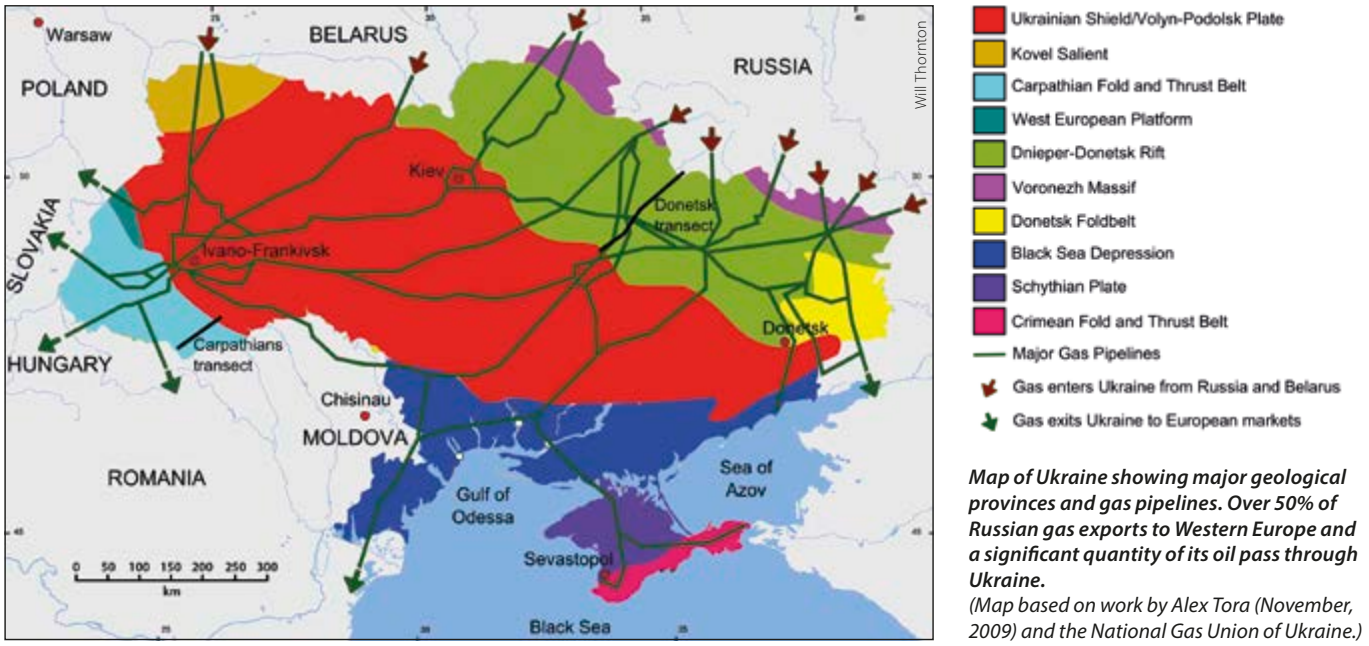
Why Ukraine?

Geo-politics and issues of national identity are central to the crisis: Russians consider the massive, central, former soviet republic to be a natural part of their territory, and moves by NATO and the European Union to draw Ukraine into their folds have been viewed with great hostility. Ukraine is crucial to Russia's economy as, not only is it Russia's single biggest foreign purchaser of gas, but it is the transit route for five major east-west pipelines. These provide a conduit for more than half of Russia's gas exports to Western Europe and significant amounts of Russian and Kazakhstani oil.

Why Now?

Ukraine has been facing economic collapse for several years. Corruption has been the main problem, with a tier of Ukrainian oligarchs controlling more than a fifth of gross national product. Energy has been a major source of funds as 'gas smuggling' and profiteering from subsidised household fuel have been common. Energy also contributes to the structural deficit. Over 60% of national gas consumption is imported from the east and the price paid has been well over $400 per thousand cubic metres, a rate far higher than that paid by Western European countries and considered discriminatory by Ukrainians.

Gas contracts have been on take-or-pay terms. These are standard in



Map of Ukraine showing major geological provinces and gas pipelines. Over 50% of Russian gas exports to Western Europe and a significant quantity of its oil pass through Ukraine.
(Map based on work by Alex Tora (November, 2009) and the National Gas Union of Ukraine.)

the trade but Ukraine drastically cut its consumption after the 2008 financial crisis and claims it gave Gazprom adequate notice of the need to reduce imports. Gazprom rejects this and in January 2013 Kiev was faced with a $7 billion bill for not having imported the agreed amount in 2012, a sum equivalent to approximately 4% of GDP. Perhaps significantly, the bill arrived just hours before a landmark deal was signed with Shell at Davos giving the company exploration rights to Ukraine's shale resources, and adding to the perception that Russia is using gas to control its neighbour.

Ukraine's economic weakness has been exacerbated further by Russia cutting off its gas supplies in the winters of 2006 and 2009. The 20-day dispute of 2009 came at a particularly critical time as the economy slowed down after the 2008 global financial crisis.

Avoiding Default

Although it was the failure of Ukraine's politicians to sign EU 'political association' agreements that sparked the Maidan demonstrations in November 2013, this has been complicated by the severe economic crisis and the need to choose between two rival, mutually exclusive bailout packages – an IMF or a Russian deal. In both, energy has been a significant factor.

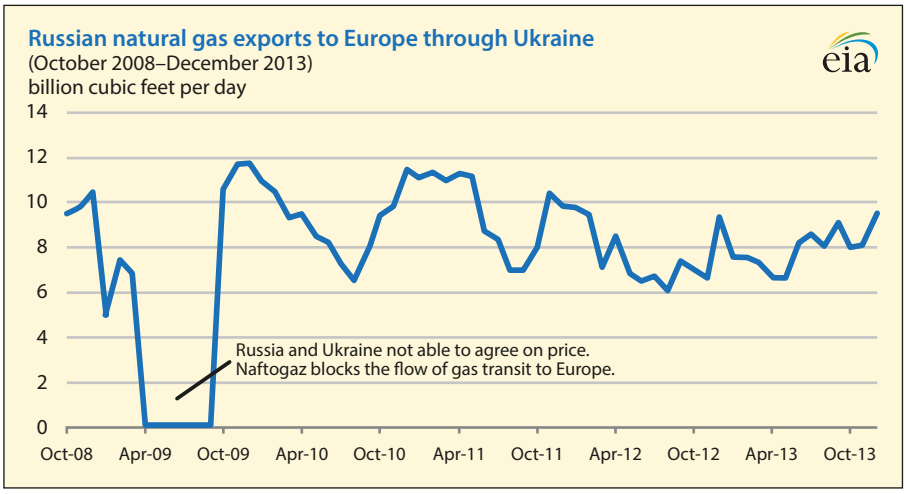
The IMF deal comes with standard conditions of freeing up the currency (in practice, a massive devaluation) and removing all state subsidies, particularly for fuel. These conditions are deeply unpopular in a country where the average wage is just $400 per month and winter temperatures can be as low as -20°C. Failure to remove fuel subsidies halted a previous IMF $15.4 bn assistance programme begun in 2010.

The alternative on offer was a Russian bailout of $15 bn, the first $2 bn of which was given at the beginning of the crisis and is now being claimed back by Moscow. The 'strings' to this deal were a commitment to a customs union with Belarus, Kazakhstan and Russia (seen as a nascent eastern counterweight to the EU), Russian control of the gas export pipelines that cross Ukraine and a withdrawal from the European Energy Community. The carrot was a gas price cut to $268.50 per thousand cubic metres, plus a loan to cover the debt to Gazprom.

The protests were sparked by President Yanukovich moving in favour of the Moscow deal, thereby closing off the option of closer integration with the EU. The eventual rejection of that deal means the country now faces the crippling price of $485 per thousand cubic metres, plus an $11 bn bill for arrears, amounts that have led Ukraine and the West to claim that Russia is using gas prices to make the country ungovernable.

Options

Alongside the IMF's renewed bailout offer, it is being argued that Ukraine needs to rapidly diversify its fuel supplies and become more self-reliant. Energy conservation is the only immediate and effective option: since



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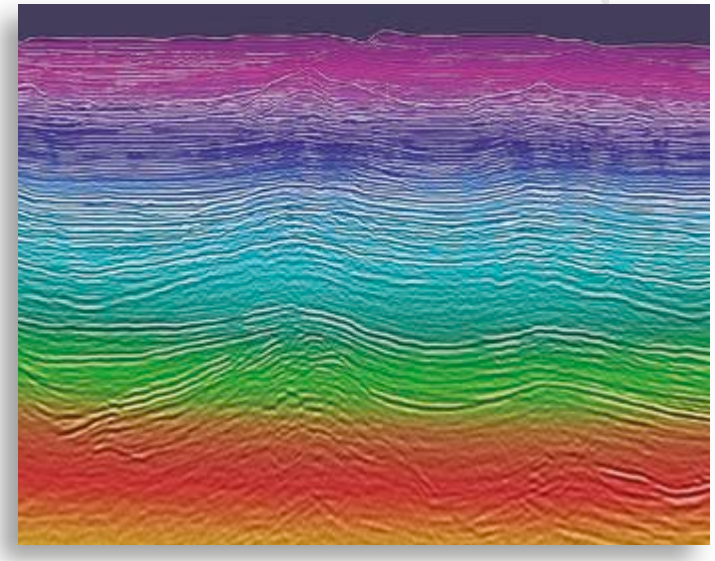
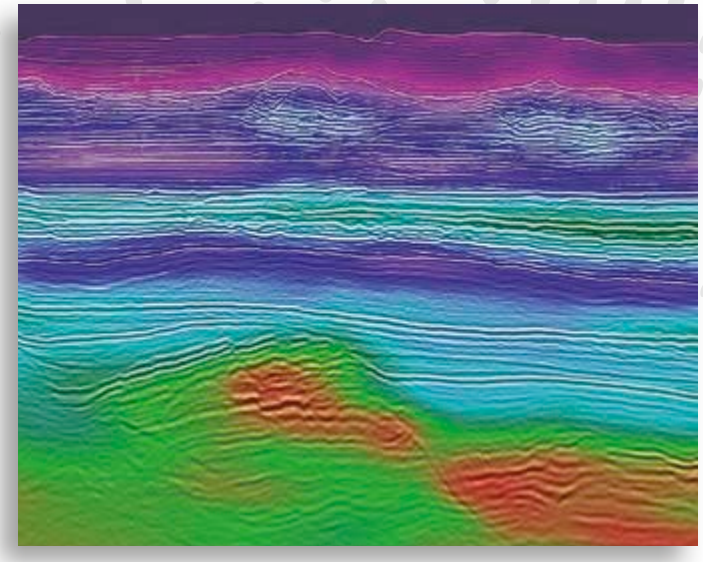


Velocity model before application of general move out tomography.



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Petroleum Geology of Ukraine

Ukraine is one of the oldest oil-producing regions in Europe. Mining for oil began in the late eighteenth century and drilling first began around the western town of Boryslav (Lviv province) in the 1880s. By 1909 the region had produced nearly 14–16 MMboe – 5% of global production at the time. The 1950s and 1960s saw rapid growth of oil and gas production in both western Ukraine and Dnieper-Donetsk in eastern Ukraine.

Since independence in 1991, efforts to increase production have been hampered by a lack of funds, problems with aging equipment and little access to modern technology. The rate of production decline increased in the late 1990s, after which infill drilling and workovers appear to have been moderately successful in reversing the decline.

Ukraine can be divided into several distinct petroleum provinces, as shown on the map on page 26. With a long history of exploration and production the regions are well understood geologically but still contain potential for new play types.

Carpathians: The Ukrainian segment of the Carpathian fold belt and foredeep is located in the westernmost part of the country, bordering Poland, Slovakia and Romania. A few fields are situated in the foreland basin but most of the production comes from the folded belt, where complex structural traps are located in a series of nappe units. A large number of the fields were found based on an understanding of the surface geology alone.

Dnieper-Donetsk Basin: The Dnieper-Donetsk Basin is situated in north-eastern Ukraine and is the principal producer of hydrocarbons in the country. Measuring 500 by 100 km, with a depocentre >15 km, the elongate, Late Devonian rift basin is bounded by the Russian craton to the north-east and by the Precambrian Ukrainian shield to the south-west. Devonian rift sediments are overlain by a Carboniferous to Early Permian post-rift sag sequence.

Most of the hydrocarbon accumulations are found within the post-rift series and are related to salt induced traps. Source rock intervals reached maturity by the end of the Palaeozoic and basin inversion episodes are thought to be responsible for the complex charge/trap timing scenarios encountered in the basin.

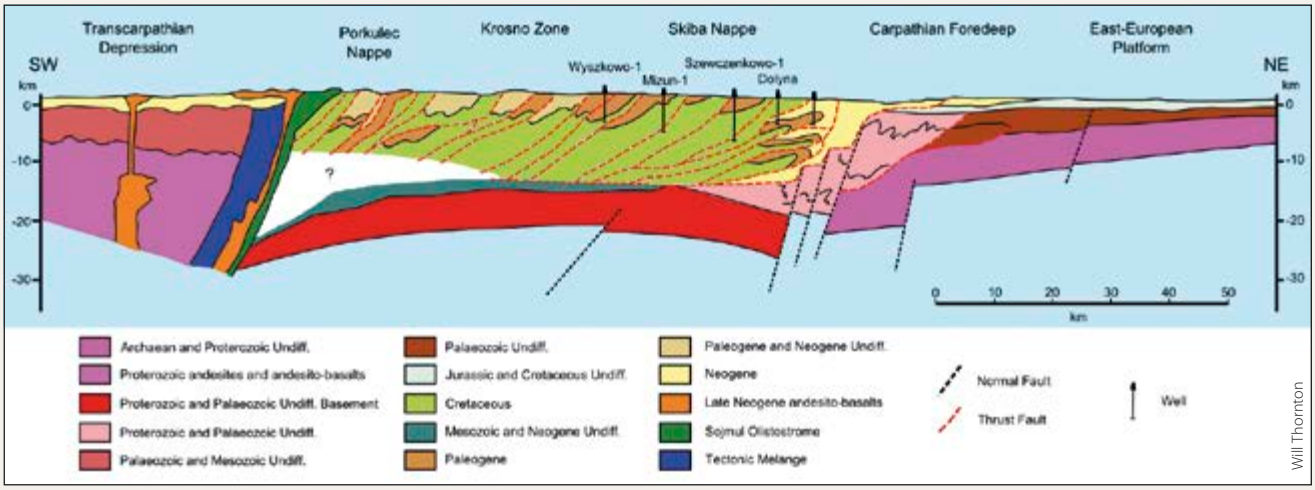
Black Sea: The Black Sea region of the Ukraine, now annexed by Russia, has two major areas of interest to the petroleum industry – the Gulf of Odessa and the Sea of Azov. In between these on the southern margin of the Crimea peninsula, the shelf is quite narrow. An offshore folded belt, situated just to the south, extends into the deepwater, where a few prominent structures provide multiple untested play types.

Only a relatively small number of wells have been drilled in the region in the last few decades (<100 in the Gulf of Odessa), with around eight gas/gas-condensate fields discovered, totalling ~2 TCF of gas. The main productive horizons are within Upper Cretaceous (Maastrichtian), Paleocene, Eocene, Oligocene and Lower Miocene sequences.

In 2013 Ukraine signed an offshore oil and gas production-sharing agreement with Italian group Eni and France's EDF, for a 1,400 km^2 area in waters off western Crimea. The area includes the Subbotina oil licence as well as the Pry Kerch block where several oil and gas prospects have been identified. Both deals are now lost to Ukraine.

Unconventional Resources and Shale Gas Potential

Ukraine has significant unconventional resource potential. The Dnieper-Donetsk Basin, for example, may have a very large basin-centred gas accumulation within the Carboniferous. In the west, the potential for shale gas and liquids is very similar to the Silurian-Lower Devonian black shale potential of Poland. Exploration sweet spots are located near the Polish border in the foreland of the ▶



Geological cross-section through the Ukrainian Carpathians (modified from Gabor Tari – after Oszczypko, N., P. et al., 2006). For location of section see map on page 26.

▶ Carpathians and between Moldova and the Black Sea coast.

Eni has a shale gas deal in Ukraine and as recently as 2013 Ukraine signed a $10 bn shale gas production-sharing agreement with US company Chevron, complimenting a $10 bn gas exploration deal with Royal Dutch Shell in the eastern part of the country. ■

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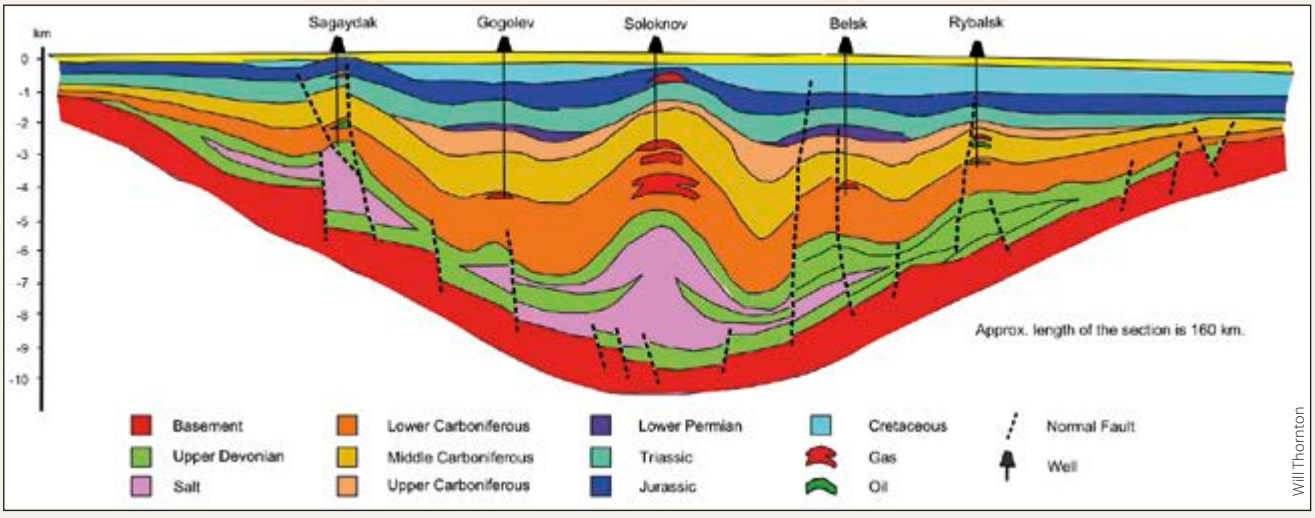

Cross-section of the Dnieper-Donetsk basin (modified from Gabor Tari – after Ulmishek, 2001). For location of section see map on page 26.

the IMF is insisting on a 50% increase in household prices from May 1, it is likely that consumption will drop, although the economy's reliance on heavy industry will limit the effect.

In fact more than half of Ukraine's energy comes from its own uranium and coal supplies (approximately 18% and 28% of electricity respectively). But the economy remains reliant on gas for 40% of its energy.

As with most of the central and east European countries, liquefied natural gas (LNG) is seen as the most obvious alternative and Ukraine is already constructing an import regasification terminal. Optimists hope that a north-south supply corridor will be created to rival Russia's east-west axis, and gas interconnectors are being improved.

Only the US is in any sort of position to increase exports in the foreseeable future and one Republican congressman has proposed an 'Expedited LNG for American Allies' bill. The aim is clearly not just to strengthen the bargaining power of European utilities but also to free up the West with regard to a more aggressive – possibly military – response should there be further annexations of territory.

However, the building of expensive liquefication and regasification terminals takes years and offers no immediate solution. Nor, given the costs involved, is American LNG likely to be cheaper than the gas on offer from Russia.

Former President of Ukraine Viktor Yanukovych, who was ousted in February after major street protests in Kiev.

Arseniy Yatseniuk, Interim Prime Minister of Ukraine.

Greater Self-Reliance

It is unclear at present whether Ukraine's shale reserves, believed to be the third or fourth largest in Europe, are commercially exploitable. The EU has, in January this year, issued guidelines that effectively ensure that environmental concerns do not prove an obstacle. However, companies will be mindful of the Polish experience where, despite large reserves, most major companies have chosen to quit, citing geological complications.

Ukraine's oil consumption is a relatively modest 0.32 MMbopd (compared to the UK's 1.5 MMbopd) and, before the annexation of Crimea, Ukraine's Chornomornaftogaz, which pumped both oil and gas, had a small off-shore production of 80,400 bopd. However, the company has now been nationalised by the Russians, and Ukraine will now not benefit from recently negotiated Black Sea exploration deals.

With regard to Ukraine's $3 bn a year earnings as an oil and gas conduit to the West, this source of income was already being undermined by new pipeline projects: in 2009 Nord Stream became operational, bringing gas direct to Europe via the Baltic Sea, avoiding eastern Europe altogether, and a South Stream project under the Black Sea is waiting EU approval. Its construction, though some way off, will ensure that all Western European demand (30% of its total gas consumption) could be met without the need to transit Ukraine at all (Ukraine is currently the transit route for 16% of all European gas requirements).

The possibility of actually reversing the flow of the pipeline through Slovakia is an option for reducing Ukraine's dependence on Russia. However, Ukraine is likely to continue to derive income from the massive Druzhba oil pipeline, one of the biggest networks in the world.

Prospects

Ukraine's interim President Yatseniuk says he is willing to pay the current $2.2 bn billion bill, but objects to the extremely high price of $485 per thousand cubic metres and the repayment of past discounts. Russia is, reportedly, insisting that gas is now paid for in advance. Supply cuts may be prevented only by the fact that Russia is wary of the escalation this would bring, the risk of pushing the West into a more rapid diversification of supply, and exacerbation of Europe's investigations into Gazprom's abuse of monopoly power.

With regard to a bailout, decisions are complicated by the fact that, till elections in May, the West is dealing with an interim government. Unpopular austerity measures – particularly the rapid removal of fuel subsidies – may produce the 'wrong' election result and drive much of the population towards Russia.

Anti-corruption measures are to the fore, with the hope that Ukraine can emulate Georgia in curbing the problem. Appeals have been made to Ukraine's oligarchs to repatriate their funds and provide their own bailout.

The immediate focus is on the possibility of civil war. If this can be avoided, economic stability will be the primary goal and for this, less dependence on Russian gas seems essential. Few options will deliver the necessary results within the next year. The best hope is that East and West co-dependence on gas and revenues will allow a negotiated compromise. ■

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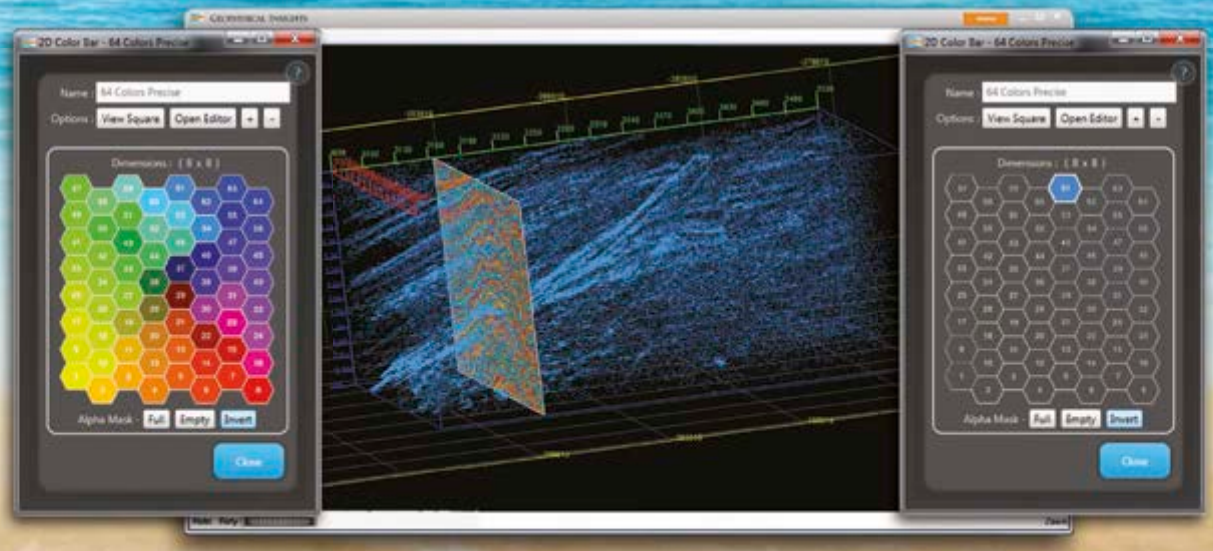

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Polarising Pyrite

PAUL WOOD

Norwegian company ORG Geophysical aims to find previously hidden hydrocarbon reservoirs by detecting shallow pyrite bodies using Induced Polarisation.

In the second decade of the twenty-first century, competition for exploration targets is increasing. Most energy companies are now faced with the need to explore for hydrocarbons in difficult environments such as ultra-deep water or complex geological settings that have technical risks such as very high temperatures and pressures. An exploration well in such environments can potentially cost $100 million or more and take many months to drill. Understandably, companies want to maximise their investment by drilling discoveries, not dry holes.

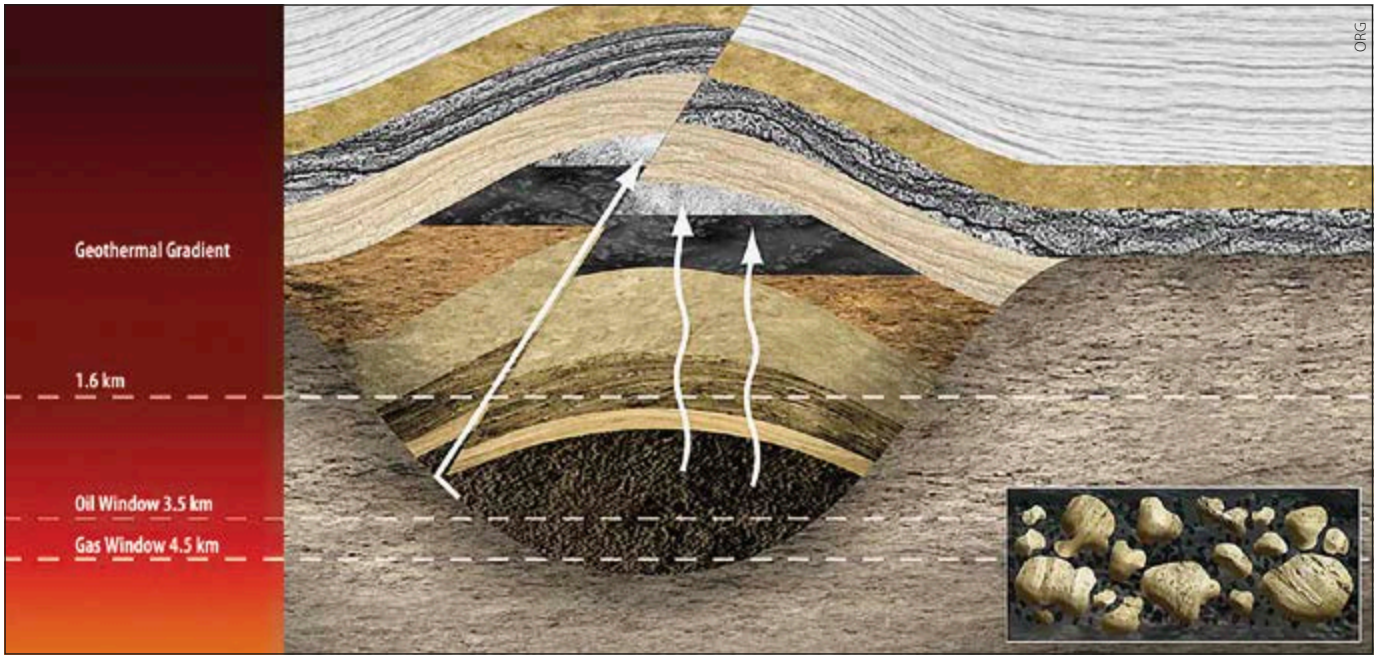
In the latter part of the twentieth century, most hydrocarbon exploration used a combination of geology and seismic. In the past decade, however, a number of new technologies have been developed as a complement to traditional seismic interpretation and to further reduce exploration risks. One of these is Controlled Source Electromagnetic surveying (CSEM), which detects resistive layers in the subsurface that are embedded in conductive sediments (e.g. hydrocarbon fill of reservoirs bounded by brine-saturated layers). CSEM can detect hydrocarbon fill directly but has low resolution and can be a relatively expensive and time-consuming technique, usually requiring a dedicated vessel and the emplacement of detectors on the sea bed.

In 2012, a Norwegian company, Offshore Resources Group Geophysical A.S. (ORG), was set up by a group of ex-oil company staff and academics with the intention of adding a new, but less complex and costly technique to the de-risking portfolio available to hydrocarbon explorers. ORG formed a partnership with a Russian company, Siberian Geophysical Research and Production Company (SGRPC), which had been using a technology called Differentially Normalised Method of Electrical prospecting (DNME) based on Induced Polarisation (IP), an electrical survey method often used in the mining industry to detect ore bodies. SGRPC had developed this technology to locate pyrite bodies that are formed over time above hydrocarbon accumulations.

Pyrite as Hydrocarbon Indicator

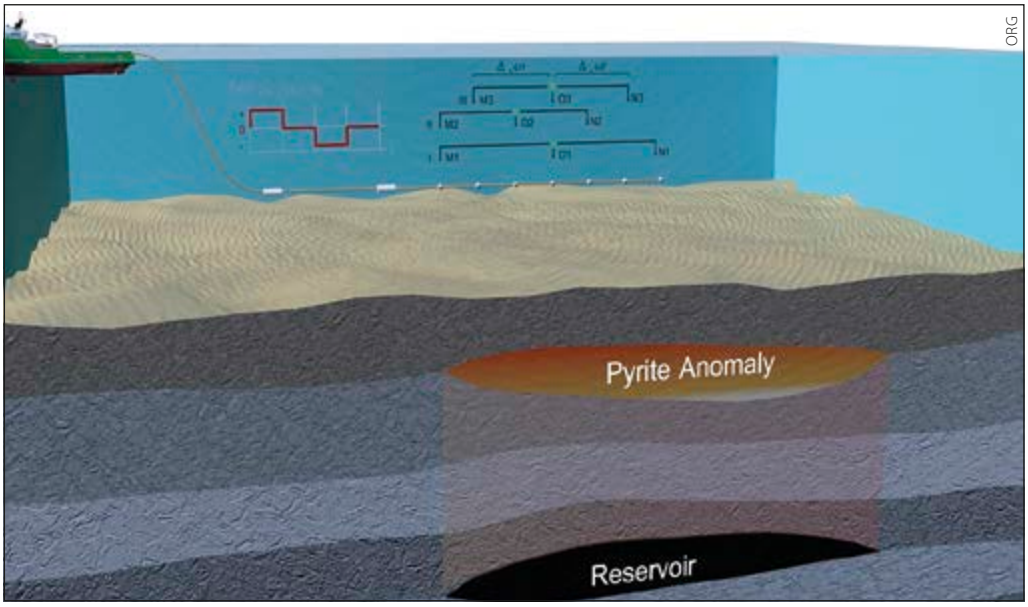
Eirik Flekkøy, Chief Scientist of ORG and also a Professor of Physics at Oslo University, explains the importance of pyrite. "There are several mechanisms leading to the induced polarisation effect. A key one is the formation of pyrite. This can be through direct chemical reactions between sulphur in micro-seepages from a hydrocarbon reservoir and pre-existing iron in the rock, or indirectly via the degradation of 'oil-eating' bacteria. These are both hydrocarbon indications." So the DNME technique does not try to detect hydrocarbons in a reservoir several

The slow micro-seepage of hydrocarbons gives rise to mineralogical changes high above a reservoir.



kilometres deep, but to see much shallower evidence for the presence of the deep hydrocarbons, with the pyrite bodies possibly only a few hundred metres below sea bed or ground level. As Eirik says: "It's like looking for a tropical island on or below the horizon which is hard to see, whereas the cumulus cloud above it is relatively easy to observe." SGRPC has acquired 35,000 km of data in Russian areas since 2002 and claims 90% success rate in their predictions of nearly 200 wells.

The DNME technology relies on inducing polarisation in the pyrite bodies with electrical signals. IP is in fact a delayed electrical response. Eirik continues: "It's like the effect you see in a battery. When a current is applied, it takes some time for the battery to be charged. We then look at the voltage decay after the current is turned off. When the current is applied and then shut off, in the pyrite grains, at pore scale, there is a chemical reaction that is similar to what happens at the electrodes of a battery when charging and discharging it." The amount of over voltage when 'charged' is a measure of the IP effect. The voltage decays to a certain level in a certain time (the relaxation time) and the method also characterises the shape of the decay.



Pyrite forms above a hydrocarbon reservoir as a result of micro-seepage. A vessel towing source and receiver electrodes can induce polarisation in the pyrite and record the resultant distinctive signals.

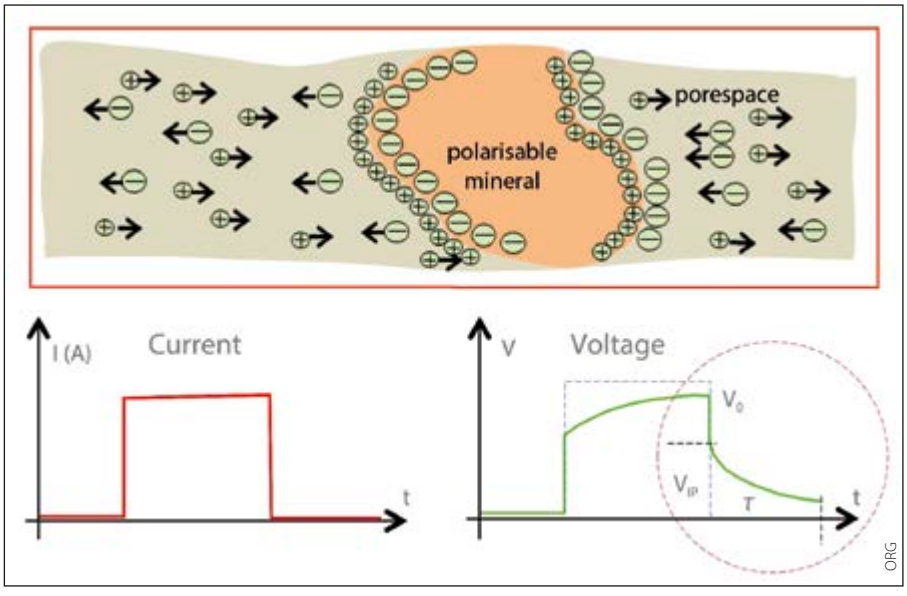
Simple Low-Cost System

ORG has taken the Russian technique and adapted it to its own backyard, offshore Norway. The shallow nature of the target means that the equipment required for surveys can be kept at a modest level, reducing costs. In fact the whole package can be put into three 7m shipping containers and placed on a workboat when surveying offshore – it is not necessary to have a dedicated vessel. The whole system is towed, with a transmitter with two electrodes separated by 600m, the first one only a few tens of metres from the vessel. The detectors are a set of electrodes spaced 200m apart and organised into three sets of three electrodes that can each measure potential differences and electric field gradients at different offsets. The depth of tow is from 50 to 500m depending on targets and operational conditions and the system is towed at about three to five knots (about six to ten km/hr).

The signal is a step pulse that is switched on for typically four seconds, then off for the same period of time,, then repeated with the opposite polarity in order to average noise. Because the targets are shallow, signal-to-noise is not usually a problem as the returned signals are still above background levels. Signals are also normalised to correct for offset differences.

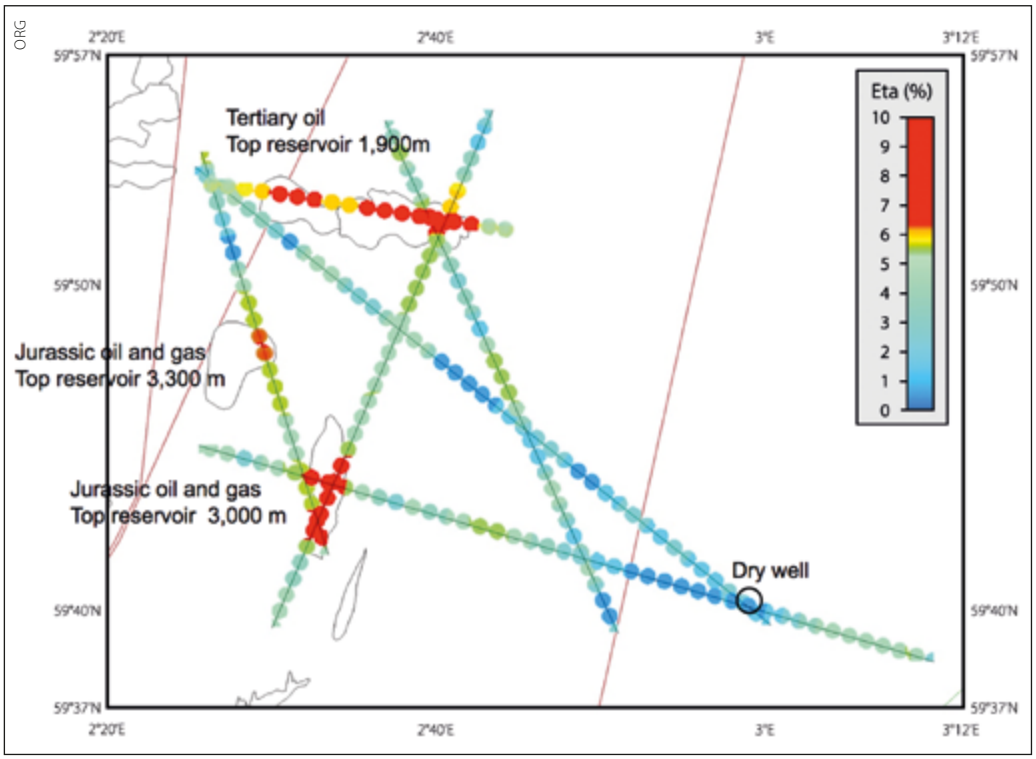
The signals are processed using inversion based on the formulation called the Cole-Cole expression for electrical conductivity. This defines a relationship between electrical conductivity, σ, and the 'chargeability' or 'polarisability', η. Two other parameters in the relationship are the relaxation time, τ, and an exponent that can be derived from the decay shape. The measurements are inverted in an iterative manner for resistivity and chargeability in layers that have been defined using seismic or well logs and η (eta) is derived as a percentage value for the shallow pyritised layer.

Polarisation occurs in a pyrite grain when a current is applied. The voltage builds up as in a battery and then decays when the current is switched off.



Norwegian Testing

During 2012 and 2013, ORG conducted a number of test surveys in Norwegian waters across known hydrocarbon fields in order to see if the method was suitable for use in these areas. Over 3,500 line km have been surveyed across 20 fields, 18 of which gave results that corresponded to known drilling results, while one measured anomaly in chargeability was offset from the field and the results of one other are as yet unexplained. Reproducibility tests were also conducted, one in 2012 re-acquiring a line with a less than 1% difference from the original, while further tests of the same line in 2012 and 2013 gave very similar results. The 2013 survey used equipment that had been improved based on the 2012 experience and was judged to give better resolution.



DNME survey across the Frigg Field, offshore Norway showed anomalies above three known reservoirs and no anomaly across a dry hole.

One of the surveys conducted in 2012 was across the Frigg area where the six lines surveyed showed 'eta' anomalies above three reservoirs, two in the Jurassic (oil and gas) at around 3,000m+ reservoir depth and one Tertiary oil reservoir at 1,900m depth. A known dry well that was crossed did not have any anomalies associated with it. Similar results were obtained on most of the other fields covered, including the Troll area. As a result of the positive tests, a multi-client survey with eight oil companies was conducted in 2013 in the Norwegian North Sea. Of the seven predictions made as a result of the survey, six have been confirmed as correct. Five of these were discoveries and in one case a dry well was predicted. In 2014, dedicated commercial surveys are due to start, with a typical 200 km survey having some £500,000 ($675,000) acquisition cost, including technical and weather risks.

De-Risking Potential

The tests conducted in Norwegian waters showed that, at least here, this new technology based on well-known principles has the potential to locate, quickly and relatively cheaply, hydrocarbon accumulations that may not be found using conventional exploration techniques, even in well-explored areas. There is a clear potential to target stratigraphic traps that may not be readily detectable on seismic data. It may not work everywhere, for example where prospects are sub-salt or there has not been any micro-seepage, so should be tested before entering new areas. It also does not detect hydrocarbon reservoirs directly, and therefore should be seen as a complement to existing techniques. However, the method shows promise as an initial low-cost screening tool before planning more detailed focused work using techniques such as CSEM and 3D seismic. ■

ORG

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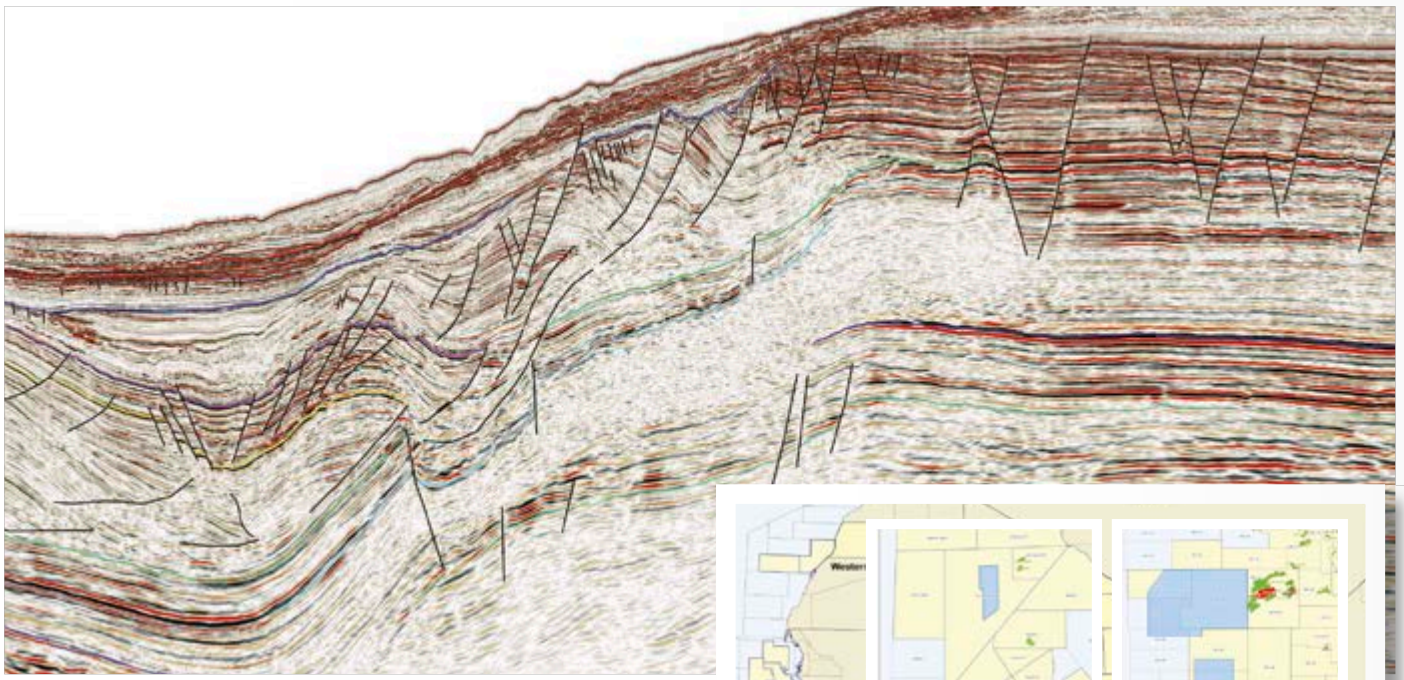

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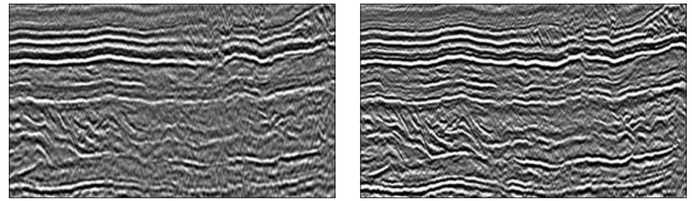
A Nigerian Renaissance

Renewed interest in Africa's largest oil producer

The Niger Delta is one of the most prolific hydrocarbon-producing basins in the world and huge discoveries in the late 1990s and early 2000s established the deepwater delta as a world-class petroleum province. Renewed focus in the deepwater areas over the past 12 months underscores the significant importance of the western Niger Delta for oil companies.

Slip evolution and gravity driven extension across the western Niger Delta has led to the development of complex, large fold and thrust belts and to a diversity of structures including toe-thrust anticlines, listric and transcurrent faults, shale diapirs and mud volcanos. The complexity of the deepwater fold and thrust belts necessitates high quality 3D seismic data.

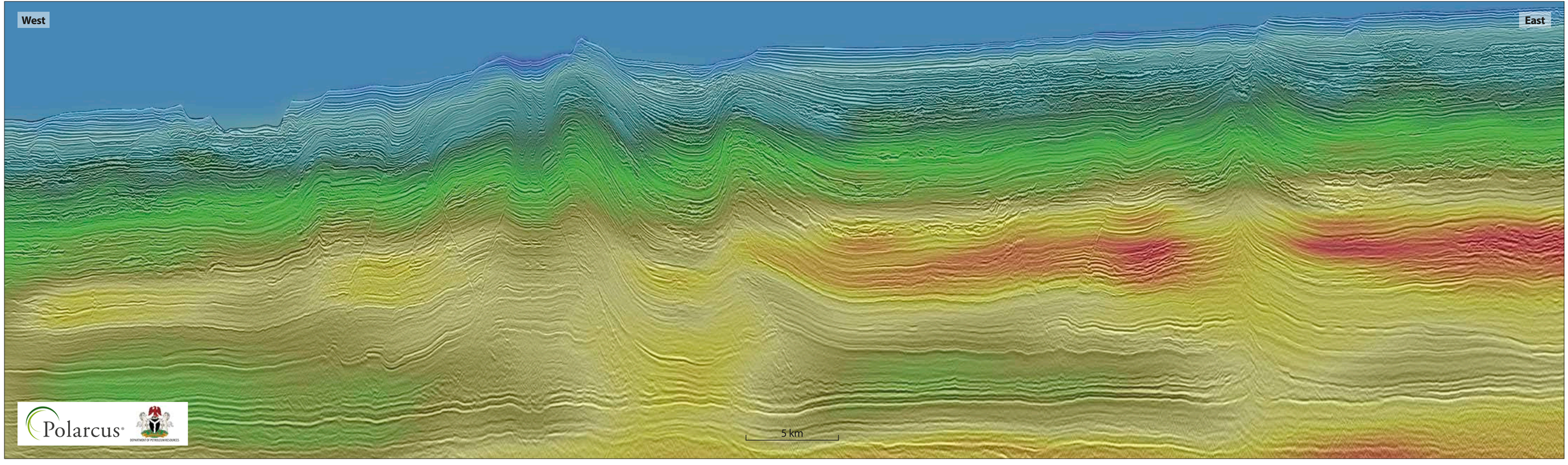
Simple time processing cannot solve the imaging issues in this diverse and structurally complex province. A pre-stack depth migration trial (PSDM) performed for Polarcus by DownUnder GeoSolutions delivers a significant uplift in image quality, which will facilitate improved interpretation and assist in the understanding and analysis of new and untested plays.



Full stack comparison at the target level. Legacy data on the left. Latest version of the pre-stack depth migration is shown on the right.

The reprocessed pre-stack depth migration section is located offshore Nigeria on the south-western margin of the Niger Delta. The latest tomographic velocity model is co-rendered as the colored overlay on the pre-stack depth migrated line below.

Processing courtesy of DownUnder GeoSolutions



A Clearer Picture

JOHN BALCH, Polarcus and **MATT LAMONT**, DownUnder GeoSolutions

The Niger Delta is one of the most prolific petroleum provinces in the world, covering an area of over 300,000 km^2 with a sedimentary succession over 12,000m thick in the main depocentre. Oil companies have been exploring the area since 1936 and have drilled more than 8,000 wells since first oil was discovered by Shell Darcy at Oloibiri creek, in 1956.

The Niger Delta developed at the site of a rift triple junction related to the opening of the southern Atlantic. The delta grew in a series of pulses of sedimentation over an oceanward-dipping continental basement onshore with possible rift sequences offshore, and then by progradation over a landward-dipping oceanic basement in the deepest water areas. The overall regressive, offlapping sequence is composed of three diachronous siliciclastic units: the deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the fluvial Benin Group.

The primary source rocks in the Niger Delta are the marine shales of the upper Akata Formation, whilst the interbedded marine shales of the lowermost Agbada Formation provide a secondary source. In shelfal and onshore areas the primary reservoirs are sandstone facies within the Agbada Formation, whilst the turbidite sands of the upper Akata Formation provide a primary target in both deepwater plays and frontier deep plays in nearshore and onshore areas. In many places channel morphology also changes rapidly from sinuous to relatively straight, with reservoir facies deposited both within channel axes and as lobes, in part determined by gravity sliding over overpressured marine shales.

Nigeria Deepwater Renaissance data set with the location of the PreSDM trial shown as a red line.

The delta has prograded towards the south-west from Eocene to Recent and is transected by several northeast-southwest fracture zones. It appears to be a primarily extensional province in shelfal areas, but has predominantly contraction dominated toe-thrust systems in the deepwater areas. The syn-depositional collapse of the clastic wedge complicates stratigraphic correlation and modelling in many areas, whilst detachment in the deep seated over-pressured Akata Formation has resulted in the penecontemporaneous development of toe-thrust anticlines, listric and transcurrent faults, shale diapirs and mud volcanos. The main structural trap types in the deepwater fold belts tend to be shear fault-bend folds and detachment anticlines within the Akata Formation.

During the 1990s a myth developed that the deepwater Niger Delta appeared problematic in terms of structuration for holding hydrocarbons and the farther and deeper you went beyond 1,600m water depth, the less likely you were to find significant hydrocarbons. The reality was that at the diverse and complex structural styles entrenched within the region created imaging issues that could not be solved with the simple time processing of the available seismic data at the time. In addition to which formation pore pressures greater than regional overpressure, local stresses and fractures could lead to seal breach and failed traps .

Chevron discovered the first commercial offshore field (Okan) in 1963, but compared to other West African Tertiary basins, Nigeria's deepwater areas remain comparatively underexplored with fewer than 10% of the country's exploration wells drilled in water depths of over 200m.

The Department of Petroleum Resources of Nigeria (DPR) has granted Polarcus Nigeria Limited, a joint venture between Polarcus and Ashbert Limited, exclusive

rights to broker 10,800 sq. km of modern high quality 3D seismic data covering large tracts of the prospective western deepwater area. Only five exploration wells have been drilled in the project areas to date, even though the world-class Bosi (ExxonMobil, 1996), Erha (ExxonMobil, 1996), Bonga Southwest (Shell, 2001) and Uge (Chevron, 2006) deepwater discoveries lie in adjacent blocks.

The brokered 3D surveys were acquired between 1999 and 2004, and have been processed through a comprehensive de-multiple and Pre-Stack Time Migration sequence. Whilst the existing 3D multi-client data is largely of good quality, the complex geology of this area creates imaging issues which cannot be solved with simple time processing. To demonstrate the uplift in image quality that is possible in this area, a 3D pre-stack depth migration reprocessing trial has been initiated by Polarcus. A test line through the 2003 vintage NG03 3D dataset has been reprocessed by DownUnder GeoSolutions from field tapes through to Kirchhoff depth migration, using high-resolution reflection tomography to iteratively build the velocity model as part of the workflow.

Comprehensive pre-processing was performed prior to velocity model building; three de-noise steps including 3D true-azimuth SRME and high resolution Radon de-multiple were utilised. Reflection tomography was then used to iteratively build the velocity model. The model was checked at each iteration and updated when and where necessary. The data were migrated using a true relative amplitude Kirchhoff pre-stack depth migration with the Green's functions determined by dynamic ray tracing – the rays are traced through a gridded velocity model with maximum energy rays chosen. Testing was performed to ensure that the sampling was sufficient to capture all frequencies unaliased, with variable depth sampling output from the migration. There were no assumptions made about lateral or vertical velocity variations, apart from the model being smooth.

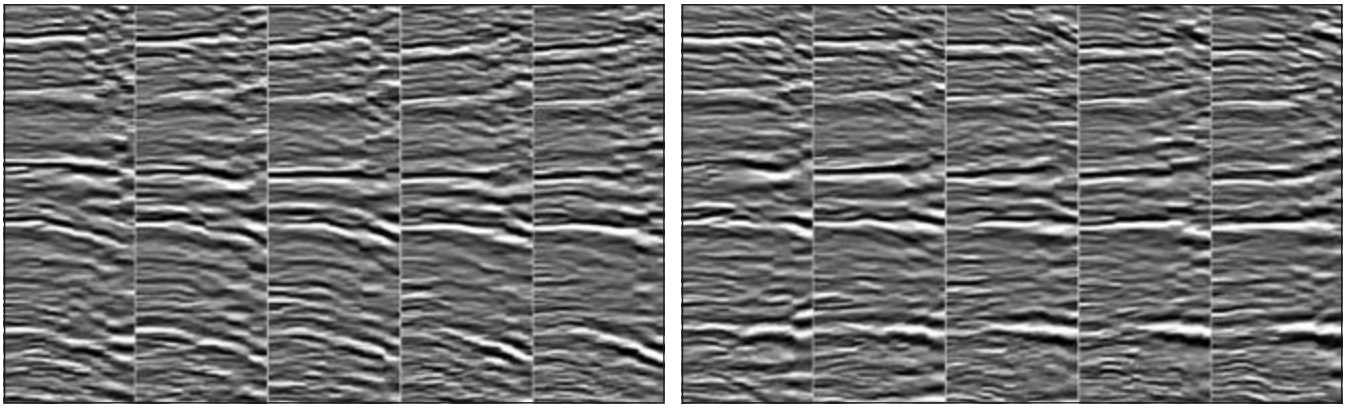
Work is not yet completed, but a significant uplift in image quality has already been achieved by DownUnder GeoSolutions using a state of the art pre-stack depth migration workflow, with further improvements expected. Structural elements such as faults are more clearly defined. Illumination issues near faults have now been resolved. Better event continuity and obvious resolution improvements are also clear – as can be seen in the full stack and image gather comparisons below. A more accurate structural picture at the target level can now be interpreted as a result of the improved velocity model and depth imaging.

The deepwater gravity-driven fold-belt structures are fundamentally different from onshore orogenic fold-belts and exploration success in the offshore fold-belt areas will depend on understanding their architecture. The results of the depth migration trial have shown a significant improvement in data quality, which will facilitate improved structural interpretation, section reconstruction, seismic stratigraphy and facies analyses and will further assist in the identification and analysis of untested plays.

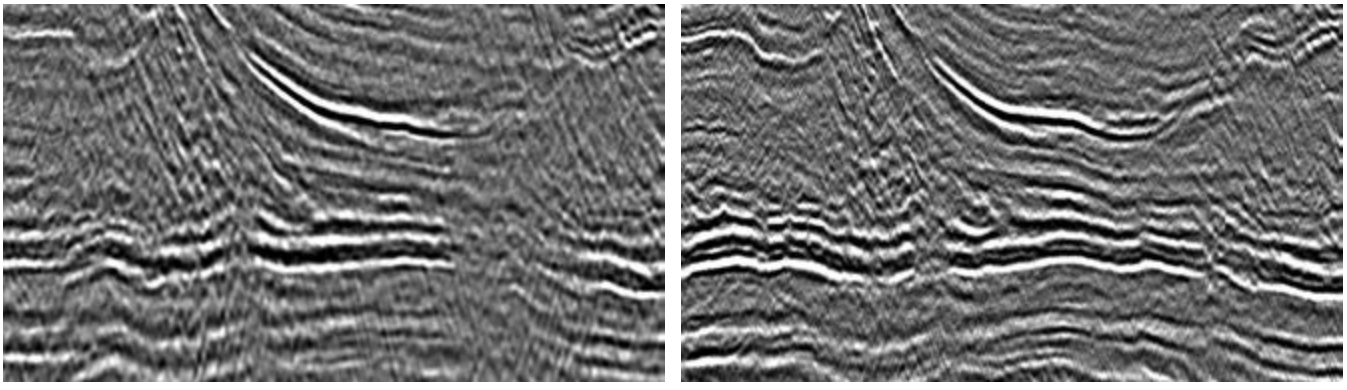
Subject to industry underwriting interest Polarcus is planning to expand the depth processing across the whole project area, and is also planning to acquire new 3D surveys in Q1 2015. ■

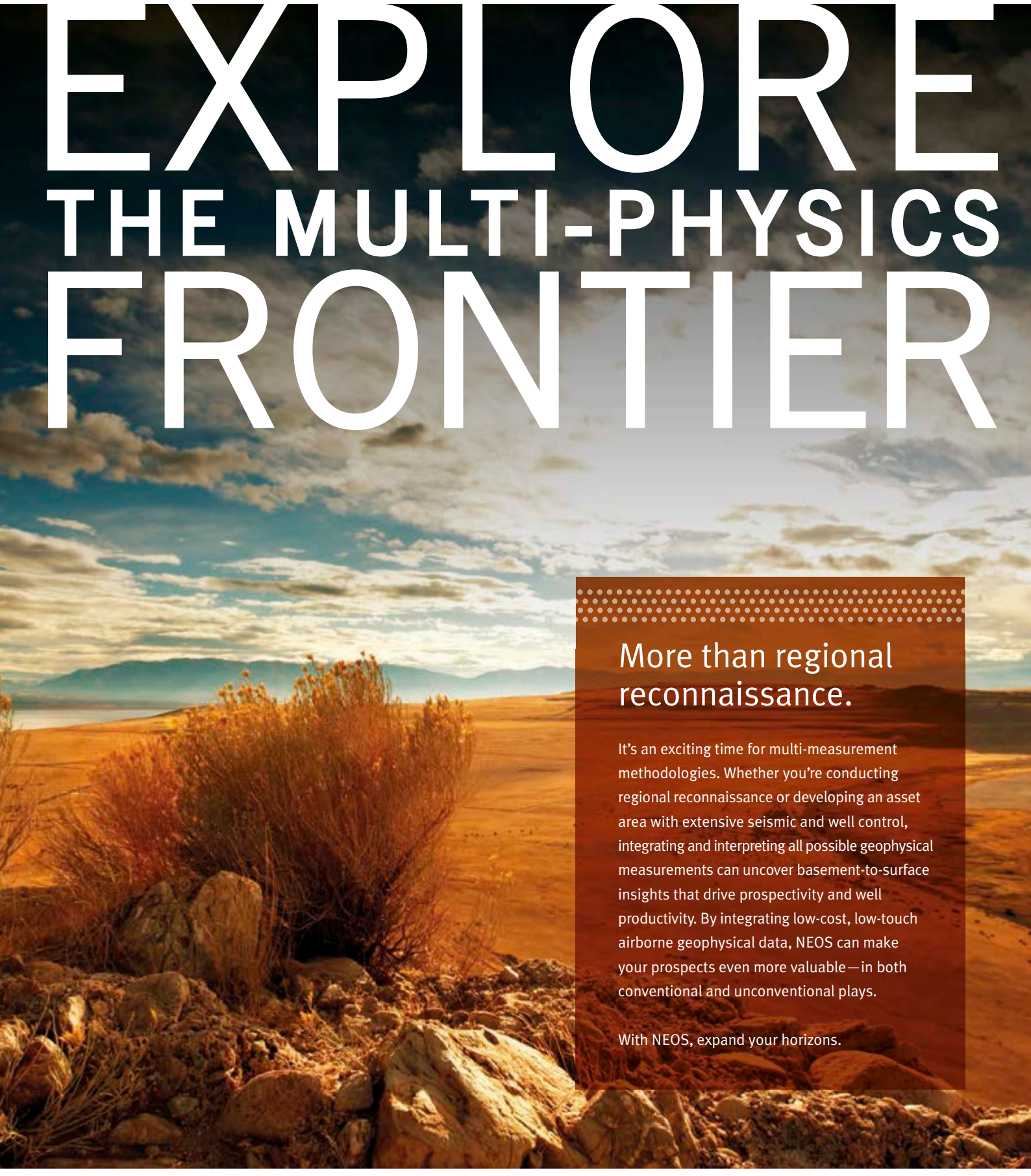
References available online

A selection of gathers at the target level in an area with complex imaging issues. Legacy data is on the left. Latest pre-stack depth migration is on the right.



Full stack comparison at the target level. Legacy data is shown in the left image. Latest version of the pre-stack depth migration is shown in the right image.





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Broadband Seismic Technology and Beyond

PART IX: BroadSeis in Production

There are benefits for field development through the application of both the low and high frequency ends of the BroadSeis bandwidth

LASSE AMUNDSEN, Statoil and **MARTIN LANDRØ**, NTNU Trondheim
Guest Contributors: **VETLE VINJE** and **JO FIRTH**, CGG

In the last edition of *GEO ExPro* we described how the broad bandwidths delivered by the innovative BroadSeis technology benefit exploration. In this second part, the advantages of an extended bandwidth to field development and reservoir characterisation are examined.

The high frequencies provide high-resolution near-surface images for geohazard identification and also enable detailed velocity modelling which can provide better deeper images. However, in many respects it is the low frequency end of the spectrum which is more important as these frequencies provide more quantitative and reliable reservoir inversion results, simplified interpretation and clearer facies discrimination.

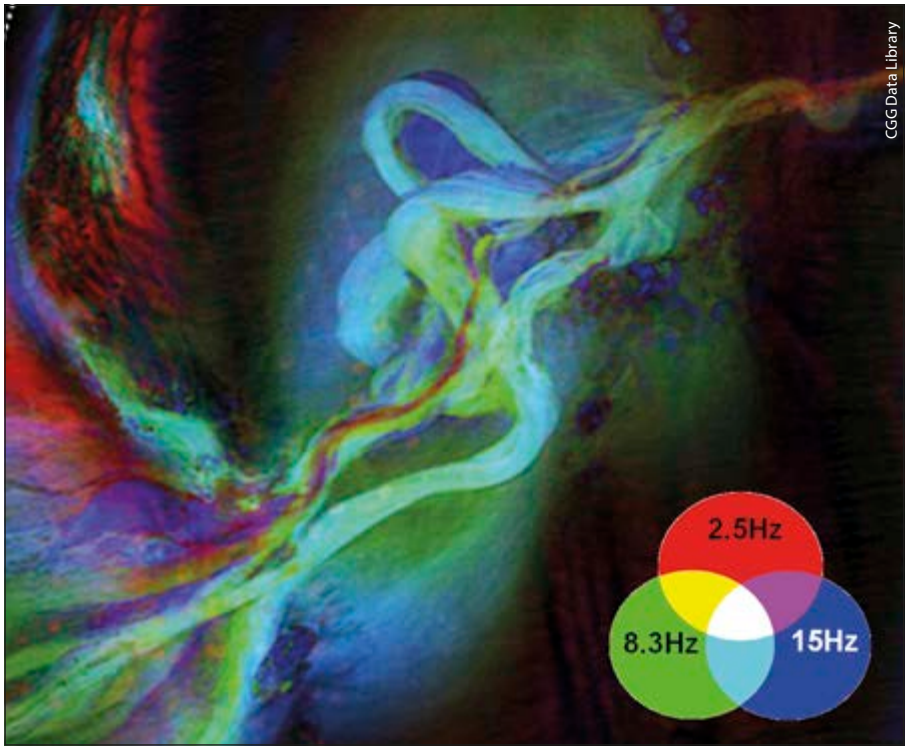
Improved Illumination

In areas with especially complex overburdens, such as the subsalt plays of the Gulf of Mexico, it is recognised that wide-, multi- or – preferably – full-azimuth acquisition provides enhanced illumination, as well as improved natural noise and multiple attenuation, in particular when used with ultra-long offsets. Combining this acquisition geometry with the benefits of broadband provides the ultimate seismic data for deep imaging in complex geological areas.

A new technique for efficiently recording full-azimuth towed-streamer data has recently been developed and used to acquire several multi-client surveys in the Gulf of Mexico. This technique uses two multi-streamer vessels, with three additional source vessels, in a patented staggered formation, in order to acquire full-azimuth, long-offset data in two orthogonal passes (Mandroux, 2013). The innovative configuration, known as 'StagSeis', maintains the advantages of a linear tow as it provides consistent azimuth, fold and offset distribution, and the linear tow means that processing is compatible with conventional wide-azimuth techniques. It can also be combined with continuous recording techniques, allowing for longer record lengths by overlapping successive shot records, so that data from the preceding shot are recorded through the water column of the next shot. This allows either denser shot spacing or longer records to be recorded, which is especially useful in deepwater areas.

The StagSeis IBALT (Integrated BroadSeis Acquisition and Long Tow) multi-client survey, in the Keathley Canyon area of the Gulf of Mexico, was acquired with this technique, which was initially developed to address the challenge of illuminating complex geologies where conventional wide-azimuth acquisition fails. In the comparison at the top of the next page the improved continuity of events and greater illumination beneath the salt are clearly visible.

This colour blend 3D visualisation of 2.5 Hz, 8 Hz and 15 Hz dominant frequencies, taken from data obtained in Block 22, Kwanza Basin in Angola, shows the advantages of the wide range of frequencies obtained in a broadband survey. The Upper Miocene channel systems and surrounding salt bodies are highlighted, but without the ultra-low frequencies the red channel would not be visible.

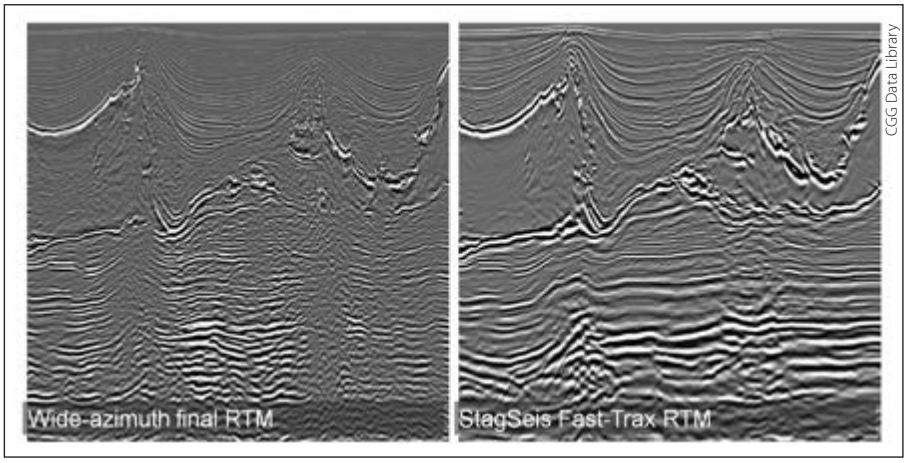


Low Frequencies for FWI

The low frequencies obtained through broadband acquisition are also crucial for Full Waveform Inversion (FWI) of towed-streamer data, a technique which is gaining popularity for velocity model building, as demonstrated in the North Sea by Jupp et al. (2012).

In the IBALT study, combining low frequencies with the full azimuths and long offsets of StagSeis proved ideal for determining the velocities of the complex overburden. This can be seen in the figure below, where a comparison of the FWI updated model using the full-azimuth data with the initial model after three iterations of tomographic updates clearly demonstrates spectacular correlation between the velocity after FWI and the migrated image (Mothi, 2013). The success of the initial IBALT study has led to the commencement of two major extensions of the survey.

The flexibility of this staggered acquisition geometry makes it ideally suited to other complex geological settings. It is already being considered offshore Brazil and Angola and is being evaluated, using shorter offsets, for the challenging geology of the Red Sea.

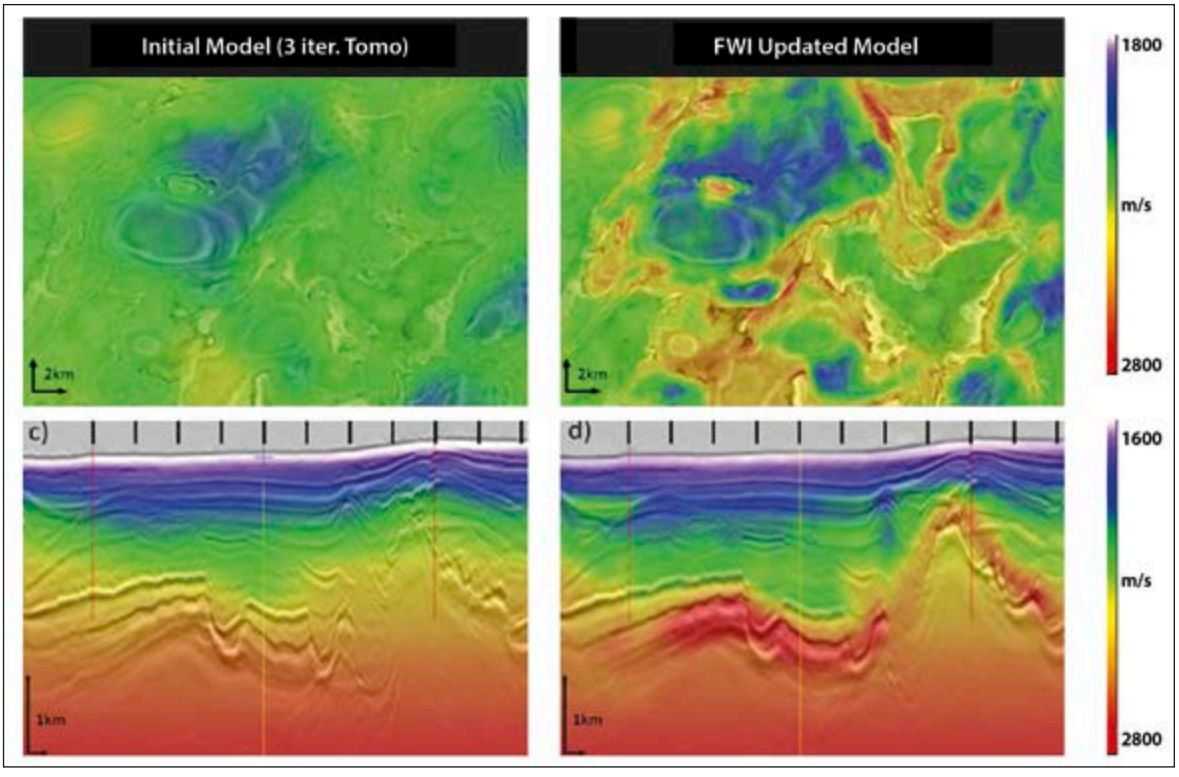


In areas of complex geology, such as subsalt and sub-basalt, illumination is a problem, which can be overcome by the use of full azimuths and long offsets in addition to broad bandwidths. This image from the IBALT survey in the Gulf of Mexico compares data acquired with StagSeis versus conventional wide-azimuth acquisition and shows a staggering improvement in subsalt illumination.

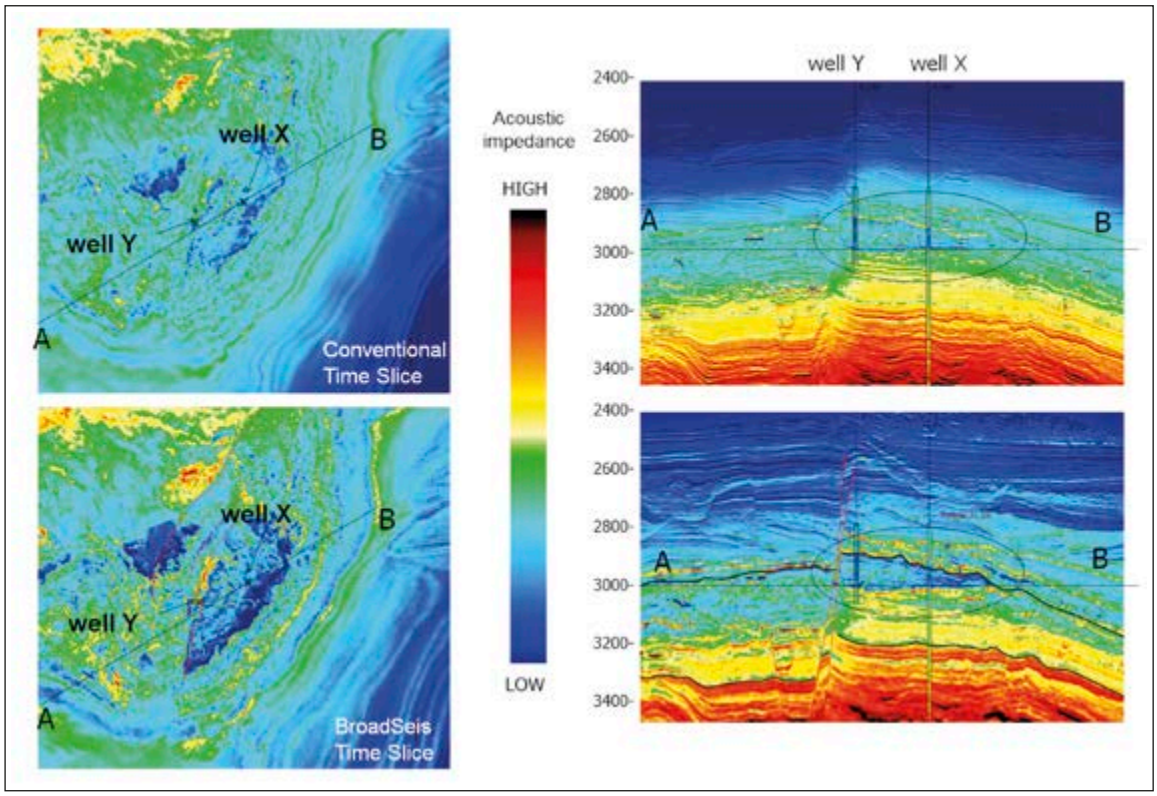
Filling the Gap

Broadband data provide significant benefits for seismic inversion workflows, especially in terms of low-frequency bandwidth extension. The lack of low frequencies in conventional seismic data means that a low-frequency model must be incorporated in the inversion process in order to recover absolute impedance values. Usually, this low-frequency information is obtained by interpolating low-passed filtered impedance logs between well locations, using interpreted horizons as a guide. If the wells are sparse and the geology complex, the low-frequency model derived from the wells may be inaccurate and tends to yield results that are biased towards the initial model.

NMO-derived seismic velocities are often used to define the initial low frequency model, which provides information at the very low frequency range, from ~0 Hz to 4 Hz, while conventional seismic covers the frequencies from around 10 Hz and



This example from the StagSeis IBALT survey demonstrates that BroadSeis ultra-low frequencies are ideal for FWI to deliver accurate velocity models.



In this post-stack acoustic inversion of data obtained in Brazil's Santos Basin, the BroadSeis inversion shows greater dynamic range, more realistic correlation with geology and a better match with the blind well (Y). There is a clear wedge visible on the BroadSeis data.

upward, meaning that the frequencies in the range of 4–10 Hz are missing. The ultra-low frequencies provided by BroadSeis fill in this gap, enabling inversion to be performed using only the seismic velocities, without needing a log-derived low-frequency model, to yield accurate impedance and Vp/Vs estimates, even where there is little or no available well data.

In the example shown above, the inversion was performed using a model based on Well X and the seismic velocity information; Well Y was used as a blind test to validate the results after inversion had been performed (Kneller, 2013). The extended bandwidth provided significantly improved and more geologically realistic inversion results over the conventional data, with greater dynamic range, and clearly defined faults as well as a much better tie to the blind Well Y.

On the other side of the Atlantic, in the Kwanza Basin offshore Angola, turbidite channels and good-quality reservoir sands can potentially be trapped around or beneath salt-related structures, so it is important to track these channels accurately. Broadband seismic data brings a new level of understanding to the mapping of these facies, as by using the full spectrum of frequencies (from 2.5 Hz to 125 Hz) it is easy to highlight greater details of the turbidite facies distribution. The image on page 32 shows an example of 3D frequency decomposition and colour blend from the Block 22 Kwanza Basin broadband dataset, where a turbidite channel complex is clearly visible, with various phases of sediment fill, meander growth and incisions. Without the ultra-low frequencies this picture would be incomplete as the channel highlighted in red would not be discernable. This kind of information is key to tracking reservoir sands around potential traps provided by salt structures, ultimately potentially aiding the discovery of further oil reserves in West Africa.

Better Models and Plans

Broadband seismic is increasingly proving its value at all stages of the exploration and production cycle. The broad bandwidth, including low-noise low frequencies, provides wavelets without sidelobes so that events become single peaks or troughs, corresponding to genuine geological layers and are closer to the genuine seismic signature of formation interfaces. This clarifies impedance contrasts to create sharp images of small features and clear differentiation between sedimentary packages for accurate delineation of the reservoir. Ultra-low frequencies deliver more detailed facies discrimination, more quantitative seismic inversion results and therefore more reliable lithology predictions away from existing wells. This leads to more accurate reservoir models and better development plans. Once production is under way the benefits of broadband for 3D surveys are extended into 4D monitoring to provide better dynamic reservoir models to maximise hydrocarbon recovery.

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Defining Shale Potential in The Netherlands

J.LUTGERT, EBN;
R.GREISS, C.HUGHES, S.LARGE, NuTech Energy

A recent study assesses the unconventional plays and bypassed conventional pay in The Netherlands

The Netherlands is a long-established petroleum economy, having successfully produced oil and gas both onshore and offshore for over sixty years. In common with other established hydrocarbon markets, the producing fields of The Netherlands are mature and many are in a state of declining production. The Dutch government, together with the state oil company, EBN, and the geological survey, TNO, have been charting the decline in hydrocarbon production in The Netherlands, as the many mature fields reach the end of their productive life, and the graph shows a worrying trend towards ever-increasing reliance on imports.

EBN has therefore taken the decision to commission a series of studies to assess what measures can be taken to arrest this decline.

The Netherlands has always adopted a proactive approach to the domestic hydrocarbon industry, as witnessed by the involvement of the state oil company, EBN. It maintains a significant stake-holding in nearly every licensed field both onshore and offshore, acting for and on behalf of the Dutch government, in a non-operating capacity, but involved both technically and commercially in exploration and production requirements in the licence.

The Dutch geological survey, TNO, are also more actively involved in the hydrocarbon business than some of their other EU counterparts. The management of the country's released data archive is central to the ease with which oil companies have been able to explore and license acreage. Fifteen years ago, TNO took the decision to design their own online repository for released seismic and well data, which it also maintains. NLOG (www.nlog.nl) contains a full digital archive of all available data associated with wells and seismic surveys, which is free for anyone to download and use – a factor that has greatly benefitted all operators and contractors working in The Netherlands.

When considering what could be done to halt the decline in production, one of the first areas of assessment was the potential for unconventional resource play development. The Dutch government has neither permitted nor banned unconventional hydrocarbon exploration and production, or the controversial stimulation technique of hydraulic fracturing, or fracking. In an effort to understand better the potential for such play development, and whether the country actually had a shale play that might be a 'game-changer', EBN has commissioned various studies to be undertaken to determine this. These have looked at the geology of the source rocks in The Netherlands in comparison with other mature shale plays in the US, and have also assessed and addressed the environmental impacts as well as the economic benefits of developing such plays. To enhance their own investigations they engaged the services of the US Reservoir Intelligence specialists, NuTech.

Pioneer in Shales

NuTech has been in the shale business ever since there was a shale business. The company was founded by former executives of Numar, a specialist in Magnetic Resonance Imaging (MRI) tool design. NuTech took their understanding of how MRI tools read in various matrix conditions in relation to how other triple-combo logging tools responded in the same conditions, and applied this knowledge to the conventional log data in order to reproduce the response of an MRI tool.

The resultant effect provided NuTech with a unique petrophysical log analysis service capable of accurately measuring very fine porosity, thereby determining clays, silts, sands, and other mineralogy within the rock matrix, as well as determining free and bound fluids within the pore space. This 'textural' approach to petrophysics gave NuTech a unique advantage and the company was soon being sought out to provide their specialised analytical services for use in bypassed pay identification in the US Gulf of Mexico offshore market, which was at the same stage

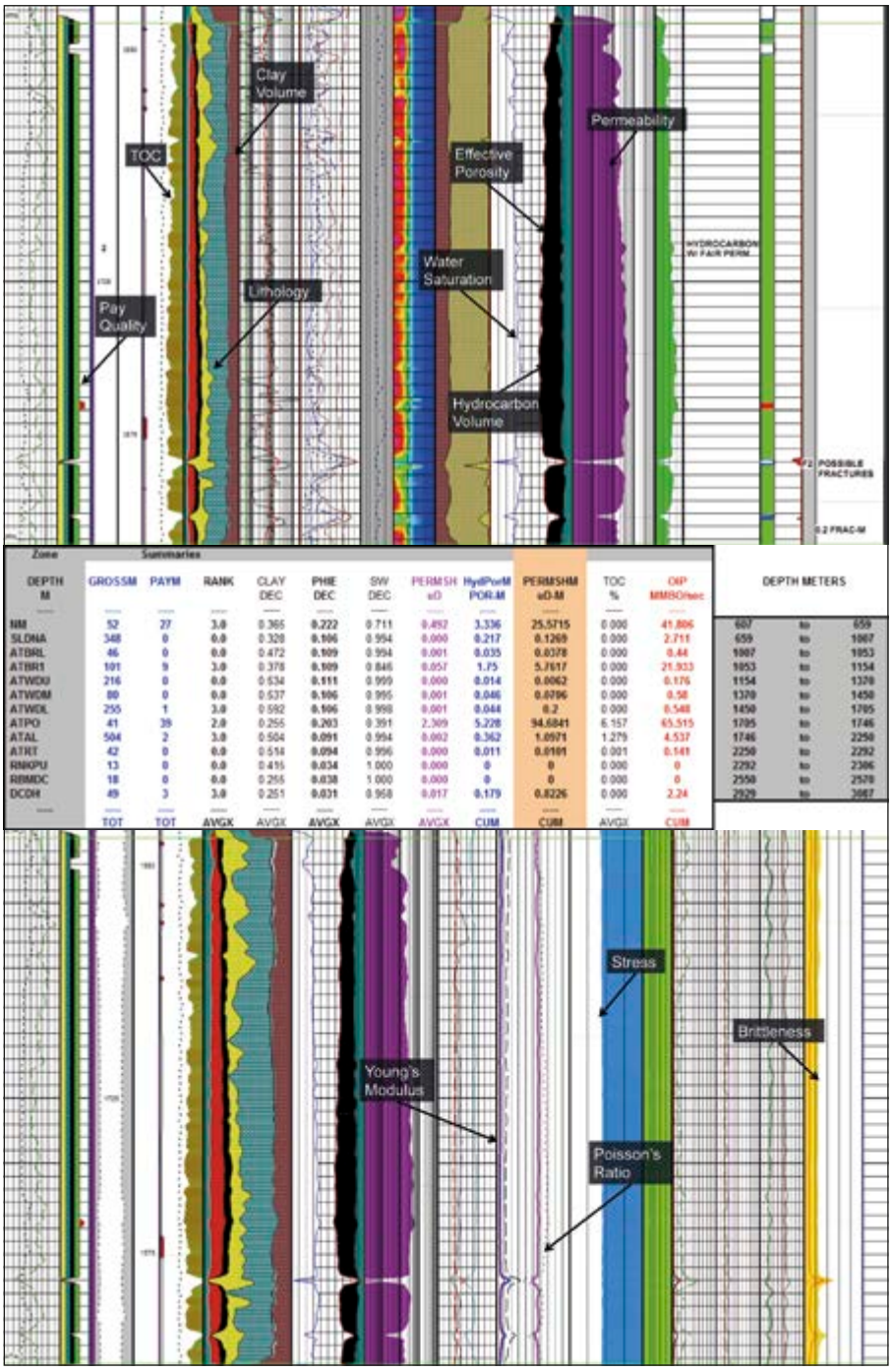

Bruce Winslade

of maturity and declining production fifteen years ago as the North Sea is now.

NuTech's ability to measure fine-grained porosity and to accurately determine permeability in tight rocks and complex formations led to the company coming to the attention of the early pioneers in the unconventional market and over the last twelve years the company has been involved in the discovery and proving of every shale play in North America.

Their approach gave oil companies the ability to explore through the effective use of datasets pulled from the archive to analyse play potential, rather than the more expensive approach of exploring with the drill bit. They set about reassessing significant volumes of legacy wells, whose original targets had been conventional pay in sandstone reservoirs, but whose drilled depth and logged data penetrated the shale source rocks. Taking a representative sample of suitable wells over the entire extent of a basin, and assessing both the log data and rock material (drill core and cuttings), they were able to provide detailed reservoir and completion parameters from this combined approach of petrophysical and rock properties analysis, all before the drilling of a single new well. The resulting parameters for each analysed well – porosity, permeability, Vclay, TOC, Ro, OIIP / GIIP, etc. – were then able to be mapped over the extent of the basin, and so determine the 'sweet spots' of the shale play, which determined where best to lease or license, and where best to drill.

This Reservoir Intelligence approach – the technical quantification and commercial qualification of unconventional plays – has been built into an impressive set of regional field studies covering the entire extent of North American shale plays, incorporating NuTech's history of work in petrophysics, core analysis, basin-wide property mapping, reservoir modelling, completions design and production optimisation.



NuTech

NuTech well log analysis results showing petrophysical and geomechanical properties for the shale sequences.

The Netherlands Study

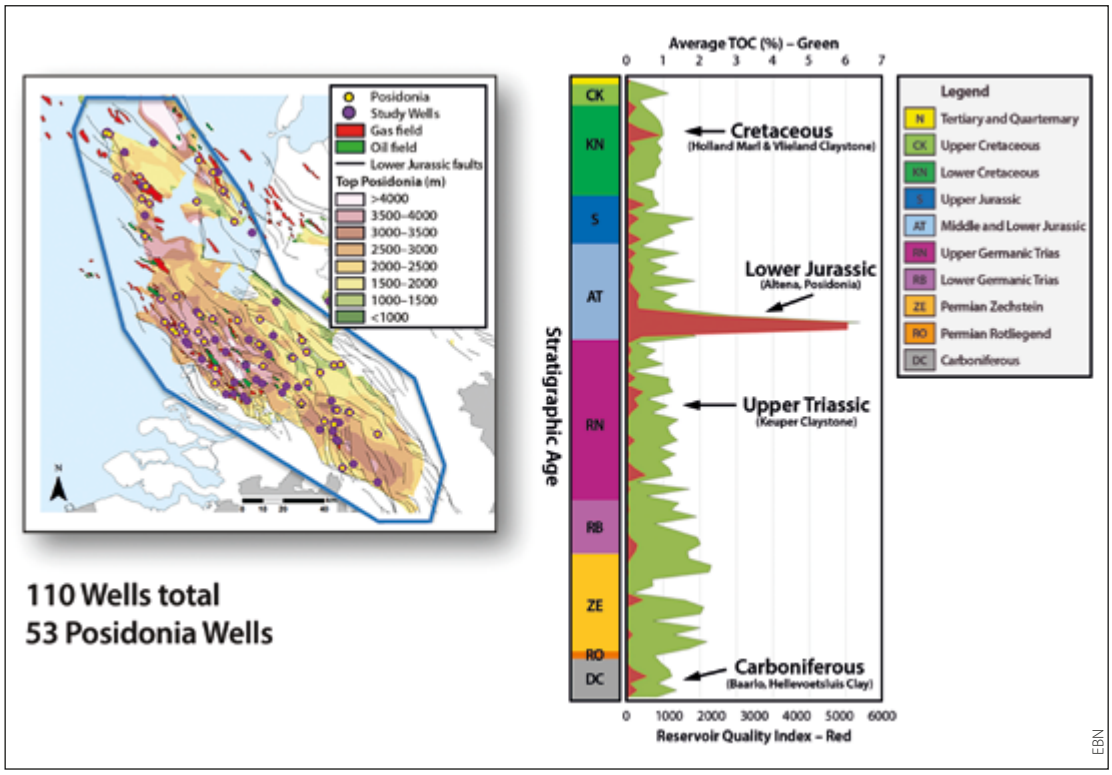
With this background in providing technical appraisal solutions for both problematic conventional and unconventional play development, NuTech was the obvious choice for EBN when tasked with the job of defining the potential for shale play development in The Netherlands.

After an initial pilot project, the geographic and technical scope of work for The Netherlands study was agreed. Geographically it would look at a series of legacy well data sets over the West Netherlands Basin (both its onshore and offshore extents) and the Geverik Member onshore in the North. The two main technical objectives were, firstly, to identify and analyse the shale play opportunities in unconventional reservoirs of the Lower Jurassic Posidonia Formation and the Namurian Geverik Member as well as other shale and marl sections in the area; and secondly, to identify bypassed hydrocarbon opportunities in conventional reservoir sections throughout both the onshore and

offshore sections of these geological basins. As such, a full Total Depth (TD) analysis was agreed for each selected well.

The decision to address both onshore and offshore wells for the study was an interesting one, and one of the first times such an assessment has been undertaken for a shale play. The geological complexity of the West Netherlands Basin and the limited pool of wells with sufficient data for analysis was one of the primary factors governing this decision. While actual development of shale plays from offshore locations is perhaps not yet a viable commercial proposition, the inclusion of bypassed pay analysis in the study, and the fact that many of the offshore fields are declining and facing decisions of abandonment and rig decommissioning, meant that more sound economic judgements could be made in this respect, weighing up the full picture of hydrocarbon potential left to be developed before approving a request to shut down a field.

Only eight wells address the Geverik Member, although there is some recent core material. More legacy data exists for the Posidonia Shale in vintage wells drilled from the 1960s–90s. A limited number of onshore wells contain core and cuttings but very few of the offshore wells do. Similarly, of the 160 or so wells for which the available logs were reviewed, a number did not penetrate the Posidonia shale, or were not logged over the shale, or did not contain a complete enough suite of logs for full analysis. However, in keeping with NuTech's equivalent US studies, sufficient legacy rock and log data was available to determine petrophysical and rock mechanical properties, and to map these characteristics for the Posidonia shale on a regional basis.



Posidonia Shale study of the West Netherlands Basin.

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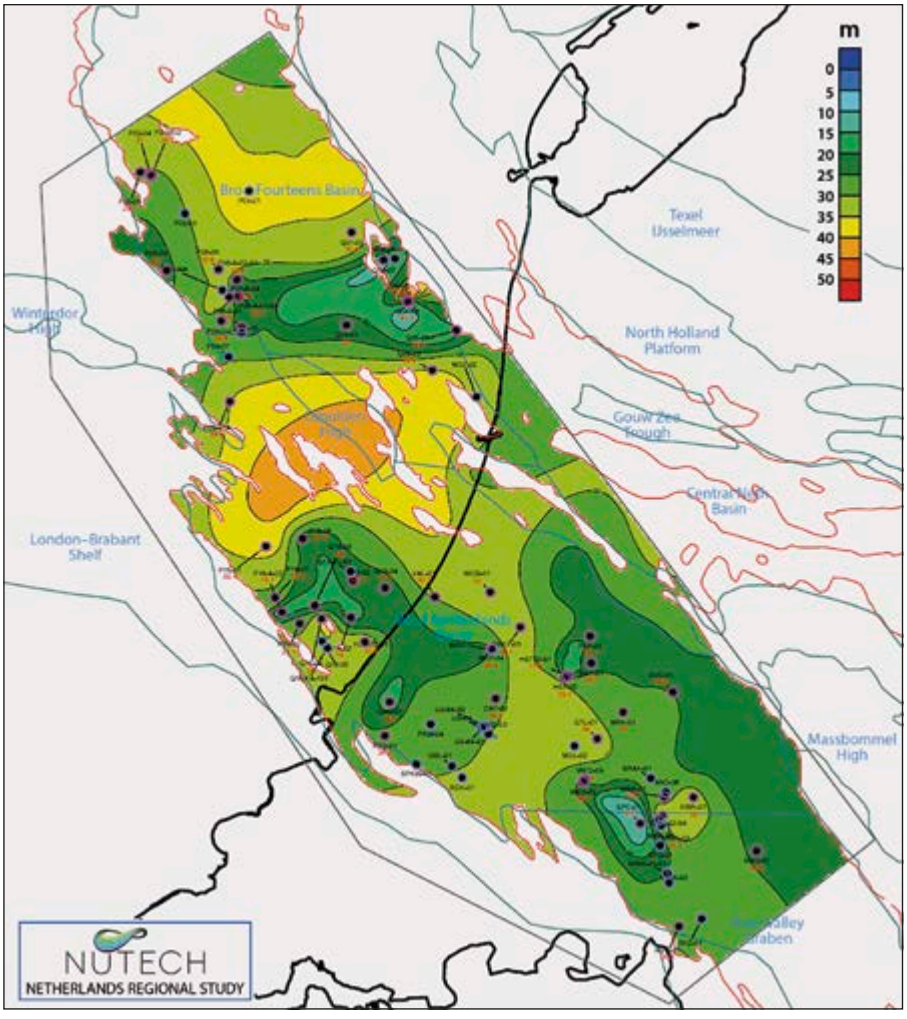
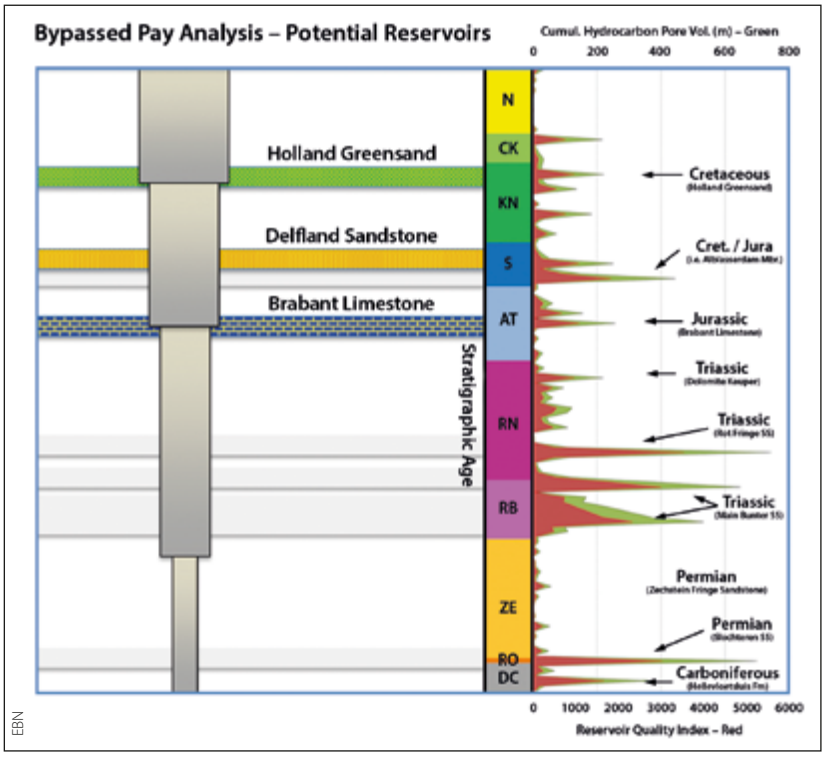


What Next?

The next steps in proving economic viability of the Posidonia, in what is structurally a highly complex part of The Netherlands, will focus on improving the understanding of geographical variations in formation thickness, reservoir quality and spatial continuity. To achieve this aim, full reservoir modelling of the basin, incorporating geological structure and faulting from the available seismic data, will be undertaken to help develop an improved understanding of the petroleum systems and assist guidance towards formation sweet-spots. However, additional vertical wells will undoubtedly need to be drilled to capture more log and core data.

The study reviewed each selected well to TD, mapping the key shale characteristics on a regional basis, but taking account of all conventional reservoir opportunities – both those produced or still producing, and those deemed to have been missed. As a partner in every well reviewed, EBN were in a perfect position to determine which of the identified and viable conventional reservoir sections had been produced, and which had not. Of the latter category of so-called bypassed pay elements, three stood out – the Holland Greensand, the Delfland Sandstone, and the most prospective of all, the Brabant Limestone. Of significant interest is the fact that the Brabant Limestone extends into the UK Southern Gas Basin where it is known as the Cornbrash, and where too it is understood that completions and production have been limited to date. ■

Conventional producing reservoirs in The Netherlands and those identified as showing potential for bypassed pay.



Responsible Resource Development

Gas development of the Haynesville Shale Play prompted a local state university, Louisiana's officials, and natural gas operators to take a transdisciplinary approach to solve the area's water use problems, which could be used as a model for the industry.

GARY M. HANSON

The rapid development of unconventional resource plays throughout numerous geographical areas of the United States have one thing in common: they all are associated with the use of significant amounts of fresh water , although recycling is increasing. Unconventional natural gas resource plays either need water for development, as is the case for tight gas sands, shale gas and tight oil, or require water to be withdrawn to facilitate the development, as is the case for coal-bed methane.

Water Use Issues

The Barnett Shale Play in north-central Texas has been undergoing development for over ten years. Over 19,000 wells have been drilled and this trend is expected to continue for decades. Operators in the Marcellus Shale Play (New York and Pennsylvania) are being confronted with severe restrictions on available water for hydraulic fracturing and the lack of facilities to treat or dispose of contaminated flow-back water.

The sources for the New York City reservoir system are three large watersheds that are underlain by the Marcellus Shale. New York has banned hydraulic fracturing while they continue to study this commonly used and historically safe method for stimulating shale formations. In addition, many of the communities in the path of this development have never experienced natural gas drilling and development activities. Residents are concerned that their water resources will be negatively

Aerial view of the LSU Shreveport Campus and Red River Education and Research Park in Louisiana, backed by the Red River with classic meanders and oxbow lakes.

Gary Hanson

impacted by contamination and excessive withdrawal of groundwater or excessive use of surface water. Their lack of industry knowledge and the overriding presence of many new operators are presenting significant challenges to natural gas development.

By comparison, tight gas sands in the North Louisiana-East Texas Upper Gulf Coast Basin have been exploited with vertical wells and single stage hydraulic fracturing wells for decades. The Haynesville Shale Play of northern Louisiana and eastern Texas developed very rapidly from 2008 through 2012; over 2,500 wells have been drilled in this play with over 2,200 producing in Louisiana alone. Now accounting for over 60% of Louisiana's gas production and with very high initial production rates up to 30 Mcfgpd, the Haynesville Shale is one of the richest gas plays to date.

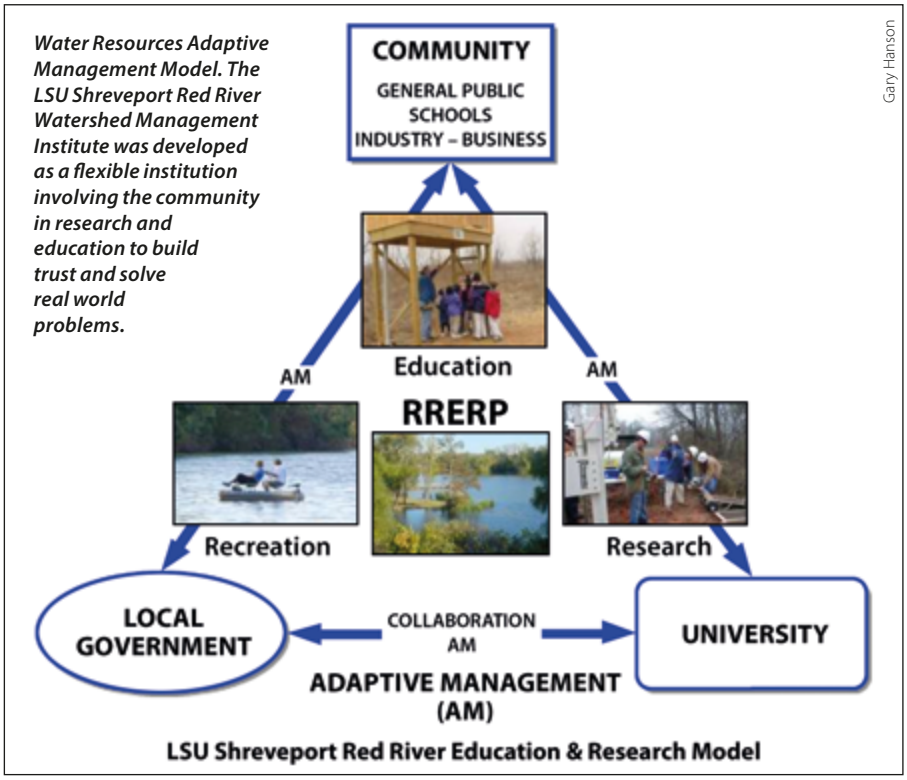
A Wake-up Call

Early in the Haynesville Shale development, significant water use issues surfaced, and the gas industry encountered a public that was aware of existing groundwater problems associated with gas production. Prior to the start of the Haynesville Shale development, the Red River Watershed Management Institute at Louisiana State University Shreveport and Caddo Parish jointly developed a groundwater monitoring well programme. In addition, the Water Resources Committee of Northwest Louisiana was established to address water issues and would later spawn a water energy working group at the university.

With rapid shale gas development came large numbers of groundwater wells to provide water for drilling and fracking operations. Early data from the groundwater monitoring project showed that the local Carrizo-Wilcox Aquifer was not capable of producing sufficient water for all the users involved. For all of this development to continue, changes in water use had to be made.

This new data was important to operators in the area in that they could see the aquifer was being negatively impacted near their gas development and started looking for alternative sources of water. The working group quickly concluded that they needed access to non-potable and underutilised surface waters to continue development operations. The Red River, its underlying Red River alluvial aquifer, and treated wastewater from a paper mill were the obvious choices. The group convened numerous meetings to iron out the many issues facing them.

Having participants such as groundwater and surface water hydrologists, water resource managers and levee board representatives, in addition to the technical oil and gas disciplines (petroleum geologists and engineers) made this truly trandisciplinary and non-statutory approach enjoyable and fruitful.



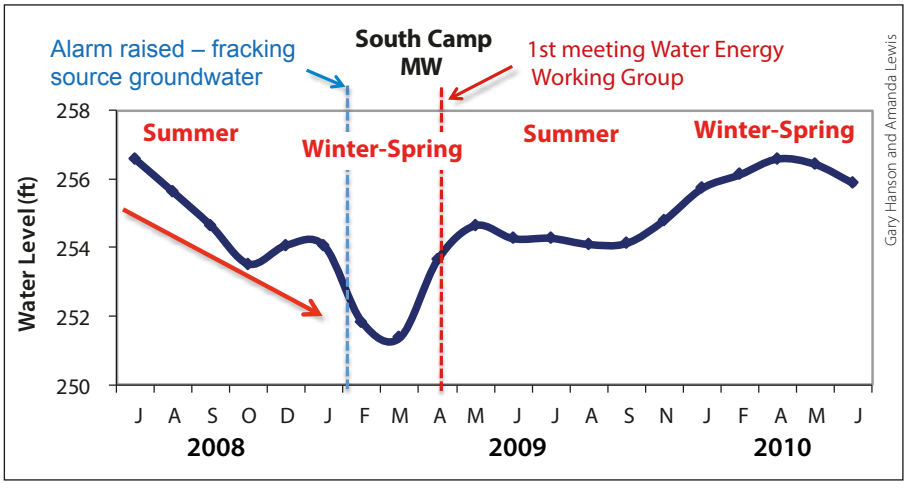
Water Resources Adaptive Management Model. The LSU Shreveport Red River Watershed Management Institute was developed as a flexible institution involving the community in research and education to build trust and solve real world problems.

Gary Hanson

Developing a Water-Energy Model

Two critical natural resources, energy and water, are key ingredients for a healthy and secure economy in any country today. These resources are linked closely, as the production of energy requires significant quantities of water to be sustainable and the distribution of large quantities of clean water are dependent on low cost energy.

Data collected by the Red River Watershed Management Institute from the area's main aquifer showed a sharp drop in water levels near Haynesville Shale development. Gas companies recognised the problem and quickly adjusted to using more abundant surface water for drilling and fracking operations.



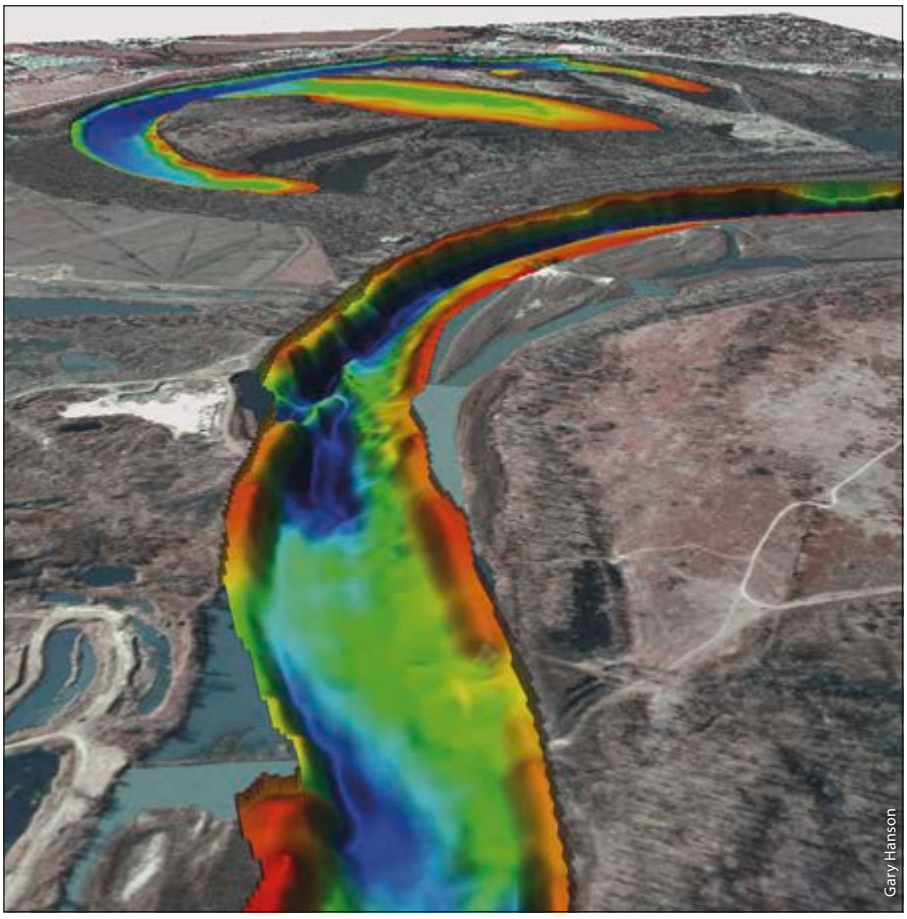
Gary Hanson and Amanda Lewis

This is the 'energy-water nexus' that is being challenged by a growing number of issues. Add to this food supplies; the challenges at a global level have been there for some time but are now becoming increasingly urgent.

With drought conditions and increased demand making water deliverability to the various users in north-west Louisiana problematic, more cooperation between multiple agencies and disciplines becomes a must. As the Red River alluvial aquifer has a shared use between farmers and natural gas operators, the shallow and deep groundwater monitoring wells are providing key data to all the users. Shell Oil is funding research for the Red River Water Management Institute, bringing in Sci-Port-Louisiana's Science Center, and supporting interns from nearby Bossier Parish Community College to work at the LSU-Shreveport Red River Education and Research Park.

The water-energy-food security nexus will have an effect on all users. Currently, the amount of groundwater and surface water used for the Haynesville Shale Play is only a minor portion of the water budget in most regions. However, during droughts and in arid or semiarid areas, this is not the case. When developing the north Louisiana model for water use and distribution, participants have worked with socio-economic, political, internal industry and agricultural policies to lay out a plan. However, implementing this plan on the ground over time is much harder.

Keeping the water-energy security nexus efforts stable requires continuing efforts from all parties. In the highly competitive oil and gas industry changes in gas prices bring changes in company strategies; for example, when gas prices dropped, operators left the gas-rich Haynesville Shale Play for the liquids-rich plays such as the Eagle Ford in South Texas. Now, with gas prices creeping higher, new operators are moving back to the Haynesville area and are attempting to use groundwater again. It is important that the industry lives up to the agreements that have been worked out over several years and hundreds of hours of effort.



Multibeam sonar images of the Red River area, showing bathymetry of the river (foreground) and Red River Education and Research Park oxbow lake (background). Hot colours represent shallow water and cool colours the deep water. These are some of the shallowest multibeam sonar images ever recorded.

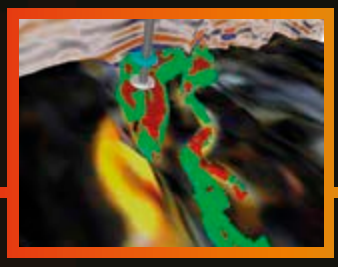
Solving the Problem

There is a need for technical experts and governing bodies to stretch beyond their normal work environment in order to solve these difficult problems. As this relates to the water and energy nexus, the problem to be solved may not, at first, be realised as a common one. At the beginning of the working sessions, no one had the answers to tough real world problems that had to be solved. They started with technical oil and gas people sitting across the table from regulators with practically no knowledge of the petroleum industry but who had the power to determine if wells were going to be drilled or not. Vulnerabilities surfaced, preconceived ideas were neutralised, and internal politics were kept out of discussions. The result was education for all; participants could solve some problems right on the spot while other problems would take more time to solve with additional agencies or

Gary M. Hanson

serves as Director of the Red River Watershed Management Institute at LSU Shreveport and holds the position of Hydrologist in Residence. With over 35 years of experience as a geologist, manager and partner in the oil and gas industry, as well as a hydrogeologist and district manager in the environmental industry, he is a consultant for both energy and environmental policy.

Here for the energy hunters, risk investigators and decision makers.



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Haynesville operators acted quickly with voluntary changes in water usage. Through public outreach and education, this area has not experienced negative backlash associated with the development of tight hydrocarbon resources. Using only an 11 acre (4.5 ha) drill pad, drilling and fracking of a previously drilled well can occur simultaneously – well spacing varies from 45 to 75ft (14 to 23m). Using horizontal drilling techniques minimises landscape impact. With this small pad, multiple wellbores can reach into four sections (2,560 acres, 1,036 ha) in the deep subsurface.

experts to be consulted.

The lack of potable water world-wide is becoming a reality. As the population increases and industry grows, more water will certainly have to be made available and all users will have to become more efficient with its use. In the US, shale gas and tight oil plays have become a catalyst to convince the public that water is a topic that can no longer be ignored. This certainly was the case in Louisiana as the arrival of the Haynesville Shale Play made officials take a hard look to find ways to solve the area's water problems. The actions taken in north Louisiana regarding the energy and water nexus can and should be used as an example for others to follow. Above all, it is absolutely critical that transdisciplinary approaches be taken for the world to maintain secure supplies of energy, water and food.

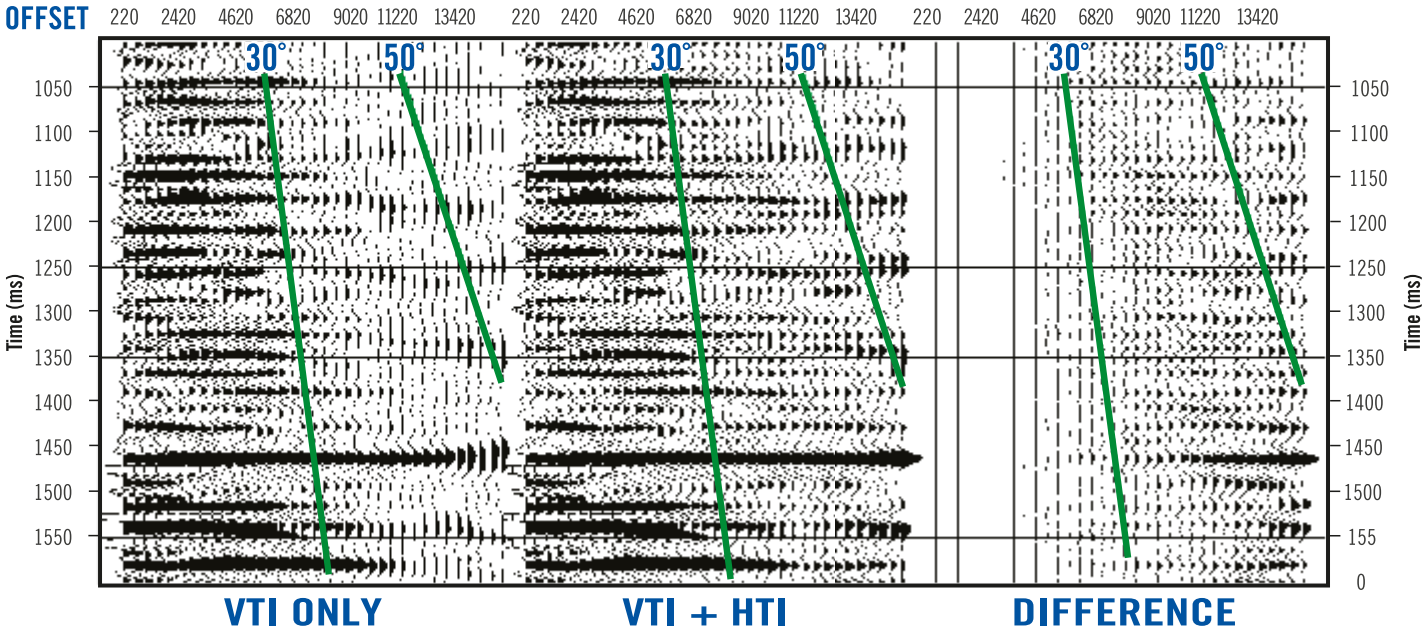
When it comes to lessons learned, unconventional resource play operators must become familiar with the state or local water issues and usage regulation prior to the start of their operation. It is a very good idea to initiate contact at the outset with local, county/parish, and state agencies to develop a rapport and mutual understanding of proposed operations. Finally, do not underestimate the concerns (perceived or real) of local citizens when it comes to the use and protection of 'their' water. Concern about water issues continues to permeate all discussions (whether water related or not) with local government and citizens in the Haynesville Shale Play. Exploration and production management must realise that water issues have to be addressed as a priority early on in any unconventional resource play.

Acknowledgements:

The author would like to acknowledge the following organisations and individuals:

Amanda Lewis, Dillon Soderstrom, Dr. Vincent Marsala and Dr. Paul Sisson, LSU Shreveport; Dr. Woodrow Wilson, Caddo Parish Commission; Ken Guidry, Red River Waterway Commission; Jim Welsh, Louisiana Office of Conservation; Nancy O'Toole, Shell Oil; Dr. John Russin and Dr. Patrick Colyer, LSU AgCenter; Dr. Van Brahana, University of Arkansas; Brandon Calhoun, Chesapeake; EnCana; Ben Warden, Conoco-Phillips; Mark Henkhaus, Apache Corp.; US Corps of Engineers; US Fish & Wildlife Service and USEPA. ■

is ANISOTROPY a PAIN in your ATTRIBUTES?



INVERSION READY GATHERS

Azimuthal velocity variations in the earth, characterized as HTI anisotropy, manifest as small shot-receiver, azimuth related timing distortions in 3D seismic data, especially on the higher (>30 degree) angular offsets. If not properly corrected for during imaging, these timing distortions adversely affect bandwidth and amplitudes when summing the migrated data into final offset traces. This far-angle bandwidth and amplitude distortion in the final migrated offset gathers negatively impacts pre-stack inversion and the accurate creation of rock property attributes.

The solution is to process the data in an offset and azimuthally friendly manner, incorporating both VTI and HTI anisotropy into the pre-stack time migration imaging step. Our patented technology produces offset and azimuth amplitude preserved final gathers, which are flat in both offset and azimuth out to 50 degrees of angular offset. We affectionately refer to these as "Inversion Ready Gathers."

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The Oil Industry Volunteer

Csilla Tunde Fabian and Niamh Mary Monaghan are committee members of the Aberdeen Formation Evaluation Society

The goal of the Aberdeen Formation Evaluation Society (AFES), the local branch of the Society of Petrophysicists and Well Log Analysts, is primarily educational with the aim of promoting formation evaluation in Aberdeen, the oil capital of Europe, and to provide support to the many education facilities, from universities to schools, located in Scotland. In order to achieve this, it holds regular lectures and seminars and is a partner of the DEVEX Conference committee. It has over 500 members and a committee of 18 volunteers.

The AFES committee is made up of a lot of people who are very generous with their time, supporting the running of the society in a variety of roles from President to Treasurer, website manager, seminar and lecture organisers. As committee members we attend lectures and seminars, regular monthly committee meetings and help with the planning of various events and in the funding sponsorship decisions. We have both been members of the DEVEX Young Professional Committee to promote and encourage young people within the oil and gas industry. We are currently organising the first Annual AFES Hogroast – if you plan to be in Aberdeen June 2014 check our website for details (www.afes.org.uk).

Sponsorship Role

We have wonderful sponsors, including operators and service companies. Through their support, and through the efforts of the committee running various seminars and our DEVEX partnership, we are able to maintain our status as a free society, while still being able to provide funding.

Niamh is also a member of AFES' subcommittee for funding, helping with student sponsorship allocations. The majority of funding goes to MSc and PhD students involved in formation evaluation at Robert Gordon, Aberdeen and Heriot Watt universities. We actively encourage students who receive AFES funding to present their work to the evaluation community through presentations and poster contributions at the regular AFES seminars and evening lectures. This is a fantastic opportunity for students to get feedback from the large network of experts, while getting to know them in a relaxed, open environment, and is brilliant for those experts to see how petrophysics and formation evaluation is progressing in academia. AFES also gives support by providing funding for equipment, recently having donated money for a new optical microscope at the University of Aberdeen, and donating money towards Geobus, a free educational outreach project for schools developed and run by the University of St Andrews.

In addition to student sponsorship, we support the ARCHIE Foundation, a local charity that raises money for Aberdeen's Children's Hospital. One of the AFES year's highlights, the annual Christmas Quiz night, has helped to provide over £16,000 for this fantastic cause.

Being a member of the AFES committee has been a wonderful experience for both of us, as it provides the opportunity to interact with other petrophysicists and formation evaluation experts in Aberdeen. It is a fantastic place to build professional network connections and make lots of friends in the process. We would certainly recommend being a member of this or a similar committee to anyone who is interested. ■

Csilla works for Nexen Petroleum U.K. Ltd as an IS Business Applications Support Analyst on a wide range of projects, based in Aberdeen. Originally from Hungary but now British, she came to the UK in 2001, and has been in Aberdeen since 2007, having previously lived in Leeds. She enjoys hillwalking, running, Nordic skiing and sailing and in her spare time she enjoys travelling and exploring the world. Csilla has also completed a RYA Yachtmaster course from the Royal Yachting Association. She aims to complete further part-time education courses in the near future.

Niamh works for Baker Hughes Reservoir Development Services, the consulting branch of Baker Hughes, as a petrophysicist on a number of multi-discipline and independent projects globally and in the North Sea. Niamh is Irish and has been living in Aberdeen since 2012, having previously lived in Norway. She spends a lot of her free time coaching and playing touch rugby.

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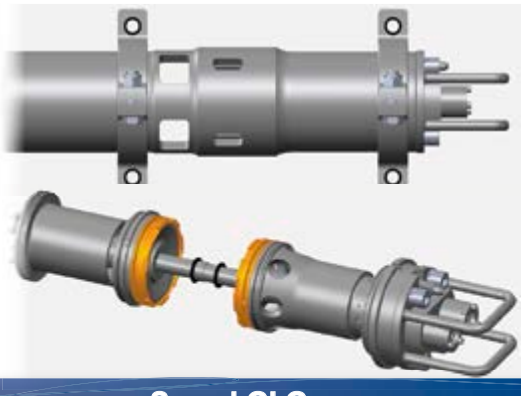

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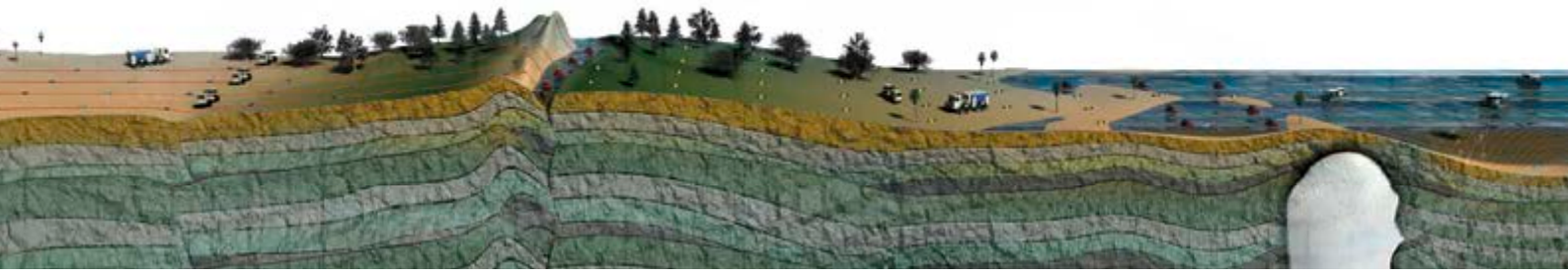

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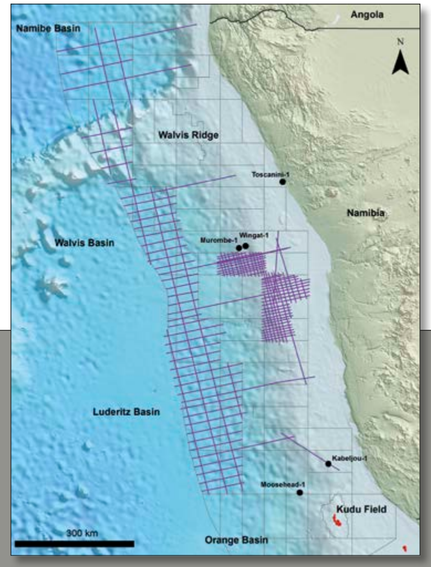
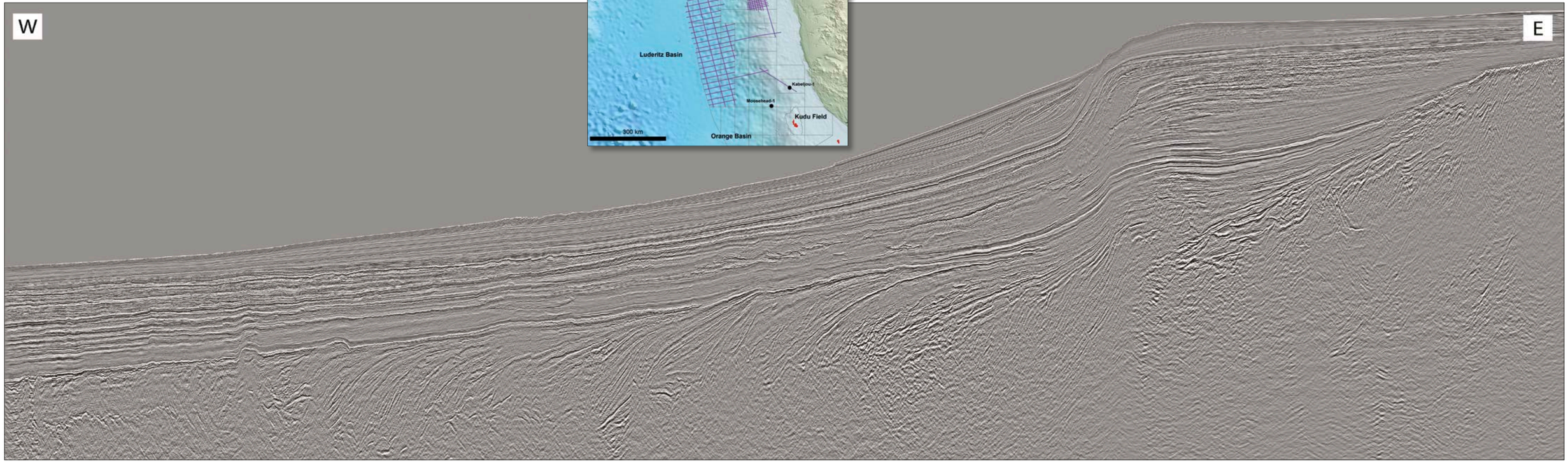
Namibia:
Frontier Exploration in West Africa



Survey area of the 2012 and 2013 PGS multiclient 2D Namibia acquisition programme.

As West Africa continues to be one of the major petroleum producing regions of the world, oil companies have been looking to the southern part of this area, offshore Namibia, to predict whether such success can be continued. PGS, in cooperation with the Ministry of Mines and Energy and NAMCOR, have acquired 15,000 line kilometres of 2D GeoStreamer® with GeoSource™ broadband seismic data over this area. As a result, this dataset now provides new insights into the possible petroleum systems and the geological structure of this exciting frontier margin.

Pre-Stack Time Migration (PSTM) GeoStreamer with GeoSource seismic line covering 320 line km offshore Namibia. Orientation is west–east and the line is 320 km in length.



Hydrocarbon Potential of Offshore Namibia

PAT COOLE and CRAIG KOCH, Petroleum Geo-Services (PGS)

In 2012 and 2013, PGS shot approximately 15,000 line km of broadband seismic data in the deep and shallow waters offshore Namibia, with a view to enhancing geological understanding of the margin and de-risking exploration in this frontier part of West Africa.

Frontier basins of West Africa have experienced a growing demand for high quality seismic data in a regional context in order to de-risk exploration. Deepwater basins offshore Namibia appear increasingly promising and recent wells drilled by Petrobras, HRT and Chariot have confirmed the elements of a working petroleum system for the first time. More wells and continued seismic acquisition are planned for 2014 and the area is set to have an exciting future.

De-Risking Exploration

To date, exploration offshore Namibia has been rather limited. Along a margin with an area covering 670,000 km^2, only 12 wildcat wells have been drilled. In the last few years, however, a renewed drilling campaign has resulted in a suite of modern seismic and several dry wells. The information gained from these drilling programmes has improved knowledge of the area substantially and has provided key insights into the working petroleum system. The wells which have provided the greatest insights were the Kabeljou-1, Moosehead-1, Murombe-1 and Wingat-1.

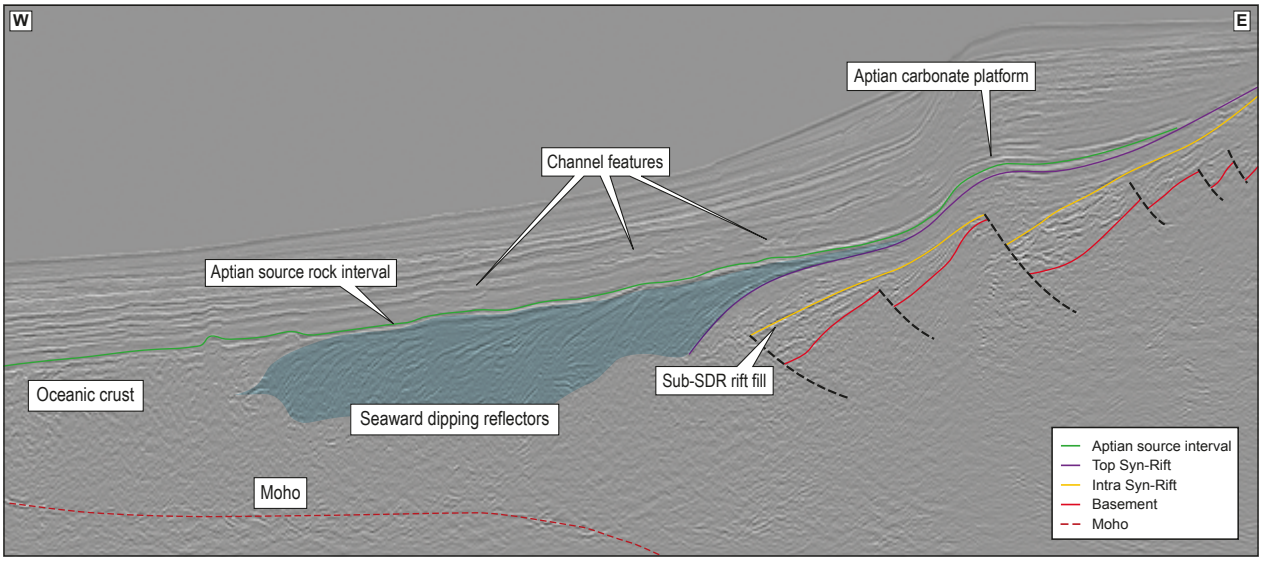
To better understand the petroleum systems of offshore Namibia, PGS in association with NAMCOR, the national oil company of Namibia, acquired two 2D surveys using the GeoStreamer® with GeoSource™ dual-sensor broadband towed streamer system. The first of these surveys was in 2012, with 5,000 line km acquired over blocks 2112B, 2113 A&B and 2413B, and in the second, in 2013, 10,000 line km of regional 2D were obtained, focused in deepwater Namibia.

Several Source Rocks

The oldest known source rocks in Namibia are Karoo-aged coals and carbonaceous shales, found in the coastal well Toscanini-1 in 1972. Offshore, the prevalence of this source rock remains unknown. The oldest proven source rock tested by offshore wells is found in the Kudu Field and is believed to be lacustrine syn-rift in origin, equivalent to the prolific Bucomazi Shales. Offshore South Africa, the effectiveness of syn-rift lacustrine source rock is demonstrated in the AJ-1 discovery (1988).

In the Aptian post-rift section, marine shales, interpreted to be deposited as part of Oceanic Anoxic Event (OAE) 1a, were encountered in Kabeljou-1, Wingat-1, Murombe-1 and Moosehead-1. In Wingat-1, the interval was apparently oil mature, with small samples of light, and 38 to 42 degree API oil recovered.

Same regional west-east line as shown in foldout, with illustration of main geological features and structural elements. The line shows clear Seaward Dipping Reflectors (SDR), a sub-SDR syn-rift system, and thick post-rift succession.



Another potential major source rock is the Cenomanian-Turonian shales associated with OAE 2. Encountered on the shelf by well 2012/13-1 with Total Organic Carbon (TOC) content of 5%, the shales were thermally immature, but indicated the possibility that, where sufficiently buried, they could generate hydrocarbons.

Syn- and Post-Rift Reservoirs

Early Cretaceous late syn-rift reservoirs have been proven by the Kudu Field. Interestingly, the original reservoir target for this field was in the Upper Cretaceous post-rift, but poor reservoir results in the post-rift led Chevron to drill deeper into the syn-rift. The reservoir at Kudu is complex, with development being hampered by high pressures and porosity and permeability reduction. These complexities, combined with commercial export issues, have led to stagnation of development from the initial discovery in 1974 to anticipated production by 2017. The reservoir lithology is Neocomian Aeolian sandstones, with porosity and permeability values reaching up to 20% and 767 mD respectively, and preservation at depth due to early calcite cementation and secondary porosity generation due to leaching. The deeper syn-rift remains untested, though thick packages are clearly visible on seismic data.

Aptian carbonates have been proven in Namibia by recent drilling campaigns. However, good quality reservoir has proved difficult to find. The primary target of HRT's Wingat-1 was a high amplitude interval interpreted as a set of prograding carbonates – the well did encounter carbonates, but found only low quality lime muds. Moosehead-1 also targeted a four-way-dip closed carbonate of Aptian age which failed due to a lack of porosity development. Understanding these carbonate systems is difficult, but as exploration increases, so does comprehension of the geology, and thus a more detailed picture of facies distribution will begin to unfold. This allows more focused targeting of good quality carbonate reservoirs.

The final and perhaps the most promising reservoirs are the Late Cretaceous turbidite channel and fan systems with up-dip stratigraphic and structural traps. The secondary target of Murombe-1 was a Santonian-age channel complex and although water-wet, the 36m of net sand within a 242m interval had an average porosity of 15%. These types of traps are becoming a common target around the world and there are some significant problems to overcome – not least finding a working trapping mechanism and defining migration pathways from source to reservoir sandstones.

Seal and Trap

An adequate seal is perhaps the final piece missing in the Namibian jigsaw puzzle. Many of the wells drilled offshore Namibia have had good evidence of source and reservoir, but have only had hydrocarbon shows. In wells located on the shelf, thick clastic sequences have been found with very little shale to act as a seal for the sandstone reservoirs. On the other hand, some wells have encountered the opposite problem – thick shale sequences with little sandstone.

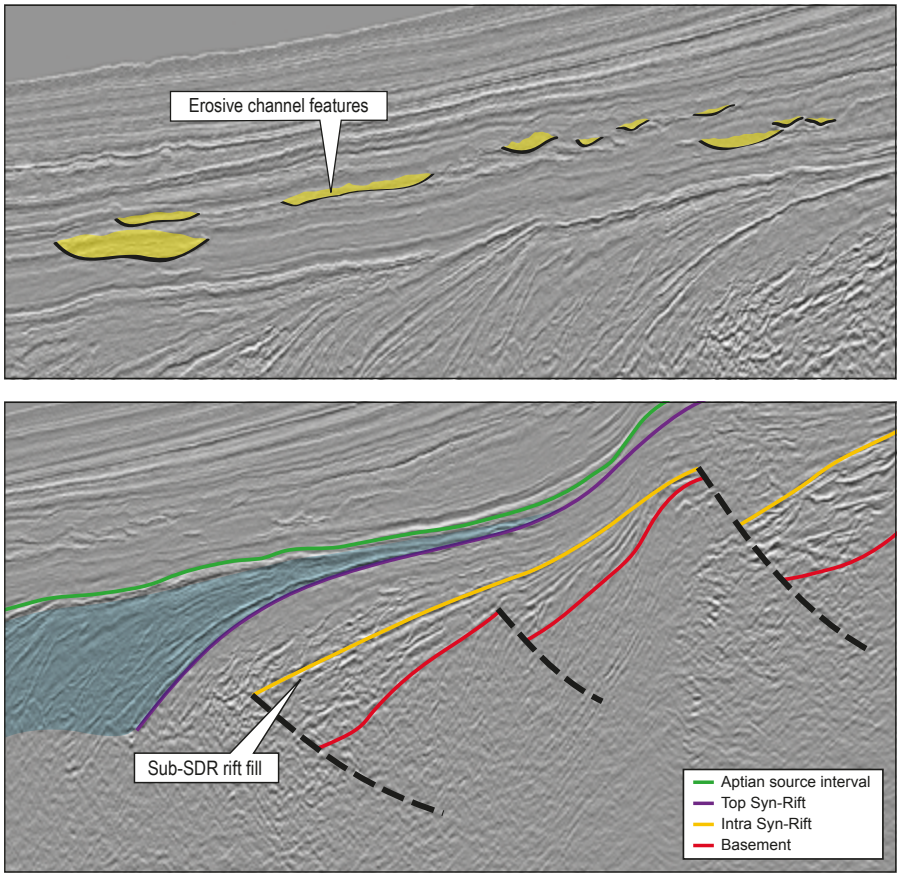
There is clearly plenty of shale in the Namibian system. As exploration is focused offshore and into deeper waters, the presence of shales will be almost guaranteed and the risk of seal failure will be significantly reduced.

Exciting Future

Even the brief analysis of the petroleum system presented in this article shows that offshore Namibia has an exciting future for hydrocarbon exploration. Although dry, the recent wells have proven several previously unknown elements of the petroleum system.

Broadband seismic has improved the imaging of syn-rift and post-rift structures, enabling more confident identification and mapping of prospects. These data clearly demonstrate the presence of thick syn- and post-rift packages and thick sediment in deep water. The improved imaging and resolution provided by this type of seismic acquisition significantly de-risks exploration in frontier areas, something that is of high importance where well costs are extremely high. ■

Broadband imaging has allowed for the visualisation of deeper and more subtle imaging as shown by clearly identifiable sub-SDR syn-rift fill and incised channel sequences.



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Rinjani

The 'Big' Volcano

Harry Matchette-Downes describes a trek to the summit of the volcano Rinjani, on Lombok, Indonesia, and down to the shores of its crater lake

The trek begins near the village of Sembalun, which straddles the north-east edge of the Rinjani National Park. Starting at 600m elevation or so, walking through the lowlands is an oddly Alpine experience: cowbells, flurrying grassland and even 'Javanese edelweiss' (*Anaphalis javanica*) further up.

This comparison can only stretch so far, and is broken by the sighting of macaques. Long-tailed grey macaques (*kera*) are ubiquitous in Lombok and further afield, and the reader must wait to hear about anything more exotic. The track traces an abandoned road, once used to supply an outpost, and is easy to follow as far as it goes.

Nonetheless, even experienced hikers are cajoled into hiring a guide, as it is an official requirement. Initially I resented this imposition: why would I pay to be led up a well-trodden path? Through time and enjoyment of the walk, my stance mellowed, and I accepted that

the system kept the park clean and funded it. I felt a little sorry for my guide, who was fasting for Ramadan and unsurprisingly found the climb difficult! The porters work even harder, yoked (literally) with food for three days, crockery, tents, latrines and, for the spendthrifts, deckchairs.

Towards the crater rim, the slope steepens and the old road runs out. The landscape is at its most eerie: drifting in and out of the mist, one passes through an ever-changing flora. Lonely, warped trees are succeeded by a sparse forest of slender white cemaras (resembling conifers). There is a thickening undergrowth of ferns, bamboo, orchids and asters. The path dips in and out of deep gullies and crosses thick andesite flows.

Spectacular Views

Abruptly, I was on the crest, and could see into the caldera for the first time, and my eyes scanned along its toothy edge, seeing the far side four miles away. Looking down, there sat Anak Luat, or Child of the Sea, a sacred lake so named for its azure colour. This blue is probably due to geothermally introduced sulphur particles. Presiding over the lake is the small, perfect cinder cone of Gunung Baru, New Mountain, which has risen from the floor of the caldera.

The sun was setting but we had reached the first camp. It had been a seven-hour walk or so, reaching around 2,700m above sea level. After examining the stars, very clear in this thin air, I was able to sleep long before my usual bedtime.

This was just as well, as we woke up at 2.30 in the morning so we could reach the top in the dark, see the sunrise, and avoid fierce high-altitude UV. The summit of Rinjani is at 3,726m, making it the second-highest volcano in Indonesia, behind Mount Kerinci in Sumatra.

I would not describe it as a noble peak, as it is the ruins of a taller volcano thought to have exceeded 5,000m: imagine Mount Fuji, but bigger! A recent paper convincingly argues that the crater-forming eruption was 'the great A.D. 1257 mystery eruption', and one of the greatest of the Holocene. Evidence is drawn from local stratigraphy, geochemical matches with both polar ice caps, and carbon-dating of charred trees. There is even a preserved manuscript, *Babad Lombok*, written in Old Javanese on palm leaves, which records a catastrophic eruption of Rinjani. Historical chronicles worldwide recall the cold, rainy year of 1258, which led to floods and famine. The eruption could have contributed to the 'Little Ice Age', a cold snap defined variously within the 14th–19th century range.

The walk was strenuous, especially near the peak. It followed the narrow rim clockwise, over scoria and ash, with the classic volcano shape of 35°

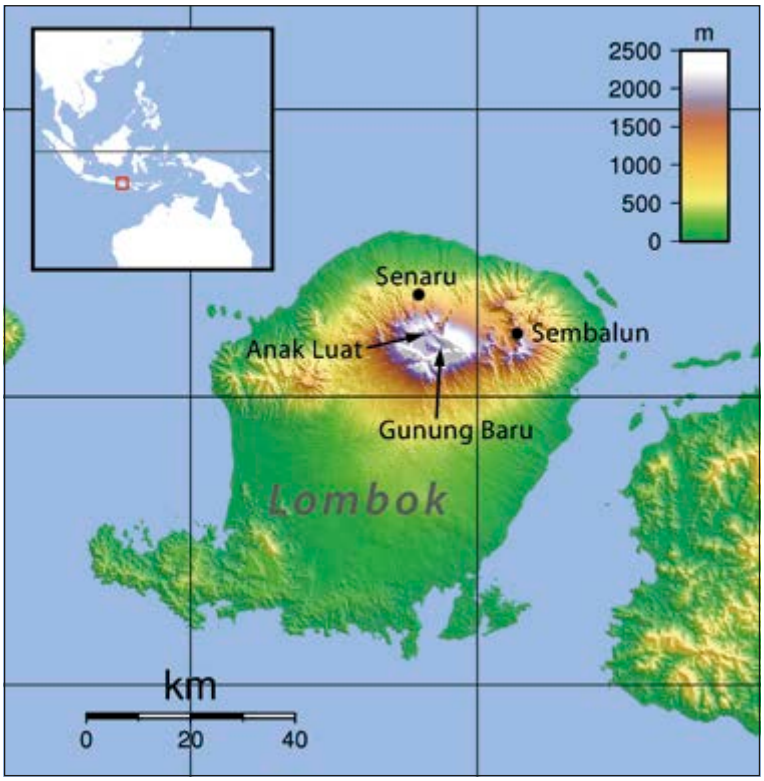
View of Rinjani's summit and cinder cone from the western crater rim.

Harry Machette-Downes

angle-of-repose slopes to one side, and a sheer cliff to the other. With a fitting sense of drama, the last stretch was the steepest, and it was a case of three steps forward and two slipping back.

From the top, one can see all of Lombok and far beyond. Before the sun arrives, the capital Mataram glows and the nightclubs of the Gili Isles twinkle. As it rises, the adjacent links in the volcanic chain are clear: Tambora (on Sumbawa) to the east and Agung (on Bali) to the west. In fact, the Sunda volcanic arc stretches much further west, to the northern tip of Sumatra. One can easily see the arc on a map, cradling South East Asia, and its volcanoes are often in the news. This February, Mount Sinabung (Sumatra) and Mount Kelud (Java) both erupted violently.

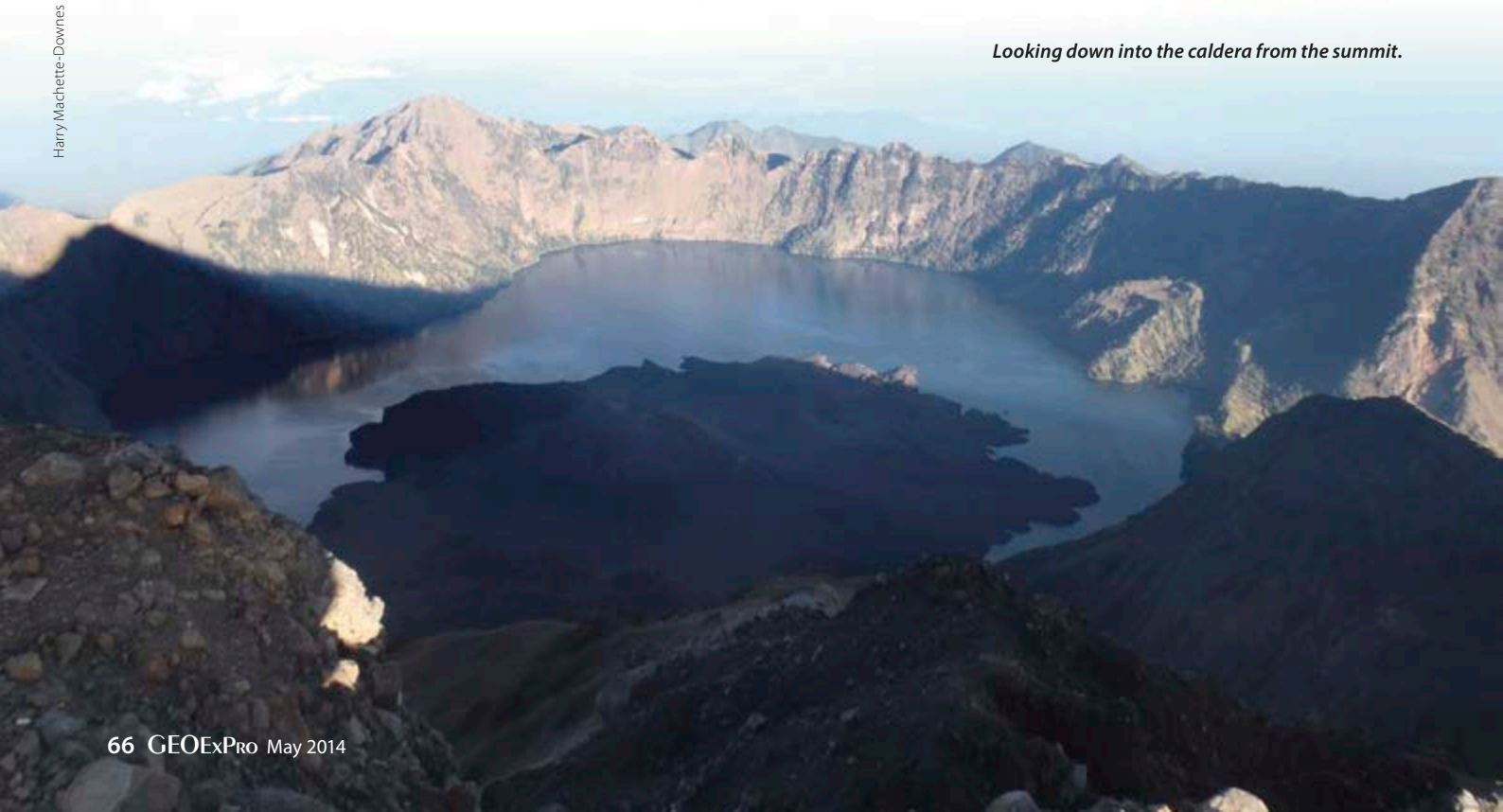
Rinjani sits between two tectonic regimes. The Sunda arc is a clear example of a subduction zone, as the Australian plate moves northwards beneath the Eurasian plate. Tracing east along the arc, one sees that the series of volcanoes runs out soon after Lombok. Until about 3 Ma ago, the subduction continued further east, but at that time, the Australian continental shelf reached the subduction zone. This had two consequences. Firstly, the volcanic arc was thrust over the Australian crust, forming a substantial part of modern Timor. Secondly, the subduction was choked, ceasing volcanic activity. Above Timor, north-facing thrusts (Wetar and Flores) indicate an incipient reversal of subduction direction.



Crater Lake

After reaching the summit, the next leg is back to camp and then down into the crater to take a closer look at the lake. It is a great relief to be travelling (in some cases hurtling!) downhill. The inner walls of the crater are very steep, and so the path must exploit a valley through which the lake runs into the Bali Sea. The point of outflow is also a source of sulphurous hot springs which provide a welcome opportunity to remove the dust and wash one's feet.

The lake itself is not warm, but good for swimming. It covers around four square miles (10.4 km^2), in a rough crescent shape, and is said by the Park authorities to be over 200m deep. Fish, probably introduced through Hindu ceremonies, are common. The lake is also holy to Lombok's majority faith, Islam. From the west side of the lake there is



Looking down into the caldera from the summit.

Harry Machette-Downes

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a view of Gunung Baru's main vent, which last erupted in 2010; like most stratovolcanoes Rinjani is fairly active.

We climbed out of the crater on its western edge, finishing as the sun set and completing 16 hours of walking and covering 38 km. Fortunately, the final half-day is all downhill towards the village of Senaru. The western flank of the volcano has more pristine rainforest, where I saw acrobatic Ebony Leaf monkeys (*lutung*) and heard their toad-like calls. Lombok is just east of the Wallace line and has an unusual mix of fauna. There were signs of other animals, such as wild pigs, but I was sad not to catch a glimpse of the deer, wildcats, owls, birds and porcupines known to live here.

After the trek, I asked my guide what '*Rinjani*' meant, or where the word came from. He thought it just meant 'big'. No other source to my knowledge confirms or refutes this. I don't think it is a very appreciative epithet: there are plenty of big mountains, but none of them is anything like Rinjani.

About the author:

Harry Matchette-Downes studies physics and geology at the University of Cambridge. ■

The steep descent to lake Anak Luat.

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The shore of Anak Luat, the crater lake.

‘What Oilfields?’ Onshore Oil in the UK

A prelude to the great discoveries of the North Sea, the onshore oilfields provide a fascinating insight into the history of UK oil.

MICHAEL QUENTIN MORTON

In Victorian times, there were many reports in the United Kingdom of oil and gas seepages accidentally discovered while coal seams and railway tunnels were being excavated – but developing commercial oilfields was an entirely different matter. Although the Scottish shale oil industry was established and lasted over a hundred years, it would take two world wars to kick-start conventional oil production.

The Shale Oil Industry

From the 1850s, Scottish companies used devices called retorts to produce oil from cannel coal (a type of bituminous coal) using a process known as pyrolysis. This involved heating the coal and capturing the evaporated liquid so that it could be sold as petroleum products.

As supplies of cannel coal depleted, Scottish entrepreneur James ‘Paraffin’ Young began applying the same processes to shale, producing oil which was then refined into various products: candles, and lamp lubricating and burning oils. In 1863 he bought a new complex at Addiewell, West Calder, near a shale deposit. As if to emphasise the pioneering spirit of the age, the corner stone of the new building was laid by Henry Morton Stanley, the famous African explorer – Young was a generous benefactor of Stanley’s expeditions.

This was the start of Scotland’s first oil boom, the ‘oil mania’ years. At first, the best seams yielded up to 40 gallons of oil per ton of shale. Mass production was established, with shale being processed at 130 sites across Scotland and, although most of these were short-lived, the industry was the UK’s only significant oil producer for many years. Production reached a peak in 1913 when over 3.2 million tons of oil shale were processed, but by then the average yield was 20 gallons per ton and production was expensive: East Lothian shale oil was more than double the price per ton compared with Persian oil, including freight.

By 1920, the Anglo-Persian (later Anglo-Iranian) Oil Company had acquired the remaining Scottish shale oil companies and created Scottish Oils Ltd

Miners in the Scottish shale fields.

in order to run them as a consolidated enterprise. Despite a brief reprise during World War II, production gradually declined and operations ceased in 1964.

In England, progress was sporadic and uncertain. In 1787 Shropshire miners had struck a bitumen spring, the famous Tar Tunnel, from whence oil was sold for treating ropes, caulking decks and medicinal purposes. In 1848 James Young created products from crude oil at the Biddings colliery in Derbyshire. Kimmeridge Clay, the main North Sea oil source rock, outcropped in a less mature form in eastern and southern England, and was worked in Dorset for many years. Several large consignments of shale were sent to Scotland for processing, but no lasting industry emerged. The oil shales of Norfolk prompted much speculation during the fuel scares of World War I, but interest dwindled after the war when it was discovered that the oil had a high sulphur content, and was therefore without commercial value.

Philpstoun Oil Works with railway oil tanker and wagons filled with shale being shunted by a works locomotive, circa 1900.

A Very Fine Show

The conversion of Royal Navy ships from coal to oil, and the demands of World War I, put great stress on the nation's oil supplies. By 1917 the situation was critical. Scottish shale oil could not meet wartime demands, and foreign oil supplies were vulnerable to attack. As fuel stocks dwindled, the government investigated ways of increasing oil production at home. One answer was to look for sources of conventional oil on the UK mainland.

Two figures emerge from a confusing scene: John Cadman, the technician and government adviser, who was knighted for his efforts; and Lord Cowdray, the oil magnate, who was convinced that oilfields might be found in the UK. As director of HM Petroleum Executive, Cadman chose the first 15 onshore drilling areas and Cowdray's firm, Messrs Pearson and Son Ltd, was contracted to manage the sites, including one at Hardstoft in Derbyshire.

British firms could not perform the necessary drilling operations, therefore plant, equipment and 40 'brawny' drillers were brought over from the United States. Using a cable drill rig, they struck oil at Hardstoft on the night of 27 May 1919 in the Carboniferous Limestone at a depth of approximately 1,000m. According to press reports of the time, the drillers called it 'a very fine show'. A year later, oil flow was estimated at 50 barrels a week, and its quality was considered to be on a par with high grade oil from Pennsylvania.

Government indifference and legal difficulties stalled this first wave of drilling. The programme had been dogged by arguments over who owned the oil: was it the Crown (i.e. the country) or the landowner? At Hardstoft, the oil was kept in a tank pending a decision. A Petroleum Production Bill, which would have settled the issue, was defeated in the House of Commons by Labour MPs who objected to royalties being paid to landowners. The Defence of the Realm Act, which allowed the government to enter land for the purpose of oil exploration, lapsed. This was not exactly what Lord Cowdray had in mind: 'I had expected a Rockefeller fortune,' he told the House of Lords.

It fell to Lord Devonshire, the owner of the Hardstoft site, to take over drilling operations there. After a work-over and with a nodding donkey pump installed, the well reached a flow of 8 bopd and then went into decline. Nevertheless, it continued to produce commercial oil until 1945, sending it by rail to a refinery in Scotland. Of the ten

Lord Cowdray (left) and others sniffing a bottle of petrol for quality at BP's Llandarcy Refinery, South Wales, 1922.

other wells in the original programme, five had oil shows. A well drilled in the Midland Valley of Scotland by an Anglo-Persian subsidiary, the D'Arcy Exploration Company, produced the best result with seven tons of oil, but all of these wells were abandoned when the government withdrew its support.

Secrets of the Forest

The Petroleum Production Act of 1934 nationalised the country's oil resources and triggered a fresh search for onshore oil. A key figure in this was George Martin Lees, chief geologist of the Anglo-Iranian Oil Company (forerunner of BP). Lees had a keen scientific mind and expounded geological theories that often defied conventional wisdom. He struggled to persuade his company to invest in UK exploration, so he invited a sceptical Sir John Cadman, then chairman of the company, to visit some bituminous sandstone outcrops on the Dorset coast in the Wessex Basin. According to Lees, it was only after Cadman sat down and found his trousers stuck to the softened bitumen that the argument was won.

D'Arcy Exploration gained the first exploration licences. Over the next ten years, the company drilled 95 exploratory wells, many close to known seepages. A subsidiary of Standard Oil (New Jersey) found a small oilfield in the Midland Valley in 1937, followed closely by D'Arcy, which found gas in the same vicinity. In May 1939 D'Arcy discovered a small oilfield at Formby in Lancashire, followed by a larger oilfield at Eakring, Nottinghamshire, in the heart of Sherwood Forest. The oil was of good quality, with a specific gravity from 0.83 to 0.89 from a depth of 583m. D'Arcy went on to discover new oilfields at nearby Kelham Hills and Caunton, and even took over the Hardstoft well and improved its flow of oil.

The advent of war in 1939 brought a striking parallel with the earlier conflict. A submarine blockade brought fuel shortages, and by August 1942 only two months' worth of oil remained in stock. The government introduced a 'short haul' policy to obtain oil from sources closer to home. The UK now had oilfields, but most officials were unaware of their existence – when Sir Philip Southwell of D'Arcy raised the issue at a meeting of the Oil Control Board, members of the audience were astounded. 'What oilfields?' they asked.

A production target of 100,000 tons per year was set, a massive increase on the 25,000 tons a year then being achieved. US companies were contracted to supply the necessary drilling equipment, including jack-knife rigs and a crew of 42 'roughnecks', who arrived in England under conditions of great secrecy – curious locals were told that they were making a John Wayne movie. These men drilled 106 wells in the Eakring area over the next 12 months, and their efforts ensured that the company achieved its target by September 1942.

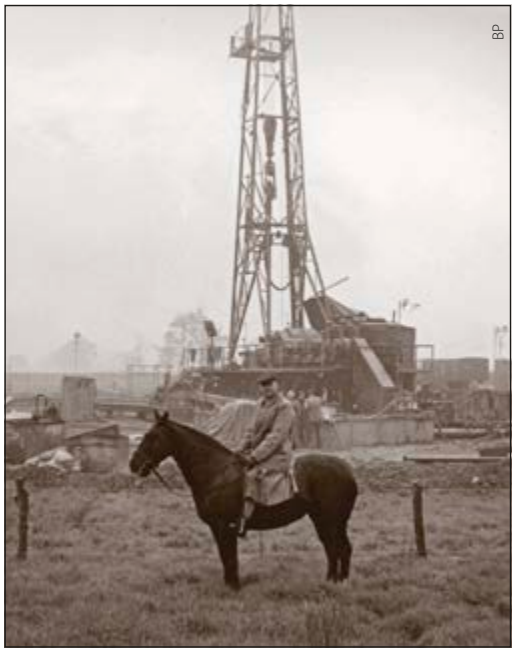
The oilfields of mainland Britain.

Wytch Farm

In 1959, the UK was producing 80,000 tons of oil from its East Midlands fields. BP Exploration (formerly D'Arcy) was based at Eakring and in charge

Workers at Well No. 146, Duke's Wood.

Horsepower meets oil power at a drilling site near Eakring.



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of the company's UK operations. Although there were several post-war discoveries in the East Midlands, it was the Wessex Basin that proved the most promising prospect.

In 1937 Lees and his colleague, Percy Cox, had delivered a ground-breaking paper to the Geological Society entitled 'The Geological Basis of the Present Search for Oil by the D'Arcy Exploration Co. Ltd.' Using their knowledge of whaleback anticlines in Iran, they identified the Jurassic and Lower Cretaceous in southern England for exploration. Anticlines at Portsdown, Henfield and Kimmeridge were tested but it was not until 1959 that oil was discovered in commercial quantities. The Kimmeridge No. 1 well produced oil from a Middle Jurassic reservoir and raised hopes of more discoveries to come, but they had to wait until 1974, when the Gas Council in partnership with BP discovered an oilfield in the Lower Jurassic Bridport Sands beneath Wytch Farm. This well was producing some 5,500 bopd in the mid-1980s, by which time BP had taken a controlling share.

Rail tankers transporting crude oil from UK oilfields.

The real breakthrough came when further drilling led to the discovery of oil in the Sherwood Sands formation at 1,585m, which was producing an additional 65,000 bopd by 1992. This oilfield is the largest onshore oilfield in Europe (see *GEO ExPro* Vol. 10, No. 6), and provided 84% of UK onshore production (as at the end of 2010). The use of extended reach drilling enabled BP to drill offshore wells from a site on the Goathorn Peninsula and, in June 1999, well M16 set a new world record by breaking the 10 km barrier for horizontal displacement distance.

Nodding donkey pumps at Wytch Farm, 1984

Back to the Shale

The search for oil in the UK tells us as much about human nature as about geology. Oilfields were traditionally associated with warmer climes and the idea of striking oil on the mainland was often greeted with disbelief. Even when onshore oil was discovered, it seemed to stop at the shoreline. The industry only began to make connections between onshore oil and the hydrocarbon potential of the North Sea after the discovery of the Groningen gas field in The Netherlands in 1959. Although the UK was recognised as a significant onshore producer following the Wytch Farm discoveries, the industry kept a relatively low profile. The future may be different, however, with hydraulic fracturing bringing shale oil and gas exploration under the public spotlight. The ghosts of the early shale oil pioneers, if they exist, would certainly be taking note. ■

Acknowledgement:
Thanks to Peter Morton for his kind assistance.

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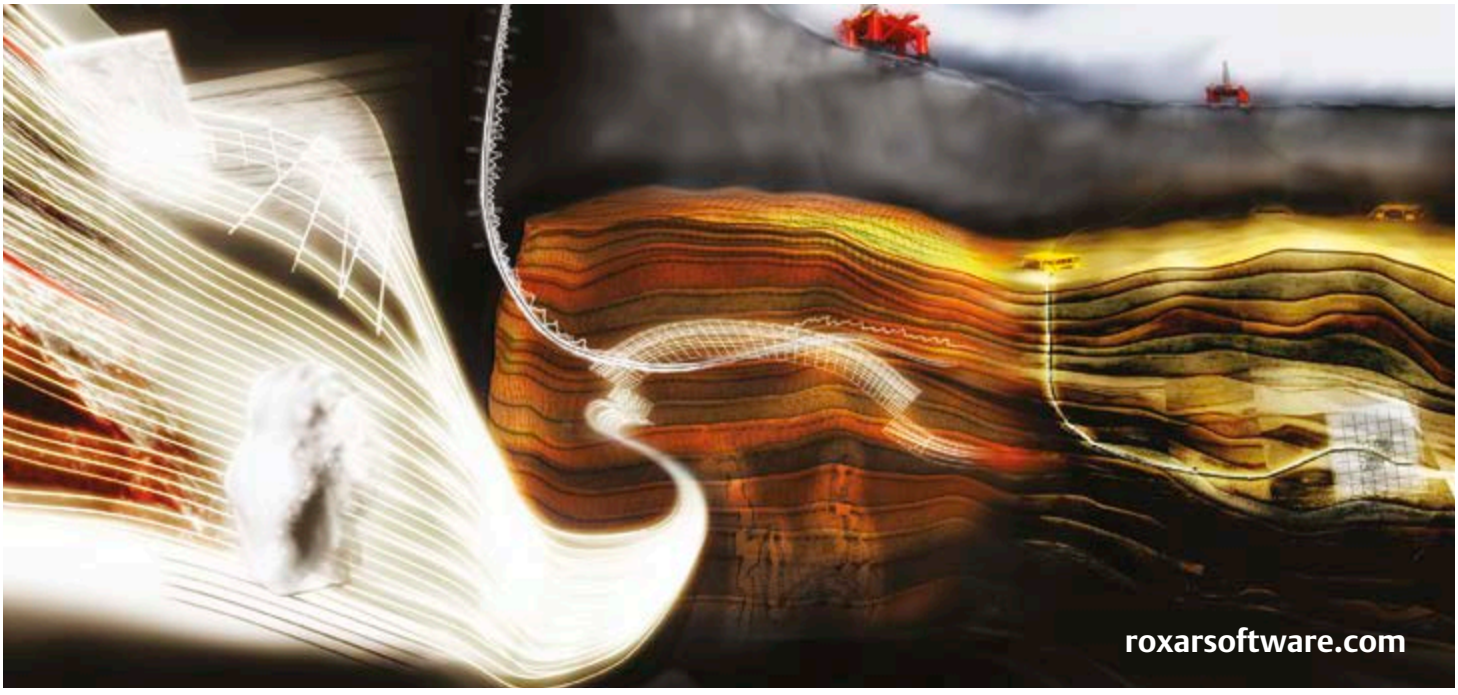

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Fun, Cooperation and Risk-Taking

Lee Krystinik, who recently retired as President of the American Association of Petroleum Geologists, tells us why he thinks the organisation is a vital resource for the industry – and why the petroleum geologist is a natural risk-taker, both at work and play.

JANE WHALEY

"This year has just been a whirlwind of seeing new places and meeting people," says Lee Krystinik, describing his time as the President of the American Association of Petroleum Geologists (AAPG). "And I've loved every minute of it! I've just come back from a two-week tour of the Middle East – my first trip to the region, taking in Qatar, Saudi Arabia and the UAE – and I was both humbled and exhilarated by the excellent geoscience being done by remarkably talented and passionate colleagues there. It is wonderful to know that the world over we geoscientists love what we do; geoscience is a common bond regardless of language or culture."

Lee's tenure as President is the culmination of a long-term connection with the organisation, which he thinks is a vital, important and growing resource for the worldwide oil and gas industry.

"I joined the AAPG while I was still an undergraduate student of geology at the University of Texas at Arlington, and immediately had the opportunity to volunteer to serve on the AAPG Publications Committee – that was lots of fun. I thought then, and still think, that AAPG is the most important oil and gas geoscience and professional society in the world."

The World in a Sand Grain

Lee's interest in geology dates back to his childhood in the Dallas-Fort Worth area of Texas. "This area is so rich in fossils that one of the local creeks in which I hunted fossils was called Fossil Creek. Some of the most beautifully preserved fossils came from a black, organic-rich shale that I later came to know as the mid-Cretaceous Eagleford Formation – all that preserved organic matter makes it a pretty good resource play too! It seemed to make sense to me to see these in the flat Texas ground, not so terribly far away from the call of seagulls on the Texas coast – but on a family holiday to Colorado when I was about seven years old I was amazed

AAPG

Lee giving the opening address at the AAPG Annual Conference and Exhibition in Houston in April, 2014.

to see these same fossilised creatures encased in steeply dipping strata at the top of a mountain. How did they get there? What did the world look like back then? I was hooked! I became particularly fascinated by the concept of palaeoenvironments, trying to envisage a world with huge trees that looked like asparagus plants, two-metre long dragonflies, and super scorpions a metre across. Imagining that kept me excited by geology – and still does."

After his undergraduate degree, Lee moved to Princeton University to undertake a Masters and then a Ph.D., in which he continued his interest in palaeoenvironments by looking at the deposition and diagenesis of reservoirs and source rock in turbidite deposits in California. At this point new techniques for scrutinising the components of rocks at the microscopic level, such as SEM (scanning electron microscopy), and XRF and XRD (X-ray fluorescence and X-ray diffraction) were just coming to the fore, and Lee was delighted to find that these new tools were helping prove many theories in sedimentology and diagenesis studies.

"I was amazed; I could see the world in a grain of sand!" he explains. "I was able to trace the turbidites I was studying as they went deeper and deeper into the earth, and using these techniques I could look at a whole range of diagenetic features and work out many aspects of the depositional history. And this ultimately led me to the oil industry, as I developed ideas about predicting the sedimentological character of a potential reservoir from inspecting the properties of sands under the microscope."

A Varied Career

"I like to find out how things work and to learn new things," Lee says. "There is so much to learn in geology, I think I'll be studying all my life." This enquiring mind has led to a varied career, from undertaking a summer field season in Alaska looking at complex sandstones ("and bears, caribou, amazing scenery; a wonderful experience"), to rising through the ranks of Union Pacific Resources (formerly Champlin Petroleum) to become Manager of Geology responsible for exploration strategy and developing the company's portfolio of assets, primarily in the USA and Canada.

"I have worked in the full range of industry arenas, including offshore and deepwater, but my big focus has been on continental, coastal and deltaic environments, not just in North America but also in the Middle East, Asia and Latin America.

"When I was with Union Pacific we became one of the first companies to turn exploring for and producing hydrocarbon resources into something like a manufacturing assembly line process, exploiting economies of scale, so our rigs were continually working. In the early '90s we were exploring in the Austin Chalk in Texas, in a band with both heavy and light oil, and as we progressed deeper we encountered higher and higher pressures and temperatures, so we required more and more progressive technology. Sun originated the horizontal drilling effort in the Austin Chalk, porpoising up and down through the formation looking for presumed fracture swarms. We followed on by drilling using the concept of 'zonation' for very specific horizontal target selection, enabling us to stay in optimally fractured and porous target zones and to used real-time geosteering to meet these. I find it fascinating to work in these high tech developments, especially when the geology is fully integrated with geophysics and engineering to derive an optimal result."

In 2000 Lee left Union Pacific to set up his own company, Krystinik Litho-Logic, a consultancy specialising in the application of new concepts and technology (such as sequence stratigraphy, syn-sedimentary tectonics, fracture analysis, horizontal drilling and various completion techniques) to reservoir prediction. He was then tempted back to the corporate arena as Global Chief Geologist with Conoco Phillips. "Working in a large multinational company with a global reach was a very different and stimulating environment for me," he explains. "I had a fast learning curve, with a remit to evaluate what we did well, what we didn't and where to focus for the best financial outcomes. The experience reminded me of how important teams are. None of us, no matter how bright or hard-working, can possibly know all that is required to execute a global exploration and development programme. Successful exploration requires a technically excellent team who make a point of open communication at all points along the path.

Giving Something Back

"I usually wake up excited to go to work and I think most geoscientists feel the same," Lee says. "It is great to see our younger colleagues approaching petroleum geoscience with the same passion, enjoyment. There is always something new to learn in geology, which is one reason I have loved being involved with the AAPG. I have been given so much through the overwhelming generosity of people I have come to know through AAPG. Through the gift of their time and knowledge, shared during many phases of my career, my colleagues have taught me virtually all I know. I owe it to the profession to give something back.

"Many people ask me what is the relevance of organisations like the AAPG today – why be a member when there is so much information available online, for example? For young people in particular there is still a huge amount of geoscience knowledge to be gleaned through membership, attendance at conferences and training conferences and in reading the journals and publications of the association.

"As you progress in your career, from the very beginning, the most important aspect of AAPG membership is the connections it gives you within the oil and gas community; connections with a group of people who have the same goal as you – simply to find oil and gas," Lee continues. "With a membership of over 40,000 people from 118 countries across the globe, the AAPG is a continuous resource of opportunities to learn from, and with, experienced people doing just that. You have the possibility of meeting people who are working on similar situations and rocks as you are, perhaps from very different countries and backgrounds, and to discuss the issues and challenges facing us all.

"The depth and complexity of the AAPG is huge – by the end of my two years in office (as President-Elect and

then President) I will just about know the job," he jokes. "We are very keen to support the long-term strategic growth of the industry. Although we are a science-based association run to a large extent by the excellent efforts of volunteers, we are becoming more business-oriented. There is a lot of competition, particularly in the conferences arena, from other organisations like the EAGE and SPE, so rather than competing we are concentrating on cooperation – arm in arm towards a common goal. The annual International Petroleum Technology Conference (IPTC), which rotates between the Middle East and the Asia Pacific region, is a fine example of such cooperation as it organised jointly by the EAGE, SEG, SPE and ourselves in the AAPG, and the specialist Unconventional Resources Technology Conference, URTeC, is another illustration. In my opinion, the more cooperation we can achieve, the better we can serve the customer – which incidentally highlights another way in which AAPG is changing. We used to be focused on our members, but now, with at some meetings as many as 75% of the attendees non-members, we think more in terms of customers, with our members being the most important of those.

Lee and his horse Kilo demonstrate their skills in the jumping arena.

Risk-Taking

Lee enjoys active sports like skiing and riding, and is a natural risk-taker "but then aren't all exploration geologists?" he asks. "You don't ever want to think you're going to drill a dry hole – but many wells don't find hydrocarbons; you have to learn to expect some failures, but not be knocked back by them. You need that element in your personality to keep exploring.

"Similarly, in my life I like to be challenged by exciting new things, with a steep learning curve – I don't do anything by halves! I want to live life to the full and experience many different things, and also to remember and learn from how they affected me. For example, a few years ago I did a tandem sky dive, which was an unforgettable experience. During it I tried very hard to concentrate on all the details of how I felt both mentally and physically, and what I experienced throughout the jump, to really appreciate the experience. The same goes for long, steep hikes at altitude – the physical challenge is intense and the risk is quite real, but the views and the feeling at the top make it more than worthwhile!"

Lee originally met his partner, also a geologist, on an AAPG-sponsored field symposium, and discovering her love for horse-riding, himself took up the sport. Typically, he wasn't content with simply jogging around the highways and byways of his home near Tulsa in Oklahoma; instead he took up the rather more challenging competitive sport of three-day eventing, in which the horse and rider compete through the very demanding disciplines of dressage and show-jumping, before hurtling at full speed round a course, several miles long, littered with 'natural' jumping obstacles like tree trunks and solid walls. "I enjoy three-day eventing because it has forced me into circumstances where I may be in 'control' but my 'sporting partner' has a huge say over the outcome," he explains. "Our relationship drives our success or failure (severe injury or death, for one or both of us, is one of those potential failure scenarios) and understanding that linkage applies in many different aspects of personal and professional life. Teamwork and mutual respect are critical in all we do. Besides, it is a blast rumbling at top speed, on a stunningly powerful, nearly one ton animal, off across the countryside and jumping over large, immovable objects. I don't find myself pondering whether the next well will be good or not while out on that cross country course!"

Next Giant Leap?

What of the future? "Many of us in society today are concerned about the earth and the effect of burning fossil fuels, and we are right to be. We need to continue supporting research into alternative fuels and systems, but meanwhile, it is our job to bridge the energy gap while these are made more efficient, and I believe that natural gas is the most efficient, low total carbon footprint resource we have at the moment," Lee says.

"We need to find more oil and gas. Spreadsheets or algorithms don't do that – geologists and geophysicists do. It's their job to aggressively address the unknown and come up with something new. This requires a different mindset – I think of it as equations and vigorous methodology versus imagination."

So what will be the next giant leap? "I don't know – but it's a challenge we all face and can solve together – and that's why I could never have asked for a more enjoyable and satisfying career," Lee concludes. ■

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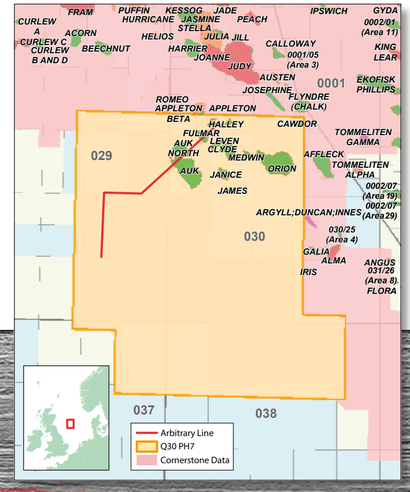
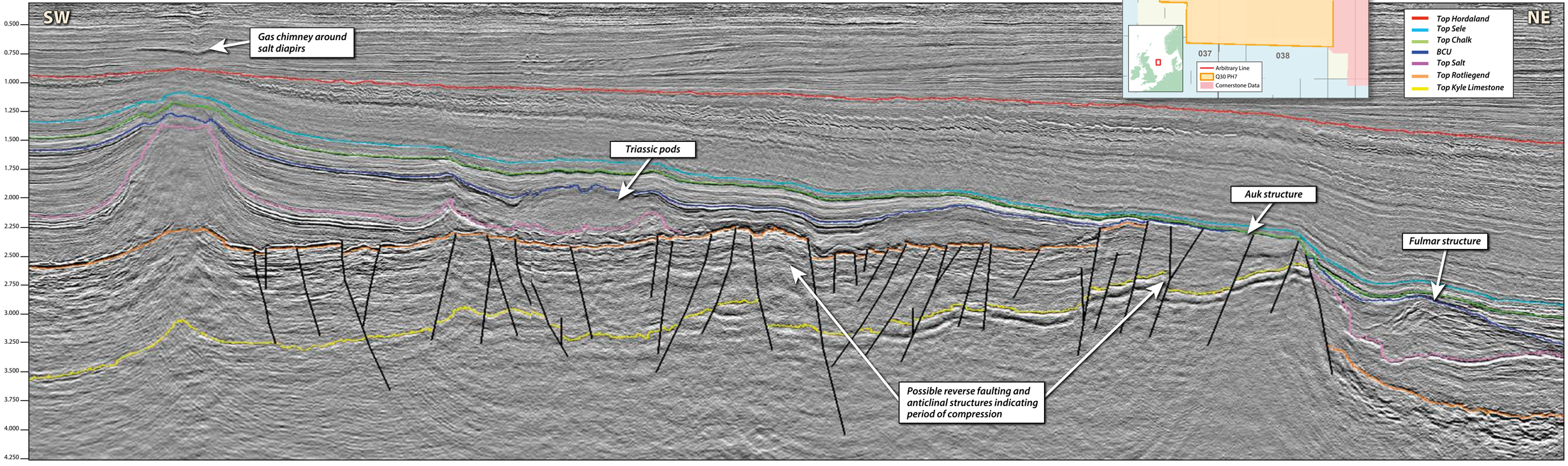
Exploring the Mid North Sea High

The Mid North Sea High is one of the last remaining underexplored areas of the UKCS. Away from the main Kimmeridge Clay source rock kitchen it is believed that a Carboniferous petroleum system could be in place but it has not yet been made evident by successful drilling. Supporting the exploration efforts in this region, CGG has acquired a new broadband marine seismic survey over the southern parts of Quadrants 29 and 30, where until now only 2D seismic data have been accessible. This 3D dataset is therefore the first of its kind in this area. It covers approximately 5,600 km^2 around and south of the Auk field and it has already revealed some interesting geological features which help to better understand the geology of the Mid North Sea High.

This interpreted seismic line is oriented south-west to north-east. It cuts perpendicularly through the major bounding normal fault defining the southern margin of the Central Graben. The Auk field is found in Lower Permian-aged Rotliegend sandstones trapped in the footwall of the South Central Graben fault and perched on a Devonian paleo-high. The low-frequency content of the data helps to image deep features such as the geometry of the mid-Devonian Kyle Limestone.





Hunting the Carboniferous Play

GREGOR DUVAL and MATTHEW DACK, CGG

New regional broadband 3D seismic data reveals more information about the geology of this poorly understood region.

CGG recently undertook the acquisition of a large 3D broadband seismic survey around the Auk field area and south of it onto the Mid North Sea High. This survey involved the use of CGG's broadband technologies, BroadSeis™ and BroadSource™, pushing the boundaries of broadband seismic imaging even further, with usable frequencies reaching as high as 200 Hz in the shallow section to image the thinnest formations and identify potential shallow hazards, while reliable low frequencies reached as low as 2.5 Hz to image deep features. Early results of the processed preSTM data are giving some interesting clues about the existence of a pre-Permian petroleum system in the area.

Probable Gas, Possible Oil Plays

Following the work of Hay et al. in 2005 and R. Milton-Worssell in 2010, the existence of a Carboniferous hydrocarbon play on the Mid North Sea High is more commonly acknowledged now. At present, only a few of the wells drilled within this part of the North Sea penetrated below Permian-aged strata to give useful information about the Carboniferous section, and in fact many of these wells were drilled on the Auk-Flora palaeo-high where the Carboniferous is absent.

Five of the wells that did encounter a Carboniferous section found source rock potential within coal measures (both Dinantian and Westphalian in age), namely: 44/2-1, 36/13-1, 36/23-1, 36/26-1 and 38/16-1. Maturity studies of these coal measures over the southern part of Quadrant 29 (Hay et al., 2005) have proved the potential for the expulsion of large volumes of gas. This is also verified by the fact that two wells found gas shows within Permian and Carboniferous reservoir intervals. In addition, hydrocarbon indicators and gas chimneys are clearly observed on the fast-track volume of the new 3D seismic data (see foldout image on previous page and Figure 1). A dozen of these gas escape features have been identified within the 5,600 km^2 area covered by the new broadband seismic survey, correlating with the maturity model of Hay et al. Coincidently, gravity modelling (R. Milton-Worssell et al., 2010) and interpretation of the deep sub-Permian section on seismic data demonstrate the presence of a deep Devono-Carboniferous basin around the southern parts of Quadrant 29 and northern part of Quadrants 37 and 38, bounded to the north-east by the Auk-Flora High in Quadrant 30.

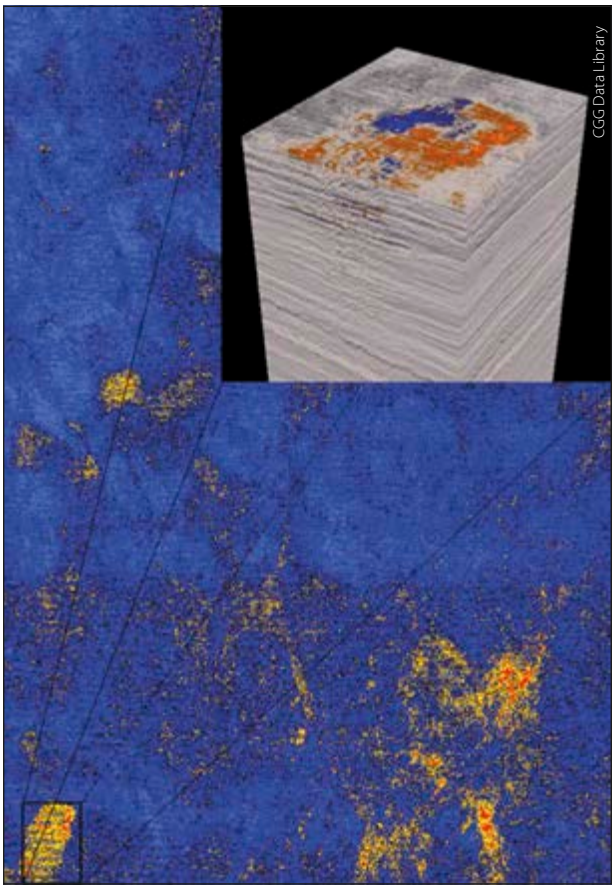


Figure 1: Shallow RMS amplitude map showing potential gas escape features over the Mid North Sea High.

Besides the Carboniferous gas play, the south-west margin of the Central Graben and the northern part of the Mid North Sea High offers potential for Kimmeridge Clay oil to migrate into traps within Palaeozoic and Mesozoic reservoirs. Interpretation of the fast-track BroadSeis seismic data reveals the large vertical throw of the main north-west to south-east bounding fault near Auk and the absence of salt along this trend. This means that mature Kimmeridge Clay source rock intervals in the hanging wall can be found adjacent to Devonian, Carboniferous and Permian reservoir rocks in the footwall, allowing oil sourced from deep in the Central Graben to migrate into reservoirs in the Mid North Sea

High region. This is exactly how the Auk structure has been filled with oil. Finding oil sourced from the Kimmeridge Clay formation over the rest of the Mid North Sea High relies on long, near-horizontal migration pathways from the kitchen area in the north-east. Oil shows found within Jurassic Fulmar sands in wells 30/28-1 and 30/28-2 have proved this to be possible.

Furthermore, there is an indication that oil may have been generated locally from Carboniferous lacustrine source rocks. A study of oil samples retrieved from the Rotliegend sandstone interval in well 29/20-1, located immediately west of the Auk field, shows that it has probably been sourced from such source rocks (PA Resources UK, 2010), hence highlighting the possible presence of a deeper oil play over the Mid North Sea High.

Reservoirs and Undrilled Closures

A number of fields located in the southern part of the Central Graben have Permian or older-aged reservoirs, including the Auk, Flora, Alma (formerly Ardmore) and Innes (formerly Argyll) fields. Reservoir intervals can be found from Carboniferous-aged deltaic and fluvial sandstones through the Lower Permian Rotliegend aeolian dune sands to the Upper Permian Zechstein dolomite or even the Triassic Bunter sands (see stratigraphic chart in Figure 2). Where Zechstein salt is present and thick enough, it acts as a regional seal for sub-Permian reservoirs, but where it is absent it provides a window for hydrocarbons to migrate into shallow reservoirs such as the Triassic Bunter sands or maybe other untested intervals in the Jurassic or in the Tertiary. Above the Zechstein salt, trapping is mainly provided by draped sediments over underlying salt diapirs.

At depth, interpretation of the Base Zechstein Salt horizon on the new seismic data has revealed several large undrilled closures over this part of the Mid North Sea High. An example is shown in Figure 3, covering over 20 km^2 in areal extent. Some of the more subtle sub-Permian closures seen in the Two-Way-Time (TWT) seismic domain would need to be converted to depth to validate the potential. The presence of salt diapirs and their inherent high seismic velocities creates artificial pull-up structures on the TWT seismic data. For this reason, the new 3D broadband seismic data is being processed with preSDM using the latest multi-layered tomography technology for more accurate velocity model building.

A Promising Area

Interest in the potential hydrocarbon plays to be found over the Mid North Sea High has clearly seen a recent uptake through the allocation of over 20 exploration blocks in the area following the 27th UKCS Licensing Round. As a result, operators have committed to the drilling of four firm wells and two contingent wells within this area to target the plays briefly mentioned in this article. In the case of the Carboniferous play, some source rock maturity studies indicate possible total volumes of expelled hydrocarbons of up to 28 Bbo of oil and 156 Tcfg from this region alone. Depending on retention and recovery factors, the actual quantity of recoverable hydrocarbons is still highly speculative, but the potential is certainly high enough to attract the interest of oil and gas explorers. ■

Figure 2: Generalised stratigraphic chart for the North Sea area highlighting the main source rocks and reservoirs to be found over the Mid North Sea High (modified from The North Sea Millennium Atlas).

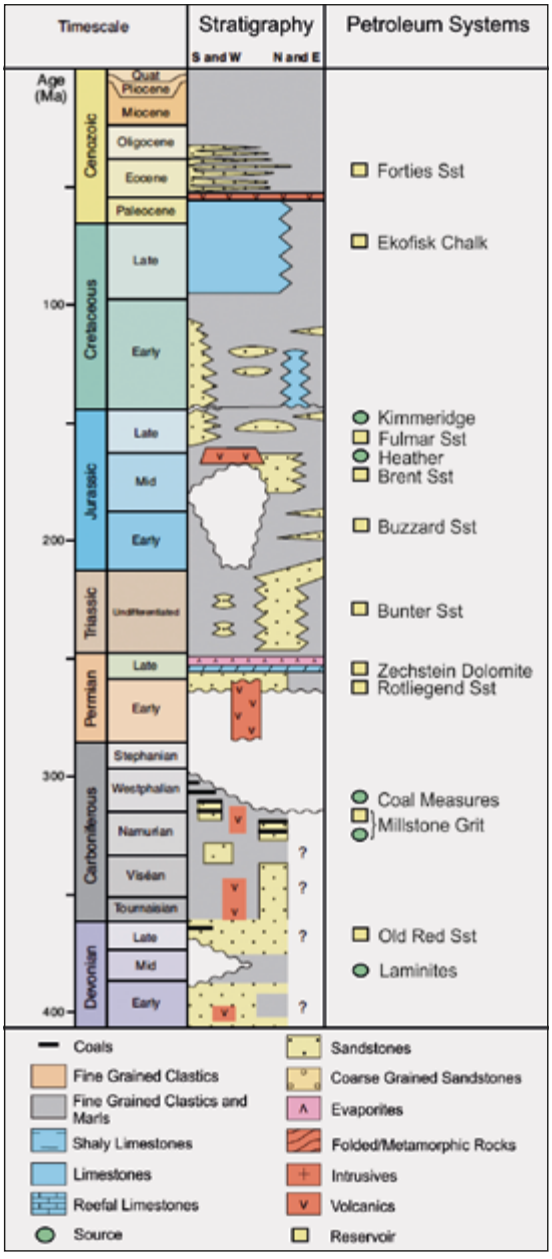
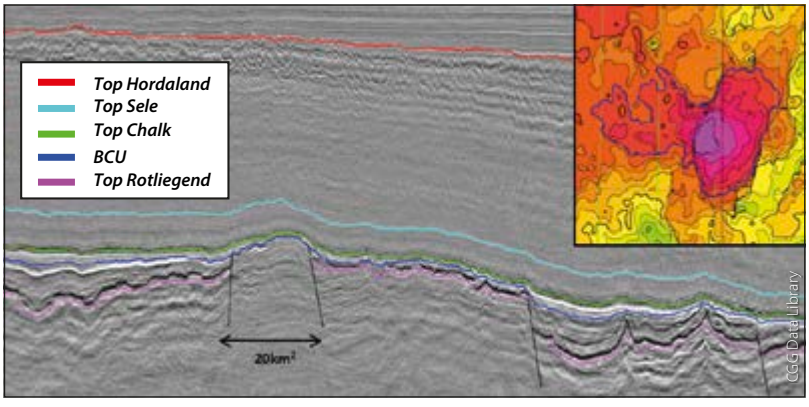


Figure 3: An example of undrilled structural closures identified at Base Zechstein Salt level within the new 3D broadband seismic data coverage.



Fracture, Fracture Everywhere

Part I

RASOUL SORKHABI, Ph.D.

Rock fractures are ubiquitous because rocks in the Earth's upper crustal levels are brittle. However, fractures show considerable variations due to their origin, geometry and rock properties. Given the petroleum industry's major shift in recent years to exploit tight reservoirs, there is now greater interest in rock fracture studies because open fractures, whether natural or hydraulic, provide the essential permeability for fluid flow in such reservoirs. A fresh understanding of rock fractures is thus timely. In this two-part article, we first review the geometry and characteristics of rock fractures. In part two, the geomechanics of fractures will be discussed.

The term 'fracture' includes any break or **structural discontinuity** in rocks in which two rock fracture surfaces (usually planar) are separated by a narrow slit, far shorter than the length or height of the fracture. Fracturing happens because of the **loss of cohesion** in the rock and is a typical expression of **brittle deformation** in the Earth's upper crust (in contrast to the flow and folding structures which occur at crustal depths under ductile conditions).

Fractures are the most common structural features that are found in all types of rocks (igneous, sedimentary and metamorphic) and in all plate-tectonic settings, from continental rifts and mid-ocean ridges to subduction trenches and continental collisions. Knowledge of fractures is important for scientific, technological as well as economic purposes. Fractures are essential parts of the geological processes that form mountain belts, sedimentary basins, coastlines, ocean floors, earthquakes, and so on. Fractures also provide fluid pathways for the movement of groundwater, oil and gas, ore deposits, and magma.

Scientific investigations of fractures date back to the nineteenth century and have grown rapidly in recent decades. These investigations include rock observations and structural mapping at micro and macro levels, experimental and analogue works, geometrical and geomechanical analysis, and numerical modelling and simulation.

In petroleum field operations, we often distinguish

Mike Norton/Wikipedia

Well-developed joint sets on flagstones at St. Mary's Chapel, Caithness, Scotland.

between **natural** (naturally occurring) fractures and those of **drilling-induced** and **hydraulic** (induced by fluid injection for fracturing rocks) origin. Even though natural fractures are found in all rocks, they are not all the same, and the simple term of 'natural fractures' does not do justice to their complexities. Characterisation of fractures based on scientific principles and data is thus crucial for their utilisation in resource exploration and production.

Fractures Come in Various Forms

Fracturing occurs at various scales from mineral to tectonic plate, and is generated in numerous forms by a number of distinct processes. Fracture is a collective term for a variety of breaks in rocks.

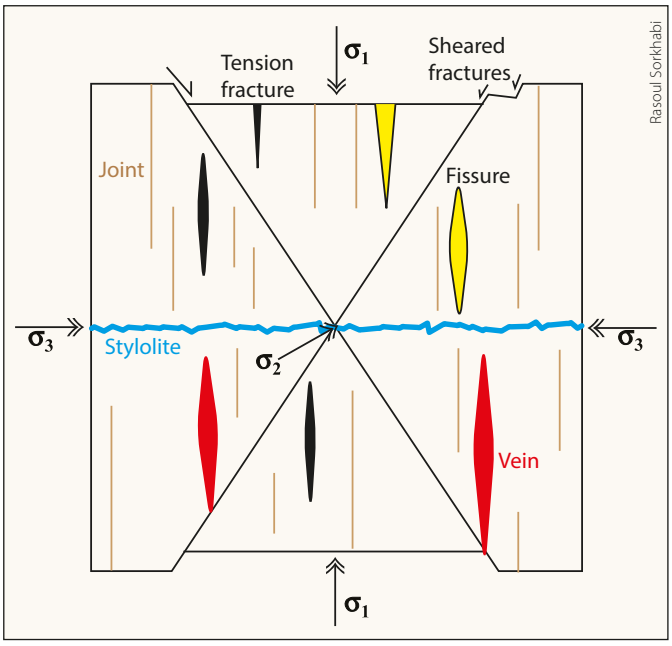
On a mineral grain scale, fracture is crystal breakage along uneven or curved surfaces; it requires external force applied to the crystal. (Fracture is different from crystal cleavage, the tendency of the mineral crystal to split along one or more smooth planes, which is related to the arrangement of chemical bonding in the mineral lattice.) On a thin-section of rock specimen, we can observe micro-fractures which may be **intragranular** (restricted to individual grains) or **intergranular** (cutting across several grains).

In outcrops of sedimentary rocks, bedding planes and joints are probably the most eye-catching rock fractures. **Bedding planes** separate layers of successive sedimentary rocks due to changes in lithology or other sedimentary properties. The term **joint** was first used by miners who thought that the rocks were 'joined' along these planes like building blocks. Joints do not show visible shearing but are **dilational** (opening) or **extension fractures** formed by tensile stress. Other types of extension fractures include **fissures** (wide openings filled with air, water or other fluids), **veins** (mineral-filled), and **dykes** (vertical, wide fractures filled with plutonic or volcanic rock).

Sheared fractures, on the other hand, show relative movement (slip) of two fracture walls parallel to the fracture plane (slip surface). Sheared fractures usually have displacements of millimetre to centimetre scale, while faults have larger displacements. Faults often have polished or striated surfaces (called slickensides) that result from frictional sliding of fault walls. Geologists can use slickenlines (grooves on the fault surface) to determine the direction of faulting.

In the petroleum and groundwater industries, fracture often refers to reservoir-scale joints and other open, extension fractures that have positive implications for subsurface fluid flow. In this limited sense, large faults, for example, are regarded as a different feature. Thus we often hear about 'fractures and faults' in reservoir rocks, which is like saying there are 'animals and dogs on our farm'. Faults indeed represent a significant type of fracturing and are genetically associated with many other types of fractures. (For various types of faults, see the two-part article 'Know Your Faults', *GEO ExPro*, Vol. 9, Nos. 5 and 6).

Some special types of fractures are also noteworthy here. **Mud cracks** (desiccation fractures) are polygons of extensional fractures that develop in highly clay-rich sediments due to shrinkage and loss of water. **Cleats** are natural, open-mode fractures in coal beds filled with natural gas or water. **Deformation bands** are millimetre-wide, planar features in high-porosity sandstones that show little offset but are characterised by low-porosity, low-permeability bands due to mineral grain flow, fracturing or cementation; they cluster around faults.

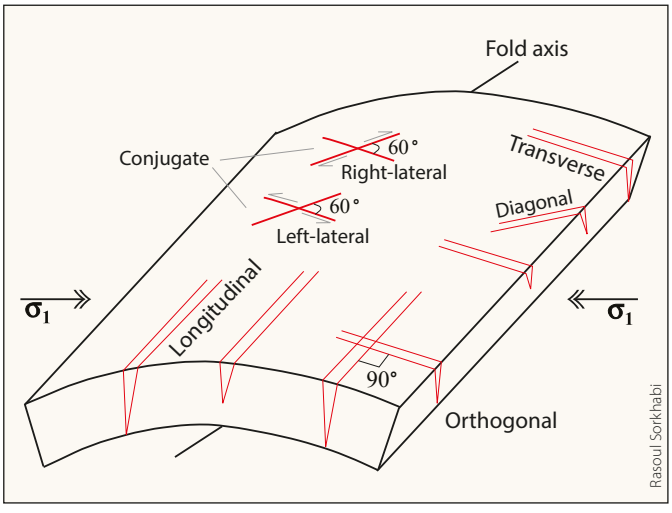


Various types of fracture on a conjugate normal fault structure. Modified from Haakon Fossen, Structural Geology (2010).

Natural fractures are found in all rocks but they are not all the same

Some fractures form spectacular features on satellite images; they are also important for fluid movements on a crustal scale. **Lineaments** are physiographic lines on a regional extent that indicate deformation of rocks by major faulting or folding. **Ocean-floor fracture zones** extend beyond the mid-ocean ridges to continental margins.

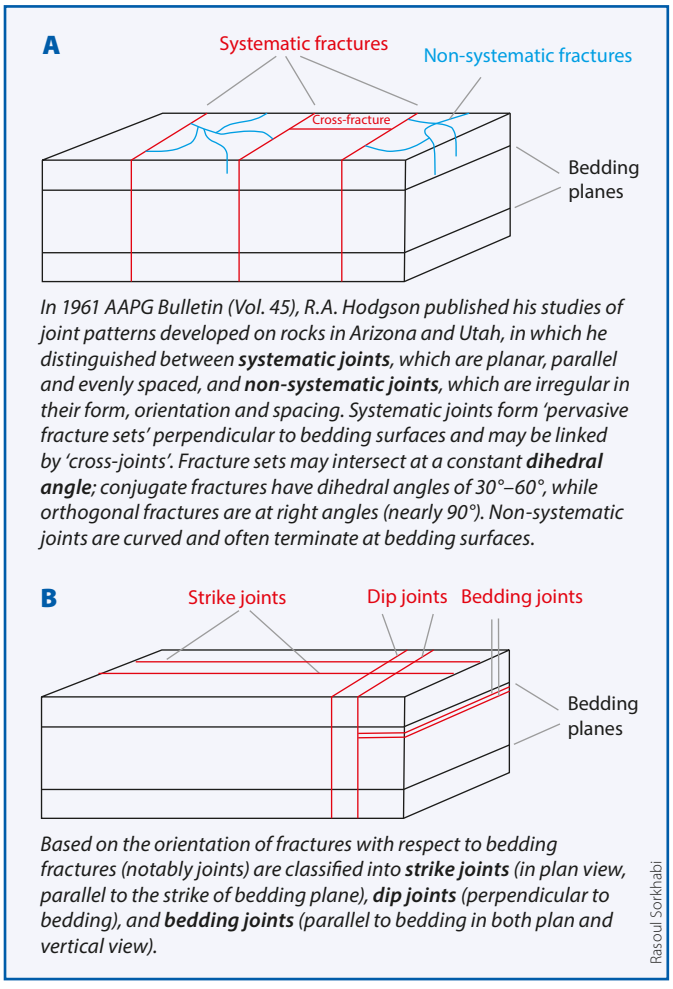
A geometric classification of fractures into longitudinal, transverse (cross), conjugate, diagonal (oblique), and orthogonal fractures developed on a fold structure. These field-based concepts were formulated by geologists in the first half of the 20th century. Modified from Singhal and Gupta, Applied Hydrogeology of Fractured Rocks (2010).



Fracture Characterisation

A comprehensive fracture characterisation involves mapping, measuring and documenting a number of parameters including the following:

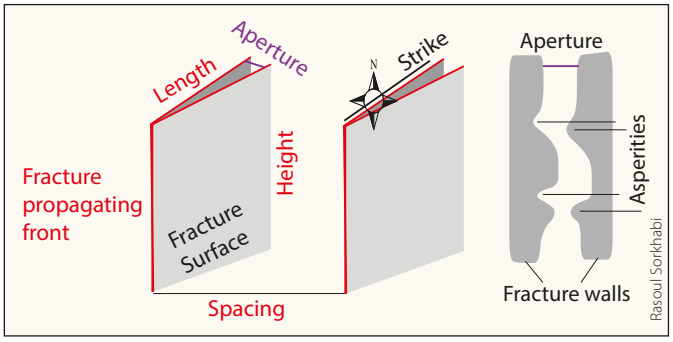
1. **Type** of fracture and its **infilling** (whether open or filled).
2. Association of fracture with particular **lithology, structure** (fault, fold or no structure), deformation history (**age**), and present (in-situ) **stress field**.
3. Systematic rock fractures often develop in one or more **fracture sets**. It is important to map and quantify these fracture sets and work out their relative ages.
4. Attitude of fractures include **strike** (with respect to North) and **dip** angle (from 0° horizontal to 90° vertical) and direction (dip direction is always perpendicular to strike direction). These data can be displayed on stereographic equal-area plots. Fracture strike trends can also be plotted on a rose diagram or a histogram.
5. **Fracture length** indicates the lateral persistence of the structure. Trace lengths of <1m are very low persistence, while those of >20m are very high persistence fractures.
6. **Spacing** of fractures and its relation to bed thickness or structural position (fault-related, fold-related, or none) are crucial data. At outcrops, fracture spacing can be measured by a tape along a scanline. Observations show that very stiff layers have more joints than very weak layers; and for a given lithology, thinner beds have closely-spaced joints. The International Society for Rock Mechanics (ISRM) has recommended the following scale for classifying fracture spacing: extremely close spacing (<0.02m), very close spacing (0.02–0.06m), close spacing (0.06–0.2m), moderate spacing (0.2–0.6m), wide spacing (0.6–2.0m), very wide spacing (2.0–6.0m), and extremely wide spacing (>6.0m). Fracture frequency is defined as the number of fractures per metre length. It is thus the inverse of fracture spacing. **Fracture frequency** is equal to 1/fracture spacing.
7. **Population**: The occurrence of fractures can be quantified in 1D (fracture frequency for a given length), 2D (fracture intensity for a given area), and 3D (fracture density for a given volume).
8. **Aperture** is the perpendicular distance between the adjacent rock walls (fracture surfaces) of a fracture. It may be open (containing air, water or other fluid) or closed (infilled by fault rock or some other injected material). Aperture may be tight (<0.25mm) for closed fractures or wide (>10mm) for open fractures. Aperture decreases along the length of a fracture toward the fracture front. Aperture may also change along the height of a fracture due to asperities (see below). Often the terms 'equivalent', 'hydraulic', and 'mechanical' apertures are used depending on the methods and purpose of their estimation.
9. Fracture walls do not have perfect parallel, smooth surfaces but contain roughness and irregularities called **asperities**, which reduce fracture permeability. Some knowledge of asperities may thus help better modelling of fluid flow through the fracture.
10. **Fracture stiffness** (measured in Pascal/mm) describes the stress-deformation of the fracture with respect to normal stress (normal stiffness or resistance to closure) and shear stress (shear stiffness or resistance to shear displacement). Data on fracture stiffness are hardest to obtain because they involve geomechanical laboratory or in-situ experiments of fractured rocks.
11. **Fracture connectivity**: intersection of natural fractures provides a permeability network for fluids, whereas disconnected, isolated fractures are not hydraulically effective. The chance of fracture connectivity increases with larger population and lengths of fractures in a given rock volume.
12. **Petrophysical properties** of fractures including porosity and permeability.



*In 1961 AAPG Bulletin (Vol. 45), R.A. Hodgson published his studies of joint patterns developed on rocks in Arizona and Utah, in which he distinguished between **systematic joints**, which are planar, parallel and evenly spaced, and **non-systematic joints**, which are irregular in their form, orientation and spacing. Systematic joints form 'pervasive fracture sets' perpendicular to bedding surfaces and may be linked by 'cross-joints'. Fracture sets may intersect at a constant **dihedral angle**; conjugate fractures have dihedral angles of 30°–60°, while orthogonal fractures are at right angles (nearly 90°). Non-systematic joints are curved and often terminate at bedding surfaces.*

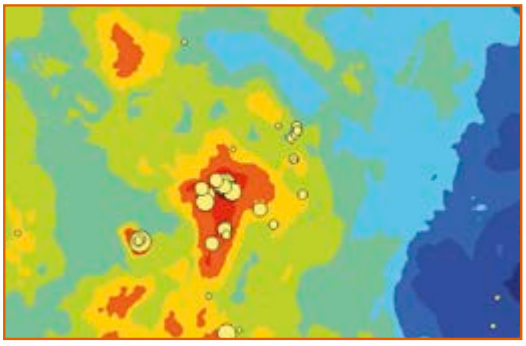
*Based on the orientation of fractures with respect to bedding fractures (notably joints) are classified into **strike joints** (in plan view, parallel to the strike of bedding plane), **dip joints** (perpendicular to bedding), and **bedding joints** (parallel to bedding in both plan and vertical view).*

Anatomy of rock fractures.



Nowhere to hide in Tioga County

Multi-measurement imaging reveals secrets of the elusive Marcellus



Sweet spot map (zoom) over a roughly 200-square-mile area in Tioga County, Pennsylvania. Hot colors indicate areas most similar to best producing wells in the region. Circles are sized to the first six months of production for all horizontal wells.

Thanks to unconventional drilling and extraction techniques, the Appalachian Basin has experienced a multi-billion dollar economic resurgence. In Tioga County, Pennsylvania, a methodology called Multi-measurement Interpretation (MMI) has been introduced by NEOS GeoSolutions to provide a better understanding of the basin.

NEOS acquired airborne geophysical data – magnetic, electromagnetic (EM), radiometric, gravity, and hyperspectral – over 1,000 square miles of Tioga County. These data were integrated with existing geophysical, geochemical, and seismic measurements from various public domain and third-party sources and interpreted by NEOS and operator geoscientists. This low-impact, environmentally friendly approach revealed subsurface features from the basement to the surface, helping explorationists pinpoint the sweet spots and avoid shallow gas geo-hazards in the play.

Using hyperspectral analysis, which classifies substances on the surface based on unique spectral signatures associated with the reflectance and absorption of both visible and invisible light, interpreters located numerous oil seeps and gas plumes. Of these, 90% were verified by geo-technicians on the ground. The seeps and plumes were then traced back into the subsurface along various pathways, including faults that had been mapped using an analysis of magnetic, seismic, log, and EM data.

Airborne EM resistivity measurements provided insights into both lateral and vertical resistivity variations throughout the geologic column, down to roughly 10,000 feet. When the EM voxel was depth-sliced at the Marcellus interval, geoscientists noted that resistive hot spots in the Marcellus corresponded to many of the county's 'best well' locations.

In addition to analyzing the airborne datasets, geoscientists on the project also incorporated more traditional geophysical measurements into the interpretation. Well logs were analyzed to enhance structural control and to calibrate the airborne EM data. Seismic data were incorporated into the regional structural model and, in combination with the magnetic and EM data, provided insights into how faults were creating pathways for hydrocarbons to migrate toward the surface.

Finally, a cutting-edge geostatistical technique called predictive analytics was applied. The technique allowed geoscientists to mine all geo-datasets for subtle patterns and correlations that corresponded to the best wells, and to then pattern search for similar 'correlative attributes' in areas that had yet to be drilled. This helped the project's underwriters to optimize their leasing, drilling, and hydraulic fracturing programs and to target future ground-based geophysical acquisitions in the most promising areas.

MMI has captured the attention of the region's major E&P producers. Since the early surveys in Tioga, NEOS has undertaken additional projects in Pennsylvania, compiling nearly 5,000 square miles of available regional data that are delivering unique, cost-effective insights into the Marcellus and Utica shale plays.

▶▶▶ To learn more about this project or others in the *Unlock the Potential* series, visit: www.ThePotentialUnlocked.com

HIGHLIGHTS

KEY TECHNOLOGIES:

- MAGNETIC
- PASSIVE-SOURCE EM
- RADIOMETRIC
- GRAVITY
- HYPERSPECTRAL
- PREDICTIVE ANALYTICS

AREA: Appalachian Basin, Pennsylvania

CUSTOMER: Supermajor

FOCUS: Regional Mapping

TYPE: Unconventional

KEY INTERPRETIVE PRODUCTS:

- Regional resistivity voxels down to 10,000 feet
- Maps of lineaments, fault networks, and intrusives
- Maps of regional prospectivity derived via predictive analytics

CUSTOMER BENEFITS:

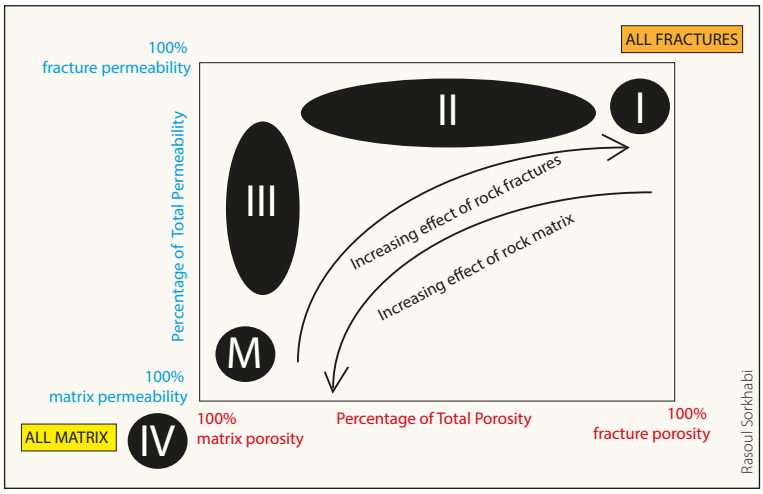
Cost-effective regional insight depicting the most (and least) prospective areas for leasing, drilling, or further geological and geophysical (G&G) study.

Fractured Reservoirs

All reservoir rocks are fractured to some degree and usually by more than one process. Nevertheless, the term 'fractured reservoir' refers to a tight reservoir (matrix permeability < 0.1 mD) in which natural fractures play a significant permeability role for fluid flow (water, oil or natural gas). In these reservoirs, therefore, the mapping and characterisation of fractures in a 3D geological model and the quantification of the petrophyscial properties of fractures is of paramount importance for drilling and production.

In his book *Geologic Analysis of Fractured Reservoirs*, Ronald Nelson has described a classification of reservoirs based on the porosity and permeability of both rock matrix and fractures. Four types are thus distinguished:

- In **Type I reservoirs**, fractures provide the essential porosity and permeability (e.g. Amal field, Libya; Ellenburger fields, Texas). These reservoirs have high declining curves per well.
- In **Type II reservoirs**, fractures provide the essential permeability (e.g. Agha Jari field, Iran; Rangely, Colorado).
- In **Type III reservoirs**, fractures contribute to the permeability of an already producible reservoir (e.g. Kirkuk, Iraq; Cottonwood Creek, Wyoming).
- In **Type IV reservoirs**, fractures actually act as fluid barriers (e.g. Beaver Creek, Wyoming; Houghton, Kansas). These reservoirs are structurally compartmentalised.



Classification of reservoirs based on petrophysical properties of rock fractures. Modified from Ronald Nelson, Geologic Analysis of Fractured Reservoirs (2001).

Subsurface fractures always pose a challenge to exploration and production. In the petroleum, geothermal and groundwater industries, therefore, a wide variety of materials, tools and techniques are utilised to identify, map and characterise fractures. These include basin tectonics, outcrop analogues, cores, borehole imaging logs, seismic sections, in-situ stress data, well flow tests, geomechanical experiments, and so forth. ■

References available online

Fractured granite in Cornwall, UK.

Completing the Picture

JAMES DODSON, ARKeX

Enhancing the understanding of the Barents Sea with full-tensor gravity gradiometry

The Barents Sea represents one of the largest areas of continental shelf on the globe and is a structurally complex region, composed of platform and basinal areas. The Barents Sea is surrounded by a series of known hydrocarbon basins, such as the North Sea, Sverdrup Basin, the North Slope of Alaska, the Western Siberian Basin and the Timan-Pechora Basin and hence is an obvious target for extensive exploration.

Since 2011, after the treaty between Norway and Russia on the maritime delimitation of the Barents Sea and Artic Ocean was agreed, the South Eastern Barents Sea frontier area has opened up for hydrocarbon exploration. The Norwegian Petroleum Directorate (NPD) has acquired a large scale multi-client 2D seismic dataset over the entire 44,000 km^2 of newly opened acreage. There are also plans in the pipeline for targeted 3D seismic surveys over nominated blocks that are currently being acquired and due to be completed mid-2015, shortly before the licence round bids are due to be submitted. Multi-client seismic surveys are an established tool in frontier exploration and for supporting licence rounds. Full-tensor gravity gradiometry (FTG) surveys are now also being offered under a multi-client business model, and are having a significant impact.

The structural complexity and sheer size of the Barents Sea lends itself to an FTG survey, both for a regional understanding and for several specific geological environments where FTG would provide uplift to the pre-existing and planned seismic surveys and interpretations. To this aim, ARKeX are currently acquiring a 42,784 km^2 multi-client FTG survey over the entire South Eastern Barents Sea that will be fully processed and ready for delivery in August 2014.

What is FTG?

FTG measures the spatial rate of change of the Earth's gravitational acceleration in response to small variations in subsurface density. An FTG dataset can essentially be thought of as a high resolution, broad bandwidth gravity survey that also benefits from a high signal-to-noise ratio at the majority of wavelengths when compared to conventional gravity when acquired from a moving platform.

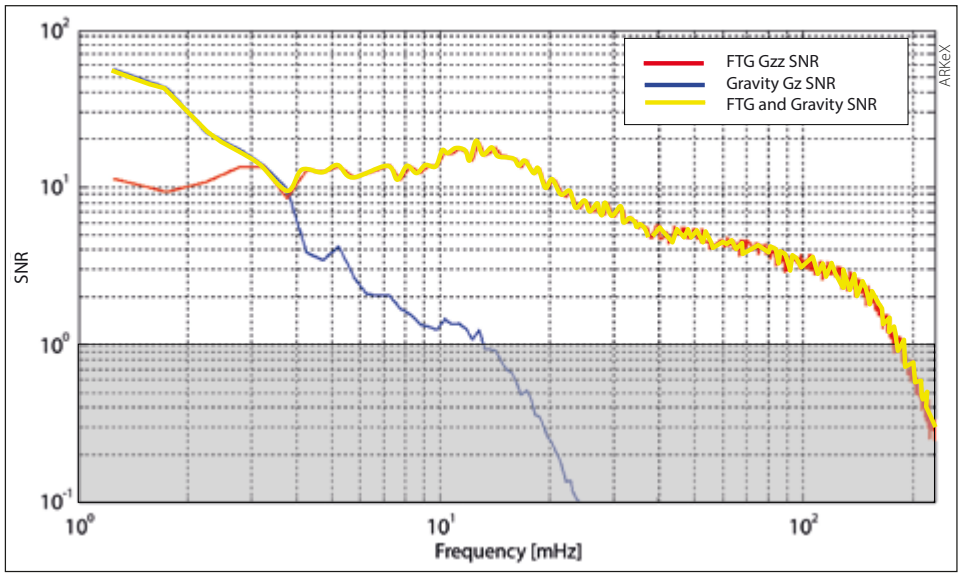
Integrated Gravity Measurement Assembly (GMA) data is acquired and processed simultaneously, which provides explorers with a high quality conventional gravity product. This is used in conjunction with the FTG data as it provides a slightly better signal-to-noise ratio (SNR) at very long wavelengths when compared to FTG. ARKeX utilises the best of both signals, combined with advanced processing techniques to provide the very best data fidelity at all frequencies.

FTG and GMA data is best when integrated with other geophysical datasets, particularly seismic. Typically, where seismic data encounters

The Glomar Arctic *was used for the FTG surveys in the Barents Sea.*

illumination difficulties, FTG data often benefits from favourable geology where lateral density contrast is evident. This includes scenarios containing carbonates, salt, volcanics and highly structured and/or heterogeneous basements. Similarly, the interpretation of FTG data benefits from integration with seismic, which provides vertical constraint to what would otherwise be a non-unique solution. This is also true of well data.

FTG surveys are very cost-effective and benefit from fast acquisition and processing rates. This enables explorers to acquire a high quality 3D dataset over large areas prior to making exploration and bidding decisions. FTG can be acquired on an airborne or marine platform and is a passive system, making it a safe and environmentally discreet geophysical survey.



Graphic representation of the signal to noise ratio of conventional airborne gravity and FTG. The blue line shows the rapid drop in signal of the conventional signal, compared to the red line that represents the much better signal to noise ratio of FTG at shorter wavelengths. The yellow line represents the 'best of both', which ARKeX uses to attain the best data fidelity at all frequencies.

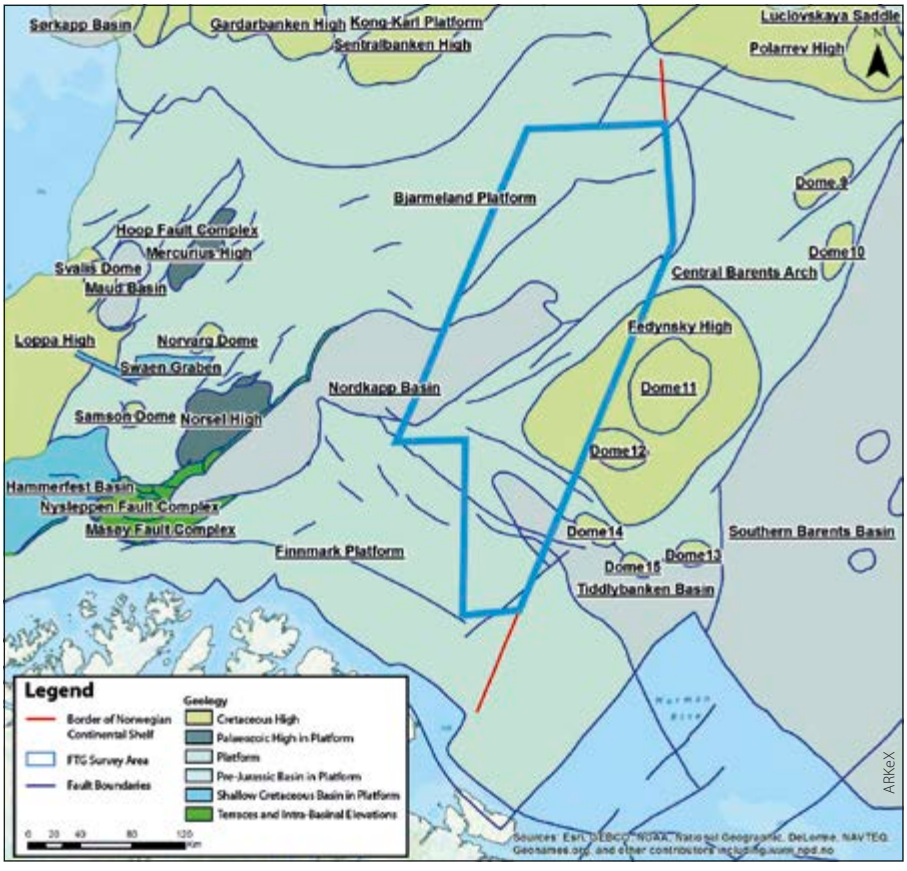
Barents Sea Geology

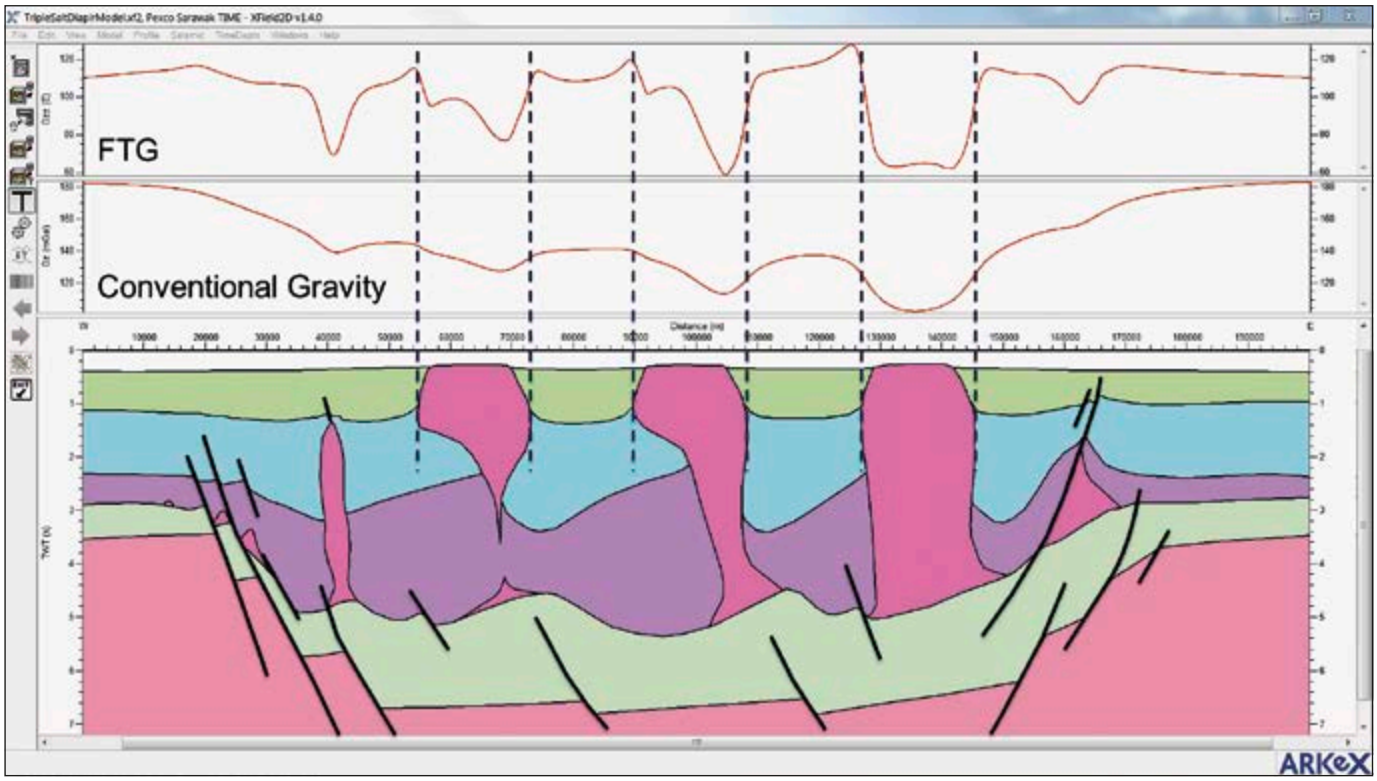
The Barents Sea has two major deep-seated structural trends as a result of two continental collision events, which dominate the tectonic fabric of the region. The first trend formed during the Caledonian Orogeny when the collision of the Laurention and Baltic plates closed the Iapetus Ocean. The second collision was between the Laurasian continent and Western Siberia, during the Uralian Orogeny. These deep structural trends have a profound influence on the basement structures within the region and on the more recent development and structure of the overlying basins and platforms.

The two dominant structural fabrics of the region can be seen in the north-east to south-west trend of the Nordkapp Basin, as a result of the Caledonian Orogeny, and the north-west to south-east trend of the Tiddlybanken Basin, as a result of the Uralian Orogeny. These basins are surrounded by the three structural highs with the Bjarmeland Platform to the north, the Finnmark Platform to the south and the Fedynsky High in the east. The fact that two major structural trends appear within a relatively confined area suggests that the complexity of the region is significant here.

The overburden within the Barents Sea is relatively thin due to the region having been through an extensive period of uplift during the Cenozoic, which removed the majority of the Cretaceous and Paleogene and had a profound effect on any potential hydrocarbon accumulations. Implications include whether the play is oil or gas, the quality of the main Jurassic reservoirs, and the possibility of once oil-filled reservoirs being empty because of spillage due to tilting, seal leakage or exsolution of gas,

The ARKeX FTG survey covers five distinct structural highlights: the Finnmark and Bjarmeland Platforms, the Nordkapp and Tiddlybanken Basins and the Fedynsky High, all of which represent hydrocarbon exploration opportunities. The structural elements of the region are also labelled.





Schematic 2D cross-section, designed to reflect three possible salt interpretations of a seismic section through the Nordkapp Basin. The change in salt volume has a significant impact on the FTG signal amplitude, including over asymmetric diapirs. The edges of the salt are easily delineated and this will be extrapolated into 3D.

forcing the oil from the traps.

Due to the complexity of the area, it is extremely important for the explorer to understand the deep-lying structural geology as well as the shallower target levels to fully define and de-risk the plays. The tectonic history of the region will play an important part in predicting the hydrocarbon type, reservoir quality and trap integrity. FTG, alongside conventional gravity and seismic data, allows the explorer to shed light on tough geological and geophysical environments both at significant depth and in the relative shallow, for an enhanced regional understanding and down to prospect scale.

FTG Advantages

Salt Definition: The South Eastern Barents Sea contains two salt basins, Nordkapp and Tiddlybanken, which are the most obvious areas for utilising an FTG survey as the salt structures can be delineated clearly and salt volume constrained. The large, sub-vertical, diapiric salt structures in the Barents Sea are relatively shallow, often reaching the sea bed. The large density contrast between the salt and surrounding sediments, along with the shallow salt dome depths, allow the salt flanks to be defined extremely accurately using FTG data, resulting in enhanced seismic interpretations.

Previous interpretations of seismic in the Nordkapp and Tiddlybanken Basins have typically included a very large volume of salt. This interpretation has a large potential for error, due to salt illumination problems in seismic data, but nevertheless it has limited the prospectivity of the basins and in particular the salt plays themselves. Using FTG and GMA data, the volume of salt can be constrained better, with necking, overhangs and detached salt bodies being imaged and interpreted far more confidently than with seismic alone. Refining the salt bodies in the Nordkapp and Tiddlybanken Basins could potentially open the acreage up for new salt plays.

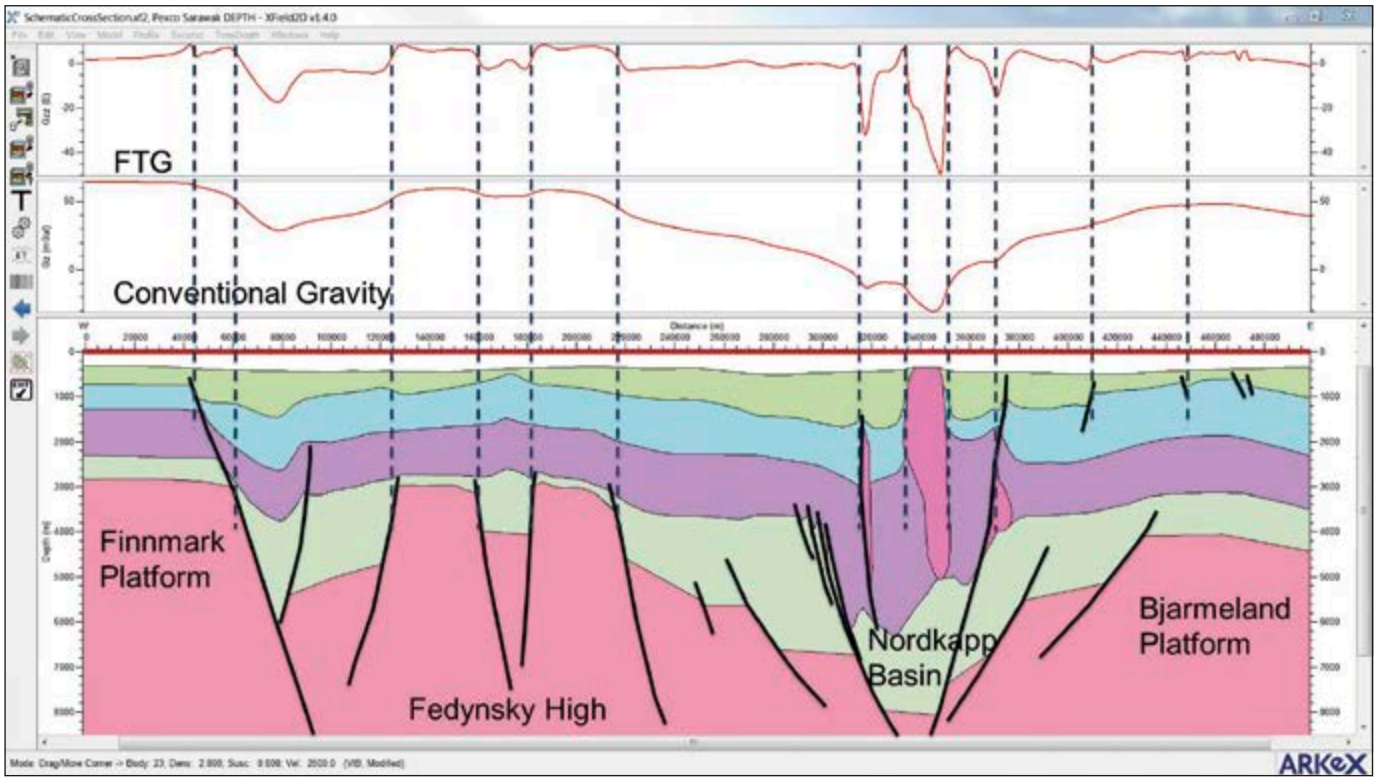
FTG and conventional gravity datasets are also used for sub-salt interpretation where previously unknown basement structure can be resolved. Once the salt bodies have been accurately modelled using the FTG data, the resultant long-wavelength residual signal must originate from deeper structural bodies, most likely the basement.

A further result of improved salt body definition is the potential for providing a better velocity model around and below the salt structures, which allows for subsequent enhanced seismic processing and, therefore, imaging.

Sub-Carbonate Illumination: The Barents Sea contains extensive Permian carbonates that appear to extend over the entire area. As seismic data often has illumination problems sub-carbonate, this provides another opportunity for an FTG dataset to contribute to the structural modelling of the region.

Similar to sub-salt imaging, despite the often high density nature of carbonates, FTG will pick up the signal from the deeper lying structural variation as well as the shallower carbonate structures. This is particularly useful in the structural high areas in the Barents Sea, such as the Finnmark and Bjarmeland Platforms and Fedynsky High, where accurately modelling the basement and overburden structure is the primary geological question.

Basement Modelling, Overburden and Seismic 2D/3D Extrapolation: In the platform areas of the South Eastern



Surmised cross-section of the different structural elements that will be seen in the Barents Sea FTG survey. The salt, as before, is clearly seen, as are the basement highs in the Fedynsky High. The Tiddlybanken Basin will show a similar profile as the Nordkapp example and the shallow faulting in the Bjarmeland Platform is also well imaged.

Barents Sea, as well as the Fedynsky High, previous exploration of relatively shallow structures in the Permian Carbonates and Lower Carboniferous sandstones has reported residual oil shows. There is also potential in Upper Jurassic sandstones immediately below the Base Cretaceous Unconformity, where there are potential flat spots and gas leakage.

The South Eastern Barents Sea has very good 2D seismic coverage and the 3D seismic surveys currently being acquired will cover large areas of the newly opened acreage. This seismic data is, and will be, an excellent tool for interpreting faults in the shallow section. As described above, FTG and GMA data can help image features where seismic struggles, but it is also an excellent tool for linking together 2D seismic interpretations and/or 3D seismic models by extrapolation and interpolation.

The multi-client 2D seismic survey has a line spacing of approximately 5 km over the majority of the region and the combined 3D surveys will cover about 13,700 km^2 over an area of roughly 44,000 km^2. Shallow faulting, interpreted only using seismic datasets, can be linked by simple extrapolation along a straight line to the next interpreted line. In reality, faults are rarely straight lines and FTG data can be used to provide a full 3D fault answer, interpolating between lines and surveys to more accurately reflect the geology. This is not only important for better modelling of the faults and shallow structures and targets, but in forming a more complete understanding of the regional structural framework, ensuring the correct trends are being picked.

Similarly, the basement structure can be modelled between 2D seismic lines and 3D surveys. Some of the blocks recently announced are located on the faulted flanks of the Nordkapp and Tiddlybanken Basins. FTG, along with conventional gravity datasets, is a powerful tool for creating comprehensive structural models in areas of basement faulting, where the basement/sedimentary fill interface provides an excellent density contrast and target for FTG data.

Exciting Frontier Region

The newly opened acreage in the Barents Sea is an exciting frontier region, in a generally well known region of the globe. Prior to the submission of licence round bids, companies are generating an understanding of the tectonic history of the region, building structural models, and generating play and prospect opportunities using multi-client datasets. Key to this is seismic interpretation through the pre-existing 2D data and the future 3D surveys; however, it is also clear that ARKeX's multi-client FTG survey also adds a significant amount of information and clarity to this geologically complex region and in a timely fashion.

Whilst FTG technology is still relatively under-utilised, there is a rapidly growing list of oil companies that have come to recognise the value of the technology at all phases of the exploration cycle. FTG is a powerful tool in almost any geological environment, but also represents a cost-effective way of covering vast areas of the globe in a much reduced timeframe compared to seismic. ARKeX's Barents Sea survey will provide an enhanced 3D understanding of the region, whilst also being available almost a year before the official bid round applications are submitted, allowing explorers to make a significantly more informed decision. ■

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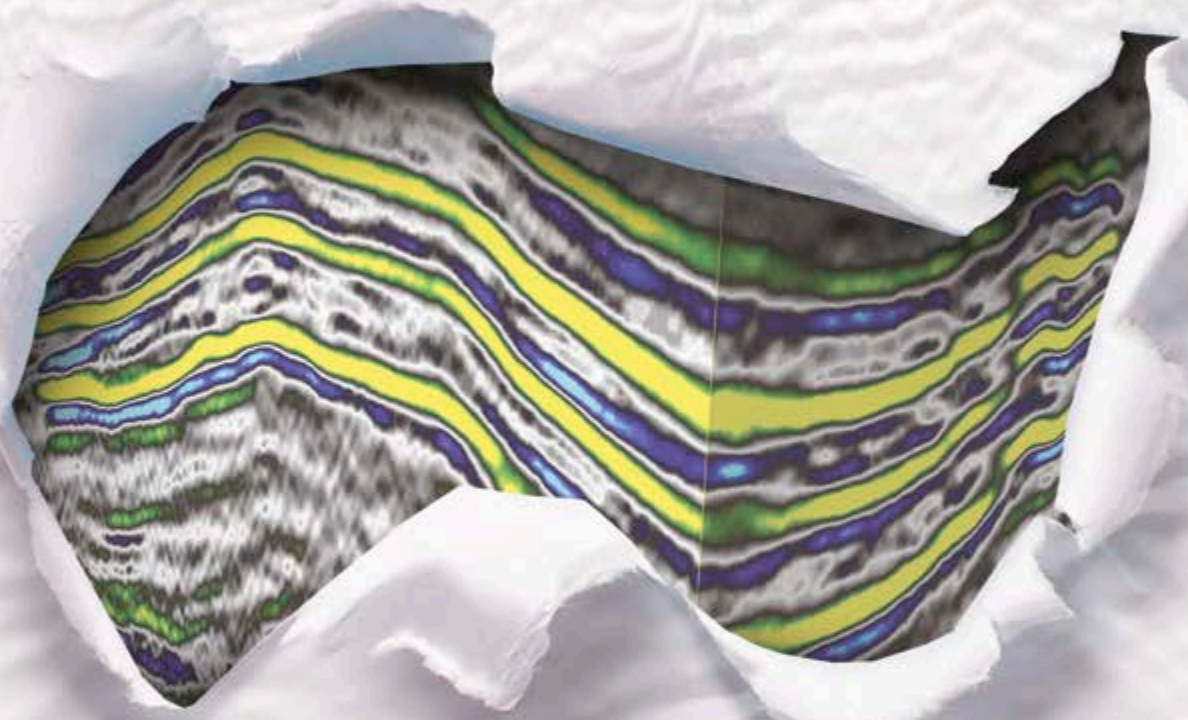

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Takoradi: Ghana's Oil City

Oil has been the catalyst for investment, reviving Takoradi's fortunes as an export hub for Ghana's many resources – but benefits to the local economy remain elusive.

NIKKI JONES

For the casual visitor, reports of Takoradi's 'booming economy' appear greatly over-stated. Smaller than Accra, it remains low-rise and relatively free of the shiny four-by-fours that clog up the capital. The presence of oil production and service companies is relatively discreet. However, it is the prospect of significant off-shore oil production that has turned round the city's fortunes over the last ten years, providing the catalyst for a major dredging and modernisation of the port facilities and a rapid expansion of the city. As new oil fields come on-stream over the next ten years, what chance that Takoradi will continue to develop and grow?

Twin Cities Divided

The area is more accurately known as Sekondi-Takoradi, a twin development of two neighbouring harbours that together have seen over 400 years of Europe-orientated commercial activity. Both benefitted from the building of deepwater port facilities in 1928, but by the 1960s the twin towns were running a poor second to the facilities at Tema, east of Accra. Oil has now firmly divided the two, reversing the decline of Takoradi but leaving Sekondi as the generally unvisited junior partner holding the consolation prizes of a low-tech fishing industry and a quiet naval facility.

Meanwhile Takoradi has become a rejuvenated commercial hub. The expansion of the port began ten years ago and continues today with the building of new quay walls and extended breakwaters. An estimated 70% of Ghana's exports are now handled by the port and the docks are dominated by activity surrounding the export of Ghana's many resources, including timber, manganese, bauxite and cocoa – as well as the vast Maersk containers bringing in the imports on which Ghana, and land-locked countries to the north, have come to depend.

Although oil has been the catalyst for the port's redevelopment, Ghana's oil does not, of course, come onshore – the Jubilee field produces 60 km off the coast using a FPSO. Development of the TEN (Tweneboa-Enyenra-Ntomme) fields is unlikely to alter this scenario since another FPSO is currently being adapted in Singapore, ready for production to begin in 2016.

The bustling fishing harbour of Sekondi (top) looks very low tech when compared to the newly redeveloped commercial port at its twin town, Takoradi (bottom).

City Expansion

Although Takoradi may so far have escaped the anonymous high-rise office blocks, oil has brought a housing boom and rent inflation, a down-side of living in this rejuvenated town. Ex-pat housing can run to US$40,000 per annum and demand has led to the cutting down of large areas of forest and a building boom. 'Land grabs' from those who do not have written title deeds and rent 'gazumping', forcing out low-paid professionals, have been widely reported.

Surprisingly perhaps, many new-build homes stand incomplete with few signs of activity: this is the result of the Ghanaian culture of building in stages since mortgages are generally unavailable, and also the result of Ghana's recession that is closely linked to the early 2014 currency crisis and lower-than-expected oil production. The net effect is a large area of isolated houses at various stages of completion, separated by unmade roads and scrub. Municipal infrastructure has not kept pace with development, evidenced by the prevalence of polytanks for water storage and private generators to avoid electricity 'load-shedding'.

For the majority, little of the new wealth is trickling down into the local economy. Incomes remain a typical US$1–2 a day and street life is dominated by the dawn-to-dusk hawking

of food products, lottery cards and phone top-ups. An interesting development, however, is the proliferation of foreign and Ghanaian banks, many of which appear to be targeting the poorest with micro-finance and micro-insurance schemes. Many of the least wealthy traders and taxi drivers are now able to save with a bank and some have ATM cards: they are considered such a valuable source of funds that many banks send out staff at the end of each day to collect the workers' profits, often a mere ten cedi (£2.50). Fortunately for the Ghanaian economy, anecdotal evidence is that the poorest workers remain wary of taking on loans and simply save: the high-risk household debt seen in other emerging economies does not yet appear to be a problem for Ghana.

Future Prospects

Despite shortages of the most basic services – water, toilets, electricity, surfaced roads – the people of Taadi (as the city is known locally) remain remarkably tolerant and warm-hearted. Crime, as in all Ghana, is relatively rare – although the demand for 'dash' at police road blocks is a notable and recurrent complaint. Moslems and Christians are well integrated and life is characterised by an absence of aggression – even in the somewhat chaotic driving. Inevitably there is a frustration with government and a perception that oil revenues are being mismanaged: the good news for Ghana is that its history of military interventions seems long gone, democracy and civil society are well established and regional divisions are minimal.

Civil unrest may be a remote possibility but clearly Ghana's oil boom is fragile. Unemployment and under-employment are the facts of life here. Happily, it appears that the government is set to deliver one very real benefit from oil production: summer 2014 should see the completion of a Chinese-built pipeline, gas processing plant and an extra 132MW of capacity at the electricity plant 17km east of Takoradi. They will take associated gas from the fields, help stabilise electricity production and eliminate the current need to burn $1bn worth of oil annually for power.

In general, politicians and oil executives are keen to stress that 'expectations' need to be 'managed': however Ghanaians are acutely aware of their poverty and lack of basic infrastructure and all eyes are on the government and conversely, *their* management of revenues. For the people of Takoradi there will be particularly keen scrutiny since so much of their 'boom' has been built on investments to facilitate commodity exports. The local economy appears particularly vulnerable to a global downturn in demand – and for the majority there is no 'cushion', only the rather uncertain prospect of increased oil-related employment and export-related investment. ■

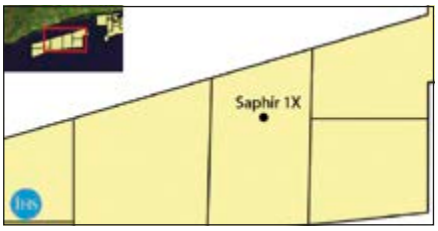
Evidence of new wealth coming into Takoradi – a plethora of half-built houses.

Nikki Jones

Côte d'Ivoire: Key Deepwater Find

Although untested, the **Total**-operated **Saphir-1XB** in **Block CI-514** is described as an important discovery in a frontier part of deepwater offshore **Côte d'Ivoire**, as it has demonstrated a working petroleum system. Located in a water depth of 2,300m, the well was drilled to a total depth of 4,655m. It encountered a series of thick sands of approximately 350m, containing a hydrocarbon column of about 40m high of 34° API light oil. Marc Blaizot, Senior Vice President, Exploration commented: "Drilled in an abrupt margin play, this first well is the first discovery in the San Pedro Basin, a frontier exploration area in Ivory Coast. Having confirmed the presence of a petroleum system containing light oil, we will next evaluate this very promising find and focus on its extension to the north and east."

Côte d'Ivoire's Prime Minister Daniel Kablan Duncan remains bullish about reaching a previously-announced target of 200,000 bopd by 2019 despite a recent drop in output due to technical issues and a political crisis in 2010–11 that forced companies to invoke force majeure. In recent years the country has lost its competitive edge to neighbouring Ghana in attracting upstream investment. However, Total



recently announced plans to spend up to US$300 million drilling exploration wells in contiguous ultra-deepwater blocks CI-514, CI-515 and CI-516, which cover nearly 2,300 km². In addition, Lukoil, Total, Tullow and Vanco have all announced discoveries in the Côte d'Ivoire Basin since mid-2012. ■

Russia: Major Reserves Boost

Appraisal drilling by **Gazprom** at its **Kirinskoye Yuzhnoye** field in the **Okhotsk Sea** off **Sakhalin Island** has resulted not only in the addition of gas reserves, but also in the discovery of a big oil pool that should allow increasing 3P reserves 'in the order of tens of millions of tons'.

Discovered in 2010, the field is located in 110 to 320m of water and is due to be commissioned in 2018. As part of the Sakhalin III project Gazprom operates three blocks: Kirinsky, Ayashsky and Vostochno-Odoptinsky. The Kirinsky block comprises the Kirinskoye gas and condensate field as well as the Yuzhno-Kirinskoye and Mynginskoye gas and condensate fields. To be mostly used for feeding the Sakhalin-Vladivostock gas transmission system, gas from the Sakhalin III project will ensure supplies to Far Eastern regions and help execute the Vladivostok LNG project. However, if the oil rim is confirmed, Gazprom may need to revise its plans.

Gazprom is investing heavily in developing new fields on Sakhalin Island and in East Siberia as part of the Eastern Gas Programme, which aims to gasify Russia's remote eastern regions and to develop the gas production and transport capacity needed to achieve Russia's goal of exporting gas to Asian markets.

In order to maintain high rates of infrastructure development in eastern Russia, Gazprom is cooperating with state authorities to create a favourable tax regime and streamline pricing

mechanisms in the domestic market as well as introducing other state measures to support eastern projects. ■

Exploratory drilling in the Kirinskoye Yuzhnoye field.

Congo: Significant Westward Extension

Eni's Nene Marine 3 exploration well in the offshore **Marine XII Block** encountered a significant wet gas and light oil accumulation in the pre-salt clastic sequence, thereby outlining a significant extension to the west of the reservoir. Drilled in a water depth of 28m, the well flowed in excess of 5,000 bpd of 36° API oil on a production test. This is an important result, allowing Eni to nearly double its estimates of in-place resources, which now stand at 1.2 Bbo and 1,060 Bcf gas.

The 1,103 km^2 Marine XII block is located 15 km off the Congolese coast at a water depth ranging from 20 to 50m. The fields discovered to date are Banga (gas and condensate) and Litchendjili (oil, gas and condensate) in the south-eastern sector of the permit, as well as Louvessi Marine (gas and condensate) and Louvessi Profond Marine (oil and gas) fields. In addition, undrilled prospects exist on the Djeno and Chela plays. The overall potential of the Nene Marine field and of the neighbouring Litchendjili Marine fields, which lie about 17 km off the Congolese coast, is now estimated to be 2.5 Bboe in place. The block also has a significant additional exploration upside which will be determined by the next exploratory and delineation campaign. Eni, which has a 65% stake in the block, and its partners New Age (25%) and Congo's national oil company SNPC (10%) are now evaluating the rapid commercial development of these reserves with the aim of launching first oil production in 2016.

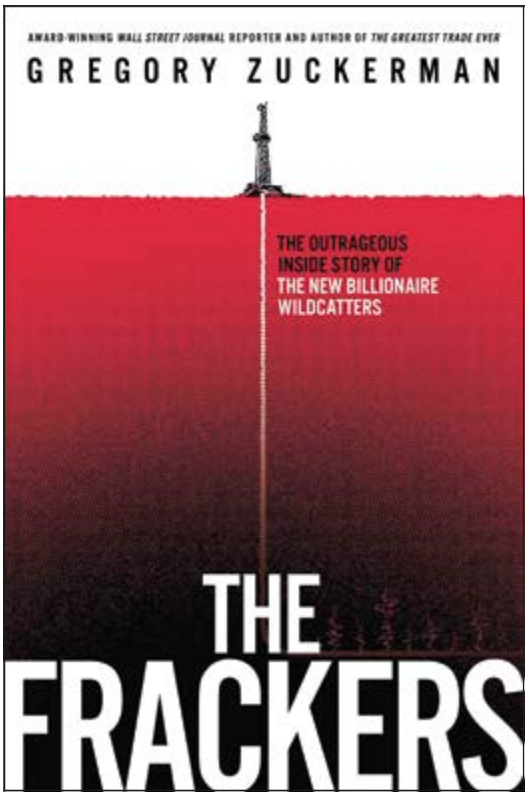
Congo is among the top five oil producers in Sub-Saharan Africa, according to the US Energy Information Administration (EIA). The country holds sizeable proved natural gas reserves but only small amounts are commercialised because of the lack of infrastructure. Oil production in Congo has been in decline for years due to maturing fields, with the ministry projecting output of 242,000 bopd in 2014. New discoveries have revived investor interest and plans for a licensing round for around 10 onshore and offshore oil blocks have yet to be confirmed. The offshore is thought to contain significant reserves of oil concealed below a layer of salt that some believe are comparable to the billions of barrels that have been found off Brazil. ■

Eni platforms offshore Congo.

Not for the Faint-Hearted

NIKKI JONES

The Frackers (2013)
Author: Gregory Zuckerman
Portfolio/Penguin



This is *the* book of our time, the story of the US shale energy revolution, told through the lives of the 'part gamblers, part salesmen, part geologists' who were at the cutting edge. For once, the term 'roller-coaster' seems completely appropriate, perhaps even a little tame. By following the personal fortunes of the key players – George Mitchell, Harold Hamm, Aubrey McClendon, Charif Souki et al. – Wall Street journalist Gregory Zuckerman tells the story not just of technical innovation but of the dangers of being in the oil and gas vanguard, the blindness of the participants to the trends they were creating and the consequent jaw-dropping fortunes made and, in some cases, lost.

The technical story is the backdrop. Zuckerman gives clear layman accounts of the geological challenges and the extraordinary coming together of a variety of technical innovations. It was Bob Hauptfuhrer of Oryx Energy who pioneered horizontal drilling in the late '80s, realising that improvements in computer imaging and seismic analysis made the increased outlay justifiable; Harold Hamm, the 'genial dreamer' who, along with his team, realised the value of combining horizontal drilling and fracking; George Mitchell and his key geologist Kent Bowker who, below the radar of the company's president, continued to experiment with fracking gel, discovering that 'less was more' for the 'secret sauce'; and Hamm at Continental Resources who perfected the formula of multi-stage fracking that allows the closing off of sections and the prolonging of well life.

The blindness of the super-majors to the potential of shale has been well documented elsewhere – embarrassingly, ExxonMobil's Irving headquarters are directly above the huge Barnett Formation. But, as Zuckerman expertly details, the individuals driving the revolution – the drillers and the money men – were also blind to the gas glut they were creating. In the 1990s, when oil and gas prices were low, adventurers such as Aubrey McClendon and Tom Ward of Chesapeake went through 'near death on a daily basis' to acquire more and more land. By the early 2000s it was as if they were playing the board game Risk, using their highly valued and incentivised landsmen – and $5.5bn of debt – to become the 'Bill Gates of energy'. As late as March 2008 the consensus was still that the world was running out of oil and gas: few realised at the time that upward prices were maintained partly by Ward and McClendon operating their own hedge fund and effectively being ten per cent of market activity.

Prices Tumble

With the subprime crisis came the 'look down' moment when McClendon realised that Chesapeake's own production could break the gas market – land was 'held by production', meaning they had no choice but to actively develop what they had acquired, sending prices down. Still, like addicts, McClendon and Ward continued to buy. The eventual, inevitable, January 2013 boardroom coup against McClendon was precipitated by a build-up of short-sellers, environmental catastrophes, law suits and, according to one investor, the 'near perfect illustration of the complete collapse of appropriate corporate governance'. This is the story of the American dream, super-charged by easy credit, finally caught short by market fundamentals.

Similar humiliation was only narrowly avoided by Charif Souki, the entrepreneur behind the LNG plant at Cheniere in Louisiana. In fact, in 2014, at the time of the Ukraine crisis, he has become the hero of the hour, the first to be in a position to start exporting US shale gas in 2015. As Zuckerman details, that is not how the dream started. As with McClendon and Ward, Souki bet on a shortfall of gas and spent seven years planning a major *import* facility, boosted at the crucial moment in 2003 by Alan Greenspan's now famous announcement that the US would require a major expansion of import capacity. Souki spent seven years raising the finance, finding the location and negotiating import deals with Total and Shell – only to be encumbered by debt, downgraded to junk status in 2007 and the target of short-sellers. By late 2008 the whole idea of importing seemed preposterous and Souki faced ruin and derision – or the challenge of raising another $12bn and converting Cheniere into an export facility. He took the latter – even though he still did not actually have permission to build and an export licence came only in 2011!

The Frackers is, in the end, an analysis of the bizarre state of capitalism in the early 21st century, where credit can become debt in the flick of an eye and the best minds available are not able to see tides turning or cliff edges coming. Zuckerman tells the story of winners and losers with verve and detail. This is a must-read for anyone who follows financial and energy markets but it should come with a health warning: definitely not for the faint-hearted. ■

New Doctoral Training Initiative

An innovative collaboration between universities, research institutions, government funding bodies and the E&P industry promises to change the face of doctoral petroleum geoscience training in the UK. Keith Gerdes, Chair of the Industrial Advisory Board for the Natural Environment Research Council (NERC)'s Centre for Doctoral Training for Oil and Gas, tells us about this important development.

Why is this development so exciting?
The NERC Centre for Doctoral Training (CDT) is a truly game-changing initiative and represents the most exciting development in the provision of training for the energy industry in the UK that has occurred during my career. The initiative is being led and co-ordinated by John Underhill, Professor of Exploration Geoscience at Heriot-Watt University, who has developed and promoted a collaborative vision linking academic, industry and environmental interests in the oil and gas sector. The collegiate structure and inclusive nature at its heart is extremely attractive to many members of the industry and will create a 'one stop shop' for industry and academic engagement for both research and recruitment. I am delighted to be involved in such an innovative, student-centric project designed to attract and train top postgraduate talent for the future energy industry.

Why is this centre needed?
At present the academic world delivers two types of postgraduate student to the oil industry: Masters graduates, who are given access to the tools and techniques used regularly in the industry, and PhDs. The latter group have skills in critical data analysis and problem solving gained during three years of independent study, but may lack exposure to industrially relevant problems. There may also be a perception amongst those applying for PhD projects that cutting-edge research is unlikely to relate to the future challenges faced by the oil and gas industry. The CDT will provide five months of formal training, allowing students to see their projects in the broader context of the future needs and challenges facing the energy industry.

What are the aims of the centre?
The CDT is seeking to attract the best and most talented students into oil- and gas-related PhD research by providing a challenging, supportive and high level research and learning environment, which will encourage PhD graduates to join the industry and also make them highly desirable candidates for recruitment. The partnership aims to achieve a balance of PhD projects across four themes: environmental impact; extending the life of mature basins; exploring in challenging environments; and unconventional resources. These themes will be modified and new ones will emerge in future years in response to developing research and training needs.

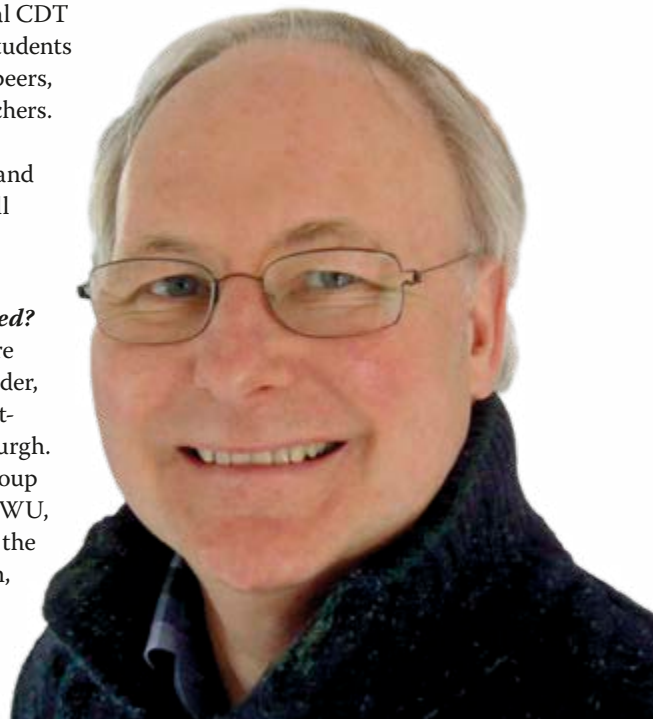
How will this be achieved?
The establishment of a Training Academy is an integral part of the CDT. This will draw extensively upon industry and academic training providers to build a structured programme of five months multi-disciplinary training during the first three years of each PhD. The Academy will cover a mix of generic and technical research skills, plus business, legal, environmental and engineering disciplines, delivered in week-long modules over the course of the studentship. It will give students the opportunity to work together in multi-disciplinary teams, a critical ability to develop for a future career in either research or the modern energy industry. The Academy and annual CDT conference will also provide the students with the chance to network with peers, industry professionals and researchers. All students will have access to industry-standard software, data and research facilities and training will also include field trips and inter-university projects.

Which organisations are involved?
The opportunity to host the Centre was the subject of competitive tender, won by a consortium led by Heriot-Watt University (HWU) in Edinburgh. The Consortium Management Group consists of seven core partners (HWU, the British Geological Survey and the Universities of Aberdeen, Durham, Imperial College London, Manchester and Oxford), all of which have extensive research programmes across a wide range of disciplines relevant to the modern-day energy industries. A further 11 UK universities (Birmingham, Cardiff, Dundee, Exeter, Glasgow, Keele, Newcastle, Nottingham, Royal Holloway, Southampton and Strathclyde) and one NERC affiliate (the National Oceanographic Centre) are Associate partners of the CDT, bringing diversity and expertise in additional disciplines to it.

How will the costs be covered?
The Natural Environmental Research Council has invested £2.7m in support of 10 PhDs and the consortium has guaranteed an additional £5.2m, allowing a total of 31 PhDs to be funded each year. The attractiveness of the CDT has already been identified by BP, Shell, BG, E.ON, Total and ConocoPhillips, who have pledged in excess of £0.88m to support the Training Academy for the first three years. Further commitment by industry and NERC is expected in the near future.

Contact John.Underhill@pet.hw.ac.uk for further details. ■

Dr. Keith Gerdes is Global Exploration Advisor for Shell International and the AAPG European Region President.



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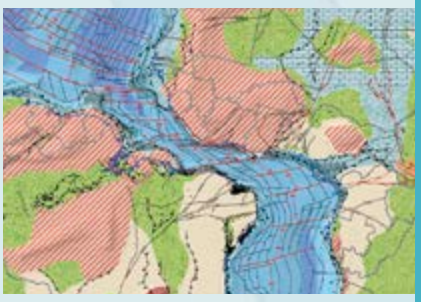

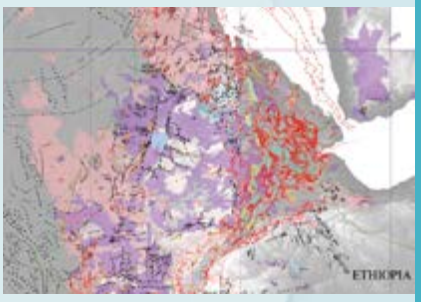

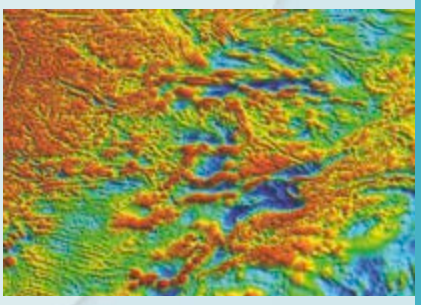

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PNG Lands on the Petroleum Map

DAVID UPTON

Papua New Guinea (PNG) is set to join the exclusive club of LNG exporting nations before mid-year when first cargoes ship from its US $19 billion LNG project. The ExxonMobil-operated facility was completed ahead of schedule and without any cost increases in almost two years, in contrast to the raft of mega-projects nearing completion in neighbouring Australia. With a two-train capacity of 6.9 million tonnes of LNG per year, the project is a modest entry by Papua New Guinea into the LNG club of countries. But one of the project's partners, Australian-based Oil Search, is already talking about being involved in the development of a number of additional trains in PNG over the next five years, which would elevate the country to a genuine mid-weight in the petroleum world.

Oil Search's central processing facility at Kutubu.

Fighting for Footholds

PNG's rapid evolution has not gone unnoticed, and already has a number of players fighting to get a foothold in the country or improve their position. Oil Search is a pioneer of the country's petroleum industry, with a history dating back to 1929 and extensive acreage in the Highlands and the Gulf of Papua, both of which are part of the Papuan Basin. It holds 29% of the PNG LNG Project, which is expected to produce more than 9 trillion cubic feet of gas over the next 30 years. The giant Hides gas field in the Highlands, an anticlinal structure 30 km long and five kilometres wide, is the foundation of the project, with gas feedstock also being drawn from the Angore field nearby and the Kutubu oil fields operated by Oil Search since 2003.

The other major gas discovery in PNG is the Elk/Antelope field in PRL15, which has been independently assessed to have a P50 recoverable raw gas resource of 7 Tfc. Singapore-based InterOil Corporation discovered the field in 2006 and, until a couple of years ago, was planning smaller LNG projects of about 2 million tonnes per annum both onshore and as floating systems. However, the company announced in December it had agreed to sell 61.3% of PRL15 to Total for between $US1.5 and $US3.6 billion, and would now pursue a world-scale LNG development with Total as operator. Two months later, Oil Search announced it had bought itself a seat at the Elk/Antelope table with the acquisition of a 22.835% interest in PRL15 from Pac LNG for $US900 million.

Corporate manoeuvring over PNG petroleum potential is only just starting. Within weeks of the Oil Search-Pac LNG deal, InterOil and Total announced they had settled on a scaled-down version of the previously announced transaction that would hand a stake of only 40.1% to Total. Oil Search immediately lodged a notice of dispute on the basis the revised deal had over-ridden its rights under the PRL15 joint venture agreement. All parties are adamant about the strength of their respective positions, and the dispute could end up in court if a commercial resolution is not achieved.

Key Geological Factors

Whatever the outcome, the arrival of Total and the start-up of PNG LNG has ensured worldwide interest in the nation's petroleum potential.

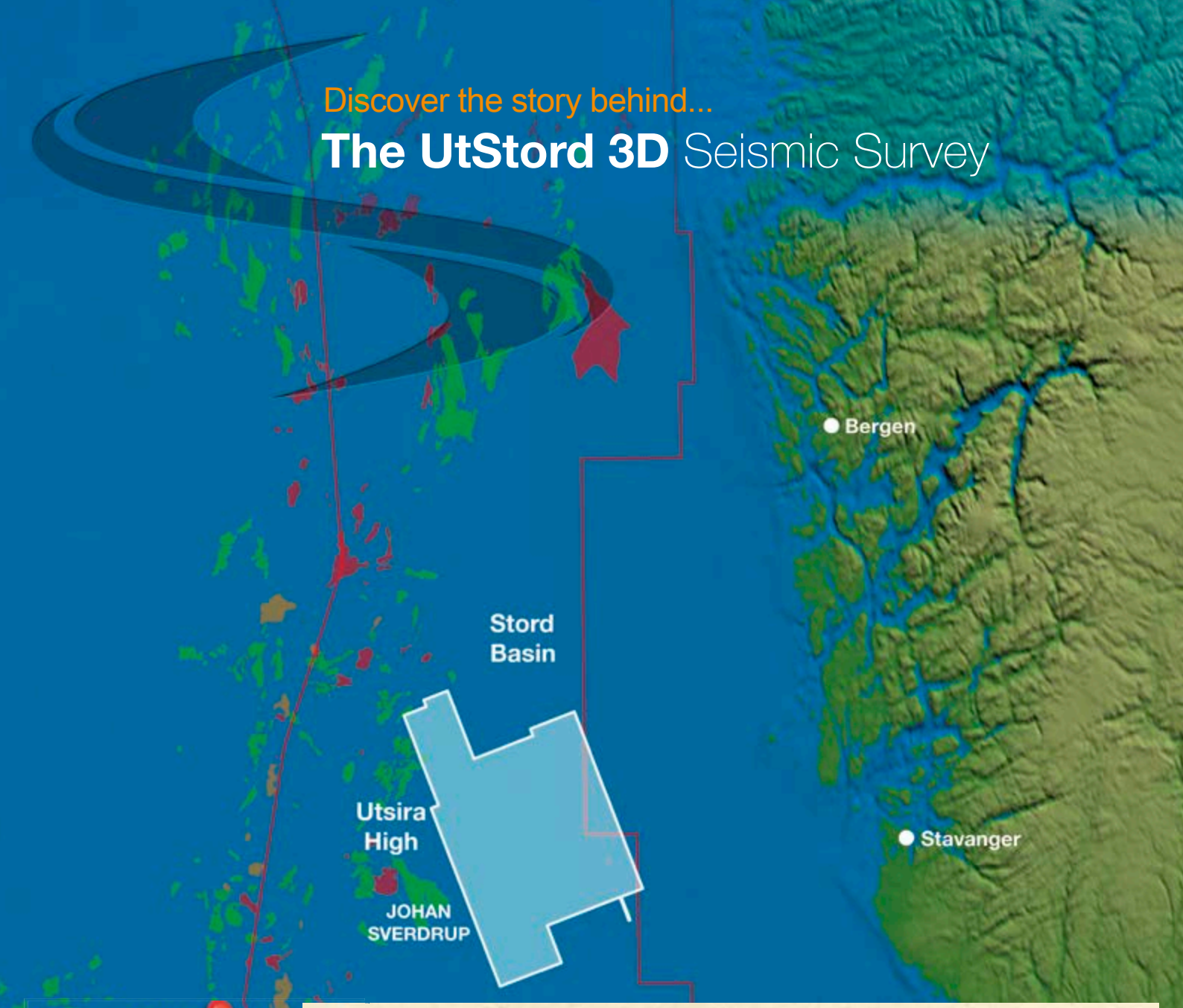
Oil Search's executive general manager, exploration and business development, Julian Fowles, told *GEO ExPro* that all of the key factors for petroleum discoveries come together in many parts of PNG.

"In the Papuan Basin, which is the focus of most of our operations in PNG, you have a good regional source rock that is mature, excellent reservoir rocks and a very effective seal horizon," he said. "The additional factor is intense folding from the strong tectonic forces near the edge of the Australian plate, which has created some very large structures such as Hides. Even though it is quite deformed, there is sufficient continuity of the regional seal. It doesn't get fractured all the time and is continuous enough to allow the hydrocarbons to be retained within these structures, with Hides, for example, having a very large gas column by world standards." ■

In the PNG Highlands, helicopters are an essential tool for field work.

Discover the story behind...

The UtStord 3D Seismic Survey



- North Sea, Norway
- 5,080 km²
- APA Acreage
- Available Q2 2014

Following the giant Johan Sverdrup discovery, industry was once again reminded that new ideas and alternate rationale are required to discover large quantities of hydrocarbons in mature areas.

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In addition, several Tertiary discoveries have been made close to the Utsira High and a further migration from this area and to the East is also likely.

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Check Your Knowledge

By 2040, the world's population will increase by about two billion. How much energy will we need to power this growth?

Did you know that China is the world's leading coal producer? No? But that's the truth; China is responsible for about 45% of the world's coal supply, while the US produces only 12%. It is also true that coal provided more than 25% of the world's energy in 2012. This is why the use of coal in power generation remains a significant challenge to greenhouse gas emissions.

Oil and gas is not only used as energy. Did you know that chemical products derived from petroleum products – from building materials to cars to medical equipment to clothing – are found in 96% of all consumer goods?

These are some of the facts that are provided by the ExxonMobil Energy Quiz. The quiz is grouped into four topics: People and Energy; Energy Resources; Using Energy; and Saving Energy. Each item has five questions with three alternatives, and after making your choice, you get the answer with up to date information and links to other websites for further information. This is good fun if you have five minutes to spare. It is also quite educational, as most of us will be surprised by some of the answers.

Did you know, for example, that 1.3 billion people live without electricity today? Without it, 'economies can't grow, literacy and numeracy rates suffer, health clinics can't function and communications can't get through'. The Energy Quiz also confirms that China will be growing faster than any other country over the next three decades, outpacing the United States. China alone will account for more than 20% of the world's total economic growth.

And as we all know, the US uses the most energy per person. Wrong! Iceland is the correct answer, because colder countries tend to use more energy to heat homes and buildings, according to the Quiz. But China is the biggest user of energy overall, having surpassed the US in 2010.

Search for ExxonMobil Energy Quiz – and have fun!

Halfdan Carstens

Checking the ExxonMobil Energy Quiz is a simple way to get updated on some basic facts about the energy industry.

Conversion Factors

Crude oil
1 m^3 = 6.29 barrels
1 barrel = 0.159 m^3
1 tonne = 7.49 barrels

Natural gas
1 m^3 = 35.3 ft^3
1 ft^3 = 0.028 m^3

Energy
1000 m^3 gas = 1 m^3 o.e
1 tonne NGL = 1.9 m^3 o.e.

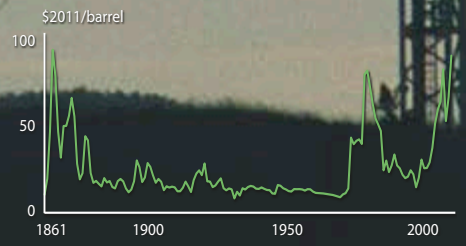
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

Supergiant field
Recoverable reserves > 5 billion barrels (800 million Sm^3) of oil equivalents

Giant field
Recoverable reserves > 500 million barrels (80 million Sm^3) of oil equivalents

Major field
Recoverable reserves > 100 million barrels (16 million Sm^3) of oil equivalents

Historic oil price



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