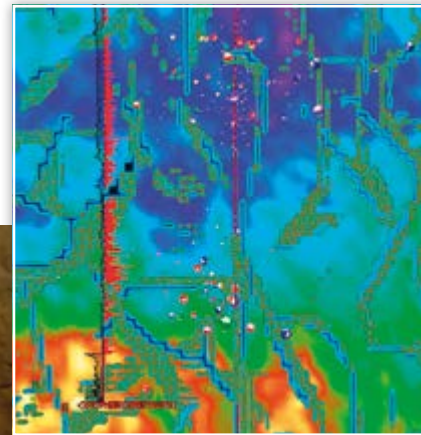


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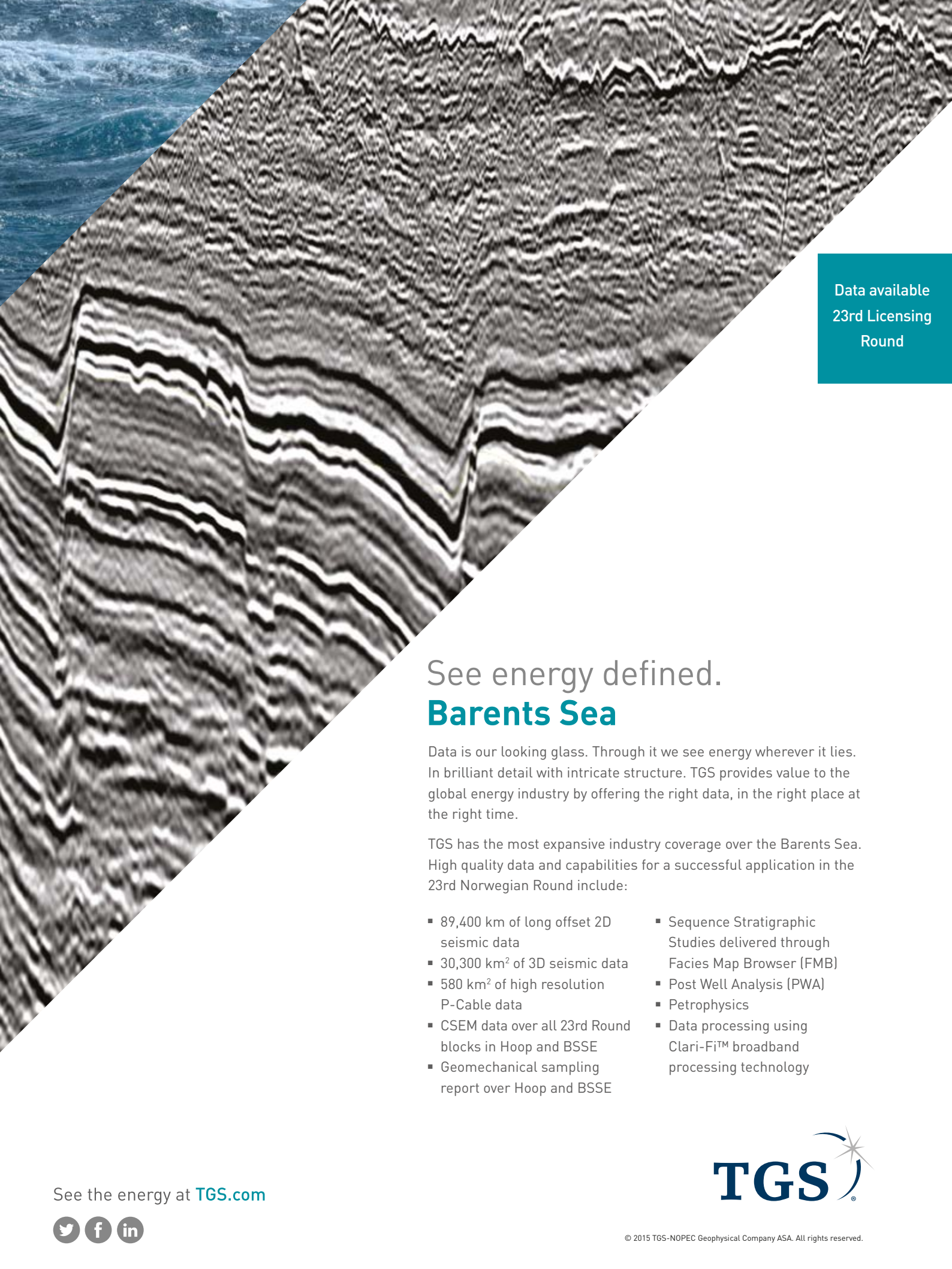
EXPLORATION

## Russian Fold Belts: The Next Hot Play?

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# GEOExPro

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## CONTENTS Vol. 12 No. 3

This edition of *GEO ExPro* Magazine focuses on Europe and on unconventional exploration.

### COLUMNS

- 5 Editorial
- 6 Market Update
- 8 **NEW COLUMN** Regional Update: Europe
- 10 Update
- 16 Licensing Opportunities
- 18 A Minute to Read
- 42 Recent Advances in Technology: Gas Hydrates in Outer Space
- 54 GEO Profile: Ian Forrest – “Oil Has Been Good to Me”
- 86 GEO Tourism:  
Malta – A Country Shaped by Limestone
- 92 History of Oil: The First Oil Shock
- 98 GEO Cities: Ceyhan – An Unassuming Hub
- 100 Exploration Update
- 102 GEO Media: The Buraimi Affair
- 104 Q&A: NORM
- 106 Hot Spot: The Weald Basin
- 108 Global Resource Management

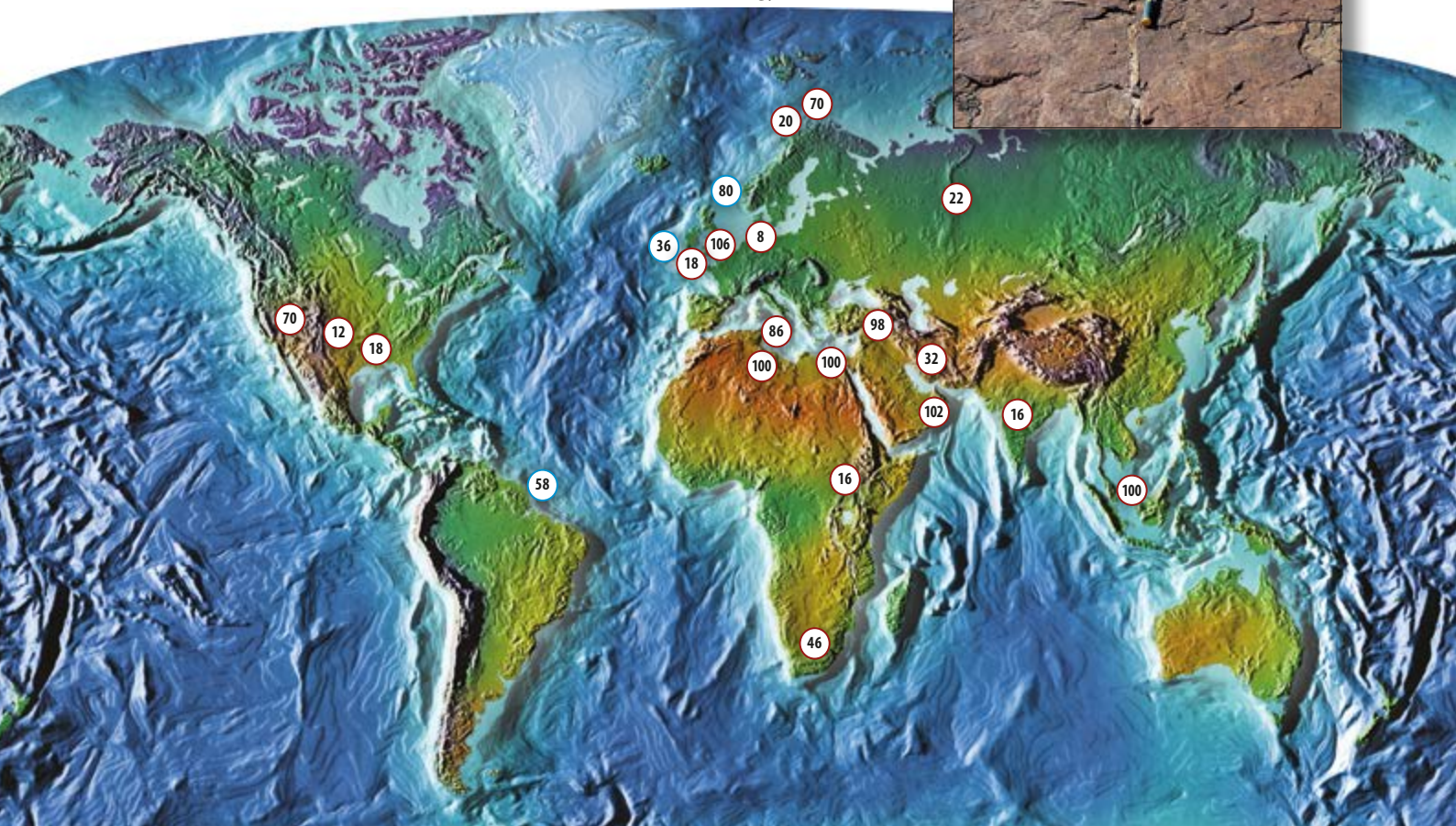
### FEATURES

- 22 Exploration: Russian Fold Belts – The Next Hot Play?
- 28 GEO Education:  
Field-Based Training – Luxury or Necessity?
- 32 Industry Issues: Iran – The Implications of Peace
- 36 **Seismic Foldout: Ireland – South Porcupine Basin**
- 46 GEO Science Explained: Shale Gas in South Africa
- 50 Reservoir Management:  
Integrating Data Types for Reservoir Characterisation
- 58 **Seismic Foldout: Foz do Amazonas Basin**
- 64 Technology Explained: A Simple Guide to Volumetrics
- 70 Exploration: Palaeozoic Plays of the Great Basin
- 76 Technology Explained:  
Hoop Area – Testing Ground for Geophysics
- 80 **Seismic Foldout:  
Horda Platform – Exploring the Cretaceous**

*Could shale gas migrating through dolerite sills provide the answer to South Africa's energy needs?*



*Malta – a country shaped by limestone (and a little bit of very old poo!)*



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## All Bad News?

Is the precipitous drop in oil prices we have seen in recent months all bad news? Certainly not for consumers, who are revelling in filling their cars and heating or cooling their homes for considerably less. Not great, however, for the many people from a range of oil and service companies who are facing layoffs and redundancy as a result of the reduction in production and associated cut backs; estimates suggest that about 75,000 jobs were lost in the industry in the first three months of 2015. Not good for new graduates clutching their degrees in the petroleum sciences, until recently a passport to employment; no longer so in times of limited recruitment.

What about the hydrocarbon industry as a whole? An interesting side effect of the reduction in prices has been a counterbalancing increase in efficiencies in exploration and production. In times of high oil prices, companies exert less pressure on this; in the UKCS, for example, production efficiency dropped from 80% to 60% between 2004 and 2012. Huge efforts are now being made to turn that around, through government and industry collaboration programmes which encourage partnerships, standardisation of best practice, optimisation, transparency and – very importantly – learning from the past.

Much has been said about how the upsurge in US production resulting from the exploitation of shale oil has been one of the drivers of oversupply and the consequent oil price drop. But, as discussed on Page 12, in many cases lower prices have resulted in increased production from fewer wells, using new technologies that reduce cost and improve efficiencies. On the downside, a Weatherford director recently predicted that possibly up to half the independent fracking firms operating in the US at the moment could be gone before the end of the year, with the pricing of fracking set to fall by up to 35%. Some shale producers are also finding it tricky to keep their heads above water, and there have already been a number of company failures.

Shell's takeover of BG signals the beginning of the inevitable round of mergers, acquisitions and consolidations which always happen in a downturn. When we reach the other side – and I am not predicting when that will be – it will be with a leaner and more efficient industry, but a lot will have fallen by the wayside. ■



**Jane Whaley**  
Editor in Chief

### RUSSIAN FOLD BELTS: THE NEXT HOT PLAY?

The cover image shows an isoclinal fold in the Upper Devonian basinal carbonates-shales-chert alteration (flisch) of the Zilair nappe (overthrusting deep water deposits, overlying platformal sedimentary cover of the East European craton), Southern Bashkiriya. Could the fold belts be the basis of the next cycle of Russian exploration?

Inset: Anisotropy from full-azimuth seismic is one of the data types used in an integrated team approach to reservoir characterisation.



North Sea operations need to become more efficient.



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# Ready for Iran's Oil?

## More oil is expected to flood the market if sanctions are lifted.

The world market is awash with oil at the moment and there are few signs of a slowdown in production short term – rather the opposite. On Thursday 2 April the five permanent members of the UN Security Council plus Germany made good progress towards a deal with Iran on the country's nuclear programme. The final and ultimate deadline for the negotiations has now been set at 1 July. The agreement must also be ratified by the US Congress. If the negotiations are finalised as planned, the tough sanctions imposed on Iran's oil exports could be lifted and the country may ramp up its oil deliveries to the world market within a few months. With OPEC's focus on protecting market share instead of acting as a swing producer, more cheap oil will flow into the market and put additional pressure on the price of oil for delivery in 12–24 months.

### Weapons or Energy?

Since 2002 when the international community became aware of two Iranian nuclear reactors that had not been reported to the International Atomic Energy Agency (IAEA), the West and the UN have conducted numerous unsuccessful talks with Iran to stop the development of the country's nuclear programme. While the West has worried that Iran will develop technology to produce nuclear weapons, the Iranian government has argued that its nuclear power will be used for the production of energy. Since 2006 the UN Security Council has imposed a wide range of sanctions on Iran due to the country's failure to comply with the Nuclear Non-Proliferation Treaty which took effect in 1970. Since 2011 the US and the EU have imposed strict sanctions against Iranian oil and gas exports as well as energy technology imports in measures designed to hit the country's main source of business – the oil industry. Oil exports account for approximately 80% of the country's total export revenues and for 50–60% of government revenues. The sanctions have hit the economy hard: oil exports nearly halved during the period from December 2011 until July 2012 and oil prices are now down some 50% since mid-June last year.

A breakthrough in the talks between the West and Iran did not occur until November 2013. President Obama's opening towards bilateral negotiations in Oman and the change of president in Iran were key factors supporting progress. So what would a deal mean for the oil market? Industry experts assume that some of Iran's main production fields that have been closed during the sanctions could quickly be brought back on stream as the shutdown may have caused the pressure in the reservoir to build. It is therefore assumed that production can increase by 600–800 Mbopd within three months.

### Serious Competition

We project an increase in oil demand of 1.2 MMbopd over the course of 2016. If the sanctions against Iran are lifted, the country's production increase alone can cover more than half the anticipated demand growth. This will result in a significantly flatter price path in 2016 with prices closer to US\$70/barrel than the US\$ 75/barrel we have assumed. An expansion of production from Iran will in other words mean serious competition to production in more expensive regions such as the Norwegian continental shelf; historically, the breakeven price there has been far higher than in the Middle East. This could put a further damper on new projects and exploration especially in more expensive frontier and deepwater areas.

**Thina Margrethe Saltvedt, Nordea**

## ABBREVIATIONS

### Numbers (US and scientific community)

|             |                        |
|-------------|------------------------|
| M: thousand | = 1 × 10 <sup>3</sup>  |
| MM: million | = 1 × 10 <sup>6</sup>  |
| B: billion  | = 1 × 10 <sup>9</sup>  |
| T: trillion | = 1 × 10 <sup>12</sup> |

### 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 <sup>3</sup> gas |
| MMscmg: | million m <sup>3</sup> 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

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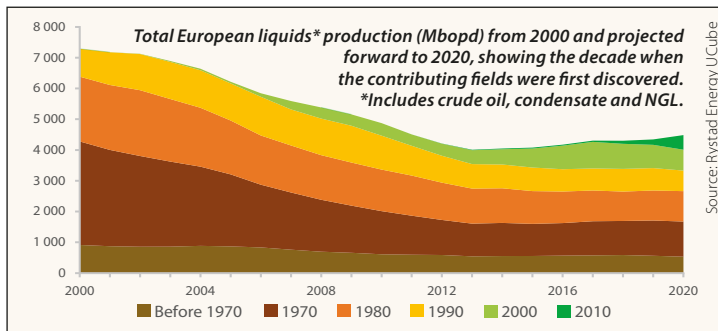
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In this new regular column, Rystad Energy brings us an update on the latest E&P trends in each edition's focus area.

# EUROPE: Old Giants Reversing Production Decline

2014 stands out as a special year for European liquids production; for the first time since 2000 this has been increasing. In the period 2000 to 2013, European production was on average declining 250 Mbopd per year. However, 2014 puts a stop to this trend with a year-on-year increase in production of about 50 Mbopd. The figure below clearly shows that 2014 marks an expected shift in how European liquids production will develop and, going forward, it is now expected that it will stabilise at around 4.2 MMBopd.



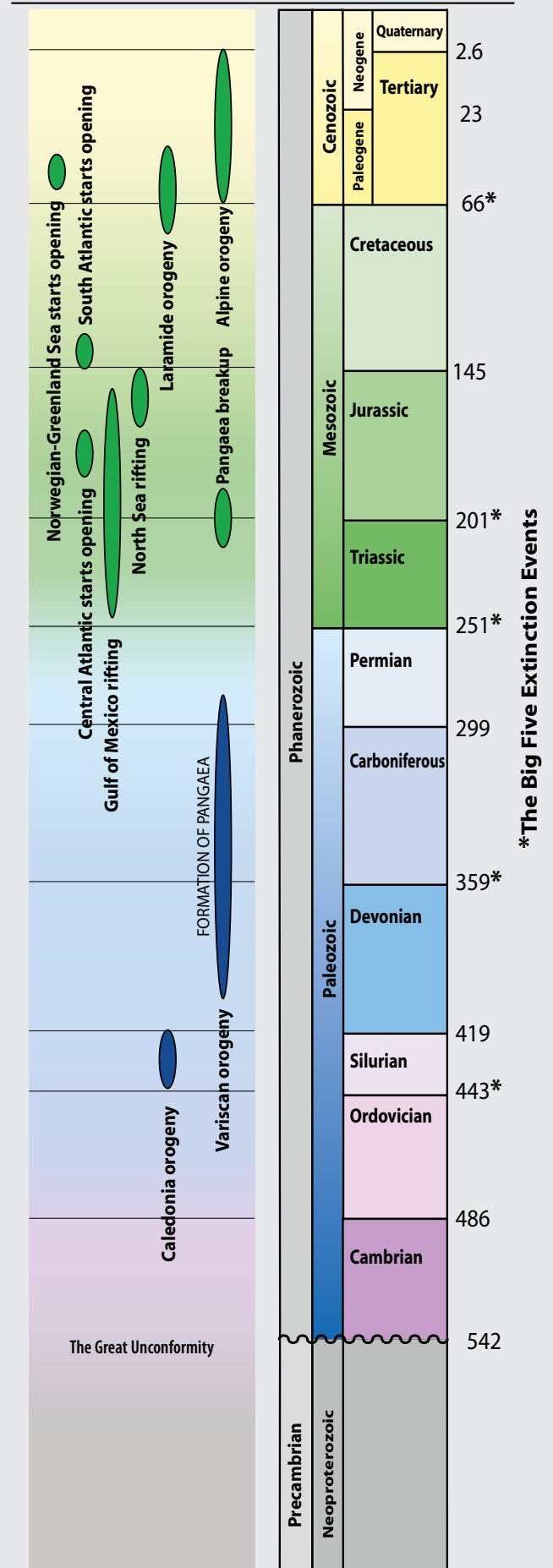
The shift in trend is primarily caused by two elements: recent exploration success and development of old discoveries. In the period 2009–2012, European E&P companies were on average discovering about 1.4 Bbo a year. This was considerably higher than the previous period, when the average discovered volumes were ~0.5 Bbo. The famous Norwegian elephant, J. Sverdrup, was the main driver for this, but also discoveries such as J. Castberg, Barryroe and Lancaster contributed to this increase. At the same time, E&P companies have over the last ten years focused on developing mature discoveries, such as G. Krogh and Gudrun, as well as extension projects on already producing fields such as Clair Ridge, Ekofisk South and Valhall. Of the 9 Bbo of resources that is expected to be put into production from 2015 to 2020, half is projected to come from mature discoveries.

Stopping the production decline also comes with a cost. From 2010 to 2014 yearly European E&P investments increased from \$50 to \$80 billion. With the collapse in the oil price in 2014, the 2015 E&P activity has been heavily affected, and total investments are expected to fall back down to \$60 billion by 2016. Several important projects have already been delayed, such as Snorre 2040, J. Castberg and Vette (Bream).

The lower oil price has also put pressure on exploration activity. In 2014 around 150 offshore exploration and appraisal wells were drilled. For 2015, Rystad Energy believes that number will decrease to around 125 wells and fall further, to around 100 wells, in 2016. Because of the lower oil prices and reduced activity, Rystad Energy has revised down the long-term liquids production potential for Europe by about 500 Mbopd a year.

In short, it is the re-development of old discoveries that is putting production decline in Europe on pause. ■

**Espen Erlingsen, Rystad Energy**

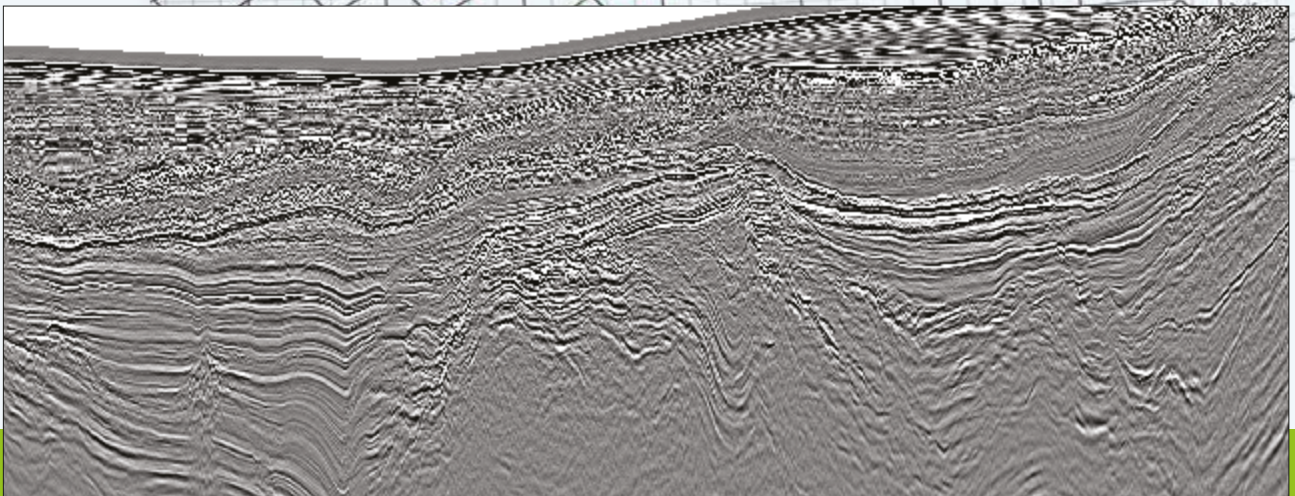




# South Porcupine Basin Regional 2D & 3D Surveys

Polarcus is pleased to announce the completion of processing of two new multi-client seismic programs in the South Porcupine Basin, offshore south-west Ireland. The South Porcupine Basin is an under explored Mesozoic rift, offering multiple exploration plays, which shares successful petroleum system elements with the proven North Porcupine Basin and the conjugate margin Canadian Basins. The two wells drilled in the basin to date have proven a working petroleum system; with the 43/13-1 well logging hydrocarbons in thin Upper Jurassic sands, and 44/23-1 encountering a thick Lower Cretaceous over-pressured carbonate reservoir sequence.

The 5,100 line km of new *RightBAND™* 2D and 4,360 sq. km of *RightBAND™* 3D data provides comprehensive coverage across the basin allowing improved understanding of a number of plays. To ensure optimum imaging of this highly prospective area, ION GX Technology has processed these new data through a *WiBand™* Pre-STM processing flow. The new 2D data infills the more regional PAD and ION NE AtlanticSPAN regional surveys, with the 3D revealing multiple plays and leads in open acreage. This is the only comprehensive data package currently available to evaluate the basin for the 2015 Atlantic Margin Oil and Gas Exploration Licensing Round.



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# Technology for a Complex Environment

## The new Weatherford technology for optimal completion design.

Two key focus areas in unconventional exploitation are cost efficiencies and managing well production variance. A better understanding of rock behaviour as measured by anisotropic brittleness analysis can help select the best fracture placement in horizontal shale wells, while proper reserve estimations and hydrocarbon production potential can be analysed using advanced TOC percentage calculations.

### Eagle Ford Case Study

Recently, an Eagle Ford shale operator wanted to optimise fracture efficiency and well productivity in a field development campaign. To properly account for the geological complexities of the lamination depositional mechanisms associated with shale formations, the operator deployed advanced logging-while-drilling (LWD) technologies to measure the variability along the lateral section of one of its wells. The introduction of the transverse isotropy anisotropy evaluation from the LWD azimuthal acoustic measurements allowed an accurate characterisation of the impact of the extensive laminations across the planned well trajectory. Concurrently, the petrophysical evaluation used isotope concentrations from a LWD spectral gamma ray tool, providing an integrated analysis that accounted for both the reservoir and rock property variability along the lateral section of the well.

After acquiring the data, the operator sought guidance on how to optimise cluster perforation and stage placement, turning to Weatherford's FracAdvisor™ for the answer. By grouping 'like rock with like rock' through an advanced interpretation of the available formation evaluation logging data, the service produced a completion design that minimised uncertainties in proppant amount and pumping times and provided pressure profiles optimisation.

By combining several key and unique formation-evaluation technologies with innovative surface logging tools and advanced laboratory techniques, FracAdvisor provided near real-time guidance for enhanced completion decision making. Using advanced and flexible modelling, the service assessed natural fractures, evaluated hydrocarbon potential, and calculated mechanical properties along horizontal or vertical wellbores. By evaluating attributes such as TOC, maturity, porosity, permeability, natural fracture patterns and mechanical properties, the operator had a reliable prediction of fracture potential.

### Key Insights Provided

FracAdvisor seeks to optimise the contribution from each stage, enabling operators to complete a well in a structurally complex geologic environment, identify and stimulate sweet spots, and optimise stage design and cluster placement, mitigating the fracturing-potential variability caused by

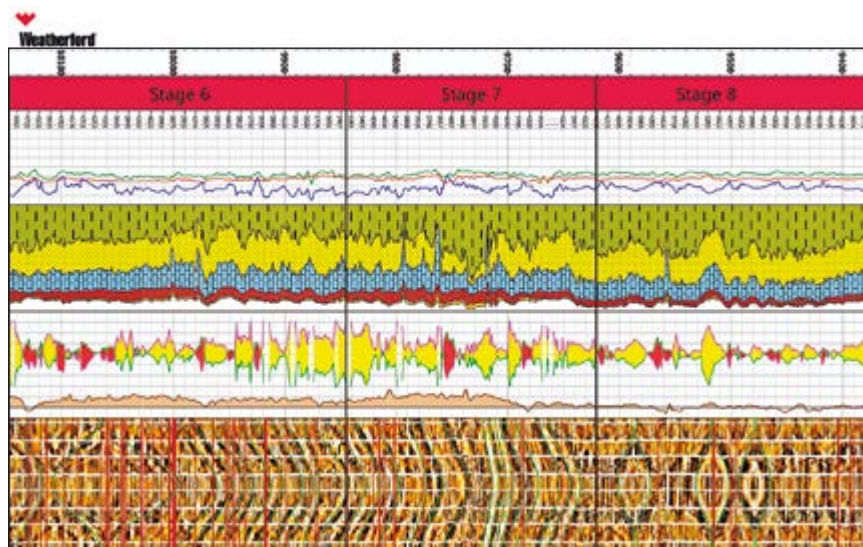
formation heterogeneity properties.

High-resolution imagers and advanced acoustic technologies evaluate structural patterns in the wellbore – including fracture and fault identification – to provide a better understanding of rock mechanical behaviour and deliver a more realistic approach under laminated structure of the shale diagenesis. A spectral gamma ray tool measures elemental radioactive concentrations during petrophysical interpretation of hydrocarbon potential, that enables the completed reservoir characterisation to be incorporated into a robust weighting model allowing the operator to select the best fracture placement and design in an unconventional environment. Furthermore, the FracAdvisor service leverages an advanced coring data technique to reduce uncertainty during evaluation, as well as wellsite geochemistry data from new-generation gas-detection technologies.

These attributes are used to calculate completion and reservoir indexes; the former indicates how the rock will behave under hydraulic fracturing, while the latter indicates whether the particular rock will contribute to production. Each attribute is weighted by factors such as basin experience, hydraulic fracturing technique, and data uncertainty. The reservoir and completion indexes are incorporated in a combined FracAdvisor index, providing input for a fully automated stage-design proprietary workflow which optimises the length of each stage and location of perforations by seeking to minimise the variability in the attributes. This enables analysts to calculate how the rock will behave under hydraulic fracturing and how it will ultimately produce.

For the Eagle Ford operator, this service provided key insights into the design of the completion programme for future wells. The ability to accurately identify sweet spots provided direct input for well planning and geosteering operations and offered a proactive design for future wells and maximum production potential.

**Nicole Ramsey Braley, Weatherford**

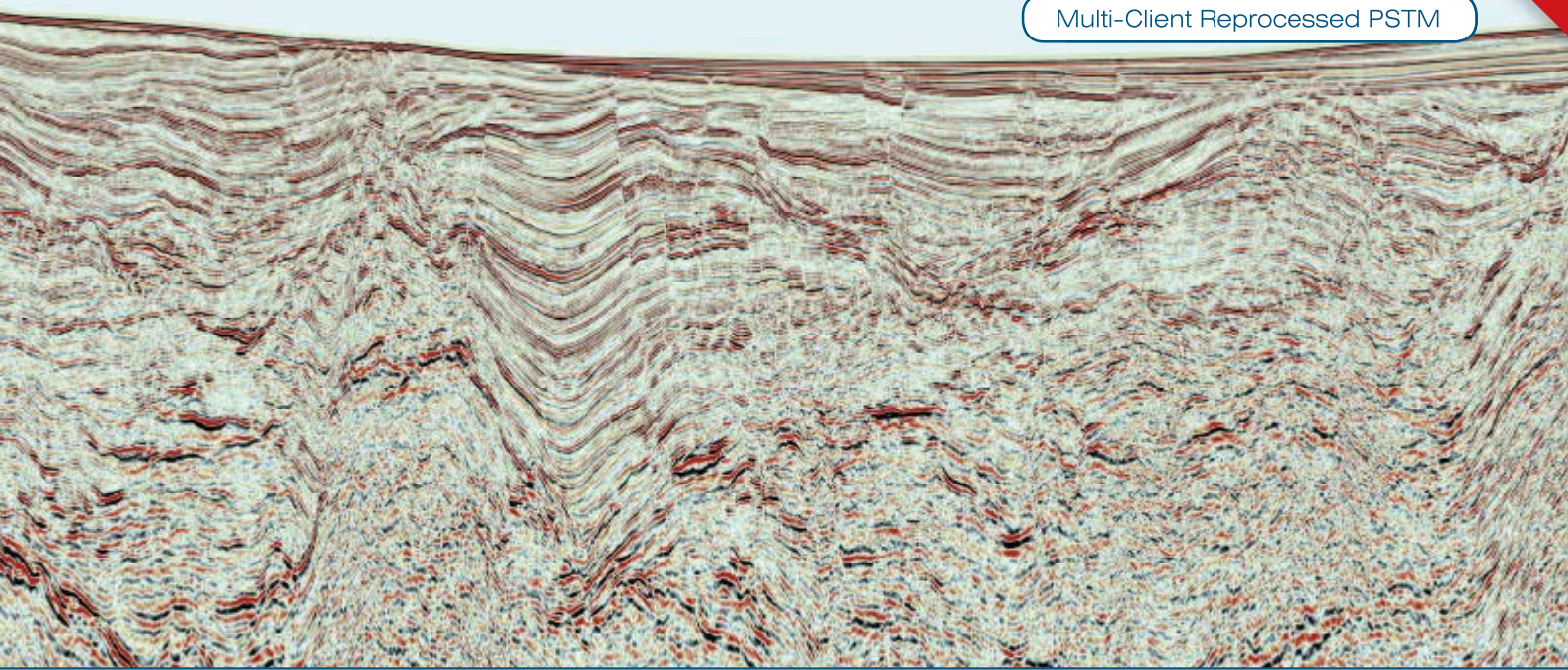


# Offshore Peru

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Spectrum, in collaboration with PERUPETRO S.A., the state company responsible for promoting and regulating hydrocarbon exploration contracts in Peru, has reprocessed 13,149 km of Multi-Client 2D seismic data to assist with the upcoming offshore bid round. The bid round will include 9 offshore blocks located in the central and southern part of the continental shelf. These blocks will cover two types of highly prospective sedimentary basins: extensional, pull-apart basins (e.g. Trujillo and Mollendo) and upper trench slope basins (e.g. Lima and Pisco).

The sedimentary basins offshore Peru are largely unexplored despite hydrocarbon discoveries along the north coast. Geological evaluations, using Spectrum's re-processed seismic data, have identified several prospective leads, proving that offshore Peru is a very attractive frontier region.

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# Getting More with Less

## Will low oil prices bring the unconventional revolution to its knees?

The past few years have brought some major changes to the global oil markets. The US has taken over as the largest oil producer thanks to high prices and technologies allowing companies to exploit the resource from very tight reservoirs. The past year has brought more dramatic changes to the oil and gas industry. Oil prices have been cut in half and gas is down nearly 40% due to the glut of those commodities on the market.

Could these low prices bring the unconventional revolution to its knees? Dr. Pete Stark, Vice President of Industry Relations at IHS, certainly does not think so. “North American oil and gas companies have shown a resolve and effort possibly never seen before in the oil and gas industry,” says Pete. “Over the last decade, they have taken on the challenges of producing oil and gas from very tight reservoirs and have made great strides in leveraging technology to boost performance while driving the surge in production from tight reservoirs.

“Dealing with a 50% reduction in commodity prices is certainly a huge challenge but competition and innovation will allow the tight oil revolution to prevail,” according to Dr. Stark. “Lower oil prices may be a blessing in disguise in a longer term outlook for companies exploiting unconventional resources. Service company costs have dropped an average of 10 to 15%. The oil and gas companies are now high-grading their drilling into the known sweet spots as drilling becomes more efficient and the technology to exploit this resource continues to improve.”

### Concentrating on Quality

“In the current environment, we are going to see less wells drilled,” says Pete. “But fewer wells do not necessarily mean less production. We know about 80% of the production comes from 30% of the wells. By concentrating the drilling in a reservoir’s known high quality areas, a higher percentage of the wells will be the better producers,

so that overall production trends will change more slowly than drilling activity.

“Technology also is critical. Failure of a significant number of frac stages to produce in some wells is a major concern.” Pete further explains that, “Service companies are developing monitoring technology to identify and remediate segments of boreholes where initial fracs were not successful. Success could improve well performance by almost 30% and the use of ‘super fracs’ also is becoming more common. The graph shows that increasing the amount of proppant results in increased production; in the best cases doubling the proppant is nearly doubling production. The net effect is that companies are able to get more production from each well drilled and thus need to drill fewer wells to sustain their performance in the current economic environment.”

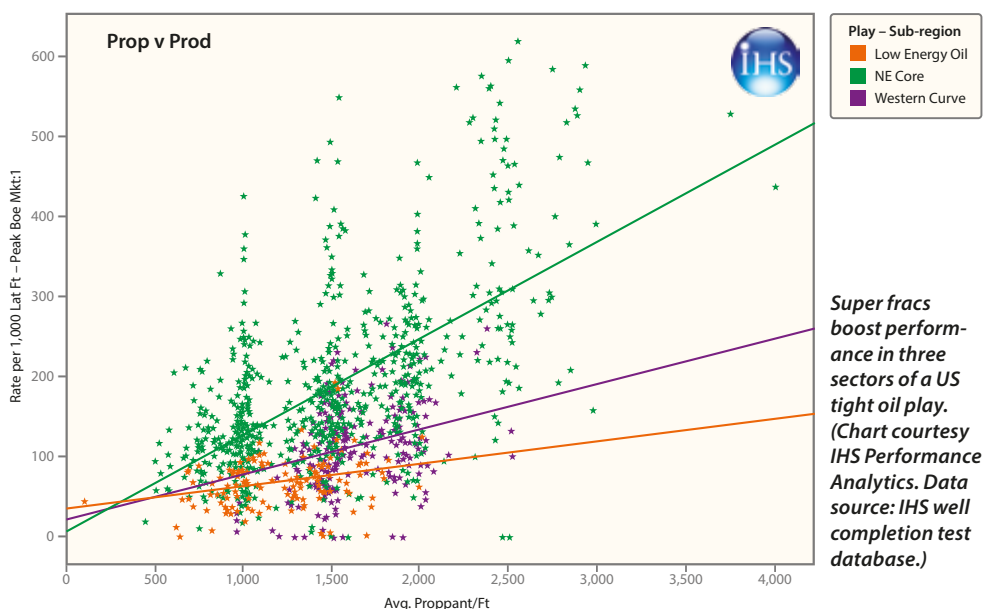
When questioned about where oil prices may go in the future and what effect that might have on the US unconventional plays, Dr. Stark was quick to point out that the US is once again a major global oil producer with global influence on oil markets. He thinks US production will flatten slowly and decline in the fourth quarter of this year. The Saudis are unlikely to slow production and with the potential nuclear deal in

Iran, the oil glut could last beyond 2015, barring any “black swans” muddying the picture. “Once oil markets rebalance and prices climb again, the oil and gas companies here in the US have the operating efficiencies and infrastructure in place to readily ramp up production, keeping the shale revolution moving ahead,” he says. “Operators are prepared to produce more barrels at tomorrow’s \$60 to \$70 oil than they were a year ago.”

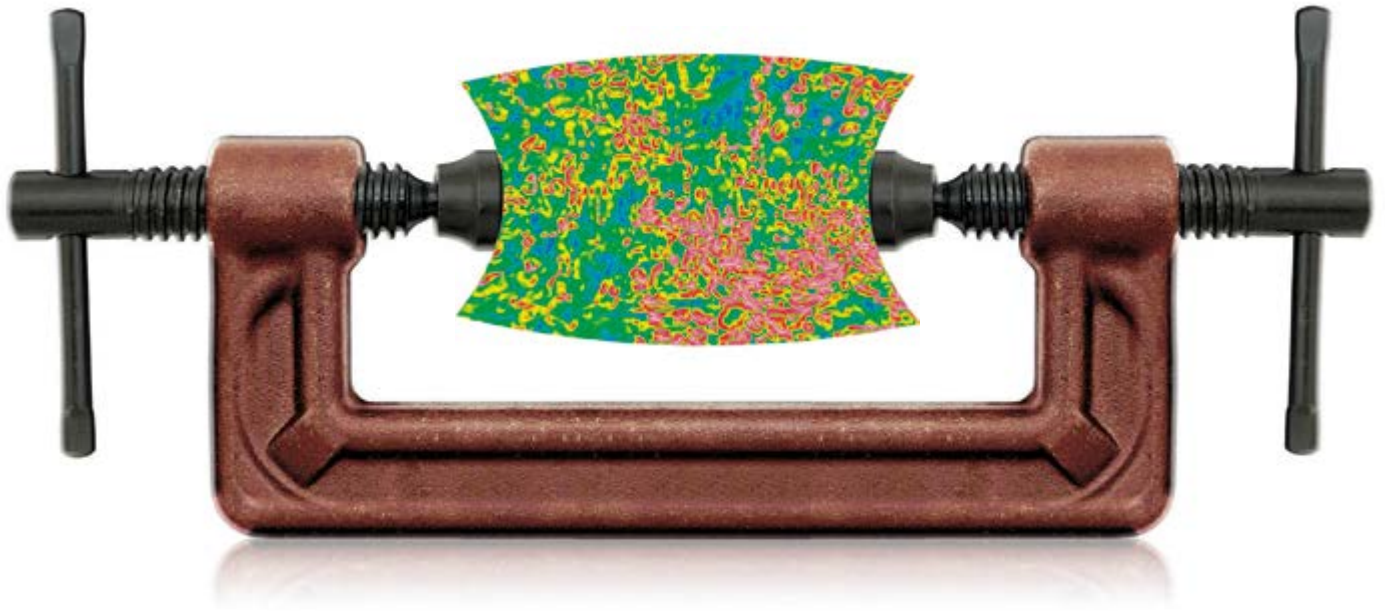
Interestingly, the ability of tight oil producers to respond fairly rapidly to changes in oil prices has positioned the US to play a role as a swing oil producer, essentially changing the way oil supply and prices can be controlled. In the past, the Saudis or the Texas Railroad Commission could control production and thus oil prices. We are now dealing with hundreds of independent producers that, through reacting to these lower oil prices by cutting costs and drilling fewer wells, will soon lower production and trigger markets to shift gears toward recovery.

“With the help of lower oil prices and a secure supply of domestic oil and gas, the US economy has remained the most competitive in the developed world,” says Pete. “This current downturn will only make us that much more competitive.”

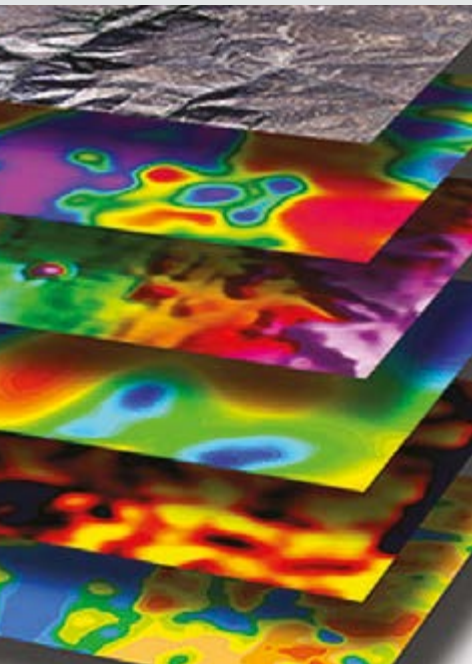
**Thomas Smith**



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# Breaking the 'Stack Barrier'

Seismic interpretation software can reveal the true value of pre-stack gathers.

In an Oilvoice article recently, David Bamford suggested a better term for seismic interpreters was 'subsurface detectives', rather than explorers. We collect lots of evidence, sift through it and analyse it before coming to a conclusion, just like real police detectives solving a crime. However, working with angle stacks alone, subsurface detectives cannot tell if their evidence has been compromised or corrupted in some way. The real quality of the data is hidden behind the stacks – only inspection of the gathers can give a true answer.

Working with limited information selected from the vast database of evidence available, subsurface detectives can easily miss vital clues and come to the wrong conclusion. Without accessing the whole data volume, they cannot look for patterns, anomalies and inconsistencies in the evidence and thereby understand the uncertainties and risks within to correctly assess the probability of success.

Like the sound barrier, which became a psychological as well as a physical barrier for pilots and aeroplanes – the 'stack barrier', marking the domain boundary between seismic processors and seismic interpreters, has somehow remained stubbornly in place, if not in the software we use, in our minds and our psyche! It sometimes seems we are too frightened that our interpretation, so carefully constructed flying through

stack data, will not stand up to the shaking it receives as we cross the 'stack barrier' to mine the rich information available in the pre-stack data. For example, the more accurate fluid prediction gained by using interactive AVO/AVA attributes directly from gathers can help identify potential reservoirs and distinguish hydrocarbons from water.

And yet we have all seen the value of moving our interpretation focus down the processing sequence, from paper to colour graphics displays, from attribute sections to original seismic stacks, from post-stack processed seismic to raw stacks; so we should embrace the idea, get comfortable with handling gathers and enjoy the ride.

## Combined Interpretation

Computer hardware and software advances have allowed us to fully manipulate and visualise all of our stacked seismic data volumes, to guide interpretation. Today's multicore hardware and optimised parallel-processing seismic interpretation software now allow the same kind of manipulation and visualisation for pre-stack gather volumes – a breaking of the stack barrier for interpreters and an opening up of a 'view-and-do' stack and pre-stack combined interpretation world.

For example, discrete, single gathers can be placed inside a 3D scene alongside surfaces, faults, well bores etc. and

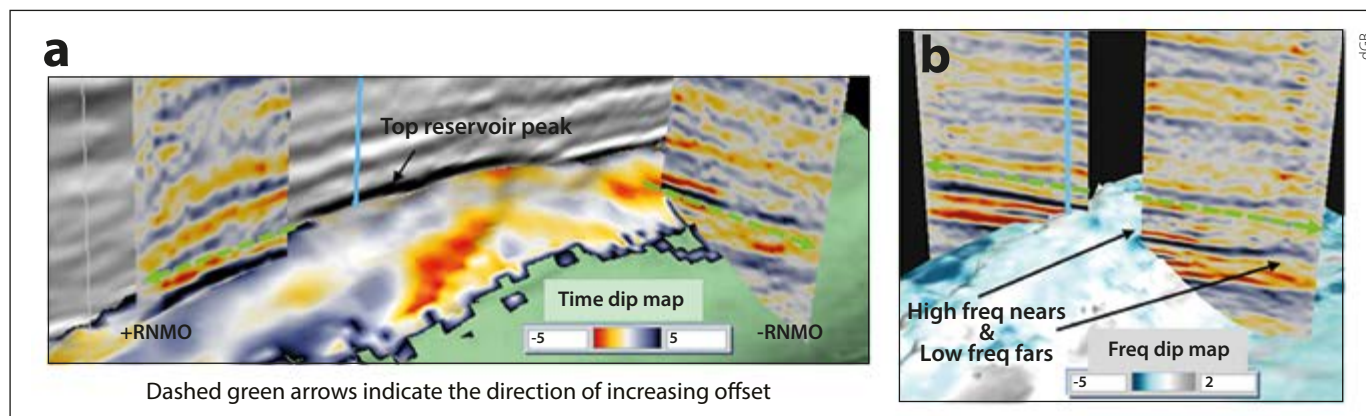
usually attached dynamically to a post-stack seismic section, made from stacking them. Inline, crossline and arbitrary line gather cross sections can be created by drawing lines on maps and interactively redrawn when dragged from one location to another. Pre-stack horizons can also be tracked through the volume and gather quality and character attribute maps used to guide the cross section browsing and analysis of the pre-stack data. It is possible to use these gather Q.C. maps to understand the geology better and to assess interpretation uncertainty (see image below). This is fast becoming a first step 'health check' procedure for interpreters preparing to condition their gathers for AVO inversion.

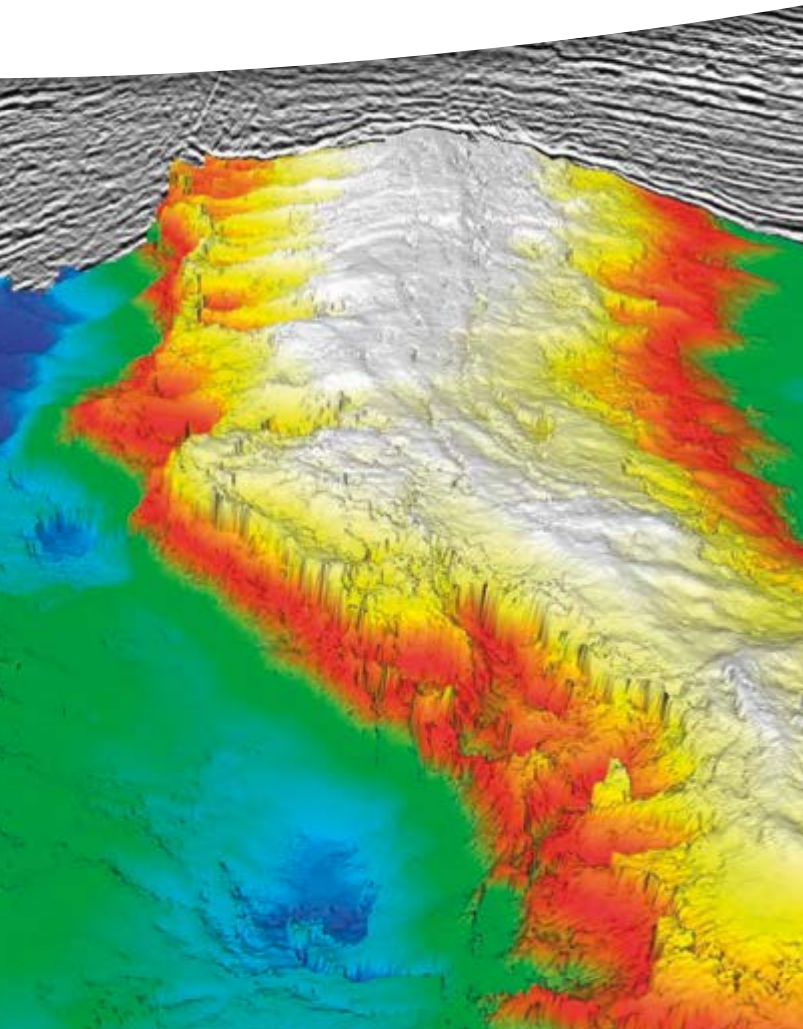
Pre-stack horizons can be turned into pseudo-post-stack seismic volumes with the vertical axis being the gather's fourth dimension, usually offset or angle, and sample values being amplitude (AVO), time (TVO) or a time-windowed attribute such as average frequency (FVO). These volumes can be mined for interesting character using classification algorithms, removing any chance of interpreter bias. ■

**John Kerr, Seismic Revelations Ltd.**

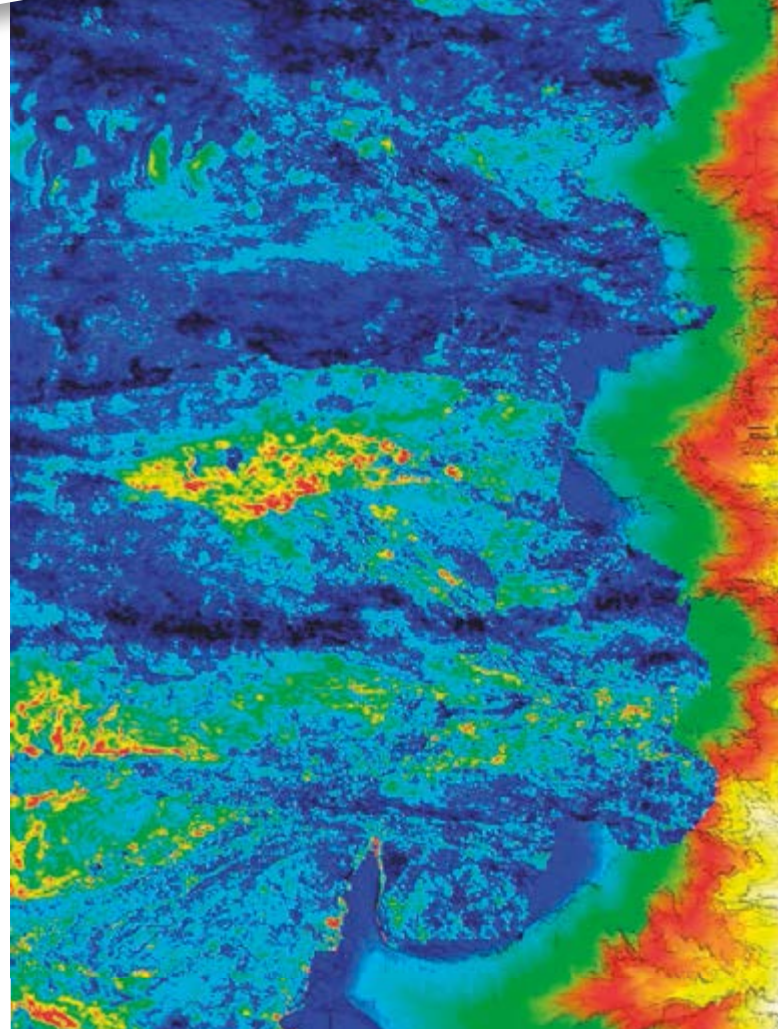
*The theme of this article will be explored in greater detail on our website. To read more please use this link – <http://www.geoexpro.com/articles/2015/04/seismic-interpretation-software-breaks-the-stack-barrier>.*

*Two 3D views of part of the top of a chalk reservoir. The time dip with offset map and the gathers, displayed in context with the rest of the field's data (a), allow the interpreter to investigate where any velocity differences may be coming from – such as channelling or fracturing parallel to structure, changing porosity and fluid content. Average frequency dip with offset maps (b) can help to highlight zones of significant multiple interference and can explain why some gather events have more time change on the far offsets than others.*





Gohta 3D:  
Gohta and Alta Discoveries



Senegal Deep 3D on trend with  
Fan-1 and Sne-1 Discovery wells

Two of 2014's top 10 discoveries covered by

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# Low Oil Price Limiting Exploration Opportunities

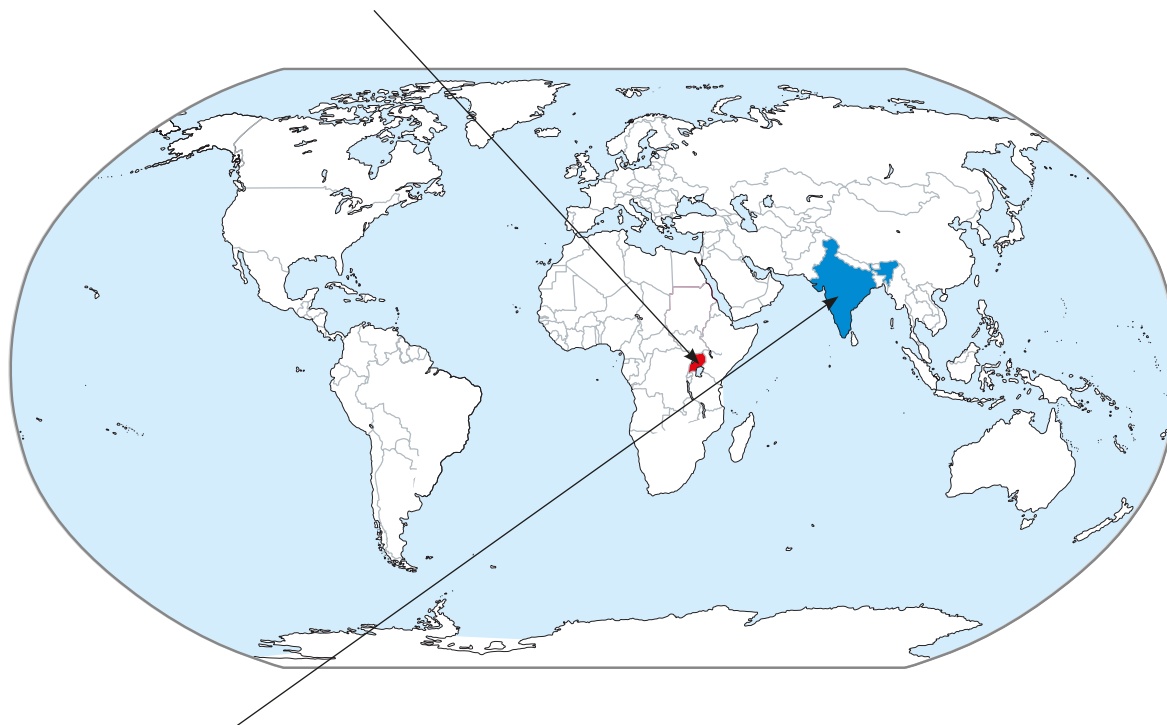
KEN WHITE

## Uganda: Seven blocks in Albertine Graben on offer

Uganda's Energy and Mineral Development Ministry is offering seven blocks covering around 3,000 km<sup>2</sup> in its first competitive licensing round for oil exploration in the Albertine Graben area, a region where oil has already been discovered. The six blocks to be auctioned are the Semiliki and Kanywataba blocks in Ntoroko district, Ngassa block in Hoima district, the Taitai and Karuka blocks in Buliisa district, the Mvule block in Yumbe and Moyo districts, all in northern Uganda, and the Ngaji block in Kanungu and Rukungiri districts in the western part of the country. The energy minister stressed that 'stratigraphic' licensing will be applied to some blocks, meaning that one prospecting company interested in exploring for oil and another

interested in gas could be assigned the same block. The government has undertaken resource and risk assessment of the areas proposed for licensing, developed a data room and is making data packages available to prospective investors in preparation for this licensing round.

Investor interest in the east African nation's potential has been growing since commercial crude reserves were first found in Uganda in 2006. However, commercial production has been delayed and is not expected to start until 2018 at the earliest. According to a statement from the energy ministry, the main objectives of implementing the new licence round are to attract additional investment in the country's oil and gas sector and to expand the country's resource base which is currently estimated at 6.5 billion barrels of oil in place (1.4 billion barrels are recoverable) and 500 billion cubic feet of gas. ■



## India: Auctioning 69 small and marginal fields

While a time-line remains uncertain, the Indian government has revealed plans to auction 69 small and marginal fields on a new revenue-sharing model. These will comprise 63 marginal oil and gas fields that will be surrendered by ONGC and six to be given up by Oil India Ltd.

Under the revenue-sharing model, bidders will have to state upfront how much oil and gas they will share with the government. This is a shift from the much-criticised PSC regime, which was seen as a system that provides incentives to operators to keep raising costs so as to postpone government share. Delhi is relaxing rules within the

existing 15-year-old upstream policy, loosening the power of government officials and the upstream regulator, in order to allow developers to make quicker investment decisions. The ministry is currently preparing the policy guidelines for the auction, which will require the approval of the Cabinet Committee on Economic Affairs.

The Indian oil and gas sector has long debated the benefits of revenue-sharing versus profit-sharing. Different government panels have sided with one or the other model citing their own arguments. The oil ministry is yet to make up its mind on following the revenue-sharing or profit-sharing model for its long-awaited new policy for larger oil and gas fields. ■



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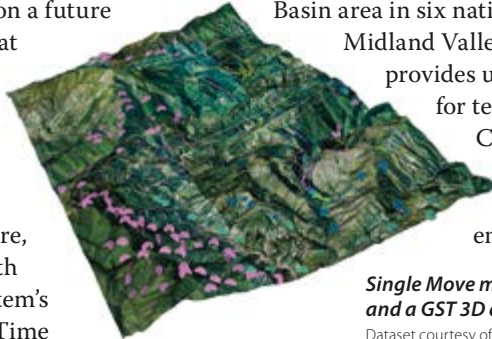
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## Upcoming 3D Geological Interoperability

Geologists from all sectors are producing and consuming greater volumes of 3D data than ever before. The challenge faced by today's geodata managers is to provide those users with secure, efficient access to the data they need – irrespective of its provenance. Data sources include traditional flat file GIS interchange formats, but can potentially include proprietary and in some cases archaic databases and stores.

**Midland Valley** are actively working on a future innovative open 3D solution, a project that involves Switzerland's Federal Office of Topography and its **GeoMol** cross-border data modelling project. This project demonstrates how the current interoperability in Midland Valley's structural modelling and analysis software, **Move**, can easily be extended to work with new 3D data stores such as GiGa Infosystem's revolutionary Geosciences in Space and Time



(GST) system. By linking directly to this system, academic and commercial users of Move will, for the first time, be able to store and retrieve data in a 3D enterprise-wide relational database and access full or partial features via spatial querying.

The GeoMol project uses Move as the geologist's access point for cross-border data covering the Alpine Foreland Basin area in six national areas.

Midland Valley's Academic Software Initiative provides universities with Move free of charge for teaching and non-commercial research. Collaboration and data sharing is encouraged amongst academic and survey partners, which will be enhanced by this new capability. ■

*Single Move model composed from GIS raster, outcrop vector, and a GST 3D database source.*

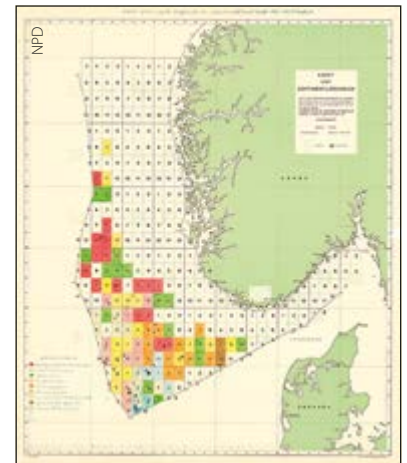
Dataset courtesy of Universidad de Barcelona

## Norway's 50th Anniversary

In April, Norway celebrated the **50th anniversary** of the establishment of the first licensing rules for the **Norwegian Continental Shelf**, which aimed to secure a sound financial return for the country. It also confirmed public control and prudent exploitation of the resources, whilst ensuring that this did not disadvantage other activities or impede prudent technical safety. The licensing rules established a long-term perspective and important principles, including ensuring that Norway developed its own expertise.

The first licensing round, announced on 13 April 1965, offered 278 blocks – the most available in any round in Norwegian oil history. The only blocks excluded were those bordering the median line between Denmark and Sweden. The application deadline was in June the same year, by which time there were 11 applications covering a total of 81 blocks, 78 of which were awarded to nine companies. The awards were supervised by the newly formed State Oil Council.

Norway's considered, incremental opening of the shelf since 1965 means that they believe that to date they have only exploited half their total in-place reserves. ■



*The first, hand-coloured, 1965 map of the Norwegian Continental Shelf.*

## Women Make a Splash

Believed to be the very first 'all female' managed marine seismic project management company in the world, **Aqua GeoProjects** is set to make a splash across a traditionally male-dominated industry. And with **four industry-experienced women** heading up the new company, this operation is aiming to do things a little differently!

Aqua GeoProjects provides cost-effective geophysical project management and bespoke seismic solutions for marine surveys within the oil and gas industry, including bespoke shallow water vessel design, seismic project mobilisation, technical outfitting, and specialised marine management services.

The senior management team (Managing Director Claire Jennings, PR and Quality Manager Kelly Richards, Senior Project Manager Kerry Thain and Emma Cox, Marketing) between them have more than 35 years global marine seismic experience, having successfully delivered projects in Norway, Azerbaijan, Panama, Greenland, Ecuador and the Russian Federation. Drawing upon their extensive operational experience in deep-

sea, shallow-water and transition zone seismic surveying, the company believes it can provide the experience gained within the larger areas of the industry to smaller scale operations in emerging areas, where reliable, cost-effective solutions which are scaled to fit the project budget are often required. ■

*Aqua GeoProjects is based in Cornwall in south-west England.*



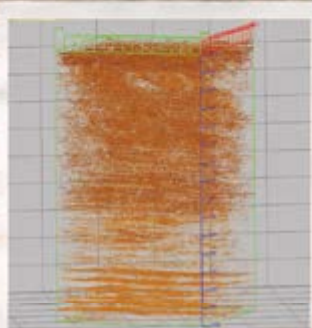
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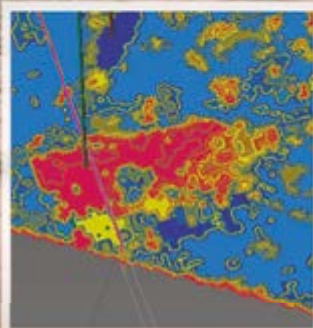
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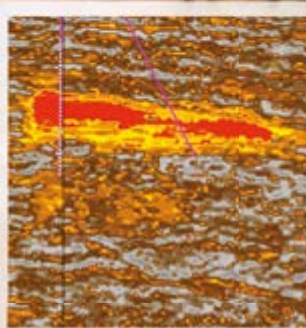
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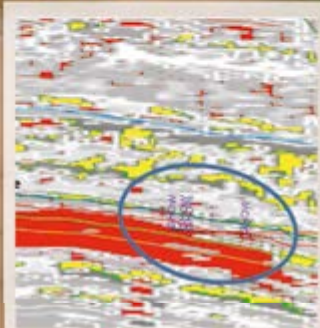
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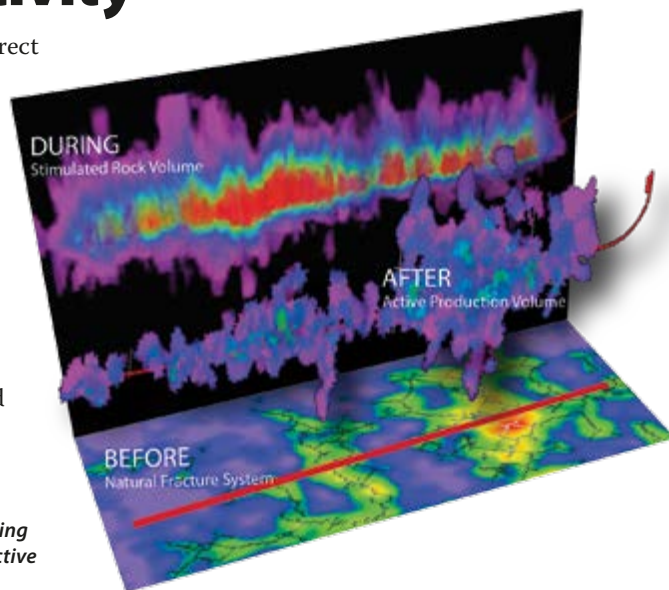


# Capturing All Acoustic Activity

Global Geophysical Services' approach to microseismic provides direct imaging of acoustic activity in the subsurface, allowing for the identification of areas or zones that are acoustically active due to naturally occurring activity, hydraulic stimulation or production-related activities. The company's microseismic results can be presented as 3D attributes such as semblance, as discrete volumes of acoustic activity or as Tomographic Fracture Images™.

A differentiating capability of Global's approach is that acoustic activity is captured **before, during and after** stimulation; providing knowledge of natural fractures and faults, the stimulated rock volume and the active production volume. The before, during and after approach discerns the impact of both natural and induced fractures and determines the cumulative affect they have on actual well productivity. ■

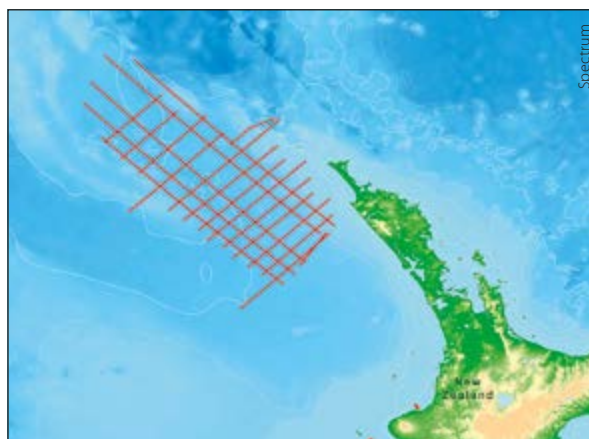
*Before: quiet time recording before the frac images natural fractures and faults. During: pumping time recording images the microseismically active volume during stimulation. After: quiet time recording post-frac reveals the microseismically active production volume.*



# New Zealand Block Offer 2015 Announcement

Owing to the success of recent licence rounds and the significant interest and investment that has been shown by major exploration companies in recent years, 2015 could be an important year for the **New Zealand** hydrocarbon industry. In late March the Energy and Resources Minister announced that acreage covering nearly 430,000 km<sup>2</sup> would be available in both frontier and developed regions across several onshore and offshore basins.

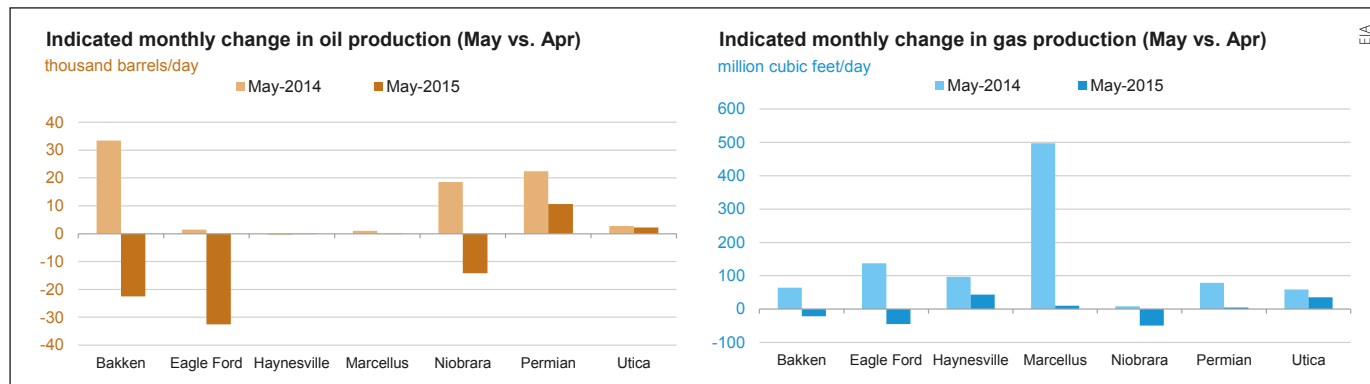
With this acreage in mind, **Spectrum** and **TGS** are currently reprocessing 5,000 km of 2D seismic over the Reinga Basin in northern New Zealand through TGS's Clari-Fi™ de-ghosting sequence. It is anticipated that this reprocessing will reveal the complex stratigraphy and geology of the basin in unparalleled detail. Spectrum sees New Zealand as a key area of survey development with more products being developed for the region. ■



# US Shale Oil Output to Drop

According to a recently released report from the US Energy Information Administration (EIA) US shale oil output is expected to fall in May, the **first monthly decline** in four years. Production from the fastest-growing shale plays is expected to drop by 45,000 bopd in May to 4.98 MMbopd in

reaction to worldwide oversupply and the associated dramatic cut in oil prices. Similarly, gas production in the major shale plays is expected to see a reduction of 23 MMcfpd to 45.97 Bcfpd in May, the first expected monthly decline in gas production since July 2013. ■



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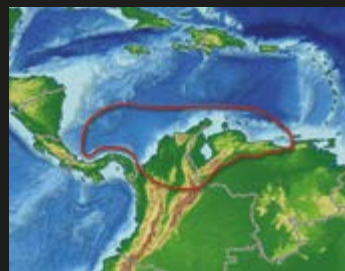
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# Russian Fold Belts: The Next Hot Play?

KONSTANTIN SOBORNOV,  
Nord West Ltd, Moscow

**Three successful cycles of petroleum reserve build-up can be recognised in the history of Russian petroleum exploration. Could the fold belts be the basis of the next cycle?**

After decades of primitive pre-industrial oil production, the first cycle of successful oil exploration in Russia took place in the foothills of the Greater Caucasus at the end of the 19th century, initially focused on natural oil and gas seeps in the area (Figure 1).

## The First Two Cycles

Eventually, with the development of the anticlinal theory, exploration efforts spread beyond the areas of natural seeps, and the young fold belt of the Caucasus provided numerous outcrops unveiling different geological settings. The principal plays were related to Tertiary sands sealed by alternating shales, with pays down to two kilometres, limited by available drilling capabilities. Figure 2 shows a cross-section through the Oktyabrskoye field in the foredeep of the Caucasus,

discovered in 1913, where several oil pools were found in the Miocene deposits in a high-relief anticline, exposed at the surface. Elsewhere, step-out drilling discovered the presence of other trap types, such as pinch-out traps and channelised sands, but these were rare and could not be predicted outside well studied areas. By the mid-1930s, after several decades of successful exploration, the stack of drillable prospects drastically reduced and exploration efficiency dropped.

Several sedimentary basins were studied in order to offset the decline in the Caucasus, culminating in success in the Uralian foreland in the late 1930s. Early discoveries related to shallow Permian reefs were made through traditional geological mapping, but the Uralian foredeep area is primarily flat and outcrops were not as widespread as

in the Caucasian foothills. Agricultural lands, steppes and forests cover much of the area, making surface mapping useless, so structural drilling emerged as an important exploration tool. The predominantly conformal bedding of the sedimentary fill meant that drilling shallow wells helped to map closures at these levels, which could be projected to deeper prospective structures in Devonian-Carboniferous strata. This technique was rapidly found to be successful and was widely implemented. Low risk deep drilling and quick learning led to a string of significant discoveries, while centralised planning helped disseminate technological solutions, accelerating reserve build-up.

The large potential of the Uralian foreland resulted from favourable conditions for petroleum generation and accumulation, including the world-

*Folded Upper Devonian basinal carbonates with shale-chert alteration (flisch) of the Zilair nappe, Southern Bashkiria.*



class mature Domanik (Upper Frasnian) source rocks, and the large areal extent of the basin, exceeding 1 million km<sup>2</sup>.

The rapid growth in production fuelled the industrial development of the USSR in the 1950–1960s. However, by the 1960s many of the drillable closures had been tested and the success rate dropped, repeating the previous cycle.

### Third Cycle: West Siberia

Initially, petroleum prospecting in West Siberia caused serious skepticism. The geology of the basin had little in common with known producing basins, confusing many Soviet oilmen.

No shows of thermogenic hydrocarbons were reported and much of the region was covered with swamps, making surface mapping and structural drilling useless. In the early days exploration efforts were focused on the western pre-Uralian margin of the basin, which lacked mature source rocks. Finally, thanks to the enthusiasm of the explorers, after several failures a discovery was made in 1961 in the Middle Ob area, heartland of the West Siberian Basin, which attracted serious attention from an oil industry desperate for new prolific plays capable of replacing the fading fortunes of the Volga Urals. Subsequent studies showed the presence of a unique, super-prolific petroleum system. Resources were relocated from the mature Volga Urals to West Siberia to ensure a continuity of reserve build-up in line with ambitious Soviet economic plans.

At this time seismic surveying started to play a leading role in prospect definition. Thanks to the relatively simple platformal geological setting and favourable seismogeological conditions of the West Siberian lowlands, seismic prospecting quickly demonstrated its enormous value. Huge areas were covered with data and a large number of drillable prospects identified. Subsequent drilling exceeded the most optimistic expectations, resulting in the discovery of the second most important petroleum basin in the world. Massive field development and infrastructure construction projects topped the list of national economic priorities as oil and

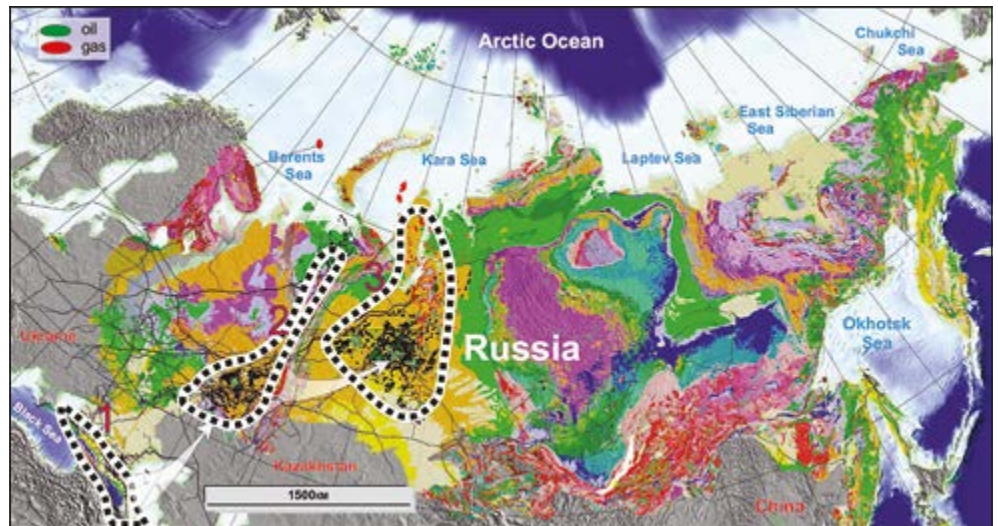


Figure 1: Geological map of Russia showing distribution of oil and gas fields, with focuses of petroleum exploration outlined: 1 – Caucasus; 2 – Uralian foreland; 3 – West Siberia.

gas revenues started to provide a large part of GNP.

The West Siberia exploration cycle generally replicated the Uralian foreland one but at a greater scale; prospective areas in West Siberia exceeded 3 million km<sup>2</sup>. Oil and gas reserve additions rapidly ramped up in the 1960s and 1970s, although exploration efficiency peaked in the mid-70s. Since then, the creaming curve has inevitably flattened out. Recently, the use of modern exploration techniques such as 3D seismic helped to find significant new reserves but failed to arrest the decline in the overall exploration performance, mainly because the size of new fields tended to get smaller.

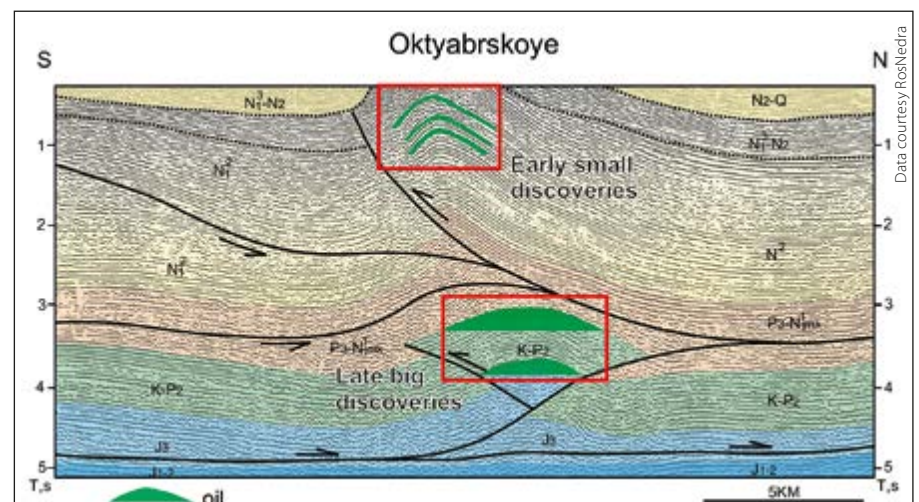
### No More Easy Discoveries

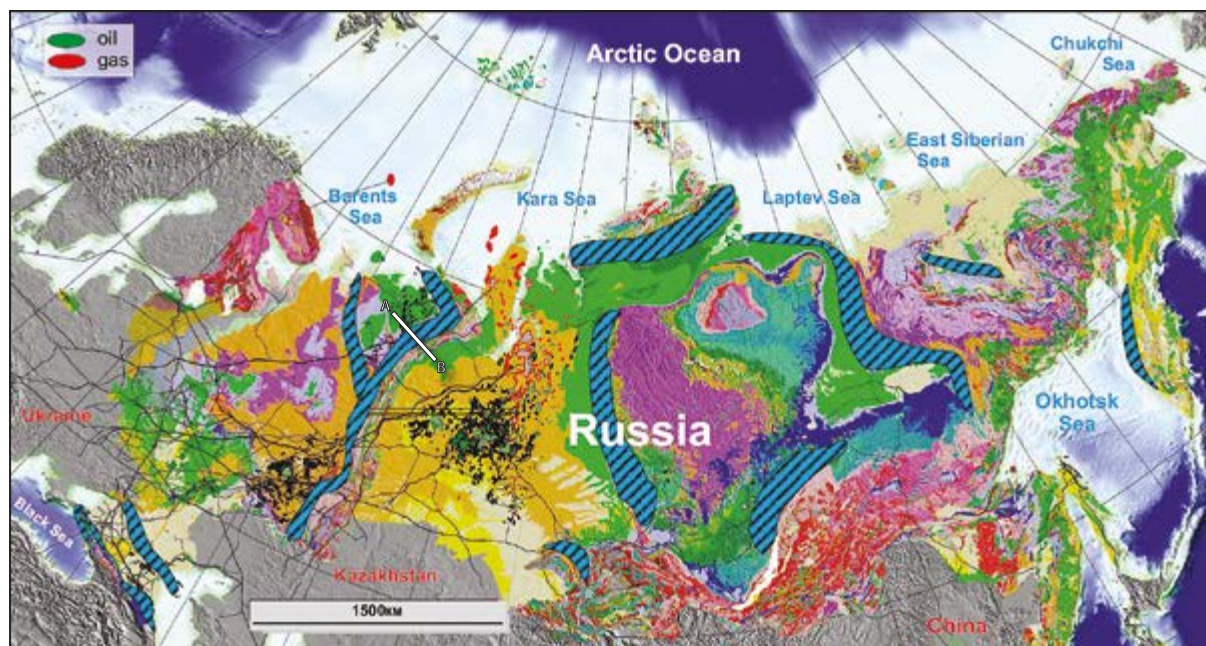
The decreasing efficiency of petroleum

exploration in the mature West Siberia stimulated studies of other basins, including the Precaspian, Central Asia, offshore Caspian, East Siberia, Far East, northern Timan Pechora and Arctic shelves. This resulted in several huge finds, but failed to offset the gradual decline in exploration success in West Siberia. Geological conditions and the technology of the time did not permit the replicable discoveries of the Volga Urals and West Siberia. In addition, the remoteness and predominance of gas made many new projects marginally economical.

Big subsalt finds in the Precaspian Basin, for example, were followed by a number of dry holes. Complexities relating to depth conversion of seismic data in areas of salt diapirism routinely resulted in significant mistakes in

Figure 2: Interpreted seismic line across the Oktyabrskoye oil field. Upper red box shows oil deposits discovered in 1913, lower box is the much bigger oil pools discovered in the 1960s.





**Figure 3:** Geological map of Russia showing distribution oil and gas fields, with the location of the most important onshore fold-and-thrust belts prospective for oil and gas outlined.

subsalt mapping. Arctic drilling yielded predominantly gas discoveries, such as the Stokman and Rusanovskoye fields – difficult and expensive to develop. Big deposits in East Siberia, such as the Yurubchen field, were too remote, and the Precambrian reservoirs were discontinuous and often tight. Overall, plays were either not as prolific as expected, or the technologies were inadequate for the subsurface and above ground complexities – all coupled with unstable market conditions in the late 1980s and early 90s. The disintegration of the USSR left attempts to find reserves replacements unfinished. The era of easy and cheap new discoveries was gone.

Over the last 20 years the Russian oil industry has undergone a period of restructuring and privatisation. Economic conditions made the new Russian oil companies focus on optimising production. Investments in the aging development facilities and infrastructure, as well as adoption of the best international reservoir management technologies, helped to increase recovery factors and created a brownfield renaissance. Newly available technologies, such as 3D seismic, were primarily used for development of the existing fields and near-field exploration. The huge Soviet legacy provided sufficient reserves to boost growing production and as a result exploration activities were drastically reduced.

It seems that this period is now over.

Production from the aging giants is getting more expensive, while existing producing fields have predominantly hard-to-recover reserves with a high water cut. The identification of new exploration plays to replace older fields is therefore a priority issue.

### The Arctic and Shale Resources

Examination of G&G data characterising the petroleum potential of Russia indicates that this task may have several possible solutions. The most popular options include exploration in the Arctic shelves and the realisation of the potential of shale deposits.

The Russian Arctic offshore has a total area of more than 4 million km<sup>2</sup>, and despite significant discrepancies in resource estimates there is huge exploration potential. Global warming has extended the ice-free period, allowing longer navigation and operations. Previous exploration and newly available data clearly indicate the presence of large prospects and leads, so geological risks seem to be acceptable. However, Arctic projects require stable, high oil prices, and the technical and ecological challenges of petroleum exploration and production in the area are huge. In addition, it is thought that a significant amount of the hydrocarbons are gas, a less economically attractive prospect than oil.

Shale development could be a very attractive option. The estimated

potential is huge; the lowest estimate of leading Russian experts is about 150 Bbo (20 Bn tonnes). Attempts to make tight rock work started decades ago; even subsurface nuclear explosions were made to increase tight reservoir performance, but with little success. Several shale projects are underway, mainly in West Siberia, with some good results. Wider development of shale is limited by taxation of oil production and the high cost of horizontal drilling and fracking, complicated by the swampy surface conditions of West Siberia. Currently, shale production is feasible in mature areas of West Siberia and Volga Urals, as secondary production objectives.

### Fold Belts – a New Alternative?

However, significant new exploration potential is thought to exist beyond these two alternatives. A critical review of G&G data shows that high impact opportunities exist in areas of complex geology, mainly represented by fold belts, which are found flanking virtually all sedimentary basins in Russia (Figure 3).

Due to limited data it is difficult to estimate total areal extend of the prospective lands, but preliminary estimates suggest up to 2 million km<sup>2</sup> onshore. The fold belts are of different types and ages ranging from Late Precambrian to Late Tertiary. Some prospective fold belts are completely buried; in West Siberia



folded Palaeozoic deposits host some significant oil and gas fields underneath gently deformed Mesozoic cover. Generally, fold belts have thicker sedimentary sections involving more reservoir-seal pairs compared to the adjacent platformal areas, along with thicker organic-rich marine shales producing huge volumes of hydrocarbons. Many fold belts have oil and gas shows indicative of the presence of working petroleum systems. Multiphase structuration provides diversity of trap types including high-relief closures capable of delivering large flow rates. Fold belts often involve reef systems which were developed within continental margins prior to onset of compressional folding, and the buried reefs along with drapes and talus deposits may host vast volumes of hydrocarbons. Under favourable conditions the fold belts may have extremely high reserve densities, as exemplified by giant fields in Iran, Iraq and Venezuela.

Ironically, the oil industry originated in fold belts, but after picking the low-hanging fruits these areas were

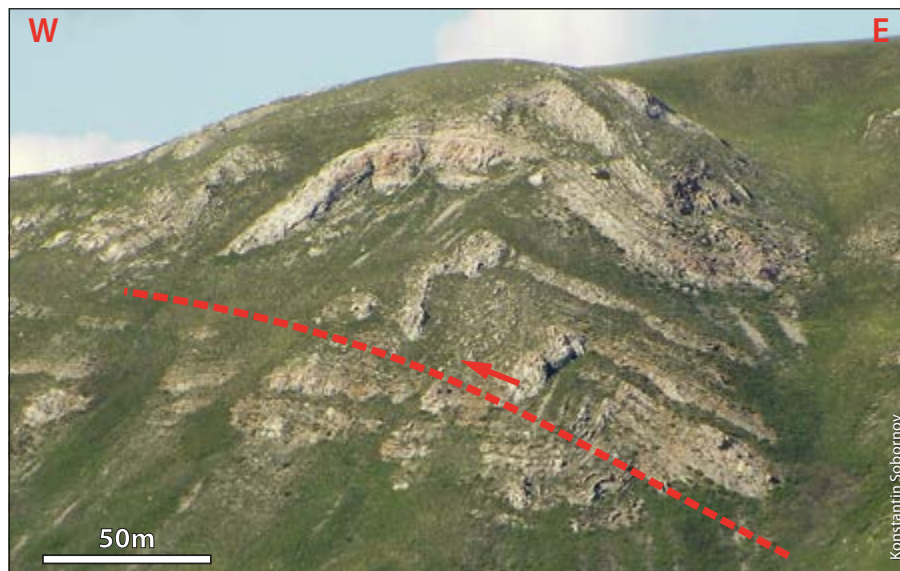


Figure 4: West-verging thrust-related fold in Lower Permian carbonates, Kruzhevnyaya Mountain, Southern Bashkiria, Southern Urals.

left behind. Exploration tools were not good enough to provide data on the subsurface to support risky drilling of poorly constrained prospects. Moreover, with the finding of low-risk opportunities in the Volga Urals and West Siberia, the complex terrains dropped low on the list of exploration priorities, reflecting limited geological

knowledge rather than hydrocarbon potential.

There are examples of important discoveries made in fold belts decades after the first exploration cycle. Large oil pools in Cretaceous carbonates were found at greater depths at the Oktyabrskoye field in 1960s (Figure 2). Note that the crest of the Cretaceous

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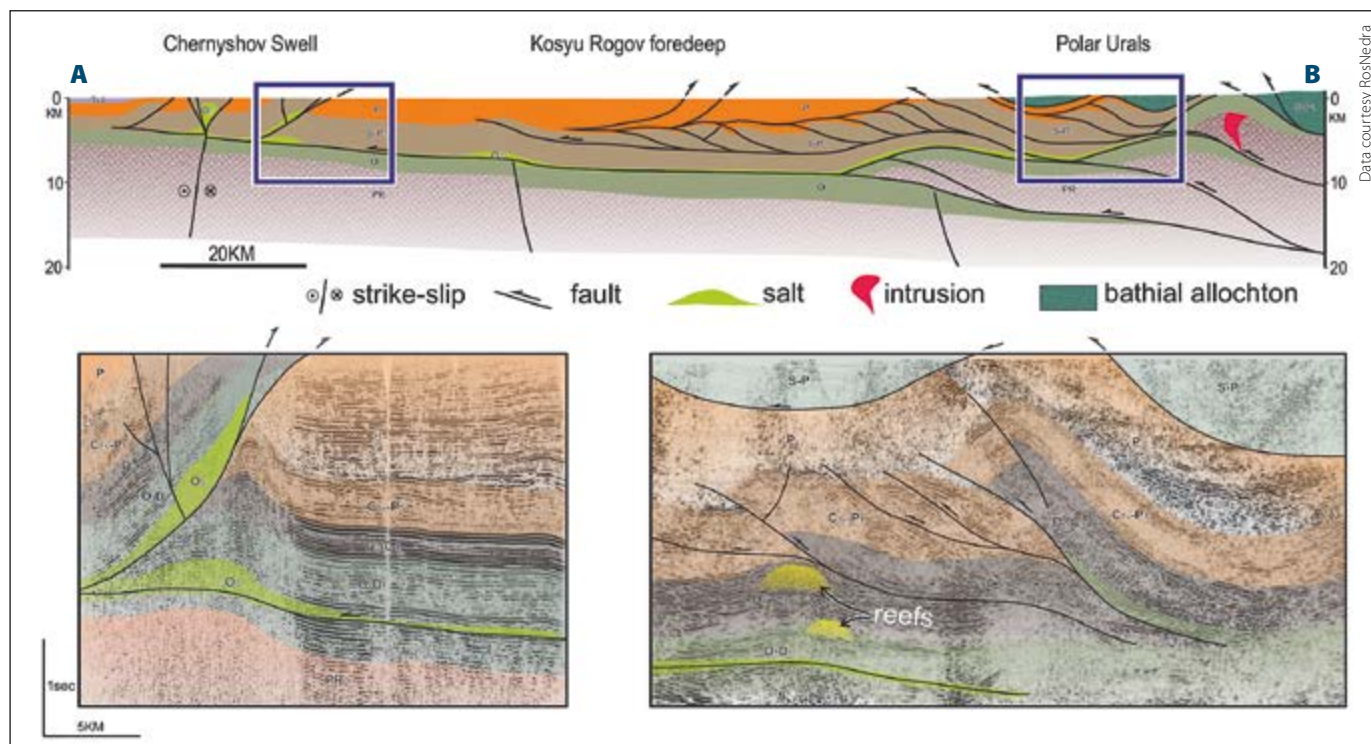


Figure 5: Regional geological section across the Polar Urals fold-and-thrust belt (line of section shown on Figure 3). Initials correspond to pre-Uralian foredeeps. Insets: interpreted seismic lines.

closure does not coincide with the Miocene anticline exposed at the surface. This structural pattern involves detachment faulting and tectonic wedging providing disharmonic folding. The thickness variations of a weak tectonostratigraphic interval masked the shift of the deeper closure. The discrepancy in the crest locations explains why the deeper Cretaceous closure hosting much greater oil deposits was bypassed by wells drilled within the Miocene anticline. Discoveries of this type could be made in most cases through seismic surveying, which was introduced well after the first exploration campaign. This case shows that the rule 'big fields are first to be discovered' does not work in fold belts.

Recent regional studies show that complex structural settings providing significant new exploration opportunities are attributable to many fold belts. The diversity of large mainly untested leads in fold belts is illustrated by a regional geological and supporting seismic line across the Polar Urals fold-and-thrust belt (Figure 5). Of prime interest in this area are high-relief 4-dip closures and reefs.

There are many other fold belts where leveraging advanced exploration

technologies could reveal new prospective plays. Currently 3D seismic surveying provides the most reliable data for the prospect generation in complex geological terrains, but the best results could be delivered through the integration of various exploration methods including electromagnetic and geochemical studies, potential field data, remote sensing and field observation. Crucial for successful exploration in fold belts are expertise in structural geology, drilling technology, overpressure prediction and hydrocarbon modelling.

Some fold belts like the Caucasus and

### Village in the Southern Uralian foothills.



Urals are situated in areas with well-developed infrastructure and significant local consumption, where even small discoveries could be economical. Taking into account the size of prospective areas in the fold belts, it seems reasonable to suggest that the fold belts could deliver a new cycle of oil and gas exploration in Russia.

### Acknowledgements:

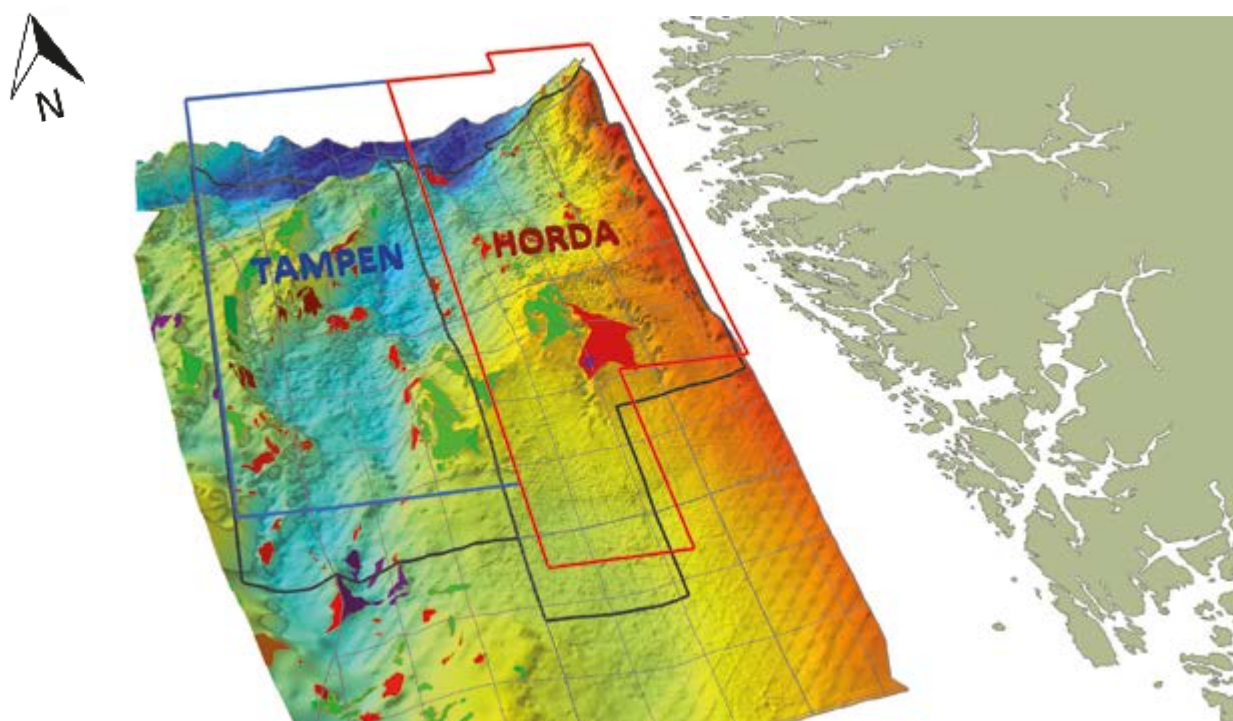
The author would like to thank François Roure, Vasilij Shein and Joe Staffurth for helpful discussions and suggestions during the preparation of this paper.

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# Field-based Training: Luxury or Necessity?

GARY NICHOLS  
and SIMON BAKER,  
Nautilus Ltd.

**What is the role of field geology today, what will it be in the future and what specifically is the importance of field-based training to petroleum geosciences? Is it a 'luxury' we cannot afford to give up?**

Now that subsurface imaging has become so sophisticated and levels of detail unimaginable in the past are routinely available, it is tempting to think that these tools are all we need to understand the geology of an area. So where is the value of field-based training to the industry? Has it become a luxury?

A degree in geology used to provide a reliable grounding in fieldwork: at one time there was a notional benchmark that an honours degree course in the UK would include about 100 days of fieldwork. In many UK university geoscience departments lack of funding has threatened to diminish the role that fieldwork plays in the training of students. More worryingly there also seems to be a diminishing number of academic staff who are experienced field geologists. Funding for field-based research has decreased, so many academics have a lab-based focus in their research and do not necessarily have extensive field experience to pass on. Consequently geoscientists

coming into the oil and gas industry from UK universities are likely to have less field experience than those of a decade or two ago. Does this matter?

The old aphorism 'the best geologist is the one who has seen the most rocks' is often presented to justify training geoscientists through fieldwork – but why should this be the case? What exactly is experienced in the field that cannot be experienced from examining samples in a lab or viewing images on a computer screen?

## Context at a Continuum of Scales

Probably the most important thing that field observation alone can provide is this – 'context at a continuum of scales'. It is only at a rock-face that it is possible to go from looking at grains of sand less than a millimetre across, to views of the regional geology that may stretch for tens of kilometres, while potentially seeing everything in between across those seven or more orders of

magnitude. Whilst it is only in places of spectacular exposure that this is possible, these are the very places where field training is best carried out: in the shoreface sandstones of the Book Cliffs of Utah, the fold and thrust belt of the Southern Pyrenees and the whole systems tracts exposed in the fjords of Spitsbergen.

There is a spatial resolution gap in the range of scales of observation within subsurface data. At the smaller scales, microscopic levels of analysis are available from cuttings and core samples, with core providing detail of features such as vertical trends. These analyses overlap with well logs, which are typically more vertically continuous and with vertical resolution in conventional logs in the order of tens of centimetres. At the other end of the scale, seismic data provides the broader context with both vertical and horizontal resolution measured in tens of metres.

In between lies a gap: a gap in which

*Outcrop of Miocene fluvial strata at Monzon, Huesca Province, Spain. (From Nautilus course N108 Exploration and Geological Model Development in Fluvial Reservoirs, Ebro Basin, Spain.)*



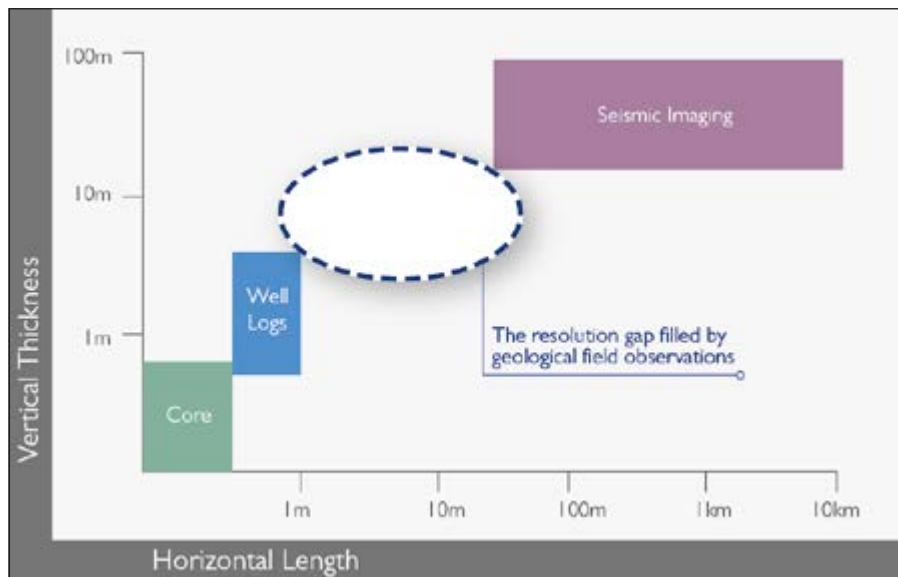
resolution in three dimensions at the scale of metres is not available from subsurface data alone. And as this is the scale at which reservoir models are built we need to have means to integrate between seismic and well-based data. Since this is not currently possible using subsurface data alone, we need to use our understanding of relationships observed in the field to integrate and interpolate, as demonstrated in the two examples that follow.

### When Only Field Observation Will Do

#### Example 1: Fluvial successions

The photograph below is of outcrops of fluvial sandstones in the Miocene of the Ebro Basin in Northern Spain. There is considerable heterogeneity at scales ranging from centimetres to tens of metres, and because of the lateral variability any single vertical section would not be representative of the succession as a whole. This cliff is less than 100m high, so none of the complexity would be discernible on a seismic reflection profile. If presented with a unit composed of sediments deposited by deposition in river channels and on overbanks, the only way to create a model is to use an understanding of the range of geometries and relationships seen in the field.

To build a credible model it is vital to apply the knowledge of the characteristics of fluvial strata gained not just from one field example, but from



*The spatial resolution gap filled by field observations.*

multiple field case studies. Observations of field examples will clearly demonstrate that reservoir models built from shoe-string sandstones are not a realistic reflection of how most fluvial successions appear in real life. The shoe-string model is based on a fundamental misconception that river channel deposits directly reflect the planform of a river channel; they don't – rivers deposit when they laterally migrate and create sandstone complexes that are sheets or linear features significantly wider than the channel.

In the case of the succession seen below, the behaviour of a gas reservoir with apparently low net-to-gross can

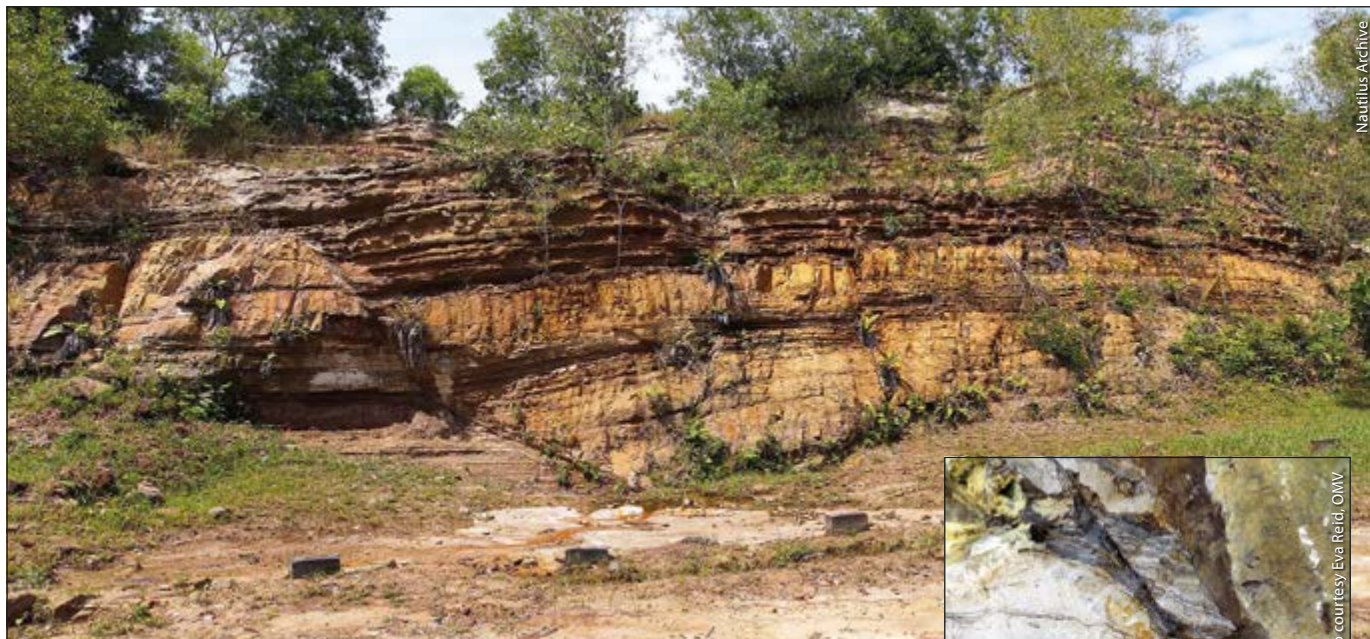
only be understood when it is realised that the thin sheet sandstones deposited on the floodplain provide connection between the coarser, thicker channel sandstone bodies. That understanding could not be reached from core, well-log or seismic data.

Put simply, it is not possible to create either a conceptual model or a reservoir model of a fluvial succession without having seen similar rocks in the field.

#### Example 2: Internal fault architecture and fault sealing

All too often subsurface maps depict faults as a single plane – the reality is that faults are complex three-





Nautilus Archive

Photo courtesy Eva Reid, OMV

**Miri Airport Road outcrop. The principal fault here cuts the 456 Sand of the Miri Hill Field and displaces it around 5m in a normal sense (downthrow to the right, or north). The fault is interpreted as part of a crestal collapse structure of an inversion anticline which forms the Miri Hill Field. Approximate height of outcrop face is 6m. (From Nautilus course N320: Prospect, Trap and Fault Seal Analysis: Mapping Key Uncertainties, Miri, Malaysia.)**

dimensional structures with much internal heterogeneity and are better thought of as fault zones. The scale-independent or ‘fractal’ nature of faults means that observation of faults at outcrop can provide critical insights into their internal structure in the subsurface and their potential to act as reservoir seals or baffles in oil and gas fields.

The figure above shows a normal fault developed in a heterolithic late Miocene succession of shoreface sandstones and interbedded marine shales. Close inspection of this fault zone (inset) reveals a highly complex internal structure composed of lenses of intact stratigraphy bounded by anastomosing slip planes with or without shale smear. It is relatively easy to trace a path, albeit a rather tortuous one, across the fault in 2D that does not cross any shale smear, implying that the fault will not seal. This simple field observation of a potentially leaky fault has important consequences at a prospect scale.

Whilst such complex and 3D aspects of faults can be taught in the classroom, it is only in the field that the real implications of these features of fault zones can be effectively demonstrated. The deeper understanding and insights gained from such field training mean that geoscientists and reservoir engineers

will critically assess techniques or software that assume certain properties for faults. As a result they will be in a considerably better position to quantify uncertainty associated with a given fault leaking or sealing.

**The Value of Field Observations**

So a few days spent studying fluvial channel bodies will help constrain the reservoir model by providing a basis for deciding whether sandstone units will be laterally extensive and connect across a field. Having a geoscientist apply calculations of shale gouge ratio/shale smear factor after observing fault zones in the field will result in a better understanding of the potential of the fault to seal than calculations applied by someone without that practical vision.

The collection of seismic, core and well-log data is a very significant outlay and is essential to exploration and field development. However, these data do not provide all the information that is needed to build a picture of the subsurface geometry at the scale required for reservoir development. The resolution gap has to be filled and that can only be achieved by field observations that provide real examples of what does, and does not, occur in the rock record.

Field examples can be provided by





**Close-up of the central portion of the fault. Note the complexity when viewed at this scale, including shale smear (continuous in this photograph), internal blocks bounded by two main slip planes and damage to the footwall (left).**

training courses that visit relevant outcrops, which provide the visualisation of comparable relationships. Alternatively, carrying out original observations of selected analogues can provide bespoke data and understanding to address a particular situation. In either case the rocks observed in the field are an essential reality check on any model for a subsurface relationship.

Admittedly we are biased: we are field geologists and we have spent our careers making field observations and being involved in running field-based training courses. There is a cost in time and money to geological fieldwork, but we are bound to ask the question – can you afford not to do it?

*Nautilus Ltd is part of RPS Training. Examples and images in this article are taken from field courses available to companies who subscribe to the Nautilus Global Training Alliance. ■*

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# Iran

## The Implications of Peace

**An agreement on Iran's nuclear industry should be signed by the end of June. What are the implications for the oil price, OPEC and the industry?**

**NIKKI JONES**

It seems that the Security Council, plus Germany, has finally come to an agreement with Iran on curbing the country's uranium enrichment programme, and a reciprocal lifting of sanctions. The deal is expected to be fleshed out and signed by the end of June, and although there is much playing to hostile audiences – Iran's hardliners as well as Israel, Saudi Arabia and US senate Republicans – there appears to be a steely determination on both sides.

### Widespread Implications

There are, inevitably, enormous implications for oil and gas prices, for OPEC and for the industry. Iran has the fourth largest oil reserves in the world and the second largest gas. Approximately 70% of the Republic's oil is onshore and most of the remainder

is in the Persian Gulf. Iran also holds largely undeveloped reserves in the Caspian. The country's gas potential is enormous with many recent discoveries, as well as the 51 Tcfg reserve known as South Pars.

A significant increase in oil and gas supply will – bar any unforeseen supply disruptions – depress the already low world price. Iran's oil production ran at around 4 MMbopd for much of the first decade of the millennium, but plummeted after new sanctions were imposed in 2011. The current output of liquids is 2.8 MMbopd, of which only 1.1 MMbo is exported.

Once compliance with international inspections is ascertained – and there are differing views on how long this will take – Iran could not only begin to increase production by a possible

500,000 barrels in six months and 700,000 within a year, but could immediately begin to release some of the 30 MMbo it is believed to have stored onshore and in tankers.

Iran's aim is not only to achieve the pre-sanctions production level of 4 MMbopd but to reach 5.7 MMbopd by 2018, although this will take billions of dollars of investment. Some analysts estimate that \$230bn is required across the energy sector.

Many western companies are poised to jump in. Shell, Repsol, Statoil and Total were all forced to pull out in 2010 but there are now reports of new contracts being drawn up, with Eni and Total believed to be among the front-runners. Whether companies will get the production sharing agreements they want with the National Iranian Oil Company remains unclear, but at the very least they will be hoping for a flexible fee structure that will allow them to book large reserves.

### Increased Supply

It seems likely, therefore, that within the lifetime of the current US shale boom significantly more oil supply will arrive on the market, depressing prices further. Some analysts are speculating that Brent could drop as low as \$20/b. However, as the IEA points out, this may be partially balanced by cuts in more expensive production elsewhere.

A secondary, price-deflating effect of the agreement will be the calming of speculation over the security of the Straits of Hormuz. At its narrowest, this

*Barrels of oil near Isfahan, Iran.*





'pinch point' is just 34 km wide, but it is the outlet for 20% of the world's crude. Over the last few years, fears of Iranian disruption have frequently helped inflate prices.

Gas prices will also be lowered, not only because most contracts are oil-linked, but also because of greater supply. In 2012 Iran produced 5.6 Tcf, although currently only 21 Bcfd comes from South Pars, the enormous field that is shared with Qatar (where it is known as North Dome). It is believed to hold 40% of Iran's reserves and it is the Republic's stated priority for investment. Under sanctions, Iranian companies have been implementing a 24-stage development plan at South Pars but this is only half complete. In addition, there have been several new gas discoveries in recent years and these await development. Iran's overall goal is 35.3 Bcfd by 2018.

#### Political Commitment

President Rouhani's commitment to reintegration with the wider world seems genuine and personal. Getting sanctions lifted was his main pledge in the 2013 election which he won with widespread, popular support. After years of corruption under President Ahmadinejad, fuelled by sanctions and attempts to circumvent them, the treasury was empty when Rouhani came to power. The country was suffering 40% inflation and almost 25% youth unemployment. In the last two years it has faced severe fuel shortages and the decimation of the agricultural sector through drought. The World Bank has estimated that a third of Iran will be empty within 20 years because of water shortages.

The Supreme Leader, Ayatollah Ali Khamenei, seems – at the moment – acquiescent towards the nuclear deal and willing to keep the Revolutionary Guards in check. The social and political context in Iran has evolved since the early 1980s, with women participating at most levels. However, the Revolutionary Guards remain vehemently ideologically opposed to the west and a political challenge for the country's leadership. They are widely believed to have engineered



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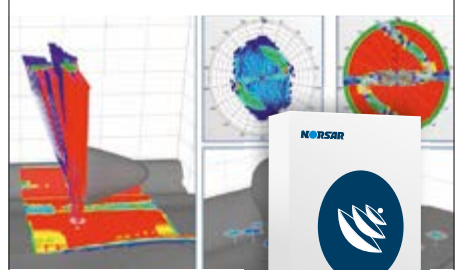
(Offshore exploration/appraisal)

##### UK: EAST MIDLANDS

(Onshore appraisal/development)

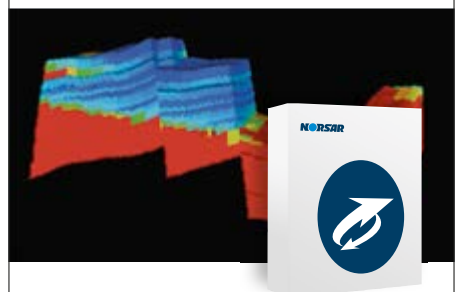
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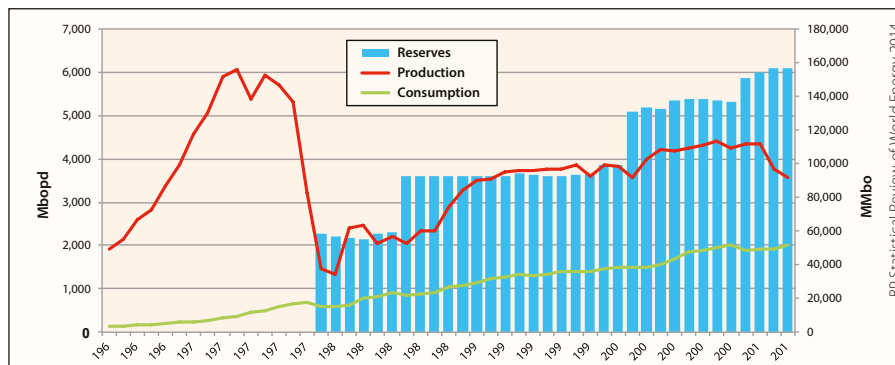
## Industry Issues

Ahmadinajad's electoral victory in 2009, and they control the Quds force which is thought to have links with Hezbollah, Syria's Assad and possibly the Yemeni Houthis.

However, the Revolutionary Guards have also become a huge commercial entity within the country, a role which developed from their taking on infrastructure construction projects during the Iran-Iraq war. Since then, they are believed to have accumulated assets worth billions of dollars, including oil and gas, from key privatisations. Their revenue is now estimated at \$100bn annually. Although they are likely to welcome foreign expertise that will boost oil and gas production, their presence in the economy and in politics will be a complicating factor for investors.

### Challenges

Increases in oil production will inevitably bring Iran into conflict with OPEC quotas. Since last November, Saudi Arabia – the world's 'swing producer' – has refused to reduce its production to help balance prices and it seems extremely unlikely that it will revise this policy in order to accommodate its much loathed Shia rival. Most members are in no financial position to cut production



Iran's oil reserves, production and consumption.

while the oil price – and therefore their revenues – are so low. It is hard to see how OPEC can continue as a cartel if it has lost the essential power to control production and fix prices.

Many threats to the proposed agreement exist, but publicly Saudi Arabia's reaction has been cautiously positive. US Secretary of State John Kerry clearly hopes that there will be a wider de-escalation of tensions in the Middle East, cooperation against ISIS and a solution to the Syrian conflict. Israel is looking increasingly isolated. Russia, which might have blocked an agreement for fear of lower oil prices, is on the sidelines and will play a key role in taking Iran's excess uranium and processing it into fuel rods. The Chinese have offered to finance the Pakistani section of the

much delayed 'Peace Pipeline' between Iran and Pakistan, and Tehran signed a gas supply agreement with Islamabad last December. Europe will be looking to benefit from gas supplies, via Turkey, that could lower its dependence on Russia.

Challenges remain however, in that although Rouhani appears unassailable from hardliners within Iran, this could change if he is unable to deliver economic benefits to the Iranian people. He is looking for a speedy lifting of sanctions. A more immediate threat comes from US Republicans threatening to pass legislation that will allow them to veto the deal. If the agreement holds, there will be a profound re-shaping of politics in the Middle East. The world, and particularly the oil industry, will be watching carefully. ■

The Dove of Peace Monument in the colours of the Iranian flag stands on Imam Khomeini square in Tehran.





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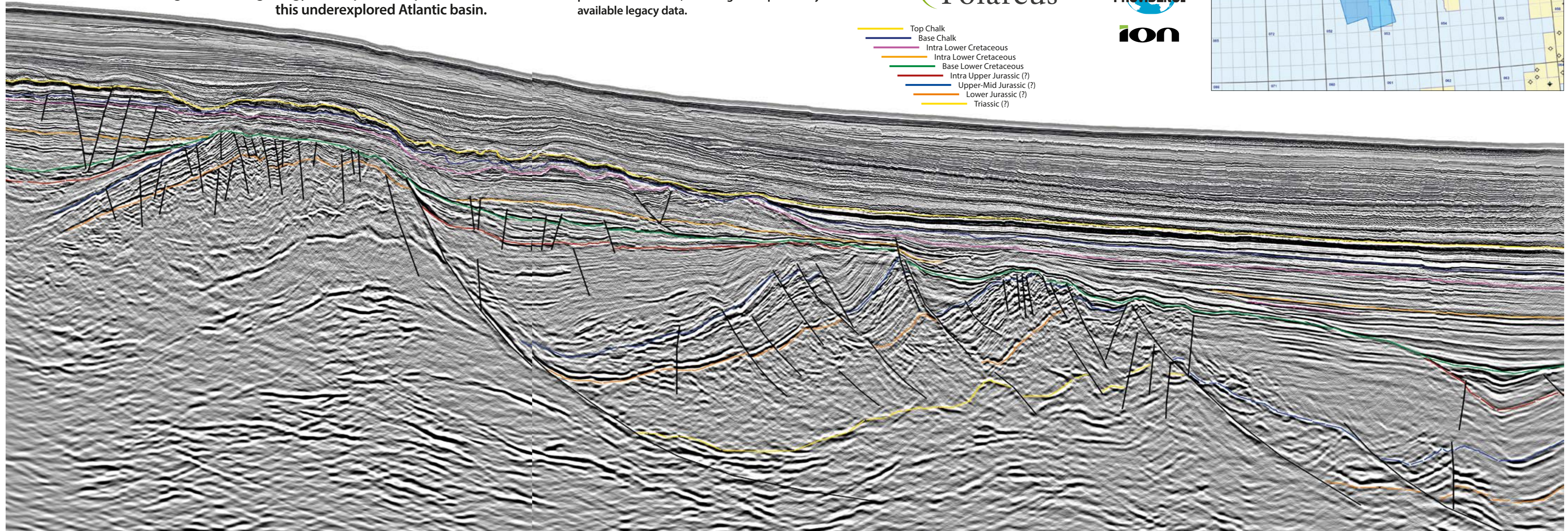
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# Ireland: South Porcupine Basin

New insights into the geology and exploration potential of this underexplored Atlantic basin.



The Porcupine Basin is a north-south trending elongate sedimentary basin located 200 km west of the Irish mainland. The basin is some 350 km long with widths varying from approximately 65 km in the north to 200 km in the south. It is bordered by the Porcupine High to the west, the Slyne Ridge to the north, the Irish mainland shelf to the east and the Goban Spur to the south. The basin has been largely underexplored, particularly in the south where only two wells have been drilled to date.

New Polarcus 3D seismic data in the South Porcupine Basin has provided new insights into the geology and exploration potential of the area, revealing detail previously unseen on available legacy data.



- Top Chalk
- Base Chalk
- Intra Lower Cretaceous
- Intra Lower Cretaceous
- Base Lower Cretaceous
- Intra Upper Jurassic (?)
- Upper-Mid Jurassic (?)
- Lower Jurassic (?)
- Triassic (?)



# The Porcupine Basin

The South Porcupine Basin contains all the elements for a successful petroleum system.

**TONY PEDLEY**, Polarcus; **GERRARD SPEAR**, Lyme Bay Consulting;  
**KEITH BYRNE**, Providence Resources

The Porcupine Basin is related to Mesozoic extension across north-west Europe and the break-up of the Pangean supercontinent. It is believed to be a failed rift arm of the proto-North Atlantic, formed within a major wrench-rift zone extending from the Biscay Seaway to Labrador. Triassic through Early Jurassic extension resulted in an approximately north-south rift system extending from the Galicia Bank, offshore Iberia, north into the Porcupine Basin. This extension was followed by a thermal sag phase, with rejuvenated extension in the Mid-Jurassic. Pronounced extension occurred in the Late Jurassic to Early Cretaceous followed by a thermal sag phase in the Cretaceous and Tertiary.

## New 3D Data and Detailed Reconnaissance Study

The North Porcupine Basin has seen the greater amount of exploration activity, with 28 wells drilled to date. Of these, four have tested hydrocarbons: wells 26/28-1 & 26/28-2 (Connemara oil discovery), well 35/8-1 (Burren oil discovery), and well 35/8-2 (Spanish Point gas-condensate discovery). Many of the reservoirs encountered in the North Porcupine Basin did, however, display low permeability due to diagenesis of the clastic source, derived from erosion of Carboniferous hinterland.

The South Porcupine Basin has a fill of up to 9 km of primarily Mesozoic and Cenozoic age and to date remains virtually unexplored. The two wells drilled in the basin have, however, offered encouragement, with 43/13-1 logging hydrocarbons in Upper Jurassic sands, and 44/23-1 (Dunquin North) encountering a thick Lower Cretaceous over-pressured carbonate reservoir sequence with a residual STOIPP of approximately 600 MMbo.

Tectonic reconstructions suggest the South Porcupine Basin formed a conjugate margin with the Canadian East Orphan Basin. Several discoveries have been made across the conjugate margin, including Mizzen (100–200 MMbo), Bay du Nord (300–600 MMbo) and Harpoon. These discoveries have been made in Mesozoic reservoirs with an Upper Jurassic marine source rock, similar to those proposed for the South Porcupine Basin.

Polarcus, in collaboration with ION Geoventures and GeoPartners Ltd, acquired in 2014 over 4,300 km<sup>2</sup> of broadband multi-client 3D seismic data over a number of blocks on the western margin of the South Porcupine Basin. These new data for the first time provide the coverage and resolution needed to evaluate both the structural and stratigraphic plays

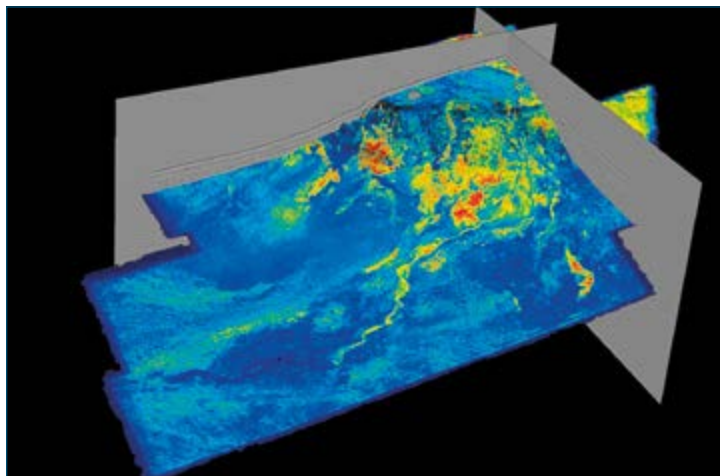
and also to carry out detailed rock physics studies to evaluate the identified prospects. The new data, as well as covering Providence Resources' Drombeg exploration prospect, also covers a number of open blocks available for licensing in Ireland's current 2015 Atlantic Margin Oil and Gas Exploration Licensing Round.

To evaluate the geology and prospectivity of these new data, Lyme Bay Consulting applied their Detailed Reconnaissance Study (DRS) workflow to the post-stack migrated fast-track volume. The DRS builds a 'GeoModel' based on the underlying seismic data, and calculates and correlates the relationship between 3D seismic points according to the similarity of the wavelets and their distance from each other. This DRS produces a horizon-consistent map for each and every reflector within the dataset. Attributes are then calculated from the original seismic and overlain on the horizons to deliver a high resolution reconnaissance tool to enable identification of structural and stratigraphic features within the data. Two hundred horizons were generated for this dataset and a number of examples are reproduced herein to illustrate features observed within the data.

## Geological Overview

The new data provides a step change improvement in imaging, as seen on the foldout line, which shows a typical data example from the pre-STM final volume where extensive faulting created during rift development can be observed. A well-developed Triassic to Middle-Upper Jurassic section can be seen within the fault blocks. Much of the Jurassic section in the South Porcupine Basin is believed to be fully marine in nature and, as well as

*Lower Tertiary DRS horizon with RMS amplitude extraction showing a number of channel systems distributing sediment from near shore slope areas into deeper marine fans and sheet sand-bodies.*



containing potential Kimmeridgian source rocks, reservoir units could also be present within these sequences.

Cessation of rifting was followed by essentially passive infill of the basin, with the Lower Cretaceous sequence overlying and infilling the Jurassic topography followed by deposition of a thick sequence of sediments with varying degrees of clastic input from the basin margins. A Lower Cretaceous source rock within the Barremian to Cenomanian may also be present and thick regional mudstones are believed to form efficient seals across the basin. Numerous stratigraphic features within the Lower Cretaceous sequence reflecting possible shoreface to deepwater clastic systems can be seen, many of which are associated with amplitude anomalies.

The Upper Cretaceous Chalk is widespread across the region and is overlain by a Tertiary sequence, which displays a number of clastic channel and sheet geometries developed within the Paleocene and Eocene.

### Lower Cretaceous Leads Revealed

Within the Lower Cretaceous, sediment supply from the western margin of the basin into the deeper marine areas can be seen for the first time in a number of distinct depositional systems. Multiple clastic channel inputs can be observed; the depositional systems display confined geometries across the palaeo-slope areas, which spread into a number of fans in the deeper water areas, often exhibiting distinct lobe geometries. These depositional inputs are long lived and were feeding sediment into the deeper offshore areas throughout subsidence and infill of the basin.

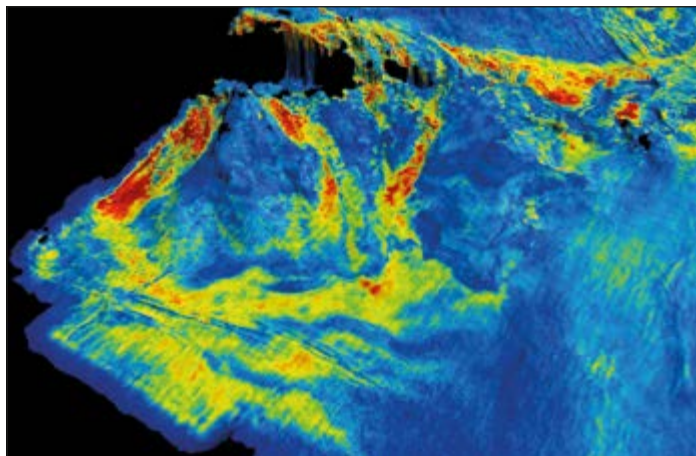
Sediment source for the turbidites was created by uplift and erosion of the Devonian Old Red Sandstone hinterland to the west, suggesting development of better quality reservoir sands than those encountered in the wells in the North Porcupine Basin. The Old Red Sandstone provenance expected in the South Porcupine Basin is a proven model in the adjacent Canadian conjugate margin.

The DRS study has identified several leads, many located in open acreage, which vary from linear channel features to lower energy down-slope fan systems. Amplitude cut-off with depth has also been observed.

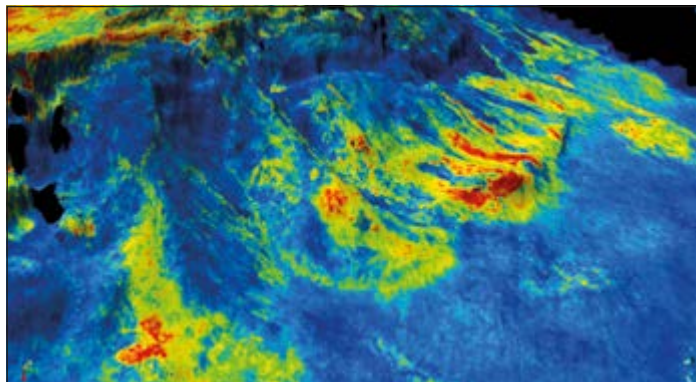
A number of structural traps can also be seen to affect the Lower Cretaceous, an example of which is a large detachment feature that has partially detached from the basin margin and has slid into the basin, generating a toe-thrust with a lateral extent in excess of 25 km along strike. A number of sand units, deposited in canyon-constrained channels or turbidites along the basin margin, can be seen to occur in closures created by folding associated with this toe-thrust development. This is an interesting suite of leads as the collapse back-scar may also provide an up-dip seal to the reservoir-quality high energy depositional systems that will have delivered these sands, thus developing a series of stratigraphic traps with an up-dip structural component.

### Promising Conclusions

The South Porcupine Basin 3D data provides new insights



*Example of a Lower Cretaceous slope to basin depositional system. A number of confined slope channel systems can be seen to feed sediment into deeper water basin distributary systems. The DRS study has illustrated the extent and evolution of such systems throughout the Lower Cretaceous and for the first time recognised a number of prospective leads.*



*A laterally extensive slump unit can be seen to have transported Lower Cretaceous sediments down slope. This has resulted in a number of dip-closures, often associated with brightening, in folding related to compression at the thrust front.*

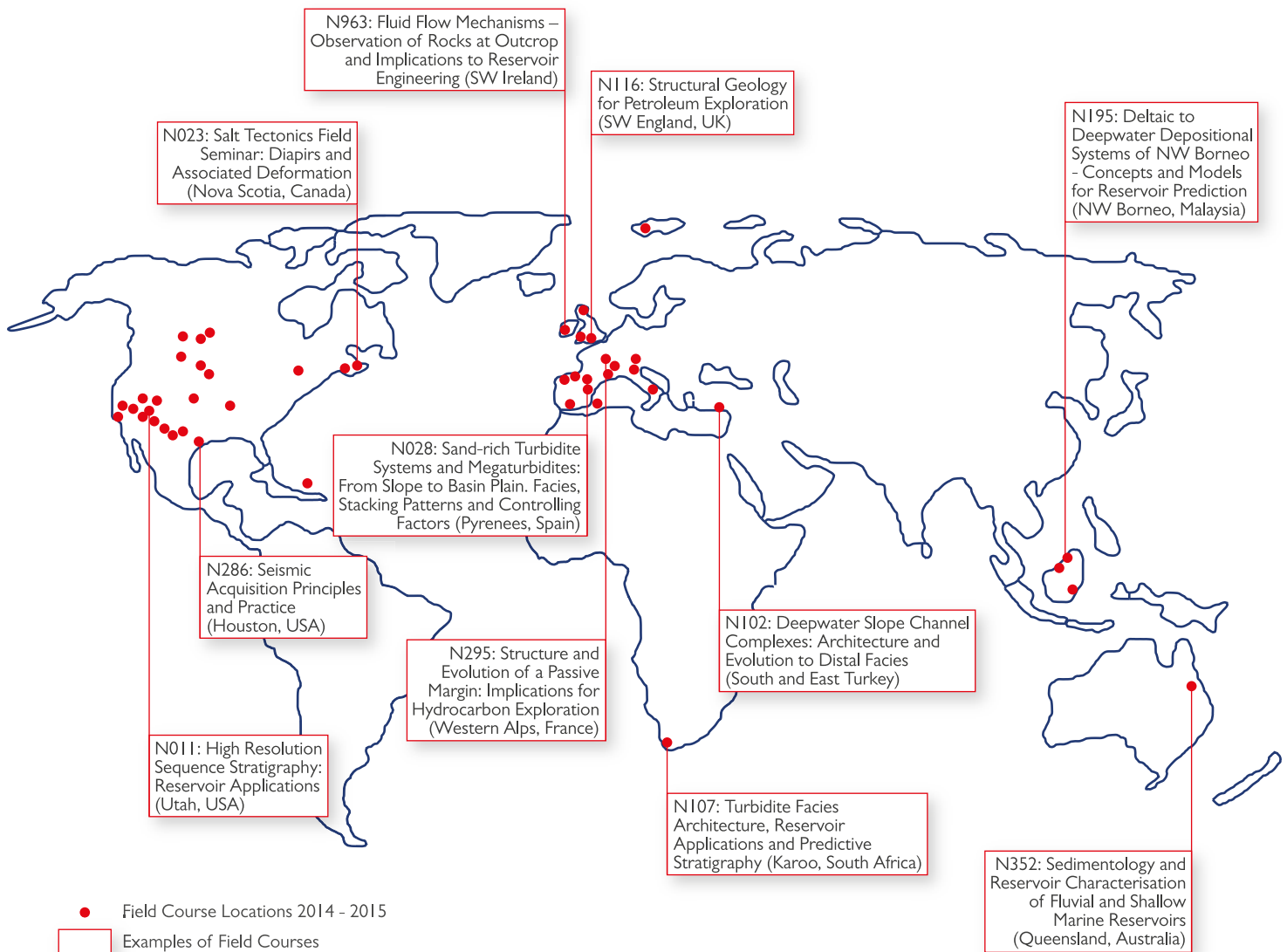
into the geology and prospectivity of the western margin of the basin. A well-developed Jurassic sequence, contained within rotated tilted fault blocks, provides potential for both source and reservoir, and several structural and stratigraphic traps can be seen. The overlying Lower Cretaceous contains a number of mapped leads in shelf to basin clastic units which often occur in stratigraphic traps, some with a structural component and some displaying an amplitude cut-off with depth. Potential also exists in Paleocene and Eocene clastic sequences, which are imaged in detail on the new data. The area contains all the elements for a successful petroleum system and the 2015 Atlantic Margin Licence Round provides an exciting opportunity to assess this underexplored and highly prospective area. ■

### Project Description

Polarcus acquired this RightBand™ multi-client survey using Polarcus Amani, towing a 10 x 150m x 8,100m ultra-quiet Sentinel® solid streamer spread and a 25m alternating shot interval, delivering 81 fold data with a 10 second record length. Data has been processed by ION GX Technology through a state-of-the-art WiBand™ Pre-STM workflow.



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# Gas Hydrates

LASSE AMUNDSEN, Statoil, and  
MARTIN LANDRØ, NTNU Trondheim

## PART VIII: Hydrates in Outer Space (1)

Today found widespread on Earth wherever stability conditions are met and an ample supply of natural gas is present, methane hydrate was originally thought to occur in the outer region of the solar system where temperatures are low and water ice is common. We look into the possibilities of gas hydrates on Mars and elsewhere in outer space.

NASA's Mars rover Curiosity sampling gas on Mars.



---

*Science is a wonderful thing if one does not have to earn one's living with it.*

---

Albert Einstein

Gas clathrate hydrates are ice-like compounds in which guest molecules of gas such as carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), ethane ( $\text{C}_2\text{H}_6$ ), propane ( $\text{C}_3\text{H}_8$ ), and hydrogen sulfide ( $\text{H}_2\text{S}$ ) are trapped within cage-like structures of water ice. Gas hydrates are stable at elevated pressures and temperatures compared to frozen water.

Mars, the 'red planet', has intrigued humans for thousands of years. It is named after the Roman god of war because of its red hue and that colour's association with blood. Mars has polar ice caps, made of water ice, surrounded by frozen carbon dioxide which expands and contracts with the seasons. On average, the temperature on Mars is about  $-60^\circ\text{C}$ . Near the equator temperatures vary from a warm summer  $20^\circ\text{C}$  in the day to an arctic  $-70^\circ\text{C}$  in the night, while in winter temperatures near the poles can drop down to  $-125^\circ\text{C}$ .

### CH<sub>4</sub> on Mars?

The debate over if and how much methane is present on Mars has been long-running. In 2004, several research teams announced that they had spotted traces of methane, which could have come from microbes or geological activity, or been delivered as extra-planetary methane by crashing comets – all thrilling possibilities. However, the observations were indirect and uncertain.

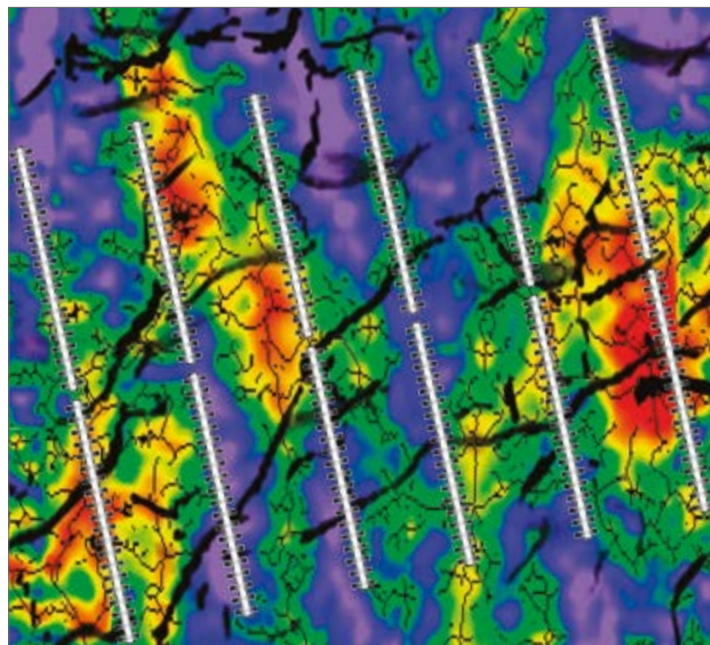
Then, at a meeting of the American Geophysical Union in December 2014, researchers announced that NASA's Mars Curiosity rover had found a small amount of methane wafting over its landing spot in Gale Crater. Over the



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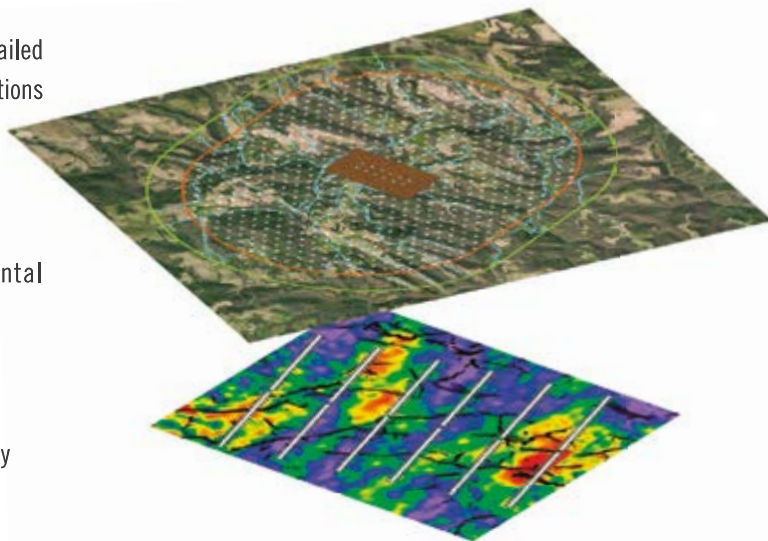
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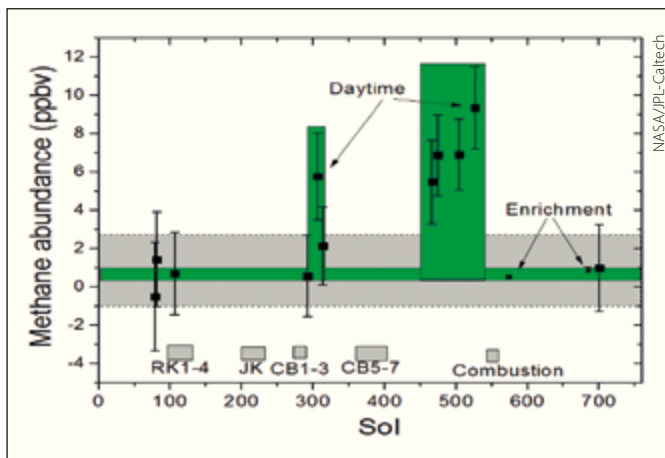


*Global's innovative seismic acquisition and quick delivery of 3D and ambient seismic attributes provides detailed and actionable information for well planning and completion design.*

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*Methane measurements vs. martian solar day (sol) at Gale Crater, with error bars. The graph covers a span of time from August 2012 to September 2014, labelled on the horizontal axis by the number of sols. The mean value of 'low methane' results averages 0.7 ppbv, meaning 0.7 methane molecules per billion molecules of Martian atmosphere. During short periods, the methane concentration climbed to several ppbv, with mean value of high methane averaging about 7 ppbv.*

course of 605 Martian days (Mars' solar day is only about 2.7% longer than Earth's), Curiosity measured background methane levels at 0.7 parts per billion – significantly lower than earlier claims. Occasionally, however, the rover recorded atmospheric levels of methane as high as roughly 7 parts per billion – a tenfold rise. Thus, Mars seems to be actively both producing and releasing methane.

However, the source, or even whether it is biological or geological, is unknown. For example, a possible biological origin could be microbes living in the groundwater below a permafrost zone, whose waste methane could percolate up and leak out. Alternatively, a geological source for the methane could be buried volcanic rocks rich in the mineral olivine, chemically reacting with water to produce methane. Another possible origin could be that the methane is escaping from possible ancient clathrates, buried deposits of methane ice formed long ago by one of the other two mechanisms.

### CH<sub>4</sub> Hydrate on Mars?

In the subsurface of Mars CO<sub>2</sub> hydrate, in addition to CH<sub>4</sub>, is predicted to be stable if the guest molecule gas is present in requisite concentrations.

CO<sub>2</sub> (commonly known as 'dry ice') is an abundant volatile on Mars, comprising 90% of the planet's atmosphere, the remaining 10% being composed of water vapour, nitrogen, and other gases. It is possible for CO<sub>2</sub> hydrates to exist just below the surface of Mars because of the very cold temperatures, and it has been estimated that the gas hydrate stability zone could extend more than a kilometre beneath the surface.

The surface temperature of Mars has seasonal changes which may cause continuous variations of atmospheric composition due to hydrate formation and dissociation. CO<sub>2</sub> hydrates may exist on the Martian surface in the impressive polar caps and also in the atmosphere in the form of clouds. If they are present in the former, then the cap will not melt as readily as it would if it consisted only of water ice, because

of the clathrate's lower thermal conductivity, higher stability under pressure, and higher strength, when compared to pure frozen water.

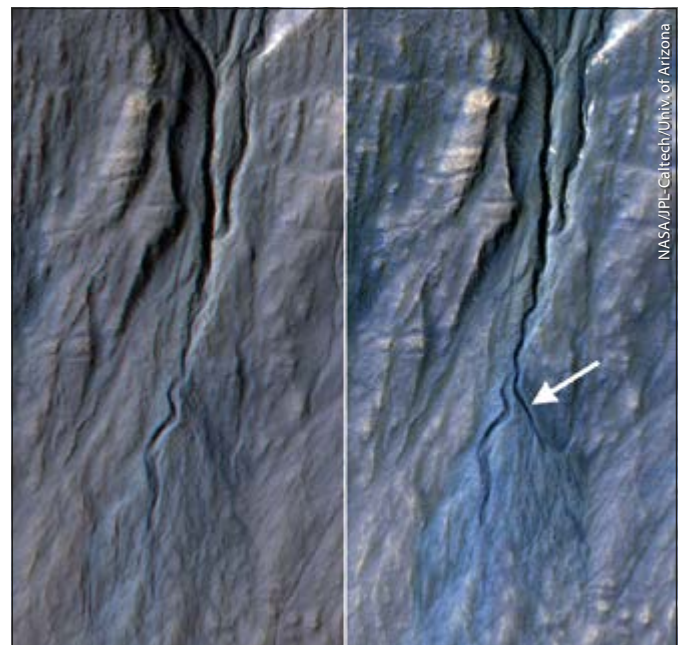
### Surface Features on Mars

It has been proposed that the decomposition of CO<sub>2</sub> hydrate could play a prominent role in the 'terraforming' processes on Mars, and many of the observed surface features may be partly attributed to it.

Martian gullies seen on the surface of the planet, for instance, have long been a mystery. The gullies are small, incised networks of narrow channels and their associated downslope sediment deposits. It has been argued that these were formed not by liquid water but by CO<sub>2</sub>, since the present Martian climate does not allow liquid water to exist on the surface in general and recent observations now indicate the gullies are indeed primarily formed by the seasonal freezing of CO<sub>2</sub>, not liquid water. The polar surface, which is covered by layers of sand and dust, is made up of frozen CO<sub>2</sub> and water. In the spring, when the sun warms up the polar slopes, the frozen gas and water don't melt. Instead the gases sublimate (i.e. change from solid directly to gas, without pausing to form a liquid). The vapour lifts the sediment off the surface, reducing the friction and allowing the sand to move more easily. This sand is moved down steep slopes, gashing the surface like water running downhill. The temperature at which CO<sub>2</sub> changes from solid to gas is -78.5°C.

We end this part of the story by noting that the possibility of extracting water from hydrates could help stimulate attempts at human colonisation of Mars. But to 'terraform' Mars, or turn the planet into a smaller version of Earth, unfortunately the first settlers will have to live below ground to protect themselves from cosmic rays. ■

*This set of images was taken by the High Resolution Imaging Science Experiment (HiRISE) camera in 2010 and 2013. A new channel is shown forming on the Martian slope. New research reveals that sand propelled on a cushion of CO<sub>2</sub> gas could be responsible for slicing into the red planet's surface.*





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# Shale Gas in South Africa

Could shale gas migrating through dolerite sills provide the answer to South Africa's energy needs?

JAMES MULLINS

'South Africa' and 'energy giant' are words infrequently strung together, as the country has almost no conventional onshore or offshore hydrocarbons of note. However, over the past couple of years the discussion over the speculated vast amounts of cheap energy situated in the Karoo Basin has reached boiling point. Potential estimates of the shale gas resource vary drastically from the original 390 Tcfg, proposed in 2013 by the US Energy Information Administration, reaching as high as 480 Tcfg by the Department of Natural Resources (South Africa), and back down to far more conservative estimates. What is certain is that the Permo-Carboniferous Whitehill, Prince Albert and Collingham black shale formations could potentially be the answer to South Africa's current and future energy needs.

These gas-rich shales are overlain by sedimentary rocks of the Beaufort Group, which are heavily intruded by large volumes of the Karoo Dolerite Suite – a complex series of dolerite sills, dykes and ring-structures. The structural geology and hydrogeology associated with the Karoo Dolerite Suite is virtually unknown, with groundwater believed to be restricted to openings including fractures, faults and intrusive body margins.

Fractures are the most common structural feature in igneous rock, often related to emplacement and subsequent

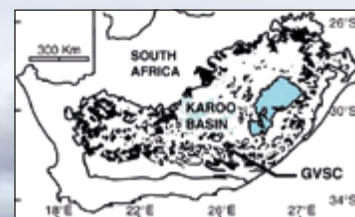
cooling and contraction. Subsurface fractures pose significant challenges to exploration and production given their considerable variations in origin, geometry and rock properties. In recent years, fracturing has become increasingly important to the petroleum industry as open fractures provide the essential (secondary) permeability for fluid flow through reservoirs. Thus far no research has investigated whether the sills themselves could provide migration pathways to fluids, but this could hold crucial insights into potential hydraulic fracturing operations. Our research\* focused on investigating flow patterns of the Golden Valley Sill, located in the south-eastern Karoo Basin, near Tarkastad, Eastern Cape Province using Anisotropy of Magnetic Susceptibility (AMS).

## The Golden Valley Sill: Fracking Potential?

During petroleum operations, geologists will often distinguish between naturally occurring (i.e. natural) fractures and those occurring as a result of fluid injection (i.e. hydraulic). Although naturally forming fractures are found in all types of igneous mediums, it is a gross oversimplification to group them all under the umbrella term of 'natural fractures' and even to suggest they all form in a similar manner. Hydraulic fractures, on the other hand, are formed through fracture stimulation via the injection of fluid under several thousand

*The Karoo Dolerite Sill area, showing the characteristic saucer- or bowl-shaped morphology describing the transition between the inner sill and the inward dipping arcuate rim.*

*Map showing location of the Golden Valley Sill Complex (modified after Galerne et al., 2008).*



pounds of pressure to artificially create a network of micro fractures or fissures in the host rock. Despite there being many different forms of natural and hydraulic fractures, all of which form during entirely different processes, they have one thing in common – they create (secondary) porosity in impermeable strata which enables the migration of natural gas from the reservoir rock to the wellbore.

Like all igneous bodies, the Golden Valley Sill (GVS) is characterised by vast quantities of columnar cooling joints which formed post-emplacement and represent the cooling and shrinking of the lava body. In our research a minor discordant dolerite dyke was observed to cut through the roof sill of the GVS in the north-east sector. Composed of microcrystalline dolerite, indicative of rapid cooling, the dyke has dimensions between 5 and 15 cm in width and is laterally concordant for 50m. The dyke was visibly observed to exploit a series of fractures of varying diameters and lengths from a centimetre scale to tens of metres, all radiating away from the dyke, implying that the roof sill of the GVS had cooled and brittle structures such as cooling joints had formed before the dyke intrusion. The occurrence of fracture exploitation by fluidised material highlights the ability of fluids in the area to readily exploit available fractures and shows that fluids can successfully (if not necessarily efficiently) migrate through the sill.

If viscous lava-type fluids can readily exploit pre-existing fracture patterns it implies that less dense fluids, including hydrocarbons and water, would act in a similar fashion and secondary intrusion events exploiting fractures and joints could act as an analogue for the fate of fluids during potential fracking operations. Often a single analogue is insufficient to truly benchmark such a complex process; however, it is clear that should fracking operations commence in the Karoo Basin fluids would not be solely restricted to the margins of intrusive bodies, including sills. Sills have been observed to effectively conduct fluids and therefore must be incorporated into drilling and reservoir models as not only would fluids be lost into the sill itself, they might also be able to migrate through the entire sill complex.

### The Fate of Pore Fluids

The vast majority of rocks in the world's basins contain pore fluid, which is controlled by porosity and permeability and in turn controls the ease with which fluids can flow through strata. Fracking aims to vastly enhance local permeability through the creation of a series of dense local fractures. The formation and propagation of hydraulic fractures are principally controlled by a complex interplay involving stress, the mechanical strength of the rock, any pre-existing fractures and the pore fluid pressure; therefore, the fate of pore fluids is amongst the most important concepts during hydraulic fracturing. Very little is known about how the intrusion of the Karoo Dolerite Suite affects the pore fluids in the surrounding local Katberg (arenaceous) and Burgersdorp (argillaceous) deposits.

Our research provides several insights into the fate of local pore fluids at the GVS margins. Numerous boulder-sized



*Dolerite dyke intrusion into the roof of the GVS:*

*A. Exploitation of non-linear fractures;*

*B. Dyke termination with branching exploitation of adjacent fracture.*



specimens in the north-eastern sector of the sill demonstrate elongated gas cavities and frequent calcite infilling. The figure on the next page is particularly interesting as there is clear evidence of the incorporation of Katberg deposits with a baked outer shell above a medium-grained sand matrix. Further hand specimens are characterised by significant percentages of mud clasts (20–30%) with metamorphic halos incorporated in a medium-grained sand matrix. Under the microscope there is evidence of disaggregation of some mud clasts and the inclusion of arenatic fragments in the middle of mud clasts, which suggests that a highly volatile mixing has occurred and highlights the possibility for rock formation via a volatile hydrothermal flow. Fibrous strong birefringence minerals observed in veins that bisect the middle of mud clasts are interpreted to represent hydromuscovite or hydromica hydrothermal sheet silicates formed during the breakdown of feldspar under late hydrothermal conditions. The incorporation of mud clasts and disaggregated quartz grains has been interpreted as high temperature metamorphism and subsequent rapid recrystallisation. These findings support refluidisation of host rock at the sill margins and at the interface between the GVS and the country rock.

Refluidisation and recrystallisation of host rock has a major implication for fracking. Firstly, during the emplacement of the GVS, fluidisation was initiated during the release of over-pressured pore fluids, allowing the phase change between a liquid and vapour phase. This caused the breakdown of the mechanical strength of the sedimentary matrix, enabling the host rock to become fluidised. Subsequent recrystallisation of the host rock creates a completely different rock type with completely different porosity, permeability and mechanical properties from the original medium. Therefore the original local in-situ stress, mechanical strength and pore fluid pressure properties for the formation and propagation of hydraulic fractures no longer hold for the new recrystallised medium and therefore must be accounted for during reservoir modelling.

These findings highlight the inherent risk with associating standardised porosity and permeability properties with a specific rock type during modelling, as it is clear that a different rock type derived from the country rock has been formed during the sill emplacement process.

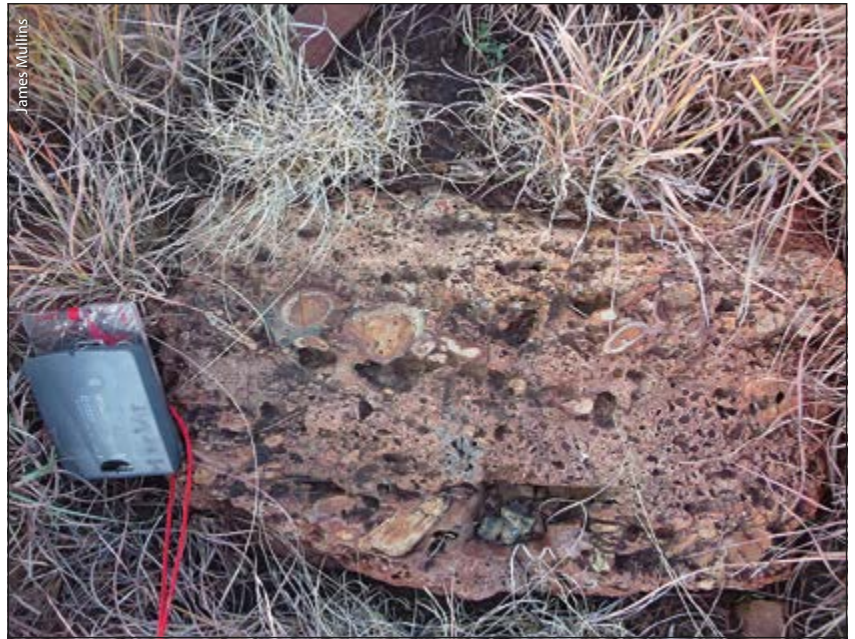
### Industry Implications

Insights from the Golden Valley Sill have highlighted several issues of importance for potential fracking operations. Fluids have been observed to effectively migrate through pre-existing fractures and joints in the GVS which could lead to substantial loss of injected fluid, requiring significantly increased volumes of fracking fluids, which is further complicated by the Karoo's arid climate and low average rainfall of 200–400 mm per annum.

In addition, fluids could migrate through the entire sill complex and therefore must be incorporated into subsurface risk analysis and fracture pathway modelling.

Fluidisation and subsequent recrystallisation of charged suspended sediment has been shown to create new rock mediums derived from the host rocks present near the sill margins. This new material will have different inherent properties which will control its ability to conduct fluids and

*Undulations along the top surface of the arcuate rim.*



*Incorporation of fragments of the Katberg facies in country rock.*

allow the formation and propagation of hydraulic fractures and therefore cannot be modelled with the same standardised porosity and permeability properties of its parent lithologies.

Modelling of the subsurface, particularly fracture patterns and flow pathways, has always posed a significant challenge to the petroleum industry. It is evident that the Karoo Dolerite Suite presents several problematic issues to the recovery of shale gas should fracking licences be granted in South Africa. Perhaps the more complex geology of the African and European continents in relation to the US Marcellus and Eagle Ford shale plays have impacted on the slow growth and uncertainty revolving around shale gas and hydraulic fracturing in Africa and Europe.

*\*The author undertook this research as part of his M.Sc. in Resource and Applied Geology from the University of Birmingham, in collaboration with the Africa Earth Observatory Network at Nelson Mandela Metropolitan University, Port Elizabeth, South Africa. The work provides novel insights into saucer sill emplacement mechanisms using Anisotropy of Magnetic Susceptibility (AMS) to define a series of flow lobes from patterns of magnetic foliations in the Golden Valley Sill, Karoo Basin. ■*



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# Integrating Data Types for Reservoir Characterisation

SCOTT SINGLETON, ION Geophysical

Traditionally, oil industry disciplines, namely geology, geophysics, petrophysics, rock physics and engineering, have educated their respective professionals to concentrate on their designated fields and only bring in other disciplines if necessary to achieve a particular result. It is common knowledge in the oil industry that increasingly complex reservoirs require more elaborate solutions in order to effectively and efficiently produce. On the technology side, what this often means is integrating data from different disciplines in order to arrive at a more accurate and meaningful reservoir description.

This article presents an example from Oklahoma in the complex reservoirs of the Mississippi Lime and clearly demonstrates that an integrated team approach to solve exploration and production problems should be adopted as a routine practice. This philosophy is gaining significant traction due to the complexities of unconventional shale plays which defy easy solutions on a regular basis. The industry-wide

recognition of this fact is exemplified at the cross-disciplinary URTeC conference, now in its third year and growing fast.

## Case Study Data: Seismic and Logs

The Mississippi Lime is a relatively new tight oil play emerging in north-central Oklahoma and may extend into Kansas. The unit is known to contain abundant natural fractures and be hydrocarbon-charged, therefore the exploration strategy is to find zones with enhanced porosity and natural fractures.

Geomechanical formation properties were calibrated from seismic inversion with vertical and horizontal log suites. (Note that a full petrophysical and rock physics study that included core data was performed and used to calibrate but these topics are beyond the scope of this article.) The vertical logs show that the upper portion of the Mississippi Lime has low Thomsen's gamma (ratio of vertical to horizontal shear velocity), meaning that it does not contain

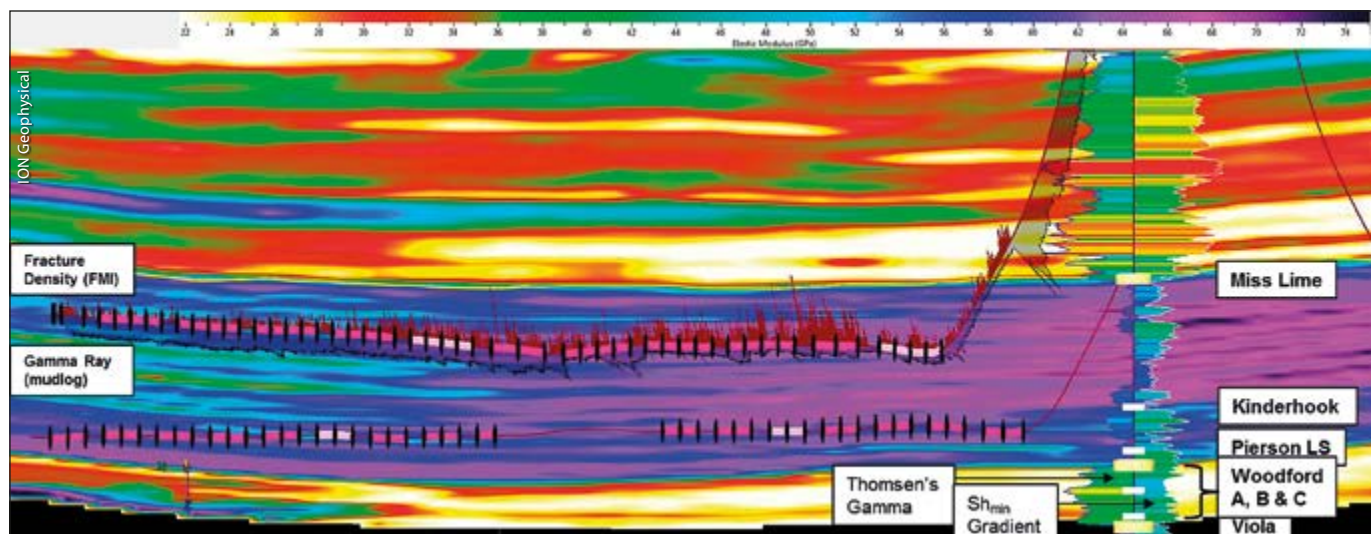
From microscopic core analysis of the wellbore to seismic data measurements of rock properties between wells, a multidisciplinary team is essential when solving exploration and production problems in complex reservoirs.

Vertical Transverse Isotropy (layering) anisotropy, and has a low closure stress gradient, suggesting it is a good candidate for hydraulic fracturing. Along the lateral well, the seismic-derived geomechanical stiffness volume (in this case, Young's modulus) shows the toe half of the well to be softer, or more ductile, than the heel (lower Young's modulus values). This is confirmed by the LWD gamma ray log, which shows higher gamma ray readings in the toe half of the well, thus indicating increased shale content. Coincident with this, the Formation Micro-Imager (FMI) fracture log shows the highest natural fracture density in the heel, in the stiffest sediments, with fracture density decreasing toward the toe.

## Microseismic

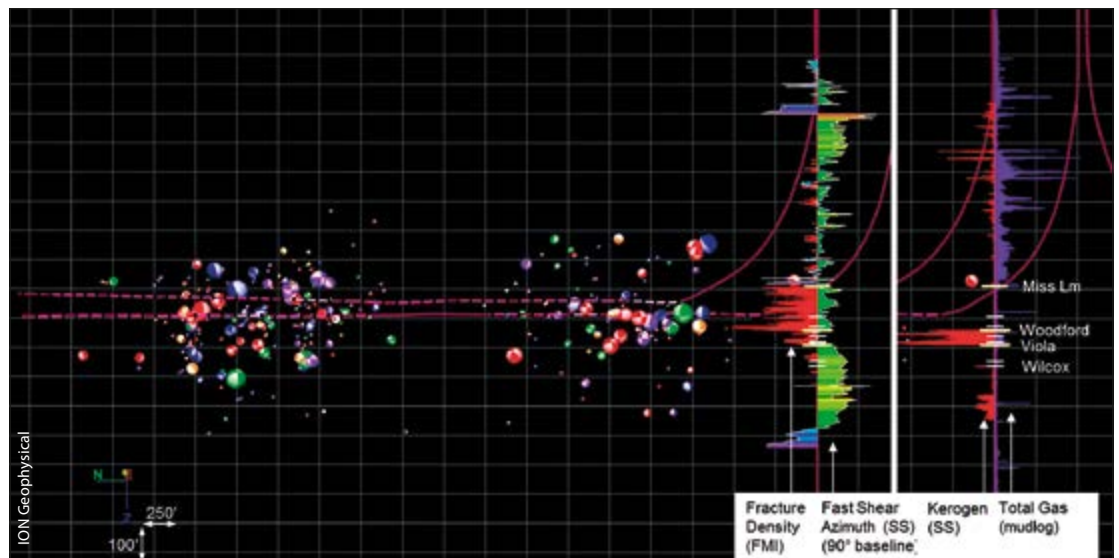
The microseismic data is in two clusters because there was a 230m stretch in the middle of the lateral that was not completed. However, given this natural division, there still are distinct differences between the toe

*Geomechanical rock properties from seismic inversion (dynamic Young's modulus) followed by well log-based facies inversion to enhance resolution. Logs are identified on lateral and vertical wells as are tops (on right). For horizontal scale, the lateral is 1,460m long. For vertical scale, the Mississippi Lime (including Kinderhook and Pierson) is about 60m thick.*





Vertical section view through vertical pilot hole and two laterals. The microseismic events are sized by magnitude, show focal planes, and are coloured by Hudson event type (open = purple, close = blue, shear + open = red, shear + close = orange, undefined = green). All events are from the lower of the two laterals. Logs from one vertical well are labelled on the figure.



and the heel clusters. The toe cluster has a larger overall vertical spread with large magnitude events occurring in the upper Mississippi Lime, as well as below the Woodford, and small magnitude events occurring close to the wellbore. The heel cluster is the opposite – it has most of the large magnitude events close to the wellbore with few events outside that zone. We suspect this difference in behaviour is related to the ductility of the sediments in those two areas, but further investigation is needed.

The FMI log shows that the Mississippi Lime, and to a lesser extent the Woodford Shale, is highly fractured, whereas the other surrounding formations are not fractured. These fractures are oriented almost due east (Fast Shear Azimuth) although there is some azimuthal rotation with depth. The Woodford Shale has high TOC (kerogen log) and is the source rock for this hydrocarbon system, including gas shows in the clastic sands of the shallower Pennsylvanian deposits.

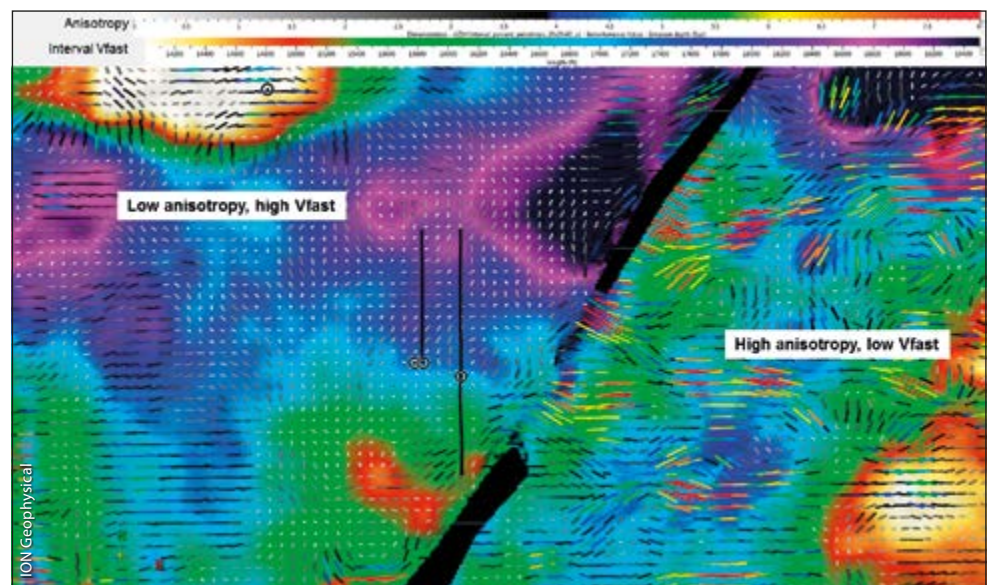
### Anisotropy from Full-Azimuth Seismic

Another element to bring into the Mississippi Lime characterisation is azimuthal velocity anisotropy, as measured from full-azimuth seismic data. Seismic P-wave energy travels faster parallel to fractures and slower when perpendicular to

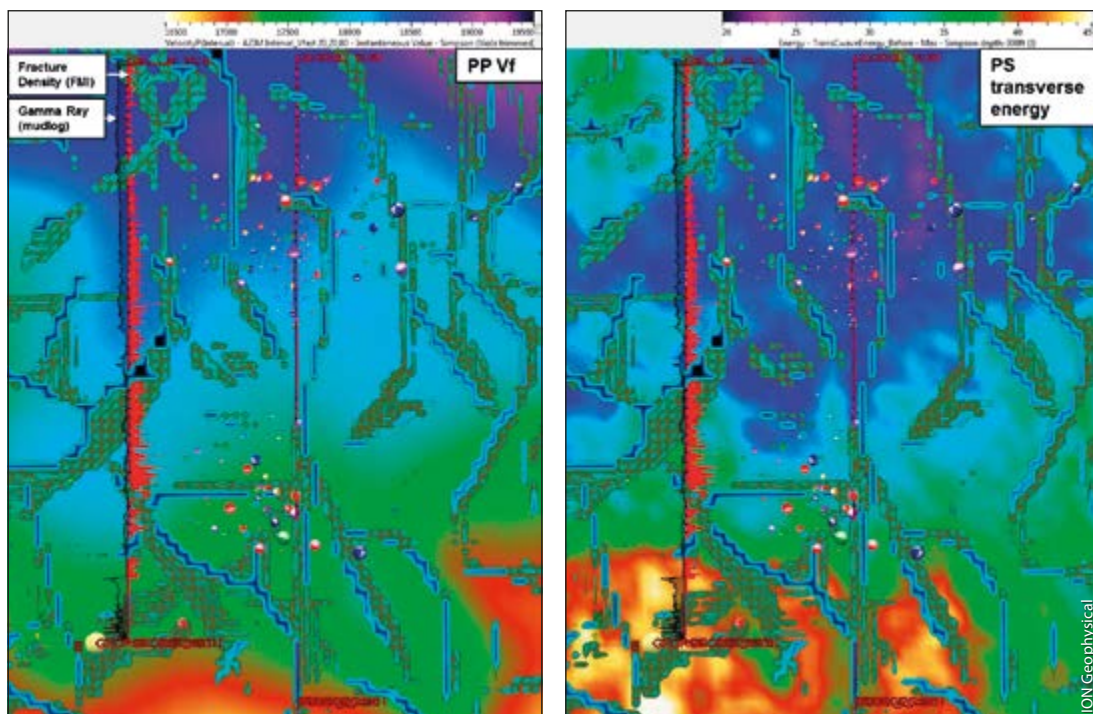
fractures, provided the fractures are not cemented (i.e. open) and especially if they are filled with fluids. Therefore, under these circumstances, azimuthal gathers will show decreased travel-time in the direction of fractures and increased travel-time perpendicular to fractures. The azimuth of fracturing can thereby be determined and the difference between Vfast and Vslow directions (known as PP velocity anisotropy) is proportional to fracture density (and/or fracture openness), as long as the formation lithology and stress conditions do not vary over the measurement area. This anisotropy can be calibrated with fracture logs, thus giving an aerial fracture density map.

The map below shows distinctly different conditions on either side of the major north-east-trending fault to the east of the well pad. To the east of the fault, the anisotropy is higher (3-8%) and a large portion of the azimuths are in an easterly direction (which is the orientation of maximum horizontal stress). There is significant local variation, presumably in response to local fracturing. In addition, the Vfast velocities are lower in magnitude than on the west side of the fault. The situation on the west side of the fault, therefore, seems to indicate that fracture density is low over much of the region except for the area to the south of the southern lateral. This correlates well

PP Vfast (base colours) with PP velocity anisotropy vectors overlain for the Woodford. Top colour bar is anisotropy magnitude from 0-8% (for vector colours), lower colour bar is Vfast magnitude from 14,000 ft (4,267m)/sec to 19,500 ft (5,944m)/sec. Wellbores used in the survey are shown in left centre. Note that PP anisotropy is significantly higher on east side of the fault. For scale, the left lateral is 1,460m long.



Left basemap shows PP Vfast (brighter colours=slower velocities), right basemap shows PS transverse energy, also referred as C-wave transverse energy (bright colours=large magnitude). Each figure shows two lateral wells; left well shows LWD gamma ray log (dark grey) and FMI fracture density (red); right well shows microseismic events with their associated focal planes, sized by magnitude and coloured by Hudson event type (open=purple, close=blue, shear + open=red, shear + close=orange, undefined=green). Fault traces (in 3D) from seismic fault detection are in green. For scale, the left lateral is 1,460m long.



with data from an FMI log in the lateral wellbore, which shows high fracture density in the heel and low fracture density in the toe.

## Assembling the Data

Bringing these concepts together, we assemble a multitude of data types in plan view to see how they fit together and to determine what conclusions can be drawn. The first observation is that the PP and PS anisotropy indicators (which are the base layers) appear to be telling similar stories, and that is that fracturing decreases from south to north along these two laterals. This message is confirmed by the FMI image log on the left lateral. In fact, the FMI can be calibrated to this anisotropy information, giving a rough idea of fracture density away from the wellbores. Associated with this is the LWD gamma ray log in the lateral which, as we have already seen, appears to have responses proportional to rock ductility. Increases in rock ductility are also coincident with decreases in velocity anisotropy and fracturing.

The microseismic data clearly shows the changes in behaviour of the heel and toe groups of events which appear to be related to the amount of seismic-scale faults, with more faults in the heel which is the brittle portion of the well. The heel grouping of microseismic

events was clustered at the wellbore level, but in map view these events are shifted to the left, or west, of the wellbore. This grouping is concentrated near several small faults in this area, and also extends towards the area in the leftmost wellbore with the highest fracture density. All of this is consistent with the hypothesis that this portion of the well is more brittle and contains a higher density of fractures and seismic-scale faults, which in turn leads to larger magnitude microseismic events.

Conversely, a different situation exists at the toe of these laterals where we have more shale and thus more ductility. This leads to fewer seismic-scale faults and fewer fractures. As a consequence, the microseismic data is more scattered with smaller magnitude events in close proximity to the wellbore. Further investigation of the locations of the high magnitude events that appear to be scattered at some distance from the wellbore indicates these events preferentially occur along or in close proximity to seismic-scale faults, many of which are above or below the Mississippi Lime and Woodford Shale units. Thus, hydraulic fracture fluids in this portion of the lateral sought pre-existing fractures, reactivating them and creating fluid pathways outside of the reservoir layer, which is something completion engineers attempt to avoid.

## More Data Integration

Therefore, as a result of this integration of data sets from a variety of sources, we are able to explain the rock and fracture properties of this reservoir. The next step in this workflow is to integrate this information with completions data to explain differences in breakdown pressure, time-transient pressure response (specifically the leak-off component), and instantaneous shut-in pressure (ISIP). Associated with this, an integral part of the evaluation of microseismic responses is time series data for bottomhole pressures, slurry rates, and proppant concentrations for each stage, which enables completion engineers to evaluate the effectiveness of induced fractures. However, each of those topics have complete storylines by themselves and so are beyond the scope of this article.

Nonetheless, this case study clearly illustrates how individual data types typically provide a piece of the reservoir puzzle. However, none by themselves comes remotely close to providing the information needed to make intelligent decisions about where and how to drill and produce a hydrocarbon reservoir. Multidisciplinary integration of all the available data is essential to understand and efficiently exploit the tight, heterogeneous mudstone reservoirs common in today's unconventional shale plays. ■

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# “Oil Has Been Good to Me”

Ian Forrest was a founder member of the Petroleum Exploration Society of Great Britain, which celebrated its 50th anniversary last year. Raised in one of the poorer parts of Glasgow in Scotland, he flew with the RAF in World War II before going on to explore for hydrocarbons in many parts of the world. Here he tells us about his long and exciting life in oil.

JANE WHALEY

“I was born in ‘red’ Clydeside – known as such for its strong left-wing leanings – where my father started life as a shipyard worker. Life was hard when I was young,” Ian says. “We lived in a poor tenement building near Paisley and there wasn’t much spare money in the house; I remember when Christmas dinner was

tinned corned beef. I first started earning when I was 12, selling bread rolls before school for my uncle who was a baker. I gave my mother three shillings a week from this and was allowed to keep the few pennies left over, so I learnt the value of money at a very early age!”

Ian was considered ‘a wee bit different’ by his friends and family, because he always wanted to study and go to university, not something most of them had ambitions towards. He passed the exam for grammar school, but was unable to go as his parents could not afford the, albeit small, fees, but he still managed to take his ‘Highers’, the final school exams in Scotland and the passport to university. One of his fellow students at Camphill School in Paisley was Ian Gillespie, later head of BP Exploration.

“I had initially concentrated on the arts, but went back for an extra

year to get my science Highers, so I wasn’t called up to fight in the war in 1942, when I was 18,” he continues. “I spent a year at university studying maths, before joining the RAF, where my mathematical skills meant I became a navigator. For training I was sent to Canada and learnt to fly – I could pilot a Tiger Moth long before I could drive a car – and was then sent to Italy, flying all over the Mediterranean. That’s when I first fell in love with that beautiful country, which was to become a significant place in my life.

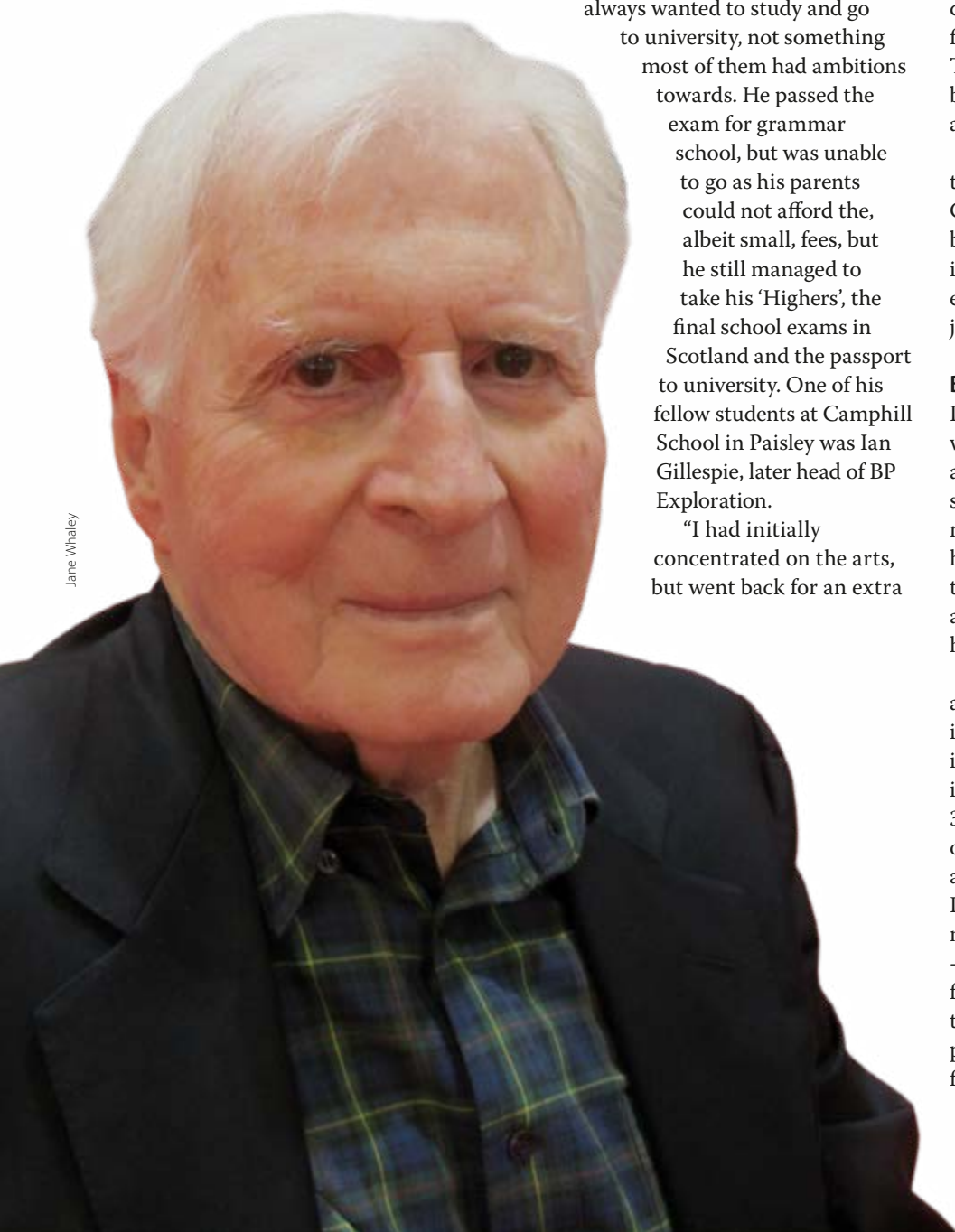
“Luck plays a part in life: I’ve always thought how lucky I was to be sent to Canada and Italy in 1943 instead of being trained in the UK and ending up in Bomber Command, where the life expectancy at that stage of the war was just a few weeks.”

## Becoming a Well Geologist

Ian remained in the RAF until 1947, when he finally returned to Glasgow and to university. He specialised in sciences, concentrating on geology, and met a young Danish girl, Alfhill, who had come to Scotland on holiday. By the time he graduated they were married, and they moved to Copenhagen, where his wife was training as a nurse.

“My brother-in-law told me about an American company drilling for oil in the north of Denmark – Gulf Oil, as it turned out – so I went to their office in Copenhagen, took the lift to the 3rd floor, marched into the manager’s office, told him I was a geologist and asked if he had any jobs: ten days later I was on a drilling rig near Aalborg in northern Denmark, learning Danish – and the finer points of well logging – fast! Can you imagine it happening like that nowadays? I hadn’t even met the personnel director – I guess my face fitted.”

Ian spent three years in Denmark



Jane Whaley



with Gulf, but unfortunately the rocks did not prove productive. “It is all glacial drift in that area, but I soon had a good understanding of the buried geology. In fact, I was the first geologist to construct a subsurface cross-section of Denmark (in 1953), which proved the presence of the Triassic Musselkalk Formation. We understood the significance of salt when looking for hydrocarbon traps, but unfortunately the Mesozoic formations onshore Denmark proved to be immature, and we had yet to move offshore at that time. There was great confidence in the country that we would find oil, so much so that testing at the first Danish deep well was filmed live, but unfortunately it proved to be a saltwater gusher – which led to a sardonic cabaret song.”

### Heading for Warmer Climes

In 1952 Gulf transferred Ian and his family, by now including his two young daughters, to Tunisia as a senior well geologist, for a three-month tour that lasted two years. As France, the colonial power, was fighting a violent uprising by Arab Tunisian nationalists, it proved an interesting and exciting time. “We were initially based in Djerba, in south-eastern Tunisia – a beautiful and historic place. The Isle of Djerba is connected to the mainline by a Roman causeway,” Ian explains. “We enjoyed living in Tunisia, but when we moved further north it could be quite dangerous, particularly driving at night, when there were a lot of hijacks and attacks. If it was getting dark before I had made it home, I used to offer the locals a lift, hoping they would act as protection against snipers. I remember one occasion when the French army

arrived at our rig unannounced and handed out guns ‘for protection’. The Danish crew, most of whom had no idea how to fire a gun but thought they’d like to try, were very upset when I insisted we gave the weapons back: it wouldn’t have been long before the rebels had heard about them and forcibly relieved us of them!”

“It was fun, but not easy for my wife and girls, so we were very happy when I was promoted to area geologist for the 200 MMbo Ragusa field in Sicily, which meant that as well as getting to know Italy, I was able to expand my professional experience with increasing knowledge of production and drilling, assisted by my team of sometimes volatile Italian geologists. On one occasion we had a major blowout, which Myron Kinley (the mentor of firefighter ‘Red’ Adair) took several days to cap, much to the entertainment of all the locals.”

“Sicily in 1954 was really quite backward, and it was hard for my wife, looking after our two small daughters with very few mod cons. We did have fresh milk delivered, though – straight from the goat! And, since this was Sicily, of course I had to meet the local Mafia boss; he was a little, round, fat guy, straight out of the movies. Luckily, I didn’t have too many dealings with him – although he did threaten to send the toolpusher back to Texas in a box for not paying him to protect our water supply. Fortunately, a higher authority intervened and a deal was made to save face all round.”

### In at the Beginning

In 1959, Ian and his family moved to Turkey, living in Istanbul and Ankara, where on one occasion their Turkish

maid invited them to a public execution – an offer politely declined. Working near the Greek and the Syrian borders, Ian has vivid memories of hunting rabbits with the assistance of the car headlights to supplement his diet. After a few years he decided it was time to leave Gulf and move back to Scotland – just in time for the beginning of the North Sea oil industry. He joined Conoco in 1963 as the company’s first UK-based geologist. “I landed on my feet, maybe because I’m a brash Scot,” he laughs. “I tend to stick my nose out and take the risk that it might get bitten off!”

He remembers undertaking an early geophysical survey along the Northumbrian coast in 1964 using explosives (now forbidden), which “provided mass entertainment onshore for the local inhabitants – and an unexpected harvest of fish as well. At the time, the average offshore shot was 5lbs (2 kg) of dynamite, detonated at frequent intervals. Off the north-east coast of England we tried using 10lb charges for technical reasons, but the pyrotechnics and blast effects along the nearby promenade put a stop to the experiment despite the enjoyment of the spectators, both on land and afloat!” He also remembers running a seismic line off the south coast near Wytch Farm, now known as the largest onshore oilfield in Europe, but at the time its presence and extent were not recognised by BP, then the permit holder, and it was passed over.

In early 1964 the first UK North Sea discovery had yet to be made but the industry was beginning to develop. “There were only a few of us working in it at the time,” Ian explains, “and we used to meet up informally for a few drinks and a chat. At one of these gatherings – in

the Westbury Hotel in London – it was suggested that we formed a specialist society, with the aim of promoting the exchange of views and information on the geology and geophysics of the North Sea. Very soon the Petroleum Exploration Society of Great Britain was born, with me as one of the founder members.”

Ian worked for Conoco for 22 years, initially in the North Sea and also in Italy, commuting back to the UK frequently to be with his family whilst his daughters finished their education. In 1972, he was asked to return to his favourite country to open an office for Conoco in Rome. “I was working in the centre of that beautiful city – it was wonderful,” he says. “For a time I rented a villa in Rome’s ‘Nob Hill’ where they say Garibaldi had slept. I was soon involved in drilling several wells, both on and offshore, as operator for a number of groups of companies.”

### Time to Relax

Conoco used the Rome office to look at opportunities below the salt in Gabon, and in 1985 Ian was offered a move to open the office there. However, Alfhill and he decided that it was time to retire, so instead of equatorial Africa, the two of them moved back to Sicily, to their house on the coast near Siracusa, which they had bought while they were in Rome. “As well as snorkelling, we spent a lot of time creating a ‘dry’ garden out of the steep hillside overlooking the beach,” he says. “It was very challenging but enjoyable, building terraces and finding the right plants for such tough, exacting terrain. Some years the rainfall was zero, but groundwater was plentiful in the outcropping limestone. Our pride and joy was a large candelabra cactus festooned with orange flowers. I also learnt to play the piano, something I had always wanted to do, and made good progress, managing to play some Mozart sonatas. I still play the piano a lot.

“However, in 1988 Conoco asked me to organise a two well offshore programme in Sicily, so I rounded off my oil career living in my own Sicilian property. By the time I retired a second time, the terraced coastal garden was mature and my wife decided she wanted a new project – an English garden – so

we bought a house with an acre of sloping meadow on the coast near Rye in south-eastern England. Within a few years the field had been transformed into another terraced garden, complete with delightful pond and resident grass snake.”

Thirteen years later, Ian and Alfhill, by then in their 80s, decided the large garden was getting a bit much and moved back to their original London home in Blackheath Village in south-east London, which has a more manageable walled garden. He describes the area as “a lovely oasis, with a great community and lots of excellent places to eat.”

After his return to the UK several oil companies had tried to tempt Ian out of his contented retirement, but he always turned them down, being more than happy with his routine in Blackheath with Alfhill, seeing his daughters and grandchildren and enjoying concerts and the occasional cruise, as well as trips back to Denmark where it all started. However, he still keeps an eye on the industry; I met him during his regular visit to the PESGB’s PETEX conference in London, and he likes to attend the society’s monthly lectures.

### Final Thoughts

“Being now 91 years of age, I am a bit bemused that in Britain we have many people who do not realise that we must use all the economic resources our country can muster. Through ignorance they are unwilling to give shale gas ventures any encouragement. Fortunately, the government seems to think differently and has given the go-ahead under sensible regulations. We need to evaluate the potential.”

Ian adds a technical footnote to this biographical story, illustrating that conventional methods are not always the best. “In 1983 I persuaded our drilling department to consider penetrating a difficult, fractured massive limestone, several thousand



*Ian Forrest and Ivar Schröder, the only surviving founder members of the PESGB, were awarded honorary membership at the society’s 50th anniversary celebrations.*

feet deep in south-east Italy, without using continuous circulation of the drilling fluid. This, of course, is heresy in the driller’s bible. However, the well programme was prepared with due care and the geological objective was successfully reached, at a cost of \$13 million. At a later date another operator drilled the same rocks to the same depth but using the conventional ‘stop and seal’ method; the well cost \$40 million. It’s important that we learn from others – and are willing to sometimes bend the rules,” he concludes.

“I have a lot to be grateful to the oil industry for,” Ian explains. “I have had an interesting and exciting life with fascinating experiences in some amazing places – like the village in Turkey where I was invited to the annual boys circumcision ceremony; and the celebration when the son of the Caliph of Djerba organised my well-site sample work. And I became proficient in French, Italian and Danish, though lack of use means I’m losing some of my vocabulary.

“Exploring for hydrocarbons has turned the poor boy from Glasgow into the professional who could choose to turn work down. Oil has been very good to me.” ■

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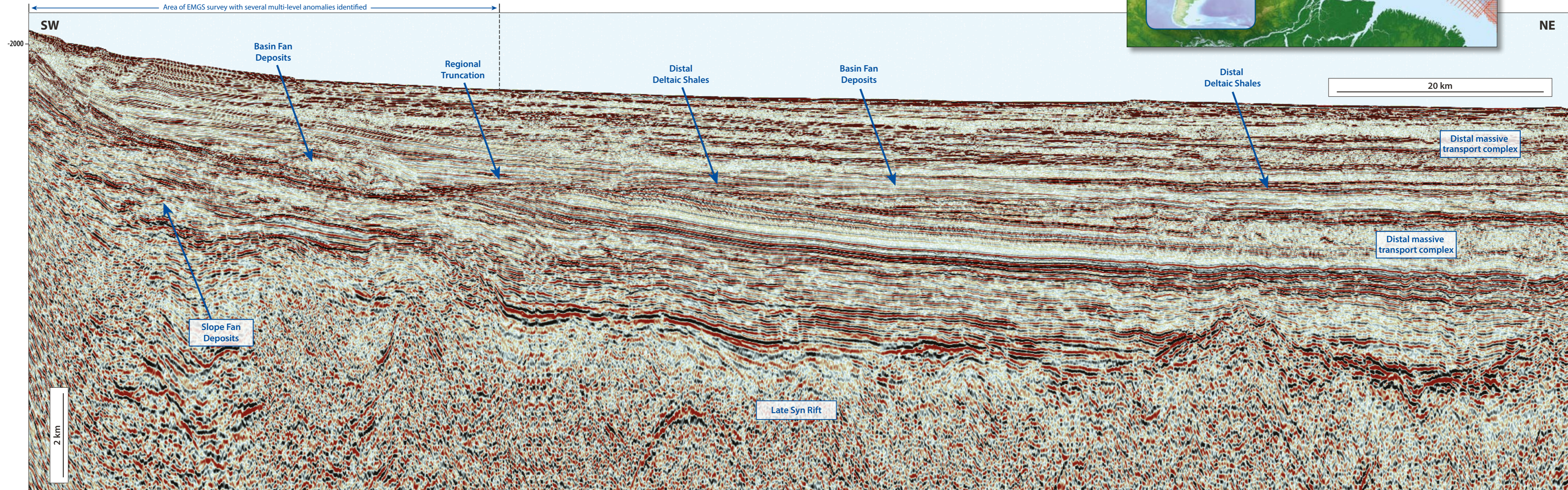
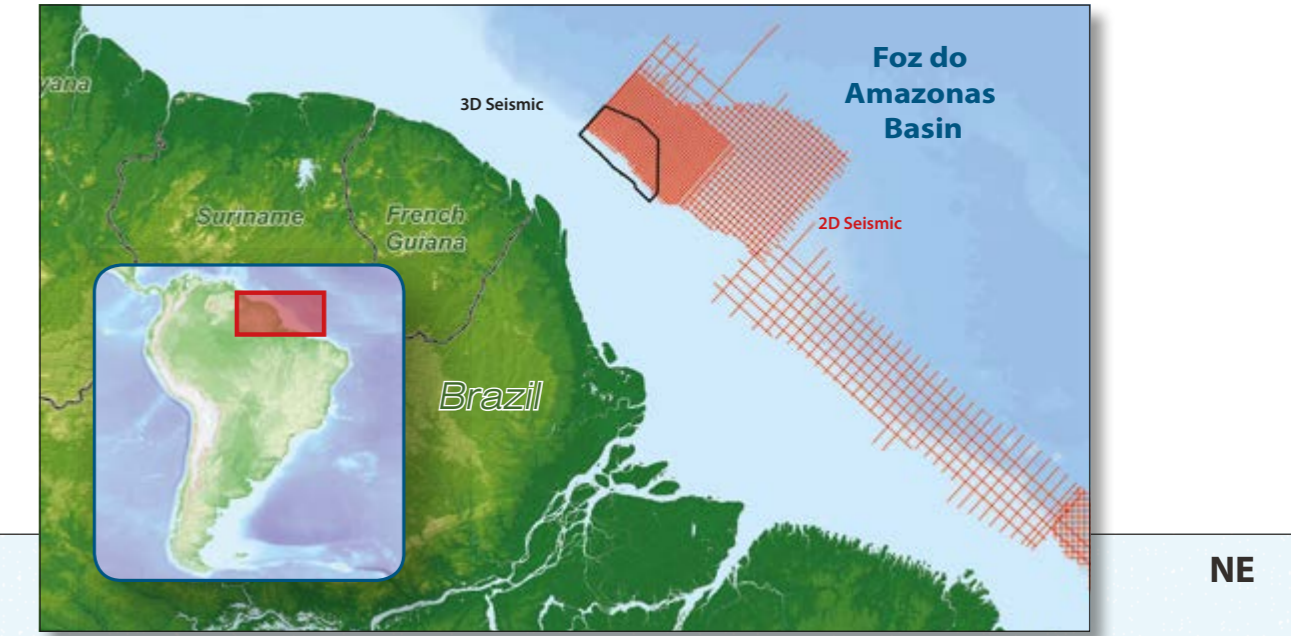
# Foz do Amazonas Basin: Latest Exploration Enhances Prospectivity

New 2D seismic data is unlocking the hydrocarbon potential of the deepwater part of this underexplored north Brazilian basin.

With a record \$1.4 billion bid total, Brazil's 11th licensing round was a significant event for the region's oil industry. High priority for many oil companies was the Foz do Amazonas Basin, offshore northern Brazil. A year before the exciting events of the 11th round, Spectrum acquired over 21,000 km of 2D seismic, gravity and magnetics data in this area, providing a regional grid and a suite of seismic data to evaluate the exploration potential of the basin. This evaluation continues into 2015 with the addition of new seismic analysis and collaborations with these remote sensing tools. The integration of seismic data with other tools and methodologies has greatly enhanced the understanding of this frontier area.



The 2D pre stack depth migration section. Depth seismic enhances the imaging of stratigraphic geometries and structures for prospect evaluation.





# Exciting Opportunities and New Play Concepts

The underexplored Foz do Amazonas Basin has huge potential, revealed through integrating seismic and CSEM data.

**LAUREN PENN, PAOLO ESESTIME and KARYNA RODRIGUEZ, Spectrum**

The Foz do Amazonas Basin, the most northerly of the Brazilian equatorial margin basins, covers an area of 283,000 km<sup>2</sup>, with water depths ranging from 50m to more than 3,000m. The offshore area is underexplored, especially in the deepwater setting where only two wells have been drilled in the Amazon Cone. Past exploration drilling has therefore been confined to the shelf. The ANP 11th Round presentation quoted in-place volumes of 14 Bbo and 40 Tcf gas, demonstrating huge hydrocarbon potential.

## Exploration

The 11th Licence Round exploration focused on the potentially large reserves predicted in distal, Late Cretaceous/Palaeogene deepwater turbidite plays, encouraged by successful wells in neighbouring French Guiana. The plays include the Late Cretaceous deepwater turbidite fans (Zaedyus discovery) that have Cenomanian-Turonian reservoirs and similar age source rocks. In addition, the Apto-Albian has indicated oil shows in the underlying Paleocene turbidite fans in the Zaedyus appraisal well. The Zaedyus announcement reported 72m of net oil pay in two turbidite fans. The Foz do Amazonas area has recorded marine carbonate biomarkers which are also present in the conjugate margin of Sierra Leone and Liberia. The biomarkers are thought to represent the Cenomanian Turonian carbonate shales which have produced the Venus, Mercury and Jupiter discoveries.

To date, the main exploration targets have been slope channel deposits as in French Guiana. This has proven to be a challenging play with several disappointing appraisal wells due to the play not being fully understood; however, the concept still contains huge potential.

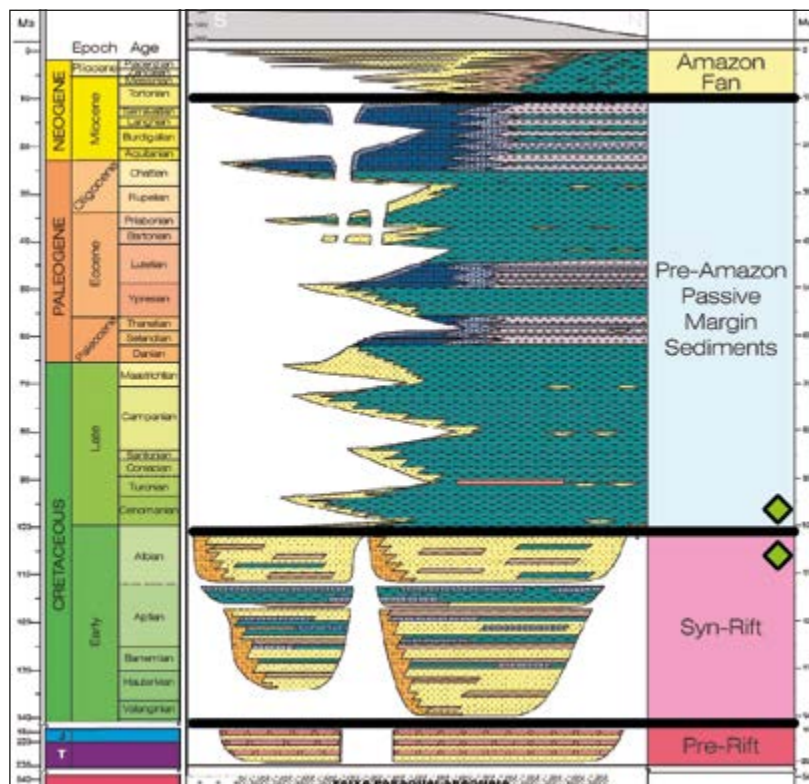
## Geological Overview

The development of the Foz do Amazonas Basin began in the Triassic through rifting which resulted in the opening of the Equatorial Atlantic Ocean. In the Early Cretaceous, a

second period of extension was followed by the Aptian-Albian sea floor spreading, which resulted in the formation of the South Central Atlantic. The basin is divided into the Para and Amapa platforms, the Tertiary carbonate platform and the Amazon Cone (Mello et al., 2001). The Foz do Amazonas Basin was exposed to both orthogonal and oblique extensional stress during the first rift episode and several graben systems developed, which were later filled with syn-rift sediments. The uppermost Albian shallow marine sediments may have been deposited first and then overlapped by transgressive marine shales and sandstones during the Cenomanian-Turonian. It is thought that this area has a maximum thickness of approximately 6,000m (Silva et al., 1999). These infill rift sediments are comprised of continental to marine shales and sandstones of the Cacipóre Formation.

The Amazon drainage system, which developed during the Tortonian, had profound influence on the region and continues to dominate in the present day. The Amazon Cone consists mostly of mud and isolated Mio-

General stratigraphy Foz do Amazonas, adapted from ANP 11th Big Round 2013.



Pliocene sands, which are estimated to have high porosity and are the main targets for exploration. To the north of the Amazon Cone the main reservoir targets are the Upper Cretaceous and Palaeogene age clastic sediments.

### Petroleum Potential

In the shallow water shelfal area of Foz do Amazonas, proven source rocks of both Aptian and Cenomanian-Turonian (Limoerio Formation) age have been identified. In wells 1 APS 0018 AP and 1 APS 0049 AP Aptian Codo Formation lacustrine source rocks (Type I) were found, with TOC of up to 10%. The shallow water shelf well, APS 29 AP, is perhaps the most interesting as it discovered oil and gas-prone Cenomanian-Turonian source rocks with Type II marine type organic matter and TOC measurements up to 3.5%.

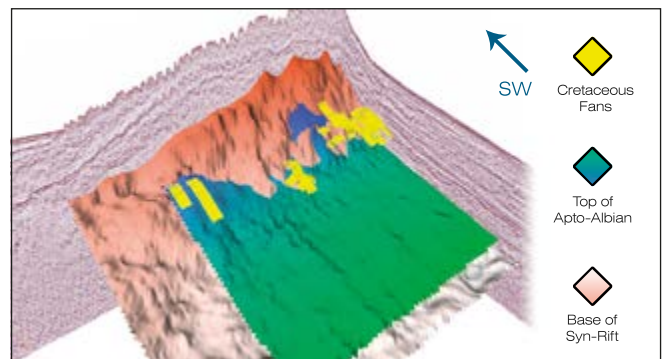
The main reservoir targets on strike to the north-west and south-east of the Amazon Cone are Upper Cretaceous sandstones, with secondary Tertiary sandstones, as proven by the 1 APS 0045B AP well. Cretaceous to Early Paleocene shelfal sands have been drilled in well 1 APS 0045B AP, proving the presence of a shallow water clastic sand system that may have fed deeper water turbidites and fans.

Seismic interpretation has indicated a potential regional Late Cretaceous seal over the majority of the basin. The main risk for stratigraphic traps is likely to be an updip seal. There is a substantial Tertiary canyon system which could break the Upper Cretaceous shale and erode into the reservoir horizon, opening up migration routes from the Cretaceous source rocks into the Paleocene with potential clastic and mixed clastic carbonate deposition. However, research has also indicated the canyons are infilled with mud, de-risking top seal integrity for some Late Cretaceous plays.

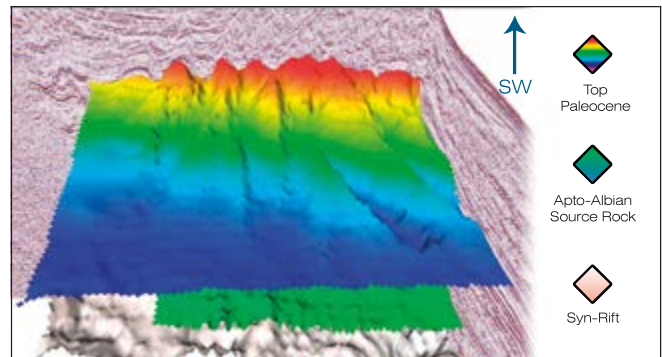
Seismic interpretation offshore Foz do Amazonas shows a steep shelf edge with an unstable slope, which may have periodically failed, resulting in mass transport and turbidites along the slope section. These debris flows can be recognised on the seismic, particularly in the Tertiary and Cretaceous sections, as high acoustic impedance slumped facies. Other features clearly imaged are incised deepwater channels and canyons which extend from the shelfal area into the deeper basin. In certain areas these canyons are over 300m deep. A number of low stands are recognised in the Cenomanian-Turonian and Campanian to Maastrichtian, when sands may have been transported via the slope channel systems into the deeper water areas of the basin. The basin floor fans have the capacity to contain significant hydrocarbon volumes.

### Leads De-Risked

To complement Spectrum's seismic data, EMGS conducted a ~4,500 km<sup>2</sup> of 3D Controlled Source Electro Magnetic (CSEM) survey with the primary aim of identifying the lithology of the canyon fill and to characterise the source of the resistive anomalies in the dataset using seismic attributes, seismic facies distribution, stacking velocities and angle stacks. The results of the co-rendering work provide an important exploration tool to aid the de-risking



Late Cretaceous fan play 3D model.



Paleocene play 3D model.

of exploration leads in the Foz do Amazonas and will be explained in further detail at the EAGE conference in Madrid (Pedersen et al., 2014; Rodriguez et al., 2015). The high quality seismic in both time and depth has uncovered many new and exciting opportunities. The structural geometries have been enhanced through depth migration and new play concepts have been recognised. The CSEM study combined with this seismic interpretation, plus gravity and magnetics, has identified several exciting opportunities in a relatively unexplored basin and developed new play models in the deepwater unlicensed areas.

### Acknowledgements:

Spectrum would like to thank EMGS ASA for their collaboration and contribution.

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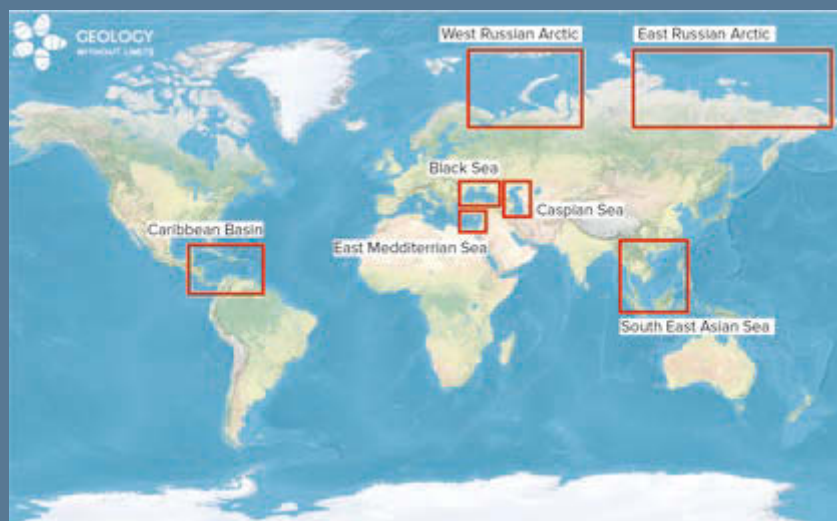
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## Regional seismic beyond the current understanding of marine basins

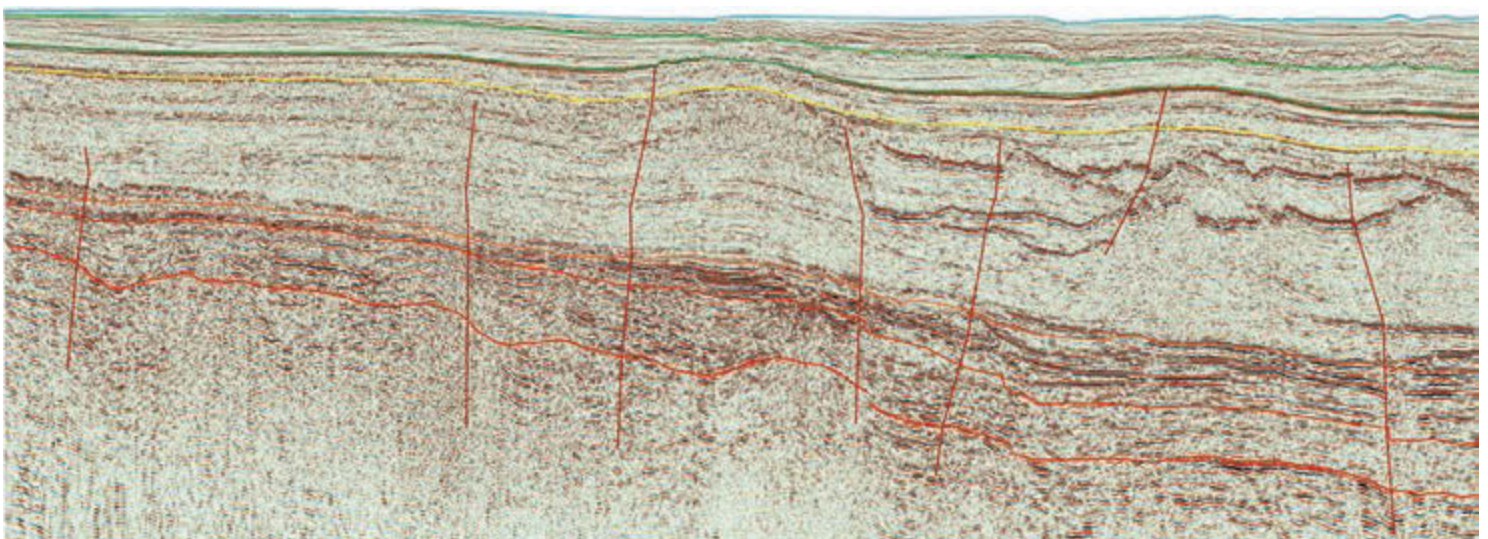
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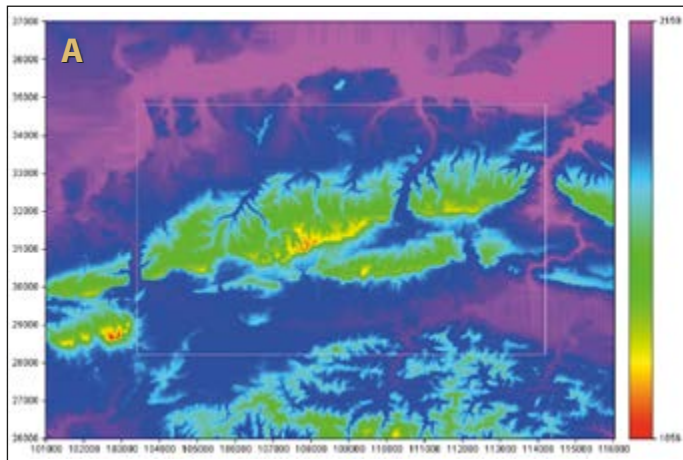


# A Simple Guide to Volumetrics

Why accurately calculating gross rock volume uncertainty is key.

ASHLEY FRANCIS, Earthworks Reservoir

Topographic surface with false datum.



We start this article with an example that many geoscientists may find uncomfortable, if not downright contentious.

A top structure depth map from a depth conversion is most commonly used for two tasks: providing a depth prognosis to Top Reservoir prior to drilling; and in the calculation of gross rock volume (GRV) for use in hydrocarbons initially in place (HIIP).

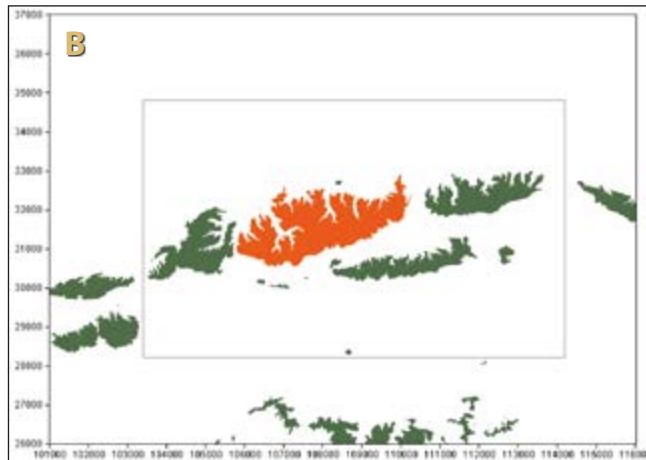
It cannot be stressed strongly enough that there is a key misunderstanding in the oil industry on the difference between the uncertainty at a point (depth prognosis) and the uncertainty of a surface (GRV estimation). The GRV estimation critically depends on spatial correlation being reproduced correctly in the mapping, whereas the depth prognosis does not. This has serious implications for estimating GRV and its uncertainty.

The conventional use of depth surfaces for depth prognosis for well targeting purposes is entirely valid. However, the use of the same surfaces for gross rock volume estimation is *not* generally valid. This may come as a surprise for many geoscientists, as this assumption forms a key part of their work.

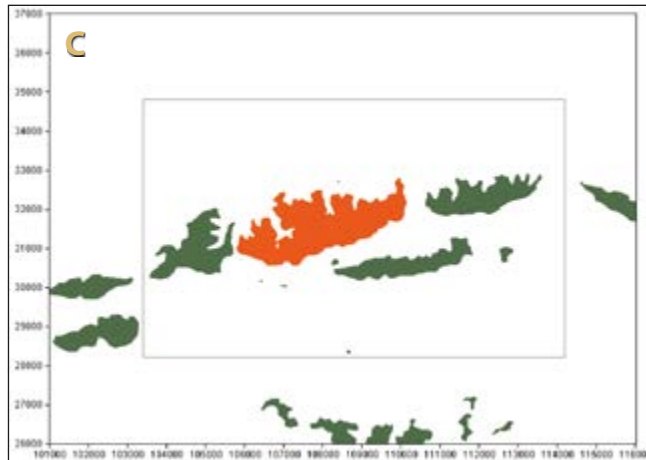
We are going to illustrate the problem with an experiment. The image above (A) is a topographic elevation map obtained from satellite measurements. This surface is known. Assuming an imaginary hydrocarbon contact we can calculate a true gross rock volume and area of possible closures, shown as the green and orange areas in B, (right). The true volume is 300 MMm<sup>3</sup> and the true area 9.84 km<sup>2</sup>. The orange area shows the connected extent above contact of the central closure. Note that the central structure is not connected to the smaller structure to the west.

C and D show the effect of smoothing of the original structure using a moving average filter. In C the topographic surface was smoothed using a 3 x 3 node moving average before

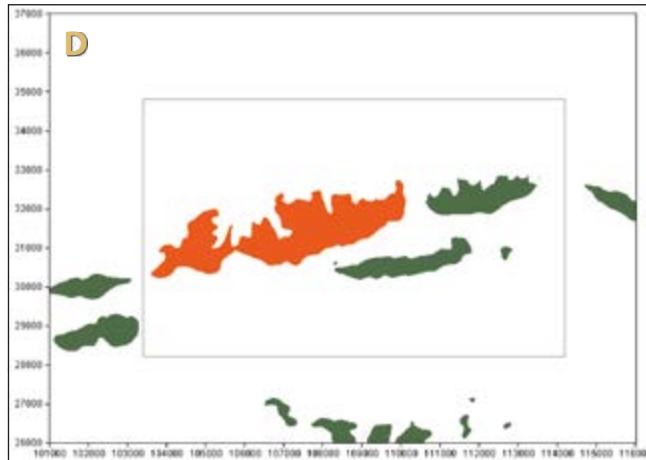
No smoothing GRV = 300 MMm<sup>3</sup>, Area = 9.84 km<sup>2</sup>.



3x3 moving average GRV = 278 MMm<sup>3</sup>, Area = 9.70 km<sup>2</sup>.



5x5 moving average GRV = 261 MMm<sup>3</sup>, Area = 9.57 km<sup>2</sup>.



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clipping with the contact; this is the smallest possible centred smoother we could use. The 3 x 3 moving average reduces the GRV by over 7% to 278 MMm<sup>3</sup>. Image D is with a 5 x 5 moving average, which reduces the GRV estimate to 261 MMm<sup>3</sup>, an underestimate of 13%. This is GRV bias resulting from smoothing and it is always present because our maps are uncertain estimates, not the true subsurface map. Smoothing also changes the connectivity of the predicted surface. For the 5 x 5 moving average (D) the main structure is erroneously shown to be connected to the western structure.

Concerned? Well, read on...

### Estimation of GRV

The estimation of the possible volume of oil or gas in place in the subsurface is a fundamental, routine and important element of the geoscientist's role. Whether it be for a lead or prospect, post-discovery or later in field life, volumetric calculations form the basis of economic value and inform our decisions on such diverse activities as drilling, relinquishment, development, farming in or out and purchase or sale of assets.

The basic equation for calculating HIIP could be summarised as one volumetric measurement and a series of multiplication factors. The volumetric measurement is of course gross rock volume (GRV) and the multipliers the factors such as net-to-gross ratio, porosity, water saturation and formation volume factor.

$$HIIP = \frac{GRV * N : G * \phi * (1 - S_w)}{FVF}$$

It is reasonable to say that GRV is the most significant factor in estimating in-place hydrocarbon volume for the majority of prospects or fields. But compared to other parameters in the HIIP equation GRV is unique: there is no tool with which it can be directly measured. Instead, GRV is estimated indirectly, using a top structure depth map and knowledge of (or assumption about) the trapping mechanism. The GRV is calculated by integrating between the top structure depth map (referred to as Top Reservoir), a base or thickness grid and a hydrocarbon contact.

GRV estimation is clearly linked to depth map estimation. Uncertainty in depth maps is therefore an important factor in understanding GRV uncertainty. A typical workflow for estimating a depth map includes seismic time interpretation, gridding, time-to-depth conversion and residual mapping. Uncertainty is present at all steps including the time interpretation, gridding, estimation of the velocity field and the choice of the method of depth conversion and the intervals or layers to be used.

### Depth Conversion Uncertainty

The accuracy and validity of a depth conversion is primarily assessed by comparing the depth converted surfaces at the wells to the target formation tops. The difference between predicted and observed depths is usually referred to as a residual. A statistical summary of the residuals allows

comparison between different depth conversion cases and is a measure of the depth uncertainty accuracy and variability. In order to tie depth converted surfaces to wells, the residuals are usually mapped and added to the depth converted surface to obtain a final depth conversion that ties the wells. The mapping of residuals will necessarily be smooth.

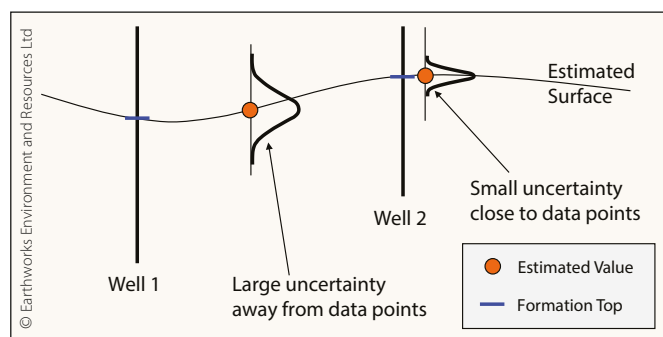
A depth conversion prepared in this way is typically referred to as 'deterministic', although geostatisticians would call this a best estimate. Of several deterministic depth conversions, a preferred one is often referred to as a 'base case'.

If kriging is used as the method of residual mapping then, in addition to the depth conversion uncertainty summarised by the residuals, an estimate of the interpolation uncertainty is also obtained from the kriging standard deviation. A kriging approach combined with a conventional depth conversion will then include the two essential elements of uncertainty:

1. The uncertainty arising at a single point through there being multiple valid models and parameters by which we can depth convert;
2. The spatial uncertainty arising from lateral prediction between data points and the spatial correlation/dependency model.

For a depth converted surface the spatial uncertainty varies laterally, being small when close to data points (usually wells) and becoming larger away from them, as illustrated below.

### Estimation uncertainty at unmeasured locations on a surface.



Many of the steps involved in producing a depth map involve spatial smoothing. Seismic volumes are laterally smooth due to the finite size of the Fresnel zone caused by limited bandwidth. A seismic interpretation is smoothed, perhaps to remove noise or improve its appearance.

Velocity functions from a few well data are simple, smooth functions. Velocity maps from well data are based on sparse control points and therefore smooth. Residuals are mapped and, again because they are sparse, the residual map is also smooth.

### Smooth Estimation and GRV

Because all estimators are smoothers and some smoothing is inherent at all stages in the process of producing a depth map, a mapped depth surface at Top Reservoir is always smoother than the true depth surface, if we were able to observe it.

Smoothness, particularly in the presence of noise, is

## Technology Explained

generally helpful in depth prognosis and has no important side effects, but it has a significant and detrimental impact on connectivity and GRV. This can be demonstrated, as we did at the beginning of this article, by starting with a known surface, calculating a GRV and then applying a smoother to the surface and recalculating the GRV. The GRV from the smoothed surface will be lower than the true GRV and this error (bias) becomes more pronounced as the level of smoothing is increased.

From this simple case we can see very clearly that even minimal smoothing modifies the GRV, potentially significantly. It is probably surprising to many readers that a small moving average filter on your maps or picks could change the volume by as much as 7–13%, but this outcome is well known and understood in geostatistics.

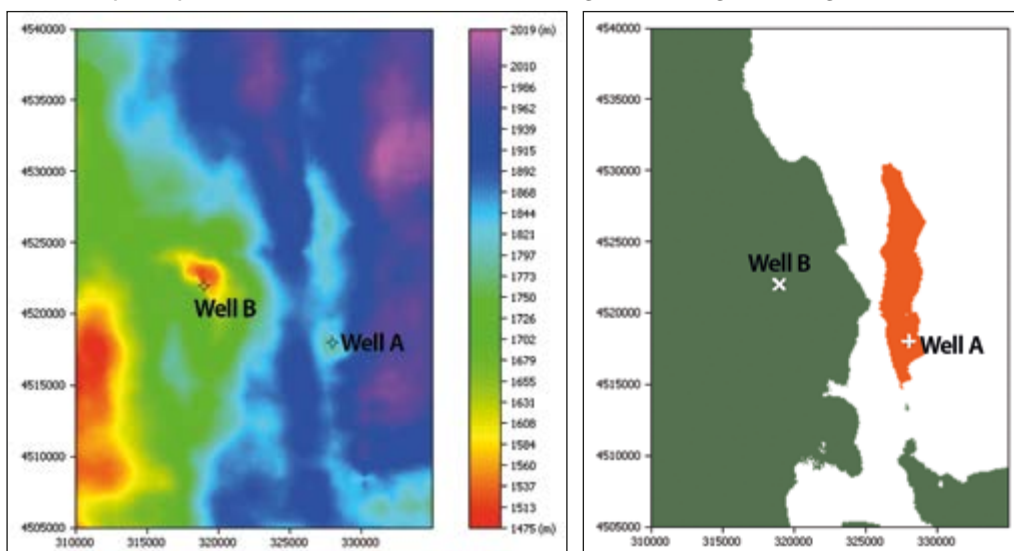
In general, smoothing biases GRV downwards, but structures can also appear more connected than they really are, increasing the apparent connected volume of a prospect, so the final outcome is complex. Smoothing has either little or some

| Seismic Control                      | Well Control                                   | GRV Bias    |
|--------------------------------------|--|-------------|
| 2D regional                          | None or sparse regional wells not on structure | -35 to -20% |
| 2D regional or tight grid            | Some wells, including one on structure         | -25 to -15% |
| 3D regional or low bandwidth seismic | None or sparse regional wells not on structure | -20 to -10% |
| 3D typical quality                   | Few wells, including one on structure          | -15 to -5%  |
| 3D good quality                      | Good well control                              | -10 to 0%   |

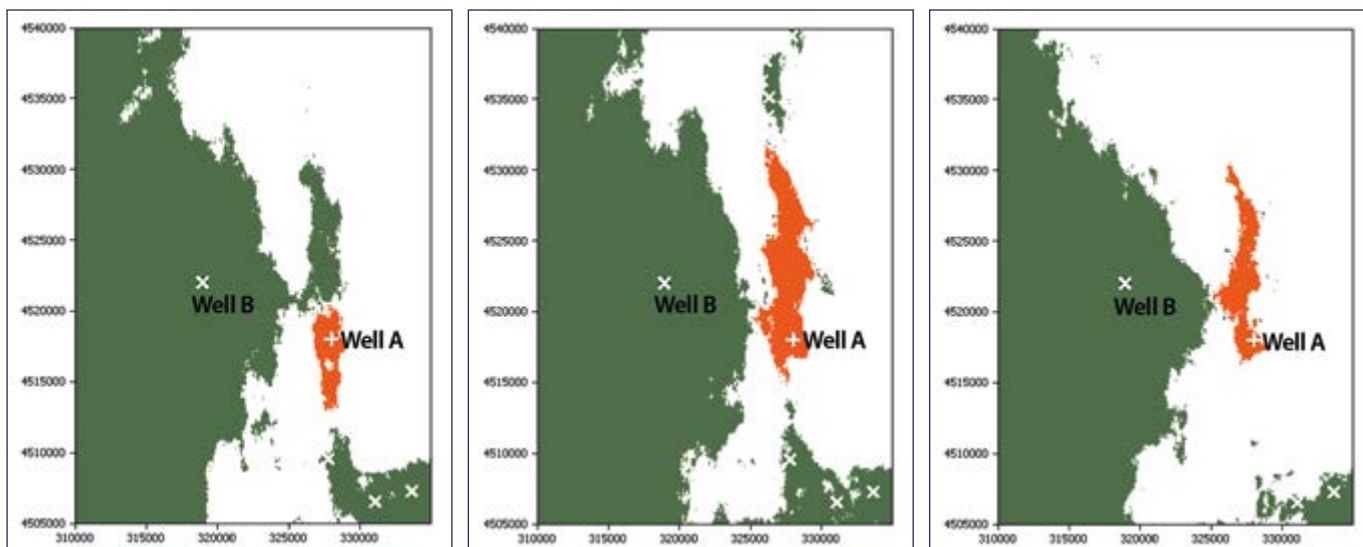
beneficial impact on depth prediction, so when wells come in on prognosis we can easily convince ourselves that if the depth map is good, so is the GRV calculated from that map – but it is not, and the GRV estimate can be significantly in error.

The table above gives some general guidelines on the expected discrepancy between GRV estimated by simple

Best case depth map (left) and connected structure to Well A using lowest closing contour (right).



Three example geostatistical realisations showing connected area to Well A based on lowest closing contour. Note how the leftmost realisation has a smaller, independent structure restricted to the south area only.



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deterministic map cases compared to the mean GRV estimated from analysis of geostatistical realisations. These are typical values based on practical experience from many GRV uncertainty studies over nearly 25 years.

It should be noted that this article is a simple, headline summary of some of the gross effects of smoothing on GRV estimation. GRV estimation bias is strongly related to the ratio of the column height relative to the depth uncertainty, this effect being more pronounced the lower the relief of the structure and the greater the depth uncertainty. Connectivity also plays an important role. A full technical explanation would require more space than we have here, so we will just proceed directly to a solution to the problem.

### Geostatistical Simulation for Estimating GRV and GRV Uncertainty

Geostatistics provides the necessary tools for solving the problem of GRV estimation and its uncertainty using a depth conversion and depth uncertainty. Geostatistical simulation, typically using an algorithm such as Sequential Gaussian Simulation (SGS), allows us to generate multiple realisations of the uncertain depth surface.

An example is shown in the figures on page 66. The top left image shows a depth map over the structure. The long, narrow north-south oriented high is the structure on which we will compute GRV. The right-hand panel shows the closure (orange) at lowest closing contour for this structure. The lowest closing contour is at 1,843m with an apparent spill to the west. The GRV of this structure is calculated as 843 MMm<sup>3</sup>. The lower panel shows three example geostatistical simulations of the depth structure. In each case the lowest closing contour connected to our target well location A has been computed automatically and the resulting closure is coloured orange. Note that, despite the result from the best case depth map, there may not be

a single structure, instead it may be comprised of two or three sub-structures with independent spillpoints.

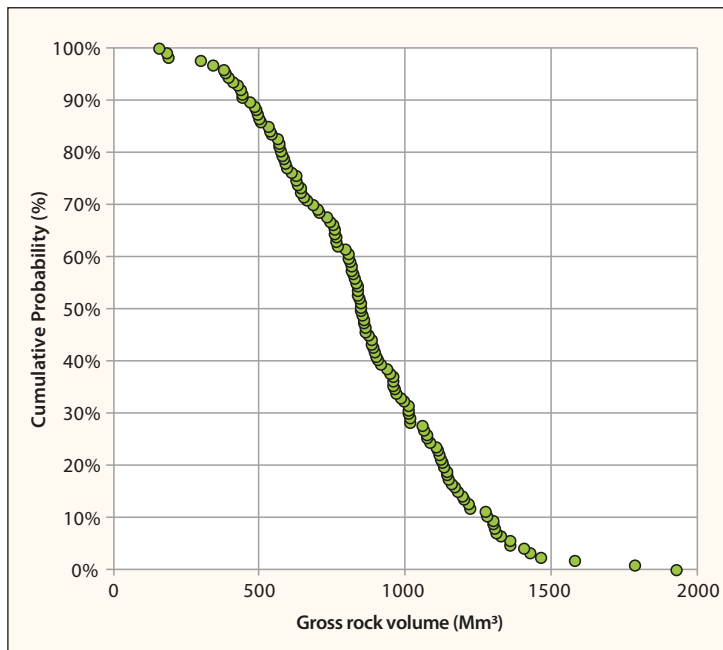
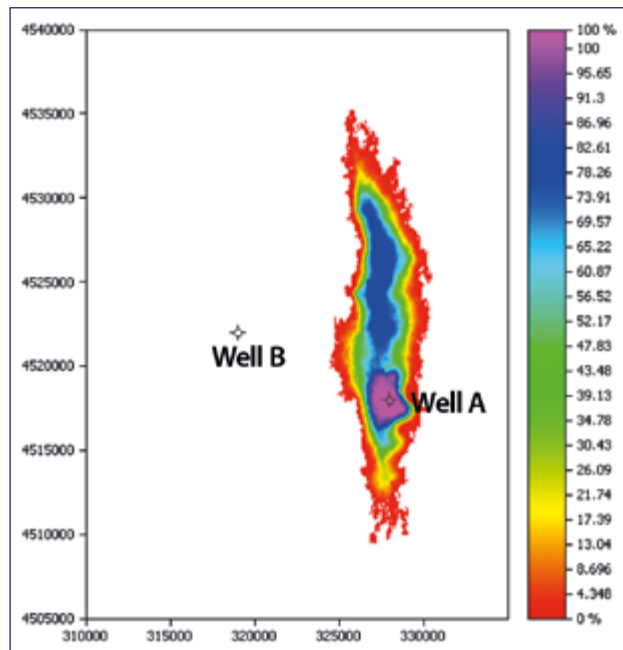
We can combine the closure results for many realisations to form an isoprobability closure map, illustrated below. The probability of a single north-south structure is 77%, indicated by the dark blue colours. By computing the connected volume to lowest closing contour for each realisation, the GRV can be calculated for each one, connected to the proposed well location. Using geostatistical realisations in this way we are converting the depth and spatial uncertainty into a GRV uncertainty. The GRV uncertainty distribution, for volume connected to Well A, is shown below right. The mean GRV from the geostatistics is only marginally higher, in this case, by about 3%. This is because (a) this is a high relief structure with relatively small depth uncertainty and (b) this is the volume connected to the well, and there may be disconnected volumes that we would have to increment in order to obtain the total possible volume.

### Summarising Uncertainty

Our simple guide to gross rock volume uncertainty can be summarised as:

1. Depth maps and testing different depth conversion models build up a picture of the point uncertainty on depth;
2. Interpolation of well residuals using kriging adds the spatial element to the point uncertainty from (1);
3. Smooth best estimate depth maps from steps (1) and (2) are ideal for depth prognosis but should *not* be used for estimating GRV or connectivity;
4. Only geostatistical simulations should be used for estimating GRV and GRV uncertainty;
5. Geostatistical simulation allows the full analysis of GRV uncertainty, connectivity and 'what if' scenarios that would not be valid on deterministic maps. ■

*Isoprobability closure map for connected GRV to Well A (left) and associated connected GRV probability distribution (right).*







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# Palaeozoic Plays of the Great Basin

The Great Basin of Utah and Nevada in south-western USA is a vast, arid landscape with hot summers and snowy winters. Its tectonic framework, a Basin-and-Range extension formed during Neogene times, was superimposed on Palaeozoic-Mesozoic sedimentary rocks. These Palaeozoic marine shales and clay-rich carbonates offer a new frontier for the shale oil and gas revolution in North America. Indeed, the Palaeozoic tectonic history of the Great Basin parallels that of the US east coast, where the Marcellus Shale has been a target of intense exploration and production.

### RASOUL SORKHABI, Ph.D.

A drive on interstate highway I-15 in Utah is immensely scenic, largely because the road runs north-south between two distinct geological provinces: the Colorado Plateau on the east and the Great Basin Desert on the west. The latter, with an area of about 360,000 km<sup>2</sup>, occupies the western half of Utah, almost all of Nevada, and the eastern fringe of California. It is actually part of the much larger Basin-and-Range province, which represents a region of

crustal stretching and thinning since the Miocene, as the continental crust under south-west USA and Mexico underwent extensional tectonics.

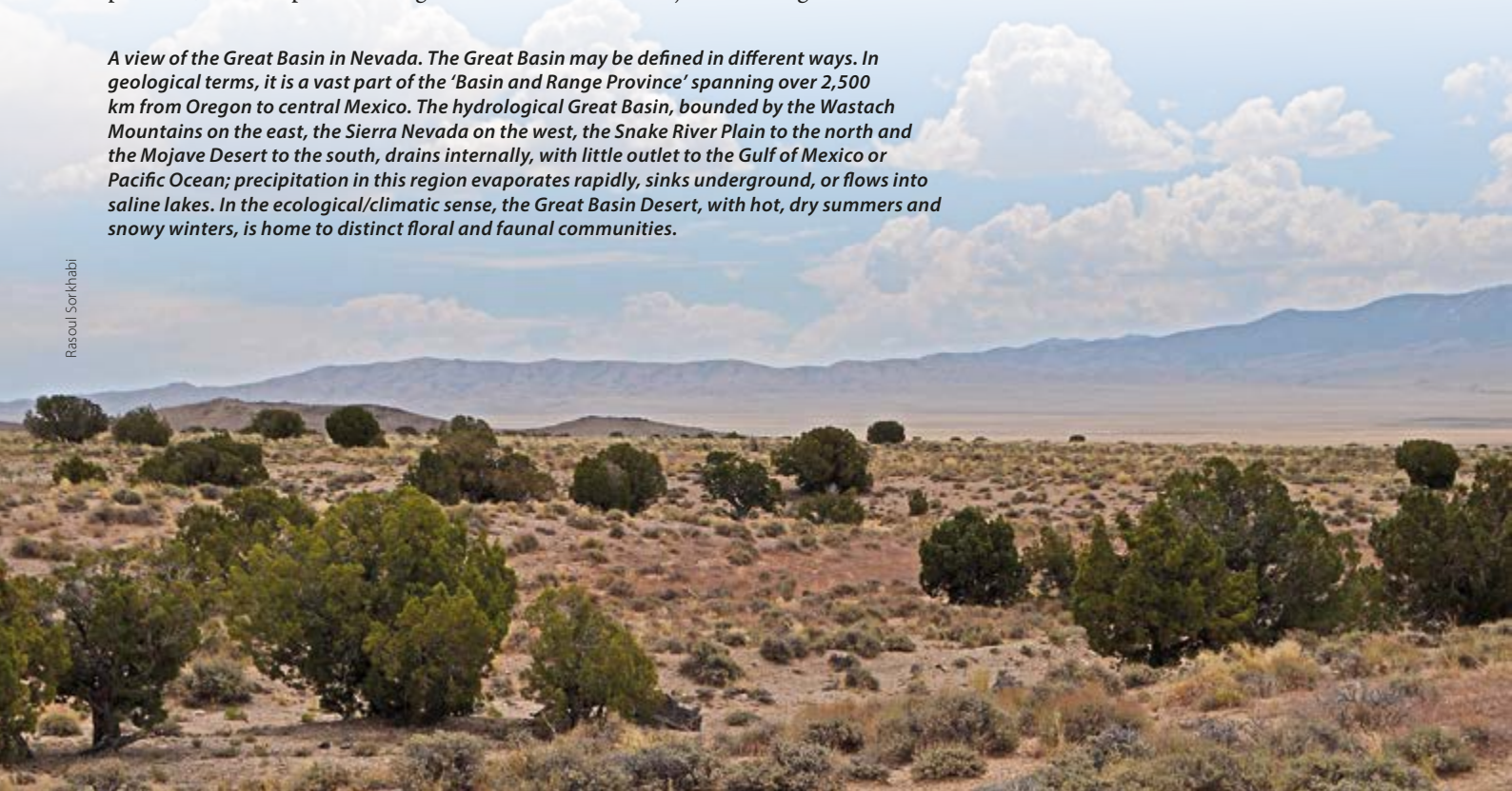
The crust under the Great Basin is about 25 km thick (compared to the 40–50 km crust of the Colorado Plateau and Rocky Mountains to the east); it has low Bouguer gravity values (-150 to -250 mgals) and high heat flow (mostly 92 mW m<sup>-2</sup>). This high thermal anomaly is due to the injection of large volumes of

Eocene-Pleistocene igneous rocks into the thinned continental crust, making the region favourable for geothermal resource development. Indeed, Nevada and Utah are (after California) the second and third largest producers of geothermal electricity in the USA. Hydrothermal solutions and veins associated with igneous bodies and carbonaceous sedimentary rocks have produced important mineral deposits, including copper, silver, gold and gemstones. Due to its arid climate, the Great Basin is also famous for saline lakes and rock salt deposits.

The Basin-and-Range province is marked by a series of north-south trending valleys (basins) bounded by rugged mountains formed along high-angle normal faults (rift-shoulder uplifts), which curve to low-angle listric ('spoon-shaped') faults at depth, before flattening to merge to a major detachment fault at the base. The exposure of rocks on the footwall of the normal faults and the arid climate of the Great Basin provide geologists with an excellent opportunity to study the rocks present deep in the valleys.

The width of the Basin-and-Range province increases from about 325 km at 36°N to about 680 km at 40°N. Studies show that the minimum amount of crustal extension in the southern Great Basin is about 140 km (*Geology*, October 1982, pp. 499-502) and the amount of crustal extension in the

*A view of the Great Basin in Nevada. The Great Basin may be defined in different ways. In geological terms, it is a vast part of the 'Basin and Range Province' spanning over 2,500 km from Oregon to central Mexico. The hydrological Great Basin, bounded by the Wastach Mountains on the east, the Sierra Nevada on the west, the Snake River Plain to the north and the Mojave Desert to the south, drains internally, with little outlet to the Gulf of Mexico or Pacific Ocean; precipitation in this region evaporates rapidly, sinks underground, or flows into saline lakes. In the ecological/climatic sense, the Great Basin Desert, with hot, dry summers and snowy winters, is home to distinct floral and faunal communities.*



A topographic map of the Great Basin.



northern part no more than 188±43 km (*Earth and Planetary Science Letters*, 1985, v. 75, pp. 93-100).

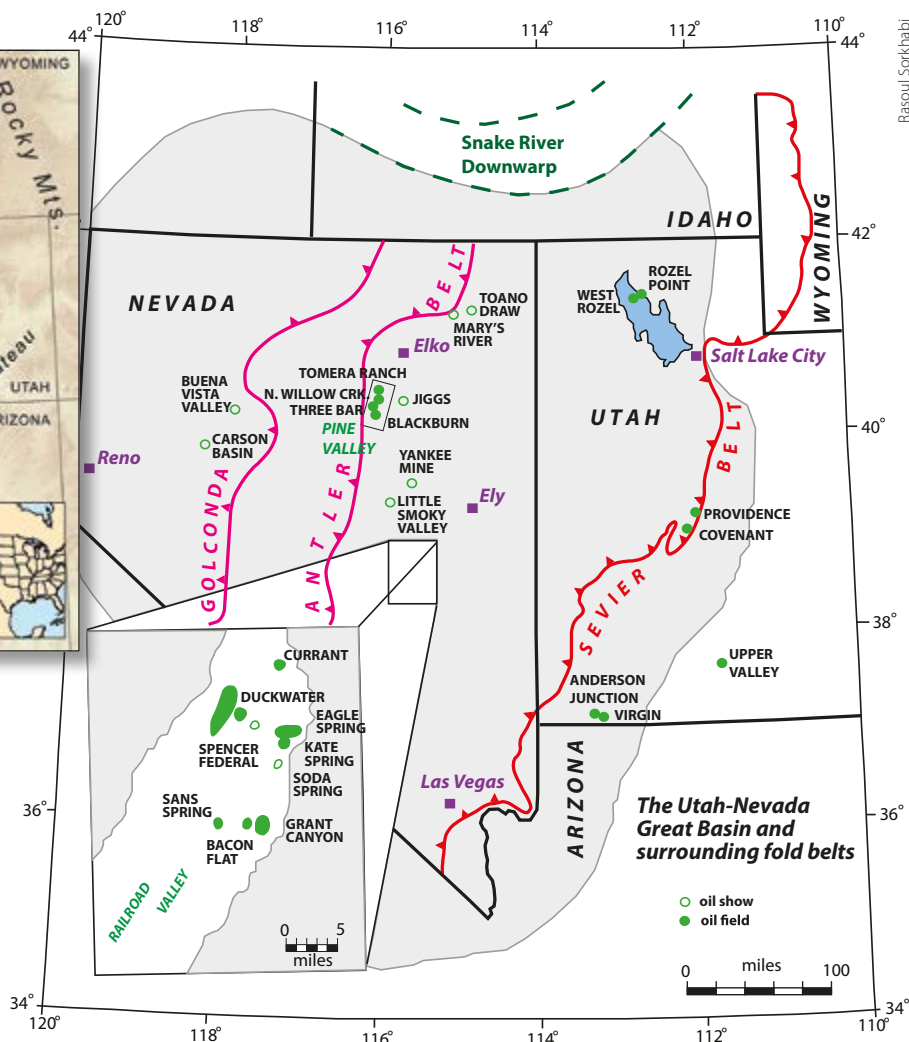
The Basin-and-Range landscape was superimposed on the Palaeozoic-Mesozoic rocks that underlie the region – it is these older rocks that are the focus of this article.

### History of Exploration

Oil seeps in the Great Basin were observed in the early 1900s at Rozel Point on the east side of the Great Salt Lake; in 1979 Amoco's West Rozel well found ultra-heavy oil in fractured Pliocene volcanic rocks in the area.

In 1892, Utah's first gas field, Farmington, was discovered north of Salt Lake City. In 1907, the Virgin field in south-west Utah was discovered, with oil (22–32° API) coming from Triassic sandstone; the field was abandoned in the 1970s. Also in 1907, the first well (dry) in Nevada was drilled south-west of Reno. From the 1900s to 1954, about 90 wells were drilled in the Great Basin, mostly close to oil seeps, but with no success.

In 1954, Shell discovered the Eagle Springs field in Railroad Valley, Nye County, Nevada. This was followed by the discovery of Trap Spring (1976), Currant (1978), Bacon Flat (1981), Grant Canyon (1983), Kate Spring (1986), Duckwater Creek (1990) and Sans Spring (1993), thus establishing Railroad Valley on the US oil map. In 1982, Amoco discovered the Blackburn field in Pine



A simplified map of the Great Basin of Nevada and Utah showing the major oil fields and oil shows (modified from *Oil Fields of the Great Basin*, Nevada Petroleum Society, 1994). The Great Basin is bounded by the Antler orogen (Roberts Mountain Thrust) and Sonoma orogen (Golconda Thrust) on the west, and the Sevier orogenic belt (the Rockies) on the east. These compressional structures are east-verging and formed prior to the Basin-and-Range extension.

Valley, Eureka County, Nevada, north of Railroad Valley, followed by the discovery of three other fields in Pine Valley: Tomera Ranch (1987), North Willow Creek (1989), and Three Bar (1989). Railroad Valley and Pine Valley are currently Nevada's only oil-producing areas. Production peaked at 4.01 MMbo in 1990, slipping to only 313,000 barrels in 2014.

In 2012, US Oil and Gas drilled Eblana-1 well into the Hot Creek Valley prospect, Nye County, Nevada (about 20 km to the west of Railroad Valley) and hit oil (28.5–33° API) in the Oligocene-Miocene, volcanic-sedimentary reservoirs at depths of 1,944 to 2,210m, in a prospect block bounded by normal faults. In 2013, Nobel Energy announced the drilling of several wells

into the Oligocene-age Indian Well and Elko Shale formations in north-east Nevada and described the wells penetrating the Elko Shale as having 'initial encouraging results.' If the Elko Shale is to be developed, it will require hydraulic fracturing. In both Hot Creek Valley and Elko, deeper wells will also penetrate the Palaeozoic sediments.

Overall, Cenozoic plays, notably the Eocene Sheep Pass Limestone and the Oligocene-age volcanic sediments of Garret Ranch Group and Indian Well Formation, have been widely targeted for oil exploration and production in Nevada.

In Utah, the Upper Valley field was drilled in 1964, and the Anderson Junction field in 1968. After the 1973 oil shock, Utah's Great Basin attracted some exploration but wells drilled into

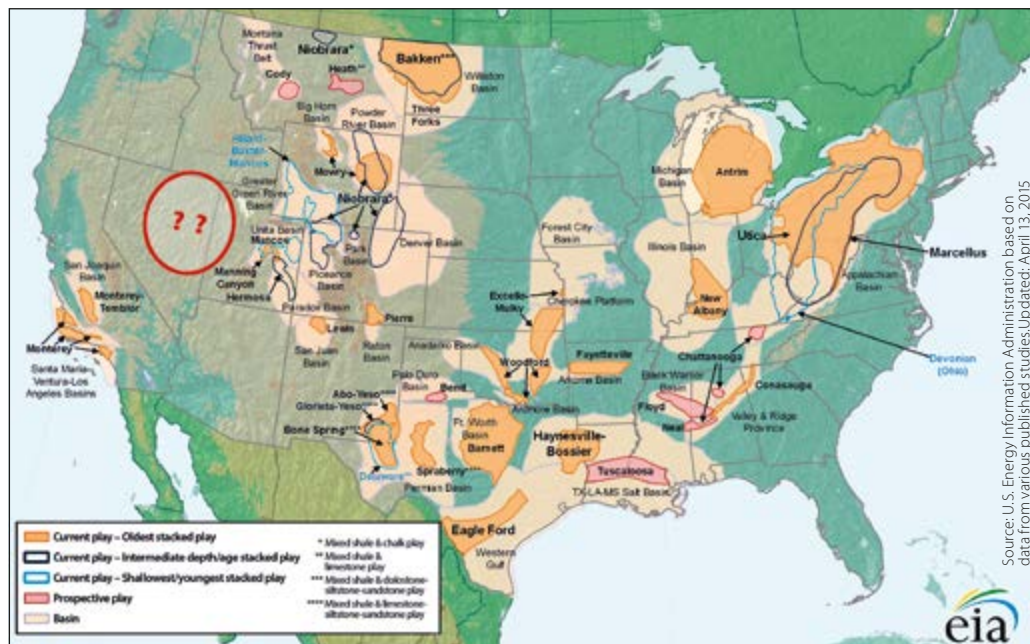
# Unconventional Exploration

the Cenozoic sediments filling the faulted valleys were not encouraging. Utah's most recent conventional oil discoveries are the Covenant field (2003) and Providence field (2008), both located on the Central Utah fold-and-thrust belt, which is a continuation of the Sevier belt extending to Wyoming and Montana (see 'Central Utah Thrust Belt: Tectonics of a New Exploration Province,' *GEO ExPro*, Vol. 3, No. 4).

## Back to the Palaeozoic

The Palaeozoic Appalachian Basin of eastern USA is a classic oil and gas province; it is home to the Devonian-age Marcellus Shale, one of the top shale plays in the world. The Palaeozoic rocks of the Great Basin, covered by Cenozoic sediments, have, however, received little attention, but a comparison of the Palaeozoic geological histories of eastern and western USA reveals remarkable tectonic and stratigraphic similarities. Both regions began as passive-margin continental platforms of North America during the Cambrian, and were later subjected to compressional tectonics as continental blocks collided with both sides of North America during the Palaeozoic. In the east coast, from Alabama to New York, a series of collisional events culminated in the Appalachian Mountains and associated foreland basins during Permian times as African collided with North America.

On the western margin, following the subduction of the ocean floor, a major island arc collided with North America; this tectonic event, called the Antler orogeny by R. J. Roberts in 1951 after Antler Peak in Nevada, spanned Late Devonian-Mississippian times. The Roberts Mountain thrust fault in central Nevada is the remarkable feature of this tectonic collision. During Permian-Triassic times, in what is called the Sonoma orogeny, another island arc collided along the Golconda Thrust in western Nevada. Later, the Pacific-side ocean floor began to subduct



US Energy Information Administration's map of the major shale gas plays in the lower 48 United States. The Great Basin of Nevada-Utah remains a vast blank area on the map.

Source: U.S. Energy Information Administration based on data from various published studies. Updated: April 13, 2015

beneath the North American continent creating the Sierra Nevada (consisting mainly of igneous rocks derived from ocean-floor subduction) and the Sevier fold-and-thrust belt (the Rockies and their foreland basins) that extends from Canadian Alberta to Utah.

The Palaeozoic rock package of the Great Basin may be divided into (1) Cambrian-Middle Devonian passive continental margin (carbonate platform), (2) Late Devonian Early Mississippian Antler sequence (mainly dolomite, limestone and shale) ending with the uplift of the Roberts Mountains and deposition of Chainman shale in a foreland basin to the east of the mountain range; and (3) Pennsylvanian-Permian carbonate sediments deposited during a regional subsidence.

## Future Prospects

A 2007 report by the US Geological Survey estimated that about 1.6 Bbo and 1.8 Tcfg remains to be discovered in the Great Basin (US Geological Survey Digital Data Series DDS-69-L). This resource evaluation was only for conventional oil and gas in the Neogene basins and fold-and-thrust belts. The unconventional resources (shale and other tight reservoirs) underlying the Mesozoic-Cenozoic have been relatively less explored.

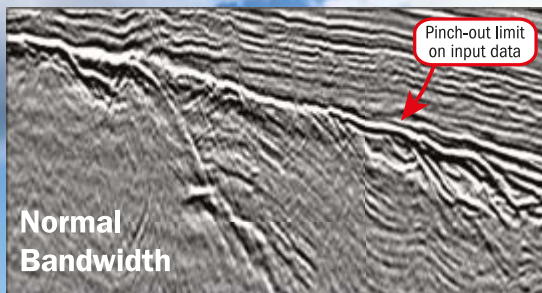
There are already some encouraging

signs for the Palaeozoic plays. In Utah, oil in the Upper Valley field was produced from the Permian-age Kaibab Limestone (17° API) and in the Anderson Junction field from the Pennsylvanian-age Callville Limestone (27° API). Although the reservoir rock in the Covenant and Providence fields in central Utah is the Jurassic-age Navajo Sandstone (API over 40°), the source rock charging this reservoir is widely thought to be the Mississippian Chainman Shale deep in the basin. In Nevada, the Devonian Guilmette Formation (brecciated dolomite) has yielded oil (25–28° API) in the Grant Canyon and Bacon Flat fields in Railroad Valley.

The following shale formations have high potential for exploration and production in the Great Basin: (1) Vinini Shale (Ordovician) in Nevada; (2) Kanosh Shale (Ordovician) in central-eastern Utah; (3) Woodruff/Slaven siliceous mudstone (Devonian) in Nevada; (4) Pilot Shale (Late Devonian) and (5) Chainman Shale (also called Manning Canyon Shale in eastern Utah) (Mississippian), both widely spread across the basin; as well as (6) Phosphoria Formation (Permian) in the northern part of the Great Basin as a stratigraphic extension of the same formation in western Wyoming where it is a rich source rock. All these marine formations have thicknesses in hundreds of metres, with a wide range of total

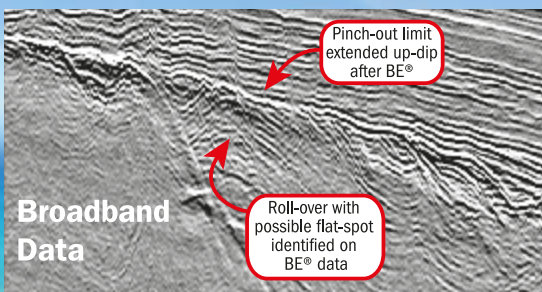
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## Unconventional Exploration

organic carbon values (0.1% to 25%). Vitrinite reflectance data also vary from 0.6% (entering the oil-generation window) to 5% (thermally over-mature).

Widespread Palaeozoic shale and carbonate rocks in the Great Basin offer a new major frontier for unconventional petroleum in North America. Changes in lithology, depositional environment, total organic carbon, and degree of thermal

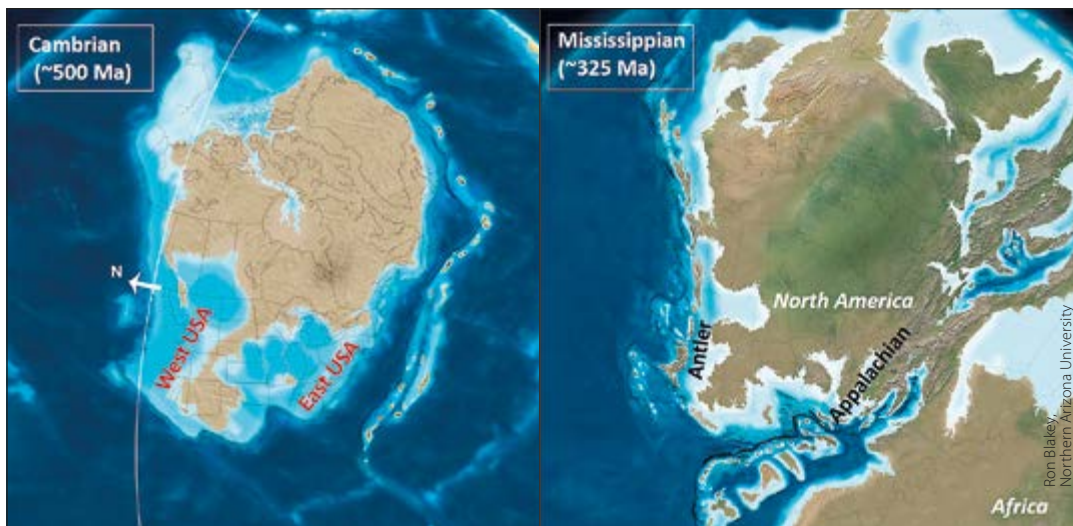
maturity across and along the Great Basin, however, place important variables in the subsurface mapping and resource evaluation of these shale plays, thus necessitating detailed stratigraphic, lithological, and geochemical analyses of the rocks. Moreover, imaging of structural deformation and stacking of rocks in the subsurface also requires geophysical surveys, well information,

and structural reconstructions.

Unlike the eastern USA, there is little urban development in the Great Basin, so both public and private lands should be attractive for oil and gas exploration. However, shortage of water, so much needed for hydraulic fracturing, can be an obstacle in the Great Basin. Investment in infrastructures such as pipelines will also be needed for long-

term development of the oil and gas plays in the region. ■

*Rasoul Sorkhabi, contributing editor to GEO ExPro Magazine and a professor of petroleum geology at the University of Utah's Energy & Geoscience Institute, is a principal investigator for the industry-funded consortium Central Utah-Nevada Deep Plays. For more information, contact: [rsorkhabi@egi.utah.edu](mailto:rsorkhabi@egi.utah.edu)*



*Palaeotectonic maps of North America during the Cambrian and Mississippian periods depicting tectonostratigraphic parallelism between east and west USA.*

*The Mississippian-age Chainman Shale is believed to be a prolific source rock in the Great Basin of Nevada and Utah.*



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# The Hoop Area: New Testing Ground for Geophysical Technologies

The Hoop Basin was named after *Der Hoop*, a ship belonging to one of the great Arctic explorers, William Barents. Meaning 'hope' in his native Dutch, this continues to reflect the aspiration of today's oil industry that the hydrocarbon potential of the greater Hoop area will be fulfilled.

## BENT KJØLHAMAR, TGS

The Hoop Fault Complex is located in the northernmost part of the Barents Sea. North of the Maud Basin and along the narrow Hoop Basin a number of production licences have been awarded and six wells drilled in recent years. Two light oil and two gas discoveries have been reported, the most remarkable thing about them being their shallow

depth – they are located in excellent Jurassic reservoirs only a few hundred metres below the seafloor.

Maximising the opportunity presented by shallow targets, the Hoop area has become a geophysical and geological testing ground for new technologies. Besides many new 2D seismic data sets and several seafloor sampling cruises,

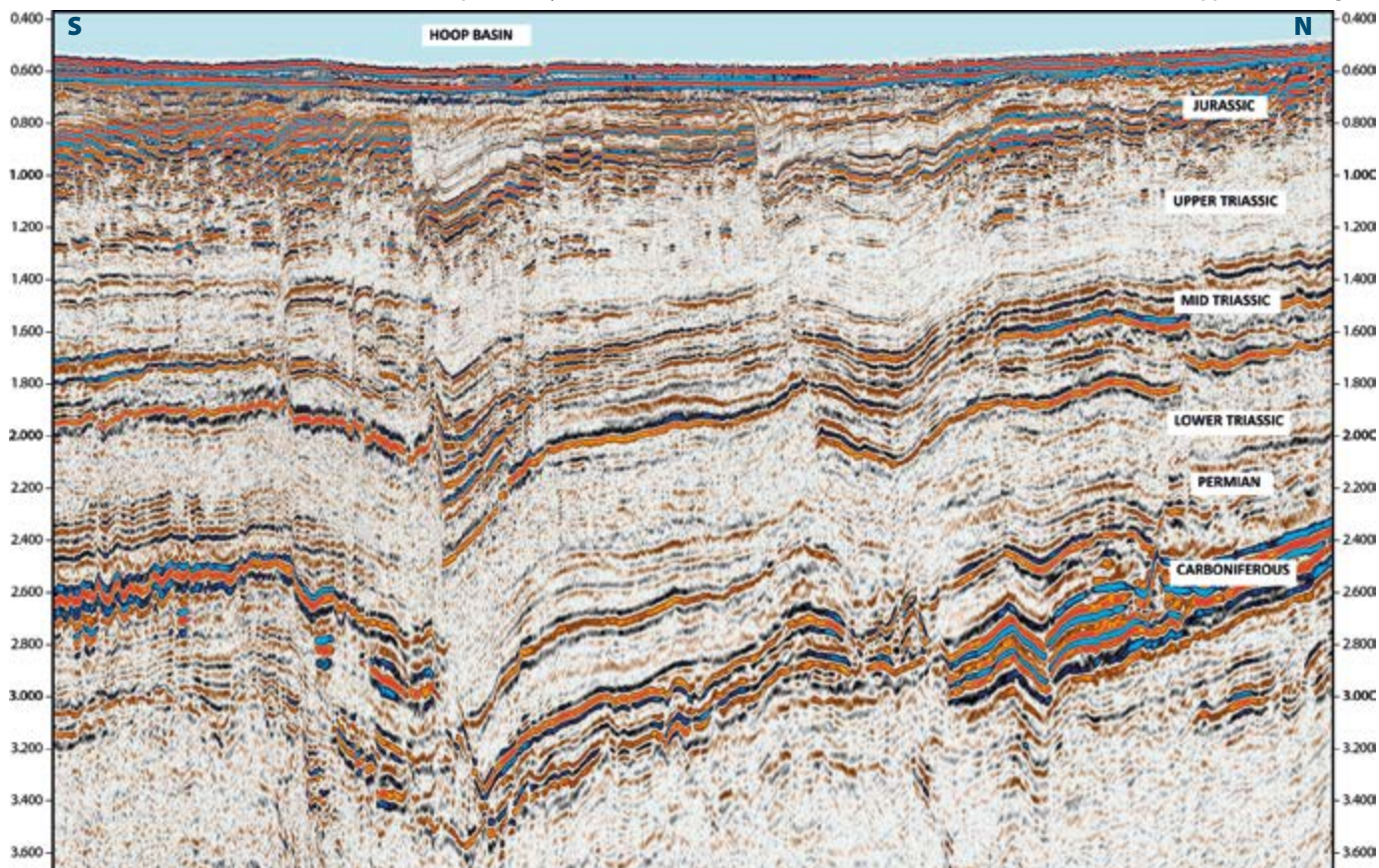
the area has a large continuous 3D seismic and 3D CSEM (controlled-source electromagnetic) coverage. Noteworthy among the new technologies tested are seismic de-ghosting processing techniques, P-Cable ultra-high resolution 3D seismic and induced polarisation (IP).

## Interesting Structural Styles

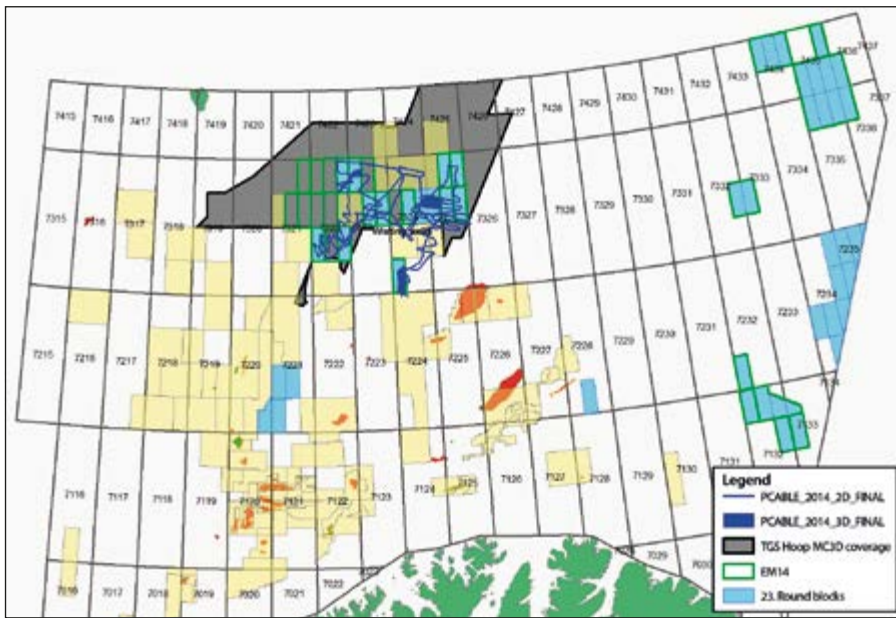
Only a few deep north-north-east to south-south-west faults can be seen in and around the Hoop Fault Complex. These were active in Mid Triassic and Upper Jurassic times, as evidenced by thicker successions within the basin, consequently opening up the possibility of locally thicker reservoirs and source rocks. Mild shortening is also observed.

On the east side of the complex, in the area where the new oil discoveries are situated, intermediate deep faults are rooted in the Early Triassic. In the greater Hoop area, east to west trending shallow faults cross almost perpendicular to the older faults. These are important for the closures and leads seen in the Jurassic. In most cases, the faults continue as flexures at the onset

*Seismic section in the Hoop Basin area. The area has a condensed geologic succession visible here from a Devonian or older seismic basement to the Lower Cretaceous with a thin Quaternary cover. The main reservoir-prone units are Permian karstified carbonates, Mid Triassic and Upper Triassic sandstones, Lower to Mid Jurassic sandstones and potentially Barremian sandstones. The main source rocks are of Mid Triassic and Upper Jurassic age.*







Map showing the Hoop area north in the Norwegian Barents Sea with different TGS data types.

of the Cretaceous. Most of these end in the upper channelised Upper Triassic and only a few offset the Mid Triassic. This points towards ductile Cretaceous and Upper Triassic, but a brittle Jurassic at the time of creation. Offsets of more than 100m are compensated a few hundred metres below. There are several theories explaining this, such as differential compaction due to diagenetic processes or being triggered by the channel systems in the Upper Triassic. Alternatively, perhaps the compensation could be due to salt movements deeper down. The problem with these theories is the regional scale of faulting which can be seen all across the large area covered by 3D seismic data. These Jurassic east to west faults can be followed westward to the Stappen High, several hundred kilometres away and in a totally different structural setting, indicating a more

regional driver for these faults.

Regional scale bending or mild east-west strike folding/bending of the northern Barents succession may provide the regional mechanism required. In the upper part of a gentle fold, ductile layers (Cretaceous and Upper Triassic) might compensate the extension by stretching/thinning whilst more brittle layers (Jurassic) show extensional faulting. Weak compressional features or shortening have been observed on the large main faults deeper down.

### Promising Reservoirs

The generally condensed Mesozoic succession in the Hoop area allows us to assess even Palaeozoic rocks as potential reservoirs. The recent 'Gotha' oil discovery in the southern part of the Loppa Ridge south of Hoop proves up a karstified carbonate play, giving

hope for similar karstified carbonate reservoirs in the western part. Here, in the continuation of the Loppa High, the Mesozoic succession is uplifted and partly eroded, bringing Palaeozoic carbonates into a shallow position.

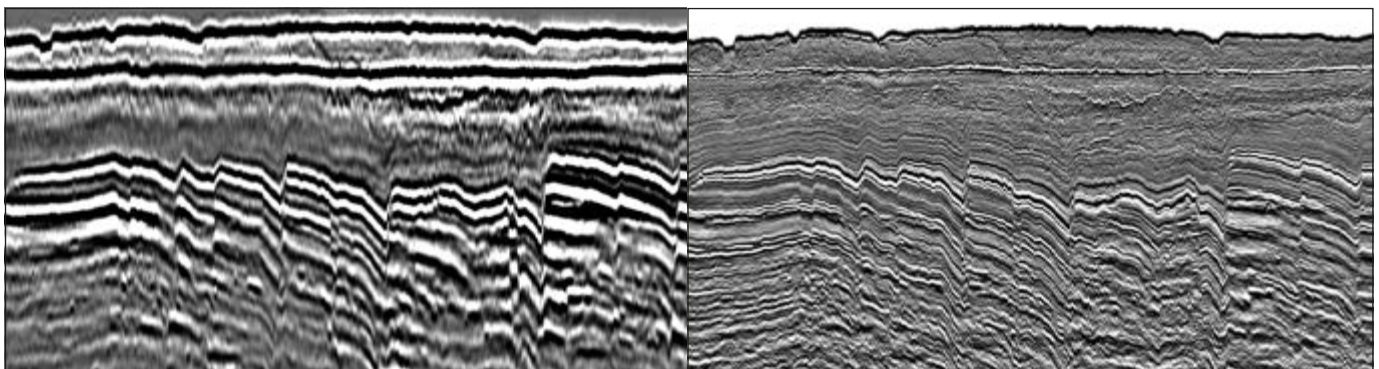
The Triassic succession is dominated by large scale deltaic deposits. High clinofolds from coastal progradation events in Mid Triassic shale out in the deep marine conditions towards the west. Potential sand in topset layers of these clinofolds, especially in the regression style prograding episodes, could create large stratified traps. The Late Triassic consists of a thick package of channelised coastal plain deposits that are also likely to contain good reservoir rocks. Two high-quality Jurassic reservoirs with thicknesses up to 70m are reported from the new wells. The Jurassic succession thickens within and on the eastern flanks of the Hoop Basin. The light oil discoveries in the Jurassic play make these the main targets to be tested further by the industry. The lowermost part of the Cretaceous is preserved and thickens significantly westward over the Fingerdjupet sub-basin with potentially sandy Barremian prograding units.

### New and Innovative Seismic

At normal prospect depths of 2–4 km, the overburden is filtering or attenuating higher frequencies. At best, these targets have seismic frequencies up to 30 Hz, which limits the details of sedimentary patterns or subtle hydrocarbon effects that can be seen in the seismic.

Jurassic reservoirs in the Hoop area, however, are typically less than 1,000m below the seafloor. These

The seismic lines below are from the same location. The left image shows conventionally processed semi-high density 3D data; the right one P-Cable and Clari-Fi processed data. The section is approximately 1 second two-way time and images the Quaternary, Lower Cretaceous, Jurassic and the uppermost part of Triassic. The second strong event in the middle of the left figure is the topmost Jurassic reservoir.



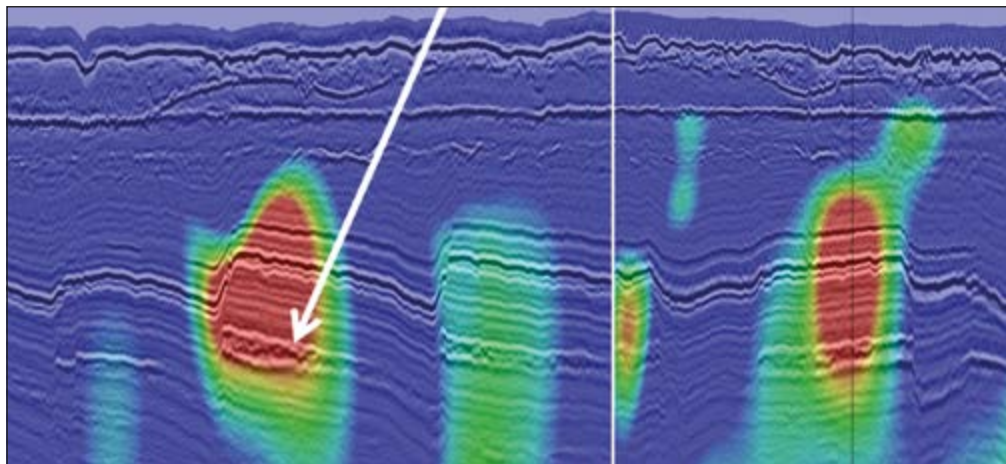


Figure shows HR14 (P-Cable 3D seismic data (courtesy of WGPS) – inline (left) and x-line (right)) with CSEM overlay (courtesy of EMGS). The P-Cable data has greater resolution in the Jurassic reservoir. Sedimentary features within the closures correspond to CSEM anomalies (arrow).

extremely shallow targets create an opportunity for new and innovative seismic acquisition and processing, as well as technologies with higher resolution. When coupled with the high exploration activity in this area, advances are continuous and challenge-driven. By way of demonstration, the recent testing of P-Cable seismic acquisition and de-ghosting processing using TGS' proprietary Clari-Fi™ technology has opened a previously unseen window to the subsurface that provides more certainty in lead identification and prospect appraisal, as well as reduced exploration risk.

More than 20,000 km<sup>2</sup> of semi-high density 3D seismic has been acquired in the Hoop area in recent years using a 3D spread of 10 streamers, 6,000m long and 75m apart, with streamers at 9m depth and gun arrays at 7m. As Jurassic targets lie before the first seafloor multiple, and customarily at less than 1,000m depth, P-Cable seismic is applicable here. P-Cable is an extreme type of 3D technology – with a typical 100m spread comprising 16 streamers, only 25m long, 12.5m between cables, streamers at 2m and gun at 2.5m depth – which maximises the potential of streamer acquisition technology to meet the specific needs of explorationists in this area.

On conventional 3D seismic processing with 4 ms vertical sampling, the contributing seismic frequencies range between 5 and 65 Hz. Clari-Fi de-ghosting processing techniques with 2 ms vertical sampling have been shown to double the measured frequencies in the top section up to 120 Hz. The P-Cable data processed at 1 ms and de-ghosted using Clari-Fi

have contributing frequencies past 250 Hz in the top section.

As a result of drilling success, the Jurassic reservoirs are in focus. When imaging data based on conventional seismic, the two proven Jurassic reservoirs (the Stø and Normela Formations) are hard to assess in terms of reservoir thickness and vertical stratigraphic heterogeneity. Thickness variations start to be seen in the Jurassic reservoir levels on the de-ghosted 2 ms processed data, and sand and shale interpretation is also possible on the relatively thin reservoirs.

On the P-Cable ultra-high resolution 3D seismic, small and subtle sedimentation features like individual meandering channels with accretion of point bars and shore-face deposits including beach ridges can be identified. Hydrocarbon indicators such as flat spots and soft kicks, commonly seen in the Jurassic here, become sharper. On some leads, even a second flat event is seen.

### CSEM and Seafloor Sampling

Since 2008, CSEM data has been acquired in the Hoop area and the major part is now covered with 3D CSEM data. The shallow targets make CSEM technology particularly applicable in this area. Numerous CSEM anomalies in different depths have been observed. To date, all of the oil and gas discoveries have been supported by CSEM anomalies with the exception of one dry well. Several such anomalies are observed on Jurassic leads elsewhere, but well-defined anomalies are also seen in the Cretaceous (Barremian) prograding system. In the western side of the Hoop Basin large CSEM anomalies are observed within the Triassic succession.

Quite a few CSEM anomalies point to large structural and stratified traps in the mid-Triassic coastal prograding units and at specific clinofolds. In the east side of the Hoop Basin anomalies are seen in the channelised Upper Triassic, pointing to combined structural and stratified traps in this well-developed system.

Last year a seafloor sampling cruise (gravity coring) was carried out in the area. The sampling was done along three transects east and west of the Hoop Basin. The drop sites were densely spaced and carefully selected based on hi-res 3D seismic and sub-bottom profiler data. All the well locations in the area were also sampled for reference and background information. Three independent laboratories were used to analyse the data for the most trustworthy interpretations. The results suggest two types of oils, C5-7 and C8-14, in the area. Strong anomalies of oil microseeps were detected above specific Jurassic leads and oils were detected on both sides of the Hoop Basin.

### Untested Plays and Leads

In the greater Hoop area (>25,000 km<sup>2</sup>) there are still many untested plays and a lot of leads in the now proven Jurassic play. The area has significant potential. In the current constrained economic environment, it becomes increasingly important for oil and gas exploration companies to be able to reduce their risk by investing in areas with proven hydrocarbon potential – and also ones where they can rely on the best available geoscience-driven data to inform their energy decisions.

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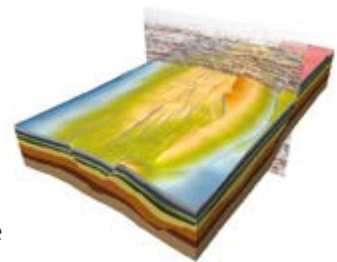


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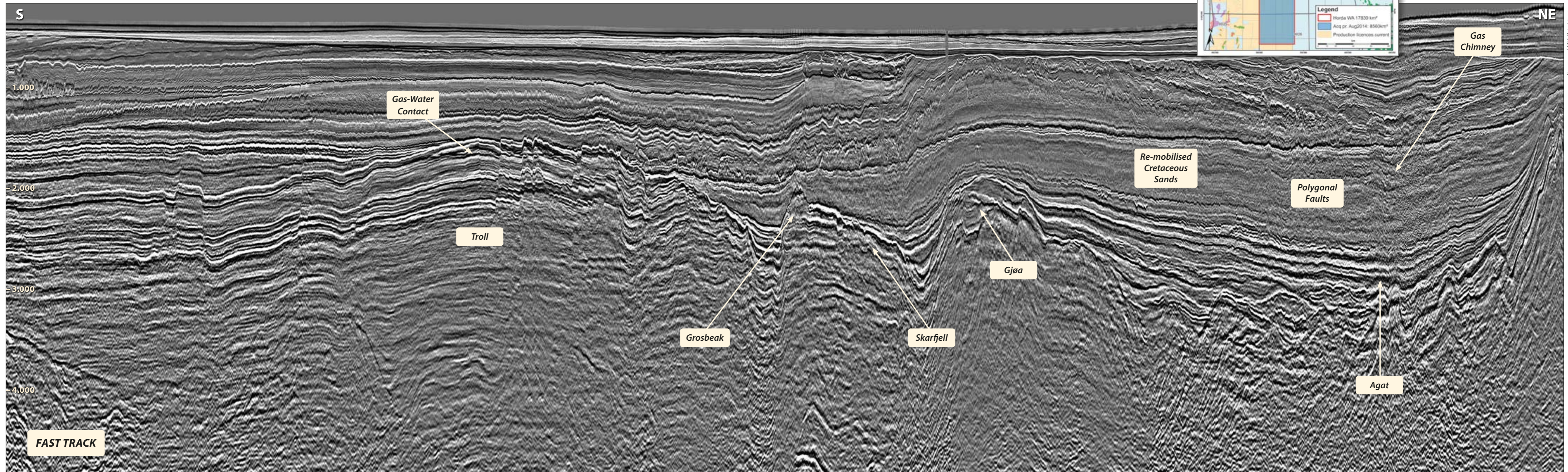
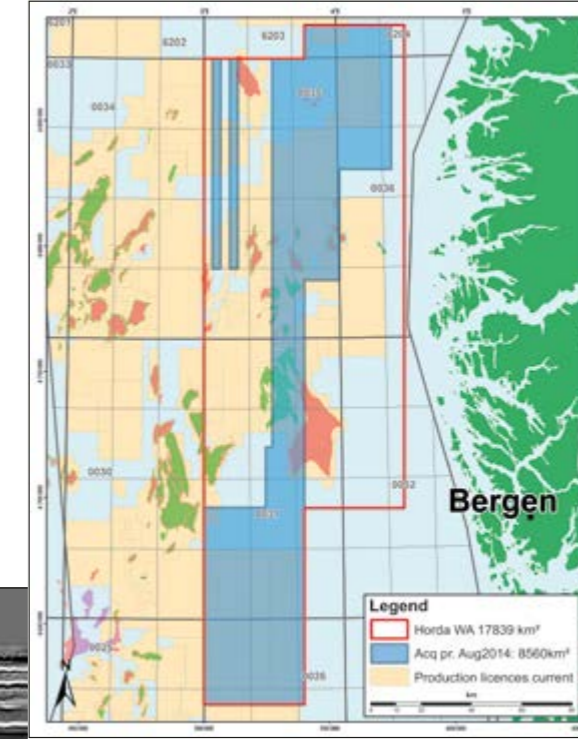
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# Horda Platform: Exploring the Cretaceous

Hydrocarbon exploration in the northern North Sea has been primarily within pre- and syn-rift Jurassic sandstones. This is with the exception of chalk reservoirs in the Ekofisk field and Palaeogene sand reservoirs of the Frigg field. Now, with ignited interest in the Horda Platform, and particularly after the discovery of the Grosbeak and Skarfjell oilfields, attention has been directed towards the hydrocarbon potential within post-rift Cretaceous sands. The prospectivity of the Cretaceous sands was demonstrated more than three decades ago with the Agat discoveries.

*This annotated seismic line has been taken from CGG's new Horda multi-client survey; it is orientated south to north-east. The seismic section cuts through the Troll, Grosbeak, Skarfjell, Gjøa and Agat fields. A clear gas-water contact can be seen in the Troll field from the fast-track seismic section. The combination of BroadSeis™ and BroadSource™ help image shallow stratigraphy as well as deeper Jurassic reservoirs.*

*Map showing the location of the new CGG multi-client survey. The annotated seismic line runs from south to north-east across the area.*



# Cretaceous Reservoirs in the Northern North Sea

Recent discoveries and development of hydrocarbon fields on the Horda Platform have led to considerable interest in the northern North Sea.

**JASWINDER MANN-KALIL, CGG**

Exploration activity in the late '70s and '80s led to the discovery of giant fields such as Troll, Oseberg, Gullfaks, Snorre and Statford and showed that large accumulations of oil and gas can be found in the northern North Sea. The recent discovery of the Johan Sverdrup and Edvard Grieg fields further south suggests that hidden gems can still be found within this part of the North Sea. The southern and eastern parts of the Horda Platform are currently still fairly undeveloped. With new play models being recognised in the North Sea, several companies have shown a renewed interest within the area. The complexity in migration of petroleum systems and late westward tilting of the entire region suggest the possibility of re-migration of hydrocarbons and new trapping potential. CGG's high-quality broadband data provides new insight into the imaging and mapping of such features, which conventional data does not allow.

## New 3D Survey

CGG recently acquired a new 3D multi-client broadband seismic survey on the eastern rim of the northern Viking Graben, offshore Norway. The Horda survey will reach in excess of 18,000 km<sup>2</sup> by the end of 2015, with 8,650 km<sup>2</sup> acquired in 2014. It extends from the Horda Platform in the south-east to the Sogn Graben in the north and covers the entirety of quadrant 35 and large parts of quadrants 31, 32 and 36. The survey was acquired with the use of CGG's broadband technologies, BroadSeis and BroadSource, with the main objective being to provide a large and uniform dataset with increased seismic resolution. With usable

frequencies ranging from 2.5 to 200 Hz, this allows for enhanced imaging from the shallow section to deeper areas of interest. CGG's six-octave BroadSeis technology combined with long offsets and a dense streamer configuration helps provide a platform for further activity in the region from exploration to production.

## Horda Platform

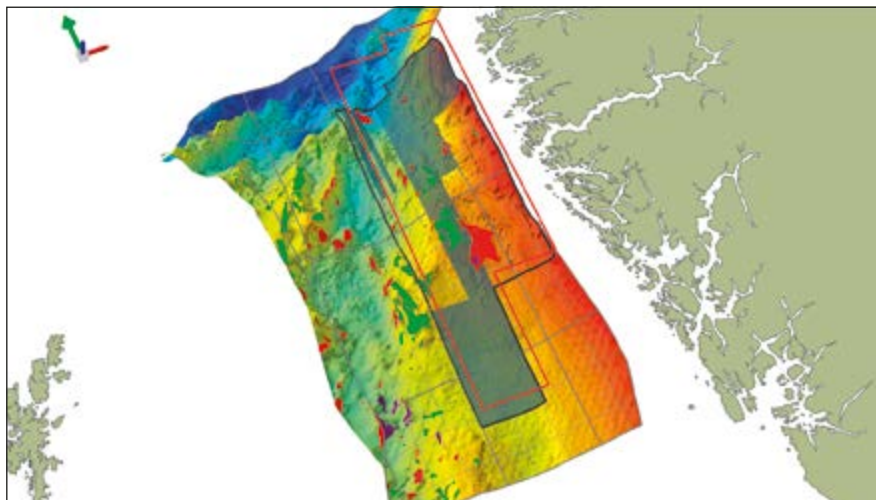
The present structural shape of the North Sea has been influenced by three main tectonic events: Permo-Triassic rifting, Late Jurassic-Early Cretaceous rifting and Late Cretaceous rifting. This was subsequently followed by a drift phase and Eocene seafloor spreading.

Prior to the Late Jurassic, deposition had been dominated by fluvial to near-shore marine environments. Following the Late Jurassic-Early Cretaceous rift episode, deepwater sedimentation prevailed due to alterations of bathymetry in the North Sea. Lower Cretaceous sediments infill half grabens in the region as a result of this rift phase. The Horda Platform is a prominent structural high, located to the east of the deeply faulted Viking Graben in the northern North Sea. The Horda Platform post-dates the Triassic rift period as sediment deposition of this age can be seen to infill half grabens at depth. Jurassic sediments are found to be sub-horizontal in large parts of the Horda Platform, allowing for a clear contrast from dipping lower Triassic strata.

## Petroleum Systems

The prolific Middle to Late Jurassic Heather and Draupne formations make up the primary source rocks for oil and gas in the North Viking Graben. The shales are the lateral equivalent of the Kimmeridge Formation in the southern Norwegian and UK parts of the North Sea. The source rocks were deposited in a restricted marine environment and are known to be interbedded with localised sandstones throughout the sequence. In the central part of the North Viking Graben, both formations are extremely thick and of good quality for generating both oil and gas at different depths. Petroleum

*CGG's Horda survey seen outlined in red with the grey polygon illustrating data already acquired. Oil and gas fields are overlain on a regional interpretation of the Base Cretaceous Unconformity.*



generated in the Graben migrated both westwards towards the Tampen spur area and eastwards towards the Horda Platform.

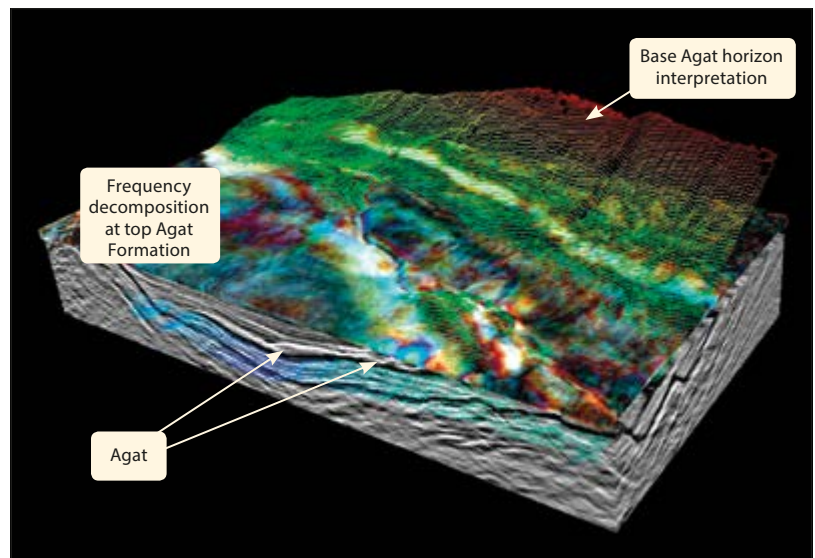
The main reservoirs in the province are pre- and syn-rift sandstones of the Middle and Late Jurassic; these consist of the Brent and Viking groups. The Brent Group is up to 250m thick in the area and was deposited as a major deltaic clastic wedge, which prograded northwards to finally become swamped by the southerly marine transgression. The Upper Jurassic reservoirs, like those found within the Troll field, have a depositional environment of open marine in the west to shoreface and restricted marginal marine in the east. Secondary reservoirs can be located within Triassic, Lower Jurassic, Cretaceous, Paleocene and Lower Eocene intervals. Fluvial and marginal marine sandstones make up the Triassic reservoirs found in the Snorre and Visund fields. Lower Jurassic sandstones consist of the Statford Formation, found deposited in alluvial to marginal marine environments, and the Cook Formation, which is comprised of marine sandstones, siltstones and shales.

### Imaging of Cretaceous Sands

Deposition of Cretaceous reservoirs in the North Sea is strongly influenced by the basin topography created by Jurassic rifting. The availability of new broadband data allows for a more accurate approach to mapping out petroleum systems and understanding new play models. Potential reservoir sandstones within the Cretaceous can be much easier to identify and the risk of mapping isolated sand bodies is reduced. Since the discovery of the Agat gas field, more attention has been given to both Lower and Upper Cretaceous sandstone plays. The Agat field is made up of two complex small discoveries in stratigraphically trapped sub-marine sandstone lobes of the Cromer Knoll Group, but the extent of the sandstones have been difficult to map on conventional seismic.

The Lower Cretaceous Agat Formation sands can be observed predominantly in the northern area of the Horda survey, infilling faulted basement highs. The top of the formation displays high amplitudes, and sand distribution can be seen quite prominently on the seismic.

Well 35/9-3 encountered hydrocarbons in the Cretaceous sequence within the Agat and Kyrre formations. The well results indicated over 1,000m of Kyrre Formation interbedded sands and shales. The sand section has been interpreted as sub-marine channel fills and fans. The seismic figure

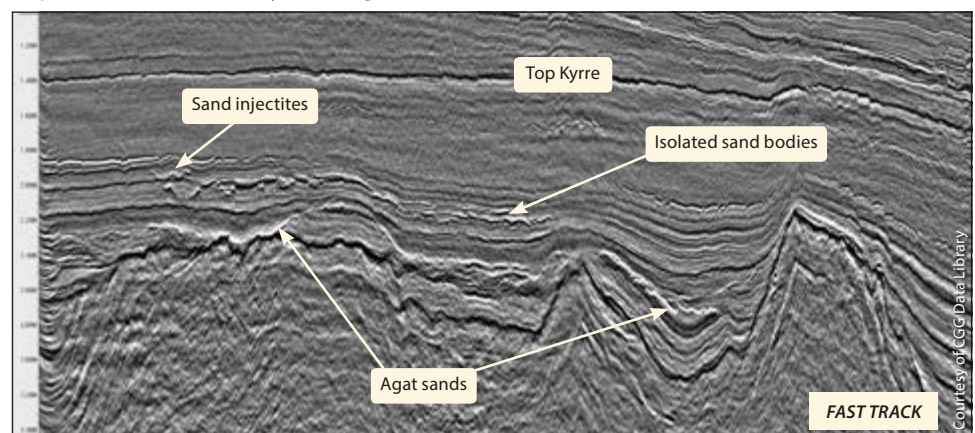


Colour blend 3D visualisation highlighting the Agat sands with horizon interpretation.

shows the high amplitude and the isolated nature of these sandstones found at the base of the Kyrre sequence. With the increasing low and high frequencies achieved with BroadSeis and BroadSource, better differentiation can be made with facies and stratigraphy. Stratigraphic pinch-outs of sand bodies can be clearly seen within the thick polygonal faulted shale section. The BroadSeis data helps identify features such as clastic intrusions typically characterised by winged edges and a strong amplitude response.

Being able to better image and identify potential reservoir sandstones within the Cretaceous section allows for a better understanding of newer plays in the northern North Sea. CCG's BroadSeis data with BroadSource is the ideal tool to determine if these sand bodies are of commercial interest, and, with the support of a number of oil companies, the survey area is now being extended to the west, to provide a dataset of over 35,000 km<sup>2</sup> of full-bandwidth data. These datasets are being processed with reservoir characterisation in mind, including the integration of well and gravity data, as well as extensive QC using AVO tools, to deliver a dataset that is reservoir-ready and will require only minimal pre-conditioning before use in elastic inversion. ■

Seismic line taken from the Horda survey focusing on the Cretaceous section. The line clearly shows high-amplitude sands within the Kyrre and Agat formations.



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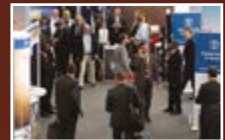
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**GEO Tourism**

# Malta

**A country shaped by limestone  
(and a bit of very old poo)**

**KARSTEN EIG**



*The shore on Comino, a small island  
between Malta and Gozo.*



If one word could sum up the Mediterranean island nation of Malta, it would be 'limestone'. Limestone has shaped the islands' topography, their economy and possibly black bank accounts. It has also made Malta, and particularly the island of Gozo, a paradise for carbonate geology studies – and diving.

In this article, I will take a look at them all. But, let's start with the (literally) fundamentals: the geology itself. Get ready to get nerdy!

Malta lies on a large carbonate platform that stretches northwards from Africa and also includes Sicily. Geo-wise, Malta is thus a part of Africa, and the islands are just the youngest tops of the rocks that peak above sea surface. They were deposited from the Upper Oligocene through Upper Miocene, from about 20 to 8 million years ago. On the geological time scale, Malta is a toddler.

The lithostratigraphy on Malta is divided into three main groups, their development controlled by changes in the sea level of the Mediterranean through time. Sea level, in turn, is the result of the complex interplay between how much water came through the Gibraltar strait relative to evaporation, and sediments dumped from the erosion of landmasses lifted up when Africa collided with Europe to produce the Alps.

### Lower Coralline Limestone

The lower of the three levels is the Lower Coralline limestone, made up of carbonate sand and gravel, mixed with shell fossils. The carbonate sediments were originally living organisms, such as coral reefs, shells, or as very fine-grained plankton – probably on what is now Sicily. These rocks were then eroded, flushed south to Malta by high-energy waves and currents, and re-deposited as sand and gravel in shallow water. Some beds in the Lower Coralline consist nearly solely of shell fossils, ground to fragments by the eternal wave movements.

The Lower Coralline limestone is hard and resistant to wear and tear, and forms steep and vertical cliffs along the coast. North-west of Marsalforn on Gozo, it has beautiful crossbeds, where each bed consists of thin layers that dip in the direction of the current.



### The Globigerina Limestone

The middle interval, the Globigerina limestone, is the softest of the three limestones. It is composed nearly completely of planktonic carbonate, and gets its name from the Globigerina foraminifera, a very tiny crustacean. Pure and fine-grained, this limestone has a distinctive yellow-greyish colour. It is used to construct buildings, aqueducts, pavements – basically everything – and Maltese towns therefore have the same yellowish-greyish colour from tip to toe. Because limestone slowly dissolves from acids in rain, some buildings have had parts of their walls washed away.

The limestone is pure because it was deposited in deep water, probably 200m, where very few organisms would mess it up before

*Coarse crossbeds and karst holes in the Coralline limestone, close to the Azure Window.*



it consolidated into rock.

However, periods of shallower water interrupted the deep calmness, and with shallow water came organisms that buried in the sediments. Their burials and tunnels, 'bioturbation' in geo-speak, left coarse dark nodules that almost entirely make up some beds. My muggle – a.k.a. non-geologist – travel mates were quite surprised to learn that the dark blobs in the light rock were literally old faeces from slimy creatures that lived in the sediments before they became hard rocks; they ate not-yet-

*The Coralline limestone can consist nearly solely of fragments of shells.*



solidified carbonate rock through one end, and left brown blobs at the rear.

The longer a layer is left in shallow water, without being buried by new sediments, the more time the creatures have to make burials. In the bay of Marsalforn, our base at Gozo, one can see how a homogeneous limestone gets more and more burials, ending in a layer that is nearly entirely made up of burial nodules – before the sea level suddenly rose again, and the rocks abruptly changed back to yellowish again.

## Upper Coralline Limestone

Above the Globigerina is the thin Blue Clay. It is the softest rock on Malta, but very important, because it consists of very fine-grained particles of clay minerals and carbonate, which make it impermeable. It catches water that sinks down through the porous rocks above, and forms the floor of a precious freshwater table.

Finally, the Upper Coralline limestone is a lookalike, although thinner, of its older sibling, deposited in the same high-energy deposition environment. On Gozo, this hard limestone stands out as caps with steep cliff sides and flat tops, above the softer rocks beneath. Therefore, castles for defence were built on top of these high parts of the island. Actually, after an Arabian pirate attack in 1556 kidnapped nearly the whole population, for a long time the remaining Gozitans stayed inside the citadels at night and went out only to work on the fields during the day.

By now, you have already seen glimpses of how the geology of Malta influences people's lives. Let's take a closer look.



**Marsalforn Bay, with houses built on the soft Globigerina limestone. Do not invest in seafront real estate if your investment horizon exceeds a few hundred years.**



**Yellow-greyish Globigerina limestone in buildings as far as the eye can see. The image is taken in Gozo's capital, whose name in Maltese is Ir-Rabat, but was renamed Victoria after the Queen. In the background, the mighty Ta'Pinu cathedral.**

## Few Natural Resources

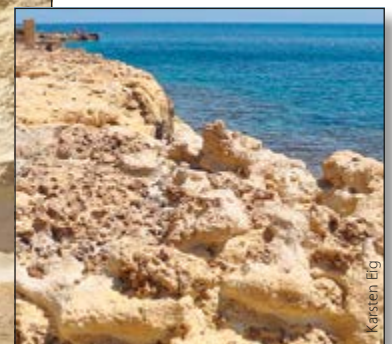
Water has always been scarce on dry Malta. It sinks through the porous limestone, and therefore the country depends on ground water. The largest fresh water body is at sea level, in the Lower Coralline, where lighter fresh water floats on salt water, but heavy use of the ground water has

seriously threatened the future of the fresh water supply. Fresh water is also obtained through reverse osmosis of ocean water, but this energy-intensive, oil-fuelled process costs five times as much as ground water, and therefore many illegal wells tap into the ground water reservoir. As a result of the water scarcity, Malta produces only around

**Benches in the Globigerina limestone that highlight how periods with calm deposition have left light limestone with little bioturbation, interrupted by low-stands with heavy treatment by the slimy creatures.**



**Hard layers composed nearly entirely of burials, in the harbour of Marsalforn. This is some solid accumulation of old poo!**



# Persian Carpet

seismic library



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The Persian Carpet 2000 MC2D Seismic Survey (PC-2000) comprises 106,000 km, and is available for Data Licensing / Data Sales.

The MC2D survey is the World's largest MC2D seismic survey, and covers the Iranian part of the Persian Gulf and Oman Sea. The dense grid of 2x2 km seismic lines and will serve as basis for all oil-companies applying for future petroleum licenses offshore Iran. The PC-2000 data also facilitates exploration in the Iranian part of the Oman Sea, which also has strong indication for having a large petroleum potential.

Numerous undrilled structures and stratigraphic prospects have been found from preliminary interpretation of the PC-2000 seismic data, which is very encouraging from the oil company viewpoint. Examples of the PC-2000 data can be shown upon request.

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one fifth of the food it consumes.

Malta has no natural resources. No metamorphism or volcanism circulated fluids saturated with metals. No ore, no coal, no geothermal, no energy resources. Sicily, with the famous Mt Etna and other active and extinct volcanic fields, lies just to the north, and the volcanic island of Pantelleria to the south-west – but on Malta, nothing.

How about oil? Malta lies on the Pelagian block, a northward extension of Africa that also includes large oil fields on Sicily. Just to the west is Tunisia and to the south is Libya, both well known for their large resources. Thus, there is no reason why Maltese waters could not hold hydrocarbons.

The first exploration well, Naxxar 2, was drilled onshore back in 1959. Altogether 12 wells have been drilled, both on and offshore. Offshore Alexia 2 found oil in 1984, while onshore MTZ 1 was a gas discovery in 1999. These were both technical discoveries but important, as they proved a working petroleum system.

In recent years, a number of oil companies have obtained acreage offshore Malta, looking into deeper and older rocks than those exposed on the islands themselves, but which are analogues to fields in Libya, Tunisia and Sicily. The most recent, Hagar Quim 1, was drilled south of Malta in 2014 by Genel Enerji and its partner Mediterranean Oil and Gas. It targeted a Lower Eocene to Paleocene carbonate-clastic reservoir but unfortunately came out dry. Upper Cretaceous reefs, and structural traps on Late Triassic-Early Jurassic platforms are other potential targets.

It is tempting to link some Maltese businesses to the lack of natural resources. The Maltese have become a prominent shipping nation – and a tax haven. At least, Malta has avoided the curse of natural resources!

### A Diving Paradise

Finally, let's, literally, dive into one of the lighter sides of Maltese life: that under water. Malta, and especially Gozo, is regarded as the best place to dive in the Mediterranean. Malta has protected its fish stock fairly well, so there is plenty to see. Karst caves and sinkholes along the coast

*The Blue Hole with the arch of the Azure Window in the background.*



create spectacular landscapes above and below the water. Among them, the Cathedral Cave is a huge dome with access only underwater. Breaking the surface inside the cave, the dome is illuminated by the sun's rays coming through small openings in the wall. Any sound, word or wave echoes from the walls. Then comes the swim out again, through the large, mighty door opening into the big blue yonder.

Even more spectacular is the Blue Hole. It is a sinkhole, where the sea has also torn away the lower part and connected it to the sea. The upper part is hard and consists of a well-cemented fossil rich layer, and creates a natural rim around the deep pool (see image above). A popular escape destination, the Blue Hole is chock full of bathers in the upper part and divers at all levels.

Just close by is the Azure Window, standing on a pillar in the sea. Once probably a cave, now only one last pillar is standing. It was an amazing experience to dive into the big Blue Hole, and see the shadow of the arch above, with waves smashing onto the pillar. Below the arch, the sea floor was covered with boulders that had fallen down from it during the winter season, a reminder that the pillar is slowly being eroded away. Geology may look eternal, but it certainly is not... ■

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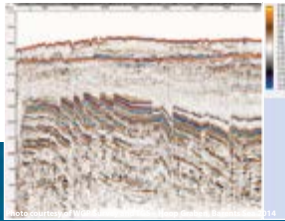


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Hoop Graben, Barents Sea 2014



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# The First Oil Shock

At a time when oil prices spiralled down from over \$100 to below \$50 within half a year, talking about 'oil shock' may seem odd. Yet, the oil shock of 1973–74 was not only the first of its kind on a global scale, but also set the political-economic stage for oil shocks and oil market crashes in the following decades.

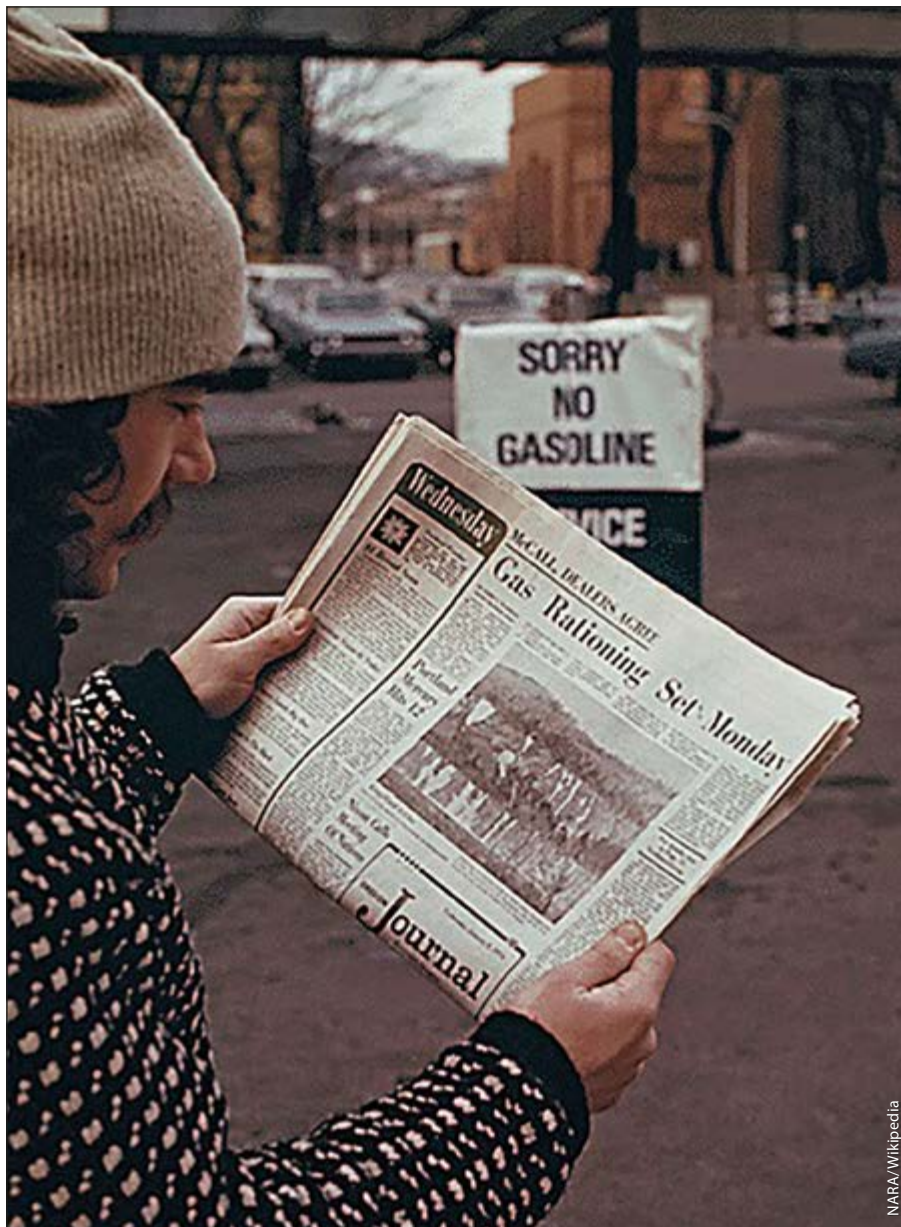
**RASOUL SORKHABI, Ph.D.**

In December 1973, thousands and thousands of cars on many US highways were stuck in traffic jams for miles and for hours. Truckers had stopped the traffic to protest at rapidly soaring gasoline (petrol) prices: in September 1973, gasoline cost 27 cents a gallon; by December it had risen to 50 cents. Gasoline queues and rationing in the industrial nations were a more visible mark of 'the first oil shock' in the world. One sign at a gasoline station in the US read: "Gas shortage! Sale limited to 10 gals of gas per customer." Another sign was even shorter: "Sorry, no gas today". People in Japan extended their fear of oil shortages to toilet paper, storming the grocery stores in panic to buy as much as possible before they ran out! The 1973–74 oil shortage and spiking gasoline prices were the result of two processes: the rise of OPEC (see 'The Road to OPEC 1960' in *GEO ExPro*, Vol. 7, No. 6) and the Arab oil embargo.

## US Countdown to 1971

The 1950s and 60s were an era of cheap and abundant oil, thanks (largely) to Middle Eastern oil. Between 1948 and 1972, world crude production rose from 8.7 MMBopd to 42 MMBopd; Middle East production rose from 1.1 MMBopd to 18.2 MMBopd. During the same period, the world's crude reserves increased from 62 to 534 Bbo; Middle East reserves increased from 28 to 367 Bbo – in other words, seven out of every 10 barrels added to the world's reserves came from the Middle East. All through these years, oil prices remained relatively stable at US \$1.8–\$2.0 a barrel, while petrochemical and automobile industries flourished at rapid rates. The low oil prices were made possible largely because international oil consortia in the Middle East increased production to catch up with increasing global demand for oil.

Interestingly, the USA, the world's



*A man reading about gasoline rationing in a service station in 1974.*

largest oil producer and consumer, had decided to rely more on its own domestic resources than on foreign oil. Considering national security measures, in 1954 the US drafted a 'Voluntary Program' to reduce its import of oil from outside the Western hemisphere. This, however, did not work. In 1959, US President Eisenhower proclaimed the

Mandatory Oil Import Quota Program, restricting US import of crude as well as refined oil to less than 9% of domestic demand (in 1962, the quota changed to 12.2% of domestic production). The independent oil companies in the USA (which all along had lobbied for it) rejoiced, while the major international companies were disappointed.

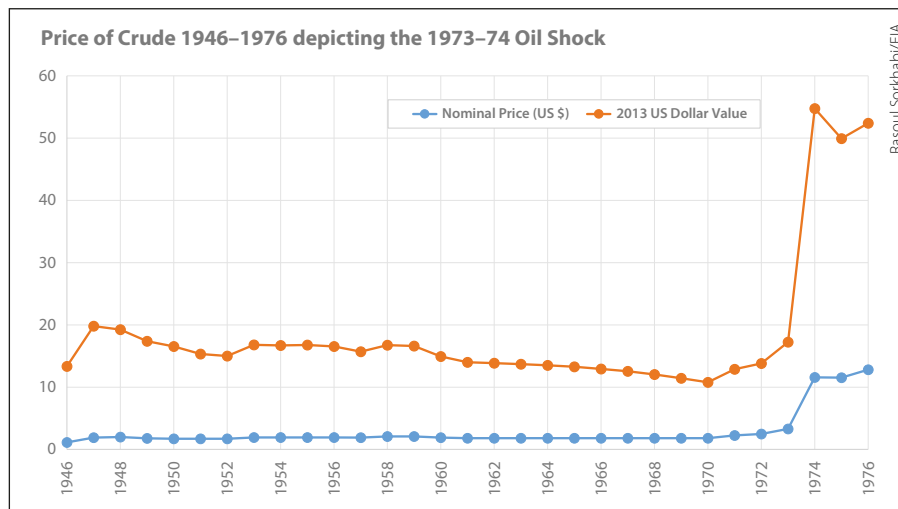
From 1948 to 1971, US oil reserves grew from 21 to 38 Bbo and its production from 5.5 to 9.5 MMBopd; however, US share of world crude production shrank from 64% to 22%. Indeed, M. King Hubbert (1903–1989), a bright oil geoscientist working for Shell, had made forecasts (dating back to 1956) that oil production in the lower 48 USA would peak in the late 1960s or in 1970. Amazingly, his forecast came true: US production of conventional crude peaked at 3.5 Bbo in 1970.

Decline in US production not only removed significant oil supply from the global oil market but was also accompanied by rapid increases in the US import of oil. In 1973, when President Nixon officially terminated the Mandatory Oil Import Program, the US imported 6.2 MMBopd, compared to 3.2 MMBopd in 1970.

### OPEC and Oil Price Surges

During the 1960s, OPEC was not taken seriously by the consortia of major American-European companies. However, changes were soon to come. In September 1969, the 27-year-old Muammar Qaddafi, leading a group of revolutionary young army officers, staged a coup d'état and overthrew King Idris of Libya, a country where 21 oil companies were operating and which supplied one-third of Europe's oil. In 1970, Qaddafi warned the oil companies in Libya that he needed a better deal. He picked his first battle with Occidental (since all its operations were in Libya) and got an increase of 30 cents a barrel (to \$2.53) and a further \$0.02 each year for the following five years. Within two months, the other oil companies agreed to similar agreements with the Libyan government, resulting in a majority (54–58%) profit share for Libya. This ushered in a series of oil price increases and renegotiations. In November 1970, the Shah of Iran won a 55:45 agreement with the consortium companies. Kuwait followed suit in the same year.

In January 1971, the oil companies wrote a letter to OPEC, seeking a comprehensive settlement of issues with oil-exporting companies – a sign of the ascending international power of OPEC. Back in December 1970 an OPEC meeting in Caracas



Price of crude in post-war years until 1976 (data from DOE/EIA). In 1973, the price quadrupled from \$3 to \$12. Note, however, that the price surges happened after more than two continuous decades of low-price oil.

had established 55% as a minimum tax rate, and in early 1971 OPEC had threatened a total oil embargo if the companies did not comply with this suggestion. Two negotiation meetings were scheduled, one in Tehran for Persian Gulf oil and another in Tripoli for Mediterranean oil.

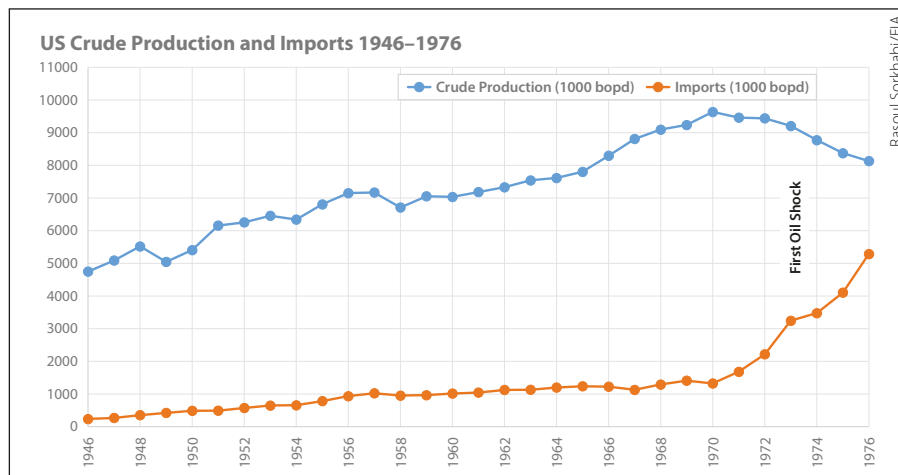
On 14 February 1971, the Tehran agreement was signed between six Middle Eastern governments and 22 oil companies for 55:45 profit sharing; it also increased the posted price of oil by about 35 cents a barrel (from \$1.80 to \$2.18 for light Saudi crude) and promised further annual increases of 5 cents a barrel and 2.5% inflation rate for the following five years. Then on 2 April 1971, the Tripoli agreement (for Libya, Algeria, Saudi Arabia and Iraq) raised the price by 90 cents a barrel (to \$3.45) in addition to

similar annual increases. The Shah of Iran was furious over leap-frogging prices.

In August 1971, the USA decided to abandon the gold exchange standard, float its currency, and expand its money supplies. This resulted in depreciation of the dollar, and because oil was traded in dollars, OPEC government revenues were reduced. In its September 1971 Beirut meeting, the organisation instructed its members to negotiate price increases with the oil companies in order to offset the decline in the value of the US dollar. This triggered a series of price rises in 1972 and 1973, further adding to the panic over oil politics.

The US government initially welcomed these price surges, mainly because the oil wealth would contribute to the economic development of OPEC nations, which would prevent them

US crude production and imports in post-war years until 1976 (data from DOE/EIA). The production data are for conventional crude from 48 states. Note the peak production in 1971. Decline in oil production was accompanied by increases in oil imports in the following years.



## History of Oil

from falling into the hands of the Soviet Union. Moreover, a considerable portion of OPEC's petrodollars would also be spent on Western technologies, weaponry, goods, services and stock investments. The executives of oil companies were also aware of the new realities and were willing to offer more profits, taxes and participation to the oil-producing countries.

### The Arab Oil Embargo

As 1973 began, excess oil supply had dried on the international market. In January 1973, the posted price of Saudi Arabian light oil was \$2.59 a barrel; by July it had increased to \$2.95 as OPEC raised the price in April and June 1973. In September 1973, the OPEC meeting in Vienna decided that Iran, Iraq, Kuwait, Qatar, Saudi Arabia and UAE (Abu Dhabi), the so-called 'Gulf Six', could negotiate as a group with the companies over prices; other OPEC members would do so individually.

On 6 October 1973, on the Jewish holiday of Yom Kippur, Egyptian and Syrian warplanes and soldiers made surprise attacks on Israeli positions, aiming to expel Israel from Egypt's Sinai Peninsula and Syria's Golan Heights, taken in 1967. Within days of the attacks, Israel mobilised its forces and not only

stopped Egyptian and Syrian advances but also began military operations within the enemy's territories.

Prior to the war, Anwar Sadat, who had succeeded Nasser as Egypt's President in 1970, had convinced King Faisal of Saudi Arabia to use 'the oil weapon' (cutting exports) against countries supporting Israel. Of course, the USA, Israel's main ally, was high on the list, especially as it was facing declining domestic oil production and increasing demand and imports. The oil-rich Arab governments were looking for a smoking gun, which they found on 14 October, when US Air Force planes carried ammunition to Israel. This was, in fact, a US response to the Soviet resupply of weapons to Syria and Egypt just days before that, but the Arab world was enraged, and the US efforts to arrange a truce between Israel and its Arab neighbours did not mean much.

On 16 October 1973, the Gulf Six unilaterally increased the price of



*Sale policy displayed on a flag in a gasoline station in Oregon during the winter of 1973–74.*

oil from \$3.01 to \$5.12 per barrel – a 70% increase. The following day, Arab oil ministers decided to use 'the oil weapon' against the states who supported Israel, including the USA, Netherlands, Portugal, Rhodesia and South Africa. The embargo involved a reduction x oil production by 5% from the September level with further 5% cuts each month until the Arabs' political objectives were met. (In reality, the scheduled additional 5% cuts per month were not made.) On 19 October, President Nixon publicly announced a \$2.2 billion military and financial aid for Israel. Within a day or two, the Arab countries completely stopped oil shipments to the US, although Iran and Iraq did not join the embargo.

On 22 October the United Nations brokered a ceasefire which went into effect on 25 October. Nevertheless, the war pushed oil prices even higher; on 22 December 1973, an OPEC meeting set the oil price at \$11.65 a barrel. The Shah of Iran, who had hosted the meeting in Tehran and had suggested the new price, was jubilant. In 1970 oil exports generated \$7.7 billion for OPEC

### International Energy Agency

The International Energy Agency (IEA) was established in November 1974 by the industrial Western governments in the wake of the 1973 oil shock and as a response to the rising power of OPEC. The initial idea was proposed by US Secretary of State Henry Kissinger in December 1973. A similar suggestion, also in December 1973, was made by Danish Prime Minister Anker Jørgensen at the summit of the European Communities in Copenhagen. In February 1974, ministers from 13 major oil-consuming countries assembled at the Washington Energy Conference to address "the need for a comprehensive action programme to deal with all facets of the world energy situation by cooperative measures", leading the way for IEA.

Headquartered in Paris, IEA, which currently has 29 member countries, functions as an energy policy advisor to member states (and non-member countries like China, India and Russia) in the framework of the Organisation for Economic Cooperation and Development (OECD). Its main concern has been energy security for the industrial economies; member countries are required to keep oil stock equivalent for at least 90 days of the previous year's net imports. IEA collects and analyses data about the international oil market, energy supplies, trade and consumption, and its annual report, World Energy Outlook, is a major reference for energy analysts around the world. Over the years, IEA has added economic development and environmental protection (in addition to energy security) to its '3Es' scope of study.

Maria van der Hoeven, former Dutch Minister of Economic Affairs, has been the IEA's Executive Director since 2011. For more information visit <http://www.iea.org>.



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# History of Oil



OPEC meeting in 1973.

governments; by 1974 this revenue had increased to \$88.8 billion; the age of the petrodollar economy (for good or bad reasons) had begun.

In March 1974, the Arab oil ministers ended the embargo against the USA and in June that year they lifted it against the remaining countries, restoring exports to September 1973 levels.

In hindsight, the Arab oil embargo did not cause a significant shortage of oil supply. According to Daniel Yergin (*The Prize*), it removed about 4.4 MMBopd from the international market, and only for five months. This amounted to 9% of the total 50.8 MMBopd in the non-communist world. However, the 'oil weapon' was something the world had not seen before; it thus created uncertainty, speculation and fear not only among industrial countries, which were nervous about being subjected to the embargo, but also among ordinary people whose consumption of oil had rapidly increased.

## Aftermath of the First Oil Shock

The early '70s oil shock happened after two decades of stable, low-price oil. It changed the world in a number of important ways. First, it gave confidence and power to many OPEC governments to take control of their oil resources either by outright nationalisation like Iraq, or by participation (phased buy-out) as in the case of Saudi Arabia.

Second, it strengthened a growing sense of environmental protection in Western nations. Earth Day was first celebrated

on 22 April 1970 across the USA. The Club of Rome's *Limits to Growth* (1972) offered a gloomy computer simulation of economic and population growth in a world of finite resources. In a similar tone British economist E. F. Schumacher published *Small is Beautiful* (1973), calling for small, appropriate, people-oriented technologies. Car manufacturers were regulated to increase the fuel (gallon per mile) efficiency of their vehicles.

Third, energy security rose to a national priority. In order to prepare for any future oil shortage, many Western countries launched emergency oil stockpiling programmes. In 1977, the US Department of Energy was established, one of whose tasks has been to maintain the strategic petroleum reserves at a total capacity of 727 MMbo, the largest of its kind in the world.

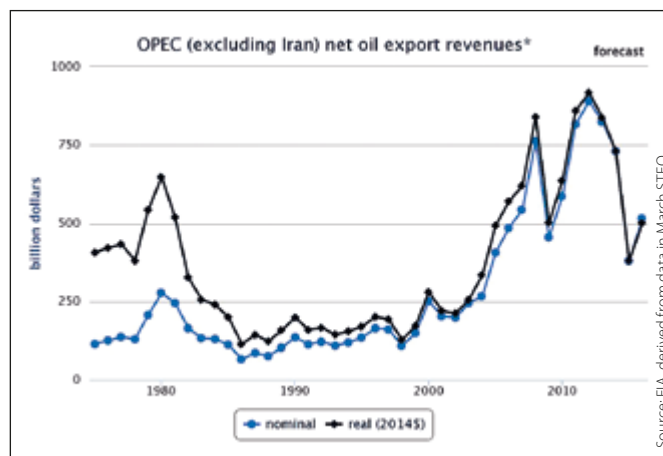
Fourth, many Western countries and international oil companies were motivated to look for alternative oil basins around the world, while higher oil prices gave financial capability for oil companies to explore and produce from relatively expensive basins around the world. Alaska's North Slope and North Sea (where oil had been discovered in 1968 and 1969, respectively) thus became new, successful frontiers for oil exploration and production.

Finally, the 1973 oil shock shifted the centre of policy-making on oil prices, production quota, and spare supply from the USA to the Middle East. It also set in motion a series of oil shocks (the second in 1979–80 and the third in 2004–05) and oil market crashes (for example, in 1985, 1999, 2008 and 2014). The story of oil booms and oil busts continues. ■

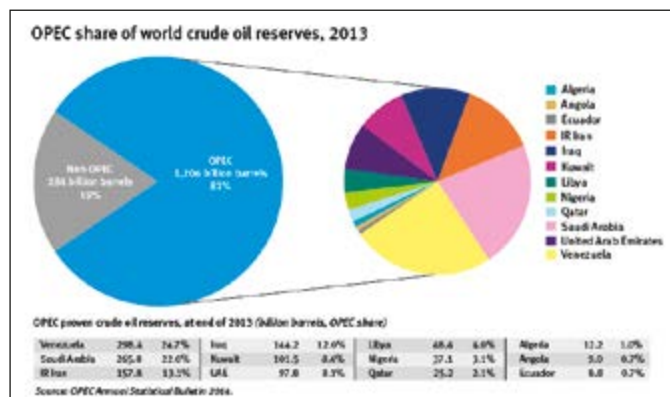
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## OPEC (excluding Iran) net oil export revenues.

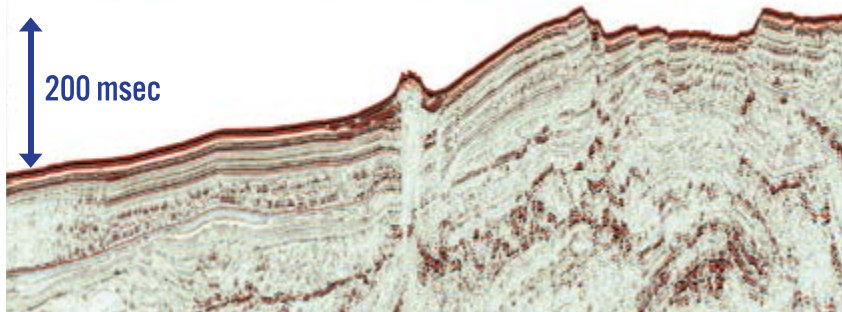
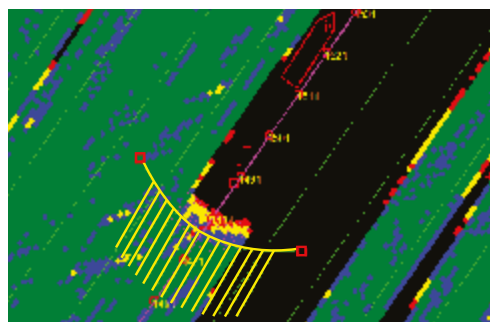


Source: EIA, derived from data in March STECO



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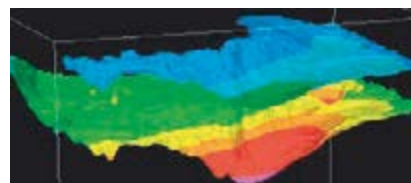
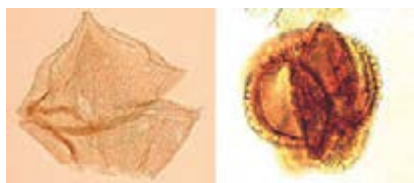


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# Ceyhan

## An Unassuming Hub

Most inhabitants of this strategically important oil export centre are unaware of the significance of their town in the world's economy.

**NIKKI JONES**

It would be hard to overstate the importance of Ceyhan in southern Turkey. At the very far end of the Mediterranean Sea, it provides a vital export terminal for both Caspian and Iraqi oil. By accessing the Mediterranean here, millions of barrels enter the world's shipping lanes daily and avoid the long and congested route via the Black Sea, Bosphorus and Dardanelles, saving both fuel and time (see *GEO ExPro*, Vol. 12 No. 1).

### Conflict with Baghdad

A network of pipelines brings oil to and from Ceyhan. By far the most important is the Baku-Tbilisi-Ceyhan (BTC) line, first opened in 2006. With a capacity of 1.2 MMbopd and a total volume capacity of 10 MM barrels, its importance to western markets can hardly be over-stated, particularly since it provides an alternative to the Russian network and, by diverting exports that could head south, has helped maintain the isolation of Iran.

Similarly, the two-pipeline Kirkuk-Ceyhan route, with a capacity of 1.65 MMbopd, also comes loaded with political significance. Prior to the signing of an agreement with the national government in December 2014, Baghdad was claiming that all Kurdistan oil exports were illegal since they did not have its approval. Throughout this period, approximately 400,000 bopd was shipped into Ceyhan by pipeline and by truck, and the Turks risked Baghdad's ire by cooperating with the Erbil government to upgrade the pipeline. The new agreement will not bring more oil to Ceyhan, but will increase the usage of the pipeline.

Ceyhan has been the focus of yet more controversy as it has been suggested that some of the estimated 80,000 bopd smuggled out of territory occupied by Islamic State of Iraq and the Levant (ISIL) may be reaching world markets via the port. The possibility exists that ISIL oil is being mixed in with other supplies at Ceyhan's storage tanks. If so, the trade will

*No evidence of the region's strategic importance: the quiet agricultural land around Ceyhan.*



*The ubiquitous Turkish shoe-shine men. Chronic under-employment is evident in Ceyhan, despite the city's oil industry links.*

be contributing to the group's estimated income of between one and five million dollars per day.

### National Hub

Ceyhan is the hub for two other pipelines that are both vital for the Turkish economy. Just a few kilometres down the coast, the port of Dortyol is linked by pipeline to Turkey's own Batman province, which produces much of the country's 300,000 bopd. In addition, the Ceyhan-Kirkkale pipeline transports some of the supplies to one of Turkey's few refineries outside of Ankara.

One more pipeline has been proposed: the Samsun-Ceyhan line which could connect the Black Sea with the Mediterranean. The current design is for a capacity of 1.5 MMopd but there appear to have been few developments over the last two years since the lead company, ENI, was blacklisted for its gas exploration in contested Cypriot waters. Ceyhan may have to wait for this addition to its hub status.

### Small and Quiet

Given the extraordinary importance of the Ceyhan area, the city itself is a surprise. Unlike Mersin and Adana to the west, Ceyhan has remained small, quiet, charmingly unpretentious – apparently forgotten by central government. It is clean but rather quaint, with its un-tarmacked streets and relative absence of cars. Street life is vibrant, more weighted towards the 1950s than the 21st century. Elderly men sell lottery tickets and bread on the roadside, smoke and chat at their traditional, gleaming shoe-shine boxes, and fill up the cafés, playing backgammon.

There is an air of under-employment, and that developing country feel of a low-wage, under-utilised workforce. This is confirmed by the locals who voice the common complaint that



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the oil and gas industry has brought few jobs and that the work available has been dangerous and poorly supervised. “They bring in their own workers, from other countries,” says one local.

Interestingly, few locals seem to have any idea – or any real interest – in where the oil is coming from or going to. When I describe their city as ‘important’, they seem surprised. Their perception is that they are the hub of an agricultural community, not a key distribution link for Middle Eastern, Caspian and potentially Russian oil.

Of course, the port facilities are not in Ceyhan itself: the city is situated a few kilometres inland. It is separated from the BOTAS terminal by an area of fertile agriculture, fed by the beautiful Ceyhan river. Travelling out to the coastal town of Yamurtalik I see women and children working in the fields. The locals tell me these are Syrian refugees who, since the war broke out just 50 km away on the other side of the border, are willing to work for half the normal Turkish wage.

“A day’s work would normally get you 40 lire,” says one shop owner, “but now the Syrians have come, and they will work for 20! A packet of cigarettes costs ten lire – so 20 is nothing!”

### Expansion Plans?

The Turkish government has said that it plans to develop Ceyhan and, on the periphery of the city, work has begun on a few bleak building sites: as yet, the forests of high-rise apartments that are common in other Turkish cities – and which look to a western eye to be a long-term social disaster – are not yet in place.

Whether Ceyhan can expand its role as an export hub is unclear. The government’s focus at the moment is on construction of the Trans-Anatolian gas pipeline (TANAP), an extension of the South Caucasus Pipeline that tracks the BTC as far as Erzurum in northern Turkey and will eventually transport Caspian gas all the way to Europe and the proposed Trans Adriatic Pipeline (TAP).

The economics of the Samsun-Ceyhan pipeline,

which was planned to bring Kazakh and Russian oil down to the Mediterranean, now seem to be in question. Nor has BTC been operating at full capacity as supplies of Kazakh oil from the Tengiz and Kashagan fields have not fulfilled expectations. BP reports that in the first nine months of 2014 only 199 MMb of crude have been transported to Ceyhan via BTC and that only in August 2014 did the pipeline consortium celebrate their two billionth barrel.



A planned new refinery at Yamurtalik (outside of Ceyhan) appears to be on hold, despite Turkey’s almost total dependence on imports of refined products. Possibly new jobs will materialise, but it seems unlikely they will come from the oil and gas sector. Ships continue to arrive empty and leave full. It seems that Ceyhan may remain, for a while, an anomaly – out of government focus, a surprisingly pleasant backwater, but a town with extraordinary, and largely unacknowledged, strategic value. ■

*It is possible that some of ISIL’s 80,000 bopd is smuggled out through Ceyhan. But the town remains quiet and unaware of the world’s focus.*



Nikki Jones



# Libya: Gas Condensate Find on Shelf

Despite the ongoing civil unrest in Libya, **Eni** is pursuing a strategy to capitalise on the significant commercial discoveries made in past years offshore, and is undertaking an important exploration programme to support the constantly growing domestic demand. This initiative has yielded early success with exploration well **B1-16/4** in 150m of water on the **Bahr Essalam South** prospect being declared a significant gas and condensate discovery. During the production test, constrained by surface facilities, the well produced 29 MMcfcpd and over 600 bpd condensate through a 1" choke from the Eocene Metlaoui Formation. The proximity to the Bahr Essalam infrastructure will allow a quick development of this new discovery, supporting plans to develop the domestic market, while maintaining Libya's position as a strategic supplier for Italy and Europe.

Libya had proved crude oil reserves of 48 Bbo as of January 2014, the largest in Africa, but the government believes the offshore has substantial undiscovered potential, a view supported by a succession of quality finds. The majority of Libya remains unexplored, and ongoing civil unrest has prevented a large-scale exploration programme. The NOC has been working with the government since March 2013 to establish a new petroleum law, which should form the basis for new E&P contracts. This will be approved when Libya has a new and permanent government. ■



The new offshore discovery is close to the Bahr Essalam infrastructure.

# Egypt: Important Nile Delta Discovery

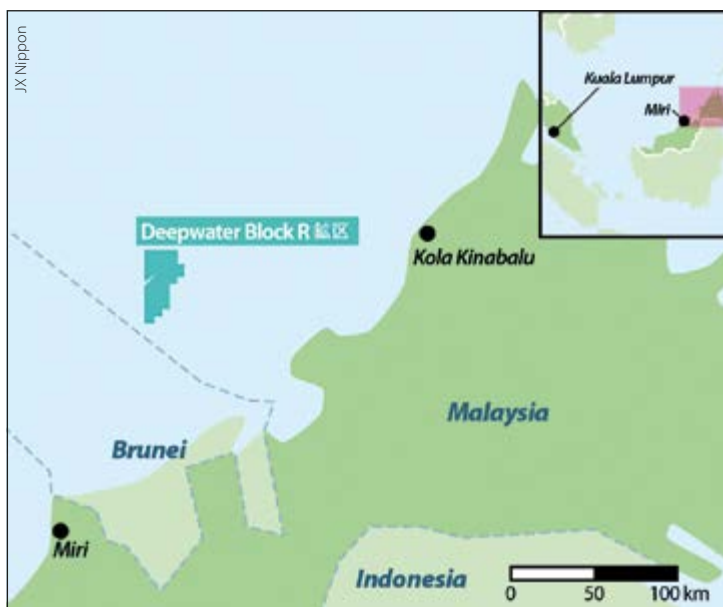
**BP** has made a second important discovery in the deepwaters of the **Nile Delta** as part of what it describes as a core exploration programme. Located in 923m of water in the **North Damietta Offshore Concession** (BP 100%), the **Atoll-1** wildcat reached 6,400m, penetrating 50m of gas pay in high quality Oligocene sandstones. Interestingly, with another 1,000m yet to drill to test the same reservoir section found to be gas-bearing in the company's 2013 Salamat discovery,

Atoll 1 is expected to be the deepest well ever drilled in Egypt. BP is now confident that the Nile Delta is a world class basin and that the estimated potential of the concession exceeds 5 Tcf, suggesting it will be the next possible major project in the country. The discovery was revealed at about the same time that BP said that final agreements had been signed for the US\$ 12 billion West Nile Delta project that will commercialise 5 Tcf gas and 55 MMb condensate. ■

# Malaysia: Significant Deepwater Find off Sabah

Much of the deepwater drilling to date has reinforced perceptions that South East Asia is gas-prone, and the fiscal terms on offer have generally failed to attract significant new investment in acreage. For **Santos** to declare its **Bestari 1** wildcat in Block R as a potentially commercial oil find in the deepwater off Sabah is therefore a significant result. The well, one of six scheduled in a US\$ 250 million campaign, encountered 67m of high quality oil in depths ranging from 1,860m to 2,702m. Santos vice president John Anderson acknowledged that there is still a lot of work to be done in determining recoverable reserves, adding "this is still a large structural closure potentially capable of supporting significant column heights." Fast track development is possible given that Bestari is close to other oil discoveries including Kikeh, which came onstream in 2007.

Other partners in Block R include JX Nippon Oil and Energy Corp, Japan's Inpex Corp, and Malaysian state oil firm Petronas. ■





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# The Buraimi Affair

ALAN HEWARD

*Buraimi: The Struggle for Power, Influence and Oil in Arabia* Michael Quentin Morton. I.B. Taurus (2013)

Buraimi and Al Ain are twin towns that today sit astride the fenced border between Oman and the United Arab Emirates. In the 19th century, Buraimi village was occupied by Wahhabis at several periods and used as a base for raiding and converting the local tribes to their form of Islam. By the mid 20th century there were nine separate oasis villages where the tribes owed allegiance, three to the Sultan of Oman (Buraimi, Hamasa and Saara) and six to the Ruler of Abu Dhabi (Al Ain, Hili, Jimi, Murtiridh, Muwaiqi and Qattarah). These villages lay on the desert caravan routes from inner Oman to the coastal ports of Sharjah, Dubai, Abu Dhabi and Sohar and were famed for trade in the needs of the day, including slaves in Hamasa. Wilfred Thesiger stayed with Sheikh Zayed in Muwaiqi on a number of occasions in the 1940s during his crossings of the Empty Quarter.

## Countries Versus Companies

A decade or so earlier, when American and British-based oil companies began exploring for oil in Arabia, there were few established borders between countries. Tribes had allegiances to sheikhs and leaders, settled tribes lived in segregated parts of villages and towns, and desert bedouin tribes had established grazing areas and water wells. Early oil concessions were often poorly defined and rulers sometimes struggled to ensure access to territories over which they had only nominal influence. Meanwhile, Bahrain field was discovered in 1932, Dammam in 1938, Dukhan in 1940 and the game-changing Ghawar in 1948. There was a belief that the prolific Arab Zone oil reservoirs of these fields might extend throughout SE Arabia. In their revised 1948 contract Aramco had commitments to explore the whole of its ill-defined concession and to relinquish 85,000 km<sup>2</sup> every three years. The Iraq Petroleum Company (IPC) was also busy trying to make headway exploring for oil in Qatar, the Trucial States (later the U.A.E), Oman and Dhofar. Early in 1948, their geologists spotted the 'beautiful' Fahud anticline in the foothills of the Al Hajar Mountains that became the focus of their exploration effort in Oman.

It is against such background that Quentin Morton weaves the story of the Buraimi dispute played out between the rulers of Saudi Arabia, Abu Dhabi and Oman; the British

and American governments with their respective declining and rising influence in the region, Britain looking after the external affairs of a number of Gulf States at that time; and the oil companies Aramco and IPC. The essence of the dispute: in response to diplomatic exchanges between Britain and Saudi Arabia over incursions by Aramco exploration parties into what was regarded as the territory of the Ruler of Abu Dhabi, Saudi Arabia laid claim to Buraimi and much of Abu Dhabi. The border with Oman was undefined, perhaps to

adopt a bedouin tactic of having captured one water-well or place, you then laid claim to the next. This was followed in August 1952 by the arrival of a 50-strong Saudi contingent in the Omani village of Hamasa, the British intervening to stop them being expelled by the combined forces of the Omani Sultan and Imam, a blockade by the Trucial Oman Scouts, a failed attempt at arbitration in Geneva and the eventual forceful removal of the Saudis and their sympathisers in October 1955.

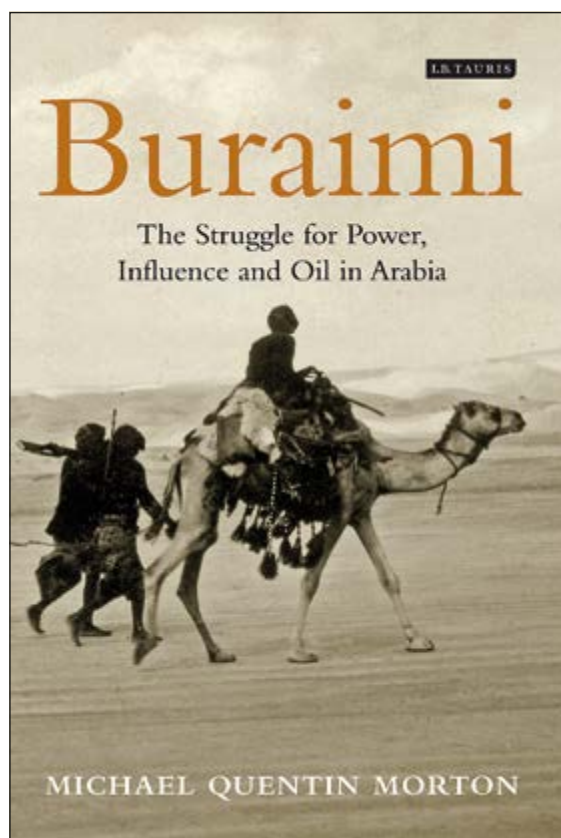
It is perhaps a blessing that the early exploration wells in the U.A.E. and Oman were dry or teasers, as major oil discoveries onshore Abu Dhabi or inner Oman in the mid 1950s would have only added fuel to the fire, as indeed the cross-border discoveries at Shaybah and Zarrara must have done in 1968. The borders were unilaterally drawn by Britain before it withdrew from the Gulf and

finally agreed by the rulers of Saudi Arabia, Qatar, Abu Dhabi and Oman, along with the ownership of the giant Shaybah field.

## A Different Outcome

There are several previous accounts that touch on the Buraimi dispute, but none I have read so extensively researched from such diverse sources. For those interested in the recent history of the U.A.E. and Oman, this book provides an intriguing background to events and consequences that, even today, continue to unfold.

As the author concludes, 'If Buraimi had fallen to the Saudis, many of the oilfields in Abu Dhabi and Oman (and most if not all of their territory) would probably belong to Saudi Arabia today.' It would be a rather different Middle East and world order. ■





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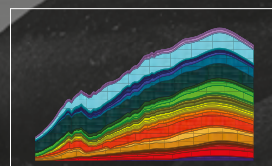
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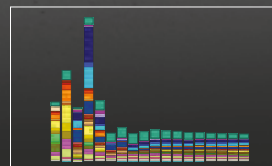
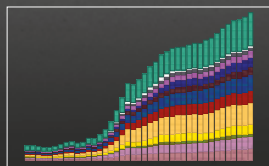
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# NORM in Shale Gas and Oil Operations

As unconventional gas and oil operations expand in Europe, understanding the nature of naturally occurring radioactive material is necessary for managing environmental effects, as Anna Kaniewska at Golder Associates explains.

## *What is NORM?*

Naturally occurring radioactive material (NORM) describes radioactive elements that are found in low concentrations in the earth's crust. Shale rocks typically contain many different kinds of radioactive isotopes, such as uranium, lead, or potassium. NORM also exists in air, water, soil and rock. Even food like bananas, Brazil nuts and carrots can contain them.

In certain types of geology, such as organic-rich shales, higher levels of NORM occur, with elements like uranium often bonding to organic material and elements like potassium and thorium bonding to clays. From our work in Europe, we know that NORM-rich geology is typical in many European shale plays.

NORM can be brought to the surface by many types of human activity and the risks are already well understood and managed across the different extractive industries. Operators must ensure workers are protected against inhalation, ingestion and prolonged external exposure to NORM-rich waste. For conventional oil and gas operations, there are well-established guidelines for dealing with NORM; and shale operators follow these industry standards.

## *Why is NORM relevant for shale operations?*

Generally, NORM found in shale operations is below the common safety limits of radioactive exposure. The waste produced in shale gas operations will usually contain low levels of NORM and operators can protect nature and people against unwanted exposure by following regulatory guidelines and best practices established by international organisations such as the IEA and OGP.

Flowback water from hydraulic fracturing can contain significantly high levels of NORM, so shale gas developers have to ensure that NORM is managed appropriately, especially within their water management plan. Our experience shows that water management in a shale gas project can best be understood as a lifecycle or supply chain, with different kinds of risks at different stages; the weakest link represents the greatest risk. A comprehensive water management plan including thorough wastewater monitoring will be able to account for these risks, and will help operators identify feasible and cost-effective solutions.

## *What preventive measures can operators take?*

NORM is not unique to shale gas extraction – its management has been used in mining operations for decades. An essential starting point for any oil and gas operation, including shale gas and oil exploration, is a comprehensive environmental impact assessment, which is also essential for securing operating permits, including a social licence from local communities.

The environmental impact assessment, along with supporting baseline studies and geological investigations,

can then be used to identify which specific preventive measures can be used to mitigate the potential impact on the environment, for example through NORM, and to ensure the highest levels of workers' health and safety.

## *How should operators manage NORM risks?*

Once an operation is underway, the risks from NORM should already be very small due to strong preventive measures put in place at earlier stages. As a project unfolds, however, operators should still use technologies to ensure the NORM risk is continually monitored, managed and kept at a minimal level. These include settlement tanks and water treatment facilities, which form part of any drilling and production operation. At the project planning stage, appropriate disposal and treatment routes will need to be identified. The legislative controls vary across jurisdictions but all are aimed at not exceeding the common background levels of radioactivity in the environment.

In Europe, shale operators can learn from mining about handling NORM, as companies with experience of handling coal residues and coal mine water discharge have transferable knowledge, particularly related to worker safety, decontamination of equipment and project closures.

## *How should shale operators handle waste and wastewater with NORM?*

In shale gas operations, flowback water can be recycled for ongoing use in hydraulic fracturing operations, but it will eventually have to be disposed of following treatment. Additionally, leftover waste from the water treatment procedures and condensate from oil and gas separators must also be transported away on a regular basis. An adequate water management plan, including transport and disposal of wastewater, is one of the essential environmental protection measures that operators should take. Even without high levels of NORM presence, it is crucial to get this right.

## *What other advice can you give shale developers?*

If operators follow best practice, the environmental risks involved are manageable. While NORM is an issue, it is one that the industry is very familiar with.

By properly managing flowback water, condensates and other wastes, companies can mitigate the risks to their staff and the environment. ■

*Anna Kaniewska, senior environmental specialist at Golder Associates, has extensive experience from unconventional and conventional oil/gas operations in Europe, Asia and the Middle East.*



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# The Weald Basin: Hot Spot or Hot Air?

There was great excitement in the newsrooms of the UK in mid-April when a small oil and gas company announced that more than 100 Bbo were lying beneath the Weald, south of London in south-east England – over 158 MMbo per square mile. Executives at the company, UK Oil & Gas Investments (UKOG), described this as ‘a possible world-class potential resource’, and suggested that it could create ‘many thousands of jobs’.

## Hybrid Play

Most of the assets of UKOG are focused on the Weald area, including the block which contains the Horse Hill-1 well, drilled late last year, the results of which had previously been announced as a rather more modest 8.2 MMb oil in place in the Late Jurassic Upper Portland Sandstone. However, further analysis of the well, which is the first one to be drilled on the licence since the 1960s and went to a much greater depth than tried previously, suggests there may be potential in older Jurassic horizons. Research on the well, undertaken in part by Nutech, a leading petrophysical analysis and reservoir intelligence company, concluded that it discovered 200m aggregate net pay section, primarily within three argillaceous limestones and interbedded mudstones of the Upper Jurassic Kimmeridge, and in the mudstones of the Lower Jurassic Oxford and Lias sections. Additional geochemical and petrophysical analyses are ongoing.

The excitement in the media was brought about because UKOG, which has a 20.358% interest in the licence, extrapolated these findings across much of south-east England, suggesting that the “Horse Hill Upper Jurassic rock sequence is analogous to known oil productive hybrid reservoir sections of the Bakken of the US Williston Basin, the Wolfcamp, Bone Springs, Clearfork, Spraberry, and Dean Formations in the US Permian Basin and the Bazhenov

Formation of West Siberia. The US analogues have estimated recovery factors of between 3% and 15% of oil in place”. The company believes that the pay thickness plus the naturally fractured limestone make Horse Hill a new ‘hybrid’ play, which could be exploited using conventional horizontal drilling and completion techniques and without the use of hydraulic fracturing. This last point is highly important in an area which has already seen major demonstrations against the possibility of fracking at a drill site at Balcombe, about 50 km to the south.

## Further Testing Needed

This positive analysis of potential in-place reserves is not, however, in accord with the British Geological Survey, who in May 2014 produced a report in which they estimated the range of shale oil in place across the Weald to be between 2.20 and 8.57 Bbo, with a central estimate of 4.4 Bbo. Meanwhile Magellan Oil, which has a 35% interest in the Horse Hill acreage, was quick to point out that, while encouraged by the technical analysis, further testing and drilling would be needed before they could form an opinion of the prospect’s economics.

A number of analysts queried the

Billions of barrels have been reported to lie under South East England, but how much of it is recoverable?

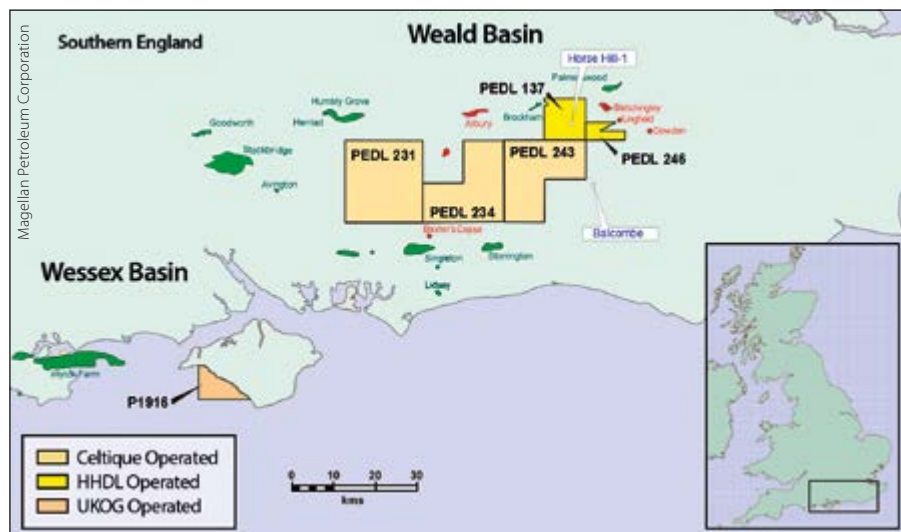
JANE WHALEY

high estimates, pointing out that there is an implied assumption of limited compartmentalisation, impossible to ascertain from the single well, and that the homogeneity which makes rocks like the Bakken so productive was unlikely to be replicated in the Wealden rocks. Many do not believe that the high level of natural fracturing reportedly seen in the limestone at the wellsite would necessarily be found throughout the area, meaning that the exploitation of any resources without fracking would be difficult.

## Environmental Issues

Geological issues aside, the Weald Basin, much of which lies within the wider London commuter belt, is relatively densely populated and contains some of the most expensive real estate in the country. It also includes large areas of protected land, national forests and parks and designated areas of outstanding natural beauty. Opposition to development of this resource will be very strong, costly to surmount and the regulations to ensure protection of the environment are vigorous. The people of Great Britain are unlikely to be relying on this resource to heat their homes and power their cars for some time to come. ■

*The Weald has had a long history of conventional oil and gas exploration with 13 currently producing fields in the basin.*



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# A Gloomy Future?

## Will the crude oil price break through in 20 years' time? Or will tight oil and renewable energy work in parallel to keep the price low?

At the time of writing, the price of a barrel of oil is around US\$ 60. One year ago the price was more than US\$ 100 per barrel, which it had been for roughly three years. The all-time high of US\$ 145.31 per barrel was reached in July 2008, almost seven years ago.

A glance at the graph below makes you wonder what the future will look like.

Pessimists should take into consideration a steady increase in the production of unconventional oil, and that the US average production for 2015 is estimated at 9.65 MMBopd, which could be an all-time high after its yearly average peak in 1970 of 9.64 MMBopd. This year's production will therefore be almost 6 MMBopd higher than the all-time low in 2008. It is interesting to learn that in 2014, tight oil production drove US oil output higher by 1.5 MMBopd – the largest single year rise in US history.

The shale oil revolution has certainly made an impact. The thought-provoking question is whether production from oily source rocks could also happen on a large scale in other countries. The first test on the Norwegian continental shelf will occur this year in the Upper Jurassic shale.

Optimists must take a close look at the global energy demand. "Despite the dramatic recent weakening in global energy markets, ongoing economic expansion in Asia – particularly in China and India – will drive continued growth in the world's demand for energy over the next 20 years," says BP in its Energy Outlook to 2035. "Global demand for energy is expected to rise by 37% from 2013 to 2035, or by an average of 1.4% a year", the report adds. Demand for oil will rise 0.8% each year, equivalent to 110 MMBopd in 2035, with China, India and "other Asia" making up for the majority of the increase. This BP prediction also includes a significant decrease in demand in the OPEC countries.

In the 30-year period from 2005 to 2035, tight oil supply growth will contribute roughly 8 MMBopd, the majority coming from the US. Renewables, if you are wondering about them, will constitute far less than 10% of the energy demand in 2035. However, the development in such energy is galloping forward, and I am curious to know if the BP forecast is too pessimistic.

My conclusion (without having in-depth knowledge, which actually few people have when it comes to the future) is simple: in the near future (whenever that is) the price will stay low, while in the distant future, the price of oil will increase as demand will outpace supply. My prediction for 2035: US\$ 155 per barrel. What is yours?

**Halfdan Carstens**

Crude oil price (Brent) since 2000. Do we see US\$ 155/barrel in 2035?



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## Conversion Factors

### Crude oil

1 m<sup>3</sup> = 6.29 barrels

1 barrel = 0.159 m<sup>3</sup>

1 tonne = 7.49 barrels

### Natural gas

1 m<sup>3</sup> = 35.3 ft<sup>3</sup>

1 ft<sup>3</sup> = 0.028 m<sup>3</sup>

### Energy

1000 m<sup>3</sup> gas = 1 m<sup>3</sup> o.e

1 tonne NGL = 1.9 m<sup>3</sup> o.e.

### Numbers

Million = 1 x 10<sup>6</sup>

Billion = 1 x 10<sup>9</sup>

Trillion = 1 x 10<sup>12</sup>

### Supergiant field

Recoverable reserves > 5 billion barrels (800 million Sm<sup>3</sup>) of oil equivalents

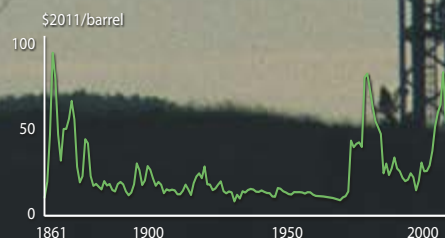
### Giant field

Recoverable reserves > 500 million barrels (80 million Sm<sup>3</sup>) of oil equivalents

### Major field

Recoverable reserves > 100 million barrels (16 million Sm<sup>3</sup>) of oil equivalents

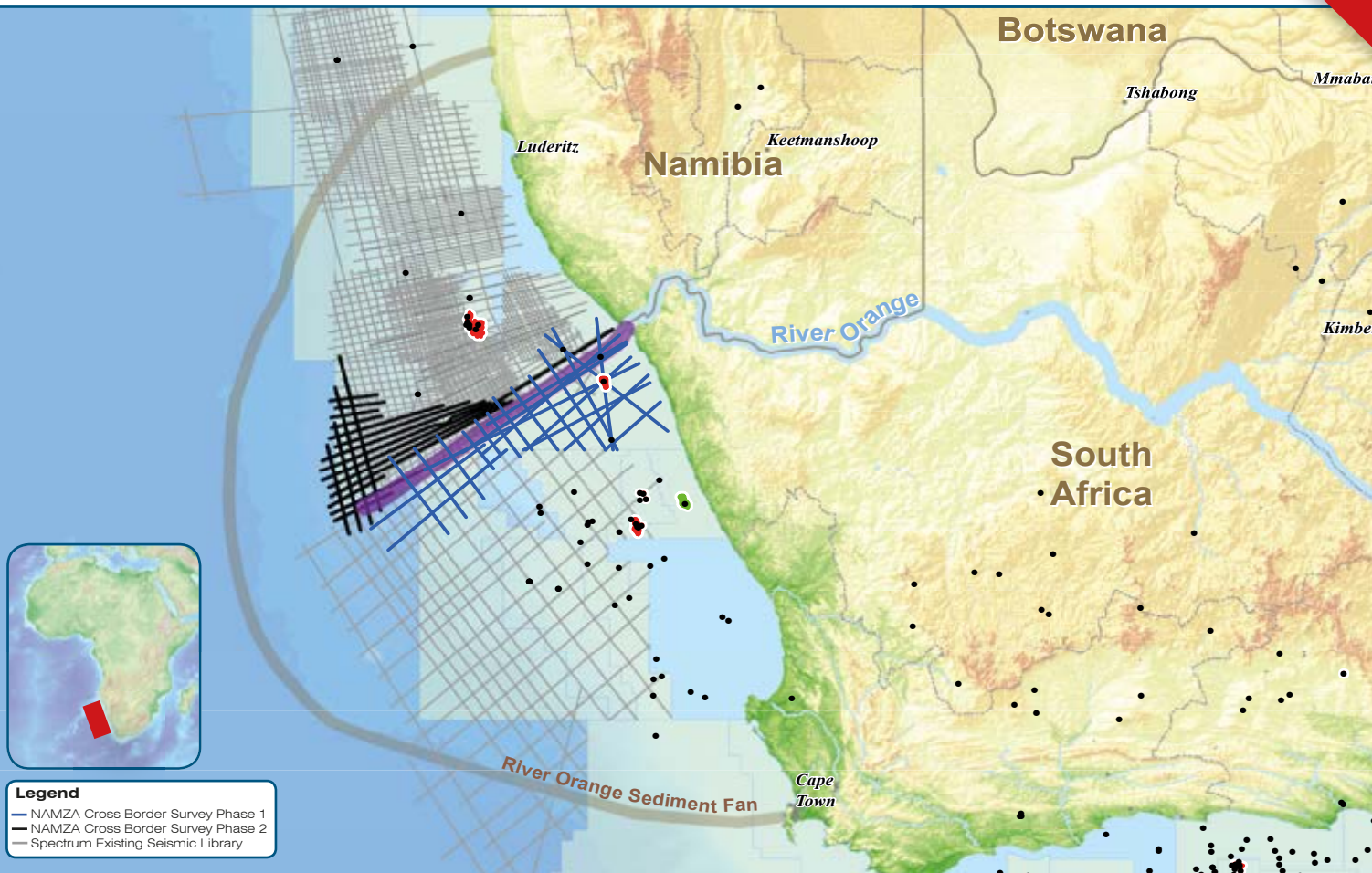
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