VOL. 9, NO. 5 – 2012

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

GEOTOURISM: Cycling the Norwegian Strandflat

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TECHNOLOGY EXPLAINED

Remote Sensing Underground

COUNTRY PROFILE

Montenegro

GEOPHYSICS

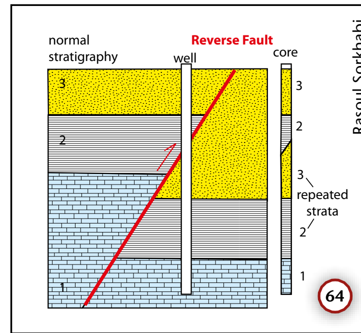
Reading Between the Lines

GEOLOGY GEOPHYSICS RESERVOIR MANAGEMENT

GEO ExPro
GEOSCIENCE & TECHNOLOGY EXPLAINED

CONTENTS Vol. 9 No. 5

This edition of GEO ExPro Magazine focuses on North West Europe, the Arctic and Geophysics

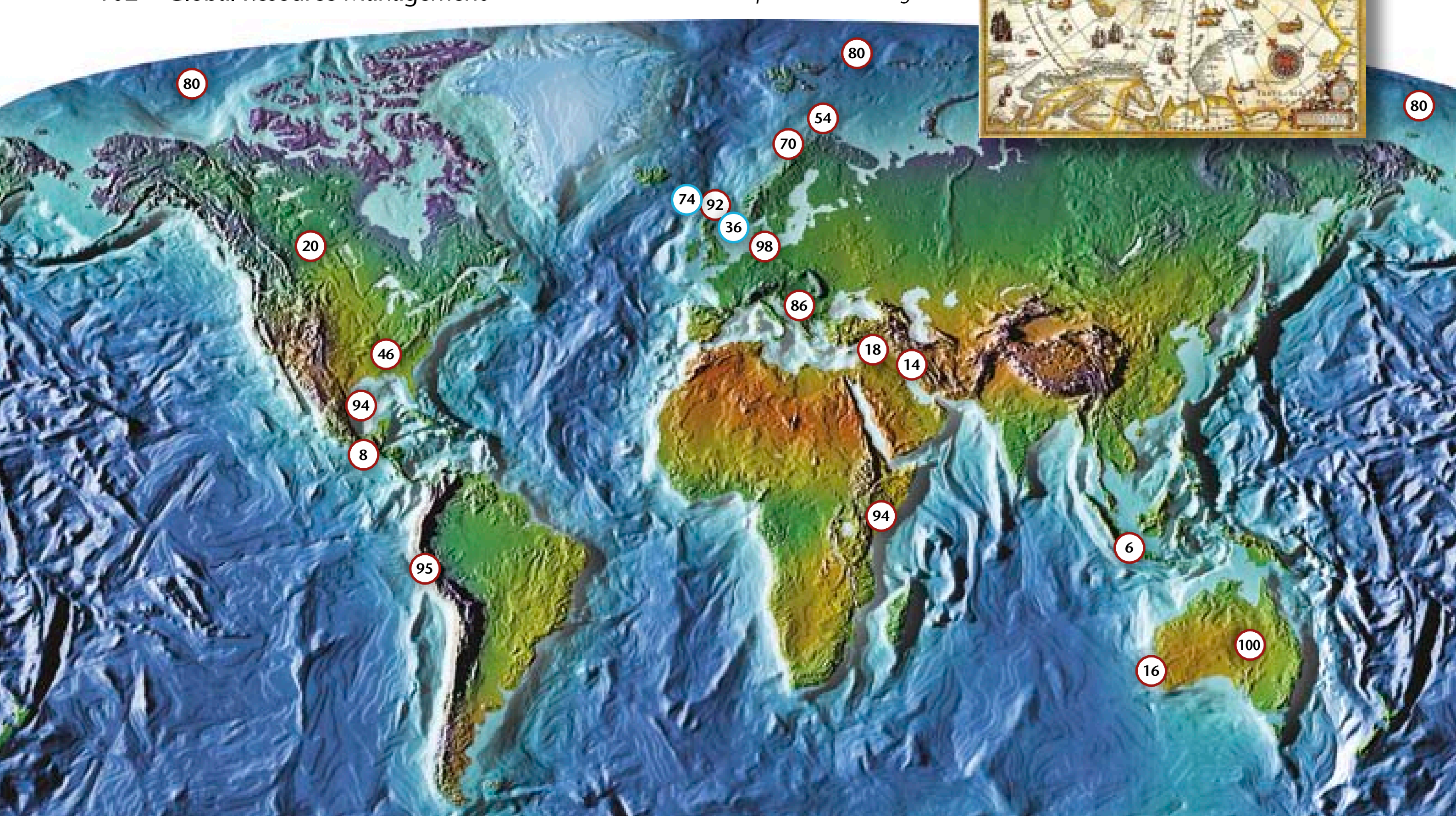


A proper understanding of faults is key to hydrocarbon geology

COLUMNS

FEATURES

Willem Barent's 1599 map of the Arctic. New Circum-Arctic digital maps reveal fresh information about the hydrocarbon potential of the region



Applauding Progress

I am old enough to remember the days of paper black and white seismic records. Head on one side, squinting along the line, trying to identify a possible real horizon among the mass of multiples and noise. And in those days we used colour pencils to delineate our carefully chosen layer – no computers capable of automatically picking a horizon available then! Brings back memories to a number of *GEO ExPro* readers, I suspect.

One of the first quartz seismographs, prototype PQ1, developed in 1931, one of the early advances made by seismic service companies to assist geologists in the search for hydrocarbons

So I am constantly amazed and excited by the quality and clarity of the multi-coloured seismic information which is available to geoscientists today, several excellent examples of which can be found within the pages of this magazine. The manifold improvements in both the acquisition and processing techniques are outstanding. Great credit must be given to the many people from both academic and organisational backgrounds who have spent many man-years – and millions of dollars – in continuing to develop these systems. It has often required new and innovative ideas, but also a lot of persistence and basic hard slog.

An example of one of these innovations, WesternGeco's Isometrix system, is discussed in this edition, and the company admit that it took over ten years of dedicated research and experimentation to develop this idea and prove its viability and commerciality. Also featured are new ways of looking at 3D seismic by borrowing ideas about frequency from remote sensing experts, and a discussion on the use of seismic recording systems deep within the well to acquire high resolution data. All excellent examples of the transference of many years of research into useful tools in the search for hydrocarbons. Few observers outside the industry have an appreciation of the amount of science and engineering research which is undertaken by the service companies in order for the industry to find the oil and gas reserves which the world continues to demand so hungrily.

We should all applaud their efforts and hope that they long persist in developing their thirst for knowledge and improvement.

JANE WHALEY
Editor in Chief

REMOTE SENSING UNDERGROUND

Landsat image of the Betsiboka River, Madagascar using bands 3, 2, and 1 to highlight the complex delta features. A team of geoscientists at Nexen Inc. in Calgary, Canada, is using this non-traditional, 'remote sensing' approach to seismic interpretation to reveal spatial detail in geologic heterogeneity that is beyond classic seismic resolution.

Inset: The island of Lovund, one of the many delights to be seen when cycling the north Norwegian strandflat.

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Preparing for the Global Economy

When she was President of AAPG in 2000–2001, Robbie Gries, on a speaking tour in Indonesia, met with eager AAPG student chapter members from Trisakti University and six other Indonesian universities who had travelled far to hear her lecture and also to help with the AAPG International conference in Bali. Gries states, "I had been to universities in Africa, Eastern Europe and Latin America whose libraries were the size of a WC and publications had to be locked away from students and professors alike, as they were so precious." Recognising that these students shared a worldwide demand for access to high-quality geoscience research, Gries, partnered with Dr. Sharon Mosher, then President of the Geological Society of America (and currently the Dean of the Jackson School of Geoscience at the University of Texas in Austin), decided to try to develop a means for serving this need. Soon GeoScienceWorld was born – a non-profit digital archive of peer-reviewed geoscience journals interoperable with GeoRef. Once the organisation was established, Gries, who is President of Denver-based Priority Oil and Gas LLC, sponsored a subscription for Trisakti University, which has continued. The donation made through GeoScienceWorld has helped educate Indonesia's emerging workforce by increasing the breadth of the university's library holdings and making peer-reviewed research more accessible and easier to use for Trisakti's 30,000 students.

"GeoScienceWorld has been very useful for students and lecturers," according to Muhammad Burhannudin, a lecturer at the University of Engineering Geology FTKE Trisakti. With no way for many universities throughout the world to have the ability to provide and continually fund a comprehensive geoscience library, "Trisakti University's access to the digital library through GeoScienceWorld has been a godsend the past three years," says Gries. "However, there are at least six other universities in Indonesia alone that still await funding for their own subscriptions."

Inspired

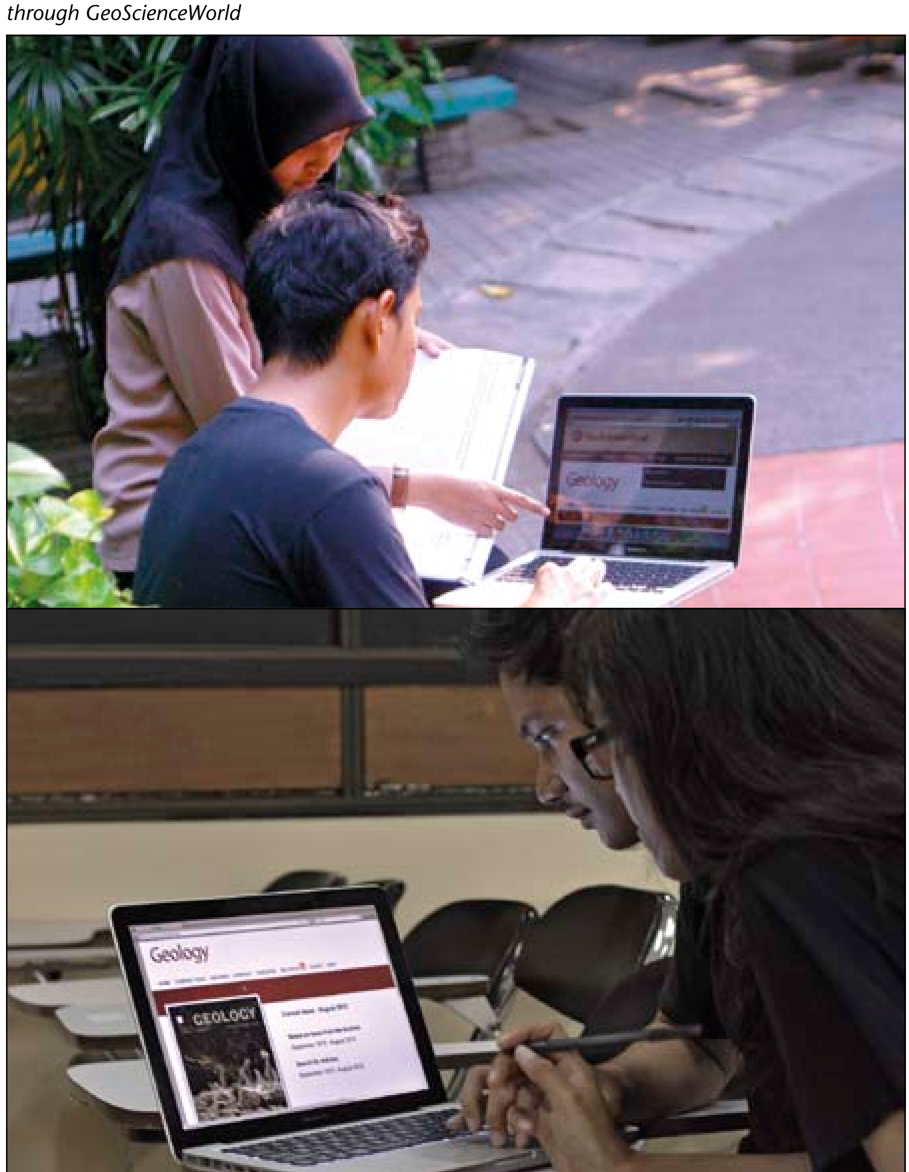
As the Secretary for GeoScienceWorld's Board of Directors, Gries continues to help shape and expand the mission and vision of the non-profit to be a comprehensive, widely-accessible, easy to use, integrated, and cost-effective online resource for research materials in the geological and earth sciences. While GeoScienceWorld now has a presence in more than 430 libraries in 41 countries across the globe, there are hundreds of academic institutions in developing nations hungry for access to this type of information for research and basic geoscience studies. Corporate sponsors like Gries are one way these schools can prepare the next generation of geoscientists to compete in a global economy. Says Gries, "I am inspired by every story available about people making it out of poverty and developing a successful career, and if this helps just one student achieve that, it has been all worthwhile."

Students at Trisakti and institutions worldwide are pleased with the recent mobile optimisation of GeoScienceWorld's 41 journals. With such a high percentage of mobile usage in developing countries like Indonesia, this is another way for students and researchers to gather necessary data from all points on the globe more easily.

For more information about GeoScienceWorld sponsorships and institutional partnering options, please contact gswinfo@geoscienceworld.org.

LAUREN MARLEY

Geoscience students at Trisakti University now have access to a wide range of geoscience publications through GeoScienceWorld



Central American Opportunity

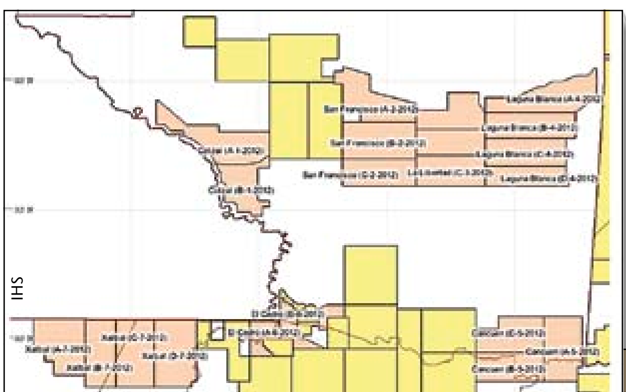
Guatemala due to open 2012 Bid Round

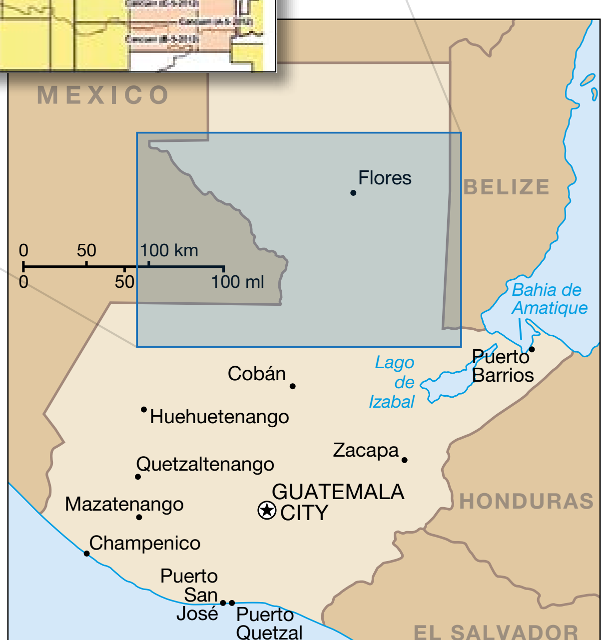
According to Energy and Mining Minister Erick Archila, Guatemala will be opening seven blocks covering nearly 8,000 km^2 in the onshore Petén Basin to international bidders and has already made several investor briefings. Guatemala's 2012 Bid Round comprises 22 blocks in seven onshore areas with a total of 7,958 km^2. The blocks are Cotzal 1-2012 (2 blocks, 809 km^2), San Francisco 2-2012 (3 blocks, 1,270 km^2), La Libertad 3-2012 (3 blocks, 1,053 km^2), Laguna Blanca 4-2012 (4 blocks, 1,589 km^2), Cancuén 5-2012 (3 blocks, 1,173 km^2), El Cedro 6-2012 (3 blocks, 347 km^2) and Xalbal (4 blocks, 1,717 km^2). No blocks will be offered in the Amatique Basin on the Gulf of Honduras, or the Pacific Basin at this time although the minister indicated the potentially gas-prone Pacific region could be ready for bids in 2014. The winning bidders are expected to be announced early in 2013.

Oil production in Guatemala, Central America's biggest crude producer, has fallen to 10,000 bopd from 30,000 bopd over the last 30 years, according to Archila, but he intends to increase production to 80,000 bopd by 2022, he said in a July interview. He had earlier advised that 'optimal conditions for investors' would be offered and 'transparency and clarity' in the bidding process would ensure successful long-term production for Guatemala.

The Petén Basin covers an area of over 59,500 km^2 and is underexplored. A relatively late structural high known as the La Libertad Arch divides the basin into northern and southern sub-basins. In the South Petén Basin more than 10,000m of sediment has accumulated since Permian times. Little is known about the Permian and Jurassic sediments because so few wells have penetrated them and the main oil reservoirs lie within the Cretaceous sediments. In the Petén Basin these Cretaceous rocks are called the Coban Formation, which is further divided into Coban A, B, C and D members. They consist of interbedded limestone, dolomites and anhydrites and most of the oil reservoirs discovered to date have been in fractured dolomites in the Coban B, C and D members. Significant production also occurs from these reservoirs in the Chiapas area of southern Mexico. The source rocks for oil have not been definitively identified but they are thought to include carbonates of the Coban A. Good quality Jurassic-age marine sediments may also generate oil in the Petén Basin. To date the country hosts around 160 drilled wells of which only 58 produced oil. The majority of the oil produced in Guatemala is heavy, with 16°API and 6% sulphur. ■

KEN WHITE





ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids
barrel = bbl = 159 litre

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

Gas

MMscfg:	million ft^3 gas
MMscmg:	million m^3 gas
Tcfg:	trillion cubic feet of gas

Ma: Million years ago

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

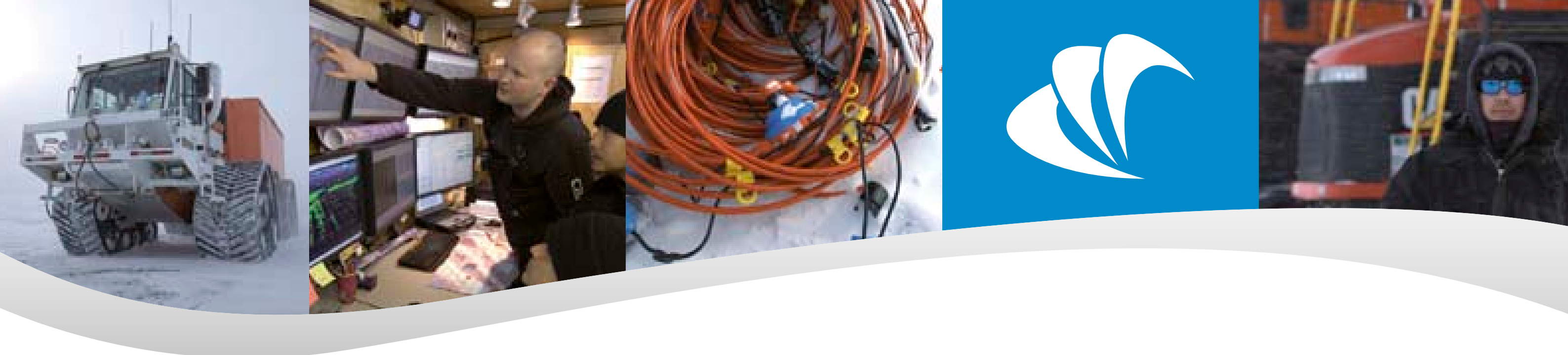
NGL
Natural gas liquids (NGL) include propane, butane, pentane, hexane and heptane, but not methane and ethane.

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

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

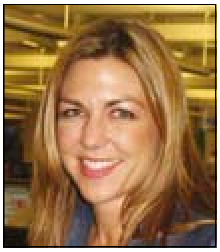
P3 reserves:
Quantity of hydrocarbons believed recoverable with a 10% probability

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



Oil Prices Stay High

– but spare capacity buffer should build

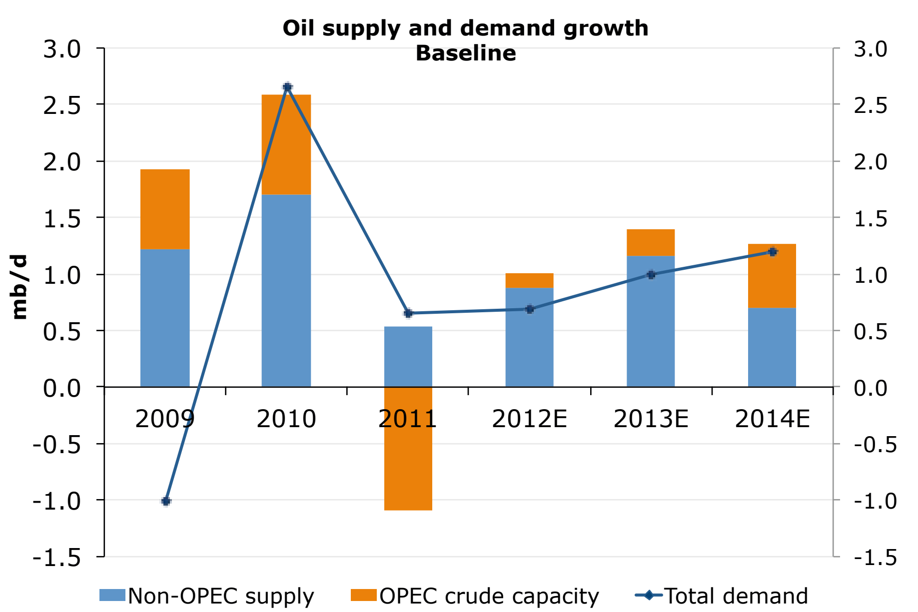


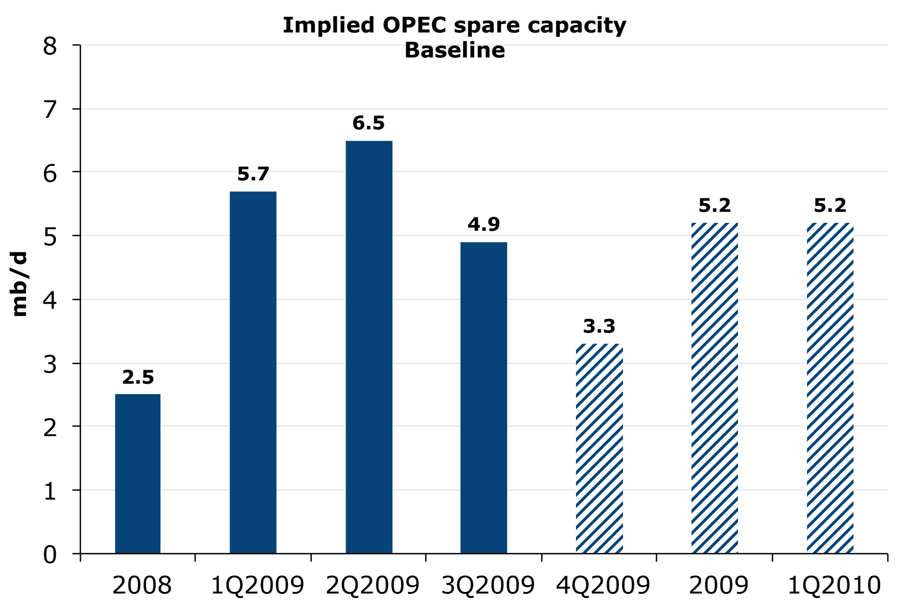
THINA MARGARETHE SALTVELT, PH.D

Oil prices are expected to remain high over the next two years as the market will remain tight by historical standards. Supply additions are expected to outpace demand growth, resulting in slightly softer oil balances in 2013. The market will remain similarly tight in 2014 as supply growth slows and demand accelerates with the global economy. Oil prices will likely remain volatile around high levels given the market tightness and risks to supply.

Income growth, economic activity and population growth are vital drivers of oil demand. Global oil demand is expected to increase at a higher pace in 2013–14 than in the previous two years as economic growth picks up, but OECD demand will continue to decline owing to efficiency gains, fuel switching and subdued economic growth. Non-OECD countries contribute to all oil demand growth, which averages 1.1 MMbpd over 2013–14. Structurally higher economic growth, rising income and population growth in emerging economies is expected to outweigh efficiency gains in oil use and a switch to other energy sources. Demand for transportation is expected to remain the primary driver of global oil use, accounting for around 52% of total oil demand.

Global oil supply is expected to grow in the forecast period mainly driven by a healthy expansion of oil production capacity in North America, Iraq, Brazil and by an increase in OPEC Natural Gas Liquids (NGLs). Non-OPEC is expected to account for the lion's share of new capacity brought online. We expect the past few years' impressive growth in US shale oil, tight oil and Canadian oil sands production to continue, although infrastructure and environmental issues may restrain future advances. In Brazil local content requirements and cost inflations could continue to challenge the country's expansion plans. We only foresee a slight resumption of the oil production in Libya, Yemen and Sudan/South Sudan in the forecast period after political unrest has cut oil production in total by around 1 MMbpd. OPEC capacity is expected to increase in the forecast period. Capacity expansions in Iraq, Angola, United Arab Emirates and the return of Libyan oil are expected to outmatch the natural production / sanctions-related declines in Iran and smaller declines in Nigeria and Venezuela. How long Iran can stand the EU/US imposed sanctions is uncertain; we expect production to gradually resume in late 2013, but the political situation could take a twist for the better or worse before or after this time. Political unrest and unplanned production outages are expected to leave global oil supply at risk. ■





Nordea

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Industry Standard Helps Decision Making

The energy industry is steadily adopting drilling data exchange standards

Standards have been around for many years, and are steadily being adopted. In the oil industry almost all the major operators and many independents and national oil companies have at some level adopted **Wellsite Information Transfer Standard Markup Language**, or **WITSML**, the standard for transmitting technical data between organisations. WITSML allows energy companies to leverage their investment in highly instrumented fields and enables new capabilities for automation and optimisation that would otherwise be impossible or difficult to achieve. It also reduces the cost of information exchange between software applications within an operating company and between operating companies, joint ventures, partners, contractors, and regulatory authorities. In addition, there is a reduction in the cost of replacing or substituting software, which results in improved functionality.

While many understand the importance of WITSML, sometimes it is used without the knowledge of many on the rig because it is embedded in most of the widely implemented software drilling packages. There are probably many people in the field who could benefit from WITSML, but may not even know their company is using it. In a lot of ways, WITSML is transparent to the user and operates inside applications, which means it is not necessarily visible to the user. One of the things that Energistics is working on is to increase awareness of how WITSML can be utilised to bring better quality information to actual real-time business decision-making.

Statoil and Saudi Aramco are the leaders in WITSML adoption. Both companies have a deep understanding of the benefits provided by utilising WITSML and have master service agreements that stipulate that service providers must use WITSML products for any drilling services. Both companies have insisted that, company-wide, all drilling data be delivered in WITSML, which allows them to run their real-time operations centres more efficiently and to archive data without additional configuration regardless of the vendor providing the services. Using the WITSML data exchange standards makes drilling decisions more efficient and allows information from multiple sources to be received in the same structure.

Not Just 'Nice to Have'

The perception that standards are a 'nice to have' instead of 'need to have' is changing. With the advent of highly instrumented fields and the demand for quality real-time data, both operators and vendors are recognising the need for open industry standards. Working around poor data quality can be devastating to productivity and operational efficiencies. And it adds cost to reconfigure data between vendor packages. In an industry where the volume of data is so massive, it is critical to have standards in order to make decisions based on accurate, consistent data. The use of WITSML, for example, solves incompatible data issues and eliminates the need for translating data into other formats, thereby increasing efficiencies and reducing the potential for human error.

With so many joint venture operations we are seeing increased adoption of the standard in the industry, particularly between the majors and the NOCs, and the ever-increasing need for higher productivity has led to widespread adoption of WITSML and other open industry standards. Additionally, more companies are specifying WITSML in their contract documents and in tenders, which will, in turn, encourage vendors to develop new products that are WITSML compliant. ■

JERRY HUBBARD,
President and CEO, Energistics

***Energistics** is a not-for-profit global consortium that facilitates the development, management and adoption of data exchange standards for the upstream oil and gas industry.*


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Conference on Prolific Zagros Area

London to host conference on hydrocarbon exploration in the Zagros Mountains of Iraqi Kurdistan and Iran

The Zagros Mountains stretch for 1,500 km from south-east Iran through Iraq and into southern Turkey. They have long been known as a prolific oil- and gas-bearing region. The first exploration well in the Middle East was drilled in 1901, in what is now Iraqi Kurdistan; and records of the local exploitation of oil seeps go back to ancient times.

However, it is only the past decade that has seen the start of modern exploration in Iraqi Kurdistan. Since 2005 a large amount of geological and geophysical data has been collected and studied, greatly increasing our geological knowledge, and according to Wood Mackenzie an estimated 8 Bboe recoverable oil and gas have been discovered in the region in the last seven years. Kurdistan is an autonomous Iraqi region providing a stable business environment, and it is therefore becoming an increasingly attractive investment destination for the international oil industry.

This conference will provide a forum where experience from the mature petroleum province of the Iranian Zagros and knowledge from the exciting early days of Kurdish exploration can be combined with new understanding to address the future challenges of exploration in this fascinating and challenging region.

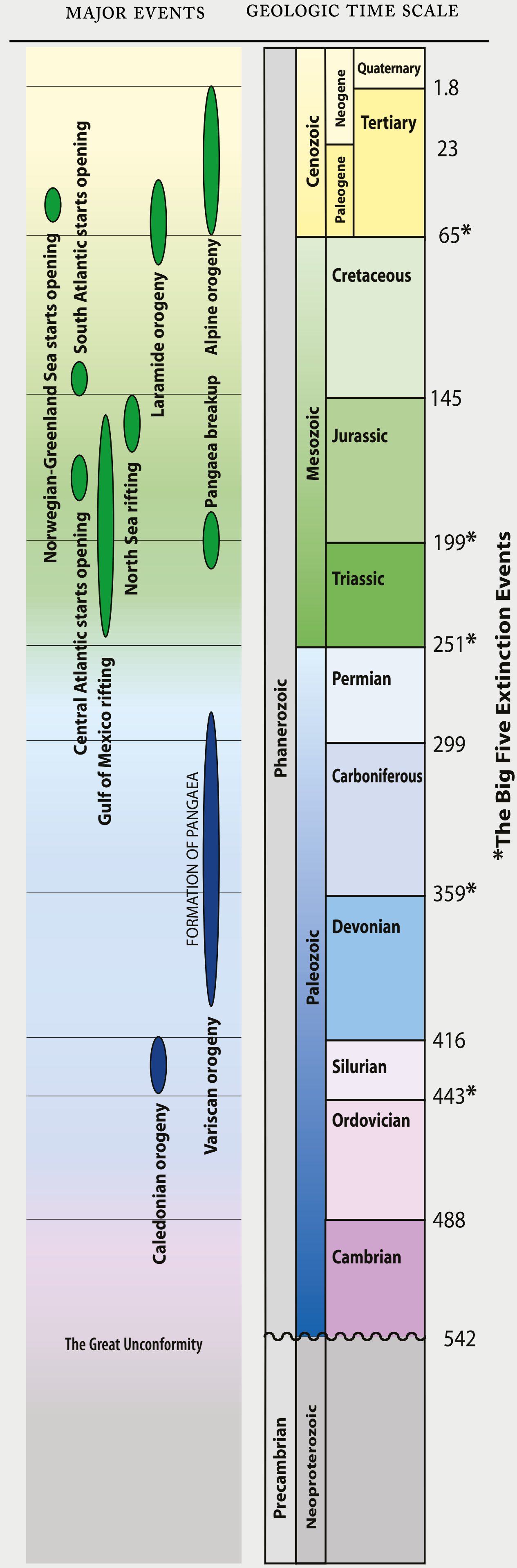
A full three-day programme will bring together industry, academics and local experts to discuss this recent data in the wider context of the Zagros Mountains, but with a particular emphasis on understanding the geology of Iraqi Kurdistan. Keynote speakers will cover all aspects of the geological evolution and hydrocarbon resources of the region, including stratigraphy, reservoir geology, diagenesis, geophysics and structural geology.

The conference, which is being held in London from 23 to 25 January 2013, is being organised by the Petroleum Group of the Geological Society. Further details, including registration forms, are on the Geological Society website http://www.geolsoc.org.uk/zagros13.

To read more about the geology of the Zagros region, see *GEO ExPro* Vol. 9, No. 1. ■

MATTHEW BROWN

Christopher Tiratsoo



Africa: Continent of Discoveries


Jonathan Danforth

The 11th annual **Conference on African E&P**, co-hosted by the Houston Geological Society (**HGS**) and the Petroleum Exploration Society of Great Britain (**PESGB**), took place on 11–12 September at its new location, the Westin Houston, Memorial City Hotel in Houston. The hotel provided spacious halls, great food, and an unforgettable African dance show for the reception. Over 400 participants attended to explore the latest ideas about plays and prospects, conjugate margins, and emerging technologies in the region.

The conference offered guests an array of presentations, networking opportunities, and vendor displays for exploring the new developments. Discoveries from offshore East Africa and down the entire West coast, which made up 70% of the finds in 2012, created a particularly exciting climate for the gathering. Developments in the technology of sub-salt imaging also served as an engine for ideas and opportunities in finding the plays and prospects for Africa's future.

The next Conference on African E & P, which will be the 12th in the series, will be hosted in London by PESGB in September 2013, also at a new location to accommodate the growing number of participants. Latest information on attendance, abstract submissions and sponsorship opportunities can be found on the PESGB website. ■

Application Ranks Top Performers

URank, an online data application which provides oil and gas industry rankings with ease and rapidity, has recently been launched. Available through any web browser or dedicated application, URank ranks companies, countries and assets by selected benchmarks. URank is the latest product of Norway-based **Rystad Energy**, internationally best known for their global oil and gas databases, research products and independent consulting services.

URank can rank companies by, for example, production, reserves, exploration success, development activity, production growth and portfolio value. Countries and assets are compared using similar additional benchmarks like tax regimes and discovery size. All lists can be viewed at different geographic levels and with particular focus on main growth areas such as unconventionals and offshore growth.

URank provides historical and current data as well as forecasts derived from annual reports, Rystad Energy's global database UCube and other company research. The application is therefore based on information of more than 65,000 assets and 3,200 companies with a data time span from 1900 to 2100, capturing a wealth of information with just a couple of clicks.

This application will not only ease and speed up the use of data for its subscribers; it is also another step to an increasingly transparent future in the oil and gas industry – an aim that Rystad Energy has set itself since day one. As such, URank is a great addition to the E&P and oilfield service databases UCube and DCube that are also currently available to the market through the Rystad website.

Rystad Energy now has offices in Norway, UK and USA as well as research and reseller teams in Asia. ■

Chemostrat Open Perth Office

Continued global demand for its specialist chemostratigraphy services in the oil and gas industry means that **Chemostrat International Ltd**, which is based in Welshpool in North Wales – a place not renowned as the centre of the hydrocarbon industry – has opened a new office in Perth, Australia. The company has been steadily growing its client base in the Asia Pacific region, with projects underway from Australia, Indonesia, China, Malaysia and Thailand, including work on the exciting new shale gas developments that are revolutionising the energy sector, so opening a presence closer to the marketplace seemed an obvious move. It already has a US subsidiary, Chemostrat Inc., based in the oil capital of the world, Houston, where a team of geologists and support staff provide services throughout the Americas. ■

IN THE DATA MANAGER'S OFFICE...
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New IOR Centre

In August Norwegian oil company **Statoil** declared that it was targeting a 60% average oil recovery rate from its fields on the Norwegian Continental Shelf. To assist in this aim, the company recently announced that it has begun building a major research centre for improving oil recovery (**IOR**).

With an average recovery rate of 50%, compared with a global average of just 35% (recovery rate is calculated by dividing the volume of recoverable oil by the volume of estimated oil-in-place), Statoil is already a world leader in oil recovery. In fact, the company was recently awarded the Norwegian Petroleum Directorate's prize for IOR for its work in increasing recovery in the Oseberg field in the Norwegian North Sea, where the plan to develop the field using injected water was changed to gas injection, generating an additional 400–500 MMbo.

The new centre is located next to the company's existing research facility in Trondheim, in northern Norway, and Statoil plans to use it to support the company in providing new technologies and methods to help maximise production on Statoil's fields both on the Norwegian Continental Shelf and internationally. The centre will concentrate on attempting to understand why different technologies perform as they do and which are most efficient at IOR. ■

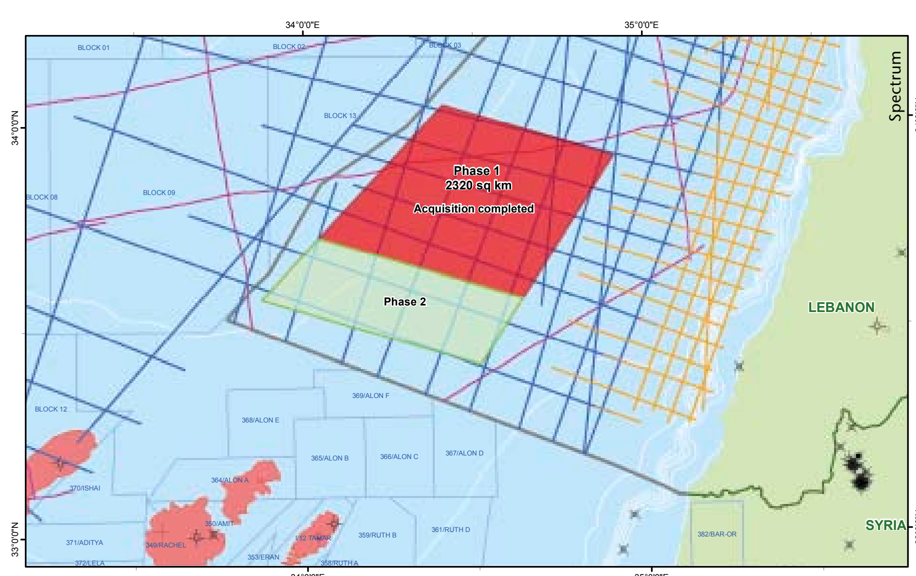
Statoil's subsurface team at the Oseberg field recently won an award for IOR

Lebanon Multi-Client 3D Survey

Seismic company **Spectrum** has completed the first phase of its 3D Multi-Client survey in the **Levantine Basin** offshore Lebanon. The survey, which was carried out in cooperation with Dolphin Geophysical using their vessel *Polar Duke*, acquired 2,320 km^2 in the highly prospective south-west corner of Lebanon's Exclusive Economic Zone, and is expected to expand to incorporate up to 3,000 km^2 when completed. Data acquisition is being undertaken under contract to the Ministry of Energy and Water of Lebanon. Some fast track data has been processed onboard the *Polar Duke* and this will be completed during Q4 2012 and the final 3D volume will be available in early 2013 to coincide with the anticipated first offshore Lebanon Bid round.

Structures and stratigraphic features are already being identified throughout the Miocene that were not seen within the 2D data. Spectrum states that the quality of the seismic data from the *Polar Duke* is outstanding and is eagerly anticipating the results from the data processing, particularly as the survey is within 70km of Noble's world class gas discoveries and with the first bid round getting increasingly close. The company presented its initial resource assessment of the study area at two recent industry conferences on the Eastern Mediterranean in London and Geneva.

Spectrum is confident that its initial assessment of 25 Tcfg in the 3D study area will increase as it identifies more structures and prospects and refines estimates in current data processing projects. ■

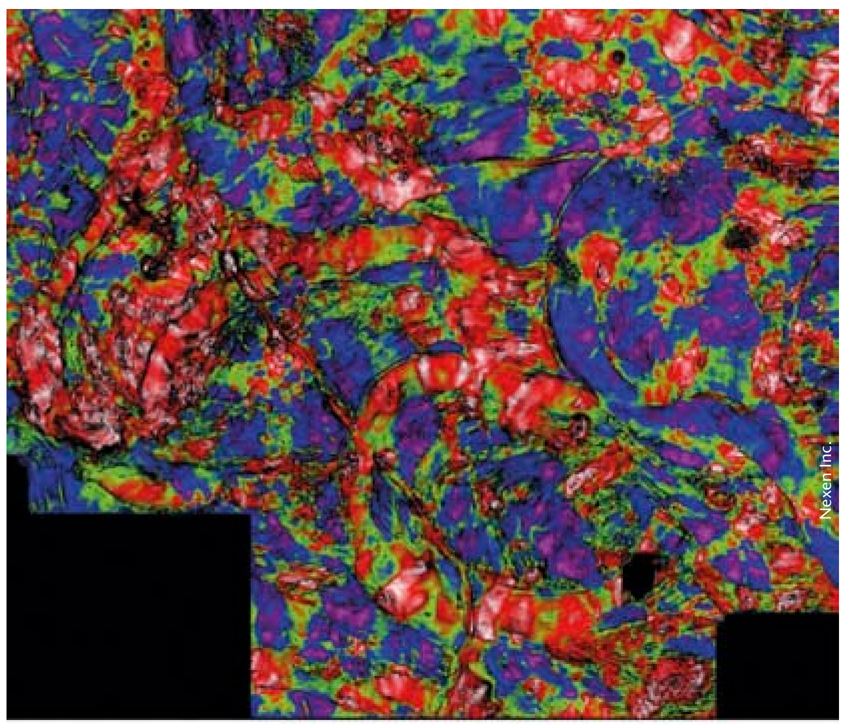


Remote Sensing Underground

Satellite remote sensing uses specific frequency bands to reveal details about the surface of the earth. By borrowing this idea and applying it to broadband 3D seismic data, reservoir heterogeneities are illuminated enabling optimal reservoir development. Nexen Inc. are using this technology to shed light on Canadian oil sands reservoirs.

DRAGANA TODOROVIC-MARINIC Nexen Inc., Canada

How does one map a three-dimensionally complex reservoir in order to position horizontal wells precisely and optimally? This is the challenge facing many geoscientists, particularly those who are working to develop McMurray oil sands plays in western Canada. By applying spectral techniques borrowed from satellite remote sensing to 3D seismic data, the reservoir 'sweet spots' can be identified, allowing more efficient heavy oil production.



Curvature Indicates Localised Structure

Curvature, a measurement of the degree of bending of a reflecting surface, is strictly an attribute of the geometry of a seismic reflector, independent of any spectral qualities. Curvature indicates the localised structure, ranging from dome-shaped hills to bowl-shaped valleys. Curvature calculated on the seismic volume may indicate the morphology of the local structure. Assuming differential compaction, the domes – localised structural highs – correspond to areas of the channel which are sand-filled; concave bowls correspond to softer mud-fill. This interpretation, based on a purely geometric attribute, is in agreement with, and independent of, the spectral results.

The Challenge

The challenge: how do you achieve precise well placement in a complex reservoir?

The Lower Cretaceous McMurray Formation in north-eastern Alberta contains an estimated 1.7 Tbo oil in place. But this significant hydrocarbon resource is in the form of bitumen: a heavy, viscous oil which is not simple to extract. An in-situ method which is being applied at a number of oil sands projects is Steam Assisted Gravity Drainage (SAGD). In SAGD, horizontal well pairs with five metres vertical separation between them are drilled; high pressure steam is injected into the reservoir through the upper (injector) well heating the bitumen so it can flow down to the lower (production) well via gravity. Drilling pads supporting eight or more SAGD well pairs are not uncommon. That is to say, SAGD production is a significant capital investment and placement of the well pairs within the sand reservoir is critical to achieving production rates and recoverable reserves, as well as minimising steam requirements – both for efficiency and environmental concerns.

To optimally place these expensive horizontal well pairs within the sand reservoir, one must find a way to reveal a detailed picture of the reservoir. While the geologic model of the reservoir is always being updated with new knowledge, the depositional environment can generally be described as one of broad valleys infilled with tidally influenced meandering river point bar deposits and associated sediments. The stacked point bar sandstones are interbedded with mudstones characterised by highly variable dip, known as inclined heterolithic stratification (IHS). Some of these mudstones extend laterally for kilometres, and can be permeability barriers or baffles between the injector and producer wells, reducing the effective pay length of a well pair.

Placing both injector and producer wells in continuous, high permeability cross-bedded sand lithofacies is best. It is therefore critical to find a way to reconstruct the three-dimensionally complex riverbed with as much detail as possible. Like a roller-coaster track: where does it rise and fall? Where are its stacked sand bars; where do they thin and thicken? In addition, one must delineate the extent and varying inclination of the potentially harmful interbedded mudstone layers. Underestimating the three-dimensional complexity of the reservoir could be a very expensive mistake.

Unlocking Spectral Information

Traditional seismic interpretation uses broadband seismic data – as wide a frequency range as possible. This broadband data contains detailed information about the reservoir, but one must remember that it provides a view of the subsurface that is biased to what the dominant frequency band of the conventional seismic data can 'see'. The problem is to unlock the valuable spectral information to reveal details of the reservoir that cannot be seen with the broadband data. A helpful analogy is to consider remote sensing of the earth's surface from satellite data. We get one understanding of the surface from what we can see with the broadband visible light spectrum, but by restricting the frequency range to sub-bands, various details can be revealed. For instance, frequencies in the visual blue sub-band reveal detail for mapping the depth of lakes; frequencies in the mid-infrared sub-band are used for forest fire detection.

The introductory image and the following pages give some examples of the way in which applying specific frequency bands to broadband 3D seismic data are illuminating and adding to the information which can be obtained from seismic data.

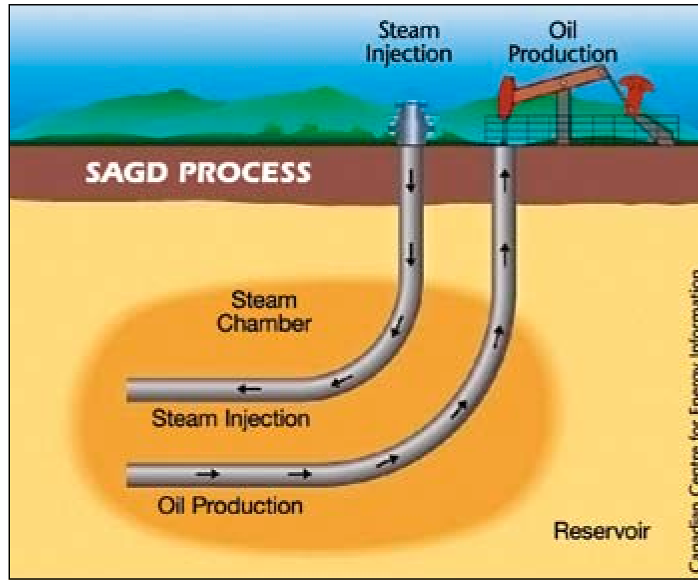
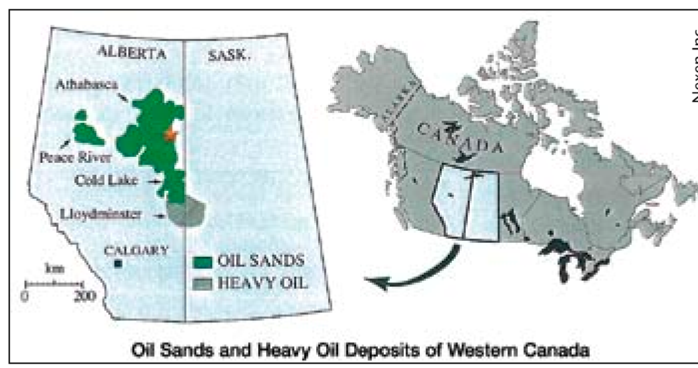
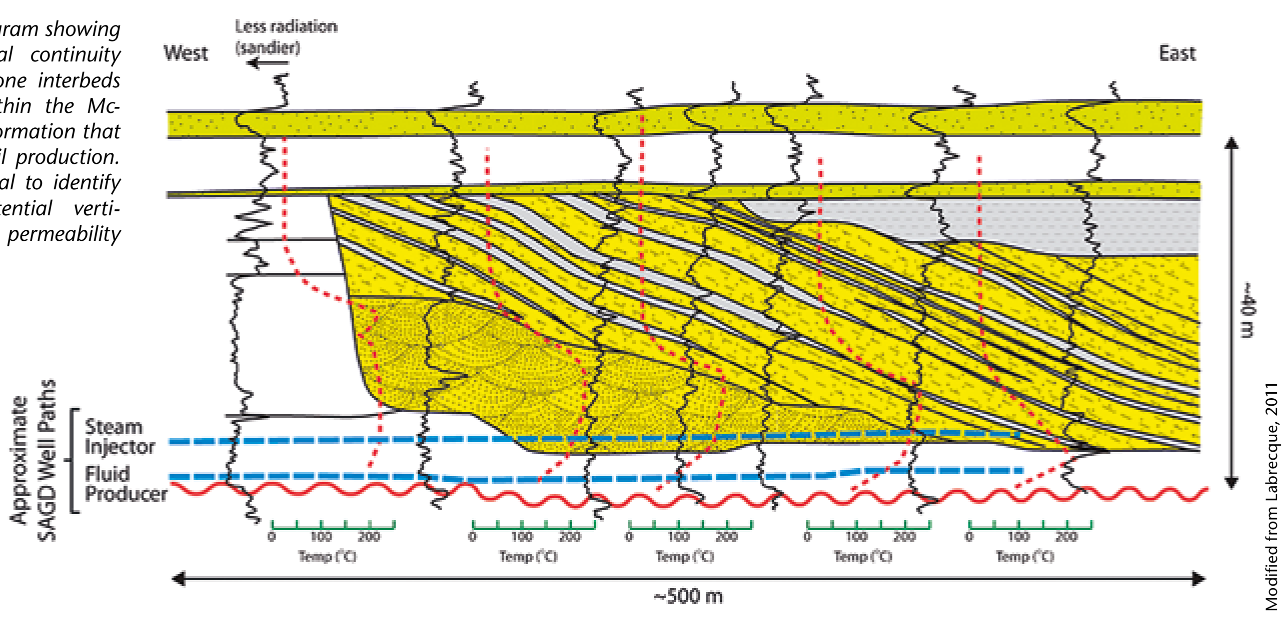


Illustration of the SAGD process where the injector and producer well pairs must be placed at the optimal position, orientation and inclination.

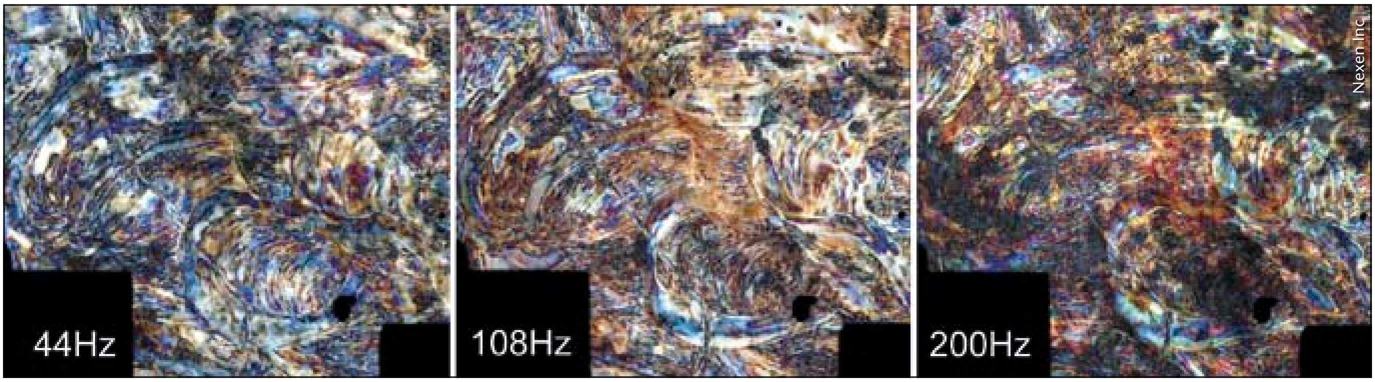


Working with OpenGeoSolutions, Inc., Nexen Inc. applied various spectral 'remote sensing' techniques to a 120 km^2 3D seismic survey from the Kinosis 1A project (starred area): Spectral Decomposition, Spectral Discontinuity™, and Spectral Inversion. At Kinosis, Nexen expects to drill 29 SAGD wells, with steam injection anticipated in 2014; production from these wells is expected to average 15,000 to 25,000 bpd at peak rates. Understanding the complex reservoir is essential for successful reservoir development.

Block diagram showing the lateral continuity of mudstone interbeds (grey) within the McMurray Formation that impede oil production. It is critical to identify their potential vertical SAGD permeability barriers.



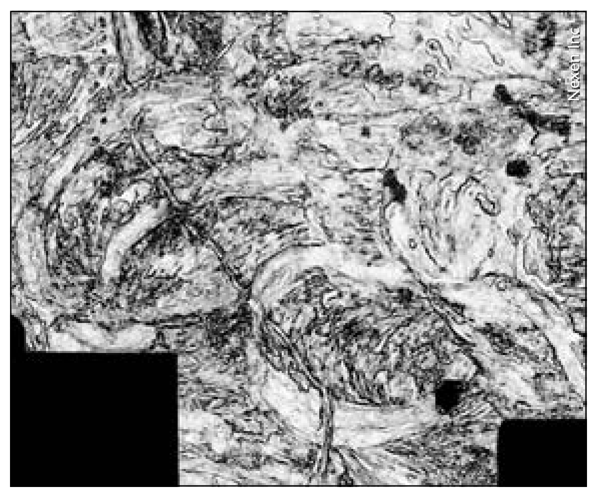
Spectral Decomposition Reveals Relative Thickening and Thinning



In remote sensing, sub-bands of electromagnetic frequencies are used to map interference patterns at the surface of the earth to depict soil, vegetation, moisture content, and so on. In Spectral Decomposition, much lower seismic frequencies are used to examine interference in the subsurface: interference caused by a variable rock mass.

Spectral Decomposition allows us to view subsurface seismic interference at discrete frequencies throughout the entire bandwidth of usable signal. This discrete spectral view provides substantially more detail and fidelity than attributes or amplitude extracted from a single full bandwidth signal. Full bandwidth seismic and attributes provide a view of the subsurface that is skewed towards what can be seen just at the dominant frequency of the seismic wavelet. Spectral Decomposition exposes a signal-band view of the subsurface that reveals stratigraphic and/or structural edges as well as layering complexity and relative thickening and thinning. Fault definition is often superior to conventional edge detection methods.

The geology lights up using different frequencies. In the example above, to image a stratigraphic feature that varies in thickness, the Spectral Decomposition images use red-green-blue (RGB) composites in order to portray the spectral information. If the frequency content is high (image on the right), thinner stratigraphic features will be tuned in and highlighted by the higher amplitude, in this case in blue. If the frequency content is lower (image on the left), thicker stratigraphic features will stand out, depicted by the red colour.

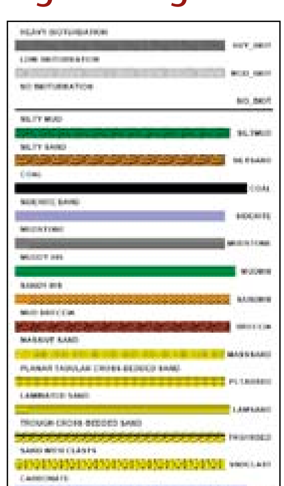


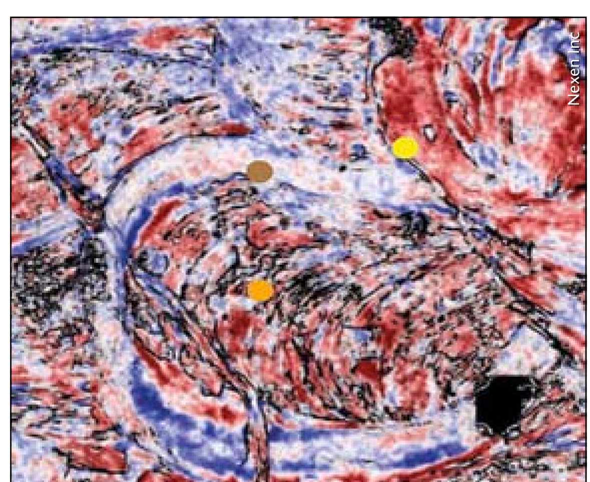
Spectral Discontinuity Exposes Stratigraphic Edges and Faulting

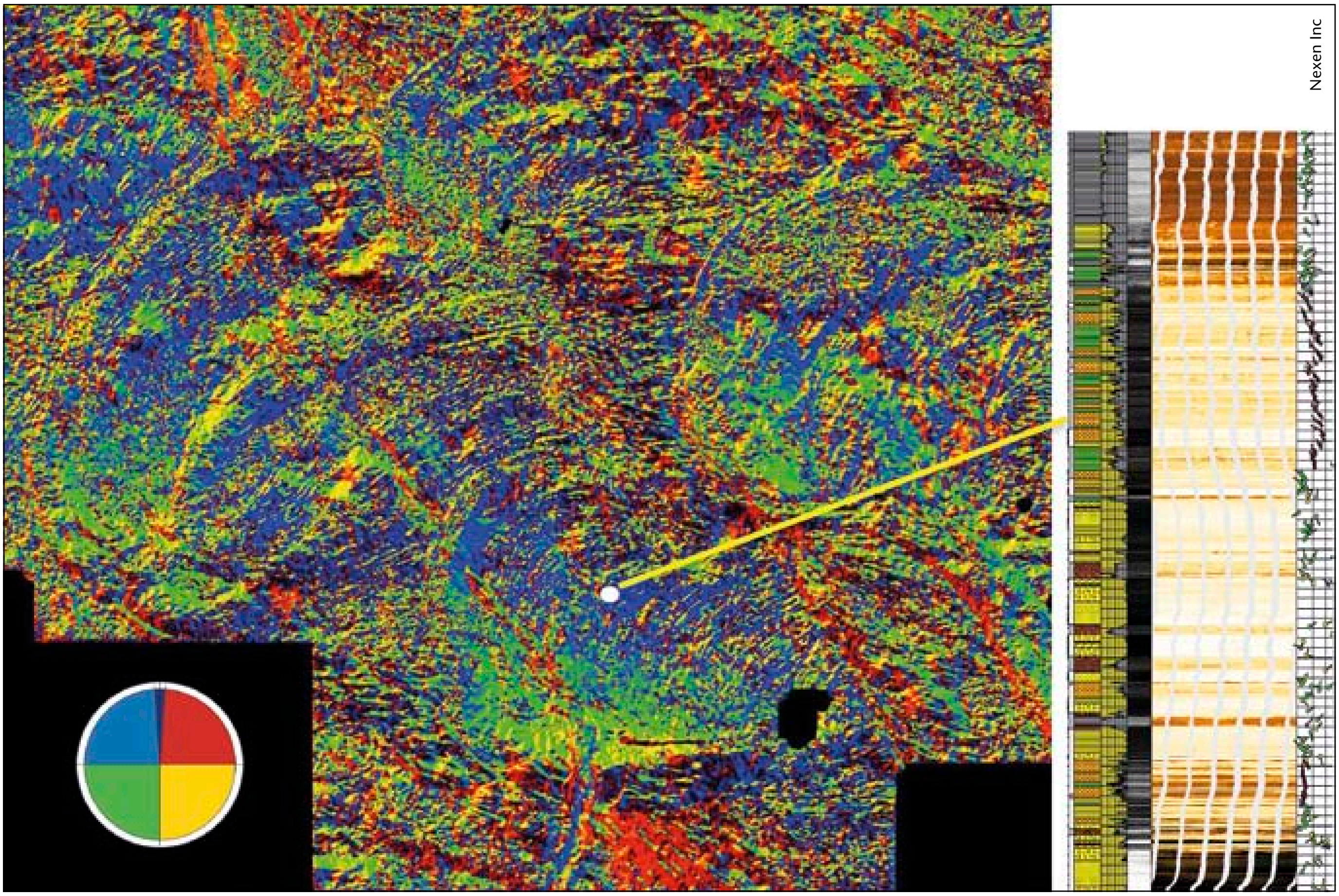
Spectral Discontinuity is an additional spectral tool to reveal stratigraphic and structural discontinuities. By staying clear of wavelet tuning pitfalls that can afflict broadband data, this approach offers distinct advantages over traditional coherency-based fault definition methods, providing less dip-sensitive detection of faults and terminations. The Spectral Discontinuity images are displayed using a grey scale where light tones represent areas of continuity, dark represents discontinuities.

Spectral Inversion Highlights Geologic Packages

Spectral Inversion is a statistical inversion to answer the question: is a given layer in the interbedded sequence likely to be sand or mud, and what is the associated probability? Spectral Decomposition data are inverted to binary layer type: that is, only two materials are allowed: relatively soft (sandstone shown in red) or relatively hard (mudstone). Additional analysis can be conducted to compute thickness and associated confidence levels. Well log data, cores and Formation-Images (FMI) logs, as this example shows, are integrated into the seismic results to anchor the seismically-derived estimates to direct measurements.







Dip Azimuth Locates the Sweet Spot

Inspired by the detail revealed by the spectral methods, the team developed a technique to detect the sweet spot of the point bar reservoir. Assuming the bitumen accumulation is associated with stacked point bars deposited by tidally influenced meandering rivers, one may exploit the relationship between the stream flow direction and the dips in the point bar to identify the size of the point bar and channel geometry, and hence infer which portion of the bar will most likely contain the cleanest sand.

From the paleogeography of this region, we know the general stream flow direction: the surface sloped gently down to the north or north-west, toward the sea. To estimate dips, 'Dip Azimuth' volumes – extremely localised estimates of dip magnitude and dip direction at the McMurray surface – were computed from the 3D seismic data.

When combined with Spectral Discontinuity, the resulting image reveals, in considerable detail, the internal structure of the point bar deposits, showing the dip regime within the point bar sequences. Continuous IHS mud beds typically correspond to lateral accretion: they are deposited on the inside bends of point bars, accumulating as they migrate over the life of the meandering channel. By assembling a 'movie' of Dip Azimuth slices, the interpreter can investigate the downstream migration of the stacked point bars through palaeo-depositional time. ■

Ongoing Work

Nexen Inc. continues to advance the application of innovative spectral methods such as Spectral Decomposition, Spectral Discontinuity and Spectral Inversion, along with Dip Azimuth investigations. To date, these tools are revealing heterogeneity detail within the McMurray reservoir beyond classic seismic resolution, helping the geoscientist to estimate layering architecture, thickness variability and probability of sand, as well as sweet spots within the sand bars.

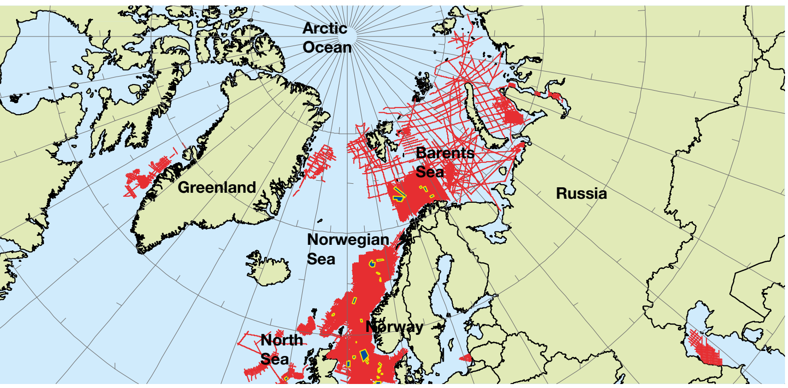
Ongoing work includes integrating these reservoir characterisation estimates with a comprehensive database of core, well log and FMI data, in order to independently verify the seismically-derived relationships and patterns of sediment distribution throughout the reservoir, and bring this knowledge to further refining the next iteration of the solution.

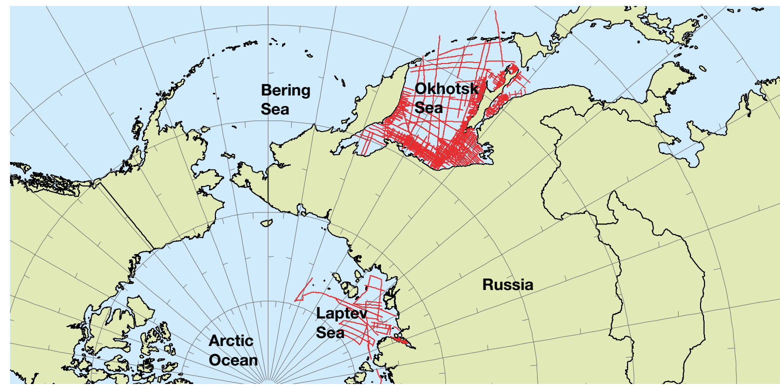
Acknowledgements

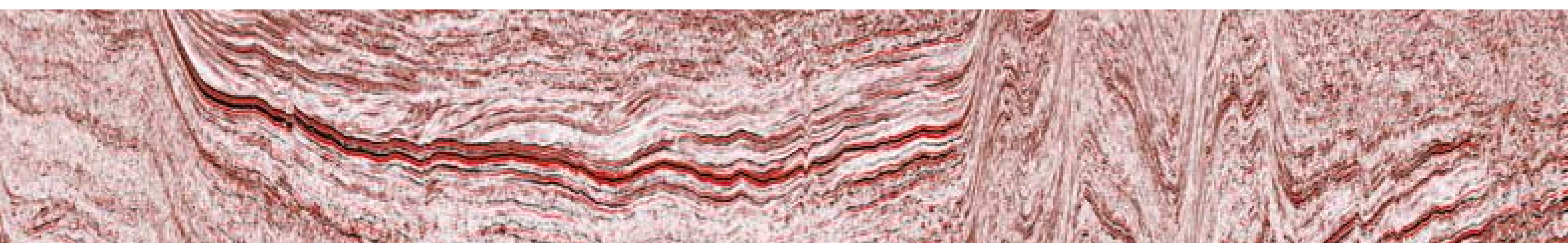
The author gratefully acknowledges Nexen Inc. and CNOOC for permission to show these results.

These findings were first presented at GeoConvention 2012 in Calgary in the paper titled: Shedding more light on an Oil Sand reservoir by applying integrated spectral method analysis – Case Study; co-authors David Gray, Dale Vanhooren and Greg Osiowy of Nexen Inc., and Paul Garossino, Paul Gutowski and James Alison of OpenGeoSolutions Inc.

WHEN **ARCTIC SEISMIC** COUNTS...







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Into the Abyss!

Borehole seismic – the technological challenge of listening at extreme depth. **William Wills** of Avalon Sciences discusses some of the principle requirements driving borehole seismic technology innovation.

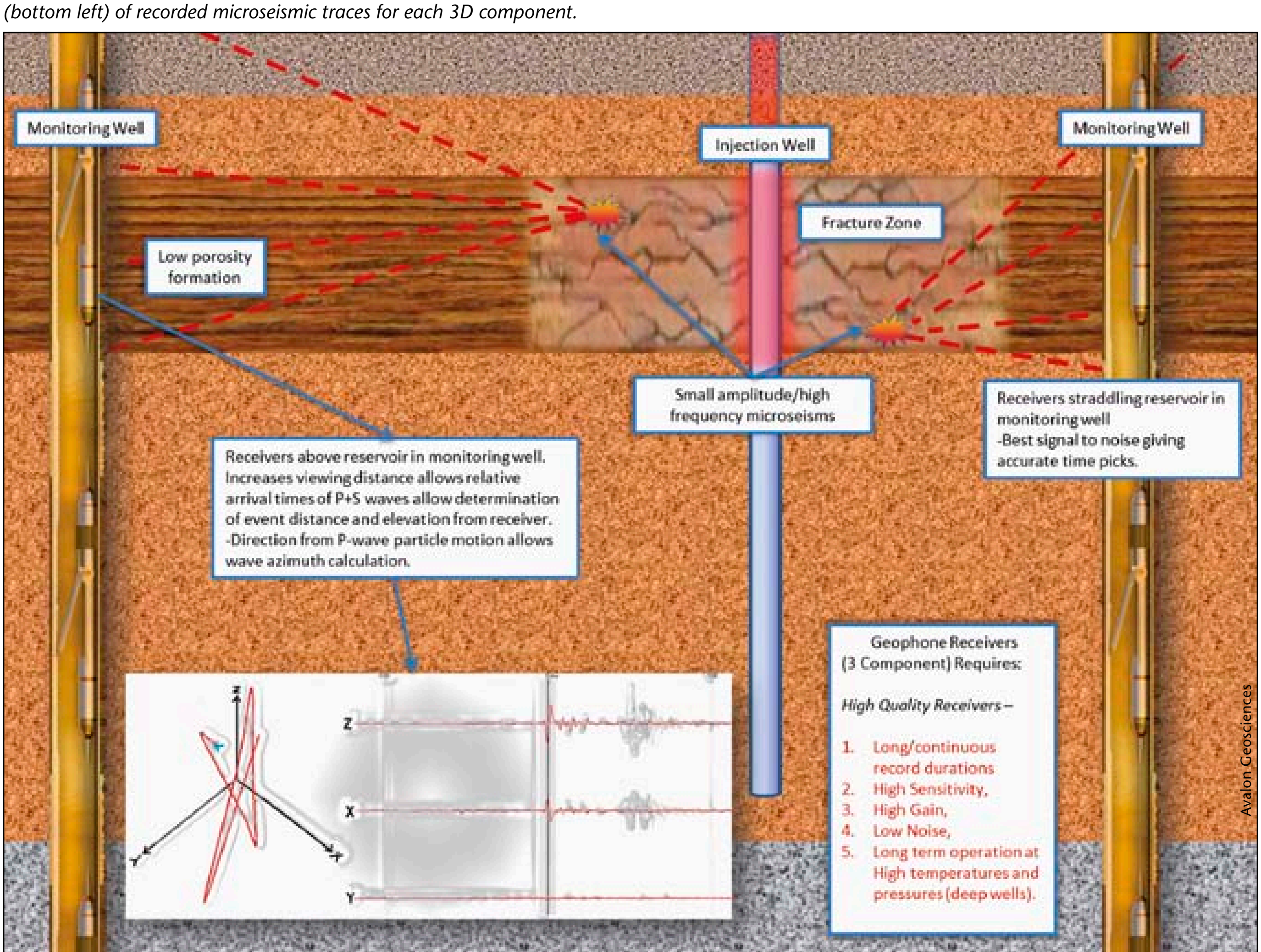
The domain of borehole seismic exploration is fast approaching a new era in technological advancement, with the dynamic and challenging requirements for mapping and monitoring continually increasing as complex, hostile well environments dominate over shallower conventional hydrocarbon reservoirs.

The deployment of seismic recording systems deep within the well to acquire high resolution data has become common practice over the last few decades. This technology has been dominantly used to complement surface seismic surveying bringing advantages such as noise reduction and immunity from the distorting effects of near-surface rocks, especially sediments. The well-established method of downhole Vertical Seismic Profiling (VSP) thus allows for much higher resolution imaging between lithologies proximal to the well whilst even revealing subtle impedance changes beyond total depth of the exploration well. At its most basic application, 'check shot' borehole seismic calibrates for any inferred depth uncertainty of reflectors presented by surface seismic, giving an enhanced velocity model around a well.

Borehole Seismic for Deep Reservoirs?

However, as directional drilling technology has advanced over the last decade, allowing for access to more complex and deeper environments (e.g. within subsalt zones), so has the

Schematic of a borehole microseismic monitoring system outlining specific requirements for fracture mapping, including example hodogram display (bottom left) of recorded microseismic traces for each 3D component.



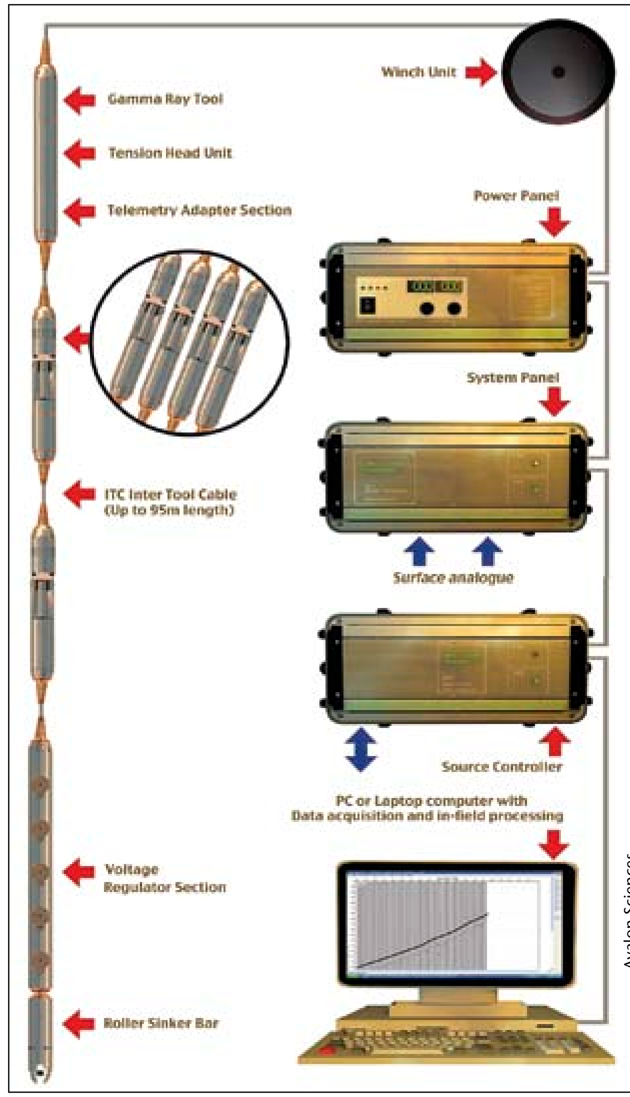
need developed for more intricate seismic surveying techniques. Conventional surface 3D seismic surveys of deep subsalt reservoirs, such as at the deepwater Wilcox Trend in the Gulf of Mexico, are complicated by the presence of 300–600m thick allochthonous salt canopies. Recent surface techniques to map below the salt have made progress in the form of wide-azimuth (WAZ) towed streamer acquisition. However, deep reservoirs, like those found in the Gulf of Mexico with well depths of over 10,500m, so far have demonstrated that this technique is not solely sufficient for such deep reservoir characterisation. At these depths the modest angle of incidence from the distal surface (mid 20° range) can potentially render reservoir amplitude analysis as an inappropriate technique, especially within poorly or unevenly illuminated subsalt environments.

Advances in surface seismic processing for subsalt settings such as Pre-stack Depth Migration (PSDM) are still sensitive to velocity error and vertical resolution, especially in areas of multifaceted salt geometry which exhibit large lateral velocity variations. PSDM is dependent on an accurate velocity model, which for profound depths rarely incorporates localised low velocity zones or takes into account anisotropy, resulting in velocity models which may be too deep and too steep, thus complicating regional reconstructions and resolution of individual structures. Further uncertainty can be introduced due to the contamination of primary energy at reservoir level by multiple signals generated above the top salt and water bottom. This can often be a serious issue when migrated multiples resemble faulted geometry.

The Engineering Challenge for Hotter and Deeper

Determining quality and integrity of reservoirs that remain below seismic resolution can be achieved if the seismic receiver can be located downhole proximal to the area of interest. However, at these depths a real technological challenge is presented. In regions such as the Gulf of Mexico these geophone tools need to be designed to function within very hostile borehole environments with temperatures of over 180°C and pressures reaching 25,000 PSI.

The current industry standard borehole seismic receiver systems in general provide a downhole pressure housing for the seismic sensor and coupling mechanism (usually in the form of a retractable arm) to the borehole casing or formation. Most modern sensor packs are three-component, allowing for full analysis wave particle motion.

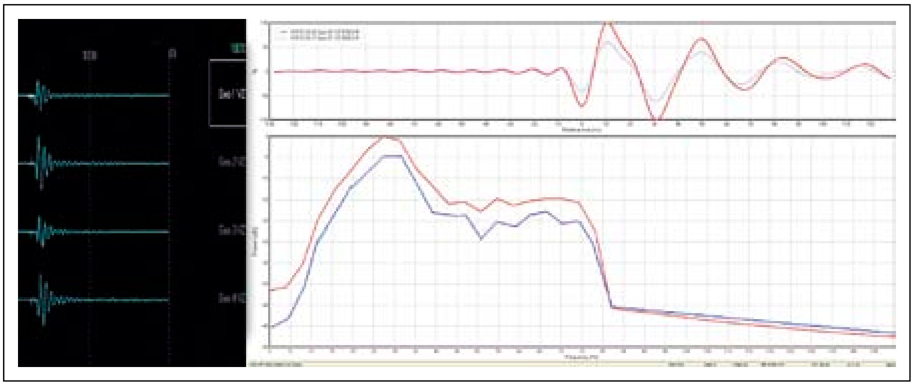


Schematic of a typical borehole seismic tool string with surface power and system panels.

Borehole seismic arrays are deployed as a series of satellites on a wireline string. The pressure housing hosts both the geophone sensor pack and coupling mechanism along

Pressure safeguards are required to ensure insulation of the system from the immense borehole fluid pressures. On the left is an example of pressure bulkhead and seals linking the wireline to a borehole seismic satellite, and the image on the right shows an associated high-temperature, high-pressure test chamber to reconstruct borehole conditions.

with the downhole digital telemetry system, maximising dynamic range and sample rate, ideally with real time data transmission and display to surface. Much borehole seismic development of the last five to ten years has allowed for downhole electronics to survive and operate with minimal noise within increasingly hot well conditions (150°C+). To do this the downhole electronic technology has introduced robust thermal insulation and active cooling within the well. Deploying such systems is not without risk; much research has been done to ensure the immense borehole fluid pressures (25,000 PSI+) on the deep receivers do not lead to ingress through mechanical seals, resulting in electrical leakage.



Correlated data from North Belt Well, Texas 2010, acquired by Digital Geochain Borehole Seismic System. Cross normalised seismic trace recorded on Dual Geophones (traces 1 and 3) vs Quad Geophones (traces 2 and 4). The magnitude spectrum shows a ~6 dB differential in signal to noise over the recorded bandwidth between the Dual (blue) and Quad (red) sensor packs.

For more complex time-lapse 4D seismic surveys involving re-visiting or continuously monitoring a reservoir site, it is more beneficial to have a permanent monitoring system in place. To survive at pressure on a semi-permanent basis, industry development has replaced compression set O-rings with metal-metal seals, increasing resilience to gas and fluid intrusion from the borehole, even in the most hostile wells.

Optimising for Borehole Microseismic Monitoring

The fundamental principles of hydraulic fracturing are broadly understood throughout the hydrocarbon exploration industry. 'Unconventional' high porosity ultra-low permeability reservoir rocks must be artificially fractured in order to provide a hydrocarbon flow pathway. As the high-pressure pumping of a liquid proppant (often a sand/water/chemical gel matrix) passes through a well at a perforated cased point into the tight formation, the fracture events generate high-frequency, low-amplitude microseismicity. This can be detected by a borehole receiver satellite ideally positioned straddling cross-well to the target zone, as shown in the introductory figure on page 42. When employing three-component geophones (X, Y, Z axis) and establishing the receiver orientation and azimuth within a velocity model, the particle motion of the geophone can be displayed as a hodogram. When combined with a picked P- and S-wave arrival time differential, this allows the fracture event to be pinpointed on a 3D grid in real time. To do this the receiver orientation and coupling quality must be initially established. Current practice is to use the downhole perforation shot, but this can be augmented further by initially deploying a repeatable downhole source within the injection well.

The quality of the geophone receiver therefore plays a fundamental part in how accurately the fracture progression is mapped. Most seismic geophone sensors have historically been passive analogue devices typically comprising a spring-mounted magnetic mass moving within a wire coil to induce an electrical signal. The response of a coil/magnet geophone is proportional to ground velocity. Excellent sensor sensitivity is a vital characteristic when trying to pick low-amplitude microseismic arrivals. Even when deployed in relatively quiet borehole conditions, sensors featuring significant electronic noise (especially at temperature) can be enough to mask a microseismic arrival. To improve on this signal to noise ratio, technology has evolved to stack the phones within the sensor pack component of a downhole receiver, with the latest technology achieving so far four phones on each component, with 12 in each receiver satellite.

As the thermal noise (En) output voltage can be expressed as $En = \sqrt{4kTBR}$ (B Boltzmann's constant, kT Temperature, B Bandwidth and R Geophone Resistance), then the sensitivity of a typical geophone is effectively doubled when in series whilst only marginally increasing En, as demonstrated in the figure above.

This provides a much more cost-effective method of increasing sensitivity compared to standard borehole satellites, which accomplish multiple sensors per axis by mechanically joining two independent 'dual' geophone satellites together within the monitoring well. Coupled receiver methods leave the stack trace vulnerable to error from mechanical coupling to casing discrepancies, cement irregularities, and inaccuracy from an increased distance between the joined sensor packs, which can be over a metre in vertical separation. Housing multiple geophones per component within a single satellite goes much further in guaranteeing perfect stacking.

Optimising the digital downhole electronics is also a key role for fracture monitoring. If the borehole geophone response has electronic downhole gain applied (54 dB), increasing dynamic range, and a high sample rate (one sample every 1/4ms), it will provide a recording bandwidth of up to 1600 Hz, which is perfectly suited to comprehensively measure all the energy content generated by the high-frequency microseisms.

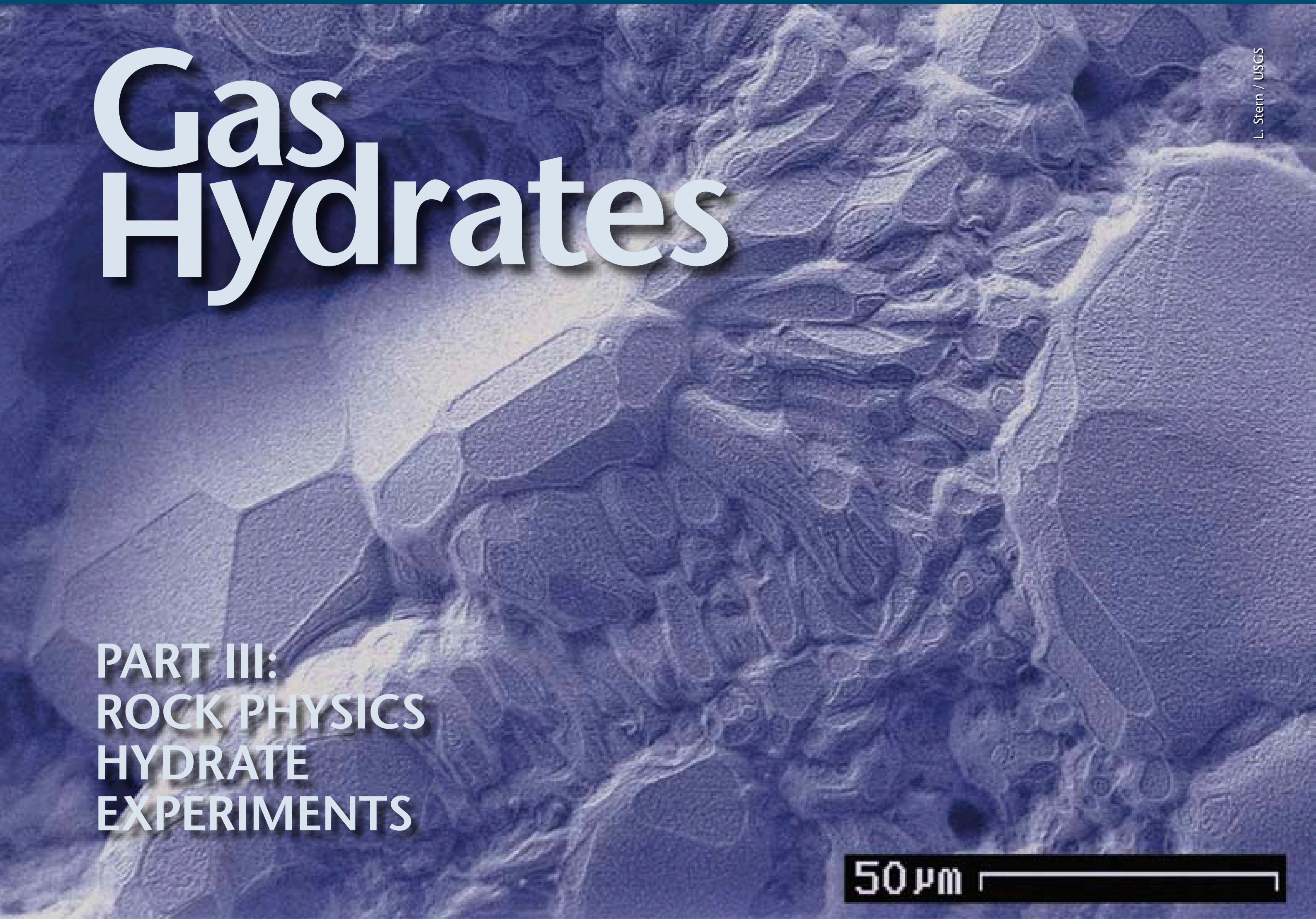
Evolution

The demand for borehole seismic receivers to operate in ever more hostile environments with increased downhole life time, whilst delivering augmented sensitivity, dynamic range and broadband, is driving sensor technology innovation. The move to multiple high-temperature geophones and high-gain electronics is only one small step in the evolution of downhole seismic tools. Distributed fibre optic systems with large broadband and low noise may be the next step in progression but are yet to establish themselves within the extremes of well pressure and temperature. However, as this technology develops, so too will resolution and confidence mature when characterising and monitoring seismic within deep complex geology. ■

William Wills is a Geoscientist at Avalon Sciences Ltd, Somerset, UK

Gas Hydrates

PART III: ROCK PHYSICS HYDRATE EXPERIMENTS



Methane hydrate crystals – cryogenic SEM images taken at very low temperatures to keep the hydrate stable.

LASSE AMUNDSEN and MARTIN LANDRØ

"In science one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite."

Paul Dirac, Physicist, Nobel Prize in Physics, 1933

In the previous issue of *Geo ExPro* we discussed whether gas hydrate is a part of the pore fluid or a part of the rock itself. It was shown that this matters if we want to estimate geophysical parameters for a gas hydrate rock. There are two ways (at least!) to investigate this further: either to observe geophysical parameters from wells being drilled through a hydrate-bearing rock, or to inject methane hydrate into a rock sample in the laboratory. We will discuss examples of both and put particular emphasis on a recent lab experiment performed in China.

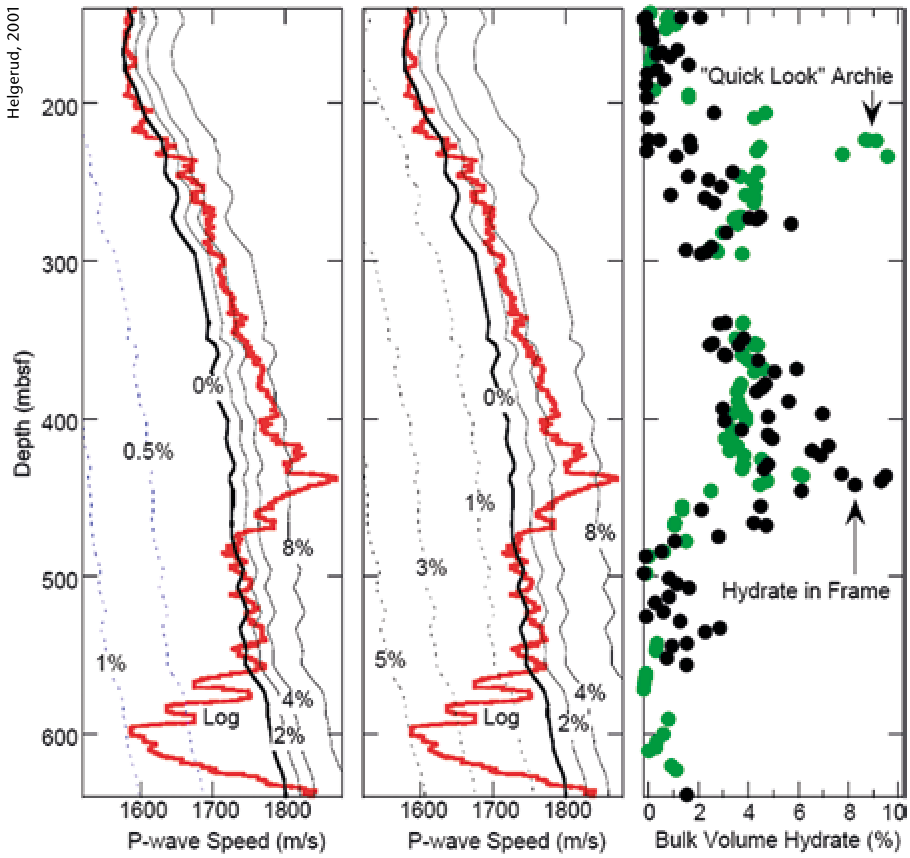
Seismic Attenuation

Like the presence of free gas, the presence of gas hydrate affects seismic attenuation. Attenuation has the potential to map hydrate concentrations through the effect of local blanking of sediment stratigraphic reflectivity. However, there are few studies related to seismic attenuation in hydrate-bearing sediments and it remains an open topic for future studies. The attenuation of seismic energy by gas hydrates is likely to depend on the concentration of hydrate, the thickness of hydrate, the mechanism of hydrate formation, and the dominant frequency of the seismic measurements, in addition to the lithology changes.

VSP data in the Mackenzie Delta indicate that quite thick hydrate-bearing zones have significant attenuation at seismic frequencies of 10–200 Hz (Q-values, which describe inverse attenuation, of around 10).

Observations from Wells

In a field example from a well drilled at the Blake Ridge (ODP site 995) offshore South Carolina, USA, Helgerud found that the rock physics model that assumes hydrate is part of the rock frame gave a reasonable fit between



Methane hydrate concentration in the sediments at ODP site 995 from P-wave sonic and resistivity logs. Column 1: Comparison of P-wave velocity (red line) with model results assuming methane hydrate (solid black lines) or homogeneously distributed methane gas (dashed lines) are part of the pore fluid. Column 2: Comparison with model results assuming methane hydrate is a sediment frame component (solid black lines) or methane gas is patchily distributed in the pore space (dashed lines). Column 3: Comparison of methane hydrate concentration estimates derived from the resistivity log to estimates derived from the compressional wave sonic log using the gas hydrate as sediment frame component model.

hydrate concentrations estimated from P-wave well log measurements and those obtained from the resistivity log. The deviation between the two models is not huge, but based on the well log observation it is clear that the model which assumes hydrate is part of the rock itself and acts as a kind of cement explains the well log data best. A relative good fit between observed saturations of hydrate and those estimated using the Archie equation (discussed in more detail below) is achieved.

Qingdao Experiment

This year, a very interesting experiment on hydrate formation and dissolution was presented by Hu and Ye of the Qingdao Institute of Marine Geology in China. They measured P- and S-wave velocities as the hydrate concentration in two rock samples was gradually increased from zero to 70%. The sediment samples were first immersed by pure water, then loaded into a high-

Microstructural Models

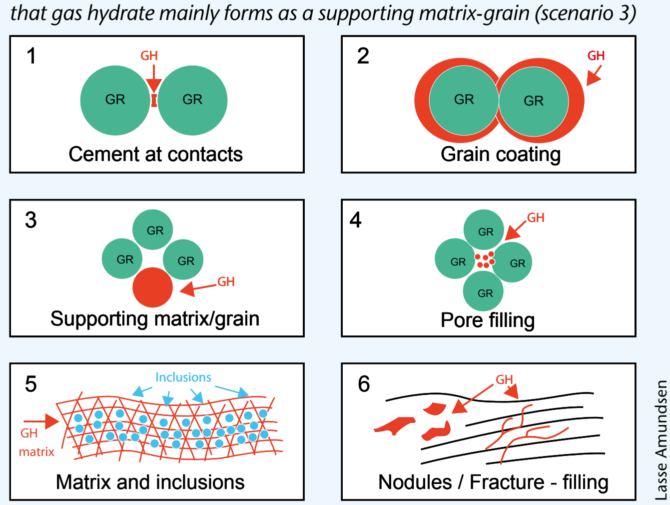
Higher gas hydrate concentrations yield an increase in the elastic properties. There are a number of rock physics models in the literature that attempt to quantify this effect (Dai et al., 2004). The 'cementation models' treat the grains as randomly packed spheres where the gas hydrates occur at the contact point (**model 1**) or grow around the grains (**model 2**). However, these models predict large increases in the elastic properties with only a small amount of gas hydrate but stay relatively flat as the concentration of gas hydrate increases further.

Models 3 and 4 are variations of the cementation models, but consider the gas hydrate as either a component of the load-bearing matrix or filling the pores. These use the Hertz-Mindlin contact theory to calculate dry rock moduli at critical porosity (35–40%). A modified lower Hashin-Shtrikman (HS) bound is used for porosity smaller than critical porosity, and a modified upper HS bound is used for porosities larger than critical porosity. The Gassmann equation is then used to derive the composite rock velocities.

Model 5 is an inclusion-type model that treats gas hydrate and grains as the matrix and inclusions respectively, solving for elastic moduli of the system by iteratively solving either the inclusion-type or self-consistent type equations.

Models 1–5 all consider gas hydrate as homogeneously distributed in the sediments. However, evidence of gas hydrate coring reveals that hydrates often exist as nodules and fracture fillings in the shallow shaly sediments. This geometry is illustrated in **model 6**. No quantitative treatment of this geometric model exists in the literature.

Existing microstructural models of gas hydrate-bearing sediments (adapted from Dai et al., 2004). Observations from various fields show that gas hydrate mainly forms as a supporting matrix-grain (scenario 3)

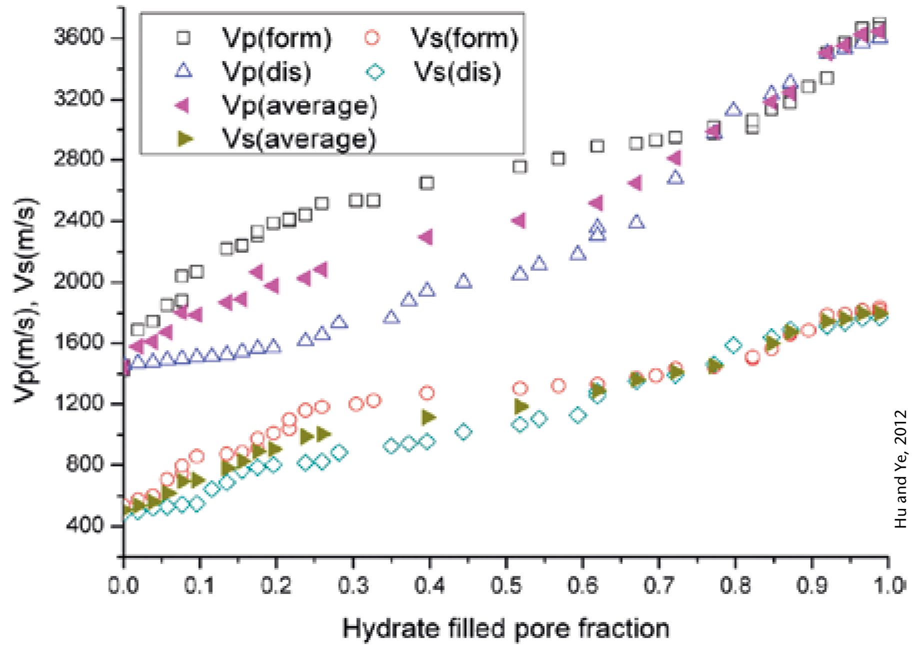


pressure vessel, and injected with methane. The temperature was kept at 2°C for hydrate formation. To simulate the effect of hydrate dissolution, the temperature was gradually increased to room temperature.

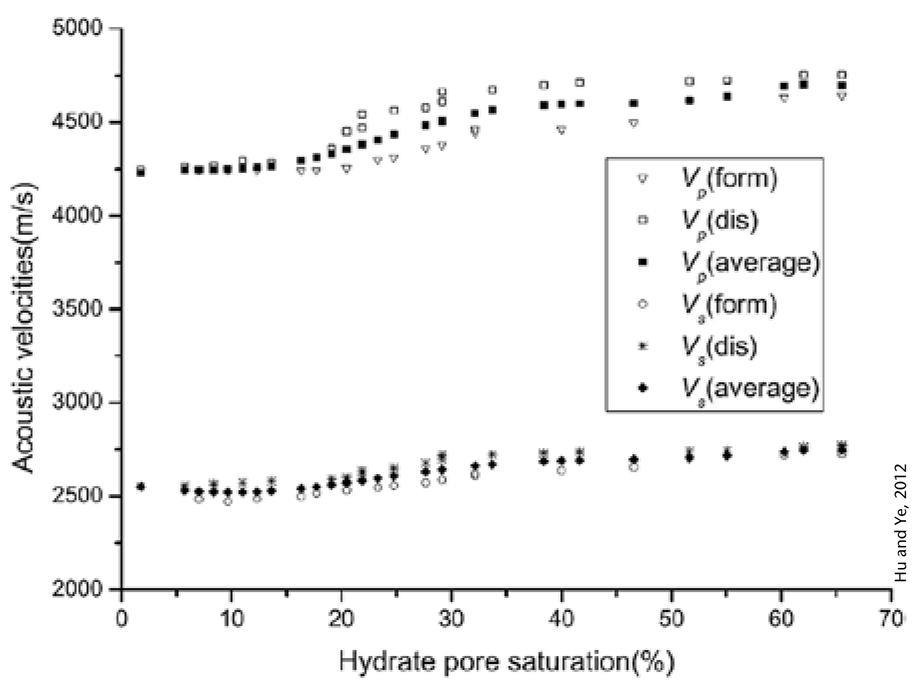
For an unconsolidated sand sample, they found that the P-wave velocity increased from approximately 1,600 m/s for zero hydrate concentration to approximately 3,600 m/s for 70% hydrate concentration. The corresponding values for the S-wave velocity were 600 and 1,600 m/s, respectively. This means that the Vp/Vs-ratio decreases from 2.7 for no hydrate to 2.25 at 70% hydrate concentration. For comparison, it is interesting to note that Helgerud (2001) measured a Vp/Vs-ratio of approximately 1.9 for pure hydrate. A linear extrapolation of the measured Vp/Vs-ratio from Hu and Ye's experiment yields a Vp/Vs-ratio of approximately 2.0.

For the consolidated sample, the Qingdao experiment showed, as expected, higher acoustic velocities: a P-wave velocity increase from 4,250 m/s to 4,700 m/s as the hydrate concentration is increased from 0 to 70%. The corresponding numbers for the S-wave velocity are 2,500 m/s and 2,750 m/s. These numbers correspond to a constant Vp/Vs-ratio of approximately 1.7, practically independent on hydrate concentration.

Hu and Ye also noticed a hysteresis effect for the P-wave velocities. For the unconsolidated sand sample they found that for a hydrate concentration of 50% the P-wave velocity was 2,700 m/s as hydrate was formed and only 2,000 m/s as hydrate was dissolved. The S-wave velocity showed a similar, but weaker hysteresis effect. For the consolidated sample they found that this hysteresis effect was opposite: the P-wave velocity during formation of hydrate was lower than the corresponding value for dissolution. Hu and Ye suggest that this hysteresis effect is caused by two very different mechanisms for unconsolidated and consolidated rocks. For unconsolidated rocks they suggest that the high velocity during formation is caused by hydrate cementation, and that this cementation process behaves differently during formation and dissolution. For consolidated rocks they discuss a two-stage formation process of methane hydrate: first a water-hydrate slurry is formed, followed by a slow solidification process. This two-stage process might explain that P-wave velocities are lower during formation compared to dissolution for the same hydrate concentration. These results are interesting, and might be of importance for geophysical analysis of data from hydrate-bearing sediments. A velocity difference of 700 m/s related to whether hydrate is slowly dissolving or being formed should be possible to detect. For instance, if a hydrate-bearing rock is being produced by heating the rock, hydrate will start to dissolve, and a significant change in P-wave velocity should be detectable on conventional time lapse seismic data. This depends of course on the initial concentration of hydrate within the porous rock; for low concentrations the changes in P-wave velocity will be less pronounced, as demonstrated by Hu and Ye's experiment.



P- and S-wave velocities versus hydrate concentration for an unconsolidated sand sample



P- and S-wave velocities versus hydrate concentration for a consolidated sand sample

Resistivity Variations

Nigel Edwards is one of the pioneers in investigating the mapping of submarine hydrates using electromagnetic surveying

Archie's Equation

Rock physicists talk about velocities and elastic parameters, because these are what link physical rock properties to seismic expressions. Petrophysicists are generally less concerned with seismic, and more concerned with using wellbore measurements to contribute to reservoir description.

In the field of petrophysics, Archie's equation relates the in-situ electrical conductivity of a sedimentary rock to its porosity and brine saturation. Named after Gus Archie (1907–1978), his empirical relationship laid the foundation for modern well log interpretation as it relates borehole electrical conductivity measurements to hydrocarbon saturations.

Archie's relation for gas hydrate–bearing sediments reads:

$$\rho_f = \frac{a\rho_w}{(1-S_h)^n \varphi^m}$$

where ρ_f is the true or measured bulk formation resistivity, ρ_w is the pore fluid resistivity, φ is the sediment porosity, $0.5 < a < 2.5$ is a constant, and $1.5 < m < 3$ is the cementation factor that increases as the grains becomes less spherical with depth. S_h is the hydrate concentration. The value of n depends on the grain-hydrate-fluid structure. If n is relatively large, gas hydrate forms in a way that strongly impedes current flow and increases bulk sediment resistivity (e.g., gas hydrate located in the pore throats), whereas if n is relatively small, gas hydrate forms in a way that has a lesser effect on sediment resistivity (e.g., gas hydrate occurrence in the pore space, making minimal contact with sediment grains). Pearson *et al.,* (1983) calculated an estimate for n of 1.94; however, modelling by Spangenberg (2001) has shown that n depends somewhat on grain size distribution and the gas hydrate saturation itself.

In practice, for marine sediments, the pore fluid resistivity ρ_w usually can be adequately estimated from the equation of state of seawater, if *in-situ* pressure, temperature and salinity are known. The gas hydrate saturation now can be estimated directly from the equation above, given that the empirical Archie parameters a, m and n are known.

methods. In 1997 he published a paper describing how seafloor transient electric dipole-dipole methods can be used to detect hydrates. He uses a simplified version of the Archie equation (see box above) to assess the effect of methane hydrate concentration (S_h) on the formation resistivity (ρ_f):

$$\rho_f = \frac{\rho_w}{(1-S_h)^2 \varphi^2}.$$

Here, ρ_w is the resistivity of the sea water (0.3 Ohm-meter) and φ denotes porosity. We clearly see from this equation that the formation resistivity increases rapidly as the hydrate concentration increases, a fact that makes methane hydrates a candidate for electromagnetic surveying and complementary to seismic surveying. Spangenberg and Kulenkampff (2006) use artificial samples (glass beads) to measure the resistivity versus hydrate concentration. They found that the resistivity increased from 5.1 Ohmm at zero percent hydrate saturation to 265 Ohmm at 95% hydrate saturation. They also investigated the accuracy of the Archie-equation given above, and found that the exponent (equal to 2 in the above equation) deviated significantly from 2, especially for hydrate saturations above 50%, where an exponent above 4 was found. ■

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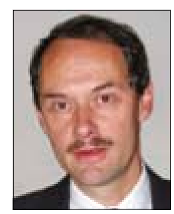

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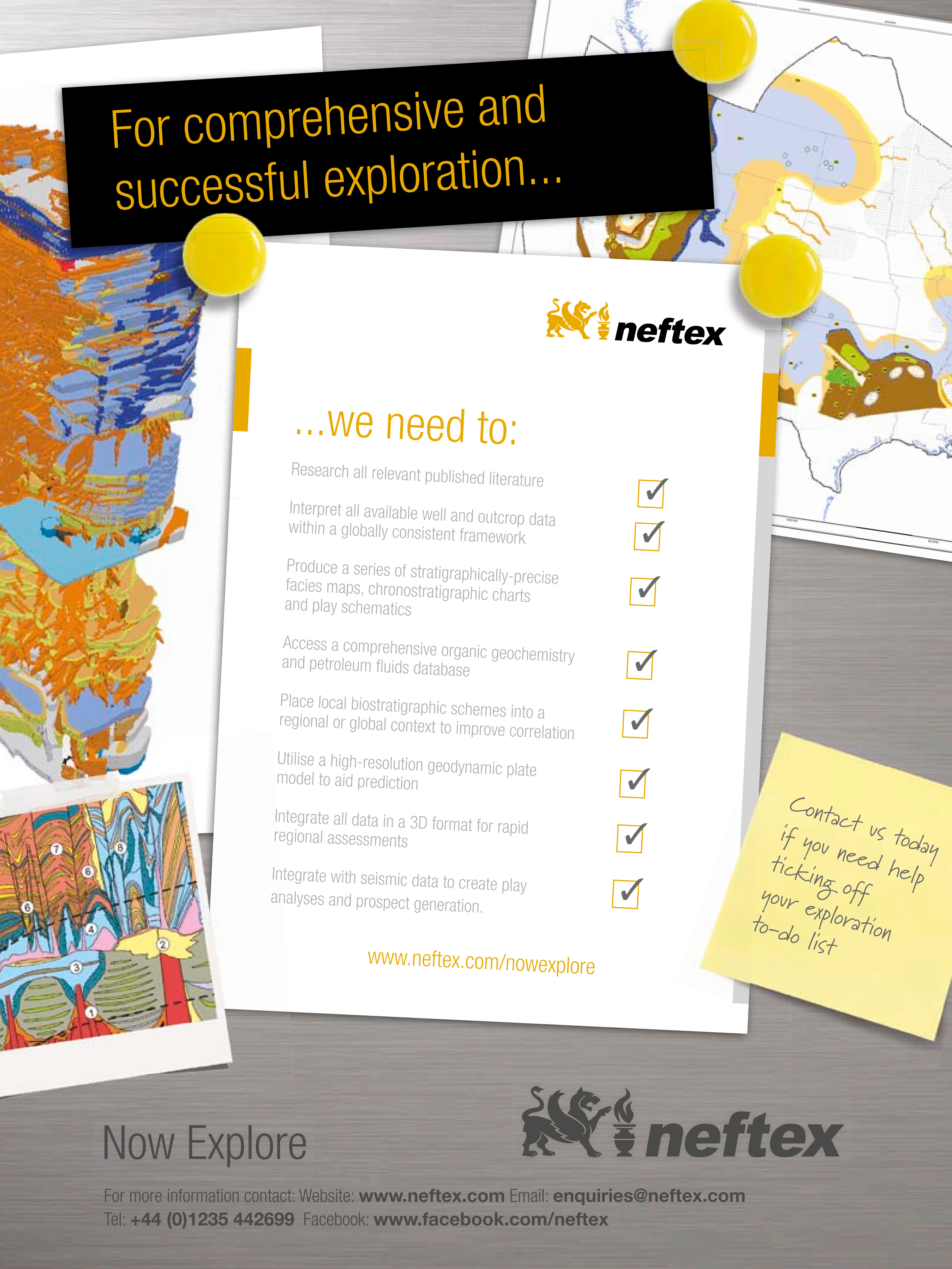
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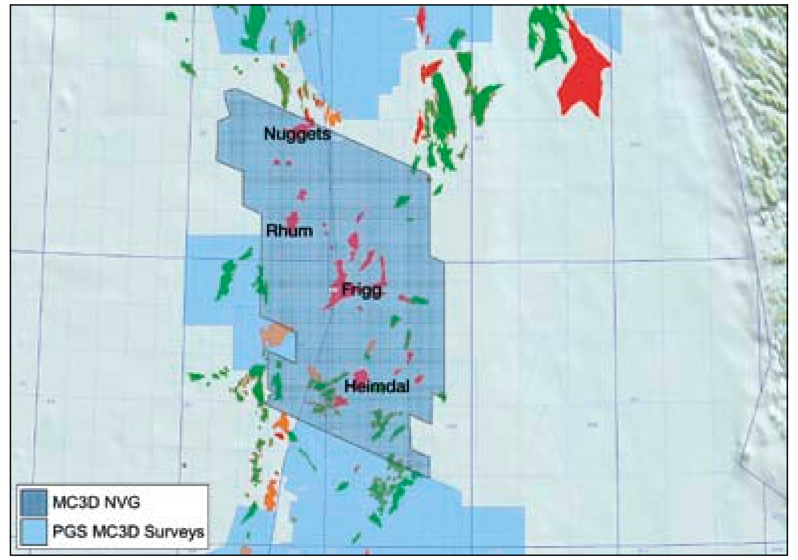
Broadband 3D:
Building Blocks for Exploration in a Mature Setting

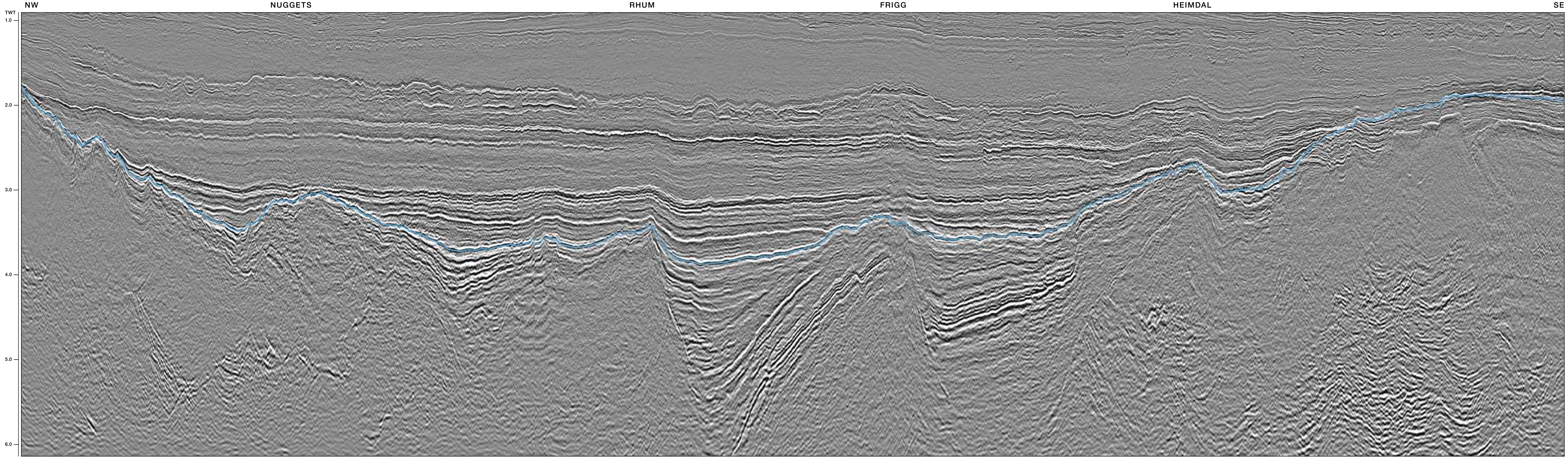
The North Sea is a mature hydrocarbon province in which there has been extensive exploration but where continued discoveries have ensured a sustained interest. The availability of modern, high quality seismic data has highlighted the continuing prospectivity of the Viking Graben such that, even after several decades of extensive exploration, development and production, it remains an important hydrocarbon exploration province.

The North Viking Graben GeoStreamer® MC3D seismic survey was acquired between 2009 and 2011 (in partnership with TGS) using the innovative dual sensor GeoStreamer technology. The result is a substantially improved dataset covering a significant area of the Nrth Sea, allowing the realisation of new potential in this mature region.

The seismic section shown traverses the North Viking Graben from the north-west to the south-east and transects several of the major fields and discoveries including Rhum, Frigg and Heimdal.



The MC3D NVG survey comprises MC3D NVG 09/10/11 GeoStreamer surveys acquired in conjunction with TGS and PGS MC3D NVG 05 survey.



Improved Resolution and Penetration with Broadband 3D

RUNE SAKARIASSEN, NICOLA O'DOWD AND CAROLINE LOWREY, Petroleum Geo-Services

The North Viking Graben is an established hydrocarbon province that after more than 30 years of exploration activity is widely regarded as mature. However, new, high quality data reveals additional potential in the area.

The NVG GeoStreamer® MC3D survey (acquired in partnership with TGS) was obtained over three seasons and provides high quality regional coverage along the North Viking Graben. PGS now has continuous broadband seismic data covering 5,800 km² in the North Viking Graben and this merges seamlessly into the SVG GeoStreamer MC3D survey in the South Viking Graben. The dual sensor technology enables the up- and down-going wavefields to be separated and this provides greater bandwidth and finer resolution of the seismic data.

PGS have championed the importance of regional datasets for many years and have been developing and extending the global MegaSurveys since the 1990s. Most recently there has been a focus upon ensuring that the regional data incorporates not only the widest possible geographic area but is also of the highest quality. In order to achieve this, PGS have embarked on a programme of new broadband seismic acquisition to produce high quality regional datasets. This enables a regional perspective and understanding to be obtained and also reveals the full exploration potential in the greatest detail.

In mature areas such as the North Viking Graben it is very important to continue to strive to improve the data and enhance image quality in order to expand upon existing plays which are far from exhausted and also to open new opportunities.

Grane in the Norwegian North Sea is an example of a field with an injectite reservoir. Such plays have complex geometries which can be recognised clearly on GeoStreamer 3D seismic

High Resolution Provides Insights

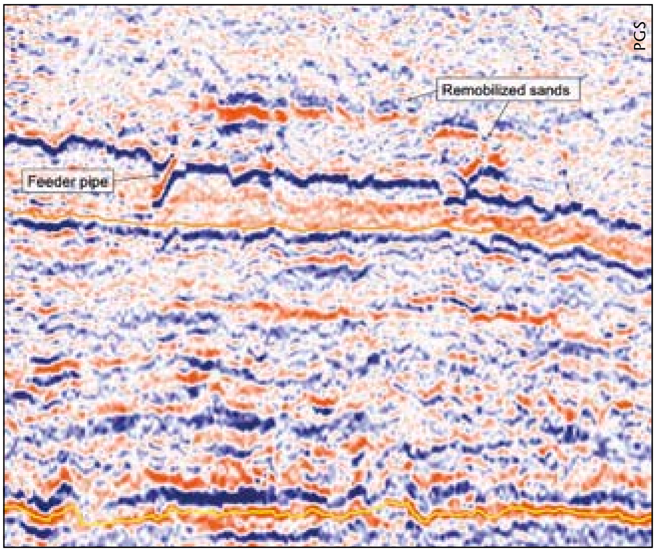
The North Viking Graben region is an established hydrocarbon province in the North Sea straddling the UK/Norway boundary and it contains important plays in both the Jurassic and Tertiary (particularly the Eocene and Paleocene) stratigraphic levels within the graben area. There are also underexplored plays in Lower Cretaceous sands and additionally the Paleocene/Eocene injectite play.

Exploration success began in the area in the 1960s with the discovery of the Balder field on the Utsira High (1966). Hydrocarbons were found in the Paleocene clastic sediments of the Balder Formation and successes within the Tertiary continued into the early 1970s with the discovery of the Eocene sands of the Frigg Field. However, these Tertiary plays can be complex in their distribution and development and difficult to model and map – the new high-quality data provides the opportunity of re-evaluating some of these difficult plays and prospects and offers the possibility of establishing new potential.

Where the fan systems are compartmentalised (such as in Frigg Field) with a variety of barriers and baffles, the production of the hydrocarbons is not simple. The high resolution retained in the GeoStreamer data could assist by providing more insight

GeoStreamer® Technology

GeoStreamer® provides broadband seismic information which enables deep penetration and high resolution data. This is achieved using dual sensor technology that enables the up- and down-going wavefields to be separated. By splitting the up-going pressure and down-going pressure and velocity wavefield it is possible to completely remove the receiver ghost. The technology also enables the streamers to be towed deeper, which both reduces the influence of noise and increases the low frequency signal, allowing for deeper penetration without damaging the higher frequencies which retain the high resolution.



A cross-section showing a high amplitude package, interpreted to be a remobilised sand body. A bright reflector indicates the location of the feeder pipe from the Eocene sands below.
Yellow – base Tertiary; orange – top Balder; blue – top Reservoir

into the overall connectivity.

Remobilised Tertiary sandstone reservoirs have become an important play to consider in both the UK and Norwegian sectors. They remain an underexplored and difficult play and the injected sand bodies generally have highly complex geometries and certain features that are infrequently successfully resolved on conventional seismic data. However, there are several well-known examples of injectite reservoirs including Gryphon and Leadon (UK) and Grane and Jotun (Norway). In these fields the injectites have excellent reservoir qualities, with high porosity and permeability values, and there is therefore every reason to believe that similar sands will in most cases form good reservoirs. The features which define the sand injectites, and which can be recognised within seismic, include mounds, detached reflectors which are often bright, and lateral wings and ridges which may cross-cut original stratigraphic relationships. The GeoStreamer data not only resolves these features, enabling a good definition of the sand geometry, but also the feeder dykes from the sand horizons below. This allows a clear assessment of the potential for charge from below and also the possibility of any top seal breach of deeper reservoirs. The GeoStreamer dataset is therefore very significant for refining any geological models and for reservoir evaluation.

Illuminating New Potential

Elsewhere, the enhanced resolution of the new NVG survey can illuminate new potential. The figure on the right shows a clear flat spot, that we are confident is a direct hydrocarbon indicator. The trapping structure is a 3-way dip closure against a low offset fault where the closure can be clearly mapped. Surrounding this feature are proven prospects and fields and we are confident that the hydrocarbon system in place can charge this structure. As the image shows, the flat spot is clearly visible on the NVG GeoStreamer survey, but is not visible in the legacy data we have over the same area.

The Lower Cretaceous has proved a significant play in the UK sector where the East Shetland Platform acted as a major sediment source. Equivalent age prospects on the Norwegian side of the graben are more difficult to locate and are arguably underexplored. However, similar sands have been found in the Lower Cretaceous on the Norwegian side of the North Sea in the recent Apollo discovery. This discovery indicates that the Utsira High area possibly acted as a local sediment source during Valanginian time and it is hoped that modern seismic may lead to discovery of more Lower Cretaceous reservoir potential in the area.

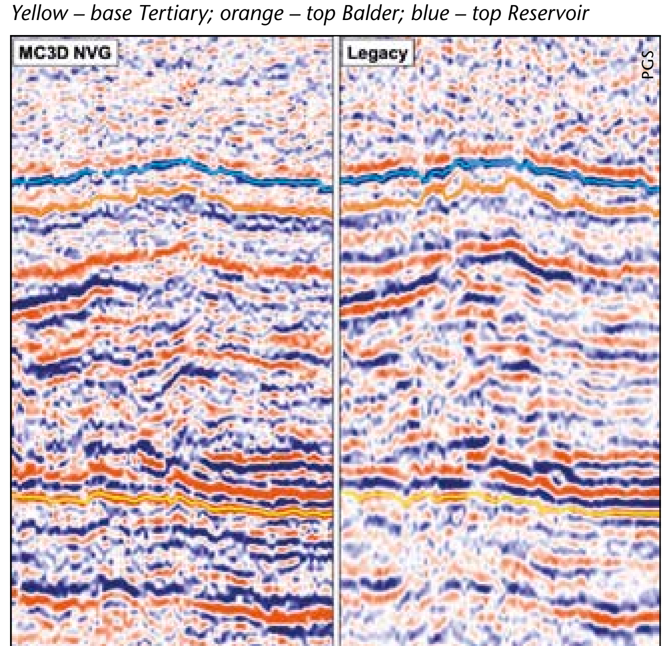
The Jurassic plays are important along both the Norwegian and UK continental shelves and the North Viking Graben is a classic sedimentary basin in which the extensional tectonics are fundamental to the distribution of oil and gas. With the higher quality broadband seismic it is possible to more clearly image the main structures at depth which control the distribution of hydrocarbons in the area – in particular in the Jurassic fields. The GeoStreamer line illustrated on the foldout shows the improved clarity and imaging of Brent fault blocks with, in particular, an improved definition (over legacy data) of the top Brent reflector which sheds new light on currently undrilled fault blocks.

Tool to Unlock New Plays

The area covered by this NVG survey represents a mature zone where the easy-to-find targets have already been discovered and exploited. The tool for unlocking further play identification and prospect generation is the newly acquired high quality 3D data. This allows us to unravel and interpret the complex geological features: stratigraphy, geometry, deep and/or fractured targets etc. and enables us to unveil new potential.

The significance of this technology was proven with the discovery of Johan Sverdrup from interpretation of GeoStreamer data, and in this NVG dataset it is now possible to see improved resolution and penetration along with previously unidentified DHIs. ■

A comparison between PGS GeoStreamer and legacy data over a 3-way dip, fault supported prospect. A large difference between the datasets is the presence of the flat spot in the GeoStreamer data, which is not resolved in the legacy data.
Yellow – base Tertiary; orange – top Balder; blue – top Reservoir



Clearing Cultural Borders to reach Common Goals

TED MOON

Steve Bate has taken diverse career paths to arrive at his current position as President and Chief Executive Officer (CEO) of INOVA Geophysical Equipment Ltd. At each stage, he has cultivated a culture of drawing on the strengths of his people and organisations toward a common cause. This perspective is helping his company achieve its goal of becoming the premier land seismic company in the industry.

Formed in March 2010, INOVA is a 51%/49% joint venture between BGP, a wholly owned subsidiary of China National Petroleum Corporation (CNPC) and ION Geophysical. One of Bate's main goals in leading the company has been to build INOVA's culture in a way that does not merely blend the cultures of its parent companies, but instead combines their strengths.

"Our operating and organisational philosophies have focused on embracing the individual attributes of ION and BGP, which include different geographies, styles of running a business and cultures," says Bate. "The end result is a unique INOVA culture, rather than a homogenised work environment."

This operational philosophy is one that Bate has developed during his entire career, which has included a stint serving as president of a light commercial and residential construction company and as founder of a consulting business that provided advisory services to small, rapidly growing businesses. He also held executive positions with Landmark Graphics and ION before being appointed INOVA's first CEO in 2010.

"In many of these positions, I was charged with rolling up different companies or taking businesses that already existed and streamlining them to drive greater operational efficiencies," he says. "I have seen first-hand the damage that can be done to a well-established company that is rebranded or restructured just for the sake of achieving a sense of sameness."

The end result is often a company that is less efficient or innovative than it was at the outset. To avoid this trap, Bate and his executive team have developed several initiatives that incorporate the positive cultural and organisational attributes of the parent companies to arrive at INOVA's operating culture.

The company's birthday celebrations are one area in which a

INOVA

global community spirit is fostered. "All 450 of our employees around the world wear the same INOVA shirt on our birthday, and have a little party at their offices," Bate says. "While each celebratory event and cuisine has its own regional flavour, we are all celebrating as part of the same team."

Long Quoc Nguyen, technician for INOVA's VectorSeis sensors, chats with Steve on the manufacturing floor in Stafford, Texas.

Face-to-Face Meetings

The INOVA culture stresses the importance of face-to-face communication to stay connected and share company objectives. For Bate and his team, this translates to travel, with frequent visits to INOVA's regional offices each year. Bate also conducts twice-monthly meetings with his global management team via video conference. These meetings are less focused on problem solving, but rather on building connectivity between managers such that everyone is engaged in the common goal of moving the business forward.

"The video conference format is a chance to break down the barriers to effective communication that arise via email exchanges or teleconferences," Bate adds. "By being able to actually see each other's faces while talking, much of the confusion or uncertainty behind a person's true message or intent is eliminated." The meetings are also an opportunity to make connections so that it becomes easier to reach out to colleagues in other offices for input on projects.

While this communication philosophy h as paid dividends, work remains to improve understanding of corporate goals on a global basis. "Even when you are talking face-to-face with a colleague from another country, cultural differences creep in," Bate explains. "We might use words or phrases that mean very different things to our colleagues, who are listening through their own set of cultural filters." Very quickly, this could lead to people reacting to a statement that was completely misconstrued and taking actions that move them farther away from the business goal.

"We have a solid business model and aggressive growth plans, and we're getting larger every year, but I don't want us to lose that entrepreneurial spirit that breeds an intimate connection between our employees," says Bate. "Without that connection, information gaps develop that prevent the best decisions from being made."

East meets West

"Special considerations have to be given to communication between teams in both hemispheres, particularly since the rules of engagement are so different in Eastern cultures versus the West," Bate continues.

The heritage BGP personnel are accustomed to working within governmental processes and regulations and to highly respect the chain of command in decision making. For instance, if a research scientist needed information from a sales person, they might send the request to their R&D manager, rather than go directly to the sales person. The R&D manager would relay this request to the sales manager, who would then seek out the appropriate sales representative to provide the necessary data.

"The Eastern 'strong leader' approach is more respect-driven, while in the West there is less attention to the chain of command and employees have no qualms about directly approaching a peer in another job function," says Bate. "Both models of communication have advantages, either in timeliness, efficiency or closing the loop across management."

INOVA employees are encouraged to communicate directly with one another, but certain information is best shared from the leadership team to their managers to maximise relevancy to the audience. Also, as Bate points out, the principles of seeking and sharing throughout the organisation encourage dialogue, which is a sign of respect for both the person seeking an answer and the person providing the information.

"Dialogue is important to me. I expect and encourage my managers to challenge my ideas," says Bate. "I need people around me who have different experiences, perspectives and opinions from mine, and are not afraid to share them. I'd say this is sometimes a stretch for my teams in both the Eastern and Western hemispheres, depending on the organisations they've worked for in the past.

"This approach has caught on, as evidenced by discussions at the executive video conferences. Not only do the Chinese executives speak more freely and offer their opinions, but executives in the West have also become more respectful of differing viewpoints."

By blending components of the Eastern and Western management philosophies, INOVA has arrived at a broader, more collaborative management team – one that not merely instructs its employees on the proper way to conduct operations, but is also open to learning and incorporating new ideas. "I would not want to hire anyone I could not teach, just as I don't want anyone on my team who could not teach me something," says Bate. "Whether you stop learning or you stop teaching, the result is the same. You stop growing."

Learning from Mistakes

INOVA is cultivating several initiatives that encourage the personal growth of its current and future leaders, including giving people the freedom to make decisions, without fear of major repercussions if the decision does not turn out exactly as planned. "Many people like to make suggestions, but may not have a great deal of experience of pulling the trigger on a decision," Bate says. "And of course, this can be a risky proposition – the bigger the bet, the harder the decision. Nevertheless, the more people making high-quality decisions on a real-time basis, the more successful a company will be."

One way INOVA is empowering its people to make more decisions is a technique called Leadership Intent, an adaptation of Commander Intent with its foundation in battlefield planning, to ensure personnel have very clear objectives when deploying to the field so they can manoeuvre through obstacles as they focus on their assigned objectives. "With this understanding, our regional personnel are empowered to deviate from the original deployment plan should unforeseen situations arise – which they inevitably will," says Bate. "The most important thing is that the final objective is met on time and within budget. And if something should go wrong in the execution of the plan, the decision-maker learns from this mistake to avoid it in the future."

To truly ensure that the company's message is conveyed so every employee has the right information to effectively understand the message and the goals, Bate is a strong proponent of a manager fine-tuning the message and conveying it directly to the next level below, rather than sending out a corporate-wide memo from the very top. "While employees in certain regions prefer to hear the message directly from me, we have seen that in other regions my message may get misconstrued," Bate says. "But because managers – whether it be in communications, finance or product development – each have their own unique style of engaging with their teams, it makes sense for them to tailor the message for maximum retention and understanding. Setting relevant context is key for good communication."

Predicting Industry Needs

"With this careful and calculated approach to conveying its corporate objectives, we plan to stay ahead of industry requirements for new seismic acquisition technologies. In particular, INOVA is trying to strike a balance between the needs of the operator and the contractor," Bate explains.

In helping an operator quantify oil and gas finds more efficiently, the company aims to provide value, which comes from higher-quality seismic data. "We are developing solutions that support denser surveys, more receiver points and provide an overall more sophisticated measurement," he says. "Ultimately, the objective is to give operators better data to make the best decisions."

Contractors need a seismic measurement platform with greater ease of use and in a package that is robust and reliable. This requires close communication between engineering teams who build the high-sensitivity equipment, and field technicians who are charged with handling the equipment in real-world scenarios and putting it through its paces to ensure reliability.

"We have recently advanced these goals with the introduction of highly flexible acquisition technologies. These include the cableless Hawk™ autonomous nodal system, which incorporates INOVA's VectorSeis® multicomponent digital sensors and supports three-channel analogue geophones for better characterisation in unconventional plays. The node is built from lightweight, high-grade aluminium for greater durability. The system has a transcription time that is at least three times faster than comparable systems, and allows for advanced quality control by drive-by or helicopter via Wi-Fi with the Connex Field Harvest Tool." INOVA also recently released its G3i™ cable system, designed for flexible land recording in rugged terrains. The system supports more than 100,000 channels and can be used to capture 2D, high-density 3D and time-lapse 4D data."

The new tools have been successfully deployed in regions ranging from the Marcellus shale of West Virginia, USA to oilfields in Western China.

"We could not continue to develop and deploy technologies such as these if we did not maintain open communications in a way that acknowledged our employees' cultural and technical differences," says Bate. "I believe that our differences, if properly aligned toward a common operational goal, will truly make INOVA an innovator in seismic acquisition for the 21st century." ■

Face-to-face meetings, onscreen and in person, are very important to keep the global hemispheres linked. Steve shares face time with his executive team in Calgary.

Sunset Magazine

Emma Summers: Oil Queen of California

"A woman with a genius for affairs – it may sound paradoxical, but the fact exists. If Mrs. Emma A. Summers were less than a genius she could not, as she does today, control the Los Angeles oil markets."
– *The San Francisco Call, July 21, 1901*

DON CLARKE

The early history of oil in Los Angeles would not be complete without the story of Emma A. Summers. The story begins when Edward Doheny and Charlie Canfield came to Los Angeles in the 1880s to get rich. Their well hit pay dirt in 1892 and started the oil boom with the discovery of the Los Angeles oil field; although this was not the original discovery of oil in southern California, it was the well that got things started. Doheny's genius was in finding a market for the oil, and he went on to become one of the most powerful and richest people in America. The movie, *There Will be Blood*, is roughly based on his life.

But in his own backyard he was beaten soundly by a piano teacher. This is her story.

Black Gold Fever

From the 1890s to the early 1930s Los Angeles was an oil boom town. New giant discoveries were made on a regular basis, from Brea-Olinda in 1880 and Los Angeles City in 1892, to Santa Fe Springs in 1919 and Wilmington in 1932. In fact, over 50 oil fields of the 68 discovered to date were found in that period. The oil men were rough and often played a treacherous game and no single company had a dominant share of the action. Businesses were started by drillers who flooded the local stock exchange with shares of start-up oil companies. The Los Angeles Stock Exchange had to open a special facility just to trade oil stocks – and the most successful entrepreneur was Emma Summers.

Born in 1858, Emma A. McCutchen was the daughter of a merchant banker and longtime mayor of Hickman, Kentucky. She was schooled at Boston's New England Conservatory of Music. After her 1879 graduation Emma married a carpenter, Alpha C. Summers, and headed west through Texas and eventually to Los Angeles, settling in 1883 on Old Fort Hill, before the old fort and gallows had vanished. She set up her piano teaching business at 517 California Street, a beautiful site with a 'majestic panorama of winter sunsets', – currently the site of the Hollywood Freeway, just north of Our Lady of the Angeles Cathedral. In 1890 Fort Moore and the gallows were replaced by Los Angeles High School, a brand new four-storey brick building. Emma prospered here and built a nice savings account.

In 1892 Doheny and Canfield drilled the discovery well for the Los Angeles oil field in the nearby Crown Hill area. This was a neighbourhood of neatly trimmed gardens and gingerbread houses, and the development of this field would change everything. The area was already subdivided into town lots which created a nightmare for development. The oil field would eventually encompass hundreds of small properties. Each owner had to drill or his neighbour would drain his oil under the 'Law of Capture', which means an individual can draw oil from under his neighbour's land as long as the oil flows from one property to the other. Oil development became so horribly managed that the first environmental laws and regulations were established to prevent it from happening again.

Emma didn't take long to get black gold fever. In 1883 she invested $700 of her savings to purchase a half interest in a well located a block or so from her house. Drilling ran into problems so she borrowed $1,800 more and sat by the well each night for weeks. Eventually it came in and she borrowed more to buy stakes in several more wells on Crown Hill. The production rate of her first wall has been lost, but it produced profitably for ten years. She later recalled, "When I found myself $10,000 in debt, I thought if I ever got that paid and as much more in the bank, I would be glad to quit." She got the $10,000 in the bank and didn't quit and soon became a constant presence in the ever-growing forest of oil rigs.

A Class Act

By 1897 Crown Hill (bounded by Temple, Figueroa and 1st Streets and Union Avenue) was overrun by oil men and promoters. There were over 500 oil derricks pumping away in the residential neighbourhood. Speculators, conmen and hopefuls turned the area into a bleak scene where some got rich and others lost everything. Tent cities sprang up and of course the prostitutes, bootleggers, gamblers and saloon keepers followed. They were busy 24 hours a day.

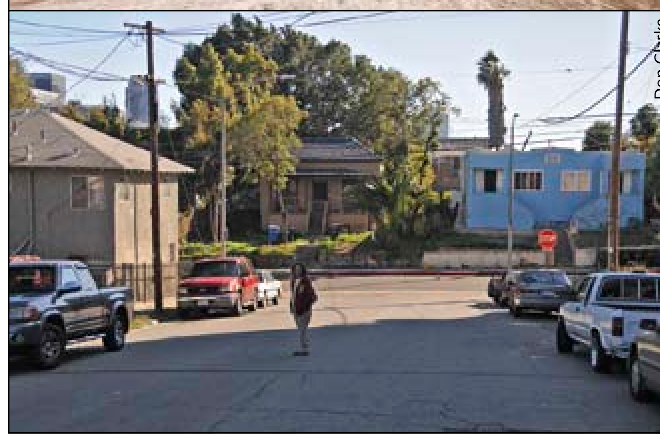
Summers could see that many of the operators were inefficient, corrupt or just incapable of participating in the oil business. She jumped right in. She went out to the wells and learned how the equipment worked and how to sell the oil. She also found ways to consolidate activities from several small operators. She directed activities and ordered equipment by day and did the bookkeeping and gave piano lessons in the evening. She also had 40 horses, 10 wagons, a blacksmith shop, and she expanded into processing with boilers. The oil in the field was thick, viscous and sediment laden (known as brea), so boilers were used to heat the oil, making the sediment fall out and the oil much more valuable. Emma was an independent self-sufficient woman, and it was said that she never let any raw edges show. She was a class act.

Emma's business absorbed many failed competitors and forced others out of business. She set out to corner the market by mastering the rules of supply and demand. Her major clients were downtown hotels, factories, several railroad and trolley lines and the Pacific Light and Power Company. She produced the oil, refined it and delivered it to the customers. "It has been like this with me always," she recalled. "I saw a chance in the oil business and sunk a well, and that carried me on and on until I couldn't stop."

Volatile Prices

By 1900 she controlled half the production in Doheny and Canfield's oil field with 14 wells producing 50,000 barrels per month! She treated her customers and workers fairly and made a fortune. They treated her like royalty and soon she became known as the Oil Queen of California.

Production peaked in 1901 when 1,150 wells pumped 1.8 MMbo. By then, with over 200 operators in the field, there were too many wells draining a limited reservoir. Oil prices went up to $1.80 and then dropped to 15 cents a barrel in 1903 because production vastly surpassed the demand. For a short period of time it dropped to 10 cents a barrel. The cheap oil was used to seal the unpaved roads of Los Angleles for dust control, but the gummy black brea stuck to the carriage wheels and to shoes. Soon asphalt was invented and oil was used instead for household and water heating and it was found to make a great fuel for locomotives. Oil



Los Angeles City oil field in the 1890s, and the same shot in 2012

prices were volatile and seesawed unpredictably, but as demand grew Emma made her move to corner the market.

Emma set up a suite of offices in the new I. W. Hellman Building at 4th and Spring Streets where she distributed oil products. She did this without taking on any other investors. Summers had an eye for detail, was well organised, highly intelligent and most of all, patient, as she bought out the busted operators for pennies on the dollar.

The cheap oil had leaked from redwood storage tanks and downtown Los Angeles had become an environmental mess. Soon Los Angeles clamped down on the oil operators with new regulations, bringing a cleaner city and rising oil prices. World War I and the rise of the automobile added to her wealth, and Emma expanded her empire to include theatres, apartment buildings, a

The last producing well in the Los Angeles City oil field, the field having produced continuously since 1892.

mansion on Wilshire Blvd., several ranches in the San Fernando Valley, Summers Paint Company and a highly valued art collection.

Oil Boom Peaks

Decline finally came to Crown Hill and the workers and their families moved to new oil strikes in Santa Fe Springs, Long Beach, Torrance and Inglewood. Summers' wells continued but their output was small in comparison to the new discoveries and after 1915 only two wells were drilled in the field.

For Emma the oil boom had peaked and troubles followed. "There are men in Los Angeles who do not like Emma A. Summers," read the July 1911 issue of *Sunset* magazine. Soon after her move to the new mansion on Wilshire Blvd. Los Angeles County Sheriff's deputies seized about $60,000 worth of oil and watercolor paintings to satisfy a $1,000 court judgment against her in a dispute over the sales of sugar stock. Emma soon left her new mansion, which was located where the Bullocks Wilshire would be built in 1929.

Emma moved into a large home she owned on California Street which sat atop the Broadway tunnel. She turned the place into an elegant and profitable hotel, appropriately called the Queen. She then moved out of the Queen and set up a very comfortable residence at the Biltmore Hotel and then at the Alexandria Hotel for most of the rest of her life. She moved into a Glendale nursing home in 1940 and died there in 1941 at the age of 83.

Several questions come to mind. What happened to her husband? He died sometime before 1939. Did she have children? What of her family – did she involve other family members in her businesses? Her brother ran the paint business and her niece got married in Emma's Wilshire mansion, but

Courtesy of Sunset Magazine, July 1911

Emma Summers' mansion on Wilshire Boulevard

there appears no mention of children.

More than 70 years after her death, Emma Summers remains an inspiration to anyone who wants to succeed in business. ■

Acknowledgements

This article was summarized from the following references and several internet sources.

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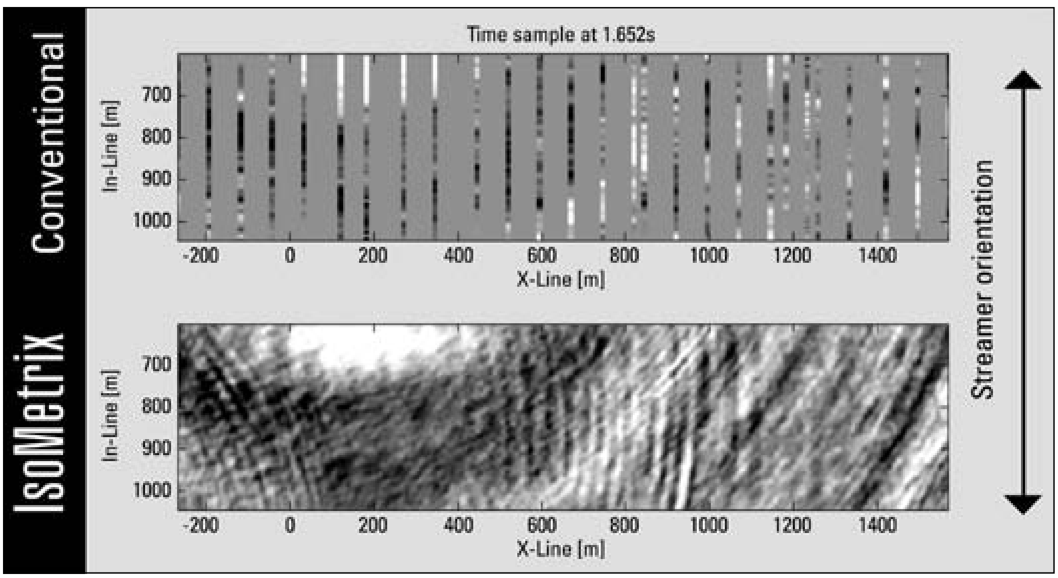
A restored Victorian house on Edgeware Street, a couple of blocks from the discovery well drilled by Doheney and Canfield and in the area controlled by Emma

Don Clarke

Reading Between the Lines

Point-receiver data, isometrically sampled in both crossline and inline directions, fully captures the three-dimensional seismic wavefield for the first time.



These two images are from a 2011 IsoMetrix test survey. The streamers were 75m apart and are represented vertically. Conventional 2½D lines are visible in the top section. Shown at the bottom, IsoMetrix technology correctly reconstructs the whole wavefield, including returns from geologic fault planes that run across the streamer spread. Point diffractors image perfectly.

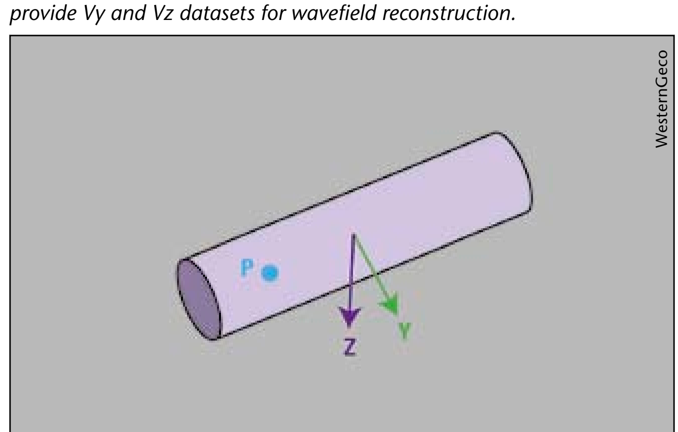
STEVE HARRIES,
WesternGeco

Even the most cursory study of an outcrop such as a cliff or quarry face will show that structural and stratigraphic variations in geology are three-dimensional. This is particularly the case for hydrocarbon reservoirs, where trap closure is required in all directions. It is nearly 100 years since the reflection seismic method was first used to image the subsurface, and since then it has evolved to deliver increasingly accurate 3D geological models and more reliable inversion to reveal indicators of rock properties.

Marine 2D seismic surveys, acquired with a single streamer, have typically covered grids of lines several kilometres apart, requiring geological interpretations to be interpolated over long distances. Before the advent of multi-streamer operations, some operators experimented with reducing 2D line-spacing to 100s of metres and interpolating to a finer grid during data processing. The method, dubbed '2½D', achieved limited success in creating reliable 3D data volumes.

The 1980s saw the development of multi-streamer marine seismic surveys. Today, these surveys are typically acquired by a vessel equipped with between 8 and 16 streamers towed 50 to 100m apart, each 3 to 8 km long. Each streamer contains hydrophone sensors, and spatial sampling of the data recorded along each streamer (inline) can be as fine as 3.125m; however, the much greater distance between adjacent streamers means that sampling in the crossline direction can be 16–32 times sparser. Although described as '3D', the method acquires data so coarsely spaced in the crossline direction that it is still essentially '2½D', as it cannot capture the whole 3D wavefield and so is limited in its ability to accurately image the subsurface. While developments in seismic sources and sensors have improved the frequency bandwidth that can be input to the subsurface and subsequently recorded back at the surface, achieving truly 3D high-resolution images of complex structures also requires adequate spatial sampling in both the inline and crossline directions.

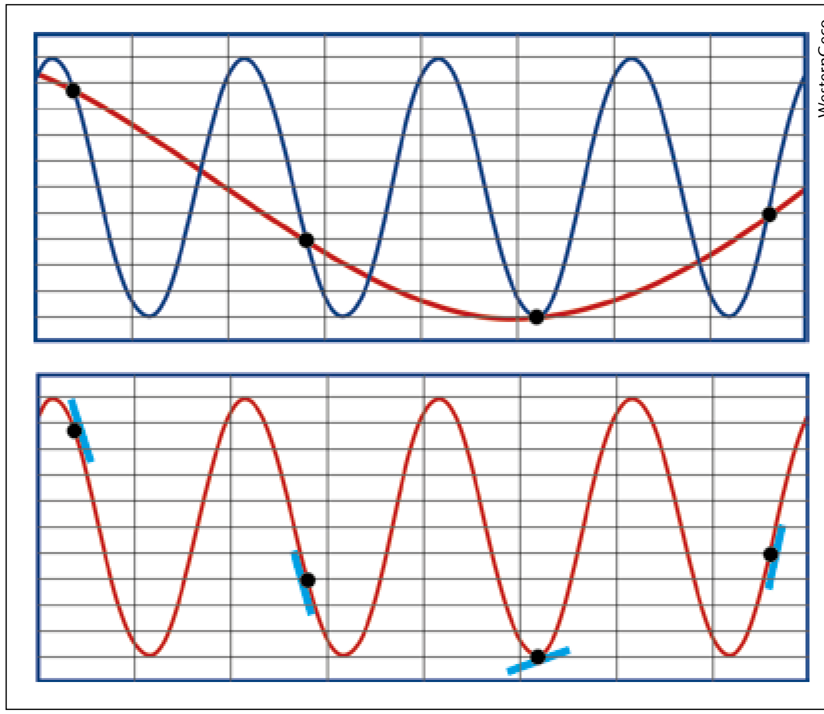
The Nessie-6 streamer delivers point-receiver sampling of pressure (hydrophone) and MEMS-based measurements of acceleration that provide Vy and Vz datasets for wavefield reconstruction.



New Towed Streamer Technology

The recently launched IsoMetrix marine isometric seismic technology delivers high-fidelity point-receiver seismic data while overcoming spatial wavenumber bandwidth compromises that have limited previous marine seismic acquisition methods. The result is a reliable, continuous measurement of the full upgoing and downgoing notchless seismic wavefield sampled at a 6.25m x 6.25m point-receiver surface grid. This fine isometric sampling in both crossline and inline directions makes the data suitable for use in a wide variety of interpretation and modelling applications, such as high-resolution near-surface imaging, deep reservoir characterisation, and 4D reservoir monitoring.

Isometric 3D sampling is enabled by a towed streamer design that combines measurements of wavefield pressure and gradient – vertically and crossline. Called Nessie-6, this new-generation streamer, a key component of the acquisition system, uses point-receiver technology that combines hydrophones with calibrated point-receiver microelectromechanical system (MEMS) accelerometers that measure the full particle acceleration due to the upgoing and downgoing seismic wavefield. Direct measurement of the vertical and crossline gradient enables unaliased reconstruction of the pressure wavefield between the streamers.



Measurement of crossline gradients enables unaliased reconstruction of the seismic wavefield between streamers. The blue waveform represents the actual signal, and the red waveform the reconstructed signal. The figures contrast reconstructed signal with pressure-only measurements as recorded in conventional surveys (top) versus pressure + gradients as recorded in IsoMetrix surveys (bottom).

Full Bandwidth Deghosting

Conventional towed-streamer marine seismic acquisition systems deploy sources and streamers at shallow depths, typically between 6 and 10m. This configuration enables recording of the high frequencies needed for resolution, but attenuates the low frequencies needed for stratigraphic and structural inversion. Shallow towing also makes the data more susceptible to environmental noise such as waves, swell and wind. Towing sources and streamers at deeper depths enhances the low-frequency content and can increase the signal-to-ambient-noise ratio (S/N); however, it attenuates the high frequencies. The attenuation is due to interference of the upgoing seismic wavefield recorded by the pressure sensors by its 'ghost' – the reflection of the wavefield after bouncing back from the sea surface above the streamer. The IsoMetrix system overcomes the need for compromise when deciding tow-depth. For each Nessie-6 streamer, high-quality measurement of the vertical particle acceleration – with good S/N down to 3 Hz – enables separation of the pressure wavefield into its upgoing and downgoing components, facilitating removal of the receiver ghost. The source ghost is addressed by a newly developed calibrated marine broadband seismic source family of notchless seismic sources.

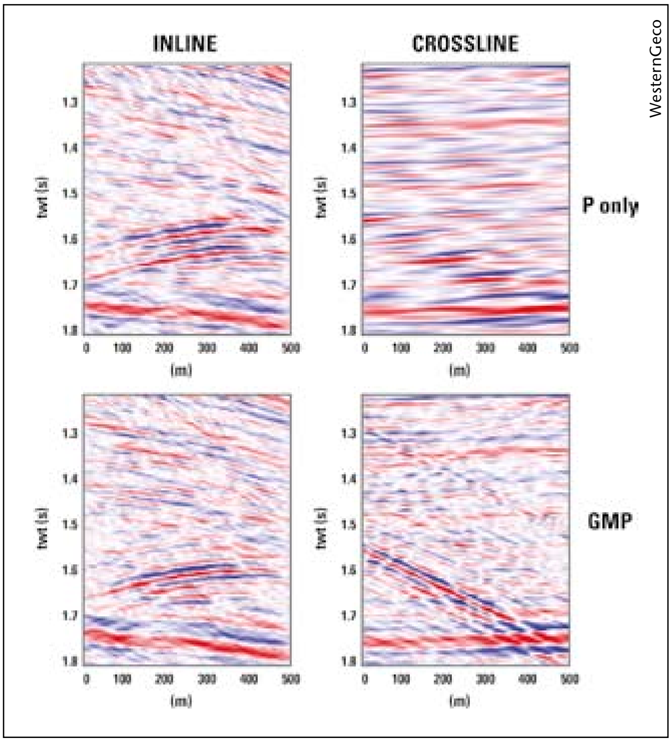
In combination with a solid streamer design, the ability for full-bandwidth deghosting allows the extension of the seismic acquisition window by making the results of data acquisition less affected by adverse weather conditions. In addition, adequate sampling of coherent noise from external sources such as rigs and other seismic vessels means that it can be effectively removed at an early stage of processing.

3D Wavefield Reconstruction

The spatial gradient of the seismic pressure wavefield is directly related to the particle velocity vector, and can be derived from measurements made independently by multicomponent sensors. This knowledge enables multichannel reconstruction of the pressure wavefield in the crossline direction far beyond the aliasing limits that are possible with hydrophone-only or hydrophone plus vertical gradient data. A new computer algorithm called the generalised matching pursuit (GMP) method uses crossline (Vy) and vertical (Vz) particle velocity components of both the upgoing and reflected downgoing wavefronts derived from the Nessie-6 multisensor streamer data to achieve simultaneous reconstruction and deghosting of the seismic pressure wavefield in a 3D sense. It can compute the upgoing and downgoing separated wavefield at any desired position within a spread of streamers and has been shown to be extremely robust in dealing with highly aliased data.

Improved 4D Repeatability and Flexible Geometries

The IsoMetrix technology incorporates several field-proven elements of the WesternGeco Q-Marine system, including its proprietary marine seismic streamer steering system and intrinsic ranging by modulated acoustics (IRMA) system to control the positions of the entire seismic spread. The ability to reconstruct the wavefield at any desired grid raises 4D repeatability to an unprecedented level to better reveal subtle variations in seismic responses related to changes in reservoir fluids and pressure. When comparing to a conventional towed streamer baseline, a set of 'virtual' streamers can be produced to perfectly match the positions of the existing survey. The



Top: Pressure (P) wavefield reconstructed using a matching pursuit method based on P-wave data alone as recorded in conventional surveys. Bottom: P wavefield reconstructed with GMP method using Vy and Vz particle velocity vector data recorded in IsoMetrix surveys.

ability to reconstruct both the upgoing and downgoing wavefields allows redatuming to further improve comparison with previous surveys. These workflows can resolve previously inherent conflicts in planning 4D projects between referencing a previous survey or creating the best possible new baseline. Now, both objectives can be met from a single survey.

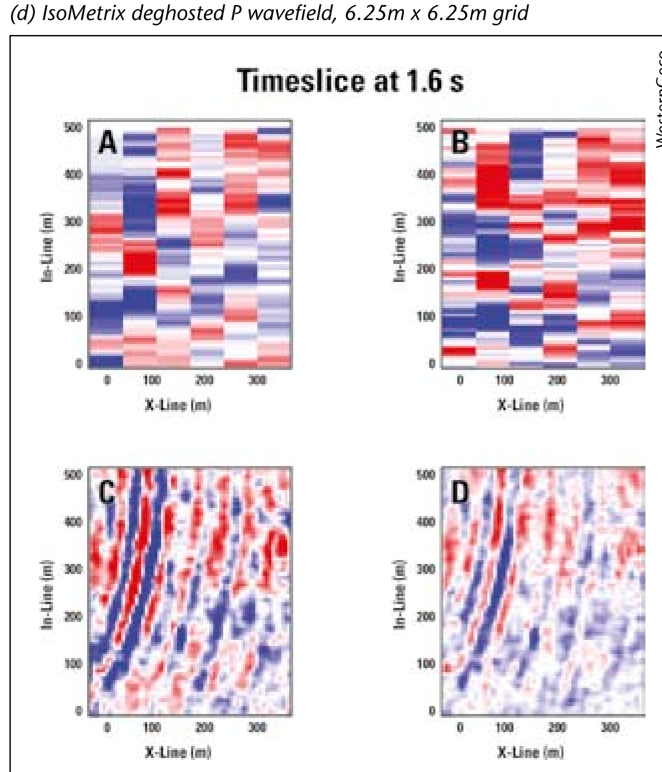
While most 3D marine surveys are acquired with linear geometries using a single vessel, an increasing number have been successfully completed using alternative configurations. Complex 3D geology and highly refractive layers cause ray bending that can leave portions of the subsurface untouched when recording seismic waves travelling in just one direction. Wide-azimuth (WAZ) seismic surveys designed using several seismic vessels working together have been shown to deliver better illumination of the subsurface; higher signal-to-noise ratio; and improved seismic resolution in several complex geological environments, such as beneath large salt bodies with complex shapes. The Coil Shooting technique goes beyond WAZ to acquire a full range of azimuths using a single vessel shooting continuously with a circular or curved path. Where long-offset data is also required, such as for imaging below deep complex structures, the Dual Coil Shooting multivessel full-azimuth (FAZ) acquisition system can be deployed. The IsoMetrix service is compatible with recording geometries such as multi-vessel WAZ, and the Coil Shooting and Dual Coil Shooting FAZ methods. The ability to deliver isometrically sampled broadband data of exceptional quality and 4D repeatability is expected to enable innovative configurations of seismic imaging technology that are able to address currently intractable exploration and development challenges while simultaneously improving productivity.

A Fully Commercialised Service

The launch of the IsoMetrix marine isometric seismic service was announced in June at the European Association of Geoscientists and Engineers (EAGE) 2012 annual conference and exhibition. It is the result of an extensive 10-year research and engineering programme that has been the largest single engineering project ever undertaken by Schlumberger. The program not only delivered the new seismic acquisition technology, but also the algorithms and workflows needed to manage the unprecedented amount of data it produces. Speaking at the launch, Carel Hooykaas, president, WesternGeco, compared the step-change in quality delivered by the IsoMetrix technology to that achieved moving from a 2D x-ray to a 3D CAT-scan in medical imaging.

Field trials in 2011 proved the new system's capabilities, achieving a 12:1 crossline reconstruction ratio and producing a 6.25m surface data grid from streamers 75m apart. During August 2012, the 3D seismic vessel *Western Pride*, deploying eight full-length streamers, transited to the North Sea where it completed acquisition of its first commercial project on schedule. During September, proprietary surveys were acquired for two other North Sea operators. The new technology has proved to be very robust during operations and is attracting considerable interest from oil and gas exploration and production companies of all sizes around the world. Manufacturing of the new system is running at full-speed in one of the WesternGeco manufacturing facilities, and the company has developed a rollout schedule for the introduction of the new technology among its worldwide fleet of 3D vessels. ■

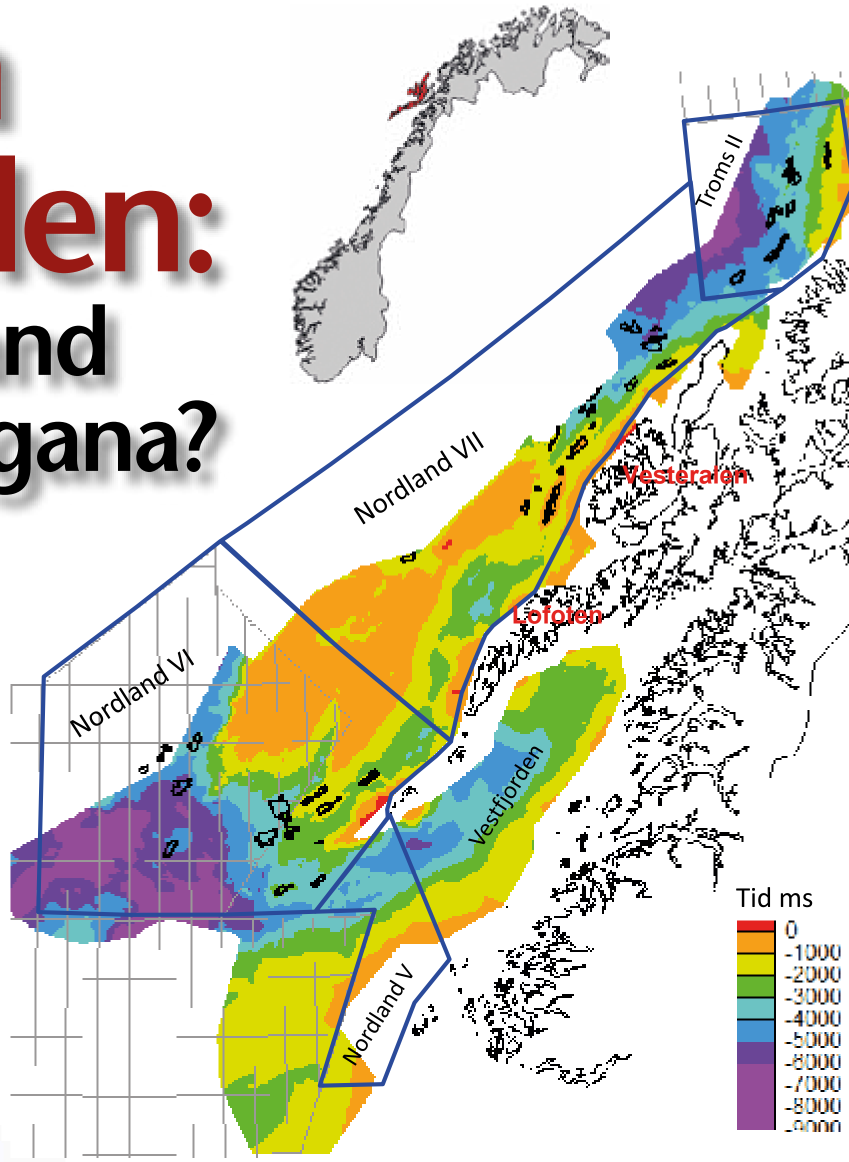
Data example from a North Sea test programme
(a) Input P data, 6.25m (inline) x 75m (crossline) conventional sampling
(b) Input Vy data, 6.25m (inline) x 75m (crossline) conventional sampling
(c) IsoMetrix reconstructed P wavefield, 6.25m x 6.25m grid
(d) IsoMetrix deghosted P wavefield, 6.25m x 6.25m grid



Lofoten and Vesterålen: Promised Land or Fata Morgana?

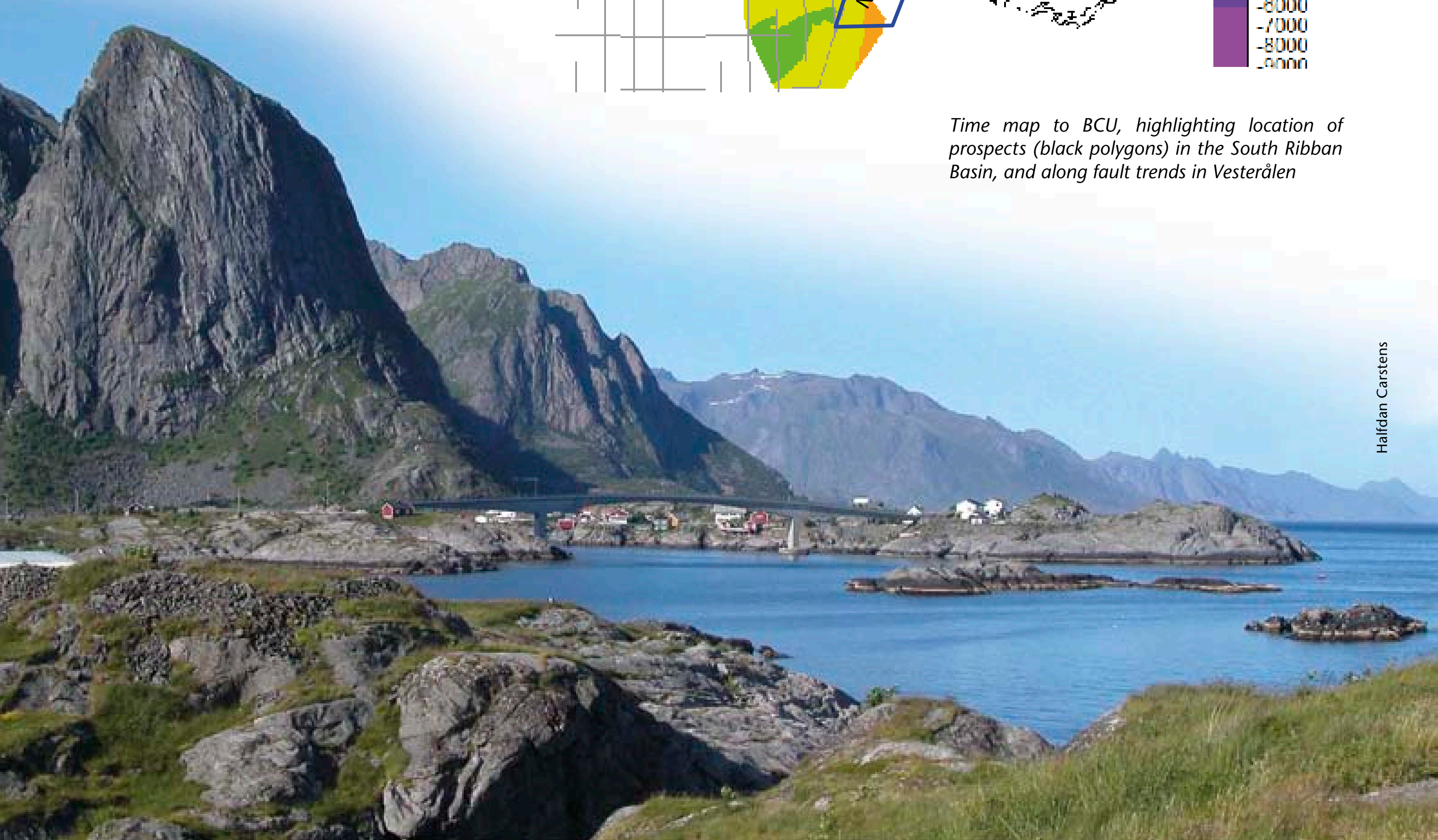
KARSTEN EIG

Offshore the remote and beautiful Lofoten and Vesterålen Islands, 1,000 km north of Oslo, is the last large, still unopened section of the Norwegian Atlantic margin.



Norwegian Petroleum Directorate

Time map to BCU, highlighting location of prospects (black polygons) in the South Ribban Basin, and along fault trends in Vesterålen

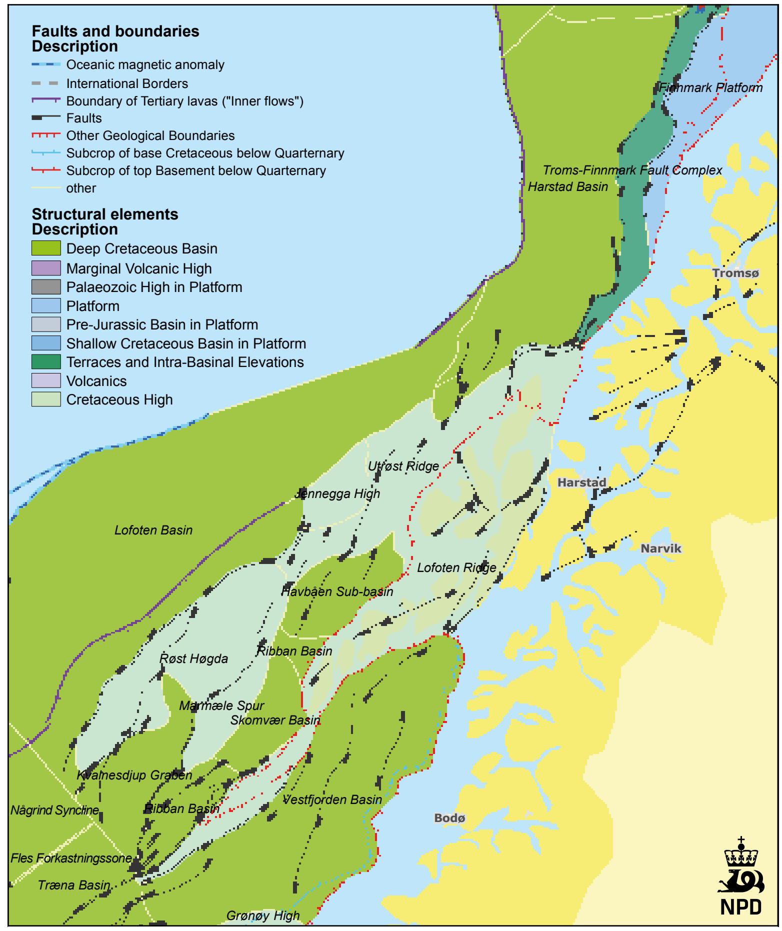


Halfdan Carstens

In 2010, the Norwegian Petroleum Directorate estimated (P50) that the Norwegian Atlantic areas of Nordland VI, VII and Troms II, near the Lofoten and Vesterålen Islands, could hold as much as 1.3 Bboe while the industry players' P50 figure is even larger, at 3.5 Bboe. Well defined Jurassic rotated fault blocks, similar to the play that holds giants like Åsgard, Skarv and Norne, make the area potentially attractive.

However, concerns for the environment and fisheries have so far kept most of the area closed to exploration. The southern part of Nordland VI was open from 1996 to 2001, with one dry well drilled into the Cenozoic. The main Jurassic play is still unexplored, but there are clear indications of an active petroleum system.

Four stratigraphic wells in the Ribban Basin and two offshore Vesterålen suggest a sedimentology similar to that found along the Nordland coast. The basement is Triassic fluvial coarse conglomerates, sand and shale. The Lower to Middle Jurassic consists of shallow marine sandstone, the main reservoir, followed by upper Jurassic shale, including the well-known rich Kimmeridgian source rock. The Lower Cretaceous consists of mainly shale in the wells, but seismic anomalies may indicate turbidite sands. From the Upper Cretaceous and the early Cenozoic, sands up to a hundred metres thick – the targets of the sole commercial well – are possibly the result of erosion of the uplifted mainland. They are overlain by Upper Cenozoic shale and Quaternary glacials.



Geological and structural map of the Lofoten and Vesterålen area, showing that Lofoten is the only exposed basement high on the Norwegian Continental Shelf.

Enigmatic Structure

And yet, Lofoten and Vesterålen are different; enigmatic even. The Lofoten Ridge itself is unique, being the only exposed basement ridge on the Norwegian continental shelf. It consists of crystalline rocks up to 1.3 billion years old. The ridge is separated from the mainland by the Vestfjorden Basin, an asymmetric graben which opens towards the south, like a fan. It is filled with sediments interpreted to be of Palaeozoic to Recent age, with the main deposition through the Cretaceous. A similar feature, the Ribban Basin, lies on the ridge's west flank, and is in turn separated from the shelf edge by the less pronounced, submarine Utrøst basement ridge. The Ribban Basin is split in two by a major fault block, the Marmæle spur. Towards the north, the Lofoten Ridge merges into the large islands of Vesterålen, while the shelf narrows to a thin band, only 40 km wide at the narrowest. Curiously, faults on this thin margin consistently dip to the east in the south and to the west in its northern part, and in both areas fault blocks are strongly rotated over (interpreted) low-angled detachment faults.

The major syn-rift phase in the Ribban Basin is early Cretaceous, followed by late Cretaceous and Paleocene post-rift sediments. In the deeper basin, a pre-rift sequence of Triassic and Jurassic age rests on crystalline basement. The Base Cretaceous Unconformity and the bright amplitude of the late Jurassic source rock are prominent on seismic data, but the unconformity becomes less pronounced updip on the western flank, and this succession seems to be eroded on fault crests. The deeper part of the basin is obscured on seismic, especially in the Vestfjorden Basin, where seismic coverage is sparse and of old vintage. Deep parallel reflections suggest that older, Palaeozoic sediments reside in the deep Vestfjorden Basin, although this is uncertain. Seismic character in the western Ribban Basin may suggest the presence of a local, deep Palaeozoic sub-basin there as well.

In contrast, the narrow Vesterålen margin exhibits narrow, fault-defined half grabens filled with a Mesozoic succession, similar to further south, but which is heavily eroded, due to a major uplift.

Origins of the Lofoten Ridge

Why is the Lofoten Ridge there, surrounded by deep basins? Why does the shelf narrow, and why did Vesterålen lift two kilometres up? The reasons stretch 400 million years back in time.

During the clash of Europe with Greenland and North America, which created the Caledonian mountain chain, the mountains probably collapsed along strike, a phenomenon known from the Himalayas today. Major detachment zones developed, and in north Norway these are consistently spoon-shaped, with axes plunging gently to the south-west or north-east.

It is likely that the Vestfjorden and Ribban Basins represent similar spoon-shaped troughs, developed as the mountain chain stretched along strike, with the basement ridge emerging between. Seismic interpretation suggests that the basin-bounding faults flatten out into low-angled detachments, and within the basement are prominent reflections that may be downthrown imbricated thrust nappes. Gravimetric-magnetometric data reveal a very prominent positive anomaly along the Lofoten Ridge, which fits with a shallow Moho. The basement below the basins is modelled to be low-magnetic, indicating that they are buried metasedimentary thrust nappes, rather than the high-magnetic basement of the Lofoten Ridge. Notably, gravity modelling also supports the suggestion that older sedimentary basins may be present deep beneath Ribban and Vestfjorden, possibly analogues to the Devonian post-Caledonian basins in western Norway. On the mainland, the Steigen detachment forms a spoon-shaped detachment parallel to Vestfjorden, the 'Sagfjorden shear zone', with Precambrian basement in the footwall and lower allochton phyllites in the hangingwall.

Different Tectonic Styles

The major part of the Lofoten Ridge consists of gneisses and igneous rocks, but the outermost islands of Værøy and Røst exhibit highly deformed mylonites. Røst is entirely flat, defined by a pervasive foliation. There is evidence for both north-east to south-west and north-west to south-east oriented stretching of the foliation, which is thought to reflect the initial orogen-parallel extension, followed by perpendicular, post-orogen extension.

Ar/Ar dating of mica by Steltenpohl and co-workers indicates that Lofoten was successively exhumed from the north-east to the south-west during the Carboniferous and Permian. A probable mechanism is reactivation of the footwall between the Caledonian troughs, which was simultaneously exhumed as the Lofoten Ridge. Thereafter, during the Mesozoic and Cenozoic, steep faults developed along the basin flanks to form the present basin and ridge configuration.

The tectonic style in Vesterålen is different from Lofoten. Seismic sections show fault blocks heavily rotated above low-angled detachments. Substantial stretching took place during the Mesozoic, followed by up to 2 km of uplift and thus erosion into the sediments. Widespread fractured and weathered basement onshore, often transformed to gravel, demonstrate that subaerial weathering took place in the basement. The structural style thus resembles a basin and range-style metamorphic core complex.

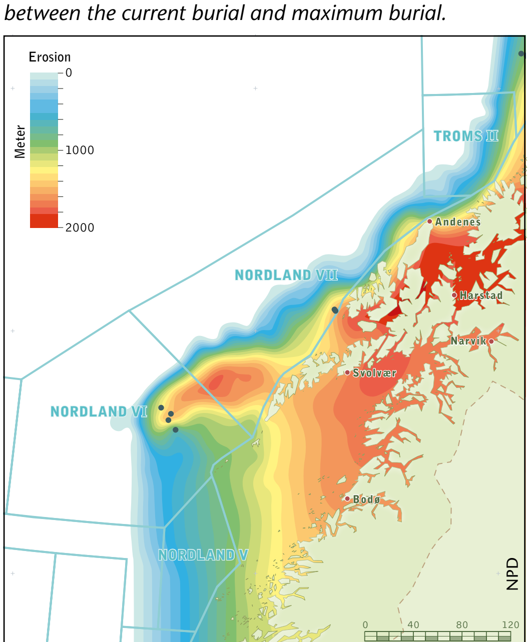
Prospectivity

As a result of this uplift, hydrocarbon retention will be a major issue offshore Vesterålen. The northward uplift of Lofoten may create migration paths from traps to the surface, although this is less likely further south. Migration from source to trap generally has low risk in Lofoten, with the reservoirs just below the source rock and some with large catch areas on basin flanks.

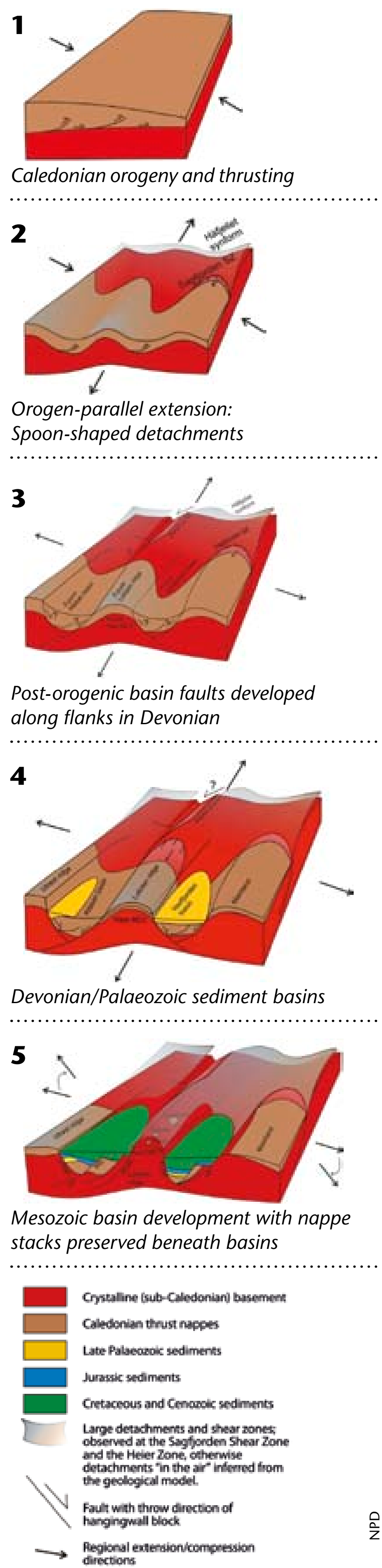
Due to the overall spoon shape of the Ribban and Vestfjorden Basins, the Upper Jurassic source may have matured during the Cretaceous across large areas, but may today possibly be over-mature in the deep basins, and within the generation window today only along the gently dipping flanks of the Ribban Basin and the Marmæle Spur. In Vesterålen, burial and maturity is uncertain due to uplift.

The quality of seismic in the Lofoten and Vesterålen area is variable. At prospect level it is generally good down to the Base Cretaceous Unconformity, but the intra-Jurassic architecture and section to basement is more uncertain. For prospects on highs or protruding fault blocks, the sediments appear to wedge out towards the crest, either due to block rotation during deposition, or as a result of erosion, and only a thin

Map showing estimated total erosion in metres in the Lofoten and Vesterålen region, expressed as the difference between the current burial and maximum burial.



Compiled model of the tectonic evolution of Lofoten and Vesterålen Islands since the Caledonian



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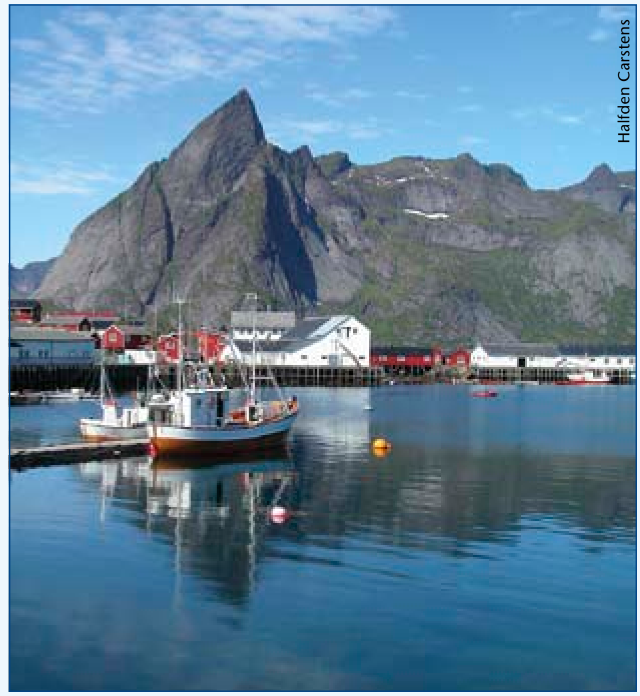
The Lofoten Islands

This remote archipelago of ten islands, around 200 km north of the Arctic Circle, is renowned for its astounding wildlife and stunning scenery, with delightful whitewashed villages nestling at the base of mountains rising dramatically straight from the sea. Although lying within the Arctic Circle, the archipelago experiences one of the world's largest elevated temperature anomalies relative to its high latitude, and it is therefore popular for fishing, climbing, mountain walking and whale safaris, while enjoying the midnight sun in the summer. The islands shelter killer and sperm whales and many different species of seabirds, and the surrounding waters are the spawning ground for the North-east Arctic cod, the largest remaining stock in the world, according to the World Wildlife Fund.

Environment groups therefore believe the areas off Lofoten are too sensitive for oil and gas production. As a result there is a moratorium on exploration, including seismic and EM surveys, at the moment, and there are moves to make the islands and much of their surrounding waters a protected UNESCO World Heritage site.


Halfden Carstens

sedimentary reservoir will be available.

As previously mentioned, fractured and weathered crystalline basement is abundant in the area and such rock may itself constitute a reservoir, although with low porosity. If located on top of a fault crest, fractured basement may provide a conduit between a sediment reservoir wedge and a leaking fault, and thus create bottom seal risk.

A Promised Land?

The oil industry in Norway has to some extent regarded this area, and especially the south Ribban Basin, as a promised land, because the main play model is similar to that seen along the Norwegian coast. As this article has shown, however, the real situation may be more complicated because of the unique tectonic history of the area.

Furthermore, the main prospects are in the middle of the richest fishing grounds in Norway and relatively close to the shore, where there are important bird colonies. Substantial precautions need to be taken if opening the area to the oil industry is to be considered.

Finally, additional opportunities may be present in both the Jurassic and the Cretaceous to Palaeocene on the distal shelf. On seismic data, flow basalts and intrusives mask much of the section beneath the upper Cenozoic, which is therefore not discussed in this article.

Acknowledgements

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See GEO ExPro Vol.7, No. 5 for further information on exploration in this region.

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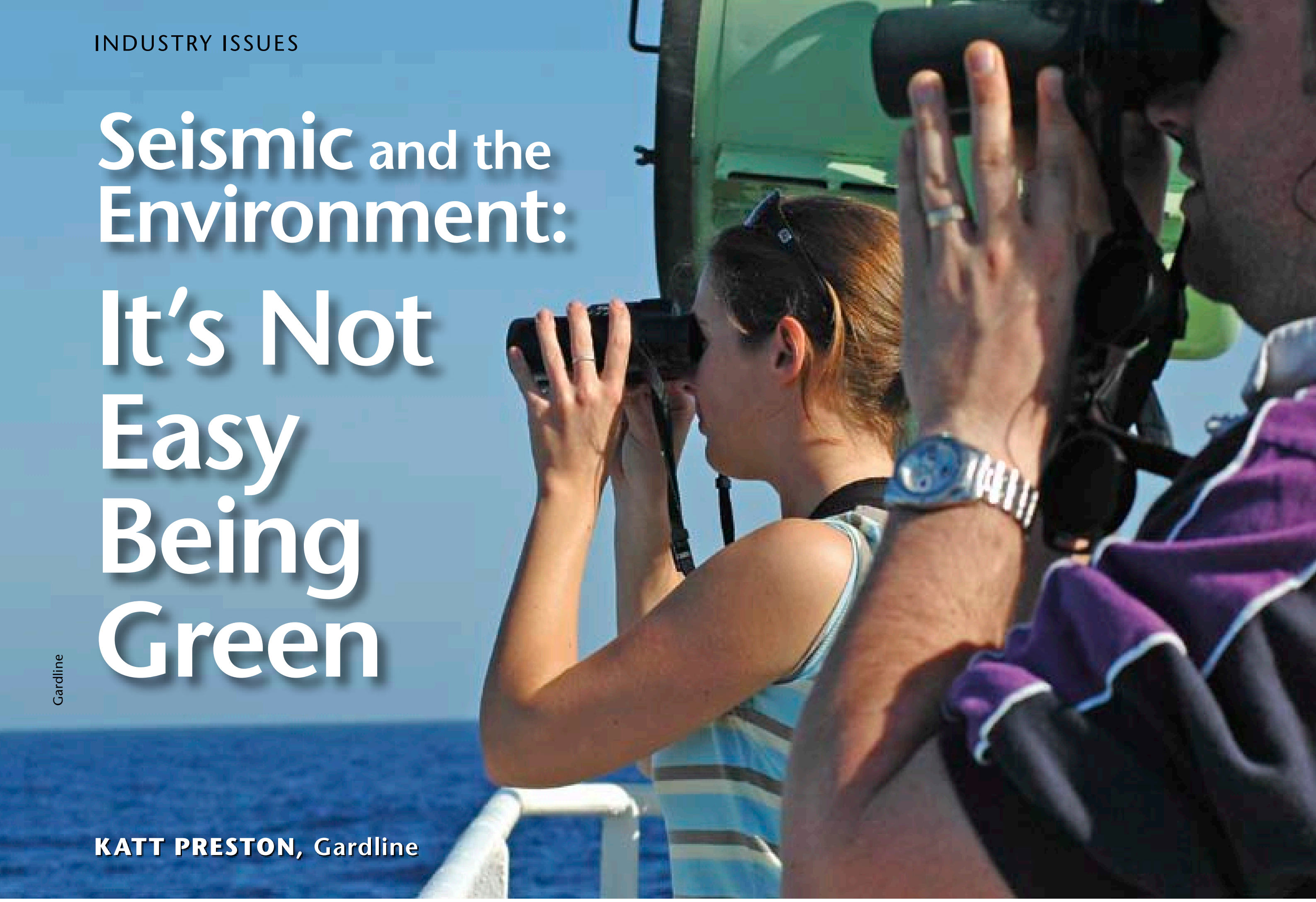
Fractured and weathered basement along a fault in Lofoten


Karsten Eig



Gardline

Seismic and the Environment: It's Not Easy Being Green

KATT PRESTON, Gardline

A look at the legislation protecting marine wildlife from the impacts of seismic noise and the practical implications for the oil and gas industry

The ocean is a naturally noisy environment. From microscopic thermal noises, through local surface movements of wind and waves, to global geological processes and tectonic movements, natural processes create sound within the marine environment. However, in recent decades, the introduction of anthropogenic sounds into this environment has meant that these natural sounds are now just a small fraction of the noise found in our oceans and seas.

In just one century, we have seen the exponential development of medium and low frequency active sonar, diesel propulsion ships and international container transportation, and seismic exploration, all of which have introduced large amounts of noise into the ocean. Studies estimate that since the 1960s, underwater oceanic noise has increased at a rate of three decibels per decade, meaning that the world's oceans are now more than ten times noisier than they were just 50 years ago. In recent years, various governments around the globe have introduced legislation and encourage 'Best Practice' to be employed in order to protect marine wildlife from the physical and behavioural impacts of anthropogenic noise, in particular those resulting from seismic surveys.

Impact of Anthropogenic Sound

For marine mammals, sound is the primary sense, being used for communication, navigation, foraging and predator avoidance. Airguns used during seismic surveys introduce high amplitude, broadband noise into the survey area and it has been shown that seismic activity can be detected above background noise as far away as 3,000 km (Nieukirk *et al.* 2004).

Anthropogenic sound impacts marine mammals in various ways. Firstly, it can cause physiological damage to the auditory system. Research shows that seismic activity leads to temporary or permanent threshold shifts in marine mammal hearing, whereby the hair cells in the cochlea become damaged, rendering the animal's hearing less effective until the cells return to normal after a period of time or completely irreparable. Secondly, the overlap in the frequencies used by seismic airguns and marine mammals can mean that the animals' communication and navigation systems are rendered useless while the survey is being conducted. While there is not enough hard evidence to implicate seismic exploration as being a main cause of marine mammal strandings, it is possible that a sudden increase in anthropogenic underwater noise in a region could lead to animals becoming disorientated and unable to navigate normally. Finally, behavioural changes may also be demonstrated by marine mammals in the proximity of seismic surveys – the exact reactions are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highly species-specific, but can include avoidance of the area being surveyed, attraction towards the seismic vessel, or a complete cessation of vocalisation. Migration routes can thus be disrupted, or key feeding and breeding areas abandoned, all of which will have serious implications on local, and even global, populations of marine mammal species.

Mammals are not the only group affected by seismic noise – turtles are thought to be susceptible to physical damage, particularly at the embryonic stage, and both turtles and sharks often demonstrate negative responses to noise.

Best Practice

In an attempt to minimise the levels of acoustic disturbance and injury to marine animals, a number of countries have introduced 'Best Practice' mitigation guidelines to be used during seismic surveys. In 1995, the UK's Joint Nature Conservation Committee was the first regulatory body to issue statutory marine mammal mitigation measures for use in their national waters. Australia's Department of the Environment, Water, Heritage and the Arts then followed in 2001 and since then a number of other countries have developed their own guidelines. While the details of these guidelines vary from country to country, the basic principles remain the same: seismic source vessels should carry trained Marine Mammal Observers (MMOs) who monitor a designated 'mitigation or exclusion zone' for the presence of marine mammals before and during seismic surveys, and advise on the mitigation requirements for the survey in real time.

It is the responsibility of the onboard MMOs to understand the relevant legislation within the survey area, which varies depending on country, season and type of seismic survey being conducted. The length and form of required pre-shooting watch, the radius of the mitigation or exclusion zone, and the species being mitigated for, all change from survey to survey. Within the UK, the mitigation requirements differ depending on water depth, volume of airguns being used, and sensitivity of the survey area with regard to marine mammal presence. For example, in one location a 30-minute pre-shooting visual watch conducted by a single MMO may be all that is needed; in another, a one-hour watch using two MMOs simultaneously as well as acoustic detection equipment is required. In UK waters, as in many other countries, the mitigation zone is designated as 500m from the source (i.e. the airguns). If marine mammals enter this zone prior to the start of firing, the survey operations must be delayed until the animals are clear of the zone, or have not been detected for more than 20 minutes within this zone. In other countries, this mitigation zone is extended to 1 km or even as far as 3 km depending on the type of survey and the animals detected, and the delay may also be extended to 30 minutes.

Once the airguns have commenced shooting, operations within UK waters may continue regardless of the presence of marine animals within the mitigation zone. However, the UK is alone in this respect. All other published guidelines require that the airguns are shut down under specified conditions. For example, in the Gulf of Mexico, shutdowns are required when any marine mammal or turtle enters the 500m mitigation zone. In Australia, the close proximity of any whale species and larger delphinid species means the airguns must be reduced to a low power, or fully shut down depending on the range of the animals. In New Zealand and Canada, shutdowns are only requested for listed 'species of concern'. Operations can be recommenced after a specified period of time since the last animal was detected. In an industry where vessels may cost in the order of hundreds of thousands of dollars each day, such delays to operations can have large financial repercussions, so it is crucial that the MMO is well trained and able to identify what animal is being detected, and its exact range from the source.

Not Always Popular

Marine mammal mitigation is a relatively new aspect of the exploration industry – and one that is not always popularly received. However, given the commitment of so many countries to the protection of cetaceans through various international agreements, it is an essential component of seismic surveys and one that is set to increase in significance. It is only through professional, dedicated mitigation and observation of marine wildlife during seismic surveys that the current guidelines can be revised and ameliorated so that exploration continues while still upholding a commitment to the conservation of our marine environment.

(see www.geoexpro.com: Recent Advances in Technology series for more information about the effect of sound on marine life) ■

Humpback whales, which rely on sound to survive, are a key species for mitigation in many areas, including Australia.

GEO Education is a new column that will be published occasionally in Geo Expro. Each article briefly explains some geoscience topic that is relevant to energy exploration and development and is written in a language comprehensible to a broad range of readers, including college students and non-specialists in the field.

Know Your Faults!

PART I: A proper understanding of faults is key to understanding the basic tenets of hydrocarbon geology. First, we take a look at fault geometry

RASOUL SORKHABI, PH.D.

In 1921, Richard Oldham delivered his presidential address at the annual meeting of the Geological Society of London; taking inspiration from an ancient maxim that 'to know your faults is the greatest wisdom', Oldham entitled his talk, 'Know Your Faults'. Decades later, detailed mapping and improved visualisation techniques have revealed even more the association of faults of various types and sizes with petroleum basins. Faults play key roles in the genesis and evolution of sedimentary basins and petroleum traps and in the migration of fluids and compartmentalisation of reservoirs. That all these processes are associated with faults indicates their complex, varied nature and necessitates a proper understanding of faults in basin tectonics, subsurface mapping, seismic interpretation, petroleum system modelling, and reservoir simulation.

Faults are a core subject in structural geology and may be studied from three different perspectives: (1) the geometry and architecture of faults, (2) the stresses that form faults (geomechanics), and (3) the sequential, temporal development of faults in a given area (kinematics). All these aspects are inter-related and need to be incorporated in a comprehensive study; fault geometry is the end-member of kinematics, which is, in turn, caused by stresses. Here we look at some key terms and concepts that describe the geometry of faults.

Surface evidence of a fault: the Ruahine Fault in the Ruahine Range, near Napier, east coast of New Zealand. The fault has offset valleys and ridges both vertically and horizontally. Uplift of the Ruahine Range has been of the order of 1 km in just 1 million years.

Dougal Townsend, GNS Science

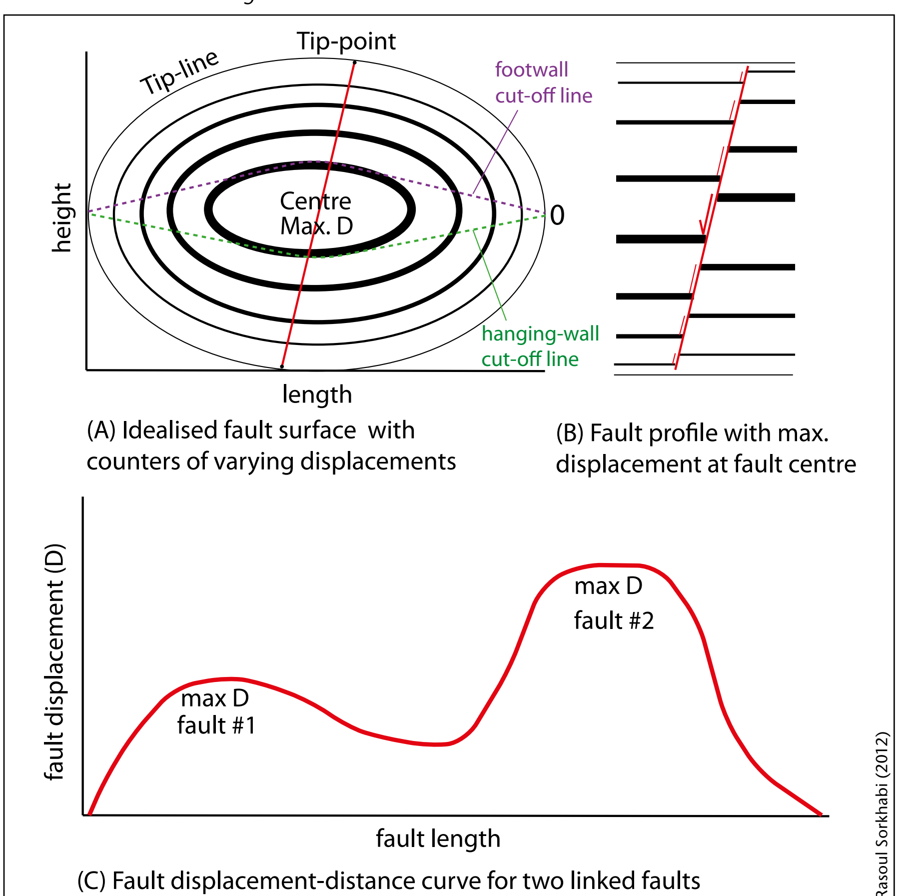
Fault Definitions

The concept of faults entered geology in the late 18th century via observations made by coal miners in mountain excavations. In his celebrated *Principles of Geology* (volume 4, 1835) Sir Charles Lyell wrote: "A Fault, in the language of Miners, is the sudden interruption in the continuity of strata in the same plane, accompanied by a crack or fissure varying in width from a mere line to several feet, which is generally filled with broken stone, clay, etc."

Using this statement as a portal of entry into our discussion, two points are noteworthy. First, **faults** are fractures or rupture planes along which the opposite walls of a rock column have moved relative to each other. The rock block above the inclined fault plane is called the **hanging-wall** because miners could hang their lamps on that block; the block below the fault plane is called the **footwall** where the miner placed his feet.

The second point is that a fault is not a smooth plane (as textbooks show for simplicity) but a concentrated zone of deformation. A **fault zone** often consists of crushed, brecciated or highly sheared **fault rock** surrounded by a damage zone characterised by fractures, hydrothermal veins, etc. Faults with greater lengths also have thicker fault zones. The nature of the fault zone depends firstly on the type of host rock; hard sandstones may show intense fracturing along the fault while ductile mudstone may smear into fault plane. Secondly, the nature of the fault zone depends on crustal depth. At deeper levels, where temperatures of over 300°C and higher pressures are prevalent, fault zones will undergo **ductile deformation** (as in metamorphic terrains); while in the upper eight kilometres of the crust, which also includes the majority of sedimentary basins, fault zones will show **brittle deformation**.

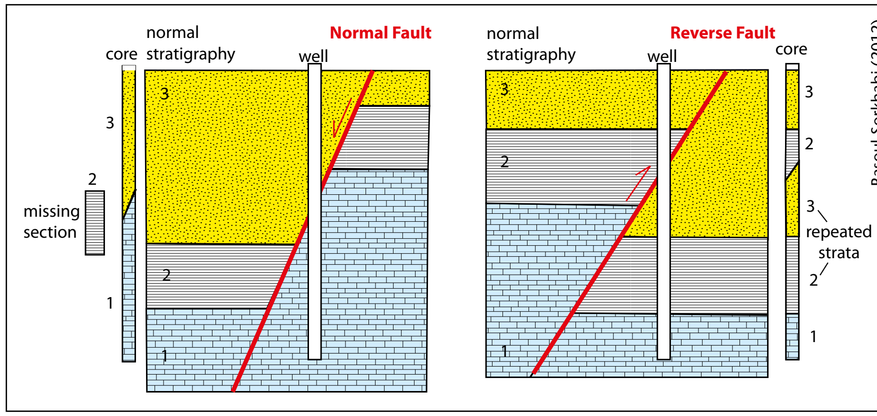
A fault is not really a smooth plane; it has undulations and heterogeneities called fault 'asperities'. Nevertheless, every fault is generated by a predominant tectonic event and has finite geometric shape. A given fault surface may be theoretically imaged as an ellipsoid whose centre (where the fault presumably nucleated) has the maximum amount of displacement, and as we move away, the displacement is reduced until it becomes zero at the circumference or tip-line of fault surface. Note, however, that many factors such as lithologic variations, cross-fault linkages, tectonic inversions, etc. alter this idealised image as shown in C.



(A) Idealised fault surface with counters of varying displacements

(B) Fault profile with max. displacement at fault centre

(C) Fault displacement-distance curve for two linked faults



Stratigraphic identification of normal and reverse faults in wells. Note also that unit 3 is syntectonic sediment thickening in the down-going fault block.

In Search of Faults

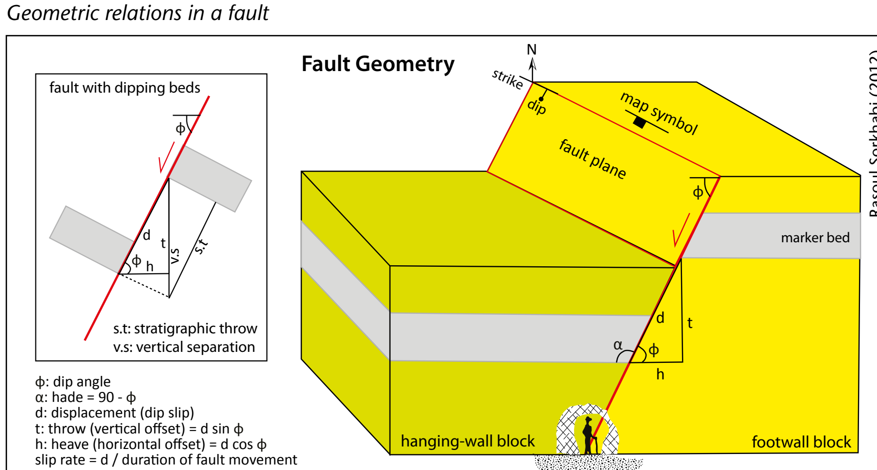
Tectonic faults are generated at crustal depths. A **blind fault** is one that still lies beneath the Earth's erosional surface (although it may have a topographic expression). An **emergent fault** is marked by a **fault line** (or fault trace) and may produce a steep topographic surface called a **fault scarp**.

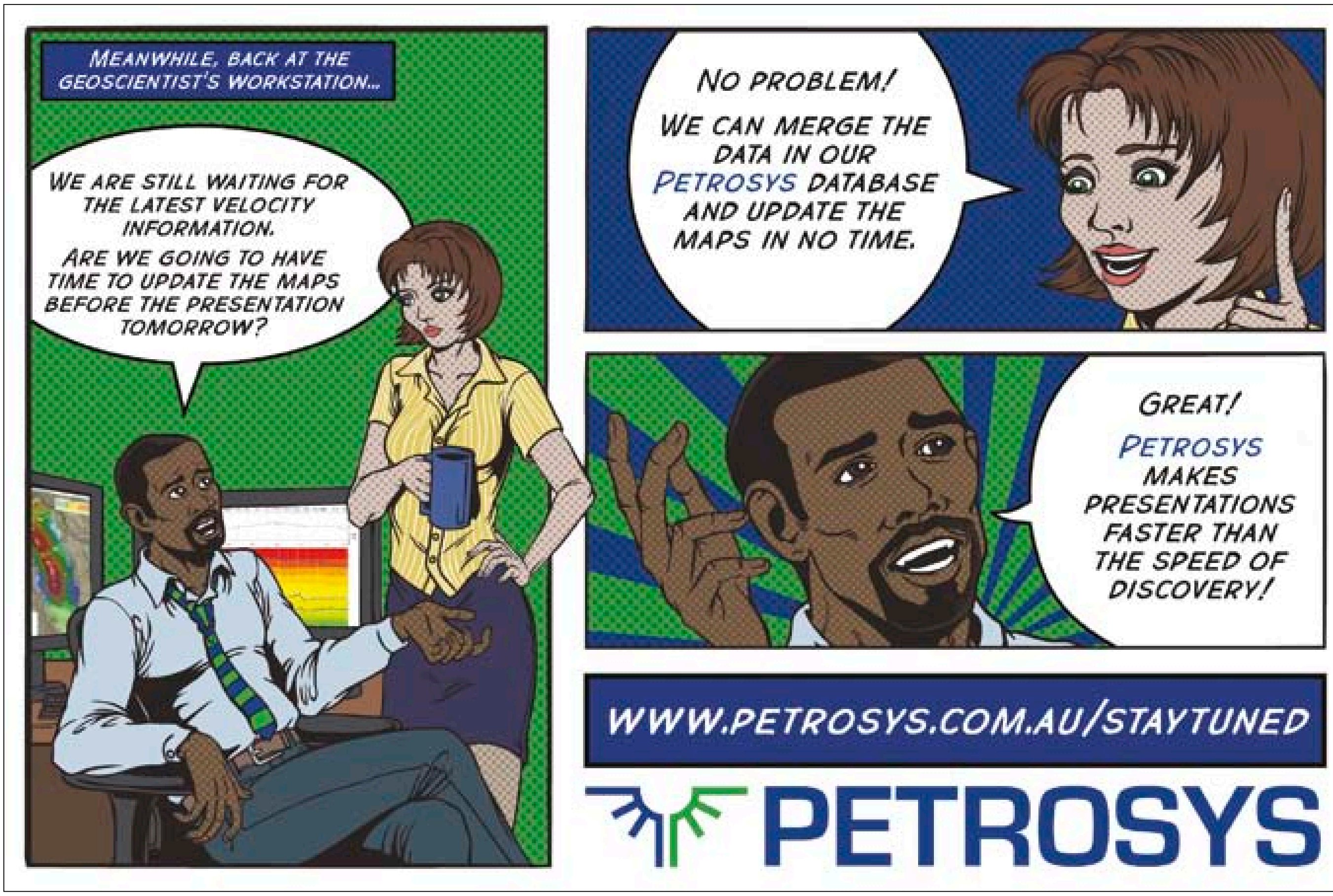
Depending on the type of available data, there are several indicators to identify fault structures. These include: (1) topographical features such as lineaments, offset streams, fault scarps, etc.; (2) discontinuity in a marker bed in an outcrop section; (3) juxtaposition of rocks of different ages (reverse faults often bring older rocks atop younger rocks while normal faults have younger rocks at their hanging-wall contacts); (4) features associated with fault zones such as gouge ('fault flour'), slickenside (smooth, striated fault surface), intense fracturing, sheared rock fabric, hydrothermal veins, etc.; (5) geophysical indicators such as displaced seismic reflectors or gravity anomalies in a particular pattern; (6) repetition (by reverse faults), omission (by normal faults) or downthrown-side thickening (by growth faults) of strata in borehole records (cores and logs). Ideally, several indicators should be used to better characterise a fault system.

Whether a fault is active or not has enormous relevance not only for construction of dams, bridges and other structures but also for oil and gas fields. An **active fault** is usually defined as one for which there is earthquake evidence in the past 10,000 years (the Holocene) while inactive faults have not moved for the past 1.6 million years (the Quaternary). Nevertheless, any fault is a plane of weakness and is prone to reactivation if sufficient stress is applied.

Faults come in various sizes. Fault structures are on the scale of at least metres, minor faults or sheared fractures on the scale of centimetres, and **microfaults** (or microfractures) on the scale of millimetres. On seismic images, faults are prominent features as they

Geometric relations in a fault

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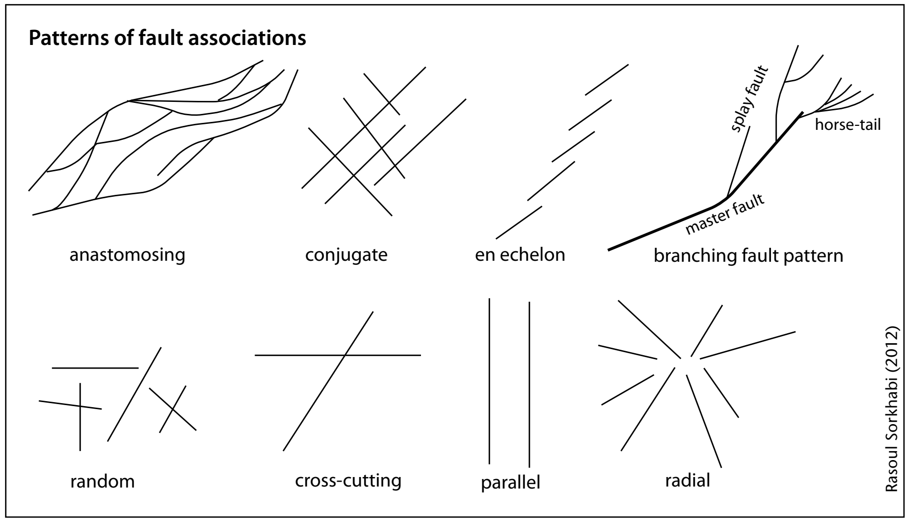
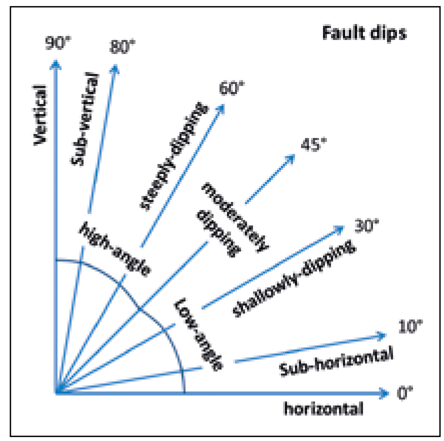
displace and distort the reflectors from sedimentary layers. However, even with the best seismic images, the population of smaller faults (say with offsets of less than 5 or 10m depending on seismic quality), which are below the seismic resolution, are not visible; these are called **sub-seismic faults**.

In the early 20th century, the American geologist Raphael Pumpelly suggested that in a given area small faults mimic the shape and orientation of larger structures of the same generation. In 1970, J. S. Tchalenko published an influential paper in the *GSA Bulletin* showing how tectonic stresses can give rise to self-similar shear structures at various scales. With the rise of the fractal theory of natural phenomena, geologists have tried to model populations of faults as a scale-invariant fractal distribution. While this is theoretically a powerful tool, for instance to predict the population of sub-seismic faults in a basin, its application is far from perfect and requires better calibrations from massive empirical data and detailed understanding of fault development.



Geometric Representation

A fault is geometrically characterised by its strike, dip, displacement, throw (vertical offset), heave (horizontal offset), and sense of movement. Faults with dip angles of over 45° are **high-angle**, while those dipping less than 45° (or less than 30° according to some geologists) are **low-angle** faults. The amount of fault displacement typically depends on fault length: a 100 km long fault may have a displacement of 1 km. Quantifying the relationship between these two parameters is the subject of many recent studies because by knowing one parameter we may predict the other; however, empirical data also show complexities resulting from lithology, fault type, and methods of analysis.



Depending on the type of data acquisition, faults are depicted in various ways: surface (2D planar), maps views (geologic maps on topographic sheets and lineament maps on satellite images), cross-sections (profiles), 3D block diagrams, subsurface structural counter maps, 2D or 3D seismic images, and fault surface maps with juxtaposed strata, curvature, and so forth. ■

Part II continued in the next issue.

This outcrop photo shows a normal fault in the Bozeman Group (continental Tertiary sediments) near the Harrison Reservoir, Montana, USA

Cycling the Norwegian Strandflat

MORTEN SMELROR
Geological Survey of Norway

For the active geotourist, cycling the Nordland coastal route in northern Norway offers an excellent opportunity to get in close contact with a scenic and unique landscape of beautiful mountains, strandflat, beaches, islands and skerries.

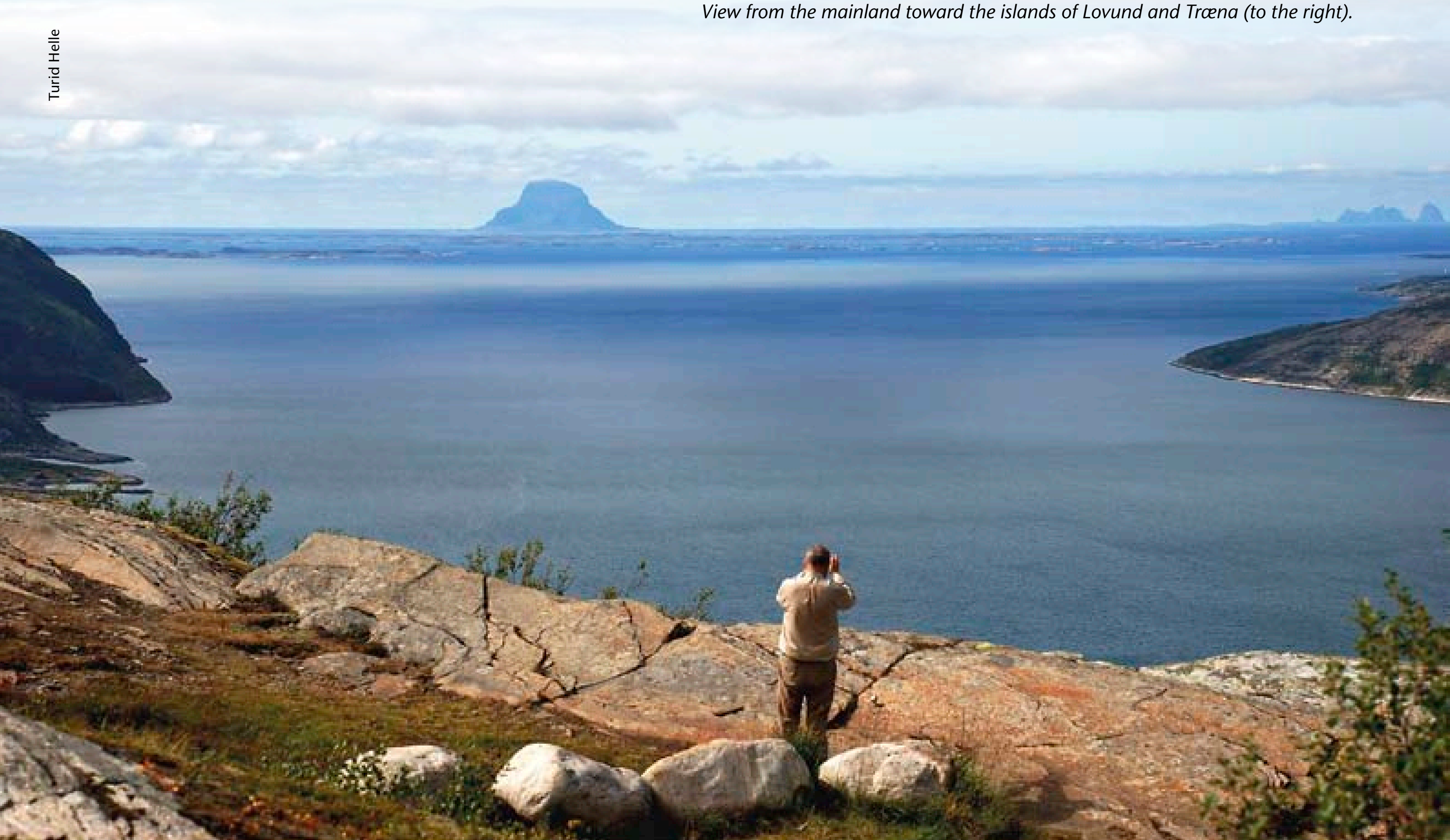
The RV 17 coastal road in northern Norway, running from Steinkjer to Bodø, is often described as one of the most beautiful car journeys in the world. An increasing number of tourists have now discovered that your enjoyment of the scenic nature along the route is more intimate and authentic from the seat of a bicycle. You have the freedom to decide yourself how fast and how far to go, and you can stop wherever and whenever you like and enjoy what the landscape around so generously offers you.

In particular, cycling in Helgeland, the most southerly part of northern Norway, has become very popular. The coast of Helgeland consists of thousands of isles, islets and skerries. Some of the isles have fairly high and steep mountains, but the local communities and roads lie on the strandflat (the typical low-lying Norwegian coastal region), and you do not need to be a well-trained sportsman to travel by bicycle on these islands. On our visit we met families with young kids, and there were bikes with trolleys carrying small children. At Pizza Hut in Brønnøysund we shared a table with a cool teenage boy and his grey-haired grandmother, who were spending a week together cycling in the area. You can bring your own bike or rent one at the tourist offices, and you can create your own route or follow some of the routes recommended by the travel agencies. A network of local ferries and express boats will take you out to the islands you choose to visit.

Caledonian Remains

The mountains along the coast of Helgeland comprise the remains of the Caledonides, a mountain chain that was created about 400 million years ago when the Baltic plate (with Norway) collided with the Laurentian plate (North America and Greenland). The Caledonides once stretched from Scotland to Svalbard, and reached thousands of metres high, like today's Himalayas. Repeated phases of uplift and erosion during hundreds of millions of years throughout the Mesozoic and Cenozoic, and finally the glacial finish during the Pliocene and

View from the mainland toward the islands of Lovund and Træna (to the right).



Turid Helle

Pleistocene, have left us with a scenic landscape of steep mountains, fjords and islands. Some of the geological sites are quite unique since they offer us an opportunity to look into the deeper part of this Palaeozoic mountain chain, and to study details of the composition and mineralogy of deep crust, and to see the geological features of large-scale over-thrusting and metamorphic processes.

The mountains stand up as majestic landmarks along the routes. Many of them are the subjects of fantastic mythological stories, such as 'De Syv Søstre' (The Seven Sisters), reaching from 910m to 1,072m and forming the great panorama behind Sandnessjøen.

The island of Lovund, with the sun setting close to midnight

The Norwegian Strandflat

The strandflat is the name of the low-lying, flat land and sea area along the coast of Norway. Similar geomorphological features are also known from other Arctic and Antarctic areas that once were covered by ice. The strandflat is thought to have been formed by glacial and marine erosion and sub-aerial weathering, where frost processes have played an important part.

The origin of the Norwegian strandflat, however, has been described as a geomorphological puzzle, and many mechanisms have been proposed for the formation of this distinct surface. While the strandflat in southern and mid-Norway to a great extent seems to be related to the Late Weichselian marine limit (100,000–11,000 years ago), along the Helgeland coast there is a great discrepancy in the height of this event and the limits of the low, geologically very mature, partly submerged strandflat. Therefore, in this area the strandflat was probably already formed by Late Pliocene and Pleistocene times (during the last 2.7 million years). However, as already mentioned, the Norwegian coastline has been subjected to several phases of uplift and erosion during Mesozoic and Cenozoic times, and in some areas, the strandflat may coincide with an even older exhumed pre-Jurassic surface.

Along the coast of Helgeland the contrasts between the low-lying strandflat and the steep projecting mountain peaks (called 'nyker' in Norwegian) form a very unique, picturesque landscape. Most of the shoreline islands are only a few metres above sea level, while others have mountains reaching up to 1,000m. A visit to the islands of Dønna, Lovund and Træna during mid-summer, when the sun sets for just a few short hours behind the oceanic horizon, is a guaranteed memorable experience.

Rich and Varied Geology and Heritage

The varied Caledonian geology, the ice-shaped landscape with sharp topographic variations, and a coastline with innumerable islands and skerries, are the basis for a rich and abundant flora and fauna. The biodiversity is considerable both above and below the water. Good fishing spots are found all around, and you can frequently watch sea eagles, otters, seals and small whales nearby. Some of the most ornithologically rich wetlands along the coast of Helgeland are found on the islands of Tjøtta, Herøy and Dønna. Every year, in mid-April, thousands of puffins return from the open ocean to nest on the island of Lovund. On 14 April, a day called the homecoming day or puffin-coming day (Norwegian: 'heimkommardagen' or 'lundkommardagen') the people of this small island and a number of visiting tourists celebrate the special event.

The small municipalities along the coast of Helgeland have

Cycling on the island of Dønna. In the background are parts of the Seven Sisters mountains on the mainland.

Vega – An Undiscovered Island Gem

Just south of the Arctic Circle you will find the Vega archipelago, which comprises about 6,000 islands, holms and skerries. On the archipelago one can experience the way fishermen and farmers have, for the past 1,500 years, maintained a sustainable living. Because of this, a cluster of dozens of these islands are protected and included on the UNESCO World Cultural Heritage list. In June 2009, the British newspaper *The Guardian* put the Vega Islands on their list of '20 undiscovered island gems'.

Vega is not only valued for its cultural heritage. It is also a dream for natural scientists. The birdlife and flora is of particular interest, and the geology is noteworthy. Among the bird population eider ducks are given special attention. On Vega the local people still raise the eider ducks for their feathers, and houses built for them to nest in are found alongside lighthouses and fishing villages.

In the northern part of the island the bedrock consists of metamorphic sedimentary rocks, including marble, calcareous shale, and limestone conglomerate. The southern part comprises homogenous, greyish granite (of Ordovician age, 475 million years). Some rocks were not fully melted and are visible as unevenly distributed, dark spots in the granite. The varied bedrock of Vega makes it a key area for understanding the Caledonian geology of northern Norway.

histories reaching way back in time, and the cultural heritages are kept well alive. Names from Helgeland appearing in the Viking Age Sagas include Sigrid and Torolv Kveldulvson and Hårek of Tjøtta, and Viking remains can be found in many places. A visit to the Petter Dass museum at Alstahaug is also recommended. The museum is dedicated to a clergyman-poet who lived in Alstahaug and was minister there from 1689. Many of his hymns are still popular today. In addition to the church, dating from about the year 1200, the foreign geotourist will also find the modern museum built in 2007 interesting. The building is in perfect harmony with the landscape, as it is literally cut into the hill, leaving spectacular, clean surfaces of Caledonian rocks to be seen on each side of the entrance. It was designed by Snøhetta, an architectural company also responsible for designing the famous library of Alexandria in Egypt, as well as the new Opera House in Oslo.

The coast of Helgeland is an Eldorado for those who enjoy beautiful landscapes, outdoor life and geological and biological treasures. Do not always expect perfect weather conditions, but on sunny days the Helgeland coastal route may indeed show itself as one of the world's most beautiful journeys – and going by bicycle will make the experience even more enjoyable. ■

Morten Smelror

View of the strandflat as seen from the top of Dønnamannen, on the island of Dønna. We are looking towards Vega (about 50 km away) and the little island of Søla. The group of islands in between includes Husvær, Blomsøy, Skålvær and Hysvær.

Morten Smelror

The mountains known as 'The Seven Sisters' on the mainland just south of Sandnessjøen: note the glacier-shaped valleys between the alpine peaks, and the low strandflat in the front.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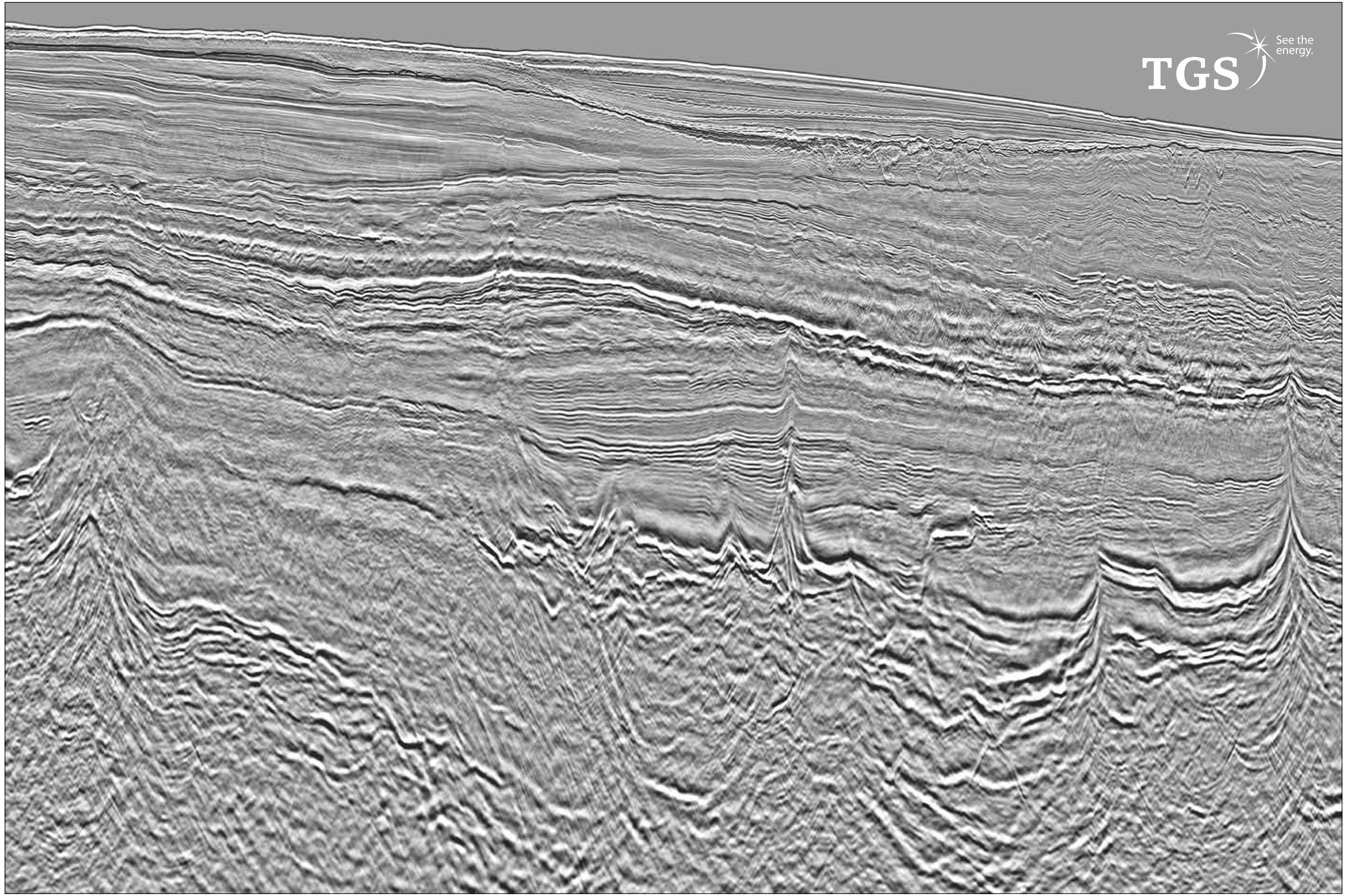
TGS data lines in the Faroe Shetland Basin

Right: 100 km seismic line from the Faroe Shetland Basin, acquired in 2006 with conventional acquisition parameters and reprocessed in 2012 using Clari-Fi.



Clari-Fi™ Your Data

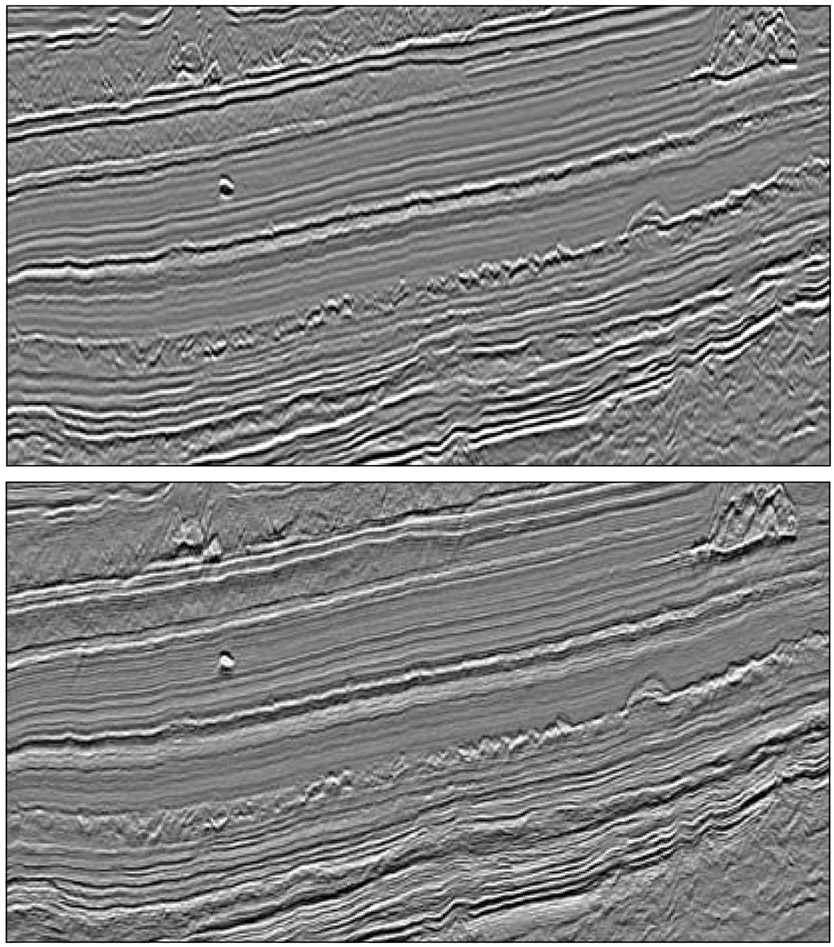
TGS's Clari-Fi™ is a proprietary three-step processing solution which allows broadband pre-stack seismic data to be generated from conventionally acquired seismic data, e.g. using single sensor streamers towed at a constant depth.

NICK WOODBURN, TOM TRAVIS & HASSAN MASOOMZADEH

The Quest for Broadband Marine Seismic

Marine seismic data acquired with an airgun source and recorded using pressure sensors towed at a constant depth has been the standard for offshore oil and gas exploration for thirty years. An inherent limitation with this technology is that its useable bandwidth is restricted, typically to around 70 Hz (bandwidth is defined as the difference between the upper and lower useable frequencies). Delivering increased bandwidth (i.e. broadband) data for exploration and production purposes has numerous advantages. However, two major factors serve to significantly reduce the useful bandwidth of the source wavelet. The first is the interference between the source pulse and reflections from the water surface – 'ghosts' – and the second is the fact that the earth acts as a filter which attenuates high frequencies in the source wavefield as it travels through the earth. In order to obtain truly 'broadband' seismic images, both factors need to be addressed.

TGS's Clari-Fi is a proprietary 3-step processing solution which accounts for both ghosts and the earth filter, allowing broadband pre-stack seismic data to be generated from conventionally acquired seismic data.



The results of Clari-Fi on 2D data from offshore West Africa. A Kirchhoff pre-stack time migration (PSTM) stack after preliminary de-noise (top) can be compared with the same PSTM after Clari-Fi (bottom). The increased resolution from Clari-Fi can be clearly seen. In addition, the increase in low frequency has helped to reduce the 'sidelobes' of events so that top and base of geological packages can be more clearly identified.

Step 1: Spectral Processing

Early in the processing sequence, the effects of the source and receiver ghosts are suppressed using a multi-dimensional deconvolution. This process replicates the benefits of broadband acquisition. Furthermore, after conversion to zero-phase, boosting operators can be applied to minimise the decay constraint between 3 to 7 Hz – a result of the inherent limitations of the signal output from marine airgun arrays – thereby maximising the signal in this band.

The decision to apply these steps at the beginning of the data processing sequence is considered key for two reasons. Firstly, the applied operators do not discriminate between signal and noise, but choosing to apply the operators at the beginning of processing enables all of the signal enhancing components in the processing sequence to work on the broadened spectrum. Secondly, seismic horizons related to deep structural geology are more easily identified in low frequency enhanced data. In consequence, more accurate velocity models can be produced throughout the processing sequence.

Step 2: Effectively Solve for the Earth's Attenuation

The result of the earth's attenuation is a preferential loss of higher frequencies during wave propagation, which induces a 'tilt' in the spectral content of deeper horizons.

This attenuation is commonly expressed as effective Q, Qeff, which is a combination of the intrinsic attenuation Qint, describing energy loss due to the propagation media, and apparent attenuation Qapp, describing attenuation due to scattering, transmission, mode conversion, etc. An important feature of broadening the spectrum in Step 1 is that more accurate measurements of the effective Q, Qeff, can be calculated from the data itself. Therefore, the attenuation caused by the earth's filter can be determined and solved for on the pre-stack data. This is beneficial for deeper targets as the apparent tilt in the spectrum is minimised.

Step 3: Multi-domain Noise Attenuation

An important aspect of the Clari-Fi process is careful de-noising of the data. Any process that seeks to broaden the spectrum must take care to broaden the signal spectrum and not the noise. In order to maximise the whitening of the signal spectrum, a multi-dimensional noise attenuation approach is used.

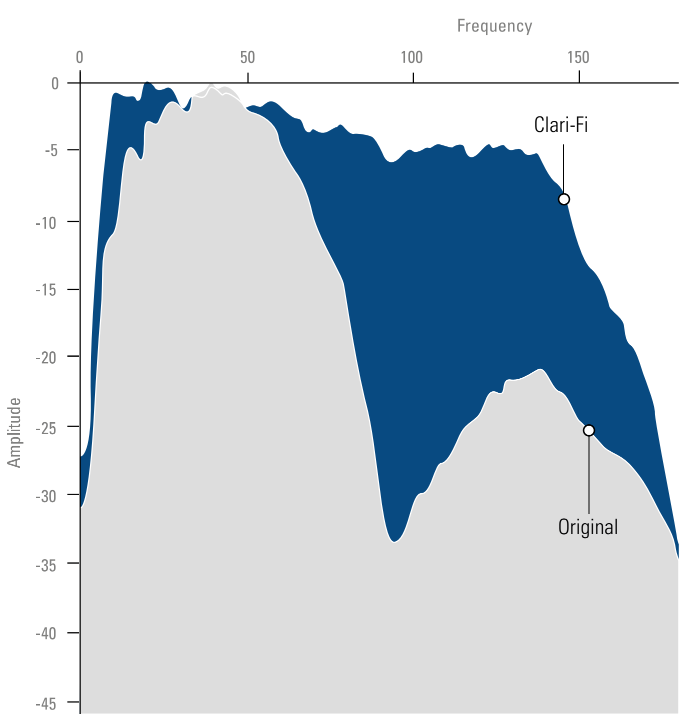
Several noise attenuating processes are performed in all of the available 'time-offset' domains. Noise attenuation techniques are applied in the shot, receiver, common mid-point (CMP), and common offset domains to enhance low frequency sub-basalt primary signal, and minimise both coherent and incoherent noise. Techniques employed include coherent noise attenuation using a time and space variant f-x apparent velocity dip filter; several iterations of an algorithm which decomposes data into frequency bands and identifies and attenuates anomalous amplitudes within those bands based on time variant thresholds; and multiple passes of time and space variant f-x deconvolution – regularly operating only below the top or base of highly attenuative horizons.

The 100 km seismic line displayed on pages 75–76 was acquired in 2006 using an 8 km conventional streamer towed at a depth of 9m. The data were reprocessed in 2012 using Clari-Fi. It represents a strike line through the Flett Sub-basin in the Faroe Shetland Basin and ties the Laggan field with gas reservoired in the Vaila sandstone. The enhanced resolution now available enables a much greater degree of confidence to be placed on the seismic correlation of events across faults, with the improved low frequency component of the data providing the greatest benefit. The data appears 'shaded' or 'textured' with the shading representing geological units rather than a top and base unit. The increase in resolution can be clearly seen in the examples shown here.

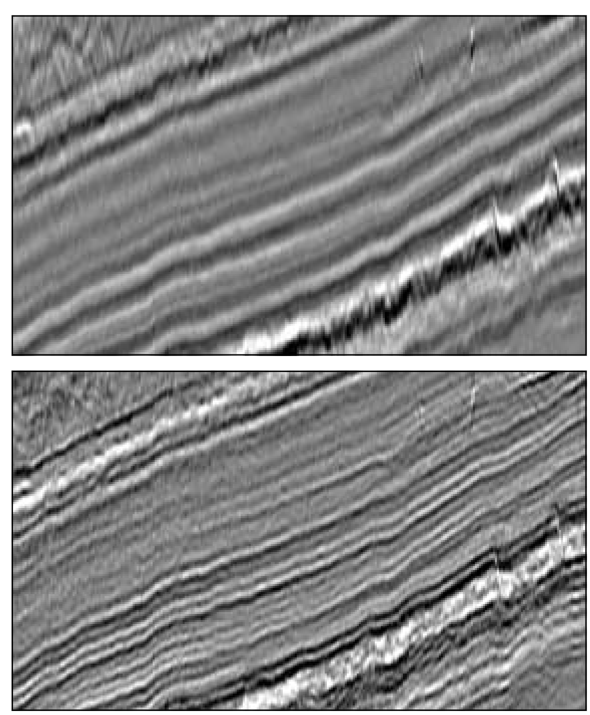
Summary

In order to achieve true broadband images, attenuation caused by both ghosts and the earth's filter must be addressed. TGS's proprietary Clari-Fi imaging technique represents a robust methodology which deals first with the ghost effect, and then solves for the earth's attenuation. The method yields seismic images that are broadband and focused, thus improving the resolution of the data. This technique works with conventional streamer acquisition and so enables reprocessing of legacy data. Furthermore, since Clari-Fi is an amplitude preserving pre-stack process, gathers are automatically available to drive AVO and inversion studies. ■

For more information, contact TGS at: imaging-info@tgs.com



Results of applying Clari-Fi to a 2D line from West Africa: Amplitude spectra shown before Clari-Fi (grey) and after (blue) – the removal of the source and receiver notches at low and high frequencies is clearly evident.



Zoom of the PSTM data shown on page 77: Top image shows the data before Clari-Fi, and bottom image after Clari-Fi. The enhanced resolution due to the increased bandwidth can be clearly seen.

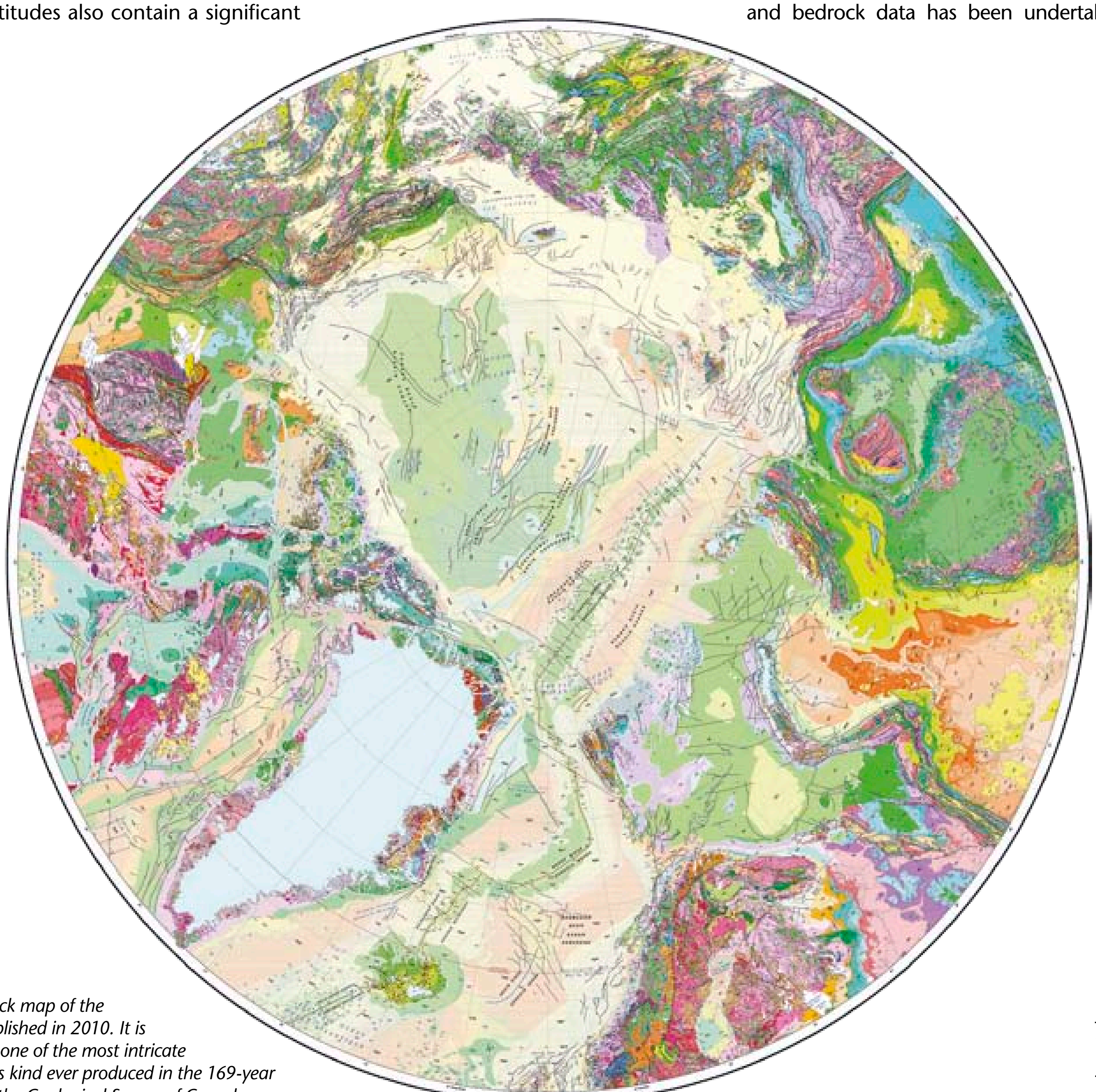
Uniting the Arctic

A new generation of Circum-Arctic geological and geophysical digital maps will reveal new data about the hydrocarbon potential of the region

MORTEN SMELROR, NGU and
OLEG V. PETROV, VSEGEI

The Arctic contains some of the world's largest hydrocarbon provinces, including the West Siberian Basin, as well as several other world-class petroleum-bearing regions, such as the Timan-Pechora Basin, the North Slope of Alaska, the Barents Sea and the Norwegian Sea. These latitudes also contain a significant potential for metallogenic resources, as well as holding large volumes of prospective industrial minerals.

However, the Arctic is largely unexplored with respect to mineral resources, and there is a rapidly growing need to effectively assess the resource potential of the Circum-Arctic region. A meaningful assessment must be based upon an evaluation using updated geological and geophysical data and knowledge. Initiated in 2003 by the Russian Ministry of Natural Resources, an international effort to compile Circum-Arctic geophysical (magnetic and gravity) and bedrock data has been undertaken



The bedrock map of the Arctic, published in 2010. It is said to be one of the most intricate maps of its kind ever produced in the 169-year history of the Geological Survey of Canada.

Harrison et al

by a consortium of national agencies from Canada, Denmark, Finland, Norway, Russia, Sweden and the USA.

The project has so far provided new geological and geophysical digital maps, at a scale of 1:5 million, for the Circum-Arctic region limited by the 64°N latitude (60°N North latitude for the NW Europe and Canadian regions). Further tectonic/structural and metallic ore deposits maps are being developed. The new Circum-Arctic maps are formally published under the Commission for the Geological Map of the World (CGMW/CCGM).

Mercator's Arctic projection from 1569

History of Arctic Mapping

The world's first specific map of the High Arctic and North Pole is considered to be Mercator's Arctic projection from 1569, where Mercator first introduces his revolutionary Polar projection. Today, the map is known as pure fantasy, but for hundreds of years a central Arctic landmass was considered very likely.

In 1599 the voyage by Willem Barents to what at that time was known as the Murman Sea (the 'Northern Man Sea') resulted in a more realistic picture. Barents mapped Svalbard (Spitsbergen) for the first time, on the map indicated as 'Het Nieuwe Land' (Dutch for New Land). However, the High Arctic still remained an unknown frontier for more than 200 years.

During the Norwegian North Polar Expedition 1893–1896, with the mission to drift across the North Pole with the vessel *Fram* frozen in the ice, the first bathymetric data and sediment samples from the deep Arctic Ocean were collected. The expedition also undertook geophysical measurements, including magnetic and gravimetric data.

In 1899 the first icebreaker, *Yermak*, entered the Arctic Seas and reached Spitsbergen. Some years later *Yermak* also made a pioneering voyage through the North-East Passage. Since then the Arctic Ocean has been investigated by American submarines, Russian Ice-drift Research Stations and icebreakers and ice-classed research vessels from various nations. A milestone was reached on 3 August 1958, when the American naval submarine USS *Nautilus* was the first ship to reach the geographical North Pole. Also noteworthy are the Russian and Soviet ice-drift stations, which were first established in 1937 and are still in operation, having covered almost 100,000 km of the Arctic Ocean, and contributed greatly to our present knowledge of the physical geography of the Arctic, including the discovery of the Lomonosov Ridge.

Bedrock Map of the Arctic

Despite the advances in understanding made through such projects as the IODP Arctic Coring Expedition on the Lomonosov Ridge in 2004, the geographical and geological secrets of this very large area are still not fully revealed. Further advances in our understanding of the geological history and the resource potential of the Arctic call for international cooperation. With this in mind the various nations signed an agreement to develop the Circum-Arctic Atlas in 2005.

The first result of this was a draft of the bedrock map of the Arctic, first presented at the 33rd International Geological Congress in Oslo in 2008. The work was coordinated by J.C. Harrison at the Geological Survey of Canada, and is now freely available in digital format from NRCan's MIRAGE website. This map is said to be one of the most intricate maps of its kind ever produced in the 169-year history of the Geological Survey of Canada. Putting together and unifying bedrock map data from so many different countries has been challenging and complicated. The final printed map is 1.5m in diameter and consists of five different sheets: the bedrock map at a scale of 1:5 million with explanatory notes and the list of contributors; the legend; a Precambrian correlation chart; and two Phanerozoic correlation charts.

But it is not just a printed map. The bedrock map of the Arctic is supported by the first complete, seamless, spatial database of onshore and offshore bedrock geology for the Arctic areas north of 60° latitude. There are tens of thousands of spatial objects, including 32,000 geological polygons, 1,220 map units, and 137 latest International Commission on Stratigraphy (ICS) timescale divisions.

The bedrock map and the related digital data sets are released in North Polar stereographic projection using the WGS 84 datum, and include a complete geological coverage for all onshore and bedrock offshore Arctic areas. The new interpretation is based on digital geological compilations for land areas, and, for the Arctic Ocean Basin, on bathymetry, dredge samples and available seismic and potential field data. Correlation of compilation map units is based on the ICS time scale, and for pre-Ediacaran rocks will primarily use the absolute time scale. The map is now freely available in digital format from NRCan's MIRAGE website.

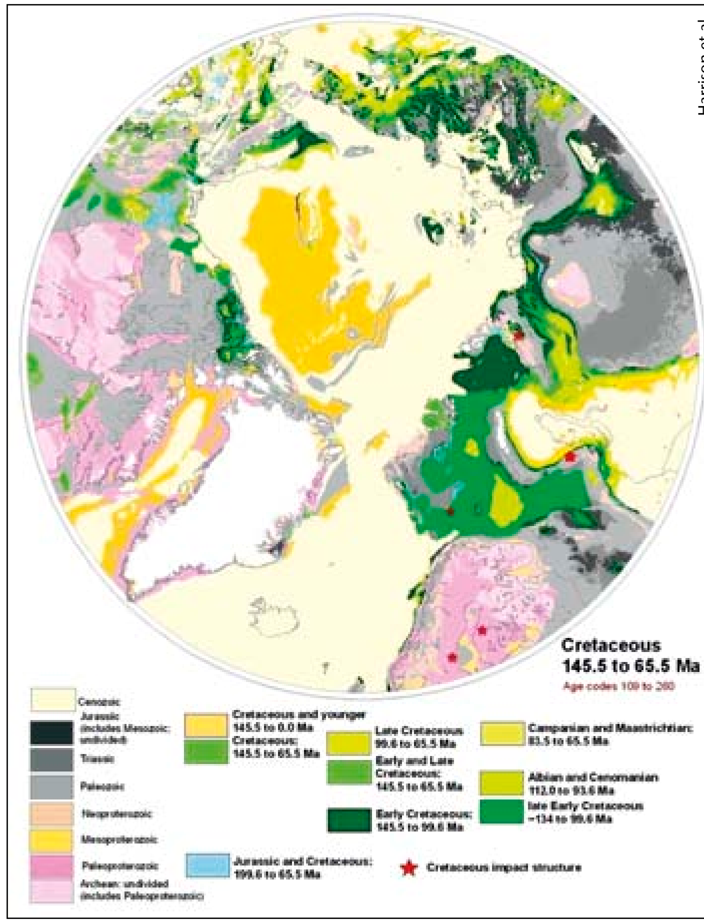
Magnetic And Gravimetric Maps

The compilation of the magnetic and gravity maps was coordinated by Carmen Gaina at the Geological Survey of Norway. New public and proprietary magnetic and gravity anomaly gridded data from each participant group were gathered and converted into a common datum (WGS84) and format. The magnetic anomaly compilation relies on 1 km gridded data for Canada, Alaska and NW Europe regions, and 5 km gridded data for oceanic and Russian regions.

In order to construct the final Circum-Arctic magnetic anomaly grid (CAMP-M) the authors have adopted the approach used by several research groups for compiling the World Digital Magnetic Anomaly Map (WDMAM) and used near-surface magnetic data for the short wavelength component of the compilation and the satellite-derived magnetic anomalies for the long wavelengths.

The new CAMP-M compilation is superior to similar gridded data over the Circum-Arctic area due to its better coverage (it includes updated aeromagnetic data in the High Arctic, west and north of Greenland and in the NE Atlantic). It preserves smaller wavelength structures by keeping the grid resolution at 2 km, and has a consistent regional long wavelength component introduced by the MF6 satellite-based lithospheric magnetic model.

The new gravity anomaly compilation was originally supposed to produce one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free

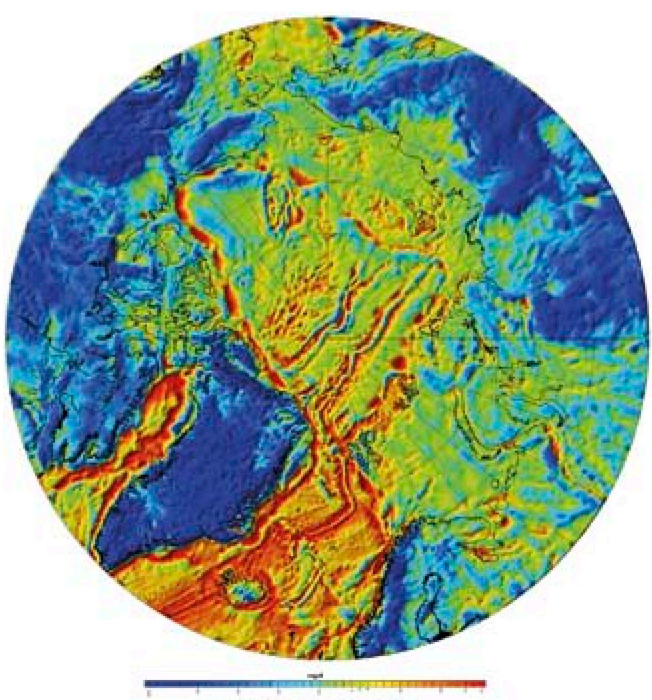


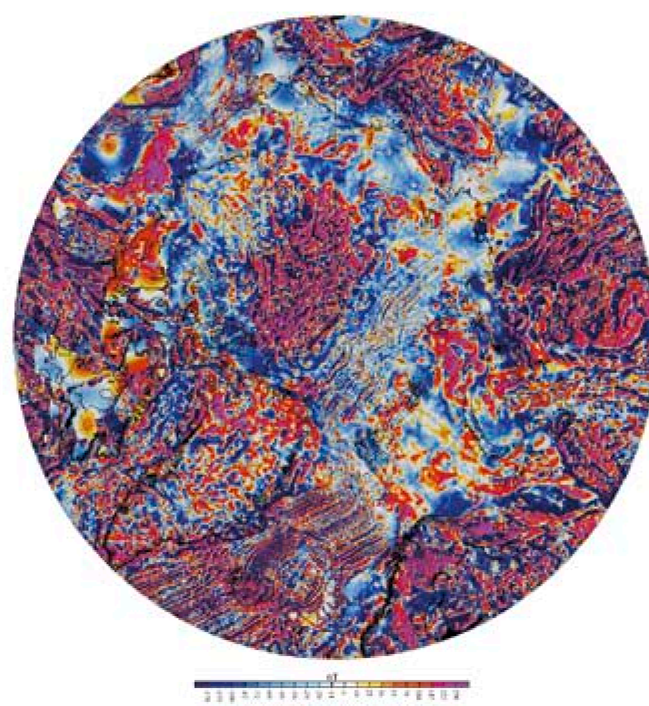
Harrison et al

The database can be queried to call up maps based on a variety of criteria, such as this one showing all rocks of Cretaceous age. Individual geology units are coded for composition, age, environment of formation and plate tectonic domains: geological contacts, faults and oceanic spreading ridges, meteor impact structures, salt and gypsum extrusions and selected point data such as kimberlites.

(Left) Gravity map of the Circum-Arctic, with Bouguer gravity anomaly data onshore and Free Air gravity anomaly data offshore. (Right) CAMPGM-M magnetic anomaly compilation of gridded data (to 60°N) based on ground/airborne regional compilations and global model of lithospheric field, based on satellite data (MF6).

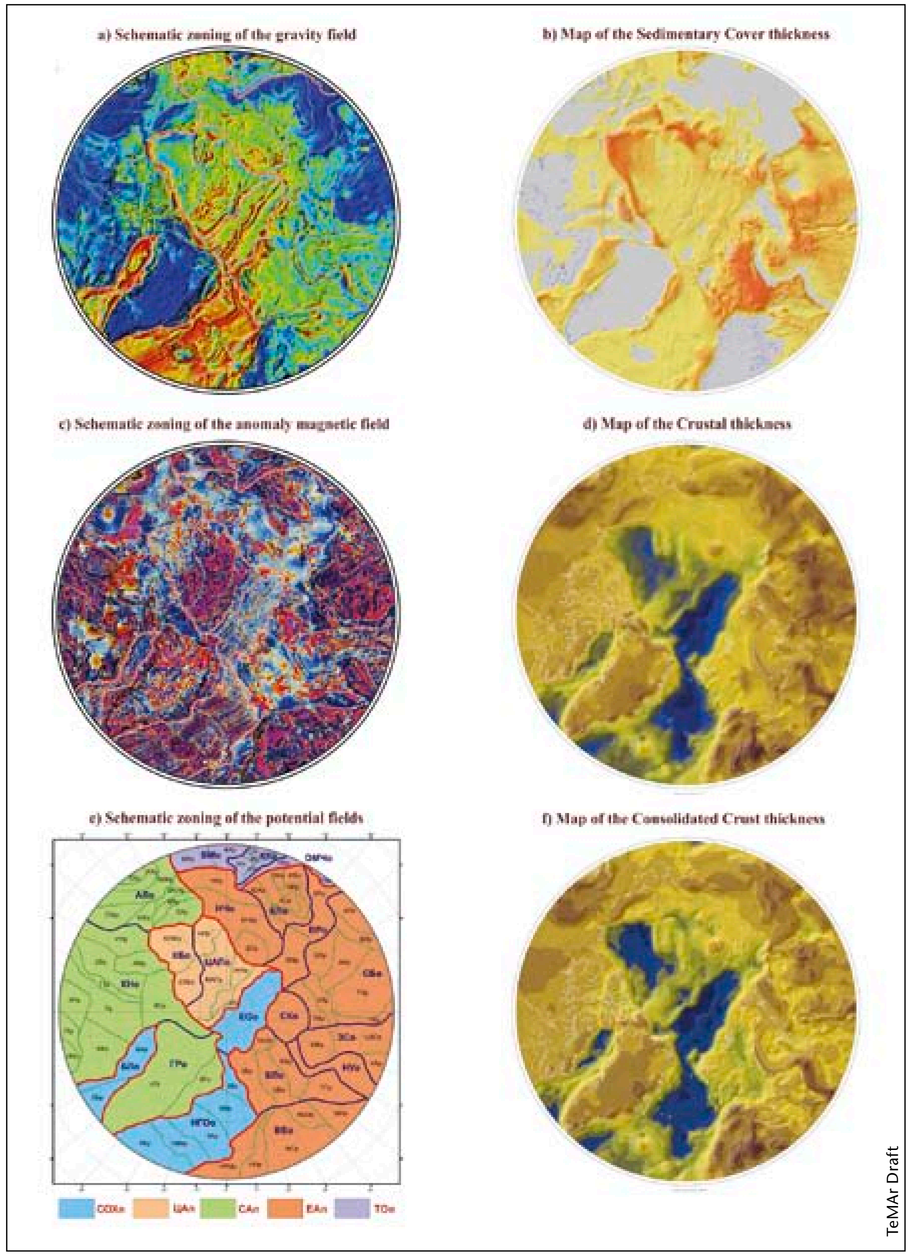
Gaina





Air for oceanic areas and Bouguer for land, both at 10x10 km grid resolution. However, a new ArcGP free air gravity anomaly grid was completed and published by Kenyon et al. (2008), and they used the new free air data on the Siberian Shelf primarily available to the CAMP-GM project. Therefore the authors have restricted the new compilation to the combined Free Air/ Bouguer corrected data set to cover the Circum-Arctic region to 60 degrees north and used satellite gravity models (EIGEN 115 GL04C) for quality control of the long wavelengths.

The new gravity and magnetic anomaly maps and their derivatives have been used to refine the outlines of some of the present-day tectonic features in the High Arctic. They allow a more accurate delineation of the boundaries between different continental blocks, micro-continents and active and extinct plate boundaries in the oceanic High Arctic. By using the new bedrock map and derivatives of the two gridded geophysical data sets and edge enhancement techniques, the authors have been able to reveal interesting features that should be taken into account when refining the interpretation of the High Arctic, in particular, the transition from continent to oceanic regions and outlines of micro-continents and volcanic provinces.



The basic tectonic map is supplemented by a set of additional digital maps which reflect deep structure of the regions, tectonic zoning of the basement and the sedimentary cover of the mapped region, geodynamic types of the sedimentary basins, and boundaries of the large igneous provinces of different age.

Tectonic and Ore Deposits Maps

In 2010 an international working group was formed in order to compile the tectonic map (TeMAr), led by Dr. Oleg Petrov, director of VSEGEI, Vice-president of CGMW, and Sergey Shokalsky, Secretary General of Sub-commission for Northern Eurasia under the supervision of the Commission for Geological Maps of the World. In April 2011 (Paris, CGMW) the map legend was agreed, and in April 2012 this first draft of TeMAr was discussed at a workshop at the Geological Survey of Austria in Vienna. The tectonic map is expected to be compiled by the 34th Session of the International Geological Congress that is to take place in Brisbane in 2012.

The Arctic area contains large amounts of mineral resources, which are likely to be explored and mined in the years to come. Information on these is available in the archives and databases of the geological surveys and other national agencies. The final step in the cooperation initiated nine years ago will therefore be to jointly develop a common database and a map of Circum-Arctic mineral resources. This will be focused on metallic ore deposits, and will probably not include energy minerals (coal and petroleum).

This initiative is be coordinated by the Geological Survey of Norway and led by Ron Boyd, and the first workshop was held in Toronto in March. It is suggested that the current Fennoscandian Ore Deposits Database will be used as a model for this work. It is estimated that it will take three to four years to complete the Circum-Arctic Mineral Resource Database and map. Therefore, the metallogenic map might be ready by the 35th IGC, and it would be great if the separate map of energy resources being compiled by the USGS on behalf of the project could also be ready for that event.

Interest in the Arctic will continue to increase in the years ahead of us, and a knowledge- and research-based approach is needed. Cooperation on the production of modern and accurate geological and geophysical data and maps is a neccessary step towards a common understanding of the potential and limitation of the natural resources of the Arctic regions. ■

Montenegro
A Small Country Thinks Big

VLADAN DUBLJEVIĆ

Montenegro has black mountains, blue sea, green alpine meadows, awe-inspiring canyons, idyllic lakes – and untapped offshore hydrocarbon potential

The beautiful country of Montenegro is located in south-east Europe, on the Adriatic Sea. It covers an area of 13,812 km^2 – about the same as the US state of Connecticut – and has a 300 km long coastline, the subject of great tourist interest. The central region consists of the most fertile land and most major industrial activities are located in this part, while the northern region is a mountainous area with significant coal reserves.

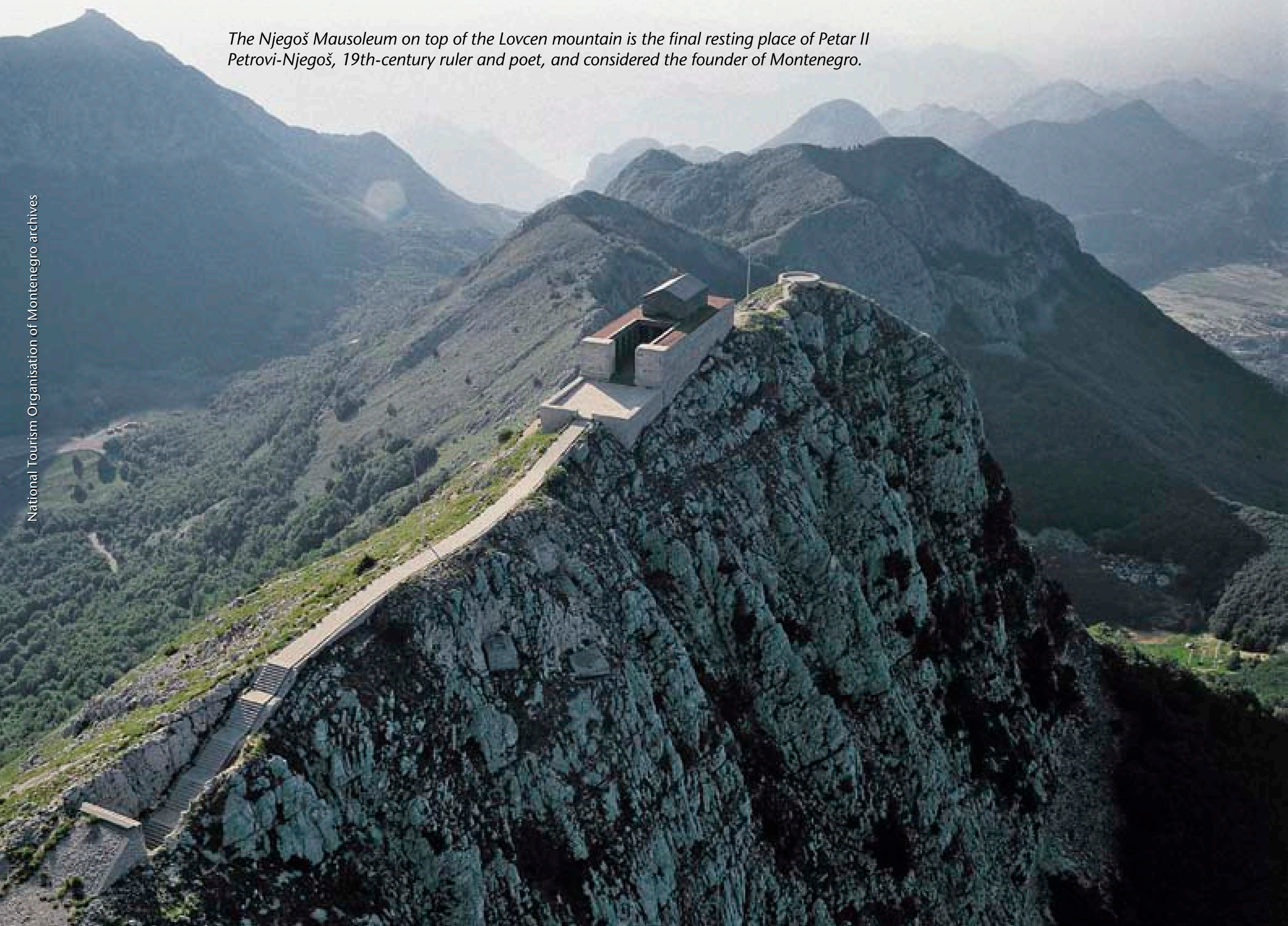
While tourism is a vital part of the economy, contributing over 10% to total GDP, the country believes that it has considerable potential in its virtually unexplored offshore waters and is planning to open the first licensing round in the near future.

100 Years of Exploration

According to the decision passed by the National Assembly and confirmed by the Montenegrin King Nikola on 18 February 1914, a Dutch industrialist from The Hague, J. Kokern, was awarded the concession for exploitation of oil in the region of Skadar Lake, in south-east Montenegro on the border with Albania. The rationale of the concession stated that oil exploitation would reduce emigration of Montenegrins, contribute to the increase of exports, improve the economic status of the state and 'save our peasant against evident financial disaster'. Due to the beginning of the World War I, the initial works were terminated.

After WWI, interest in oil exploration reappeared, and in 1922 the Zuber brothers commenced drilling the first exploration well, also in the region of Skadar Lake. At a depth of 250m the drilling rig broke and the discovery attempt failed, never having reached the target.

Although it will soon be the 100th anniversary of

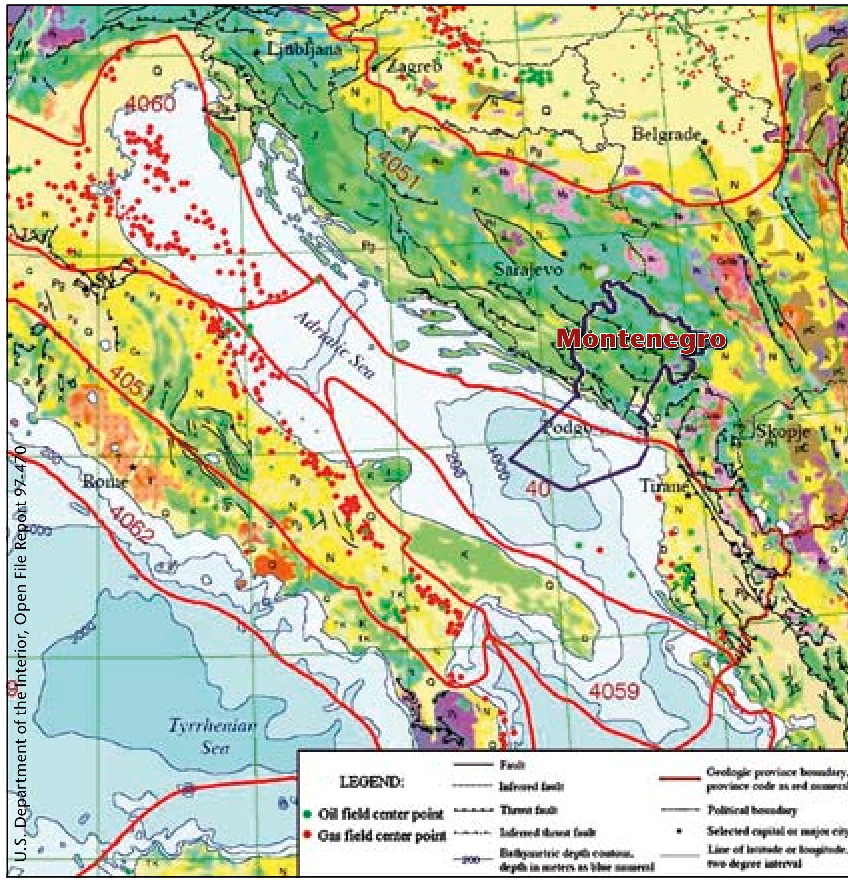


The Njegoš Mausoleum on top of the Lovcen mountain is the final resting place of Petar II Petrovi-Njegoš, 19th-century ruler and poet, and considered the founder of Montenegro.

National Tourism Organisation of Montenegro archives

the beginning of the search for oil in Montenegro, the syndrome of the 'first well failing to reach its target' continued many years afterwards. Over the total area of Montenegro covering 21,500 km^2, including 8,500 km^2 offshore, only 20 exploration wells have been drilled. Sixteen were onshore in the period from 1949 to 1966, undertaken by the government company Nafta Crne Gore, which was established for this purpose. Although in some wells traces of oil and gas were identified, the absence of modern geophysical methods together with the location of wells based only on the results of surface geology, resulted in no discoveries onshore. Soon afterwards Nafta Crne Gore was terminated, and the state discontinued financing oil and gas exploration at the end of the 1960s.

In 1973 the exploration for hydrocarbons in this territory was taken over by the government-owned Jugopetrol Kotor, which was primarily engaged in downstream activities. In cooperation with foreign oil companies, Jugopetrol Kotor acquired over 10,000 km of 2D seismic offshore and 1,250 km onshore, as well as 400 km^2 of 3D seismic. Three offshore and one nearshore well were drilled between 1975 and 1991.



Geology, oil and gas fields and geological provinces of south-east Europe. Although commercial deposits of oil and gas have not been found yet off Montenegro, in parts of the Adriatic Basin belonging to neighbouring countries Italy, Albania and Croatia, oil and gas have been found and commercially exploited for years.

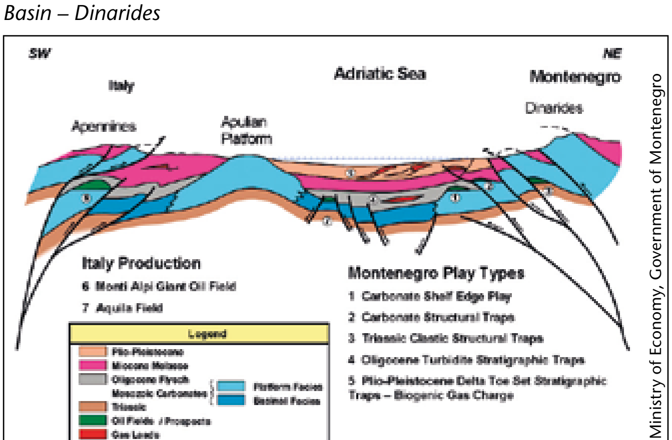
Range of Play Concepts

The Dinarides fold belt is separated from the Italian Apennine fold belt by the Adriatic foredeep basin, and these two fold belts almost form a mirror image of each other, as can be seen on the cross section. The far side of the Adriatic-Ionian Basin is represented by the Apulian Carbonate Platform in Italian waters. The edge of the platform trends obliquely to the modern marine basin in the Italian Apennine fold belt, where giant oil fields were discovered in thrusted Mesozoic carbonate traps, and a great variety of gas fields also occur in Tertiary reservoirs of the foredeep sequence.

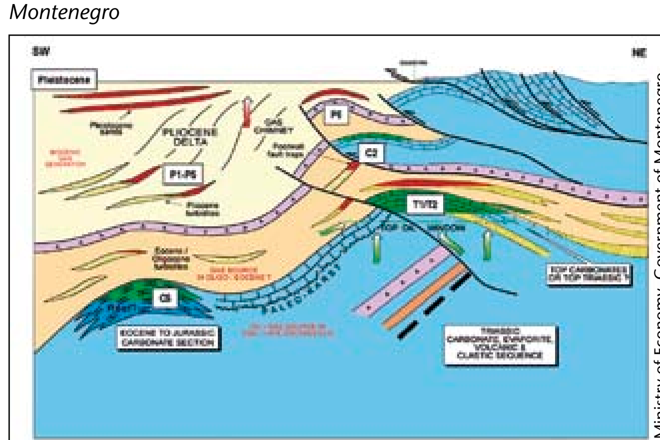
In Albania the oil and gas fields occur in both Cretaceous carbonate and Tertiary clastic reservoirs of the Dinarides fold belt. The Adriatic-Ionian Basin comes ashore in Albania where it is known as the Ionian Zone. Near the coast this is overlain by the post-tectonic 'Post Adriatic Depression', formed of Miocene to Recent molasse. The Ionian Zone crops out in southern Albania, where seven oil fields were discovered in the carbonates, demonstrating that basinal carbonates can be effectively charged with commercial volumes of oil.

In the offshore area of Montenegro prospects have been identified both within the Dinarides Thrust Belt and in the adjacent

Schematic cross-section Apennines – Apulian Platform – Southern Adriatic Basin – Dinarides



Schematic cross-section summarising the hydrocarbon play concepts in Montenegro



Adriatic-Ionian foreland basin.

The stratigraphy offshore Montenegro is dominated by a Mesozoic to Middle Eocene rift to passive margin sequence with up to 3.5 km of platform carbonate, shale and evaporates deposits. This sequence contains a number of source, reservoir and seal intervals, proven both in wells and from outcrop studies. Beneath the carbonates, the Lower to Middle Triassic, primarily continental sequence, includes some marine clastic intervals with combined reservoir and seal potential. The carbonates are succeeded by prospective Palaeogene (Oligocene, Eocene), Neogene (Miocene, Pliocene) and Pleistocene sequences with thick developments of turbidite shale and sandstones, deposited in the foredeep in front of and beneath the carbonate thrust structures. In offshore wells, gas-bearing sandstones and conglomerates have been found, which are thought to be involved in both stratigraphic and combination traps. Direct hydrocarbon indications are interpreted on the marine seismic data in the offshore Montenegro, with bright events, positive AVO effects and gas chimneys in several zones within the Oligocene, Pliocene and Pleistocene sequences.

Interesting Trap Styles

Thermogenic oil generation of source rocks took place from the Eocene to Late Triassic carbonates with indigenous oil and gas migrating up dip and up faults into traps at Triassic clastic and top carbonate levels. Evidence from the Apulian Platform suggests that there may be significant additional hydrocarbon source potential from within the Triassic sequence offshore.

In 1980, Amoco reported the results of an onshore reconnaissance surface sampling describing Cretaceous samples from near Podgorica in the centre of the country. Three of the four samples had TOCs averaging 15%, with high HI's indicating an oil-prone character.

Regarding maturation, temperature data is available from wireline logging runs for wells. Relatively cool geothermal gradients predominate, ranging from around 23°C/km in the north-western offshore, to 17°C/km and 14.6°C/km further north-east. It appears that depression of the geothermal gradient has occurred due to the thermally conductive nature of the predominant carbonate lithology, structural loading beneath thrusts and rapid Neogene subsidence of the Adriatic area.

Structural trap types include hanging-wall ramp anticlines and footwall anticlines and fault traps. The Eocene and Oligocene clastic reservoirs could form both structural and stratigraphic traps with thermogenic oil and gas migration into them, while Pliocene and Pleistocene traps would most likely be charged by biogenic gas in a similar fashion to many of the Italian and Croatian foredeep basin gas fields.

Wireline data gives a good indication of Palaeogene and Neogene seal potential, with observed reservoir intervals capped and interbedded with marl and silty claystone. Miocene sequences in the wells comprise a massive claystone, thick, slightly silty in places and with Messinian anhydrite at the top providing an excellent seal potential. The carbonates reservoir zones have potential top-seal comprising Eocene or Oligocene shale.

Plenty of Potential

Offshore Montenegro is an attractive exploration area and identified prospects span a wide range of stratigraphic units.

There is no data concerning Pleistocene reservoir quality from any of the Montenegrin wells, but there are analogues in Italy and Albania, such as the Barbara field in Italian waters in the northern Adriatic, which produces from high quality Pleistocene sands. The field has reserves of around 1.4 Tcfg, which is 99.5% methane and probably biogenic in origin. Production is from Pleistocene turbidite sands between 1,000m and 1,400m depth. The average porosity is 30%, and permeability varies from 5–100 mD, locally as high as 1 D.

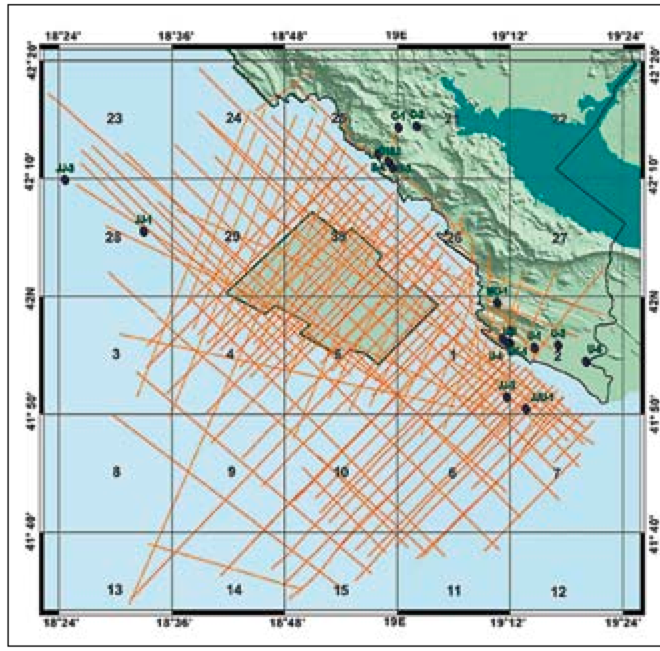
Gas is produced from comparable Miocene shelfal sand facies in Albania, where the reservoir quality of Miocene shelfal sand may be more representative of the Pleistocene in Montenegro. Three oil and six gas fields have been developed in the Neogene Durres Basin, which overlies the Mesozoic Ionian zone in northern Albania. Porosities vary from 10–30% with a mean of 23%; the permeability of the Albanian Miocene shelfal sands varies from 2mD to 2 darcys, which should support significant gas production. From this it could be concluded that the reservoir quality of Miocene shelfal sands in Albania is likely to form the closest analogy to the Pleistocene reservoir in Montenegro. Data supports the suggestion of a porosity range of 15%–40% as input to reserves estimates for Pleistocene prospects with target depths of around 1,000m. ▶

Skadar Lake was the site of the first exploration for oil and gas in Montenegro, nearly 100 years ago

National Tourism Organisation of Montenegro archives

During Early Pliocene times, a prominent delta system prograded from east to west across the Montenegrin offshore. Based on seismic data, bright areas can be identified at the bottom of a prograding delta, which have been interpreted as gas-charged turbidite sands. The stratigraphy of the Pliocene was evaluated from well summary logs from offshore wells in Montenegro, Croatia and Albania.

Several Pliocene prospects have been identified at depths ranging between 700m and 1,300m in waters of 75–120m. The area of these prospects is covered by 3D seismic data and the gas indicative nature allows the exploration risk to be considered as medium to low. An exploration well on one of the features would allow the drilling results to calibrate the seismic response. Given an initial successful result, it would seem likely that most of the prospects identified here would also be successful.



Ministry of Economy, Government of Montenegro

Data acquired offshore Montenegro includes 2D seismic (orange lines), 3D seismic (green block) and exploration wells (blue circles). Block delineation is represented by grey lines. The deepest water is 600m.

Mesozoic Carbonates

Potential for oil accumulations within Mesozoic carbonates has also been identified. Both Mesozoic and Palaeogene carbonates form a primary reservoir target offshore Montenegro, with the potential to produce substantial quantities of oil and gas. The carbonate reservoir facies with the optimum primary reservoir quality is believed to lie along the shelf break separating the Dalmatian Platform and the Adriatic-Ionian Basin. Seismic data demonstrates that the carbonate reservoir is likely to be developed in shelf edge facies, regarded as a low risk reservoir, in the centre of the offshore area.

In Albania there is production from carbonate reservoirs in ten oil fields and one gas field, all in the pelagic Ionian Zone. Reservoir quality in the central Montenegrin offshore is expected to be better than for the Albanian fields, perhaps closer to those at the Aquila field on the slope of the Apulian Platform, which produces from carbonate slope and pelagic facies. The field lies close to the base of the Apulian platform palaeoslope, in a location which is essentially a mirror image of the Montenegrin side, and would correspond to down dip of the crest of identified prospects. The reservoirs are a mix of tight pelagic limestone and much coarser detrital, porous limestone, derived from the crest of the shelf.

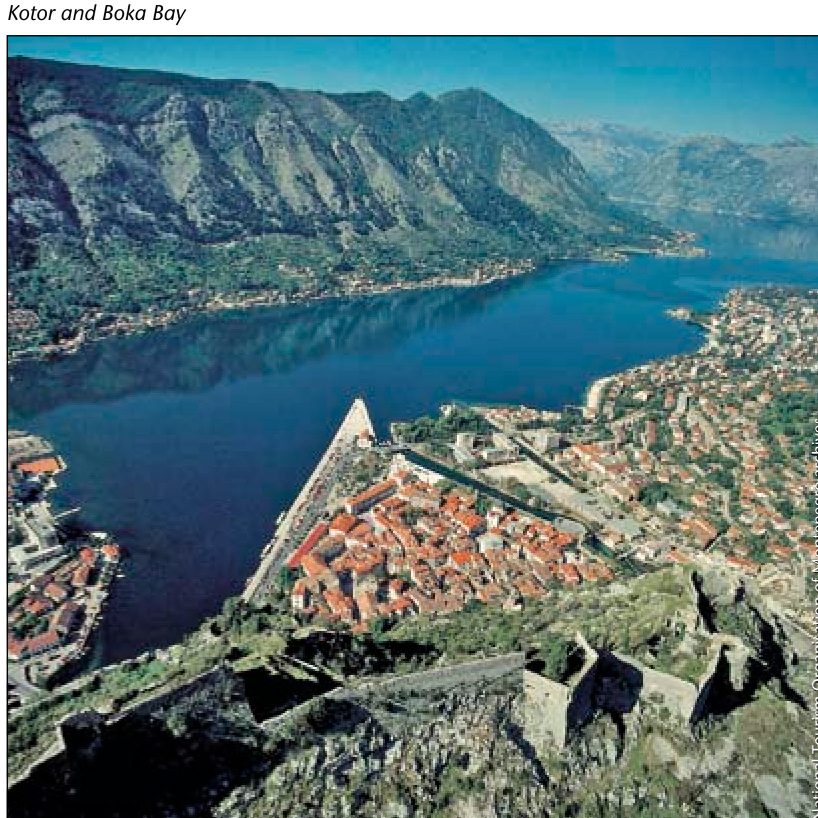
Looking Forward

In July this year the government of Montenegro adopted the Hydrocarbon Upstream Industry Fiscal Policy, defined for the purpose of creating a sound fiscal system that implies a stable and transparent long-term tax policy, and the first bidding round is expected to be announced in the near future. At the moment Montenegro does not envisage any state participation. A data room with seismic, geological, geophysical, geochemical and other data is available.

Having been part of Yugoslavia from the end of WW1 until it dissolved in 1992, Montenegro federated with Serbia until June 2006, when after a referendum it declared independence. The economy has been slowly growing since then, although affected by the global financial crisis. It is, however, heavily dependent on tourism and refined aluminium, and imports all its energy needs, so the exploitation of hydrocarbon reserves could be an important factor in its development.

Luckily for Montenegro, it would appear as though there is plenty of potential in their almost completely unexplored offshore waters. ■

Kotor and Boka Bay



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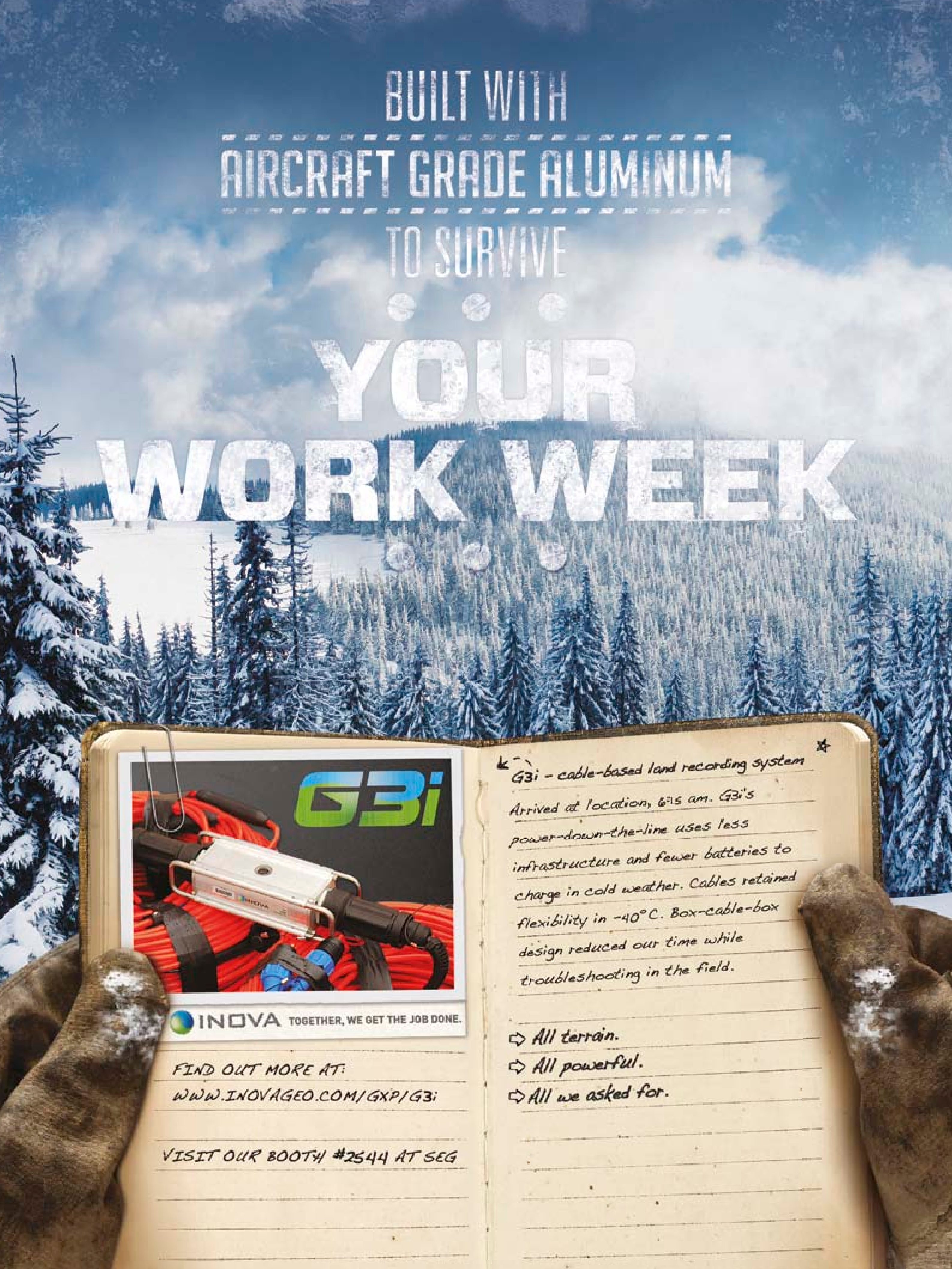
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G3i - cable-based land recording system
Arrived at location, 6:15 am. G3i's power-down-the-line uses less infrastructure and fewer batteries to charge in cold weather. Cables retained flexibility in -40°C. Box-cable-box design reduced our time while troubleshooting in the field.
All terrain.
All powerful.
All we asked for.

Adeliepenguin/Dreamstime.com

Lerwick
Small Yet Influential

ELEANOR ARCHER

Lerwick, the capital of the beautiful Shetland Islands off north-east Scotland, may be a bit small for the term 'city' – but its influence on our ideas on how to exploit our oil resources in harmony with the environment has been considerable.

Lerwick, Shetland's capital, takes its name from the Old Norse Leirvík, meaning 'muddy bay'. It is situated on a natural harbour on Bressay Sound, on the eastern coast of Shetland Mainland, the largest of the 16 islands which make up the Shetland Archipelago, 600 km north-east of the northern tip of Scotland. It is Shetland's only town, a bustling, cosmopolitan seaport home to 7,500 inhabitants. The advantages of the port's strategic proximity to operations in the northern North Sea and Atlantic are complemented by well-developed facilities and services, making it one of Scotland's leading marine centres for industry.

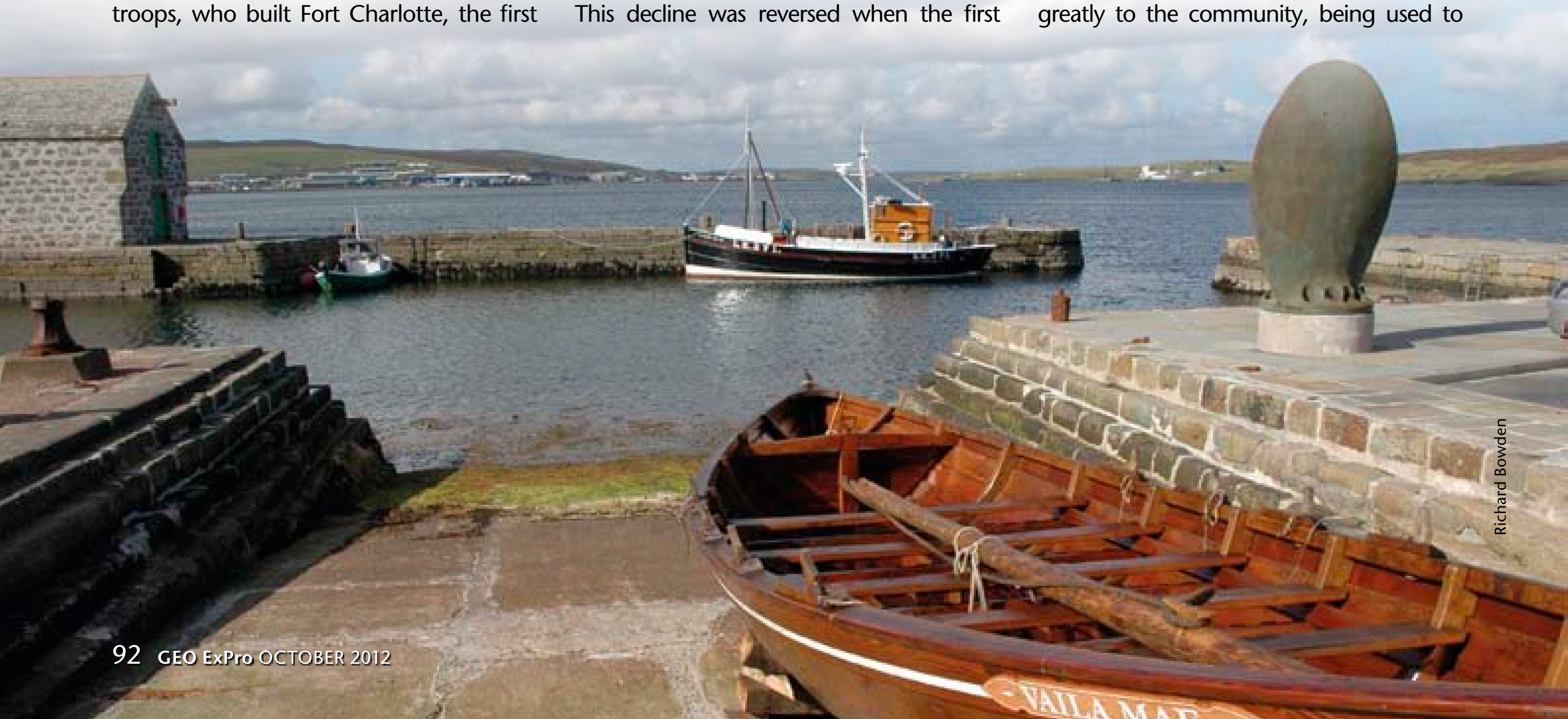
It was probably founded by Norsemen, who are known to have gathered a huge fleet there in 1263, but it did not become Shetland's capital until the 17th century, when Dutch herring fleets used it as an unofficial market place. Cromwell tried to oust the Dutch and lay claim to the surrounding fishing grounds by landing troops, who built Fort Charlotte, the first permanent building in the town. Despite attempts to burn down Lerwick through the 17th and early 18th centuries, the area continued as a fishing village, becoming the centre of herring and cod fishing industries, as well as Arctic whaling.

During the First World War, the war's effect on the herring industry led to mass emigration of islanders to Canada, Australia and New Zealand. However, the Second World War brought a temporary economic boom, as the Shetlands became the base from which operations against Nazi occupation in Norway took place. In particular, Lerwick's geographical position made it a strategic and important maritime base during this time. However, after the war, many Shetlanders again could not make a living and emigrated, so that by 1971, the total Shetland population had dropped to 17,325, from the 31,670 in 1861.

Oil Reverses Decline

This decline was reversed when the first crude oil was discovered in the North Sea in 1969. Built about 30 km north of Lerwick and completed in 1982, Sullom Voe became the largest terminal in Europe, loading oil onto tankers from pipelines coming from the Brent and Ninian oil fields. The Shetland County Council evolved a policy which restricted all major facilities to a single complex on an area of land in council ownership, so that all oil companies operated within one terminal. This made the council a 50% shareholder, providing a notable influence on Shetland's economy, while limiting the physical impact on the environment. Because of rigorous control with a long-term programme of environmental monitoring in place, despite the fact that it is one of the largest, Sullom Voe is one of the cleanest oil ports in the world with no discernible effect on the harbour's abundant marine life.

The money that the Shetland Islands received due to the oil has contributed greatly to the community, being used to



Richard Bowden

improve social care, conserve the environment and promote arts, sport and economic development. The population saw a sustained increase, with more than 22,000 people now living there. As a response to the economy, partly in association with the development of pipeyards, oil supply depots and harbour improvements, the Lerwick population grew in parallel with this, from 6,000 to 7,500.

In 2012, due to recent investments into deep-water infrastructure, larger oil-related ships are now able to reach Lerwick Harbour, with the number of such vessels arriving in the first half of the year up by 43% in comparison to 2011. As well as this, the tonnage has also risen 77% to 1.4 million gross tonnes, and cargo shipped in support of offshore operations by 58% to 65,308 tonnes (Lerwick Port Authority).

Popular Tourist Destinaton

As well as this success in becoming a key part of North Sea oil activities, Lerwick today is also home to one of Europe's largest pelagic fish factories, Shetland Catch, and frequently sees many cruise liners during the summer season.

It is also growing as a popular tourist destination, providing a choice of eateries, shops, pubs and clubs, as well as a leisure centre and a theatre. Lerwick is also celebrated as a place to sample Shetland's renowned musical heritage and to enjoy the spectacular scenery of the island on walks in which seals, otters and other wildlife can be spotted in their natural habitats. The Shetlands themselves are a popular destination for geologists, with an incredibly varied geology spanning almost 3 billion years.

In January, the town particularly comes to life, celebrating its chief festival, Up-Helly-Aa annually on the last Tuesday of January. Echoing a long tradition, the day involves a series of marches and visitations, culminating in a mass torchlit procession behind a Viking long boat. This is then subsequently burnt with great ceremony, before a long night of revelry commences, lasting until the morning. Understandably, the following day is a public holiday in Lerwick to allow everyone to recover! ■

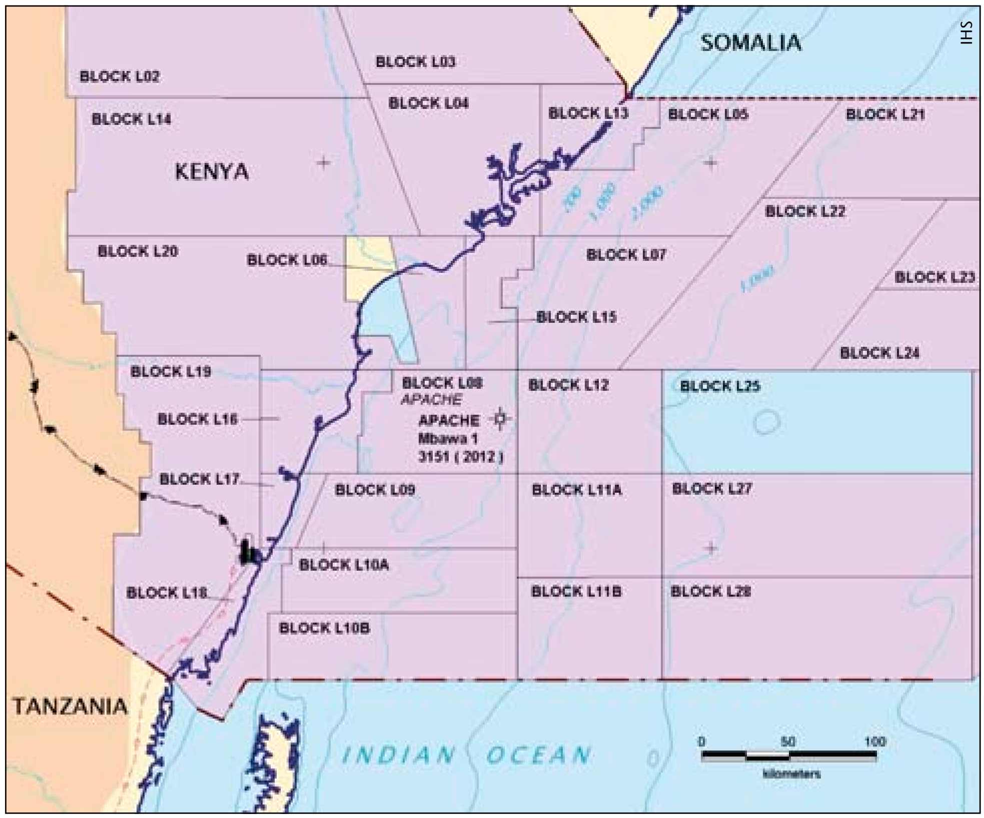
Kenya: Reality Check

After the excitement of the finds off Mozambique and Tanzania in recent years, the prospectivity of the east African coastline has had a reality check following the outcome of the **Mbawa-1** wildcat operated by Apache.

Located in the 5,123 km^2 Block L8 in the Lamu Basin, the well was drilled in 864m of water using the Deepsea Metro 1 D/S. In an interim update, Apache said that it had encountered 52m of net gas pay in Cretaceous sandstone, the primary target. The well reached a total depth of 3,151m to test for any deeper oil potential within this gas-prone region but no hydrocarbons were found. Nonetheless, even though the Cretaceous gas is deemed non-commercial, the well is claimed by the consortium as the first hydrocarbon discovery off Kenya.

The Mbawa structure is described as a large but complexly-faulted anticline mapped on 3D seismic data with potential for both oil and gas at inferred Tertiary/Cretaceous and Jurassic reservoir levels. Apache said in July that the Mbawa well is likely to strike oil based on seismic data and slicks seen on the Indian Ocean's surface and that the drilling targeted as much as 700 MMbo.

Block L8 interests are held by Apache (50%), Origin (20%), Pancontinental (15%) and Tullow Kenya (15%). ■



Mexico: Major Gulf Oil Find

In the final months of his presidential term, Mexican President Felipe Calderon proudly announced that state-owned PEMEX has made its first big crude oil discovery in the deep waters of the Gulf of Mexico. Lying in 2,500m of water, the **Trion-1** wildcat lies 39 km south of the US-Mexico maritime border and 180 km east of the Gulf state of Tamaulipas. Preliminary estimates suggest in-place reserves of up to 400 MMb of light crude.

The new discovery lies in the so-called Perdido Foldbelt of the Gulf and, according to Calderon, Mexico's Perdido complex of deposits could hold between four billion and 10 billion barrels of crude. He said PEMEX is entering into a new phase of oil discovery in the Gulf, where reserves are estimated at 27 Bbo. The success comes after a decade of deepwater exploration where investments have exceeded US$ 4 billion, prompting the country's regulator, the National Hydrocarbons Commission, to criticise the company, saying it was devoting far too much capital to risky exploration. The discovery underlines the view that the deep waters of the Gulf are likely to provide PEMEX with rising oil production after eight years of steady decline.

However, it is also certain to intensify the debate over further opening of PEMEX and Mexico's petroleum resources to private investment. Proponents have argued that PEMEX needs private investment from companies to fully develop the country's petroleum potential. Succeeding Calderon, President-elect Enrique Peña Nieto has stated that he will amend laws to allow private companies to invest with PEMEX but such moves have encountered stiff opposition in the past. One likely development option is a possible tieback to Shell's Perdido facilities located on Great White Field across the maritime border. ■

Peru: Repsol Gas Strike

Repsol has made an important gas discovery with its **Sagari-1** wildcat in its sub-Andean Block 57 in Peru, establishing gas pay in both the Nia Superior and Nia Inferior formations. Production tests carried out at depths of between 2,691m and 2,813m produced gas flows of 26 MMcfgpd with 1,200 bcpd in one formation, and 24 MMcfgpd with 800 bcpd in the other. Repsol plans to carry out further exploration in the block once the production tests are complete. Preliminary estimates indicate the field may hold between 1 and 2 Tcf of gas resources.

The Sagari find reinforces the potential of this area in Peru, home to the company's **Kinteroni** find, ranked as one of the five biggest discoveries made worldwide in 2008. This field is currently under accelerated development with first gas planned for the end of 2012. It is expected to produce 155 MMcf of natural gas daily in its initial phase.

Repsol is the operator of the block with a 53.84% stake. Petrobras holds the remaining 46.16%. Repsol has been stepping up exploration activities as part of its strategic plan in the years to 2016 that it outlined in May this year. ■

The new gas discovery is close to the Kinteroni field, due to come on stream by the end of the year

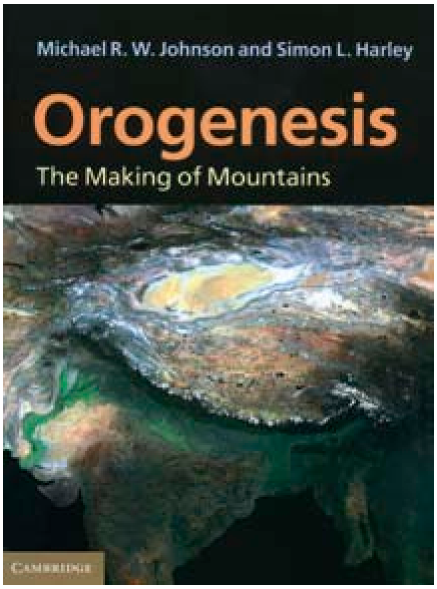
Orogenesis:
The Making of Mountains

A new book describes the processes involved in mountain-building and sheds light on the significance of orogenesis to the petroleum industry.

Through the centuries, people have been drawn to mountains for a variety of reasons: sports, adventure, war, exploration, mining, pilgrimage, and so on. When George Mallory was asked why he wanted to climb Mount Everest, the English mountaineer gave his often-quoted answer: "Because it is there." The existence of mountains has a special significance for geologists: the very science of geology owes its existence to mountains. In the late 18th century when geology was born, Horace Benedict de Saussure, the Swiss founder of Alpine geology (and indeed one of the earliest scientists to use the term 'geology'), remarked: "It is above all the study of mountains that will accelerate progress in the Theory of the Earth. Plains are uniform; it is not possible to investigate in them a section of the earth and its different layers." Ironically, there is no particular branch of geology that exclusively studies mountains, possibly because all of geology is concerned with mountains: igneous and metamorphic rocks, faults and folds, fossils and sediments, landscape development, and even many types of sedimentary basins which are formed and fed by mountains.

Nevertheless, the rapid specialisation of numerous disciplines in geology over the past century has created a void in our geoscience education and research. It is high time we developed an integrative, multi-disciplinary field that focuses on the study of mountains in a holistic way, not only for purely scientific reasons but also because mountains exert great influences on highland and lowland populations, river courses, regional climate, agriculture, tourism industry, and so forth.

Orogenesis: The Making of Mountains fills an important niche in our geoscience education. Perhaps the first of its kind as a textbook, it is written by two geologists who each have decades of teaching and research experience. Michael Johnson, a structural geologist, and Simon Harley, a metamorphic geologist, are both from the University of Edinburgh, the very place James Hutton laid the foundation of geology more than two centuries ago.



Review of Mountain Geology

The term orogenesis ('mountain-building') usually refers to the formation of mountains by the convergence of tectonic plates. This takes place by ocean-continent collision (e.g., the Andes), continent-continent collision (the Alps and the Himalayas), or island arc-continent collision (e.g., New Guinea). All these tectonic processes create sedimentary basins of various types. ('Orogen' is a mountain system, and 'orogeny' refers to a particular mountain-building event such as the Alpine or the Andean. These terms were introduced by the German geologist, Leopold Kober.)

This book focuses on mountain belts like the Alps, the Himalayas, the Andes and the Cordilleras. (Continental rift-shoulder mountains are not discussed in this book.) These are all modern mountains with high relief (over 600m, the definition of a mountain) but to the geologist, even the tectonically old and low-relief features like the Appalachians and the Caledonides are also orogens because they allow us to investigate deep-seated tectonic processes.

Through twelve chapters, the book offers an up-to-date review of various aspects of mountain geology. The first two chapters are an introduction to the plate-boundary types and driving mechanisms of plate tectonics. This is followed by basic information about geodynamics, geochronology, and thrust tectonics (Chapters 3 and 4). The meat of the book is two chapters which together account for 40% of the entire volume: Chapter 5 is on the tectonic evolution of orogens, analysed both in theory and with examples from around the world; and Chapter 7 deals with metamorphism and metamorphic rocks in mountain belts. The erosion and denudation of mountains and the formation of foredeep basins are treated in Chapters 8 and 9. One chapter titled 'Mountains and climate' discusses the role of the Himalayas in shaping the monsoons in southern Asia. The last chapter of the book, 'Secular change in orogeny', touches on a hot debate: are there particular periods in the Earth's history during which mountain-building processes predominate or is orogenesis a uniform process through geologic time? This last question obviously has important implications for the global distribution of foredeep basins. A set of 47 colour photographs and a list of some 500 references for further reading come at the end of the book.

Mountain outcrops provide a unique opportunity to observe formations and structures which are responsible for petroleum systems in the subsurface. Moreover, mountain-building and basin formation processes are geodynamically coupled. A modern and comprehensive understanding of orogenesis, as presented in this new book, deserves to be part of the petroleum geologist's reading. ■

RASOUL SORKHABI

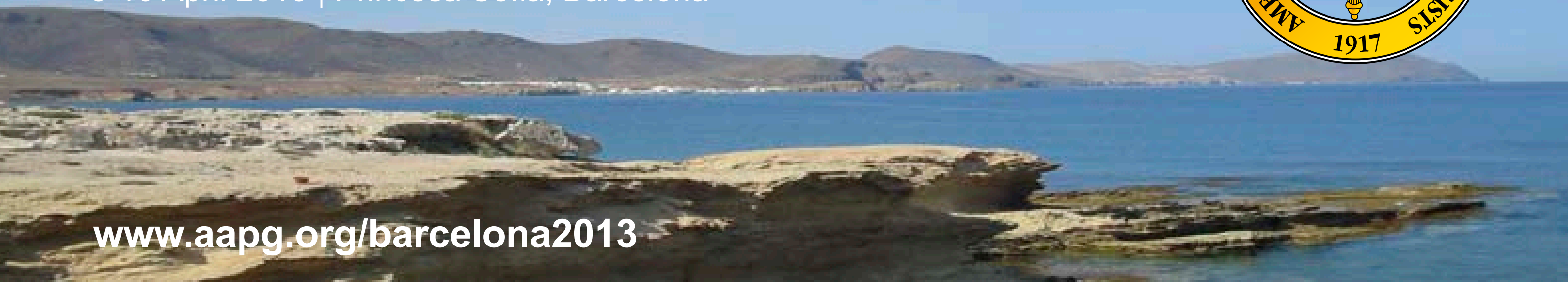
Orogenesis:
The Making of Mountains

Published by Cambridge University Press in 2012.

AAPG European Regional Conference

Exploring the Mediterranean: New Concepts in an Ancient Seaway

8-10 April 2013 | Princesa Sofia, Barcelona



A rich human history of civilisation, trade and war is deeply rooted in the complex ancient geology that underlies the Mediterranean region, having evolved through the convergence of the European and African plates and the closure of the Tethys Ocean. In more recent times, oil and gas exploration has found success in the diversity of resulting extensional and compressional tectonic regimes, with a procession of new plays being identified over decades of industry and academic activity. Despite intensive exploration, the region continues to deliver tangible success through its rich diversity of play types, as recent discoveries in the Eastern Mediterranean have testified.

This significant conference will assemble some of the best current thinking in Mediterranean petroleum geology, from the tectonics that underpin the basin, to the Messinian salinity event and its impact on exploration. From North Africa to the Adriatic, this conference will bring together the multiple cultures that surround this diverse region to reflect on a common geological framework and the petroleum systems that transcend political boundaries.

With its position to the west of 2.5 million sq. km of water, Barcelona will form the ideal backdrop to this timely event.

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North West Europe – Optimism or Pessimism?

After many years of production, many consider North West Europe to be past its prime. Hannon Westwood's **Jim Hannon** and **Andrew Vinall** take a look at the region's future

Is North West Europe a mature province?

This depends on your definition of mature. Certainly the easy oil and gas has gone in the traditional areas and many would have us think that the game is over. But consider this: only around 50% of what has been discovered has been produced and both the UK and Norway have many years of production left in them. Back in the 1970s, when the UK was being converted to natural gas, we were told the same story – the North Sea only had 30 years remaining. Look where we are today, 30 plus years on and still with 30 plus years production in both the UK and Norway ahead of us. With improvements in subsurface imaging, better calibration of rock physics and innovative geoscience, new plays are being uncovered in mature areas (Catcher, Cladhan, Johan Sverdrup), and frontier areas like West Shetlands and the Barents Sea are showing significant promise. Resource plays in Europe are largely unproven as a viable economic alternative, but may become a modest component of the overall production mix in the future.

With a finite and ultimately declining production base we see the real challenge to the future of North West Europe as being not so much the geology, but the management of the investment climate to support efficient exploration and exploitation of the resource potential. A realistic and stable tax regime, investment incentives and oil and gas prices are all considerations and while global commodity prices cannot be controlled, governments have a key role in determining if these basins can thrive and continue to compete internationally.

What were the most exciting developments in the region in the last two years and what is the knock-on effect?

There are probably two main developments: firstly the opening up of the frontier areas where sufficient reserves are now being found to create new hubs that will enable the export of gas in particular to be economic; and secondly, the Utsira High discoveries. Both are creating interest in areas that were either unloved or were seen as having too long lead times for most companies. The result has been a resurgence of exploration activity in both areas and a serious review of potential analogues, both of which could lead to significant new discoveries.

What challenges will be important in the next 10 years? What technological developments will help?

Advances in geoscience technology have significantly improved the chance of exploration success over recent years. Now the greatest challenge facing the UK today and Norway in the future is the need to ensure the presence of an effective export infrastructure to secure both the remaining known and the potential yet-to-find resources. Given the ageing of the current infrastructure, putting new oil down old pipelines may not work. Most importantly, we will require industry and government collaboration to ensure efficient access to infrastructure and a good investment climate that will promote innovation in technology to reduce costs and facilitate satellite developments. We are seeing re-usable solutions in spar and buoy technology advancing that could allow cost-effective exploitation of small developments, providing that access to infrastructure is available or offshore loading is feasible. Unmanned and remote controlled seabed installations may also be increasingly used, but these will either require substantial reserves or nearby existing infrastructure tie-points to be economic.

What should the UK government do to encourage investment in the UKCS?

Government has shown that it is already listening to industry in removing some of the damaging effects of the special corporation tax that was introduced in 2002, initially at the rate of 10% though it has since been increased twice, in 2006 and 2011. Now standing at 32% it has clouded investment for nearly 10 years. More than anything, attempts to increase government tax take generally prove more harmful than oil price reductions and destabilise the fiscal climate, creating investment uncertainty. It is a perfect example of the difference between good and bad management. It is a relief to see common sense prevail with almost all UKCS projects now subject to minimal extra taxes. This can only be good for resources, good for jobs and good for the UK.

Next 10 years – optimistic or pessimistic?

Optimistic! ■

Jim Hannon (right), co-founder of Hannon Westwood, is an expert in portfolio rationalisation, strategic analysis and the use of market intelligence, and Technical Director Andrew Vinall has had an extensive career spanning production, development, exploration and commercial aspects of the UKCS.

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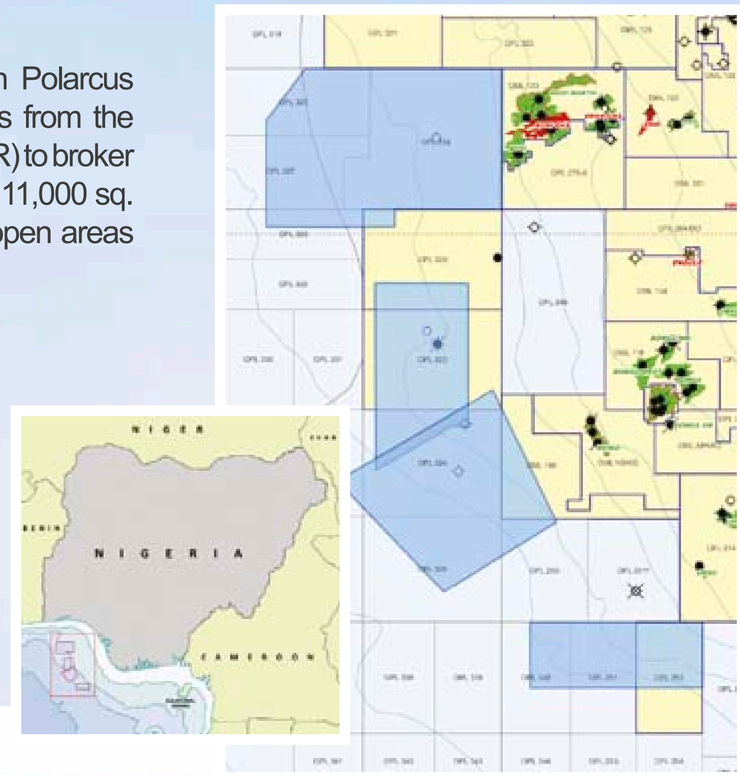

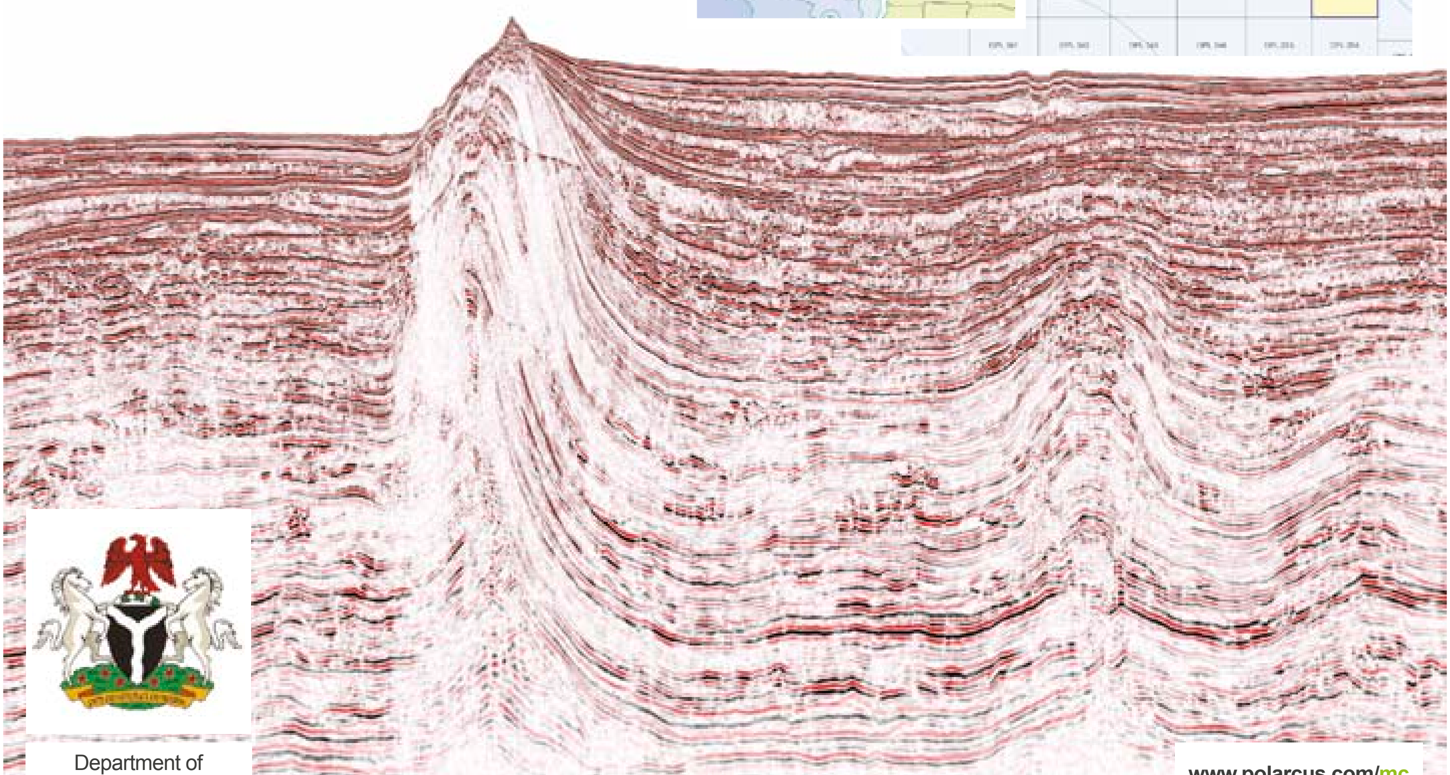

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A Significant Milestone

Is an Australian unconventional gas boom on the cards?

KEN WHITE

Santos has declared itself to be on track to produce Australia's first commercial shale gas after its Moomba-191 shale gas well in the Cooper Basin licence PPL 7 flowed at a stabilised rate of 2.6 MMcfg/d for more than two weeks. Activity in Australia's shale and tight gas sector has seen increased investment by international majors in recent months but while some, like Beach Energy, have established flow rates from their unconventional gas wells, none has announced plans to put the wells into production. Santos' move to connect Australia's first commercial shale gas well to existing gas infrastructure therefore marks a significant milestone of game-changing proportions.

Analysts believe the result has given Australia's security of energy supply a significant boost, as until Moomba-191 the shale potential of the Cooper Basin was just that – potential; even though the basin has been producing 'conventional' gas from reservoirs above and below the shale tapped in this well for over 40 years. According to GeoScience Australia, the nation's total identified gas resources, excluding shale gas, are around 392 Tcf. Shale gas resources are estimated to be as much again, at around 400 Tcf.

The Cooper Basin, in a remote desert region of central Australia, is sparsely populated, so shale gas development projects are unlikely to face the same level of opposition from affected communities and competing land-users felt elsewhere. Horizontal drilling and extensive fracturing trials are planned for the period to end 2013.

Holloman Energy

Active Exploration

The range of Australia's unconventional resources has attracted the likes of ConocoPhillips, BG and other major players, a move that has signalled to some that maybe another unconventional gas boom is on the cards. For the moment, however, it is the domestic players that are leading the way on shale gas, none more so than Beach Energy. The company has drilled two wells in PEL 218 – Encounter-1, which spudded in late 2010, followed closely by Holdfast-1, both located in the deepest part of the Nappamerri Trough – and seeking a reasonable shale thickness in the Roseneath-Epsilon-Murteree (REM) sequence and a decent flow rate of gas. The results showed that not just the shales of the REM sequences were gas-saturated, over-pressured and thicker than first thought, but also that the sandstones and other lithologies located above and below the target shales were gas-saturated. Beach booked a 2 Tcf contingent shale gas resource after drilling these two vertical wells, a result that changed the outlook for the development of this unconventional opportunity entirely. Further analysis by the company has suggested the potential for at least 15–20 Tcf of gas in terms of 2P resources within PEL 218, something it intends to assess by drilling at least five vertical exploration wells. Moonta-1, the first unconventional vertical well of the 2012 shale and basin-centred gas programme, was drilled to the base of the Patchawarra Formation to a depth of 3,810m. Logs indicated gas saturation over more than 1,000m of the Permian target zone (Toolachee Formation to the base of the Patchawarra Formation). Streaky-1, the second well in the unconventional programme, reached a total depth at 3,821m with cores taken in the Epsilon and Patchawarra sections. Both wells are expected to be fracture stimulated in late third quarter 2012.

Beach also has a 60% stake in adjacent block ATP 855P where on 4 August 2012 with partner Icon Energy, it spudded Halifax-1, a vertical exploration well evaluating the shale gas and basin-centred gas potential in the REM and Patchawarra Formation intervals within the Queensland portion of the Nappamerri Trough. The well is located approximately 12 km north-east of Encounter-1 and has a planned total depth of 4,130m. Icon reported that at 2,670m Halifax-1 intersected an interval of sandstone with elevated gas values in the Nappamerri Formation, approximately 530m above the primary target, where a 7m interval flowed around 0.2 MMcf/d on test. The potential of the zone as a secondary target will be evaluated further at the conclusion of the well.

Ultimately the development of shale gas will come down to cost and whether it can compete as it is more expensive than gas from conventional reservoirs and gas produced from coal-beds. At current eastern state gas prices, Cooper Basin shale gas is not a viable economic business, except where the wells are close to existing facilities, as is the case with Moomba-191, just 350m from existing gas-gathering infrastructure and some 770 km north of Adelaide. ■

Deep Energy

Exploring and exploiting geothermal energy benefits the environment and creates opportunities for geoscientists.

Geothermal energy is stored in the form of heat below the Earth's surface.

The main source of this heat is radioactive material in the crust and mantle, as well as heat from when the Earth was formed some 4.6 billion years ago. In the upper 100–200m of the crust, however, solar energy is the main heating source. The resource is basically available everywhere. However, it is more abundant and more accessible along plate boundaries such as in Japan (converging plates) and Iceland (diverging plates) where active hydrothermal resources are found.

It is considered an energy source of the future because it is a renewable and provides continuous power and/or heat production regardless of weather (i.e. sun, wind or rain). Geothermal resources thus have great potential as a nearly emission-free energy source.

There is a distinction between shallow geothermal systems that extract the energy for heating and cooling through heat pumps, and deep geothermal systems for power generation or direct use of heat. The former utilises geothermal heat pumps which are one of the fastest growing renewable energy technologies.

It is being said that the scientific and technical solutions are at a point where the deep resource can be made commercially viable in areas without active hydrothermal resources. Geothermal exploration, requiring geophysical measurements and skilled geologists, will therefore have an interesting future.

IPCC has estimated that the potential for production in 2050 will be 1,255 TWh of electricity and 2,184 TWh of heat. Others are of the opinion that the potential for exploiting the resource is nearly unlimited if we develop this science and technology.

According to BP's Statistical Review of World Energy 2012, geothermal capacity grew by just 0.8% (88 MW) in 2011, to reach 11 GW. Also, BP says, geothermal capacity has now been overtaken by solar power capacity, but geothermal power runs at a much higher load factor than solar (its source is continuous rather than intermittent), so geothermal still produces significantly more electricity than solar.

Only two major geothermal projects were completed in 2011, in Iceland (90 MW) and Costa Rica (42 MW), while Mexico shut down an old plant (78 MW).

The US has the largest geothermal capacity (the larger amount in California), now just over 3.1 GW, 28.3% of the world total, followed by the Philippines (2.0 GW), Indonesia (1.2 GW) and Mexico (0.9 GW). BP has listed 20 other countries that have an annual capacity exceeding 0.3 MW. Japan and Iceland have capacities of 502 and 665 MW respectively.

HALFDAN CARSTENS

The Svartsengi geothermal plant in Iceland contributes 75 MW in electrical energy and about 150 MW in thermal energy. The Blue Lagoon with the famous outdoor swimming facilities is probably the most popular Icelandic tourist attraction.

CONVERSION FACTORS

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

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

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

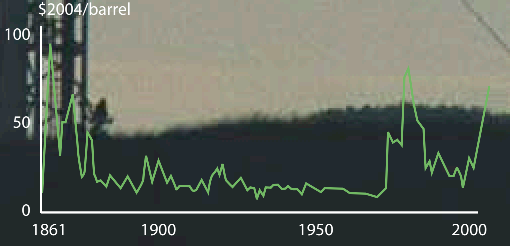
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

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

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

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

Historic oil price



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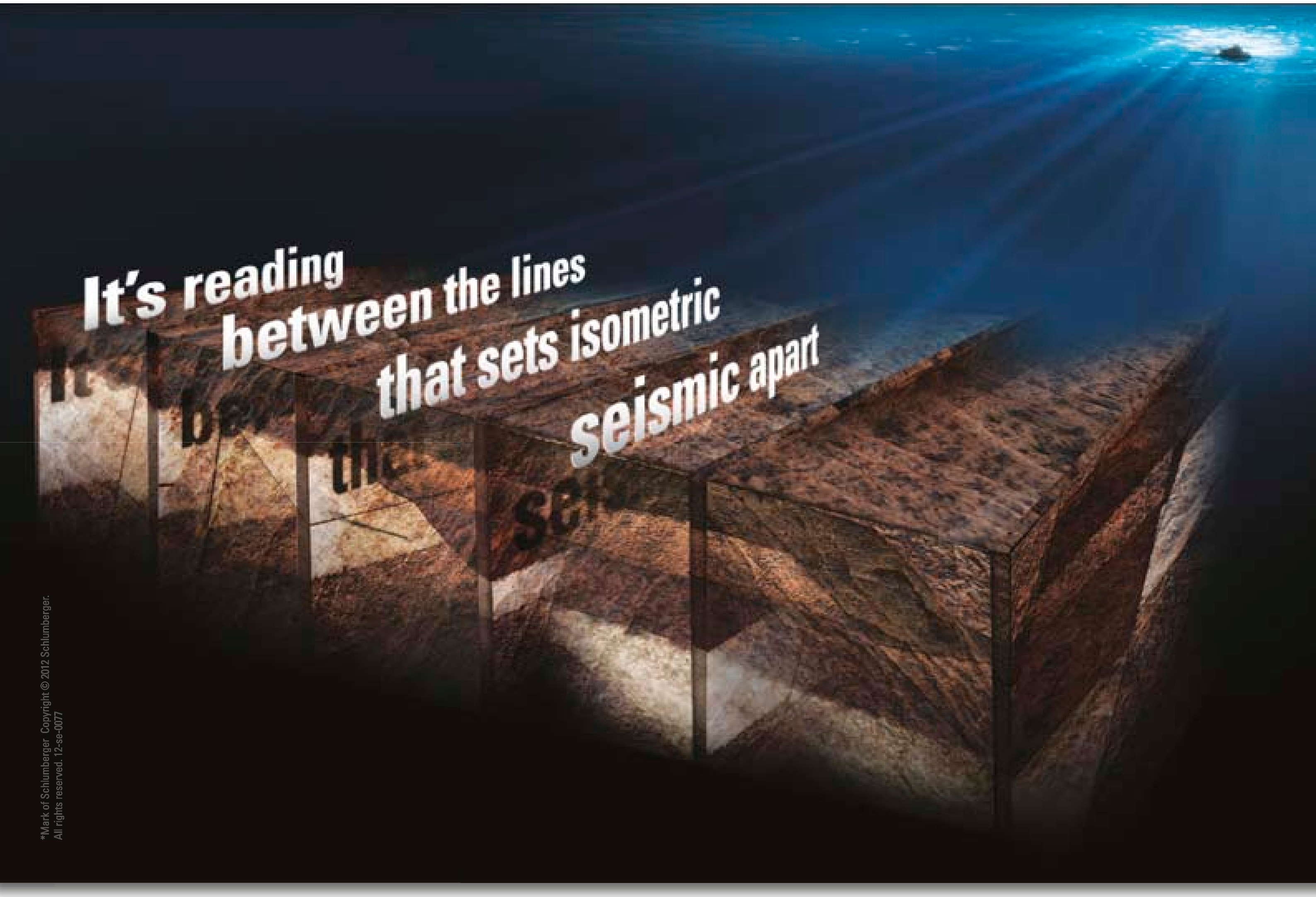

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