

GEOExPRO

GEOSCIENCE & TECHNOLOGY EXPLAINED



GEO TOURISM:
Oki: A Japanese Island
Geopark



geoexpro.com

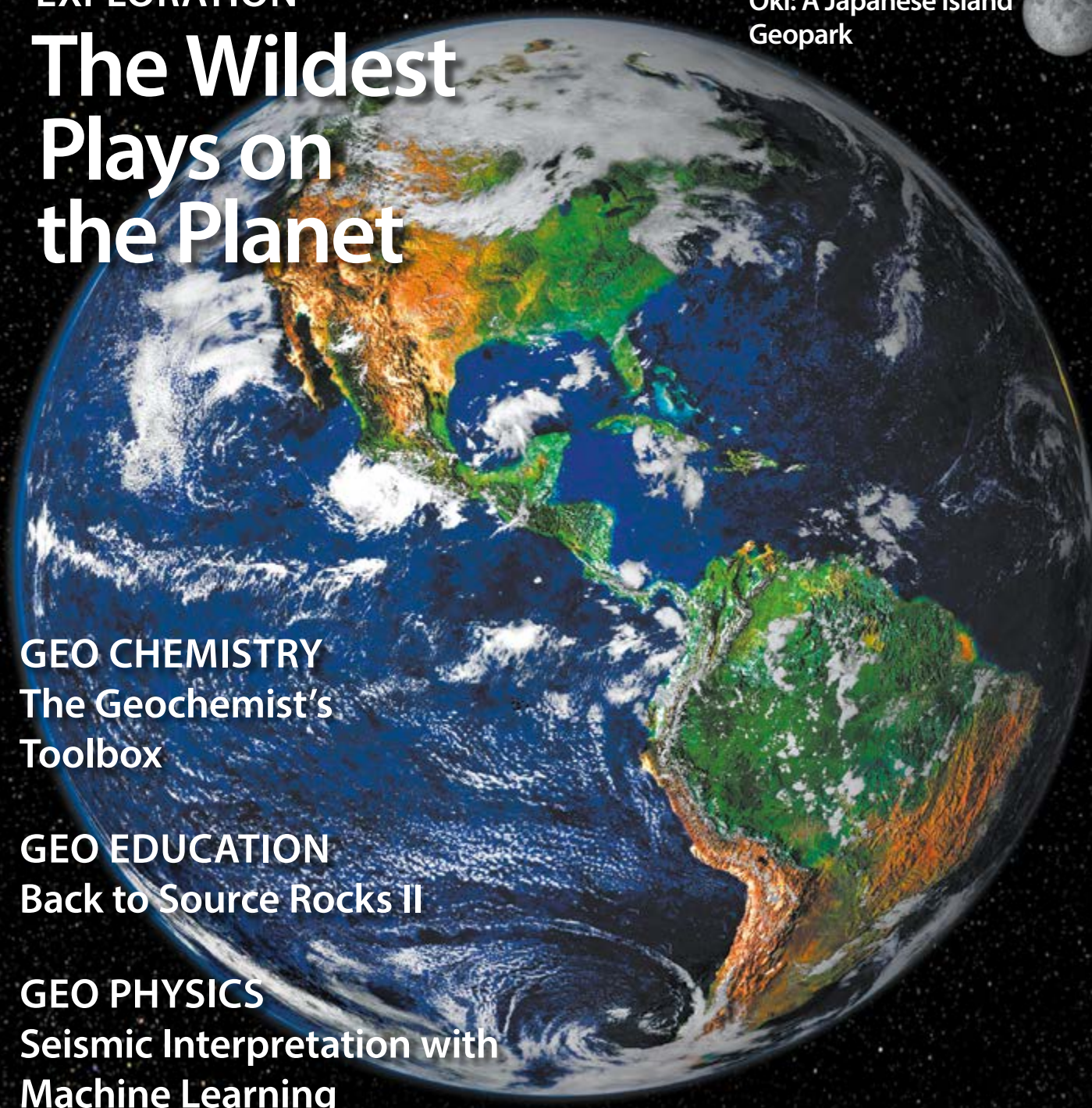
EXPLORATION

The Wildest Plays on the Planet

GEO CHEMISTRY
The Geochemist's
Toolbox

GEO EDUCATION
Back to Source Rocks II

GEO PHYSICS
Seismic Interpretation with
Machine Learning





Move2017 Highlights

Arriving December

- New 3D pdf export for 3D views and 2D section animations
- Significantly enhanced interactivity in 2D and 3D Kinematic Modelling
- Support for user-defined compaction curves in the Decompaction tool
- Improvements in Fault Analysis, Stress Analysis and the Move Link for Petrel

mve.com/move-latest

Diary Dates for 2017

TRAINING

Glasgow – 24-26 January
Houston – 14-16 February

USER MEETINGS

Houston – 29-30 March
Glasgow – 9-10 May

EVENTS

AAPG ACE Houston – 2-5 April
EAGE Paris – 12-15 June

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Source rocks are the foundation of petroleum systems.

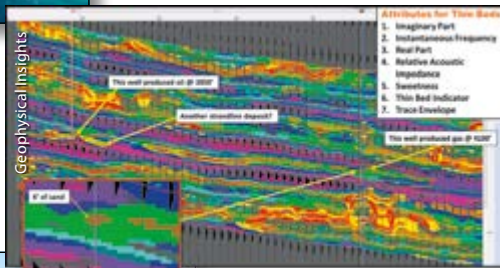


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KNOWLEDGE IS OPPORTUNITY

C&C Reservoirs

Mapping the Seafloor

It has been said that our present world view and comprehension of the Earth's processes is a direct result of mapping and understanding the nature of the seafloor (Dierssen and Theberge, 2015).

Sailors have always needed to know how far the seabed lay beneath the keel of their boat and for centuries used a 'line and sinker' – a marked rope or wire with a lead weight, dropped over the side of a boat – to measure the distance to the seafloor, but few of these measurements were kept for posterity. In the early 19th century, however, partially spurred by the desire to lay deep sea telegraph cables, national navies and other bodies started to record detailed depth soundings, using them to build maps of the seafloor. Much to their surprise, these revealed that deep beneath the oceans the seabed was not flat and featureless, as they had expected, but contained very deep trenches and canyons and submerged mountain ranges higher than the Himalayas. These discoveries fed into the concept of plate tectonics and are thus crucial to our understanding of the Earth.

However, it was not until the realization that sound travels easily through water and the development of acoustics and the echosounder in the 1930s, followed by the advent of the multibeam sonar, that truly detailed maps of the seafloor could be constructed. These charts have proved vital for the advancement of the oil and gas industry, both for exploring offshore and for transporting hydrocarbons by ship and undersea pipelines.

Yet more than 85% of the world ocean floor remains unmapped by modern methods, according to the organization responsible for the task, the General Bathymetric Chart of the Oceans (GEBCO), a joint project of the International Hydrographic Organization and the Intergovernmental Oceanographic Commission of UNESCO.

GEBCO now plans a comprehensive mapping of the entire ocean floor. As part of this it will develop a new structure for the global coordination of mapping activities and the gathering of all available depth measurements into a database, encouraging businesses and organizations which routinely collect bathymetric data to contribute. As a major player in this area, the oil and gas industry should be encouraged to participate. ■



Early (1752) bathymetric and geologic map of the English Channel area by Philippe Buache.



Jane Whaley
Editor in Chief

WILDEST PLAYS ON THE PLANET

Where will exploration move to next? Meteor craters? Caves filled with oil? Gold mines? Some of the ideas discussed here may sound wacky, but many are known to have large reserve bases and have already resulted in major discoveries. The geologist must always keep an open mind.

Inset: The remote Japanese archipelago of the Oki Islands boasts spectacular scenery, and text book examples of volcanic island development and coastal erosion abound in this beautiful Geopark.



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GEO EXPRO is published bimonthly for a base subscription rate of GBP 60 a year (6 issues). We encourage readers to alert us to news for possible publication and to submit articles for publication.

Cover Photograph:
Main: Image created by Reto Stöckli, Nazmi El Saleous, and Marit Jentoft-Nilsen, NASA GSFC
Inset: Club Noah

Layout: Winslade Graphics
Print: NXT Oslo Reklamebyrå

issn 1744-8743

Somalia: First Round in 2017

In recent years, Somalia has made great strides on the road to effectively exploiting its natural resources. The Somalian Ministry of Petroleum and Mineral Resources is now operating from a new building, complete with a dedicated data room, and its employees have undergone extensive training to fully understand the different aspects of licensing and the exploration cycle. With assistance from the African Development Bank and the World Bank, the ministry has made substantial advances in developing a solid legal and regulatory framework through appropriate amendments to the petroleum law, the completion of a petroleum registry, the introduction of a downstream law, and resource sharing agreements within Somalia's upstream sector. A new production sharing agreement model, including fiscal terms, has also been developed.

In addition, the ministry has entered into key agreements with multi-client seismic provider, Spectrum, to acquire over 40,000 km of modern, high quality seismic data which will greatly assist the crucial decision-making processes of oil companies interested in conducting exploration activities offshore Somalia. These seismic surveys have already produced some extremely interesting findings across all three of Somalia's offshore basins – the last true hydrocarbon exploration frontiers of the Indian Ocean. Seismic imaging gives strong indications of oil and gas potential, which the Somalians hope will be tested and proven in due course.

With all this in place, Somalia recently announced its first offshore hydrocarbon licensing round, which will cover areas off central and southern Somalia and will exclude shallow water block concessions signed in 1988 with Shell and Exxon Mobil. ■



Equatorial Guinea: New Bidding Schedule Announced

In early November the Equatorial Guinean Ministry of Mines and Hydrocarbons announced the full schedule for bidding on Equatorial Guinea acreages in EG Ronda 2016. By the end of January, 2017, all interested parties must have submitted pre-qualification data, so that the list of pre-qualified companies can be announced on 3 February. The round will close on April 28, 2017 and after negotiations with successful companies it is hoped to ratify the resultant PSCs on 15 December.

EG Ronda 2016, which launched on June 6, 2016, offers all exploration blocks in the country not currently under direct negotiations for bidding – 17 licenses in total, predominantly offshore in water depths ranging from shallow to over 2,000m.

According to H.E. Gabriel Mbaga Obiang Lima, the Minister for Mines and Hydrocarbons, "Now is the best time to explore for oil and gas in Equatorial Guinea, when the cost of drilling a well is cheaper and when you have access to a wealth of advanced geological data. Equatorial Guinea's legacy of exploration success and strong partnerships with international companies create a perfect environment for upstream investment." ■

ABBREVIATIONS

Numbers (US and scientific community)

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

Liquids

barrel	= bbl = 159 litre
boe:	barrels of oil equivalent
bopd:	barrels (bbls) of oil per day
bcpd:	bbls of condensate per day
bwpd:	bbls of water per day

Gas

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

Ma: Million years ago

LNG

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

NGL

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

Reserves and resources

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

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

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

Oilfield glossary:

www.glossary.oilfield.slb.com



BGP Multi-Client – Cuba

~25,000 km multi-client seismic lines are planned around offshore Cuba. The whole project consists of lines in the Economic Zone of the GOM, lines in the south of Bahamas Border, and lines in the southern sea of Cuba. BGP and potential partners will jointly undertake the project.

In-filled well-tie 2D seismic lines are designed by BGP with assistance of CUPET. Those lines will help to improve seismic imaging in deep targets in offshore Cuba. High density of seismic lines are designed in prospective GOM-CEEZ, where excellent levels of source rocks, reservoirs and leads have been identified these years.

The project will be commenced by three phases:

Phase I: ~20,000 km – GOM-CEEZ (Red lines) Phase II: ~2,500 km – Yellow lines

Phase III: ~2,800 km – Blue lines

The first phase will be acquired by BGP Pioneer in November 2016.



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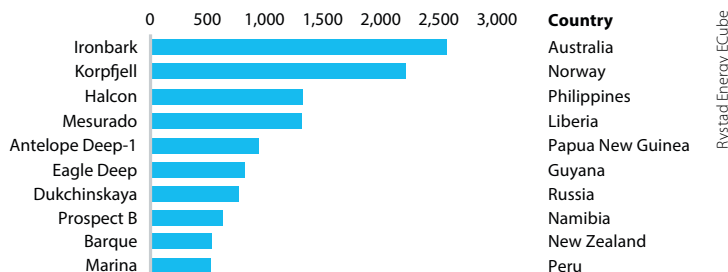
The Most Exciting Upcoming Exploration Wells

E&P exploration has been struggling in 2016, with lower investment budgets resulting in lower overall activity. In 2016, a total of 440 offshore exploration wells will be drilled, compared to 740 in 2014. At the same time, the exploration results have been disappointing so far this year.

There has been one positive aspect for exploration in 2016: due to more efficient drilling operations, the speed of drilling has increased considerably. In Norway, the drilling speed per meter increased 20–30% between 2014 and 2016. At the same time lower prices within the industry have decreased exploration costs with, for example, rig rates dropping 55% over the last two years.

High Impact Wells

However, there are several exciting exploration wells coming up. The illustration shows some of the highest impact wells expected to be drilled over the next year.



Upcoming high impact exploration wells with predrilled resource estimates, with figures in MMboe based on the latest reporting from operators.

Statoil is planning to drill Norway’s northernmost oil well, Korpjfell, next year in the Barents Sea. The Korpjfell prospect was the most sought-after acreage in the 23rd licensing round. While NPD originally believed the formerly disputed area was gas-prone, the 3D seismic revealed clear liquid hydrocarbon indicators. The structural closure is about four times bigger than that found at Johan Sverdrup.

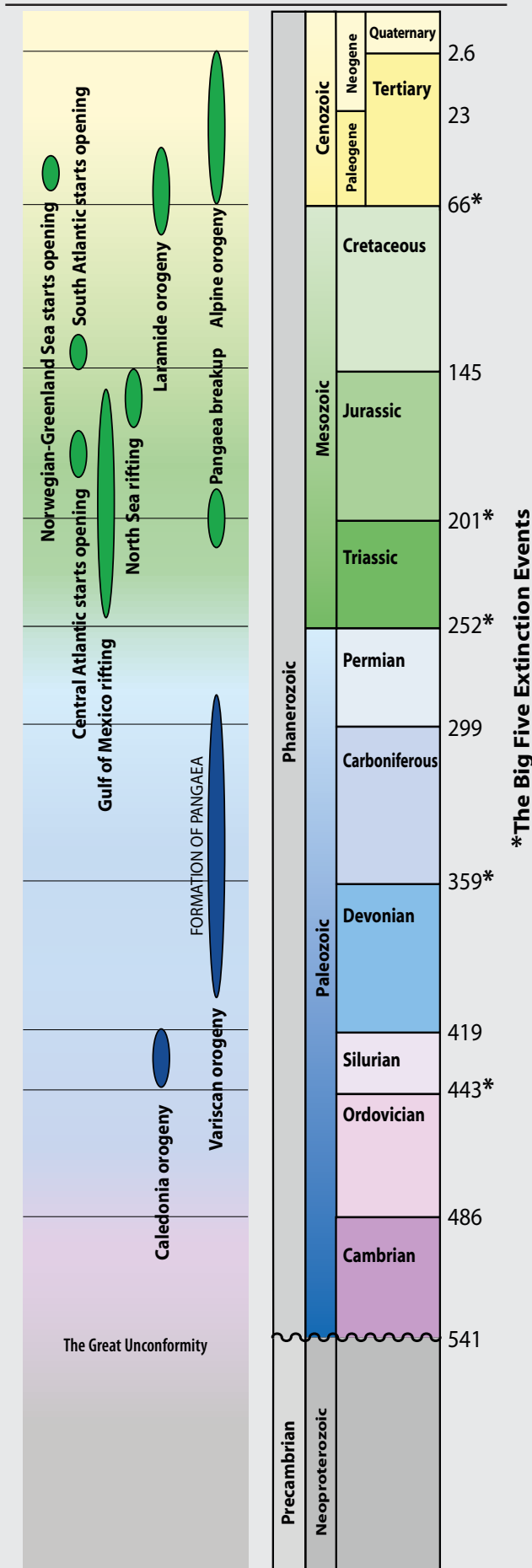
The Ironbark prospect is a large, simple, untested structure in Australia, operated by Cue Energy. The prospect is estimated to contain 15 Tcf recoverable gas resource in two reservoirs in the Mungaroo Formation.

In the Philippines, Total is planning to spud the Halcon prospect. Gross prospective resources at Halcon have been estimated at 6.736 Tcfg and 169 MMbc.

The JV partners (ExxonMobil and COPL) plan to spud the Mesurado prospect in Liberia in Q4 2016. The pre-drill prospective resource estimate for the primary prospect is in excess of 1.3 Bbo. The Ebola crisis and the decline in oil prices since 2014 have curtailed recent activity in Liberia, but Mesurado-1 will represent the renewal of exploration activity in the area in 2016/17.

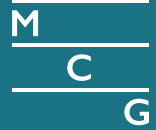
Despite offshore exploration going through a difficult time, we see improvements in efficiency and costs. Over the next 12 months, several high impact exploration wells will be spudded and the success of these wells will determine the commerciality of exploration going forward. ■

Espen Erlingsen, VP Analysis, Rystad Energy



MCG PRESENTS

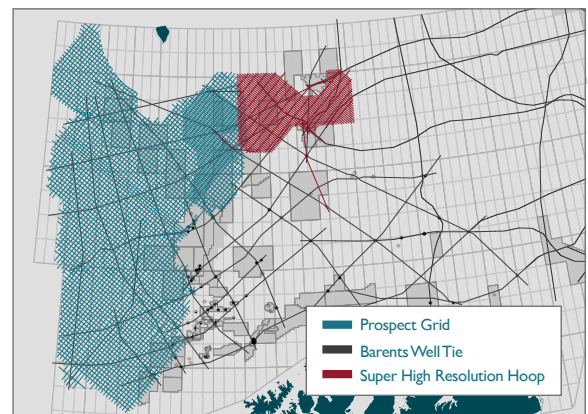
BARENTS SEA WEST PROSPECT GRID



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Visit www.mcg.no/prospectgrid for more information on the reprocessed MCG Prospect Grid.



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PNG: Reprocessing Offers Offshore Potential

Reprocessing of vintage seismic has opened up new frontier exploration potential in Papua New Guinea.

SUBRATA KUMAR DAS, Samit

In recent years Papua New Guinea (PNG) has hit the industry headlines with the development of an active LNG export business, which since 2014 has been supplying gas from several large discoveries in the southern and western highlands of the country to the Asian region and is on target to produce 6.9 million tons of gas a year. Crude oil production from the country's existing mature onshore oilfields has been in decline for some time, however, and the search for new hydrocarbon resources has of recent years been moving offshore.

To this end Australian-based DataReSource have reprocessed over 6,600 line-km of vintage Papua New Guinea 2D offshore seismic. The data covers areas of the Gulf of Papua in the south, as well as off the eastern side of Papua New Guinea including the Solomon and Bismarck Seas. This reprocessing, undertaken in collaboration with SAMIT Enterprises Pvt. Ltd., is the only known contemporary data set to cover four of the five major sedimentary basins offshore PNG, namely the Papuan, Cape Vogel, New Guinea, and New Ireland Basins. The reprocessed lines pass through all four of these basins, leaving Bougainville as the only major offshore PNG basin without coverage.

Of these five basins, the Papuan Basin is the most explored, with over 275 wells drilled, and oil and gas potential is well

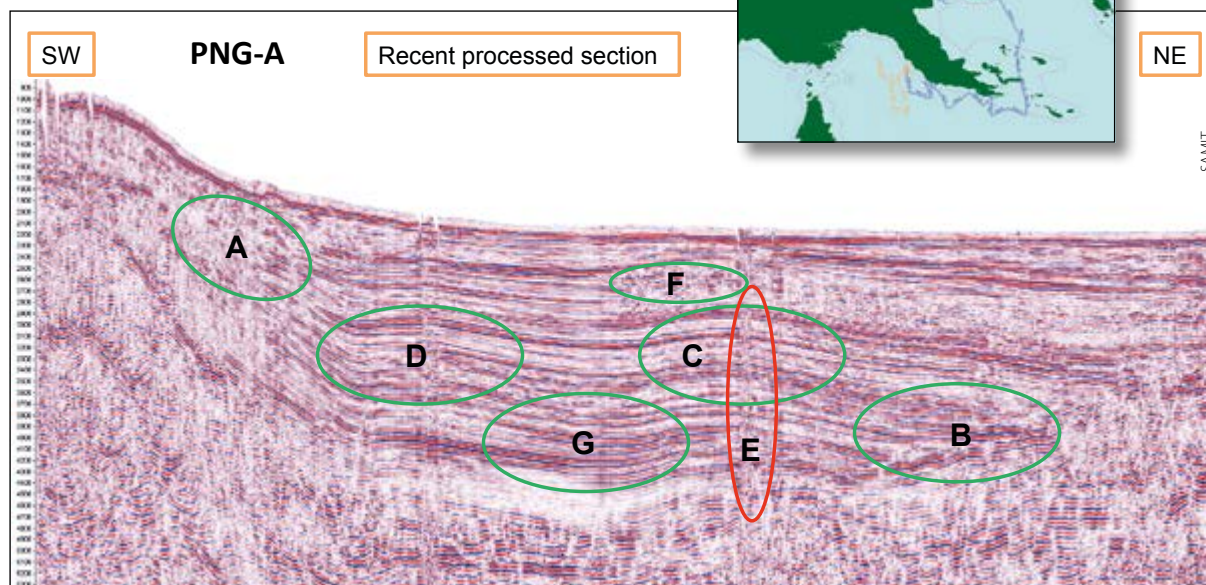
established there, with known structural and stratigraphic traps in Jurassic, Cretaceous and Eocene-Miocene reservoirs. For the other areas the generation, migration and entrapment mechanisms are yet to be fully understood and the newly processed data provides an enhanced look into this potential. Drilling activity in these basins has been minimal to date, with some entirely undrilled. The interpretation of this newly processed vintage data is therefore going to be a valuable tool for a new understanding of the hydrocarbon potential of these frontier basins.

State of the Art Processing

The reprocessing of the vintage data has been carried out using state of the art processing methodology. The application of pre-stack time migration, surface-related and other multiple elimination techniques, carefully tested and parameterized noise elimination and signal enhancement routines have resulted in much improved subsurface imaging of the moderate to complex geological subsurface when compared to the earlier processed sections from the 1970s.

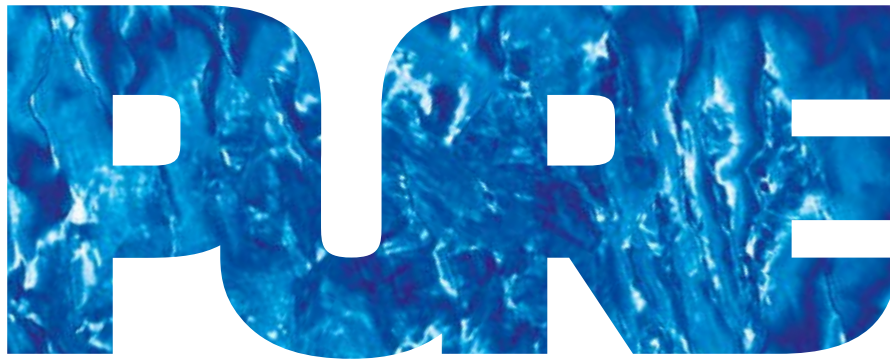
More confident structural and seismo-stratigraphic interpretation of the geology seems feasible with the reprocessed data. A number of structural and stratigraphic features can already be identified in a preliminary review of the processed sections. Detailed interval velocity analysis based on migration velocity is expected to throw valuable new insight into the nature of lithology and porosity in these basins, leading to hopes of opening up a new frontier very near the heavily explored acreage in onshore eastern PNG. The presence of limestone reservoirs in PNG is already established and reservoirs in the various basins can be expected from the published literature and now through this new processing.

The data can be obtained from Zebra Data Sciences as a full survey or on a basin by basin basis and can be viewed through a Virtual Data Room. ■



Seismic example showing several areas of interest including a facies variation from shelf to slope (A); thick basal sediments (B); several anticlinal features providing the opportunity for structural traps to exist (C, D); faulting and a possible gas chimney (E); and higher amplitude features over crest of anticlines (F). Map shows location of the offshore survey lines.

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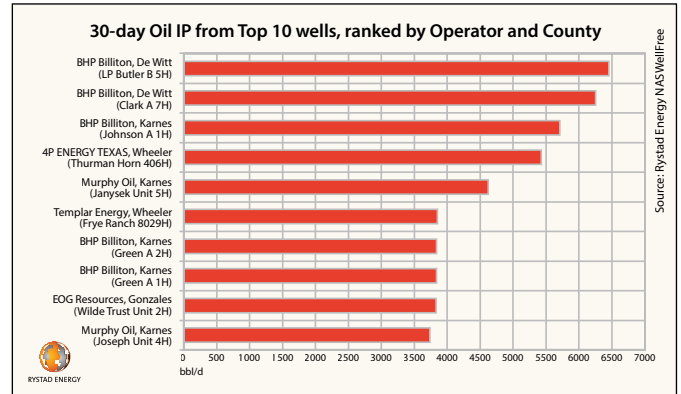


North American Shale Wells Uncovered

What are the most productive wells in the North American shale plays? Where are they located? Which operator has the longest lateral length YTD 2016? Answers to these and many other up-to-date questions can be easily obtained with **NASWellFree**, a free and limited version of North American Shale Well Cube (**NASWellCube**), recently released by independent oil and gas consulting services and business intelligence company, **Rystad Energy**. The tool ranks the top ten wells by production and different completion benchmarks and allows users to view the data in table and chart formats, as well as to filter data by state, play and completion year for easier analysis. Information is based on more than 300,000 wells and updated daily.

NASWellFree is available as a **Rystad Energy Ranks** tool, which is a user-friendly web-based tool for those who need to conduct analysis and have an overview of the industry in a quick and timely manner. It can be accessed through a browser (ranks.rystadenergy.com) or by using the Rystad Energy Ranks app, available in Appstore and Google Play.

Rystad Energy Ranks offers a similar free tool for global upstream O&G data – **UCubeRank**, which contains data such as production profile, exploration costs, revenue and cash flow for the top 1,000 oil and gas companies globally. (See www.rystadenergy.com/Products/#Free-Products.) ■

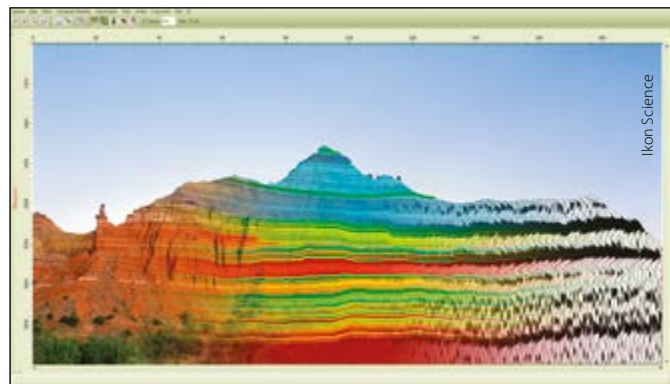


Reducing Costs and Boosting Efficiency

Ikon Science provides comprehensive software and solutions to enhance the value of reserves while reducing drilling costs and operational uncertainty, and its **RokDoc** software is well known in the E&P industry as an efficient way of analyzing well and seismic data in order to apply quantitative methods

to predict rock, fluid and pressure properties. Ikon recently launched the latest release of the software, **RokDoc 6.4**, which focuses on stability, usability and performance to help users ‘do more, more efficiently, with more data’.

Highlights include an enhanced multi-file reader to speed the process of loading LAS files, substantially reducing the amount of user interaction necessary; an MPI performance enhancement option for RokDoc Ji-Fi to maximize usage and efficiency of available cluster computing capacity; usability enhancements to RokDoc 3D and RokDoc Ji-Fi, including support for non-linear rock physics depth trends and non-contiguous seismic data; and batch RokDoc 3D export improvements, which allow export processes to be scheduled and queued for execution at a specified time, saving users’ time and allowing them to focus on quantitative interpretation instead. As a result, Ikon Science believes that RokDoc is now faster, more flexible and more powerful than ever. ■

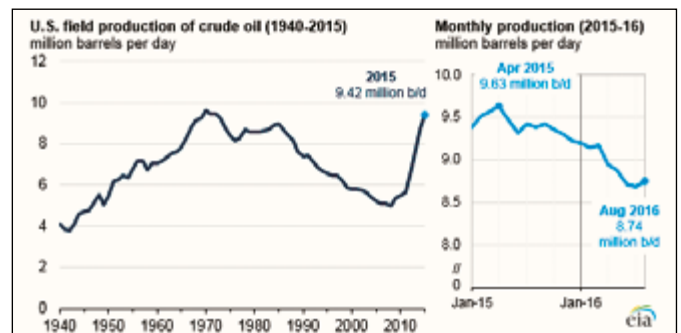


OPEC Freeze Looks Doubtful

Oil production from OPEC rose to a record high for the fifth month in a row, despite discussion between the cartel to finalize a freeze by the end of November. OPEC countries produced an average of 33.54 MMBopd in October, according to a survey by S&P Global Platts, with output rising from **Iran, Iraq, Libya** and **Nigeria**, although it dropped slightly in **Angola** due to temporary field maintenance. The production freeze looks to be in some jeopardy, as **Iraq**, the second largest producer, said it will continue to produce at current levels of 4.56 MMBopd regardless of any agreement reached, while Iran intends regaining its pre-sanctions production level of 4 MMBopd (it is currently at about 3.7 MMBopd) before it will consider freezing output.

By contrast, according to the EIA, US oil production has

begun to drop slightly from its 2015 annual average of 9.42 MMBopd, the highest since 1972, to 8.74 MMBopd in August 2016. ■



Martley – A GeoVillage



Introducing schoolchildren to local geology.

The Geopark idea, now supported by UNESCO, has been around for a while (see GEO Tourism, page 46), but a new concept on a smaller scale is that of the **GeoVillage**: a community that has distinctive geology within its bounds, a policy of locally managed geological discovery and conservation, educational offerings for both schools and adults and that uses its geological assets in support of the local economy.

Martley in Worcestershire, close to the border between England and Wales, has the honor of being the first GeoVillage in the UK. The geology in the small area of Martley parish shows remarkable diversity. As you traverse the parish from east to west – a distance of barely three kilometers – you walk over rocks representing hundreds of millions of years of the Earth's history, from the Precambrian Malvern complex (670 ma) to Triassic sandstones (~230 MY); seven periods of geological time in one parish. The River Teme, the longest tributary of Great Britain's longest river, the Severn, flows through the village and provides exposures of many of these rocks. Around 40 known features of geological interest have been identified and visitors are able to follow a number of marked trails, using downloadable guides to help them understand the geology, as well as information boards placed at strategic points in the village. There are also interactive 3D apps that explain the geological scene. (For further information, see www.geo-village.eu)

This very picturesque, historic and interesting corner of England is leading the way in making geology more accessible, and it is hoped that other geologically rich villages will follow in its footsteps. ■

Old entry to Penny Hill Quarry through the Silurian Much Wenlock Formation.



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Conference for Asia Pacific Region

From April 26–28, 2017, **SEAPEX (South East Asia Petroleum Exploration Society)** will host its biennial Exploration Conference, which, similar to the successful 2015 conference, will be held in the Fairmont Hotel in Singapore. This is the only industry gathering that covers the **Asia-Pacific** super-region and its history goes back to the early 1970s. More commonly known as SEC2017, the conference comprises case studies, acreage discussions, and country and regional reviews, as well as a farm-out forum. There will be designated sessions covering Papua New Guinea, Indonesia, Myanmar, Vietnam and Australia, while other talks include activities in Bangladesh, China, Mongolia, Korea, the Philippines, Thailand, New Zealand and Timor Leste.

The conference has always prided itself as being world class for networking, possibly comparable only to Global Pacific Partners' Africa Oil Week. It is held the same week as the **Asia-Pacific Scout Meeting**, which complements this event.

Social activities include the ice breaker, quiz night, a pub crawl along the famous Boat Quay, a post conference function to join the scout meeting members and, of course, golf.

Details can be found at www.seapexconf.org. Registration is underway and sponsorship opportunities are still available. ■



APPEX Offers Opportunities

The AAPG is again delighted to be hosting **APPEX Global** in London in its traditional slot during the first week in March 2017 (February 28 – March 2, 2017). This well-established international upstream asset A&D forum, now in its 16th year, is commonly described as one of the 'must attend events' for upstream entities seeking to acquire and/or divest international upstream E&P assets. APPEX Global will again be held at the **Business Design Centre** in Islington, **North London**, and is definitely the place to come if you are looking for lower cost opportunities while costs are down and competition is limited, or if portfolio rationalization, budget management or risk sharing requires the sale/farm-out of assets.

The recent cancellation of the **Regional APPEX** event in Warsaw, due to insufficient backing and limited A&D activity in North West Europe, is a reflection on the currently depressed markets. The next APPEX Regional event, however, will be affiliated with the AAPG's European Regional conference on January 17–18 in Larnaca, Cyprus, and is already well supported due to the recent major exploration successes and resulting new ventures focus in this

underexplored east Mediterranean region.

With a more stable oil price and the prospect of progressive rises through 2017 and beyond, this point in the cycle presents the ideal time and best value for new acquisitions and farm-ins for work commitments in 2018–2019. 'Short-termism', which plagues oil price volatility, is currently overshadowing the medium to longer term view essential to ensuring long term production from existing conventional fields is maintained. These were declining globally between 5% and 9% annually before the current downturn, a decline which will only increase and accelerate due to the significant under-investment of the last few years. Even with short-term inventories at record levels and the USA's dramatic growth in unconventional resources, the 'conventional' field reserve decline is still higher than the current <4% global over supply. A medium-term switch to 'under supply', though not yet predicted by many traders and short-term profit-takers, is now a real prospect which many upstream players agree is inevitable in the medium and longer term, with underlying commodity prices likely to rise through 2017 and beyond, albeit with the inevitable short-term volatility. ■

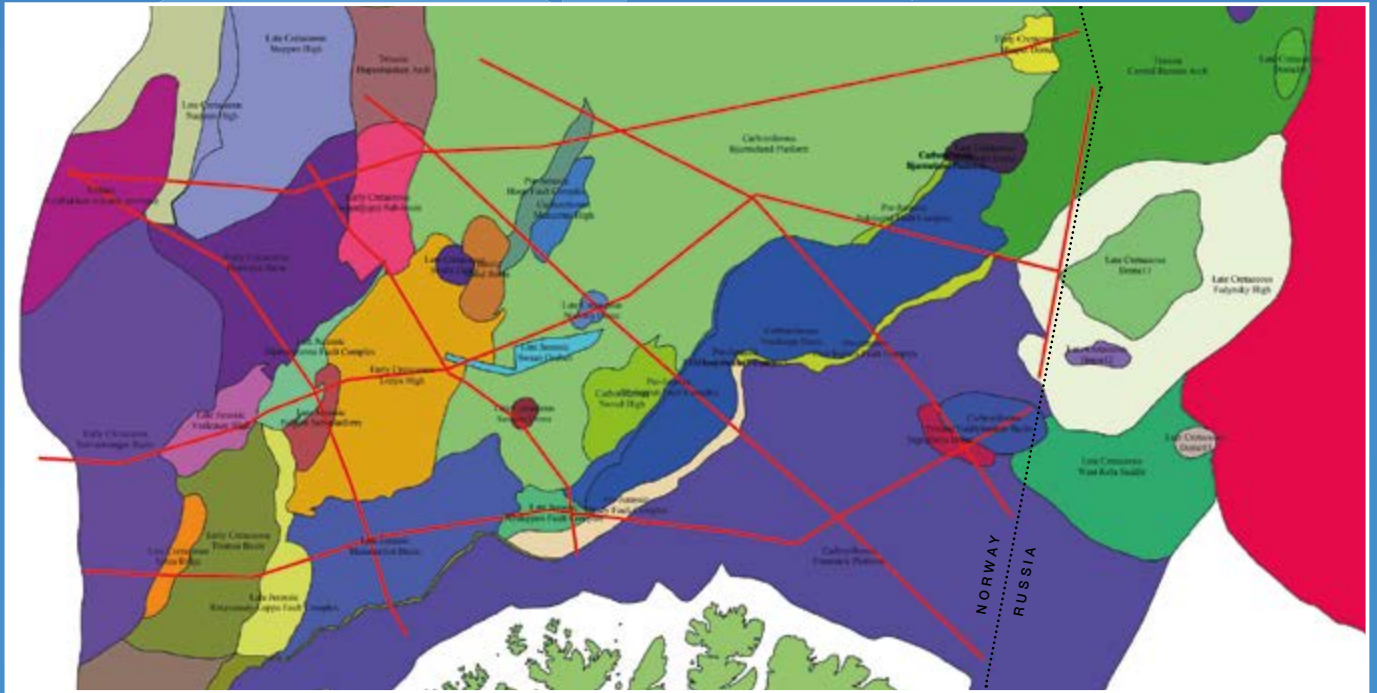
SeaBird Source in West Africa

Seismic services provider **SeaBird Exploration** has signed an agreement to provide a source vessel for an upcoming ocean bottom seismic survey in the **Gulf of Guinea**. The project is anticipated to commence in late Q4 2016 and will have a duration of approximately two to three months. SeaBird has long been the established market leader in the source vessel segment of the industry and offers a range of services, including 4D repeat and wide azimuth surveys and in-house source modeling and environmental decay analysis.

SeaBird will be using the 81m-long *S/V Osprey Explorer* for the project, which was rebuilt in 2006 as a specialist 2D long offset/source ship. During the third quarter of 2016, *Osprey Explorer* finished its source project in North West Europe before embarking on and completing an undershoot survey in the North Sea. SeaBird has source vessels available in all major operational regions. ■



Barents Sea Multi-Client Survey 2016: Long Offset & Deep Tow for Crustal Imaging



Key info

- Survey size approx. 4000 km
- Gravity & Magnetics data
- Data available Q1 2017

Acquisition

Long Offset: 12 km
 Deep towing: 15 – 60 m (slanted)
 SP interval: 37,5m
 Source volume: 6100 cu.in.
 Source depth: 7m
 Continuous recording
 ION 2Hz Digi-streamer

Objectives

- Acquire a unique data set
 - New broadband seismic acquisition and processing with longer offsets and record length, unlike existing data
- Image the deeper parts of the Barents Sea
 - Long-offset profiles that image large scale deep seated crustal structures beneath the Norwegian Barents Sea

- Solve some of the issues regarding the understanding of the tectonic history
 - Seismic lines will link released wells to validate new seismic interpretations

Processing

- The processing is to be headed by Lundin Petroleum on SeaBird's behalf
- DownUnder Geosolutions' (DUG) center in London will undertake the processing

Survey Sponsors



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The Wildest Plays on the Planet

JON NOAD, Sedimental Services

Apparently wacky play ideas have already proved profitable, even resulting in the discovery of supergiant fields. There are probably many more unconsidered plays waiting to be discovered. Is it time to think outside the box?

The vast majority of the world's hydrocarbons have been discovered in what are termed conventional settings. These are primarily structural closures into which oil or gas has migrated, becoming trapped in layers of porous reservoir sandstone or limestone beneath an impervious cap rock. Stratigraphic traps, in which similar reservoirs are encased in shales, make up a smaller proportion of successful hydrocarbon plays, and recent years have seen the rise of a variety of unconventional plays. But beyond these accumulations lie a subset of truly unconventional, even wacky plays, where the geologist needs an open mind to appreciate the 'wildest plays on the planet'.

Ranging from astrobleme-hosted reservoirs to caves full of oil, and from hydrocarbon-filled granites to gas accumulations where animal sacrifices are the norm, there are some truly mind-boggling plays around the globe – and, potentially, in other parts of the solar system. There are also a variety of commercially viable, non-hydrocarbon gases, such as helium and nitrogen, which can be produced directly from the subsurface. Often discovered serendipitously, these

plays are components of some of the world's largest fields. Examining their rich variety should provide those exploring for hydrocarbons with new insights and ideas.

Coming from Outer Space

The plays discussed here would probably have management laughing the exploration geologist out of the room, yet key features of many of them are the large reserve bases and high exploration success rates. Nowhere is this truer than in plays related to meteor impact craters. Around 40 commercial oil and gas fields have been discovered in craters, out of around 160 such structures identified worldwide, giving an impressive one in four discovery rate.

The largest (and most famous) is Chicxulub in the Mexican Gulf of Mexico, the remains of the impact event that may have wiped out the dinosaurs. Following the meteor collision at the Cretaceous/Tertiary boundary, the collapse of a carbonate platform deposited a series of coarse, shattered breccias, which form an excellent reservoir, complemented by the sealing ejecta layer. The resulting

An astrobleme, the Barringer Crater in Arizona, also known as the Meteor Crater.

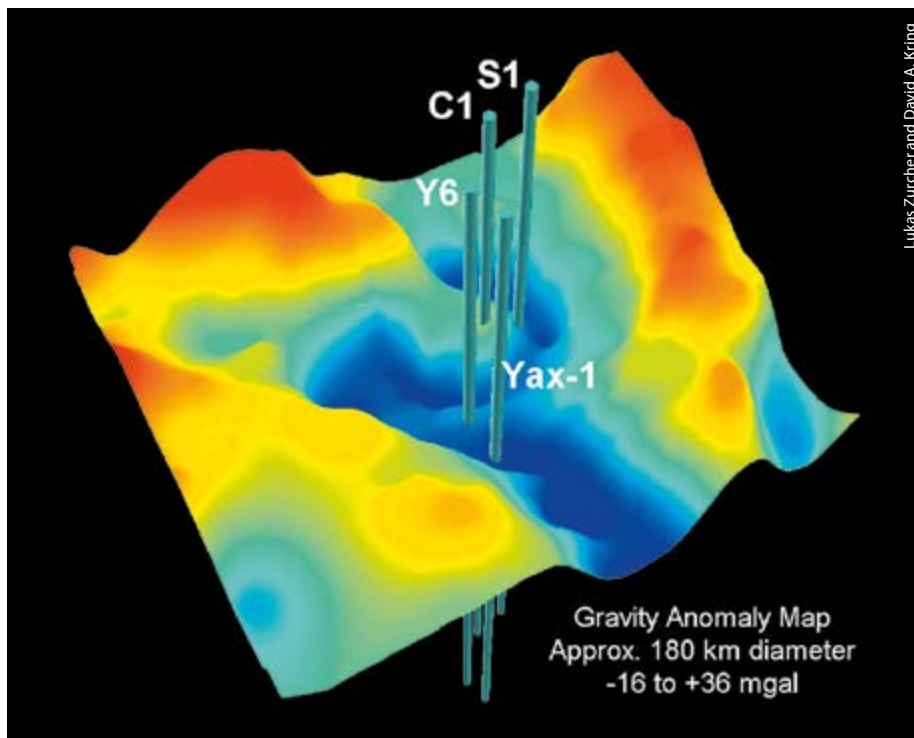


supergiant Cantarell field, discovered in 1976, delivered more than 2.1 MMBopd at peak production.

A further nine astroblemes are known to be producing in North America alone. One of these, the Avak Crater in Barrow, Alaska, was drilled by the army to fuel the military base there. The concussion that created the crater folded the surrounding rocks, trapping natural gas beneath impermeable cap rocks. The target reservoir comprises strongly deformed Ordovician and Silurian argillites. Overlying the crater are younger marine sandstones and shale seals, defined by gravity data.

Another such feature is the Ames Crater, which was discovered in the Sooner Trend in Oklahoma in 1991, based on some exceptionally productive wells. When examined, cuttings included brecciated granite with good shows, as well as shattered quartz and feldspar with cleavage faces. The crater is more than 10 km across, and following the meteor strike, it filled with fine sediments, ultimately producing a thick source rock interval and seal.

Other examples around the world include the Oblon crater, one of three potential astrobleme producers in central Ukraine, and the Viewfield field in Saskatchewan, which produces 400 bopd from fractured Mississippian carbonates. The Tookoonooka Crater in Queensland hosts several small oil fields.



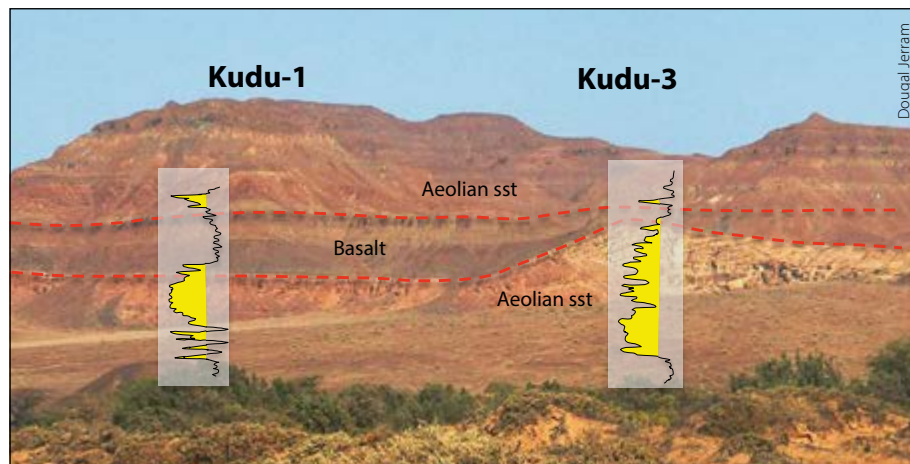
Lukas Zurcher and David A. King

Gravity and borehole map of the Chicxulub crater, which is buried beneath Tertiary sediments. Gravity contrasts – between breccias created by impact-generated shattering of the rock and the denser rock resulting from melting of the Earth's crust – create a semi-circular anomaly in the gravity of the northern Yucatán Peninsula. S1, C1, and Y6 were exploration wells drilled by PEMEX in the '80s, and Yax-1 was drilled by the ICDP in 2002.

Cracks in the Basement

Most people would not expect igneous rocks to host hydrocarbons, but more than 30 countries have fields that produce from igneous, volcanic or metamorphosed basement. The Suban Field in Indonesia, for example, holds more than 8 Tcfg in fractured granites, while fields in Thailand and Libya have also produced oil and gas from granitic basement.





An outcrop analog of the Kudu field, where volcanics form an important part of the petroleum system.

Production may exceed 20,000 bopd from extensive fracture networks. Generally, a high proportion of deep seated fractures in these rocks are subvertical, so horizontal wells can be key to unlocking these resources.

Typically basement reservoirs are considered more difficult to evaluate than conventional reservoirs, and are often discovered by chance rather than by design. However, several companies are now targeting basement plays, with both Russia and Thailand drilling into crystalline basements. As discussed on page 62, Hurricane Energy has drilled several such wells in the West of Shetland area.

Volcanic rocks are also associated with the Kudu Field in Namibia (*GEO ExPro* Vol. 8, No. 6), where the Cretaceous Twyfontein Sandstone hosts gas in aeolian deposits that are 'frozen' beneath outflowing basalts. These volcanic rocks were formed as the Atlantic opened.

In several Chinese basins such as Bohai and Songliao, the volcanic sediments can act as reservoirs (when fractured), as seals and as trapping mechanisms. Porosity is usually preserved because the rocks are strong enough to resist compaction. Lava tubes filled with gas have reportedly been identified in the subsurface in the Xingcheng gas field.

Caves Filled with Oil

A significant proportion of laymen still believe that oil is sucked from underground caverns using pipes. In the Rospo Mare Field, in the Gargano region of southern Italy, this is literally the case. Oil is trapped in vugs, fractures and subterranean caverns in Cretaceous karstified wackestones. Emergence of the limestone platform at the end of the Cretaceous allowed the development of caves, which were later onlapped by transgressive Tertiary carbonates and (sealing) evaporites. The field has an estimated recovery of 94 MMbo. The oil has been produced from the karstified interval using horizontal wells since 1982, one of the first fields ever to use this now commonplace technology. Production from a single well may exceed 3,000 bopd.

End Member Hydrocarbons

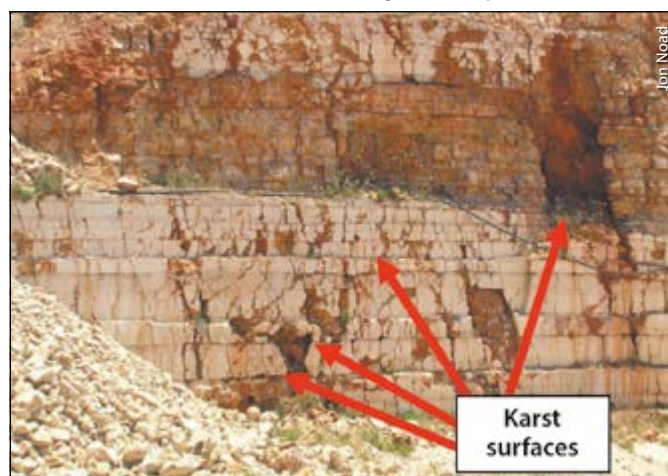
Several types of hydrocarbons do not fit the standard blueprint, including gas hydrates, a naturally occurring, crystalline, ice-like substance composed of methane hydrate gas molecules.

They are constrained by a narrow range of high pressure and low temperature, with the vast majority located on oceanic continental slopes. Typically stable around 300m below the seafloor, the main controls are the reservoir lithology and available methane. Gas hydrates are usually recognized on seismic data through bottom-simulating reflectors, and the estimated resource potential worldwide may exceed 40,000 Tcft, although they have yet to be produced commercially (see <http://www.geoexpro.com/collections/6/>).

Gilsonites are natural, resinous hydrocarbons, in the form of 'frozen' oil left after the volatiles have evaporated. They form vertical seams many kilometers long and up to 500m wide, filling existing fractures, and are mined in Utah and Kermanshah, Iran. In Utah the source of the gilsonite is the Green River Formation, which hosts the world's largest oil reserves (though currently not commercially viable). The brittle, jet-black gilsonite was used in the lacquer applied to Model T Fords, and is now a key component in photocopy black and in newsprint.

Tar mats are immobile, heavy oil deposits similar to pyrobitumens. They are common in carbonate reservoirs

Sediment-filled caves in an onshore analog in the Rospo Mare Field.



Natural gas emanating from disassociation of natural gas hydrate, Monterey Bay Aquarium Research Institute.



in the Middle East, and are often located close to the oil-water contact in a reservoir, accumulating due to biogenic activity, gravitational settling or to increases in solution gas. They can be potential reserves, and also provide excellent seals, as in the Orinoco Petroleum Belt in Venezuela, the world's largest single accumulation of heavy crude. A tar mat cap seals the Bolivar Coastal field, one of the world's largest conventional fields.

Other Molecules

The Kabir Kuh field in north-west Iran is 220 km in length, and 85% of the fill is nitrogen. Possible explanations for this unusual deposit include an underlying hot spot, a volcanic source rock or basement rocks with a nitrogenic component. The gas occurs in Ordovician and Permian carbonates, and could replace the Haber-Bosch process in providing feedstock for fertilizers.

There is often a link between high nitrogen and helium values, which is important because experts suggest that the world has only 25 years' remaining supply of helium. It forms from the breakdown of uranium, radon and thorium, usually found in basement rocks, and is then trapped in overlying natural gas reservoirs. The minimum commercial concentration is only 0.3%. The US produces around 40% of the world's helium, the majority from Kansas and from the Hugoton Panhandle on the border of Texas and Oklahoma.

Several gas fields in Arizona have high concentrations of helium, such as the Dineh-bi-Keyah oil field, which is 6% helium, sourced from black shales, occurring in a fractured syenite sill reservoir. The Holbrook Basin hosts the St. John's carbon dioxide and helium field, with up to 10% helium, and Kinder Morgan are reportedly planning to exploit this resource. Further resources have been identified in Canada in Saskatchewan and Alberta, with several projects actively exploring.

A recent project in South Africa is targeting helium dissolved in groundwater in former gold mines. The helium was generated from the breakdown of uranium, which is associated with gold deposits (see below), and then goes into solution in groundwater, which is transported along faults towards the surface. The helium occurs in association with methane sourced either from coal-bearing Karoo-age rocks or produced at depths by microbes.

The La Brea tar pits are near Los Angeles, California.



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The 4th Faroese Licensing Round
will open during the conference
and will be open:

17 May 2017 - 17 February 2018



JARÐFEINGI
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Finishing on a High

Among a cavalcade of extraordinary hydrocarbon plays, a few stand out. The Witwatersrand of South Africa has produced around 50% of all the gold ever mined on Earth, around 40,000 metric tonnes. Much of the gold is found in association with kerogen, thought to represent cyanobacterial remains some 2.2 billion years old. The gold has been locally remobilized, forming an amalgam with the carbon, which has been produced by the baking of the bitumen over time. Gold grades may reach kilograms per tonne in these Archaen, carbon-rich hydrocarbon reservoirs, which equates to hundreds of thousands of dollars per barrel.

Pammukkale, in south-western Turkey, is a UNESCO World Heritage Site because of the stunning travertine deposits and hot springs found there. It is also the site of Pluto's Gate, famous in biblical times as a place of sacrifice. Animals were driven into a cave by priests, and expired in the poisonous carbon dioxide atmosphere within. Their bodies were later removed using long ropes. The cave was rediscovered in 2013, partly due to the number of dead birds surrounding its entrance. The gas is emitted from a deep cleft in the rocks, through which fast-flowing hot water passes, degassing before feeding the hot springs in the area.

Finally we turn to the 'Door to Hell', in Turkmenistan. The location was originally drilled for oil in 1971, but intersected methane in the shallow subsurface. The small field collapsed to form the Darvaza crater. Russian geologists set it on fire to

prevent the spread of methane gas, expecting it to burn for a few weeks, but 50 years later it is still aflame and has become a popular tourist attraction despite a government edict in 2010 to extinguish the fire. A member of the Explorers' Club of New York, clothed in a heat-resistant suit, reached the bottom of the crater in 2013, and collected a variety of extremophile bacteria.

What Can We Learn?

At first glance, many of the plays above appear of little more than academic interest. Yet almost all of them have proved profitable, and several have resulted in the discovery of supergiant fields. The Cantarell Field is considered the world's sixth largest oil field, Bolivar Coastal the eighth largest, and arguably the world's largest oil reserves lie in the Green River shales. Production has often required new technologies that can later be applied to less obscure plays. Many other fields continue to produce hydrocarbons from unusual plays, often discovered by chance.

This should encourage young exploration geologists to keep an open mind, and to look for evidence of unexpected shows and play elements. It only takes a single, repeatable play opportunity (that may have sat unrecognized for decades) to change the fate of a company. And not only on Earth: it is only a matter of time before a geologist convinces their manager that the next test should be carried out on the hydrocarbon lakes of Titan.

Now that is definitely thinking outside the box. ■

Natural gas burning at the 'Door to Hell', Darvaza Crater, Turkmenistan.





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Back to Source Rocks: Part II

RASOUL SORKHABI, Ph.D

Source rocks constitute the foundation of both conventional and unconventional petroleum systems. The first part of this article (*GEO ExPro*, Vol. 12, No. 6) discussed the formation of organic matter in sediments. Here we review the parameters that make a sedimentary rock an effective petroleum source rock, and the analytical methods used to characterize source rocks for successful petroleum exploration and production.

Although fine-grained, clay-rich rocks with particle sizes less than 1/16 mm account for about 70% of sedimentary rock mass, not all of these are effective source rocks. Petroleum is made up of hydrocarbon molecules originating in a rock in which organic matter (kerogen) is dispersed in the sedimentary formation and has been buried and thus heated enough to transform kerogen to hydrocarbons (i.e. thermal maturity). In addition, the rock formation should have considerable volume (thickness of meters and length of kilometers) in order to generate large amounts of hydrocarbons. Rock volume becomes especially important for exploring shale plays, in which the source, reservoir and seal rock are the same.

Organic Richness

The organic richness of source rocks is measured by total carbon content (TOC), which is described in weight percentage of the sample. Rocks are ranked from poor to excellent; higher percentages of TOC indicate organic-rich sedimentary rock.

Direct methods of measuring TOC are made by the Leco carbon analyzer. About a gram of powdered sample is treated with acid to remove the inorganic carbon (carbonate). The dried residue is then mixed with a metal accelerator (iron and copper), and combusted (rapid reaction with oxygen) using a high-frequency induction furnace (1,200–1,400°C). The mass of the carbon dioxide gas thus formed is

	TOC in shale	TOC in Carbonate
Poor	<0.5%	<0.2%
Fair	0.5–1.0%	0.2–0.5%
Good	1–2%	0.5–1%
Very Good	2–5%	1–2%
Excellent	>5%	>2%

Source rock ranking based on TOC.

measured in a non-dispersive infrared detection cell and converted to percent carbon based on the dry sample weight. TOC values can be underestimated if there is loss of immature organic carbon in the acid treatment or overestimated if carbonate is not completely removed prior to analysis.

Indirect methods of estimating

Jurassic Oxford Clay outcropping near Weymouth, England.



TOC include pyrolysis (see below) and well logs. A high content of organic matter in sedimentary rocks gives positive (high) feedback in gamma-ray and neutron logs, and results in high transit time in sonic log, high resistivity and low density (if free hydrocarbon molecules occupy pores). Recently, some geophysicists have also attempted to locate very high TOC sedimentary layers by their significantly low acoustic impedance on seismic data (Løseth et al., 2011).

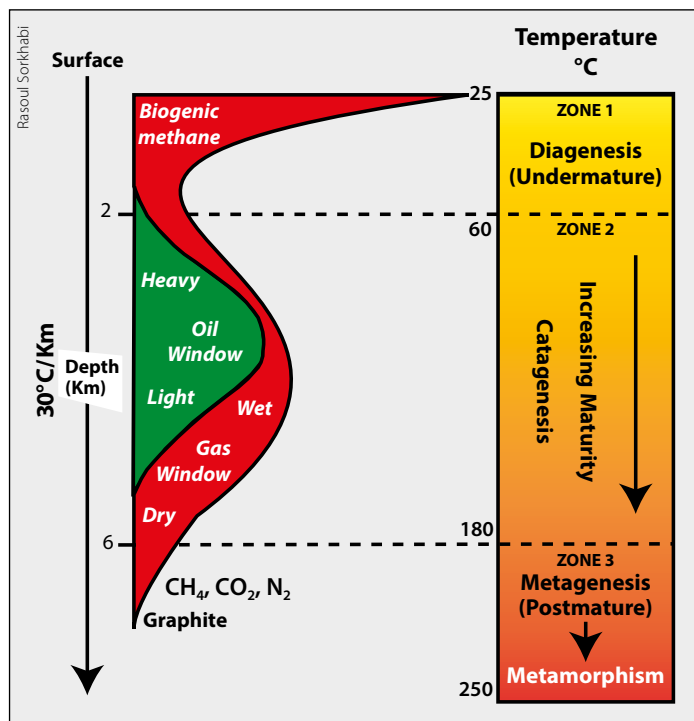
In interpreting TOC values for prospect evaluation, one needs to consider sample lithology, sampling procedure and the TOC measurement method. For surface sampling, the specimen should not come from the exposed surface, although even then, outcrop samples will often yield lower TOCs compared to samples of the same formation collected from cores because of weathering of surface rocks. Several regularly spaced samples from the entire thickness of a formation should be collected – a single sample from an organic-rich or organic-poor layer of the formation could be misleading.

TOC data based on a large number of sample analyses from around the world provide some guidelines for prospect evaluation, suggesting average TOC of all shales is 0.9%; for shale source rock it averages 2.2%; for calcareous shales 1.9%; for carbonate sources 0.7%; and the average for all source rocks is 2.2% (Tissot and Welte, 1984). In general, dark, laminated clay-rich sedimentary rocks with no bioturbation are indicative of organic carbon content and anoxic depositional environments, thus often making good source rocks.

Thermal Maturity Indicators

Burial temperature ‘cracks’ the complex kerogen molecules into simpler hydrocarbons. There are several methods of estimating the thermal maturity of a source rock. Burial history (stratigraphic time vs. burial depth curve) together with reasonable

Petroleum geologists usually divide the burial depth-temperature zones in a sedimentary basin into three zones from top to bottom (with increasing temperature). (1) The zone of diagenesis, compaction and cementation converts loose sediment into sedimentary rock. In this shallow zone, bacterial action on organic matter produces biogenic (microbial) methane gas. (2) The zone of catagenesis corresponds to oil and gas windows. (3) In the zone of metagenesis, thermogenic methane as well as non-hydrocarbon gases (carbon dioxide, nitrogen, and hydrogen sulfide) evolve. At deeper levels, the rock enters the zone of metamorphism (involving mineralogical and textural changes). The entire transformation sequence consists of (1) kerogen (insoluble in organic solvents); (2) bitumen (solid hydrocarbon soluble in organic solvents); (3) heavy oil; (4) light oil; (5) condensate/wet gas; (6) thermogenic dry gas (methane) and non-hydrocarbon gases; and (7) residue carbon or graphite. Catagenesis is governed by chemical kinetics of kerogen; for every 10°C increase, the cracking of kerogen doubles (Waples, 1980).



assumption of geothermal gradients informs us whether the target layer ever resided in the oil or gas window zone.

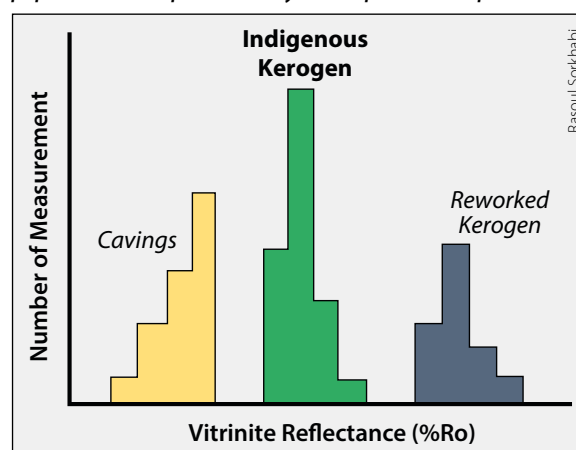
A common method for estimating sample paleotemperature (maturity) is vitrinite reflectance (VR or Ro). Vitrinite is a type of maceral particle derived from the cell-wall or woody tissue of plants, and is found in coal and kerogen. It has a shiny (vitreous, from the Latin *virtum*, glass) appearance which irreversibly increases with increasing temperatures (due to aromatization).

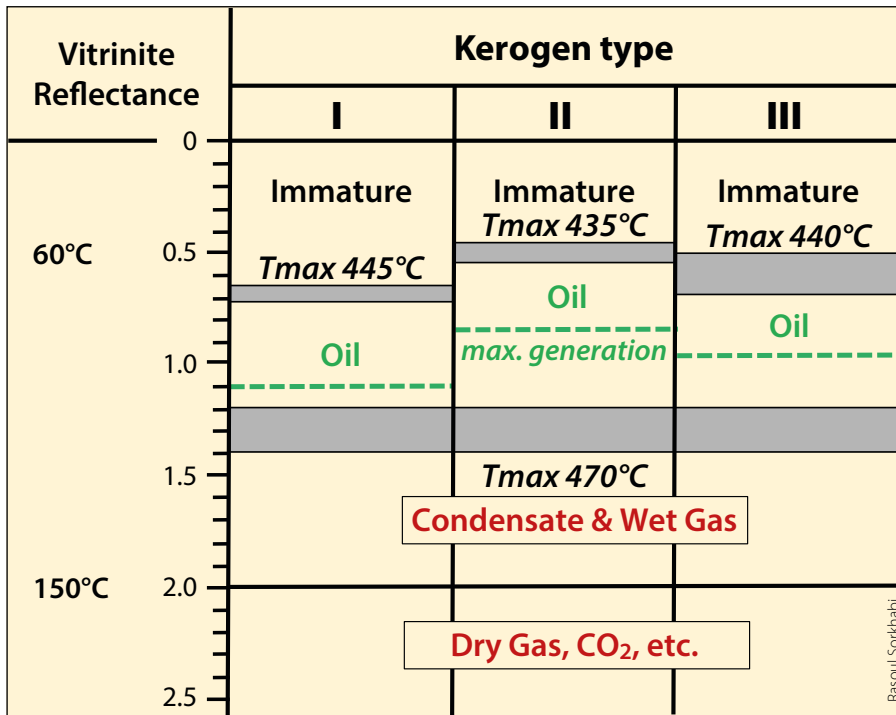
VR analysis may be performed on whole rock powder or on kerogen extracts from the rock. The sample is mounted on epoxy resin or similar material and is observed under a reflected light microscope. The reflectance (%Ro = % reflectance in oil-immersion objective lens) of vitrinite particles can be used to evaluate the thermal maturity of rocks. The VR scale has been calibrated empirically and experimentally, and is

widely used in the petroleum industry.

At least 50 vitrinite particles should ideally be measured for each sample. The data are plotted in the form of a histogram that gives the minimum, maximum and mean values of Ro as well as the number of data points and standard deviation. Sometimes the histogram gives a complicated distribution with more than one cluster, in which case results should be interpreted considering sample conditions as well as data distribution. Lower Ro values probably indicate contamination of the sample by caving,

Histogram of vitrinite reflectance data with more than one population and a plausible way to interpret the sample.





Effects on kerogen type on the onset of oil window (modified after Tissot and Welte, 1984).

(i.e. immature kerogen from shallower levels caving into the borehole). Alternatively, higher values may come from reworked kerogen eroded from a more mature rock.

The onset of oil generation corresponds to Ro values of 0.5–0.6% and the maximum generation of oil to 0.85–1.1%. The onset of gas generation (wet gas and condensate) generally corresponds to Ro values of 1.0–1.3% and the gas window continues for Ro values of 3% for dry gas. Temperatures and corresponding Ro values will vary for different types of kerogen present in the source rock.

VR cannot directly be used for samples older than Devonian because land plants only flourished on Earth after then. For Early Paleozoic rocks, graptolite reflectance or conodont alteration index (CAI) can be used. VR scale has also been calibrated for reflectance of bitumen (solid hydrocarbon), so samples lacking vitrinite particles can be measured for bitumen reflectance, and 'VR equivalent' values are then obtained. VR

equivalent values can also be calculated from pyrolysis (see below).

Another important technique for estimating thermal maturity is the Thermal Alteration Index (TAI) based on color changes (from light yellow through orange and brown to black) in spores and pollen as a result of the burial heat the sample has experienced. Several TAI scales relating the observed color under the microscope to temperature have been formulated by scientists. The oil window corresponds to TAI values of 2.6–3.3.

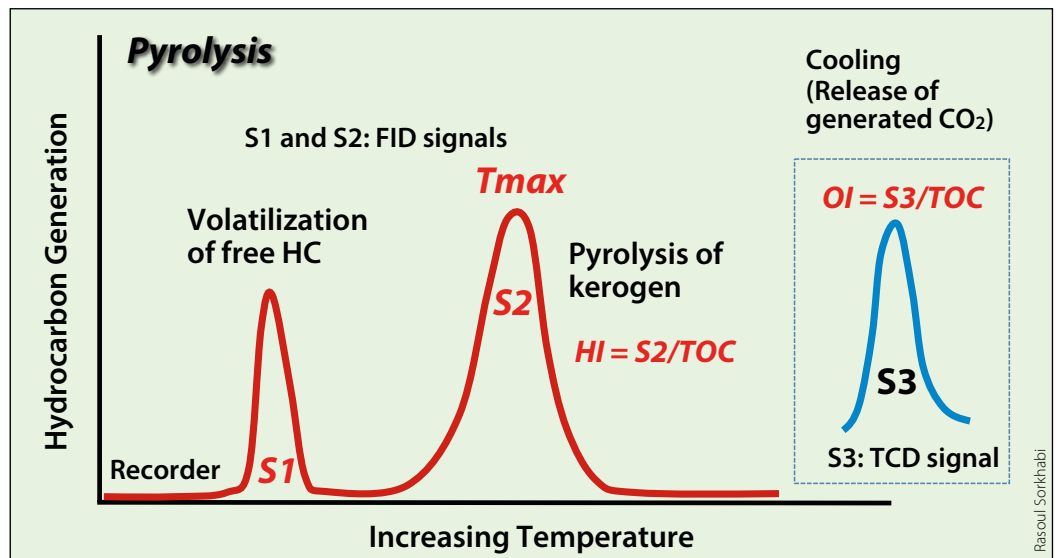
For samples which have been analyzed by pyrolysis the results include a parameter called Tmax, which is also a paleo-temperature indicator. The oil window corresponds to Tmax values of 435–470°C.

Petrographic methods such as VR provide information about the maximum temperature that the rock experienced in the past but they do not tell us about timing. A comparison of VR or similar data with the burial curve is one way to assess the rock's thermal history. Another is fission-track thermochronology of apatite minerals separated from sandstone layers adjacent to the source rock. Uranium fission tracks in apatite shorten at temperatures of 60–120°C, which correspond to the oil window temperatures. Therefore, by determining the fission-track age and the track lengths in apatite, one can reconstruct the time-temperature pathway of the rock sample (GEO ExPro, Vol. 7, No. 1).

Pyrolysis

Pyrolysis is the process of heating a rock or kerogen sample in the laboratory in order to measure the type, richness and maturity of hydrocarbons by thermal decomposition in the absence of oxygen. This can be done either in the presence of water (hydrous) or in its absence (anhydrous). RockEval™, developed by the Institut Français du Pétrole, is a programmed instrument for anhydrous pyrolysis of rock samples. Similar instruments include the Source Rock

Various terms related to pyrolysis of a source rock sample in the laboratory.



Analyzer™ by Weatherford Laboratories Instruments and HAWK by Wildcat Technologies.

In pyrolysis, nearly 100 mg of crushed, dried rock sample is progressively heated (~25°C/minute) up to at least 550°C under an inert helium or nitrogen atmosphere. The first step is to heat it to 300°C to volatilize the pre-existing free hydrocarbons in the sample. The amount of these hydrocarbons is measured from a peak area (S1). The next step is to pyrolyze the kerogen present in the sample at higher temperatures and measure it at peak area S2. The carbon dioxide generated from the cracking of kerogen (up to 390°C) is collected as S3. S1 and S2 are measured by the Flame Ionization Detector (FID), and S3 by the Thermal Conductivity Detector (TCD). Residual carbon in the sample is also collected and measured as S4 (at 600°C). All of these peak areas are expressed in units of mg/g rock. High S1 indicates an active source rock while S2 values measure the remaining hydrocarbon-generating potential of the rock. Tmax is measured from the S2 peak.



Outcrop of Ordovician oil shale (kukersite) in Estonia.

Data from pyrolysis are used to calculate the following parameters:

Hydrogen Index (HI) = (S2 x 100) mg/g / %TOC; HI values of >600 indicate oil-prone kerogen type I while those of <200 indicate gas-prone kerogen type III.

Oxygen Index (OI) = (S3 x 100) mg/g / %TOC; OI values of >50 are indicative of immature kerogen.

Production (Generation) Index (PI or GI) or **Transformation Ratio (TR)** = S1 / (S1/S2); PI values of 0.1–0.4 correspond

disruptive;

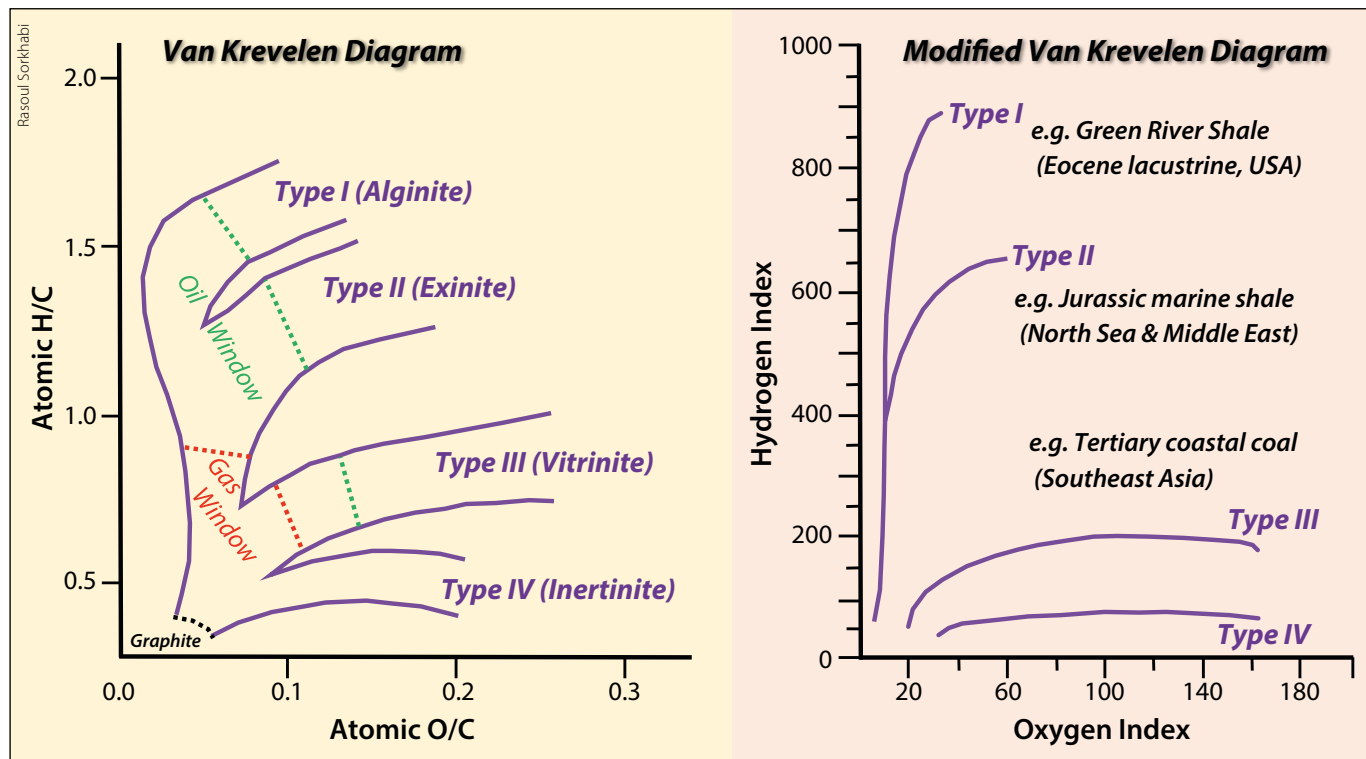
adj. relating to or noting a new product, service, or idea that radically changes an industry or business strategy, especially by creating a new market and disrupting an existing one.

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Kerogen types plotted on the Van Krevelen and Modified Van Krevelen diagrams. (Rasoul Sorkhabi from Tissot and Welte, 1984, and other sources.)

to the oil window. Lower values are for immature source rock and higher values indicate gas generation to destruction.

Potential Yield (PY) or Generative Potential (GP) = S1 + S2 (mg/g or kg/ton of rock): PY values of <2 indicate poor yield, those between 2–4 fair and >6 very good.

Calculated Vitrinite Reflectance = $0.018 \times T_{max} - 7.16$ (Jarvie, 2012).

Calculated TOC = $[0.082(S1 + S2) + S4] / 10$ (Espitalié, Deroo and Marquis et al., 1985): Calculated TOC is the sum of carbon obtained in pyrolysis of the sample.

Kerogen Types

Kerogen is categorized into four types:

Type I is derived from lipid-rich algal material (alginite) preserved in anaerobic environments, especially lacustrine and similar marine conditions. This kerogen is abundant in aliphatic (non-aromatic) compounds, and is highly oil prone.

Type II, rich in liptinic macerals, is derived from waxy and resinous parts of plants including extinite (skins of spores, pollen, and cuticles of leaves and herbaceous plants) and

degraded, amorphous phytoplankton from marine environments. This type commonly has higher amounts of sulfur than other kerogens. It is mainly alicyclic (naphthenic) and produces moderate amounts of both oil and gas.

Type III is relatively hydrogen-poor, predominantly vitrinite macerals, derived from terrestrial woody and fibrous plant fragments and structureless, colloidal humic matter. It is rich in aromatic compounds, and mainly gas prone, although liptinitic kerogen, if present >15% in the sediments, also generates oil. Kerogen type III is deposited in terrestrial or shallow marine environments. Coals usually contain this type of kerogen.

Type IV refers to extremely hydrogen-poor, carbon-rich residual (reworked from older sediments) or oxidized kerogen. It is the chemical equivalent of inertinite maceral group, and is considered as dead carbon with no potential for generating oil and gas.

The Dutch chemist Dirk Willem van Krevelen (1914–2001) noted that various kerogens can be recognized on the basis of their atomic H/C versus O/C plots. In the 1970s French

petroleum chemists Bernard Tissot and J. Espitalié extended van Krevelen’s work from coal to kerogen and substituted the elemental parameters with Hydrogen Index and Oxygen Index obtained from pyrolysis (a pseudo- or modified Van Krevelen diagram). In this analysis, kerogen type I has H/C >1.5 and HI >600; type II has H/C of 1.0 to 1.5 and HI of 200 to 600; type III has H/C of 0.7 to 1 and HI of 50 to 200; and kerogen type IV has H/C of <0.7 and HI of <50 (Peters and Cassa, 1994).

Geochemical Logs and Basin Modeling

Geochemical data from single or multiple source rock horizons can be plotted as geochemical logs for wells in order to compare and contrast the data vertically and horizontally. If there are considerable data from various wells, specific parameters, such as TOC or VR, may also be plotted on formation top maps and contoured to decipher lateral variations. Basin modeling indeed began with source rock burial-maturity-generation modeling in the early 1980s, and source rock data still constitute the critical input data for basin modeling software packages.

References available online ■

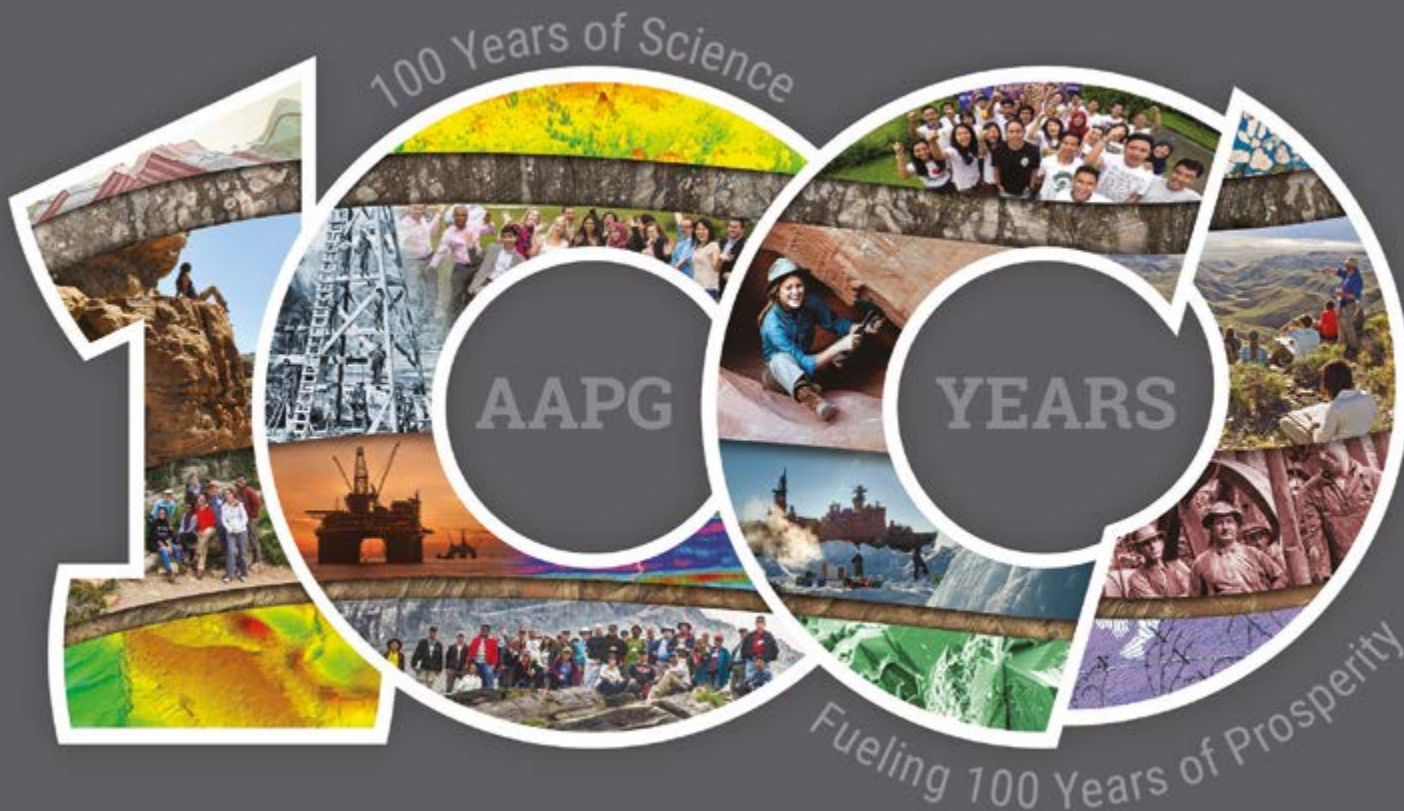
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A Light in the Downturn

**Geochemical innovation
for today's explorers.**

HUNTER C. EDEN and MOHAMED SAID
StratoChem Services

In today's hardscrabble upstream economy, meager analytical budgets are the rule even among E&P companies with a strong scientific focus. When only 'necessary' analyses are approved by cost-conscious management, geochemistry – especially advanced geochemical studies – is all too often glossed over as an unaffordable scientific luxury. In a market where many companies only drill due to pre-existing obligations or forgo drilling entirely, this is an understandable mindset, but an unfortunate one. The proper application of basic geochemical analyses can save exploration teams millions of dollars and months of drilling time.

What makes geochemistry such an indispensable analytical tool for explorers feeling the pinch of the downturn? Inexpensive geochemical procedures can reveal play characteristics impossible to discover by other methods. Equally applicable in conventional and unconventional plays, geochemistry is a Swiss army knife of a science; its use is limited only by the creativity of the scientists involved. The following techniques build simple analyses into highly affordable studies with the potential to stretch a tight science budget much farther.

Good geochemical analysis can mean the difference between a dry hole and exploration success.



StratoChem Services

One-Run Kinetics

Source rock kinetics is not a new procedure; indeed, it has been used for decades. Traditional kinetics uses a thermal pyrolysis oven (such as a Rock-Eval or Source Rock Analyzer) to heat rock samples at three different heating rates (See Back to Sources II, page 22). The results are used to determine variables in a kinetics equation which allows geochemists to extrapolate information about a play. Used properly, kinetics can delineate organofacies, pinpoint sweet spots, measure thermal maturity, and assess hydrocarbon generation from a given source rock.

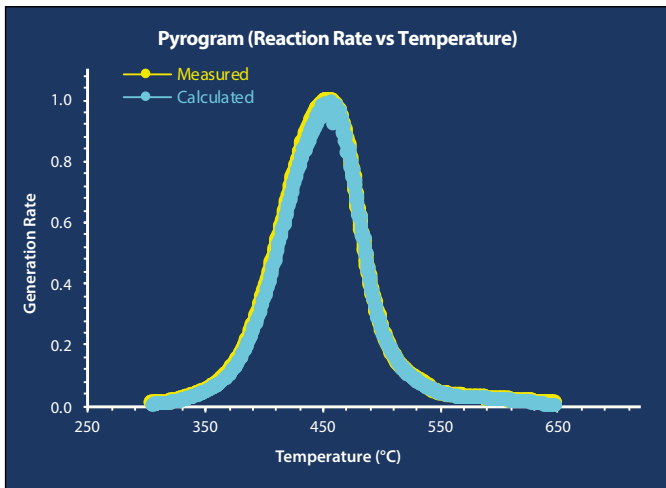
Given its potential, one would think kinetics would be a standard procedure, yet it has failed to attain widespread popularity even among trained geochemists due to some inherent flaws. Heating a sample at three different rates can be prohibitively expensive and time-consuming, barely worth the amount of data generated. Worse, traditional kinetics is prone to inaccuracy – sometimes egregiously so. Even if performed correctly, the triple-temperature heating method can produce results that violate the laws of thermodynamics, making geoscientists rightly wary of using it – until, that is, Dr. Douglas Waples developed one-run kinetics.

Through careful study, Waples determined that if one of the variables in the kinetics equation was filled-in prior to analysis, it is possible to determine the rest of the variables by heating the samples at only one heating rate, cutting the time and cost of analysis significantly and eliminating the persistent inaccuracies in three-run kinetics. At the same time, one-run kinetics produces much more data at the same cost than three-run kinetics by significantly reducing analysis time, which in turn provides exploration teams with a much clearer sense of play dynamics with a greatly reduced price tag. One-run kinetics can also be determined from archival pyrolysis data, making the cost of further analysis unnecessary.

Reservoir Pyrolysis

Total organic carbon content and thermal pyrolysis (or 'TOC/Rock-Eval' in industry parlance) have long been the workhorses

of geochemistry, easily and quickly determining source viability, hydrocarbon type, productivity, and depositional environment while giving a basic idea of thermal maturity. Lately, thermal pyrolysis has been used to identify sweet spots in unconventional plays, addressing oil mobility by comparing light, thermally vaporized hydrocarbons to the heavier hydrocarbons in a pyrolysis run. By using the appropriate initial temperature, heating rates and hold times, multiple peaks representing the desired light, medium, and heavy fractions can be obtained for a given rock. Especially useful in shale plays, the heating parameters in pyrolysis runs can



Output histogram from one-run kinetics analysis, generated with ORFA software.

be customized to the individual exploration scenario. Additional assessment can be obtained by running pyrolysis on samples prior to solvent-cleaning and subsequent to solvent treatment of the samples. Comparing the results before and after solvent treatment provides means for assessing the mobility of the hydrocarbons present in shale plays. A contamination baseline can also be applied to subsequent analyses should the samples be contaminated by oil-based mud. Moreover, reservoir pyrolysis allows quantifiable estimations of the gas-oil ratio, backing up or refuting estimations for greater accuracy.

A Window Into Your Play

Every oil carries its own chemical fingerprint, a unique set of components that distinguish it from all other oils. Using gas chromatography, it is possible to determine if two oils come from the same reservoir compartment or from two separate compartments. While gas chromatography has obvious applications in correlation studies, it has two additional uses with the potential to save production teams millions of dollars and months or even years of delays.

The causes of lost productivity can be hard to determine. When a well's production drops, standard procedure calls for well injection, an operation with the potential to restore productivity in a field. But well injection comes with a serious potential drawback: if significant obstructions exist within a reservoir, productivity will not be restored. For years, this was seen as a necessary risk, albeit one with the potential for significant loss of time and money. But in a price climate where every drilling decision carries financial uncertainty, the risks become even more serious.

Few production teams realize that inexpensive gas chromatography can



Reservoir pyrolysis, performed inexpensively on a Rock-Eval or Source Rock Analyzer, can yield a wealth of information about your play.

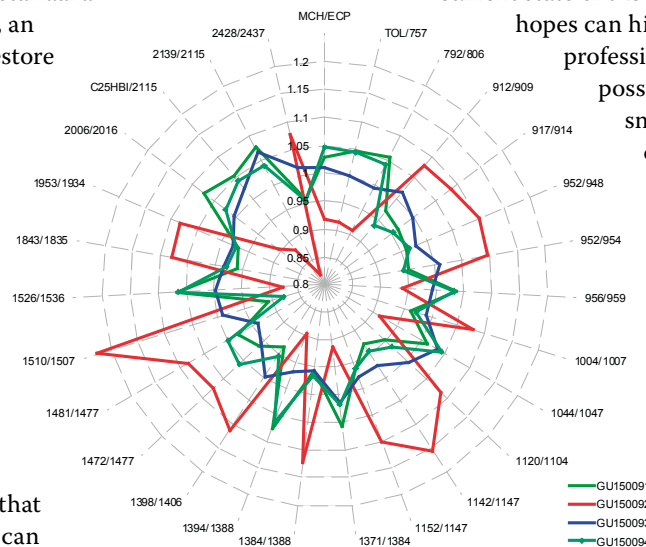
completely prevent such loss. Because gas chromatography investigates all the components of a given oil, the resulting chromatograms can be compared to the chromatograms of other wells to determine if they truly come from the same compartment. If any two wells show a greater than 10% difference, they are not in communication and well injection will not restore productivity.

Similarly, each productive zone in a given well has slight differences from those above and below it. Regular application of gas chromatography in a production allocation study allows exploration teams to be familiar with these differences, so that in case of a loss of well productivity it is possible to determine which zones have suffered a drop in output, making costly well-logging tools unnecessary. And with the advent of interpretive software, it has even become possible to automate chromatogram correlation, putting the power to perform production allocation and reservoir continuity directly in the hands of E&P companies.

Hope in a Difficult Market

Even with the recent stabilization of oil prices, upstream companies face significant budgetary challenges from the current state of the industry. When a company's hopes can hinge on a single well, E&P

professionals need to leverage every possible advantage to ensure smooth, inexpensive, and lucrative operations. While the temptation to slash science budgets in favor of other expenditures can be strong, drilling with insufficient data can be a very costly gamble. Geochemistry, far from being an unnecessary frill, might just be the hope your team needs to weather the current market. ■



A star chart comparison of different oils.

A Time-Saving Taxonomic Tool

A new online taxonomy database has proved invaluable for both industrial and academic biostratigraphers.

DR. SALLY MORGAN, IODP; DR JEREMY YOUNG, UCL; and ALIYA MUGHA

Researchers from University College London (UCL) have earned high praise for the money- and time-saving capabilities of a rigorous open-source online taxonomic database. Nannotax was developed in response to extensive user demand, from both academic and industrial biostratigraphers, for an online database which counters the discrepancies found when accessing information from multiple sources.

Database Development

Over 360 km of sediment core has been collected from across the world's oceans via deep sea drilling since 1966. Packed with billions of microfossils, these cores provide one of the most detailed indicators of environmental and evolutionary change across millions of years. However, the variety and volume of taxonomic classification systems on which paleontologists rely pose a significant challenge when it comes to extracting and analyzing data with the requisite degree of accuracy.

To address this issue a small UCL-based team with unique expertise – Professor Paul Bown, Dr. Jeremy Young and Dr. Jacqueline Lees – has been progressively developing a universally available, standardized system collating these taxonomic records since 2007. Calcareous nannofossils have been extensively used for biostratigraphy and in paleoceanographic research and data on them is scattered through a wide range of reports and academic publications. The web database draws heavily on microfossil occurrence records from the material recovered by the International Ocean Discovery Program (IODP) and the IODP's previous incarnations, the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), and the Integrated Ocean Drilling Program (IODP1).

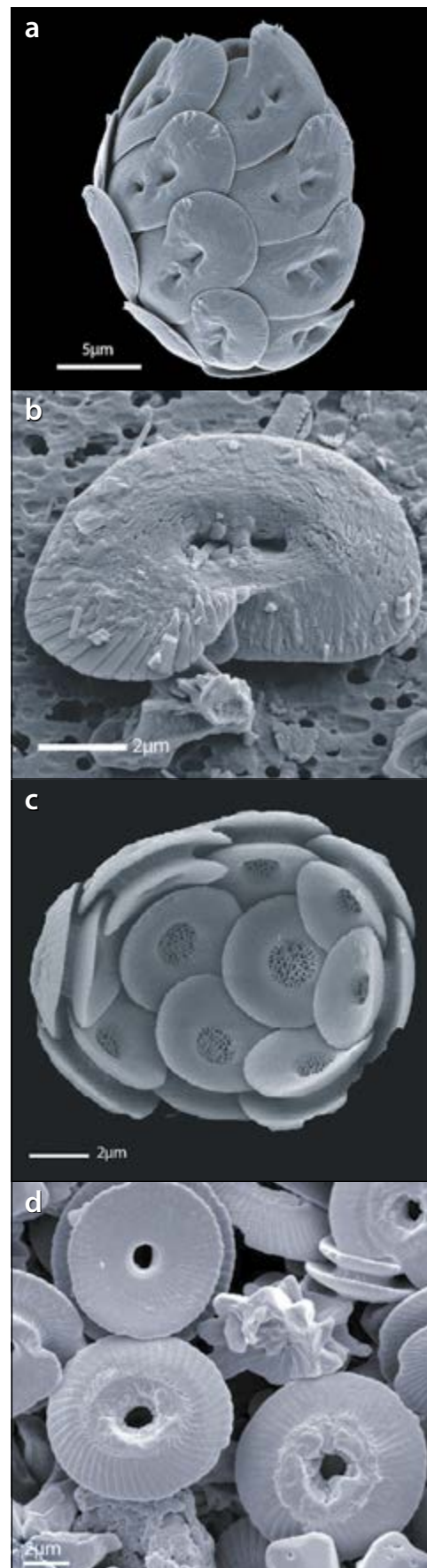
"There's nothing else like the IODP," says Prof. Bown. "It has an enormous and unique archive that is invaluable for industrial and academic scientists."

Nannofossils are one of the key groups used for determining the age of marine sediments in paleoceanographic research, as well as in exploration for and exploitation of hydrocarbon resources. By providing a single authoritative guide to the taxonomy, which is openly accessible to anyone worldwide, Nannotax has made the use of these invaluable microfossils far easier. It covers virtually all described living and fossil species, and includes over 20,000 images. It is probably the most comprehensive online database for any group of fossils.

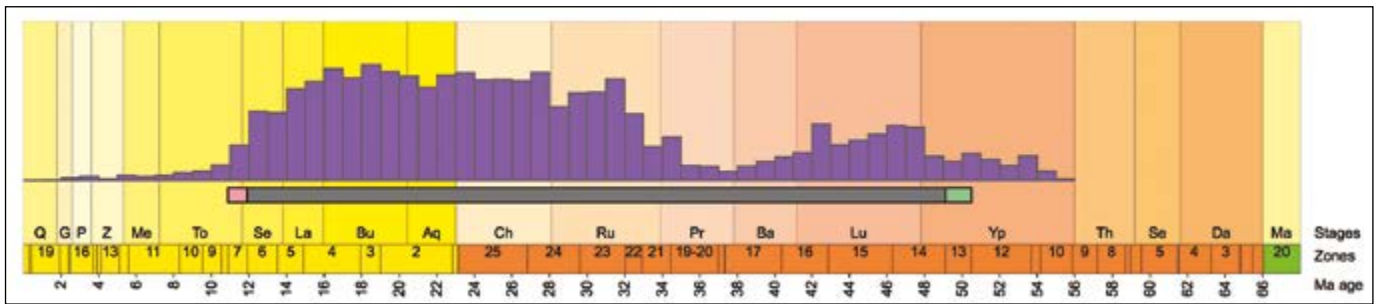
One special feature of the database is that it is integrated with a separate project called Neptune. Lead by scientists from Berlin, Neptune has collated hundreds of thousands of occurrence records of microfossils from DSDP, ODP and IODP projects, and also includes other data published across a wide range of reports, literature and academic publications. Nannotax is an attempt to assemble and synthesize these scattered data sources so that the information is much more accessible. This data is presented on each page as plots of the occurrence frequency of the species, providing a unique and objective record of their distribution through time.

A Reputable Resource

According to Google Analytics, between September 2015 and October 2016, Nannotax was used for 66,000 sessions, equating to approximately 250 sessions



(a) SEM image of a modern *Helicosphaera carteri*; (b) SEM image of a single fossil coccolith; (c) and (d) Typical species – *Cyclocarolithus floridanus*.



Screen grab of a plot of occurrence data from IODP records.

every weekday. The age-dating resources and tools within the Nannotax system are used by specialists from multiple sectors, most notably the biostratigraphic consultancy sector, in both the UK and internationally. The degree of rigor and detail applied to all Nannotax entries means that practitioners can use nannofossils extracted by the IODP and other projects more effectively as stratigraphic indicators. It helps achieve higher temporal precision, and provides a resource that has enhanced expertise in the field.

Mike Styzen, Senior Biostratigraphic Advisor at Noble Energy Inc, has been an advocate and user of Nannotax from the very beginning. He has subsequently contributed many tips to the database via an inbuilt feature that allows experts to informally share useful ideas that might otherwise never be distributed.

Mike added: “Nannotax is the first place I look when I’m presented with a nannoplankton taxon that I am unfamiliar with. I am always working on multiple projects, and I don’t have time to dig through old books and new literature, so Nannotax is a real time saver.

“I have used it extensively in all of the areas I’ve worked, including the Eastern Mediterranean, West Africa, South America, The Caribbean, and the Falkland Plateau. The benefit is more reliable modeling of what we are drilling. In West Africa in particular I have data that ranges from 35 years old to freshly generated data. Nannotax is a key tool, allowing me to put together a picture of the basin histories, which means we can more efficiently develop the resources available in the area.”

The time-saving benefits of Nannotax readily translate into monetary savings for companies such as Shell, because the database can provide answers in seconds rather than hours or days. This means that the efficiency of biostratigraphic work is optimized and the interpretations can inform operational decisions in a more timely and cost-effective way.

Rui Da Gama, a biostratigrapher for Shell, added: “One of Nannotax’s other key strengths is its ability to reconcile historic taxonomic terms to their modern equivalents. This is really important when reviewing data from sites that were deemed not economically viable when originally drilled in, for example, the 1970s, but which may well be viable now given recent advances in extraction technology. There is no doubt whatever that interaction between the

environmental research and oil and gas communities can be highly beneficial to both parties, and that governments should encourage and support both relevant research and closer interaction between them.”

Forams in the Future

Following the success and associated strong endorsements of the project, the group at UCL recently secured funding to apply the same approach to a second major group of marine microfossils, planktonic foraminifera. The PlanktonicForaminifera@Nannotax system, similar to Nannotax, will provide a highly accessible and essential resource of authoritative taxonomic and stratigraphic information for both industrial biostratigraphers and academic paleoceanographers. This new database is currently under development and will be openly available online soon.

Additional Information

Dr. Sally Morgan is a Research and Knowledge Exchange Fellow for the International Ocean Discovery Program (IODP) at the University of Leicester, UK.

Nannotax can be accessed online: <http://ina.tmsoc.org/Nannotax3>

The research underpinning Nannotax has been enabled by funding from the Natural Environment Research Council (NERC), the International Nannoplankton Association (INA), The Gulf Coast Section of Society of Economic Paleontologists and Mineralogists, and Shell. ■

Screen grab of a typical index page.

Helicosphaera
 Ancestry: Coccolithophores → Zygodisciales → Helicosphaeraceae → Helicosphaera
 Sister taxa: Helicosphaera,
 Short diagnosis: Coccoliths with helical flange; arranged spirally on the coccosphere

Daughter taxa (blue => in age window 0-300Ma)			Granddaughter taxa
			<ul style="list-style-type: none"> <i>H. carteri</i> group Living and Neogene medium to large species (typically 7-11 microns) with flanges that end in distinct wings. <i>H. puviventum</i> <i>H. fyalina</i> <i>H. carteri</i> <i>H. wallichii</i> <i>H. princei</i> <i>H. inversa</i> <i>H. sellii</i> <i>H. intermedia</i> <i>H. euphratis</i> <i>H. granulata</i> <i>H. ethiopia</i>
			<ul style="list-style-type: none"> <i>H. walbersdorffensis</i> group Miocene small to medium sized Helicosphaera species with wing ending flush with flange rather than terminating abruptly. Openings usually strongly oblique. <i>H. magna</i> <i>H. stalis</i> <i>H. redderi</i> <i>H. walbersdorffensis</i> <i>H. waltrans</i> <i>H. wacloni</i>
			<ul style="list-style-type: none"> <i>H. ampliporta</i> group Early Miocene group of large Helicosphaera species with weak wing, and broad central opening <i>H. ampliporta</i> <i>H. mediterranea</i> <i>H. scissura</i> <i>H. truempfi</i>

The Faroe Islands A New Beginning

The 4th Faroese Licensing Round offers a new beginning for exploration in this North Atlantic archipelago, with a better understanding of the geology and a wealth of improved data now available.

ÓLUVA EIDESGAARD, Jarðfeingi

Exploring the Faroese Continental Shelf for almost 20 years has taught the geoscientists working on the area some important things. Firstly, they know there is an active hydrocarbon system in the area; furthermore, multiple large structures have been confirmed in the region but exploration has also shown that the area has a complex volcanic history.

Since the first three of a total of nine offshore wells were drilled in 2001, great improvements have been made in drilling technology as well as major steps forward in seismic methods, which give the opportunity to image deeper and in more detail than previously. Drilling in basalt has undergone an impressive development,

increasing the rate of penetration from one to ten meters per hour. All these improvements have come about after a lot of effort and are the result of significant scientific developments.

Lessons Learned and New Ideas

Exploration on the Faroese Continental Shelf has shown that previous interpretations underestimated the thickness of the volcanic section, but drilling through the basalts has been found to be less complicated than initially anticipated. It has also shown that the Vaila play type known from the West of Shetland is more complex on the Faroese Continental Shelf than previously thought, but there is evidence that the interaction

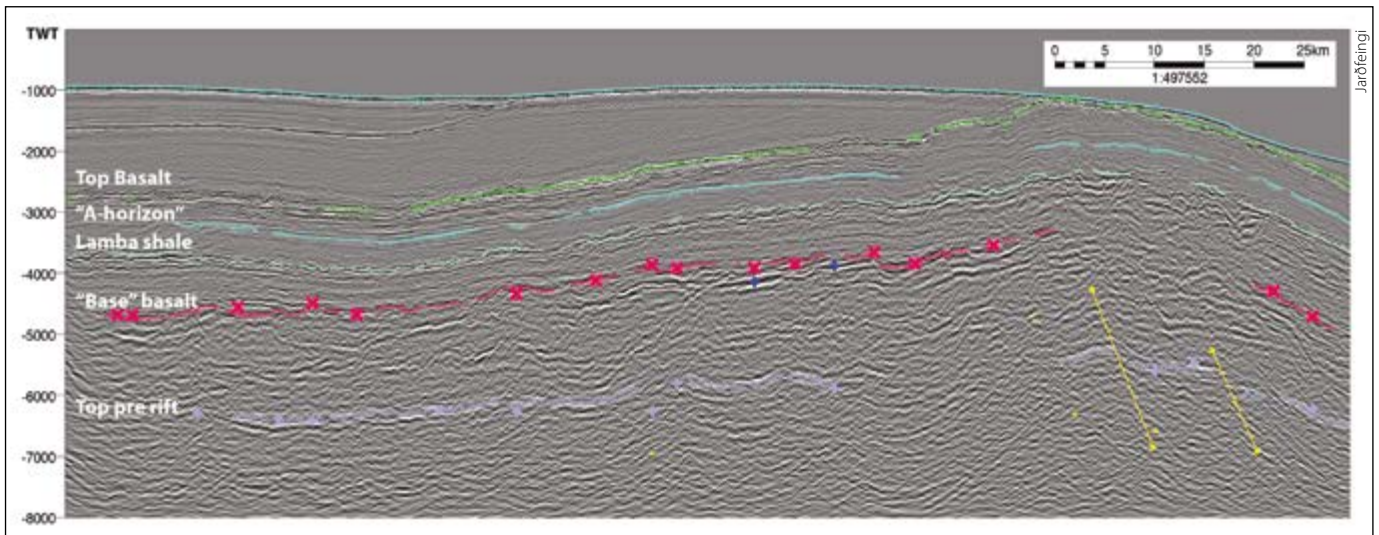
between the siliciclastic sediments and the volcanic cover can open up new structural and stratigraphic play types.

With this improved vision geoscientists at the Faroese Geological Survey (Jarðfeingi) are now revisiting the large amount of data available at the Jarðfeingi data repository in order to achieve a regional update of the eastern part of the Faroese Continental Shelf before the opening of the 4th Faroe Islands Licensing Round on May 17th, 2017.

The widespread volcanic cover has had a large impact on the Faroese Continental Shelf, but with improved data and additional knowledge from the nine offshore exploration and the three onshore scientific wells, geoscientists

Gáshólmur and Tindhólmur on the western side of the Faroe Islands with the islands of Vágar and Streymoy behind.





Interpretation of recent seismic shows how it is possible to image deep into the basalt with the new data. This seismic line crosses one of the largest structures on the Faroese Continental Shelf.

are now gaining a better understanding of the volcanic history. With a superior grasp of the relative ages of the different volcanic phases it is possible to gain greater knowledge about the volcanic development, the tectonics associated with it and the thermal impact it has had on the different areas. With this knowledge it is also possible to see where and when the source rock has been affected and hopefully by how much. Based on improved seismic data the geoscientists have also been able to gather more knowledge of the relative ages of the tectonic phases in the area. Combining this intelligence with better information on source rock maturity means there should be sufficient material to try to understand the underlying hydrocarbon potential, including possible migration pathways and the timing of structural evolution, which should result in the identification of the key elements which will indicate the presence of interesting plays.

The work being undertaken by the Faroese geoscientists is divided into three main areas: a reassessment of the hydrocarbon system in the region, a fresh look at all available reprocessed seismic data, and a renewed examination of the volcanic history.

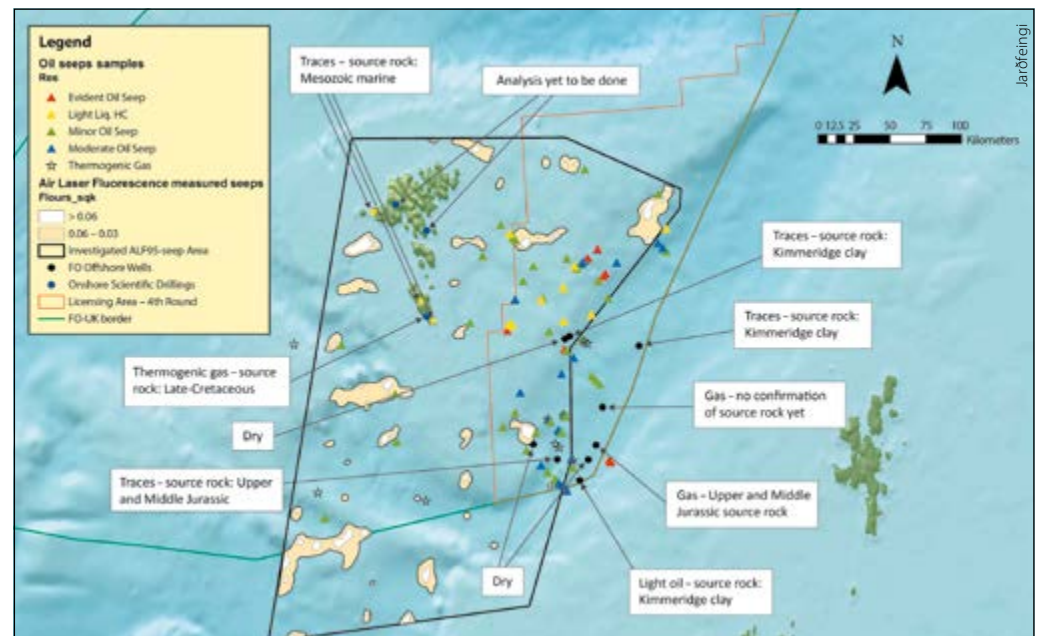
Deeper Structures and Sources

The initial results from the renewed look at the hydrocarbon system has already given us a better idea of the distribution of the Kimmeridge Clay Formation, which is the primary source rock in the area. Together with the new seismic interpretations, which in areas has given information on pre-rift structures and base volcanics, Jarðfeingi now has more data than previously on the distribution of the pre-volcanic sediments such as possible Upper Jurassic source rocks in parts of the area. Heat flow history, source rock maturity and possible migration

pathways are also being looked at.

With improved seismic, not only can deeper structures and horizons now be seen, but also more detailed intra-volcanic structures. This opens up the possibility of understanding the intra-volcanic play types as well as the interaction between the volcanics and the siliciclastic sediments at their base and at the point where the volcanic cover meets the siliciclastic material from the east. In both cases these are areas where there is potential for both structural and stratigraphic plays. This work has already provided us with a better picture of some of the deeper

A seep data map showing all available data from the Faroes Continental Shelf including onshore Faroe Islands. The map is based on an Air Laser Fluorescence survey, a seabed core survey and source rock data from the nine offshore wells, in addition to outcrop samples and one deep onshore well.



Exploration

large 4-way dip closed structures previously known in the area, and it has also opened up interesting play types at the border between the volcanic and siliciclastic units on the eastern edge of the Faroes Continental Shelf.

An improved understanding of the tectonics in the area is also a key factor because better knowledge of the relative age of the structures and their timing will help determine whether or not the structures were present after expulsion of the hydrocarbons below and therefore if they could have acted as a hydrocarbon trap.

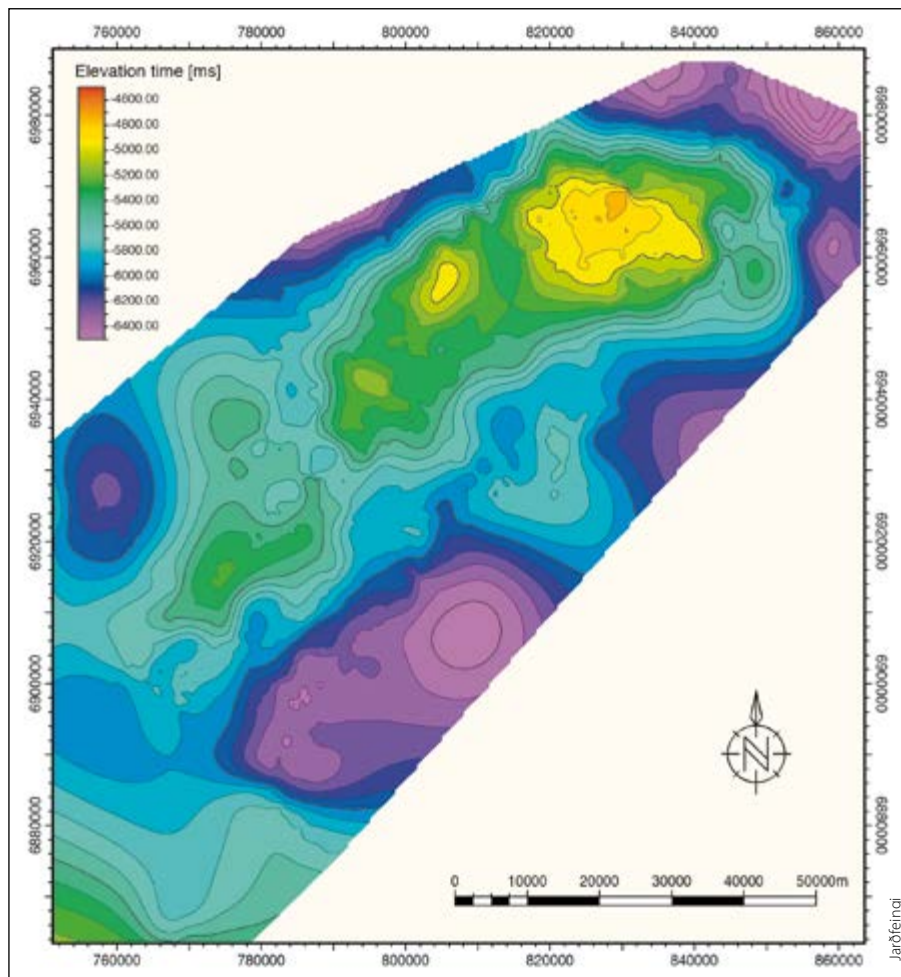
Revisiting the Volcanic History

A comparison study between the well data interpretations and the cores and cuttings from the volcanically influenced horizons has been undertaken in order to create a new and better understanding of the volcanic history. Together with a detailed study of the seismic facies distribution of the volcanic sequences on the Faroes Continental Shelf, this work will give a better and more detailed knowledge of the geology of the area. These new ideas will help us comprehend the various phases and regional differences in the distribution of the volcanic facies. The new maps will also give the depth conversions of the regional seismic horizons better quality control.

Understanding the regional distribution and relative timing of the various volcanic facies will also improve the knowledge of their thermal impact on the hydrocarbon system in the region.

Greater comprehension of the timing of the different phases of the volcanic complex will also provide the opportunity to learn more about the tectonic development of the area. This can again give ideas on the relative age of the structures and the possibility of the presence of structures which could act as traps for capturing the migrating hydrocarbons from below.

The only discovery on the Faroese Continental Shelf was made in well 6004/16-1/1z (Marjun), which is thought to contain light oil. The oil stains are clearly visible in the core.



Map showing the pre-rift horizon in the same area as the seismic line on the previous page. The map is in two-way time.

Furthermore, probing the data repository of cores and cuttings for lithological and geochemical signatures of the basaltic lava sequences will also allow for new correlation between the well-known onshore volcanic stratigraphy and the offshore sequences, thus affording better chronostratigraphic control.

May Conference to Unveil New Ideas

The upcoming 4th Licensing Round is only the beginning of a new proposed licensing strategy. While the area south-east of the Faroe Islands is included in this round, preparations for a 5th Licensing Round on the western side of the Faroe Islands are underway. The aim

is to open this in 2019, followed by a 6th Licensing Round in 2021, when the plan is to include the remaining area of the Faroese Continental Shelf.

During the 5th Faroe Islands Exploration Conference, which will be held in Tórshavn from May 16–18, 2017, all new data together with the results of the recent work undertaken by Jarðfeingi and collaborators will be presented. Depth maps to key horizons such as base volcanics and pre-rift, together with, if possible, paleoenvironmental, heat flow and source rock maturity maps will also be presented, as well as suggested leads and play types. During the conference, a core store will be open, where it will be possible to look at the cores from previous exploration wells, together with a description of each core. There will also be a data room facility open for attendees, which will be available to interested oil companies throughout the round. ■

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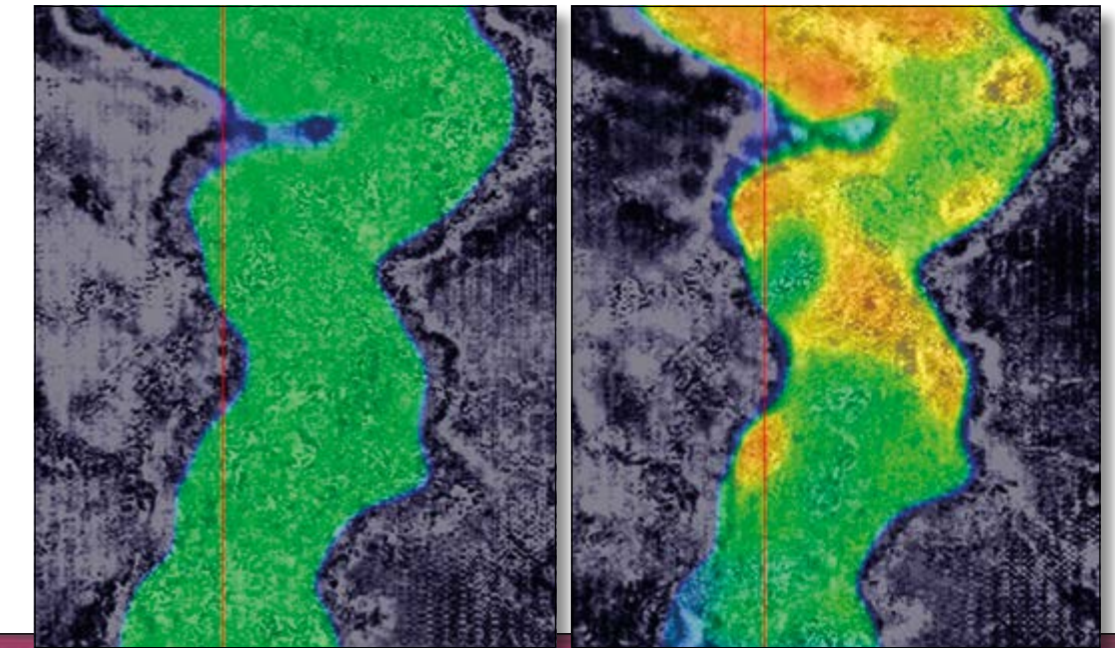
WE CAN'T TELL YOU WHAT
YOUR NEXT DEAL WILL BE.
BUT WE CAN TELL YOU
WHERE IT WILL HAPPEN.



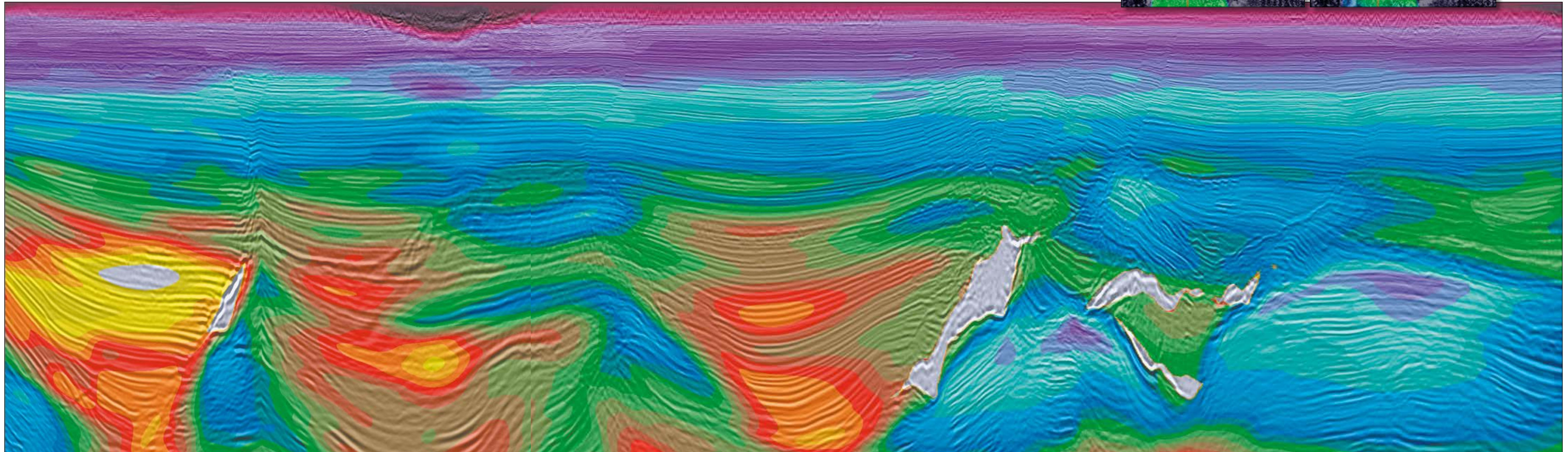
High-Resolution Model Building in a Full-Azimuth Nodal Survey in the GOM

The tomography algorithm within TGS's ImageZ™ depth-imaging software suite implements a tomography that involves intelligent interpolation and smoothing of a tomographic inversion update in order to accurately reflect underlying geological structure. Resulting velocity updates preserve edges observed within the stacked image, respecting visible faults and layering automatically.

The section below is an oblique line selected from the 3D to show several faults, the trench and a few salt bodies.



The velocity variation in the trench before and after the high-resolution tomography. Red line indicates the location of the line in Figure 2 on page 40.



High-Resolution Image-Guided Tomography

High-resolution image-guided tomography (IGT) can be used to resolve the complex structure below a shallow trench in the Gulf of Mexico.

SANDIP CHATTOPADHYAY, GARY RODRIGUEZ, TEFERA ESHETE and GUY HILBURN; TGS

The Nessie project is a full-azimuth ocean-bottom node survey located in the ultra-shallow water of the South Timbalier trench area of the Gulf of Mexico, an area known for complex static problems. These are often addressed in the time domain by applying time shifts generated from a refraction statics solution. In the depth domain, however, the same time shift will produce kinematically incorrect depth migration results and can lead to velocity distortions during successive tomography-based model building.

The problem is instead addressed in the depth domain by high-resolution tomography. The high frequency nature of the surface consistent residual statics is difficult to resolve via tomographic inversion; therefore this portion of the statics is instead applied to the data prior to depth migration.

The final depth-imaging results demonstrate significant uplift, with accurate images, improved image focusing, correctly positioned steeply dipping events and better well-to-seismic ties. The improvements are due to proper well-to-seismic calibration, anisotropic parameter estimation and multiazimuth tomographic inversion. Offset-dependent event picking and geologically constrained image-guided tomographic inversion further enhance the image quality.

Initial Anisotropic Model Building

The time-RMS model derived from PSTM velocity analysis was the starting velocity model for the project. The velocity model was converted to the depth-interval velocity

domain, and an isotropic shallow tomographic inversion was run before calibration with checkshots, twenty-two of which were selected for this purpose. Anomalous trends were edited before using them for calibration. Scalar functions were derived at checkshot locations to match the migration velocity to the checkshots and these scalar functions were interpolated and extrapolated along key interpreted horizons. A scalar grid was produced from the fully interpolated scalar functions in order to match the migration velocity field to the checkshots.

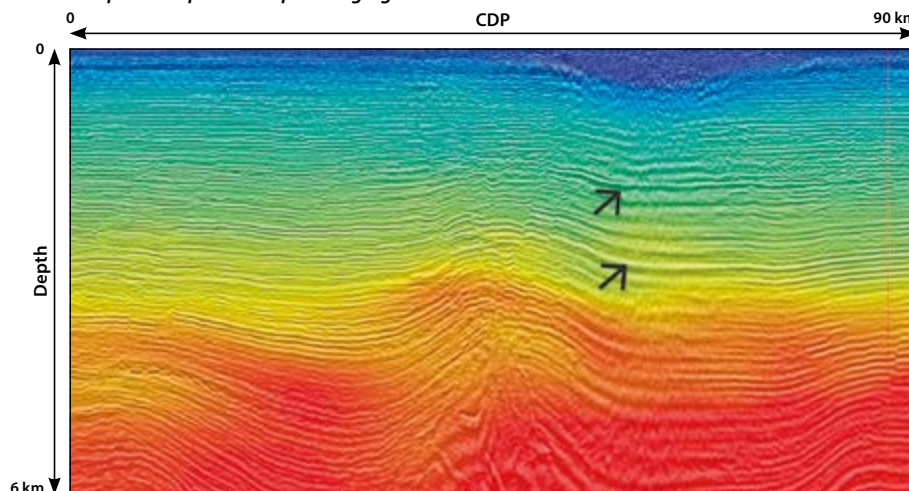
Prestack depth migration was performed with the calibrated velocity model. A lack of checkshot information in the trench area meant the velocity model did not reflect the low velocity trend present in the trench. This lack of slow velocities resulted in a migrated image with a significant structural sag (Figure 1).

To ensure tomographic velocity convergence, a slow velocity trend was manually inserted in the trench area. A constant velocity value of 1,350 m/s was inserted in the region between the water bottom and an interpreted base of trench and successive iterations of high-resolution shallow tomography would further refine the velocity model in this region. Outside of the trench the previously calibrated model was used as an initial vertical velocity model V_z for the subsequent model building process.

An isotropic Kirchhoff prestack depth migration was run using the resulting V_z model. Since the model matched the checkshot velocities at checkshot locations, residual moveout at these locations is attributed to anisotropy. Therefore, common image gathers (CIGs)

at the checkshot locations were then fed to a focusing analysis tool to derive anisotropic parameters δ and ϵ at the well locations, which were edited and smoothed to identify a general trend for the study area. Since the project area was relatively small, a single δ and ϵ function is sufficient for the entire area. To this end a single average function which best represented the anisotropic function in the study area was derived and extrapolated along the

Figure 1: The initial calibrated model shows depth-sag (arrowed) due to removing long-period statics from the input data prior to depth imaging.



previously interpreted horizons to generate fully populated δ and ϵ volumes for the successive anisotropic model-building and depth-imaging processes.

TTI Model Building

The initial V_z model and the derived anisotropic parameters can be used to convert vertical velocity V_z to normal velocity V_0 for anisotropic depth migration. The initial 3D dip fields were generated from an isotropically migrated stacked image volume and fed into the TTI depth migration flow.

Shallow Trench Tomography

The 3D OBC data was then azimuthally sectorized during the binning process, to ensure the full azimuthal illumination of the study area. The input data was divided into six azimuths, each of which was migrated using TTI prestack Kirchhoff depth migration. To ensure a high-resolution model update at very shallow depths and in the trench area, a finer tomographic inversion grid was adopted. Single parameter curvature-based residual moveout (RMO) was picked on scanned semblances derived from TTI PSDM CIGs. We noted that a positive curvature (increasing reflection depth with increasing offset) was picked in the trench area, which translates into a velocity decrease. This velocity slowdown is consistent with what is expected for unconsolidated gas-charged mud. Velocities as low as 1,000 m/s resulted after two tomographic updates (Figure 2).

The tomographic updates not only better flattened the CIGs, but dramatically diminished the structural sag (Figure 3). Additionally, faults are better focused, all of which gave more confidence that the velocity updates were converging towards a correct velocity model.

High-Resolution, Image-Guided Tomography Update

A higher resolution, geologically conformable model update was achieved by offset-dependent RMO picking and image-guided tomography (Hale, 2009; Hilburn et al., 2014). Offset-dependent picking is a robust process utilizing an event-finding technique which is guided by analyzing amplitude variation between traces in the CIGs, geological dips, continuity of the reflector, displacement of events within gathers and a required

Figure 3: High-resolution, offset-dependent and IGT update at 2,500m depth. The arrows show improvement of image quality (a) PSDM depth slice with initial model and (b) after shallow and high-resolution tomography update. The IGT updated velocity follows the underlying structure.

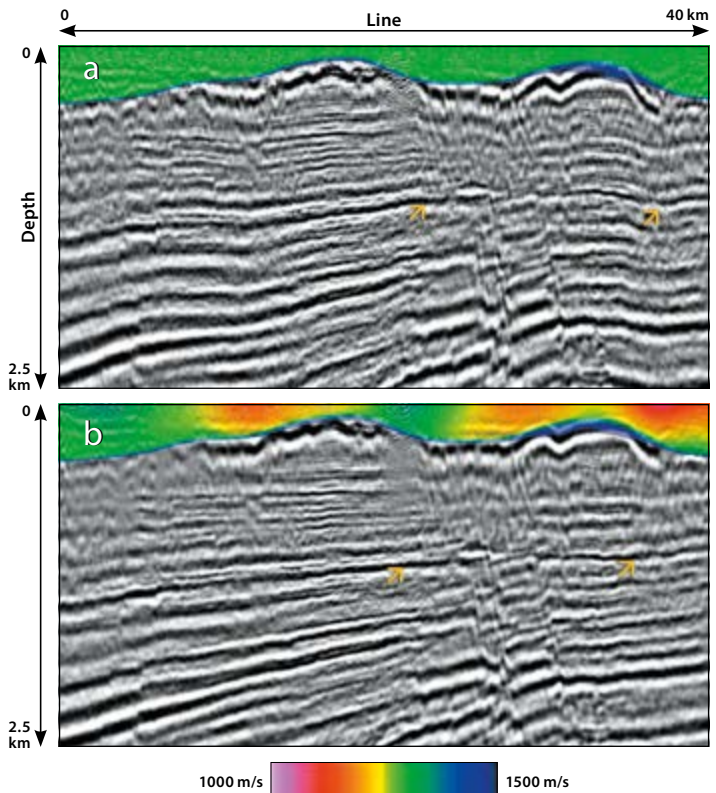
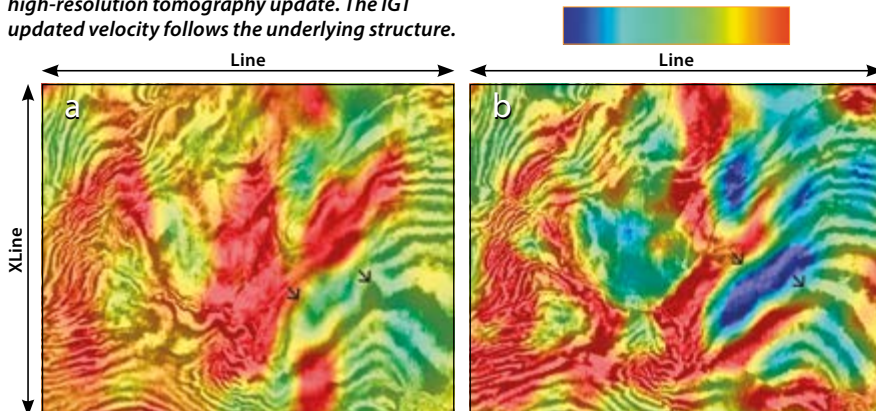


Figure 2: Velocity update in the trench area (a) initial model and (b) after shallow tomography update in the trench area. The color bar is restricted to show velocity values only in the trench area. The arrows show that velocity update in the trench area helped to improve image quality and diminish structural sag.

flatness-constraint (Hilburn et al., 2014). This procedure honors events with complex moveout patterns well. More accurately sampling the residual depth error should also allow for better resolution in the velocity model.

The directionality and continuity of events were employed to calculate a set of tensors that are used to define update zones whose boundaries are computed by minimizing structure-oriented propagation time within the underlying image. Disruptions in this propagation time identify the coherent and incoherent structures (e.g. faults). The zonal distribution, computed tensors and the propagation time combine to describe a preconditioning operator for the tomographic inversion. This higher resolution and geologically conformable IGT update produced a higher resolution background sediment velocity model (Figure 3) for depth imaging.

Acknowledgements

We would like to thank TGS management for permission to publish this paper. We would also like to thank Ashley Lundy, Kenny Lambert, Steve Hightower, George Cloudy Jr., Bin Wang, and Zhiming Li for their support and suggestions, and Connie VanSchuyver for proofreading the manuscript. The Nessie survey is a cooperative project between TGS and FairfieldNodal. ■



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Exploration Geochemistry in the Digital Age

The companies that lead the next wave of exploration will be those that concentrate their time on analysis and not on data acquisition.

J. ETHAN BROWN, GeoMark Research

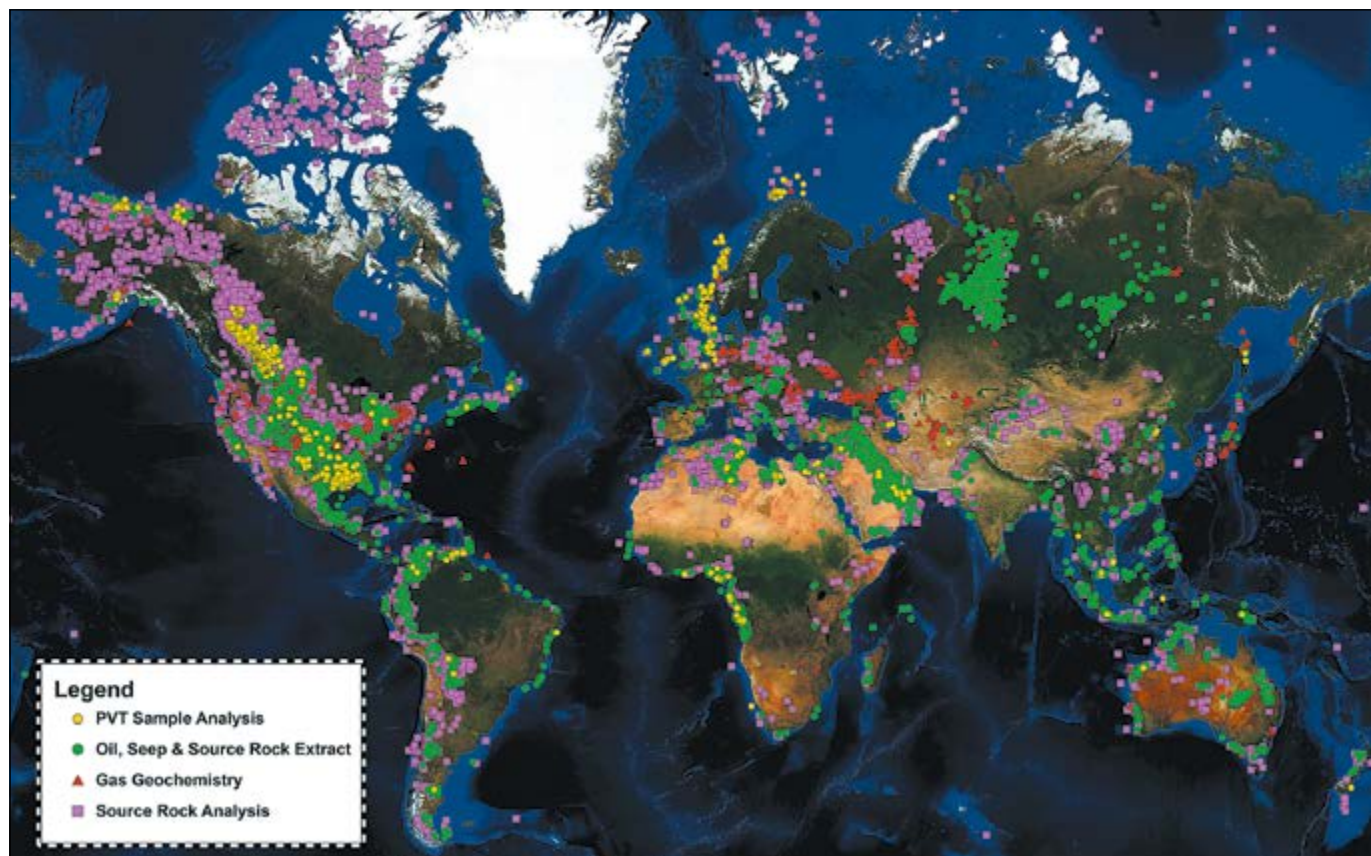
Oil and gas exploration is experiencing revolutionary change. The advent of lateral drilling and multi-stage fracking, along with other technological innovations, is resulting in an explosion of attractive new plays. E&P companies are currently racing competitors to evaluate prospective opportunities and acquire attractive acreage. As the industry recovers from the current slowdown, evaluation periods will shorten and workloads increase, most likely with smaller teams due to recent restructuring.

To prepare for this new world of more rapid decision-making, energy companies must turn to databases and digital technology to help meet this challenge. It is critical that exploration teams do not use vital time gathering or generating the data needed, but rather spend it interpreting the required data and implementing the interpretation.

Geochemistry, along with a myriad of other technical disciplines, is an example of an exploration component that

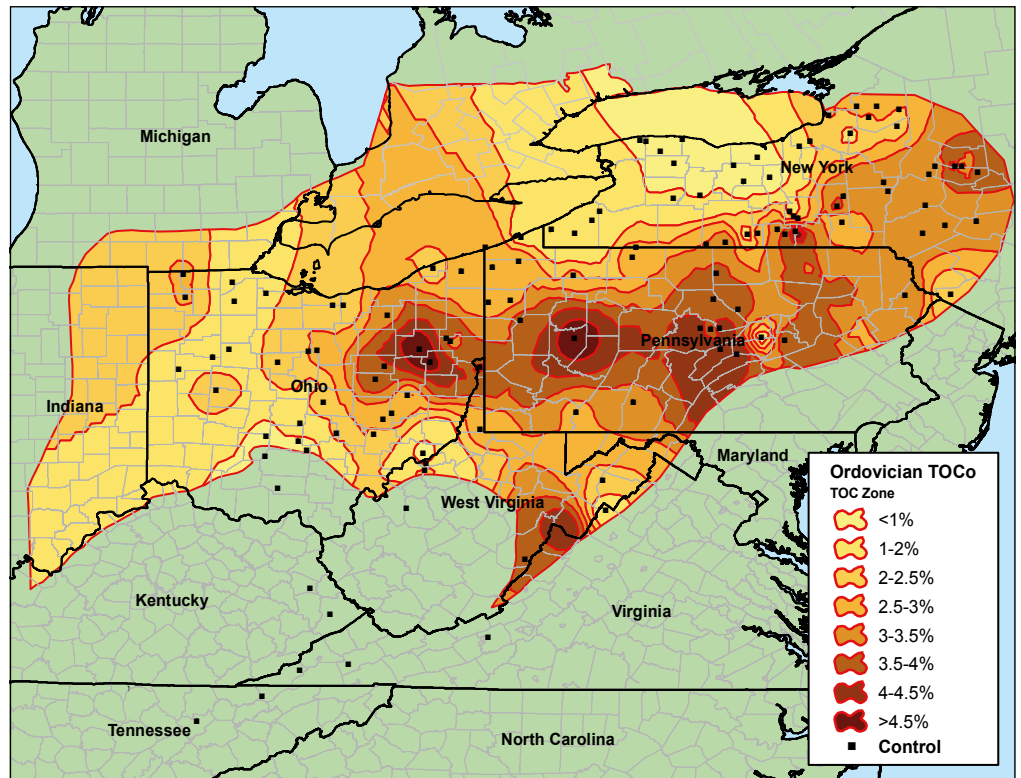
is ideally suited to a database solution. A tremendous amount of high quality geochemical data have been generated during the past 40 years, and much of it is available, although not necessarily easily accessible or quality controlled. Though always an input in conventional drilling, geochemistry has been elevated to a key role in the process of understanding unconventional plays. More than any other science, geochemistry provides insight for unconventional players into the depositional environment, volume and type of organic matter that was deposited, and, most importantly, the thermal maturity history that determines the extent to which kerogen has transformed into volumes of oil and gas. While individual types of data can be used to tell the geochemical story, we have found that it is the convergence of multiple types of data that combine to tell the full story of a particular play. Geochemistry can provide tangible benefits in a multitude of ways, as the following case studies demonstrate.

GeoMark's Rock & Fluid Database (RFDbase), the portal through which customers access the company's repository of geochemical data, contains analyses on more than 300,000 source rock, oil, gas, and PVT samples throughout every major producing basin in the world.

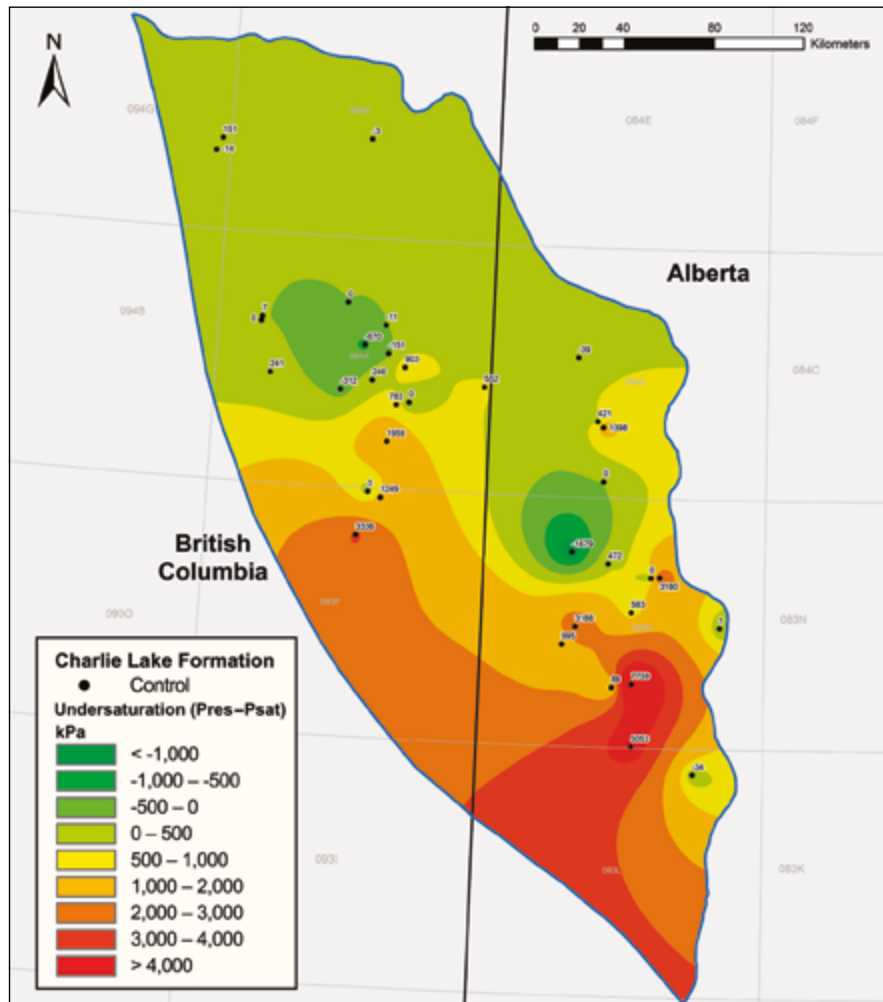


**Case Study 1:
Utica-Point Pleasant
Potential**

Geochemical data should be an important part of any regional study. In 2007 GeoMark studied the source potential of the Appalachian Basin in the north-east United States. Although the Devonian section was the prime target for this project, it also mapped the potential of the Ordovician sources, and thus identified an organic-rich region of north-east Ohio within the Utica/Point Pleasant Formation that had excellent hydrocarbon potential. The companies that participated in this study were some of the first leaseholders to enter the play.



The potential of the Utica/Point Pleasant Formation in Ohio was detected in the study of the Devonian and Ordovician of the Appalachian Basin.



**Case Study 2:
Undersaturated Zones
in the WCSB**

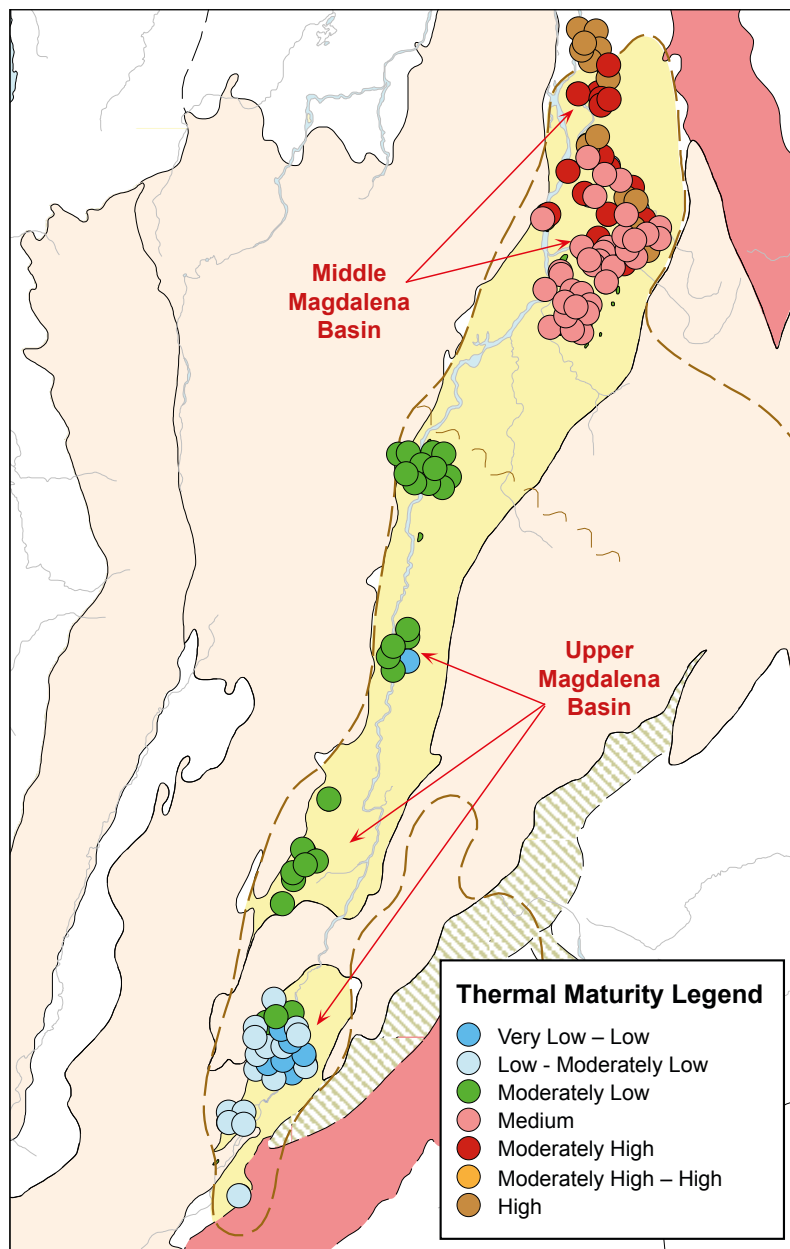
In unconventional plays pressure/volume/temperature (PVT) data can be mapped to provide regional indications of zones of best production. Undersaturation is the difference between reservoir and saturation pressure. High reservoir pressures provide a strong driving force for production and low saturation pressures keep the fluids in a single-phase condition longer. The map (left) shows the undersaturation levels across the Triassic Charlie Lake Formation in the Western Canada Sedimentary Basin (WCSB). Zones of best production (orange and yellows) can be distinguished from zones with diminished production (greens). Once the data from a set of PVT reports are standardized and QC'd, regional predictions of phase behavior character are possible in both unconventional and conventional plays.

PVT data allows zones of best production (orange and yellows) to be distinguished from zones with diminished production (greens).

Case Study 3: Importance of Thermal Maturity to Unconventional Production

A quick assessment of the overall thermal history of a basin can be made from crude oil biomarker ratios. The maturity of an oil sample reflects the source rock maturity when the oil was expelled. In unconventional resource plays, the success often depends on the level of maturity of the source rock (which is also the reservoir rock): low maturity has a much higher risk than higher maturities since at higher ones, gas is co-generated which provides more reservoir energy for successful light oil production rates. In the search for optimal unconventional acreage in Colombia's Magdalena Valley, known to contain a world-class Cretaceous source rock (La Luna Formation), it was quickly determined from GeoMark's global crude oil database that 50% of the La Luna-sourced oil from the Middle Magdalena Formation was from moderate to high maturity organic matter, while 95% of the oil in the Upper Magdalena was of low maturity and at high risk for unconventional production problems. Mapping of the oil maturity within the Middle Magdalena revealed potential 'sweet spots' of higher maturity.

Thermal maturity variations measured by oil biomarker analyses predict and explain production quality of La Luna-sourced oils in the Upper and Middle Magdalena Basins.



Digital Databases Needed

As the case studies outlined here illustrate, geochemical data are highly useful for the evaluation of both unconventional and conventional plays. However, very few E&P companies treat geochemistry data as a corporate asset. From conversations with mid-cap to large-cap E&P companies, a consistent trend is the absence of a centralized geochemical database that is quality checked, digitized, and easily queried so that data can be identified, selected and efficiently integrated into analytical packages. Too often large swaths of companies' historic analyses remain undigitized, either in store rooms of paper or as PDFs that are digitized yet entirely unsearchable. Many companies have unknowingly fostered research islands, with analysis being done by individuals but not centrally captured and made available across the company. Still others have the data resident locally on hard drives, but are dependent on the institutional knowledge of their employees to know what data are available and where it can be accessed. The risk involved with these last two scenarios has been exacerbated by the volume of restructuring and layoffs that has resulted from the downturn of the past few years.

E&P companies need to make concerted efforts to empower their exploration teams by providing easy access to internal geochemical data, supplemented by publicly available data, or data available for purchase as needed for a comprehensive understanding of a play. GeoMark supports the industry by providing the largest and most comprehensive geochemical dataset available in the market. Populated with source rock, oil, produced gas, mud gas and PVT data, the company's Rock & Fluid Database (RFDbase) offers a robust dataset coupled with an easy-to-use portal that quickly allows users to view, query, and download geochemical data for further analysis. GeoMark further supports analytical efforts by allowing companies to load their proprietary data into RFDbase, enabling employees to utilize the features of RFDbase to access their company's proprietary datasets.

The discovery of massive unconventional plays like the Bakken, Permian and Eagle Ford are becoming rarer and rarer. The future of unconventional success will be found in smaller footprints. Exploration teams, now reduced in number through the downturn, will be increasingly pushed to make more detailed interpretations, faster. Energy companies must recognize geochemical data as a corporate asset and put the required digital capabilities in place to quickly respond to internal data requests. The companies that can concentrate their time on analysis and not data acquisition will be those that lead the next wave of exploration. ■

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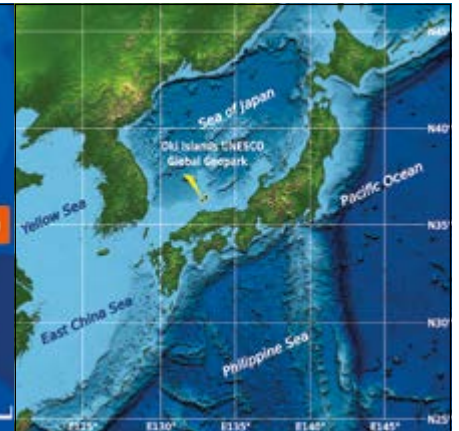
PROVIDENCE

An Isolated Island Geopark in the Sea of Japan

TERESA SADKOWSKY
Oki Islands UNESCO Global Geopark

A well-kept secret in the Sea of Japan, the Oki Islands UNESCO Global Geopark is transforming the outlook of remote islands and developing new prospects for sustainable geotourism.

UNESCO Global Geoparks are often found in remote locations around the world, and the Oki Islands UNESCO Global Geopark is no exception, consisting of a group of isolated islands located in the Sea of Japan, between the Japanese Archipelago and the Asian Continent. The geopark has a total area of 673.5 km² and encompasses four inhabited islands – Nishinoshima, Nakanoshima, Chiburijima (the Dozen Islands) and the larger Dogo Island – as well as numerous uninhabited islands and a sea area stretching 1 km from the coast. This distant island group makes a stark contrast to the sprawling crowded cities that may come to mind when one thinks of Japan. With a population of only around 20,000, the islands encompass



vast and untouched nature, coasts dotted with tranquil fishing villages, and a rich cultural history. Alongside idyllic island scenery, the Oki Islands feature impressive geological features that tell a

story much greater than the formation of the islands themselves.

Small Islands in the Sea of Japan

The landscapes of the Oki Islands are

One of the most celebrated landscapes in the Oki Islands, the Kuniga Coast of north-west Nishinoshima Island demonstrates text-book examples of coastal erosion, including sea-eroded cliffs, sea caves, sea arches and isolated stacks and flat wave-cut benches.





Oki Islands UNESCO Global Geopark

Oki gneiss from Dogo Island.

quite unlike those of the rest of the Japanese mainland and surrounding islands. They reveal an unusual combination of geological features that tell the story of the formation of the Sea of Japan.

A marginal sea surrounded on one side by the Asian continent and on the other by the Japanese Archipelago, the Sea of Japan was formed by the back-arc spreading of the continental plate from around 26 to 10 million years ago. Records of the expansion of the sea can be found in the rocks of the Oki Islands, which are separated into two main areas: the three Dozen Islands, and the largest island, Dogo. These islands were created by vigorous volcanic activity via two large volcanoes around seven million years ago which also uplifted the basement rock, comprising Oki gneiss, a metamorphic rock that formed on the eastern margin of the Eurasian continent 250 million years ago, long before the opening of the Sea of Japan. This rock, often referred to as the 'backbone of Japan', is a precious piece of history revealing the continental origin of the Japanese archipelago and the fragmentation of the continent. Oki gneiss is easily visible in an exposed outcrop in the largest mountain of the islands, Mt. Daimanji, on Dogo Island. In the polished surface of the cliff face visitors can admire the black and white banding and mineral crystals such as garnet within the rocks.

Besides Oki gneiss, lacustrine and marine deposits found around the geopark record the stages of

formation of the Sea of Japan and provide important information about the environment at the time. One particularly scenic site on the Jodogaura Coast in north-west Dogo Island features sediments that were deposited in a huge lake that formed on the continent around 26 million years ago.

Eroded Coasts and Mantle Pebbles

The powerful volcanic history that formed the islands can be observed in the awe-inspiring indented coasts of the islands, which are continuously transforming under heavy erosion from the sea and strong north-westerly winds from Asia. These coastlines are text-book examples of coastal erosion, with vast sea cliffs, eroded archways, sea caves and strangely shaped stacks, all in close proximity. One distinctive rock in Dogo Island is shaped remarkably like a candle and can be seen lit by the sun at sunset from sightseeing boats.

Twelve kilometers to the west of Dogo, the massive sea-cliffs of the Dozen Islands expose incredible views of the cross-section of a volcano, such as Sekiheki (Red Cliff) on Chiburijima Island or Matengai Cliff on Nishinoshima Island. A spectacular walking track will take you from the top of Matengai Cliff, through open pastures with horses and cattle and down to a magnificent eroded arch called Tsutenkyo on the coast. The high pastoral landscapes on the mountain tops of these islands are still used today as grazing land. The undulating fields are remnants of a rotation farming method developed on the islands to maximize the use of the steep terrain and thin soil. You may find some stone walls that were used to mark out the fields up until the mid-20th century.

Evidence of another type of volcanic activity that occurred here can be found on a nearby uninhabited island, called Kuroshima, or Black Island. This island

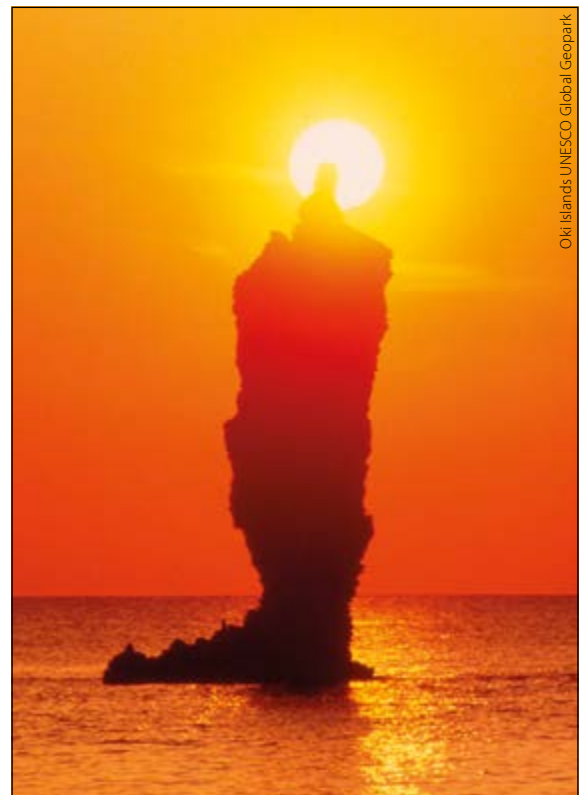


Oki Islands UNESCO Global Geopark

A fragment of mantle rock caught up in magma and brought to the surface.

contains abundant mantle xenoliths, which are fragments of the upper mantle brought up from a depth of more than 25 km beneath the Earth's crust during eruptions of basaltic lava. These mantle xenoliths are exposed in the cliffs of the island, but are also commonly found in pebbles and rocks washed up on the beach, so they tell us about the internal

The aptly named Candle Rock (Rosoku-jima in Japanese) appears lit by the sun at sunset.



Oki Islands UNESCO Global Geopark



Sea-kayaking – a great way to explore the Oki Islands.

structure of the Earth's mantle while we are strolling along the beach, and are commonly used in Earth science education and tourism.

Ancient Culture and the Ecosystem

Another important geological asset of the islands is the presence of 'volcanic glass', obsidian, one of the major

materials used to make stone tools in the Paleolithic. Though obsidian can be found in numerous areas of Japan, in only a few places was it mined and

The red coloration in the rocks of Sekiheki (Red) Cliff are the result of the high iron content in the magma erupting from the island-forming volcano. When this burst into the air at high temperature it rapidly oxidized and the entire body of the magma turned red. Evidence of repeated eruptions is given by the layered cliff sediments, with the greyer layers resulting from slower, less explosive magma flows.



used to make stone tools. Artifacts of stone tools made with Oki obsidian found across the mainland of Japan tell us that it was a highly valued resource that was traded widely up to 30,000 years ago. Today, obsidian fragments and outcrops can be easily found on the north-west and southern coasts of Dogo Island. Visitors can participate in educational obsidian arrowhead-making experiences, or simply have a chat with Mr. Yawata, who facilitates research of archeological sites around the obsidian outcrops and has a permit from the Ministry of the Environment to mine a small amount of obsidian every year.

In general, culture and traditions on the islands have been preserved with little influence from outside, and a number of unique or rare festivals and ceremonies can still be observed here. Moreover, the mountainous terrain of the islands has preserved a cultural diversity within the islands themselves, and one can find a multitude of different festivals celebrated in the villages around the islands today. Numerous shrines date back over 1,000 years,



Oki Islands UNESCO Global Geopark



Oki Islands UNESCO Global Geopark

Renge-mai Court Dances are performed at Kokubunji Temple in Dogo Island during a festival in April every year. They originate from the Heian Period (794–1185).

including primitive tree shrines still preserved in the forest.

Closely connected to the geological history of the land is the unique ecosystem found on the islands. Though they are isolated, the stretch of sea between the islands and the mainland is less than 100m deep. As a result, the islands have been connected to the mainland during glacial ages a number of times throughout history. The unusual distribution of southern and northern plants found on the islands, including the presence of subalpine plants in coastal areas, is a remnant of the most recent glacial age which occurred 20,000 years ago. Alongside this, a number of endemic plants and animals have evolved in isolation on the islands, such as the Oki salamander, the Oki hare, and the Oki rhododendron.

A New Geopark Initiative

The Oki Islands Geopark developed from a grassroots ecotourism initiative called the 'Kaze-machi Kaido Club', and was designated as a Global Geopark in 2013. The work of the geopark is changing the way that local people and visitors view the islands, and paving the way for preservation and a holistic and sustainable use of their geological, biological and cultural resources. Like many remote areas around Japan, the islands show a rapid decline in population and visitor

numbers. Consequently, one of the core goals of the geopark is to help create new employment opportunities in the areas of tourism, preservation and education, and to promote the islands both domestically and internationally. Thanks to the work of the geopark, visitors and local residents can discover the story of the Earth that this region has to tell, and experience the stunning landscape through geo-tours, trekking, or geo-seakayaking tours, accompanied by qualified geopark guides. Self-guided visitors can also enjoy the geopark with signboards, maps, walking trails and other facilities.

The slogan of the geopark is 'Discover Connections, as the connections between the land, nature and culture to be found here are infinite. Why not come to the Oki Islands to discover some of these connections for yourself?'

Further Information

Though remote, the geopark is easily accessible by air and sea. A daily flight with JAL Airlines departs from Osaka Itami Airport and Izumo Airport, and the Oki Kisen ferry liner services a ferry and jetfoil fast ferry from the ports of Shichirui and Sakaiminato in Shimane and Tottori Prefectures. The islands have a mild climate and are well-suited to tourism from March to November.

For more information about the Oki Islands UNESCO Global Geopark, please see the website: <http://www.oki-geopark.jp/en/> or contact info@oki-geopark.jp ■

Seismic Interpretation with Machine Learning

Machine learning resolves two significant issues in seismic interpretation: firstly, the 'Big Data' problem of trying to interpret dozens, if not hundreds, of volumes of data and secondly, the fact that humans cannot understand the relationship of more than three types of data all at once.

ROCKY RODEN, Geophysical Insights, and DEBORAH SACREY, Auburn Energy

Today's seismic interpreters must deal with enormous amounts of information, or 'Big Data', including seismic gathers, regional 3D surveys with numerous processing versions, large populations of wells and associated data, and dozens if not hundreds of seismic attributes that routinely produce terabytes of data. Machine learning has evolved to handle Big Data. This incorporates the use of computer algorithms that iteratively learn from the data and independently adapt to produce reliable, repeatable results. Multi-attribute analyses employing principal component analysis (PCA) and self-organizing maps are components of a machine-learning interpretation workflow (Figure 1) that involves the selection of appropriate seismic attributes and the application of these attributes in an unsupervised neural network analysis, also known as a self-organizing map, or SOM. This identifies the natural clustering and patterns in the data and has been beneficial in defining stratigraphy, seismic facies, DHI features, sweet spots for shale plays, and thin beds, to name just a few successes. Employing these approaches and visualizing SOM results

utilizing 2D color maps reveal geologic features not previously identified or easily interpreted from conventional seismic data.

Steps 1 and 2: Defining Geologic Problems and Multiple Attributes

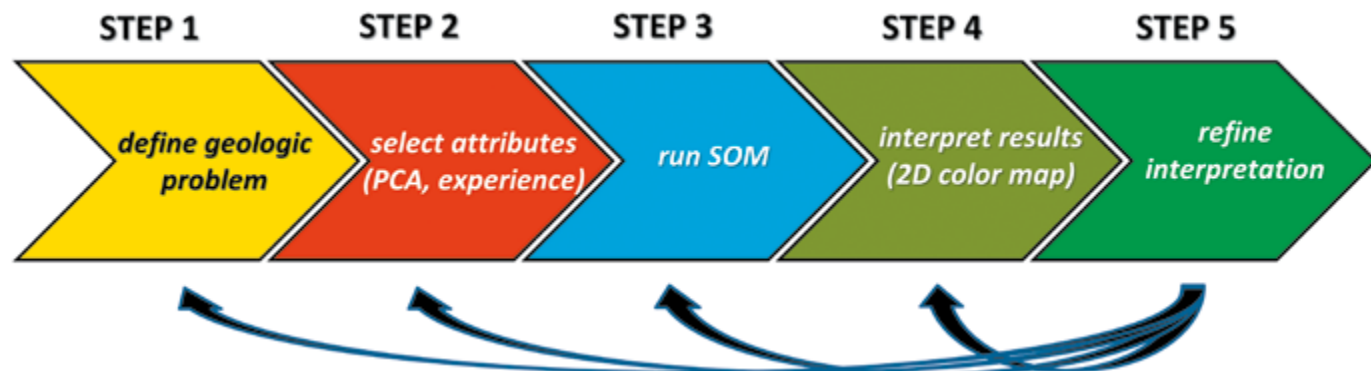
Seismic attributes are any measurable property of seismic data and are produced to help enhance or quantify features of interpretation interest. There are hundreds of types of seismic attributes and interpreters routinely wrestle with evaluating these volumes efficiently and strive to understand how they relate to each other.

The first step in a multi-attribute machine-learning interpretation workflow is the identification of the problem to resolve by the geoscientist. This is important because depending on the interpretation objective (facies, stratigraphy, bed thickness, DHIs, etc.), the appropriate set of attributes must be chosen. If it is unclear which attributes to select, a principal component analysis (PCA) may be beneficial. This is a linear mathematical technique to reduce a large set of variables (seismic attributes) to a smaller set that still contains

most of the variation of independent information in the larger data set. In other words, PCA helps determine the most meaningful seismic attributes.

Figure 2 is a PCA analysis from Paradise® software by Geophysical Insights, where 12 instantaneous attributes were input over a window encompassing a reservoir of interest. The following figures also include images of results from Paradise. Each bar in Figure 2a denotes the highest eigenvalue on the inlines in this survey. An eigenvalue is the value showing how much variance there is in its associated eigenvector and an eigenvector is the direction showing a principal spread of attribute variance in the data. The PCA results from the selected red bar in Figure 2a are denoted in Figures 2b and 2c. Figure 2b shows the principal components from the selected inline over the zone of interest with the highest eigenvalue (first principal component) indicating the seismic attributes contributing to this largest variation in the data. The percentage contribution of each attribute to the first principal component is designated. In this case the top four seismic attributes

Figure 1: Multi-attribute machine-learning interpretation workflow with principal component analysis (PCA) and self-organizing maps (SOM).



represent over 94% of the variance of all the attributes employed. These four attributes are good candidates to be employed in a SOM analysis. Figure 2c displays the percentage contribution of the attributes for the second principal component. The top three attributes contribute over 68% to the second principal component. PCA is a measure of the variance of the data, but it is up to the interpreter to determine and evaluate how the results and associated contributing attributes relate to the geology and the problem to be resolved.

Steps 3 and 4: SOM Analysis and Interpretation

The next step in the multi-attribute interpretation process requires pattern recognition and classification of the often subtle information embedded in the seismic attributes. Taking advantage of today's computing technology, visualization techniques, and understanding of appropriate parameters, self-organizing maps, developed by Teuvo Kohonen in 1982, efficiently distill multiple seismic attributes into classification and probability volumes. SOM is a powerful non-linear cluster analysis and pattern recognition approach that helps interpreters identify patterns in their data, some of which can relate to desired geologic characteristics. The tremendous amount of samples from numerous seismic attributes exhibit significant organizational structure. SOM analysis identifies these natural organizational structures in the form of natural attribute clusters. These clusters reveal significant information about the classification structure of natural groups that is difficult to view any other way.

Figure 3 describes the SOM process used to identify geologic features in a multi-

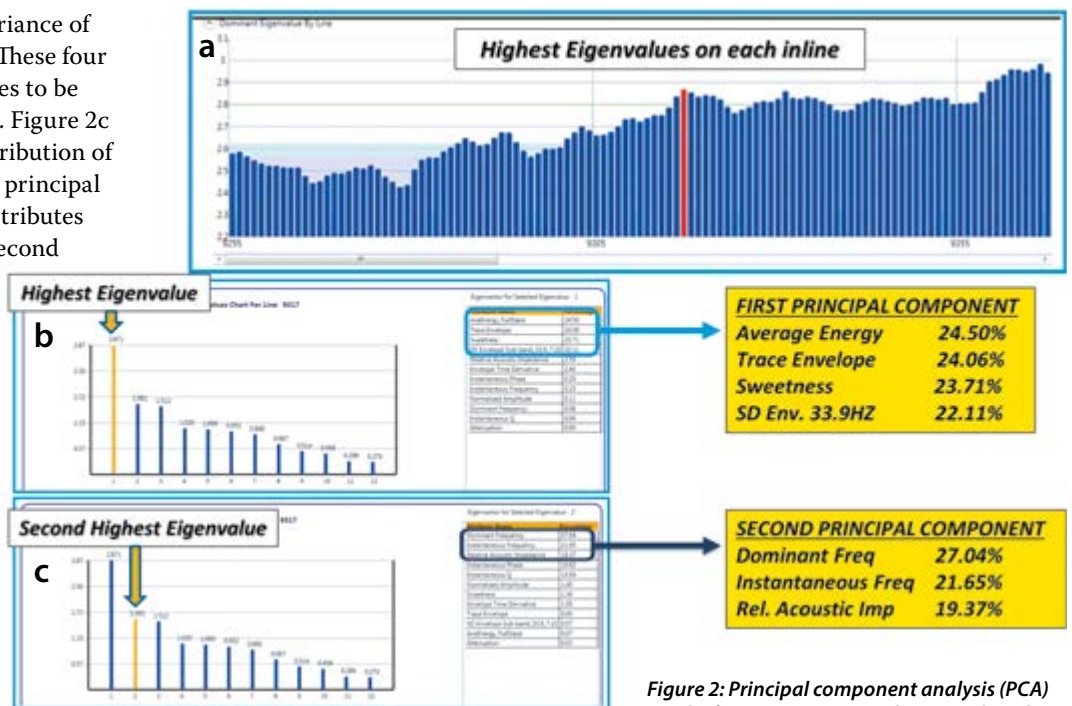


Figure 2: Principal component analysis (PCA) results from 12 seismic attributes: (a) bar chart

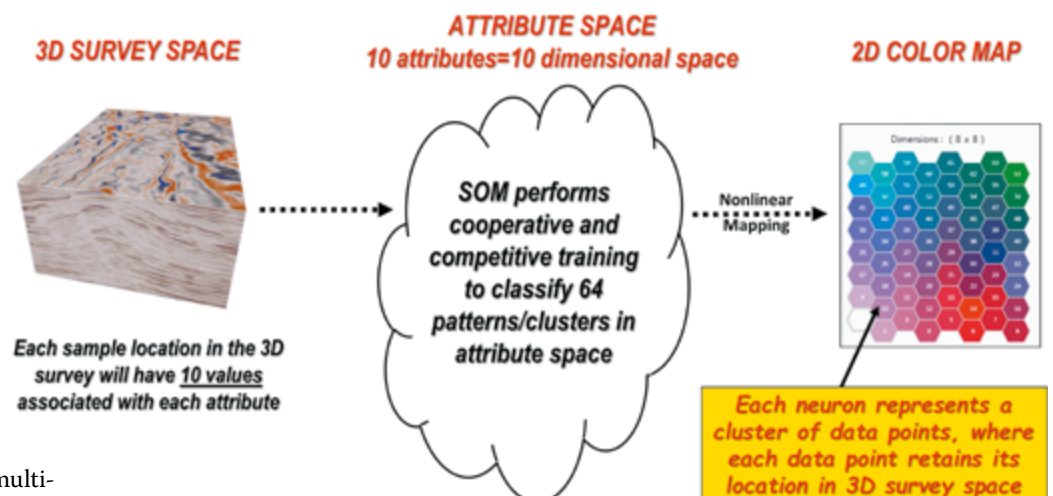
with each bar denoting the highest eigenvalue for its associated inline over the displayed portion of the seismic 3D volume. The red bar designates the inline with the results shown in 2b and c; (b) first principal component designated in orange and associated seismic attribute contributions to the right; and (c) second principal component in orange with the seismic contributions to the right. The highest contributing attributes for each principal component are possible candidates for a SOM analysis, depending on the interpretation goal.

attribute machine-learning methodology. In this case 10 attributes were selected to run in a SOM analysis over a specific 3D survey, which means that 10 volumes of different attributes are input into the process. All the values from every sample from the survey are input into attribute space where the values are normalized or standardized to the same scale. The interpreter selects the number of patterns or clusters to be delineated. In the example in Figure 3, 64 patterns are to be determined and are designated by 64 neurons. After the SOM analysis, the

results are nonlinearly mapped to a 2D color map which shows 64 neurons.

At this point the interpreter evaluates which neurons and associated patterns in 3D space define features of interest. Figure 4 displays the SOM results, where four neurons have highlighted not only a channel system, but details within that channel. The next step is to refine the interpretation and perhaps use different combinations of attributes and/or use different neuron counts. For example, in Figure 4, to better define details in the channel

Figure 3: How SOM works (10 seismic attributes).



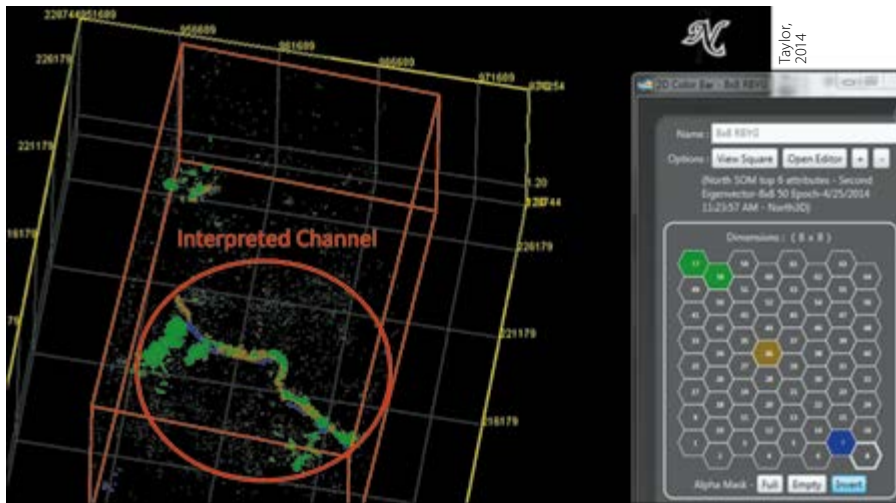


Figure 4: SOM analysis interpretation of channel feature with 2D color map.

system may require increasing the neuron count to 100 or more neurons to produce much more detail. The scale of the geologic feature of interest is related to the number of neurons employed; low neuron counts will reveal larger scale features, whereas a high neuron count defines much more detail.

Workflow Examples

Figure 5 shows the SOM classification from an offshore Class 3 AVO setting where direct hydrocarbon indicators (DHIs) should be prevalent. The four attributes listed for this SOM run were selected from the second principal component in a PCA analysis. This SOM analysis clearly identified flat spots associated with a gas/oil and an oil/water contact. Figure 5 displays a line through the middle of a field where the SOM classification identified these contacts, which were verified by well control. The upper profile indicates that 25 neurons were employed to identify 25 patterns in the data. The lower profile indicates that only two neurons are identifying the patterns associated with the hydrocarbon contacts (flat spots). These hydrocarbon contacts were difficult to interpret with conventional amplitude data.

The profile in Figure 6 displays a SOM classification where the colors represent individual neurons with a wiggle-trace variable area overlay of the conventional amplitude data. This play relates to a series of thin strandline sand deposits. These sands are located in a very weak trough on the conventional amplitude data and essentially have

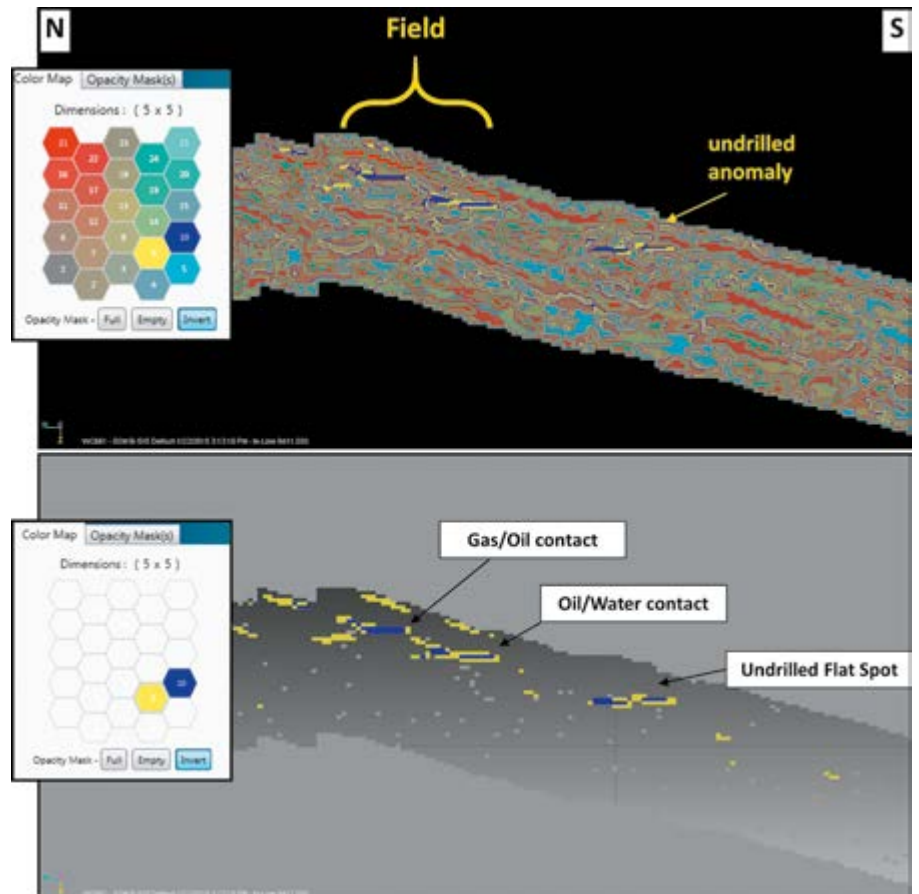
no amplitude expression. The SOM classification employed seven seismic attributes which were determined from the PCA analysis. A 10x10 matrix of neurons or 100 neurons were employed for this SOM classification. The downdip well produced gas from a 6' thick sand that confirmed the anomaly associated with a dark brown neuron from the SOM analysis. The inset

for this sand indicates that the SOM analysis has identified this thin sand down to a single sample size which is 1 ms (5') for this data. The updip well on the profile in Figure 6 shows a thin oil sand (~6' thick) that is associated with a lighter brown neuron with another possible strandline sand slightly downdip. This SOM classification defines very thin beds and employs several instantaneous seismic attributes that are measuring energy in time and space outside the realm of conventional amplitude data.

Geology Defined

The implementation of a multi-attribute machine-learning analysis is not restricted to any geologic environment or setting. SOM classifications have been employed successfully both onshore and offshore, in hard rocks and soft rocks, in shales, sands, and carbonates, and as demonstrated above, for DHIs and thin beds. The major limitations are

Figure 5: SOM results defining hydrocarbon contacts on a seismic line through a field. Attributes chosen for the identification of flat spots were: 1. instantaneous frequency; 2. thin bed indicator; 3. acceleration of phase; 4. dominant frequency.



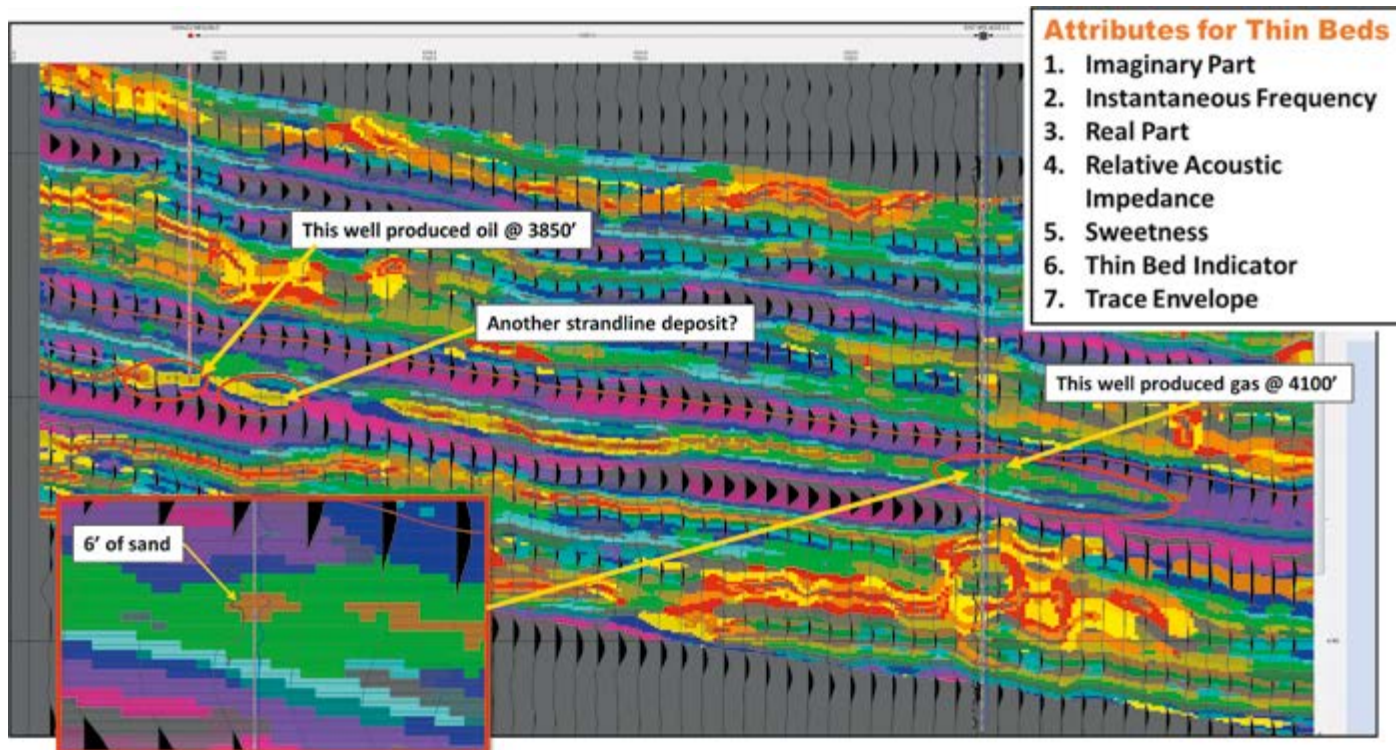


Figure 6: SOM results showing thin beds in a strandline setting.

the seismic attributes selected and their inherent data quality. SOM is a non-linear classifier and takes advantage of finely sampled data and

is not burdened by typical amplitude resolution limitations. This machine-learning seismic interpretation approach has been very successful

in distilling numerous attributes to identify geologic objectives and has provided the interpreter with a methodology to deal with Big Data. ■



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Magnetics for Hydrocarbon Exploration

CHRISTINE FICHLER, NTNU

Column Editors: LASSE AMUNDSEN and MARTIN LANDRØ

How can a tiny mineral called magnetite help to unravel hydrocarbon seepage and subsurface petrology? It's not MAGIC – it's MAGNETICS... in integrated workflows!

Magnetite has the ability to respond to a magnetic field by generating its own field, known as the induced magnetic field. Magnetite is the most important member in the family of magnetic minerals, which are found in varying amounts in crystalline rocks and to a lesser extent in sediments. In oceanic crustal rocks, it is common for magnetic minerals to permanently hold substantial magnetic fields. These remanent fields date back to the moment when the rocks in the hot and just solidified magmas of mid-oceanic ridges cooled through the Curie point (the temperature at which magnetic materials undergo a sharp change in their magnetic properties) and captured and stored the acting magnetic field characteristics. This can be used to unravel the paleomagnetic history of the rocks.

Magnetic Anomalies

We know the direction of the Earth's magnetic field from the compass needle pointing north. The Earth's field looks like that of a magnetic dipole – a huge blueprint of your refrigerator magnet, but which is located in the Earth's core. All rocks on Earth, as well as you and me, are bathed in this magnetic field and respond with induced magnetic fields. But since we do not have much magnetic material in our bodies, the fields of the rocks will dominate.

Geophysics uses a parameter called 'magnetic susceptibility', which expresses the strength of the response of a rock to an imposed magnetic field – an easy alternative to estimating the amount of magnetic minerals in a rock sample. High magnetic susceptibility

Rob Lavinsky/Wikipedia



will give a strong induced magnetic field and vice versa. These induced magnetic fields, together with the remanent magnetic fields, cause very small deviations to the Earth's magnetic field strength, known as magnetic anomalies. They are measured by intricate yet backpack-sized instruments, typically mounted on airplanes for hydrocarbon exploration applications. Onshore and offshore areas are mapped line by line and the results processed to create maps of magnetic anomalies, which present the sum of the induced and remanent magnetic anomalies of every single magnetic mineral in the subsurface; in other words, they reflect the distribution of magnetic susceptibility and remanence.

The Magnetic Choir

In order to understand the recorded anomalies at the surface, imagine that the magnetic minerals form a choir and you are the magnetometer 'listening' to the choir from the front.

You will easily hear the nearest singers, but listening to those further away gets more and more difficult with increasing distance – only if somebody far away is singing very loudly with a megaphone, will you hear them. The shallowest magnetic rocks in the subsurface are nearest to the magnetometer and will as such generate the strongest anomalies and show a lot of details. With increasing depth, the anomalies become smaller in amplitude and lose details, as illustrated in the left part of Figure 1.

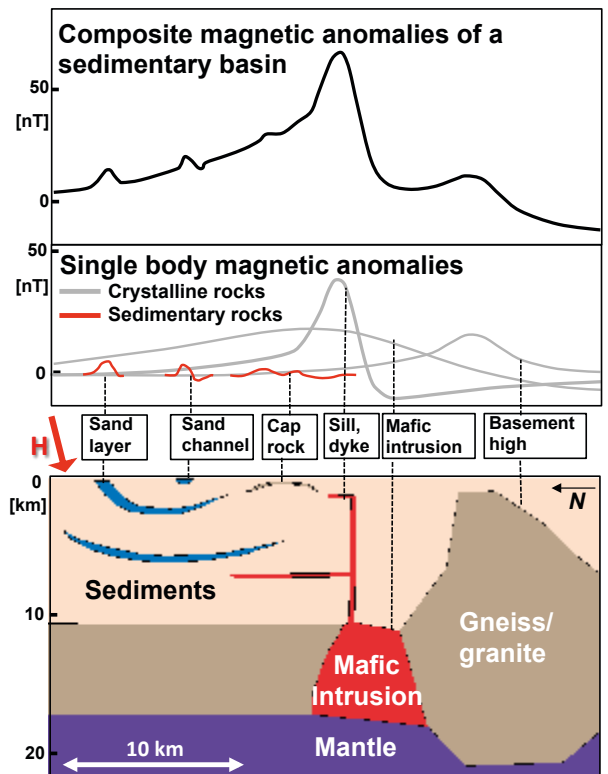
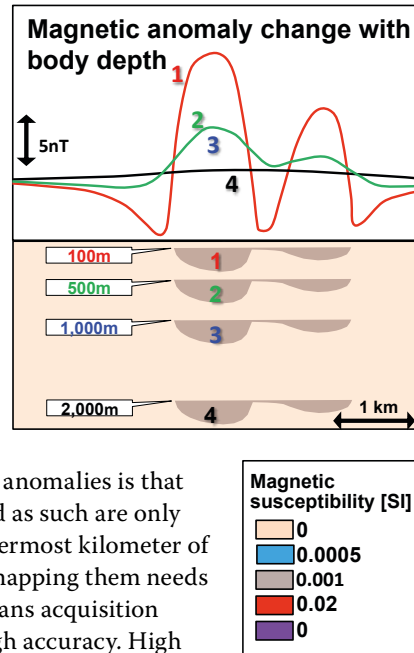
Magnetite from Bolivia. These crystals measure over 1 cm across.

Magnetism, as you recall from physics class, is a powerful force that causes certain items to be attracted to refrigerators.

Dave Barry

Figure 1: (Left) Magnetic anomalies caused by the same body at different depths; (Right) A synthetic section with calculated magnetic anomalies for magnetic rocks typically found in sedimentary basins. The induced Earth magnetic field (H) is typical for the North Sea. (Generated using GEOSOFT GMSYS2D.)

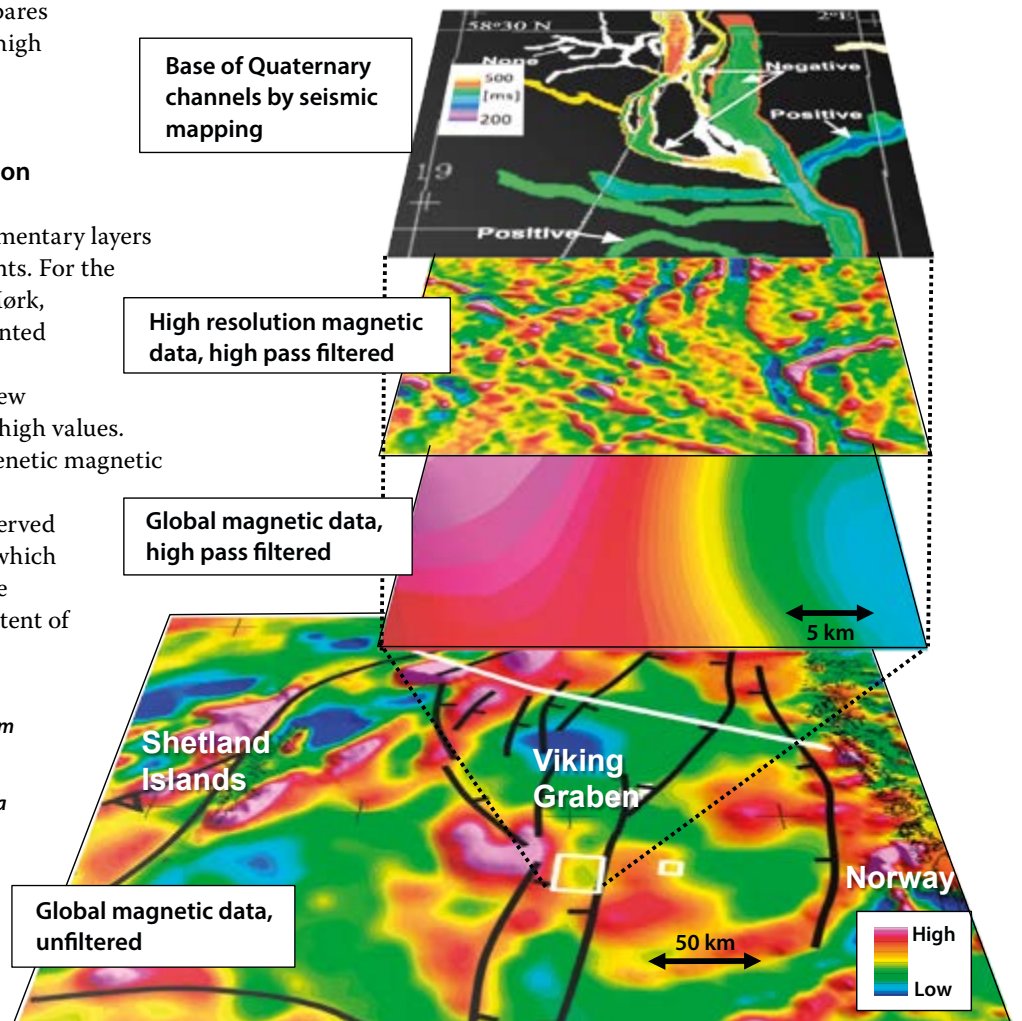
The right-hand image of Figure 1 illustrates magnetic rocks in sediments and crust and their associated magnetic anomalies: in our choir analogy, the large anomalies (grey) from the crystalline rocks are the 'singers with megaphones', while the tiny, small scale anomalies (red) from just a very few structures in the sediments are the 'singers in the front'. The most important thing to understand about sedimentary anomalies is that they are small in amplitude and as such are only detectable if located in the uppermost kilometer of the subsurface. Furthermore, mapping them needs high resolution data, which means acquisition with dense line spacing and high accuracy. High pass filtering of the magnetic data brings out the shallow sedimentary anomalies of short wavelength. This is illustrated in Figure 2, which compares high pass filtered anomalies of both high resolution magnetic data and global magnetic data; note the difference!



Magnetic Anomalies as Hydrocarbon Indicators

Magnetic minerals deposited in sedimentary layers reflect the provenance of the sediments. For the continental shelf offshore Norway, Mørk, McEnroe and Olesen (2002) documented that the magnetic susceptibility and remanence are generally small, and few sands and shales were found to have high values. These workers also showed that diagenetic magnetic mineralization in the form of highly magnetic siderite cementation is observed in some dark shales, a phenomenon which can also be seen at outcrops of source rocks. In Venezuela an increased content of

Figure 2: Upper maps: seismically mapped Quaternary channels and high pass filtered, high-resolution magnetic data (modified from Fichler, Henriksen, Rueslåtten and Hovland, 2005; magnetic data: VGVG/TGS-Nopec, 1995). Lowermost map: global magnetic data (EMAG2; www.geomag.org, 2009) of the northern North Sea; the area marked by the larger white box is filtered in the same way as the high resolution data and shown in the second lowest map. The smaller box marks the area shown in Figure 4 and the white line shows the location of the profile in Figure 5.



magnetic minerals was found in cap rocks of oil-filled reservoirs by Perez-Perez, Onofrio, Bosch and Zapata (2011). These and other effects may cause small magnetic anomalies and it has been suggested that they form indirect hydrocarbon indicators; many case histories can be found if you dig into the literature.

However, the big problem is the inherent ambiguity in the interpretation. Small magnetic anomalies are caused by many shallow sources, not just by chemical changes due to hydrocarbons. Common sources are depositional and erosional patterns, sills and dykes, hydrothermal systems and, looking at onshore environments, the tropical weathering product called laterite. How can you tell the difference? The only way forward is through integrating magnetic anomaly interpretation with other data.

Let's look at some examples from the North Sea where combining the interpretation of magnetic and 3D seismic data could explain some of the shallow anomalies. One distinct group of sedimentary magnetic anomalies is related to melt-water channels which are eroded and filled

Figure 4: Depression on seismic section correlating with a circular magnetic anomaly; interpreted as gas hydrate expulsion crater filled with magnetic glaciogenic sediments (modified from Fichler, Henriksen, Rueslåtten & Hovland, 2005); for location see Figure 2. Black line indicates line of section.

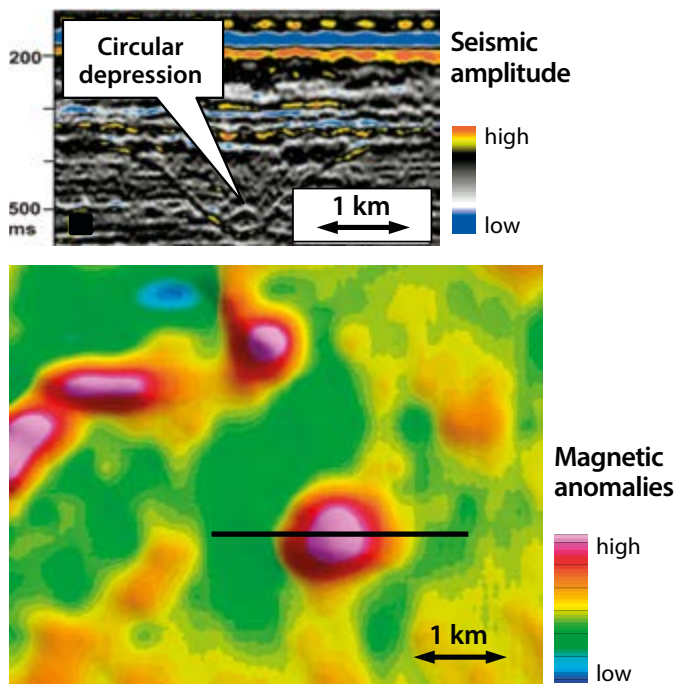


Figure 3: Gas blowout crater in the Russian Arctic.

by glaciogenic sediments due to repeated glaciations and deglaciations in the Pleistocene. The resulting spaghetti pattern of cross-cutting channels is shown in Figure 2. Some channels generate positive anomalies, others negative ones as a consequence of the susceptibility contrast between infill and host rock, which can vary between negative, zero or positive. These channeled sands may form a reservoir rock, as proven by the small, shallow discovery, Peon, in the northern North Sea.

Magnetic anomalies have yet further relevance in the search for hydrocarbons. If hydrocarbon gas seeped into the permafrost during the Pleistocene glaciation periods, gas hydrates will have been precipitated and, in the next warm period, would melt and be released. The melting of gas hydrates below tight cap rocks is known to create blowout craters, as spectacularly observed in the Russian Arctic (Figure 3), and if such a crater is later filled with magnetic sediments, the result is a magnetic anomaly. This rather special hydrocarbon seepage indicator is illustrated in Figure 4, showing a circular magnetic anomaly from the eastern shoulder of the Viking Graben.

Basement Anomalies

Let's now look at the 'singers with the megaphone' – the crystalline basement with wide and large magnetic anomalies as introduced in Figure 1. Crustal magnetic anomalies rarely mimic the topography of the top basement, whereas gravity anomalies often do. There are several reasons for this. The magnetic susceptibility of crustal rocks varies between 10^{-4} and 10^{-1} SI units, i.e., by a factor of 1,000, whereas crustal densities just vary between 2.5 and 3.4 g/cm³, meaning that large magnetic anomalies can be generated by deep as well as by shallow rock units. An example is the deep mafic intrusion

in Figure 1, which gives almost the same magnetic amplitude as the shallow basement high. However, the anomaly of the intrusion has a larger wavelength than the basement high. Such differences in shape can be used to find the depth to the top of the structure by various manual or automatic methods.

Another factor affecting induced magnetic anomalies is related to the change of the Earth's magnetic field direction, from vertical at the poles to horizontal at the equator. This explains why a magnetic body at fixed depth generates different anomaly shapes depending on its location, with a maximum anomaly over its center at the poles, a minimum at the equator, and in between a combination of maximum and minimum. The North Sea shows near-polar characteristics.

Integrating Data

The final example shows the workflow for crustal rock classification through the integration of different geophysical data. A deep seismic depth section along a 300 km-long transect crossing the northern North Sea was loaded into a gravity and magnetic modeling program. The subsurface was divided into polygons, each representing a different rock type. The divisions reflect the boundaries within sediments and crust as defined by the seismic data. Each polygon was assigned a magnetic susceptibility and density. Well data provided sedimentary densities and magnetic susceptibilities as well as the depth to the top crystalline basement, the latter found to consist of mainly granitic rocks. In the initial model, the parameters for granites were used for the entire

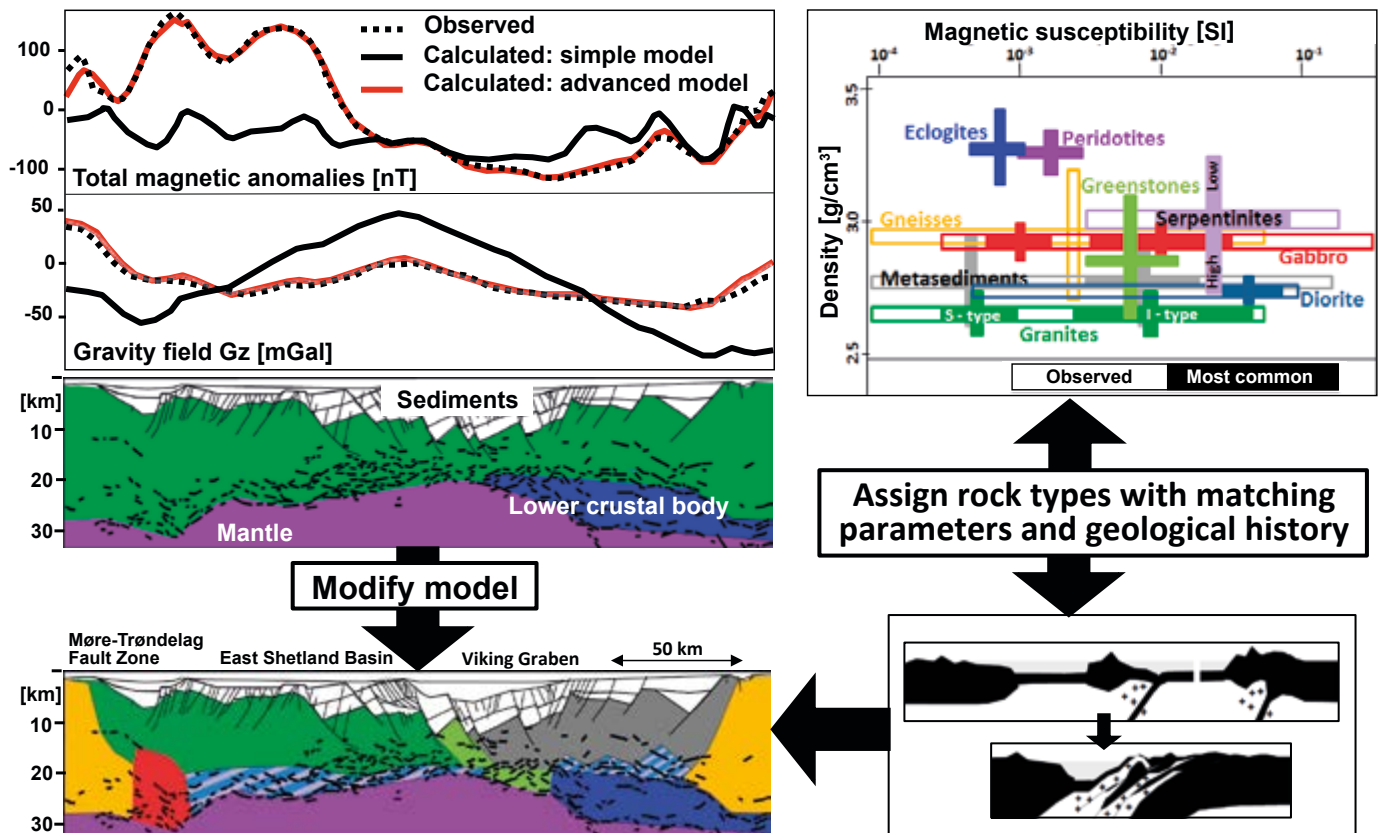
crust. The mantle was assigned peridotite parameters and the high velocity body in the lower crust was given eclogite parameters.

The calculated gravity and magnetic anomalies of this simple model showed a large mismatch, especially in the long wave length-range, indicating a need for modification in the deep parts of the crust. The gravity and magnetic anomalies governed the crustal modification, which resulted in a model of more complex density and susceptibility distributions. The final model matches observed gravity and magnetic anomalies as well as rock types considered geologically reasonable with respect to the geological history. Modeling in general carries an inherent uncertainty and the interpreter should therefore include alternative models where feasible.

You can apply this workflow to detect granitic rocks, known for their high radiogenic heat production which influences hydrocarbon maturation (Hokstad, Tasarova, Kyrkjebø, Fichler, Wiik and Duffaut, 2016), or to map the boundary between oceanic and continental crust. Furthermore, detection of intrusives, which have brought hot magma into crust or sediments, may also be of importance for unraveling the thermal history of a sedimentary basin.

Summing up, magnetic data contributes to hydrocarbon exploration on a broad scale and in mainly integrated geophysical interpretation tasks. It can address problems from the deep crust to the shallowest sedimentary strata. Magnetic data on a large scale is globally available at low cost or even free. High resolution data is more expensive, but is still only a fraction of the cost of a seismic survey. ■

Figure 5: Magnetic susceptibilities (Clark, 1999) cross-plotted against densities (Hinze, Frese and Saad, 2013); location of profile see Figure 2. (Modified from Fichler, Odinsen, Rueslåtten, Olesen, Vindstad and Wienecke, 2011.)



The Geochemist's Tool Box

The conjugate petroleum systems of the North Atlantic, finding hydrocarbons and developing the assets – all viewed through the oil-stained spectacles of geochemistry.

PATRICK BARNARD, IAN CUTLER and HELEN KERR, APT

The North Atlantic region has seen some phenomenal success over the last 60 years with first the hydrocarbon discoveries in the North Sea and then in Mid Norway and the West of Shetland regions. On the North American side the Jeanne d'Arc Basin has seen major discoveries and further north-east the Flemish Pass region has yielded good ones, as has to a lesser extent the Scotian Shelf. However, in the conjugate margin basins in Ireland (Porcupine Basin), the margins of Rockall, and further south in Brittany, offshore Aquitaine, Cantabria and Lusitania, exploration has been much less successful (Figure 1).

So what are we to make of the basins that have failed to date to yield commercial hydrocarbon discoveries?

One of the key questions is do we actually have working petroleum systems in these basins? We regularly read in the press about a well apparently having discovered hydrocarbons in a new basin or sub basin or play and claims made that this proves there is a 'working petroleum system'. Sometimes it is accompanied by encouraging flowed hydrocarbons as DST or MDT fluids that can be physically seen in a bottle on your desk. Great stuff. Sometimes the evidence is a little less certain. In any case, whether shows or flowed liquids, how can we be certain it has shed real light on what is going on in the deep subsurface? What does this 'working petroleum system' claim actually mean and how can we use this to develop our exploration concepts?

The Geochemist's Perspective

As geochemists we know that hydrocarbons are highly mobile in the subsurface and that while we rely on the geologists and geophysicists to find the 'bumps' that we drill, the actual source of these hydrocarbons and shows are much deeper in the basin in the so-called 'kitchen' zone. This region is rarely explored as it is often below viable depths and where exploration targets are difficult to identify.

In well records we commonly find hydrocarbon shows recognized either in the primary or secondary target horizons but log interpretation suggested there was insufficient potential or the mud loggers determined there was not enough reason to test. Sometimes this is a time constraint on expensive rig time or perhaps

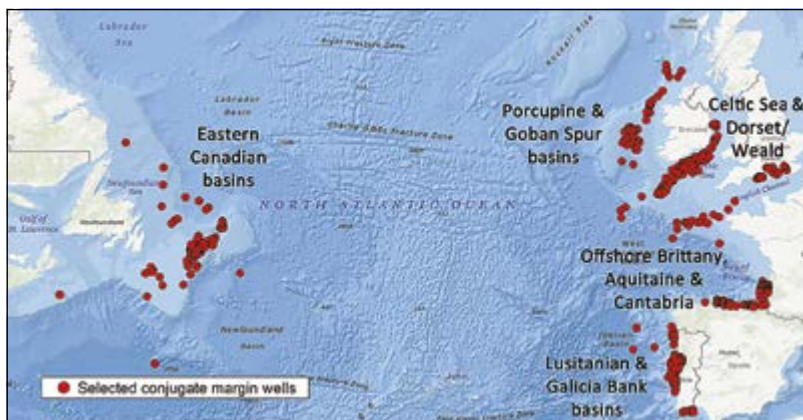


Figure 1: North Atlantic margin study area showing distribution of exploration wells.

the shows were not even in the target horizon and there were no contingency plans to evaluate them. At the time the operator and partners probably decided to cut their losses and P&A the well or even relinquish the license.

The evidence of shows in the wells, even where no further tests are undertaken, is proof of what is going on in the deep subsurface. So how can we determine if the reported oil shows are really a demonstration of a working petroleum system? Well, geochemists with their petroleum system hats on have various methods and means at their disposal to establish the facts.

Comparing Flowed and Proxy Oils

Shows may be visible oil stain in core or cuttings (Figure 2), cut or fluorescence recorded at the rig site or elevated gas readings on the rig site chromatograph. Sometimes a lab may have been commissioned by the operator to do some basic work on the shows. However, what is often missing is a systematic, quality controlled dataset on the hydrocarbon evidence from the basin.

In a frontier exploration area, where huge investment effort is to be made, unified evidence for the character and age of the source of the hydrocarbons is required. The ability to extract shows from rocks (proxy oils) is a key process which allows detailed characterization of the hydrocarbons. Such analyses allow us to determine information on the type of organic matter in the source rock, its depositional environment, probable age, the temperature at which it was generated and any

Figure 2: Wet cuttings through an oil-stained reservoir (note increase then decrease in color corresponding to oil concentration).



processes of alteration the hydrocarbons may have experienced since generation, whether during migration or after entrapment.

The analytical sequence begins with quantitative solvent extraction of the rock as core, washed or unwashed cuttings or even the whole wet cuttings. If the show is validated a solvent extract is obtained that can be quantified in terms of the amount of hydrocarbon recovered and a qualitative gas chromatographic (GC) analysis of the extract. For example, we can readily demonstrate that the whole extract GC of a 'proxy' oil is highly similar to the whole oil GC of a tested zone (Figure 3) for a core from a proven oil field in the West of Shetland Basin. We can take this process of evaluation of the show much further by examining the high resolution biomarkers and the important bulk properties of the oil and the carbon isotopes of the extract or its fractions. In making this leap from a flowed to a proxy oil we need to be certain that what we are extracting is truly representative of the flowed sample. APT has established the close correlation of the parameters for core and cuttings extracts compared to the flowed liquids through extensive comparisons, a process validated by the PCA analysis of the biomarker data for a number of samples (Figure 4).

Conjugate North Atlantic Petroleum Systems

In the case of the North Atlantic it is not enough to simply identify the presence of shows. The conjugate margins of the region have a complex rift-drift morphology and paleogeographic evolution with multiple potential source horizons. We need to know the geochemical character of the shows and what the data tell us about variations in source rock type and depositional conditions across the complex margins, so explorationists can better understand the petroleum systems they are dealing with and thus reduce exploration risk.

To address the questions raised by the complexity of the conjugate margin and in an effort to provide tangible data

Figure 4: Statistical comparison of data from flowed and proxy oils.

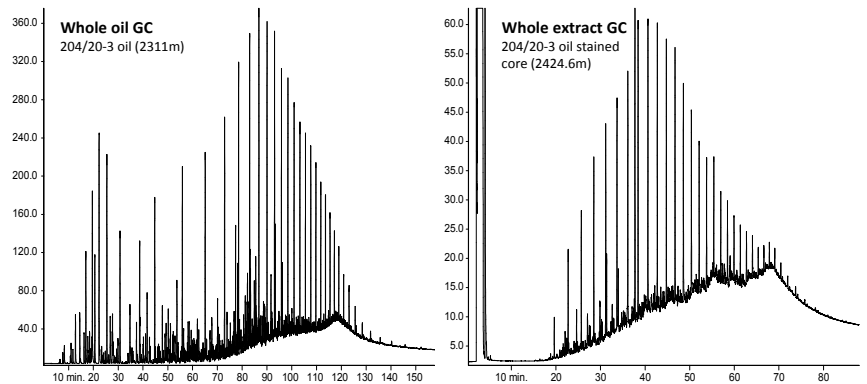
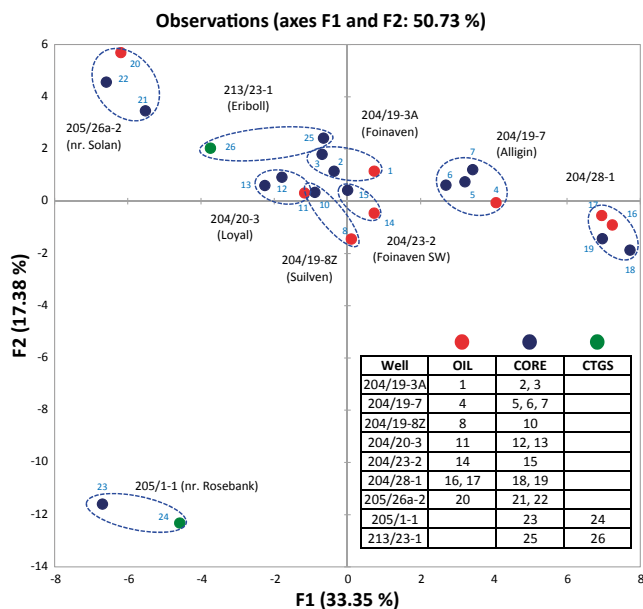
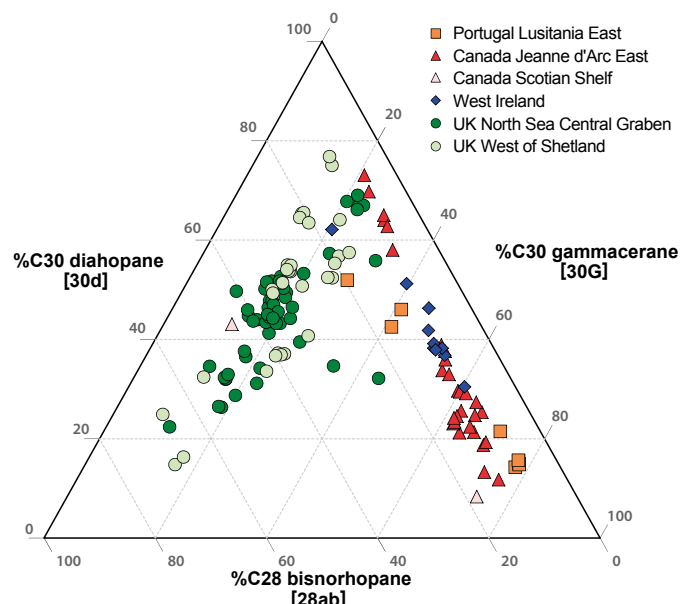


Figure 3: Comparison of flowed and proxy oils from a West of Shetland well.

points to constrain plate reconstructions and play fairway generation, APT UK have completed a major new analytical work program. The objective has been to investigate the isotopes and biomarkers of source rocks and oils across the region, using new analyses of 102 oil samples from 90 wells from the Jeanne d'Arc, Flemish Pass and Orphan Basins on the Canadian side to the West of Shetland region, through the Porcupine, Celtic Sea, Wessex, Aquitaine, Galician and down to the Lusitanian Basin. Critically, this major new data set is augmented by the addition of new analyses on a further 288 samples of 'proxy oils' in 116 wells obtained through solvent extraction, as described above.

Surprising differences in the source rock character have been revealed. Quite apart from the variation in maturity of the sources, related to the temperature at the time of generation, there are big differences in source input markers. Figure 5 compares the relative abundance of three important source dependant biomarkers, each of which has significance. Gammacerane, for instance, is a marker for varying salinity in the water column while bisnorhopane is thought to be related to the intensity of bacterial activity in the sediment – it is present in particularly high abundances in the North Sea and West of Shetland Basins but present in very low abundance in the Porcupine and other basins to the south. It can be clearly

Figure 5: Relative abundances of three source dependent biomarkers.



demonstrated in this ternary plot that the extracts from these different basins have strikingly different geochemical fingerprints reflecting major differences between the basins – but what is driving this?

We believe these observed characteristics relate to major differences in sea water chemistry, organic input and most importantly differences in the water masses between the boreally influenced northern waters (West of Shetland and the North Sea) and the Tethyan influences in the basins further south (Eastern Canada, Lusitania and the Porcupine Basin).

Fluid Quality Prediction and Field Density Mapping

Having established the source and post-generative history of the observed hydrocarbons, can geochemistry help in the development of these discoveries?

Knowing the gravity, density and viscosity of the accumulation is key to effective production. The proxy oil approach can also be of value to the development of the resources found. Proxy oils extracted from cuttings are ideally suited to make predictions about the type of oil encountered without having to acquire a physical sample for PVT and assay. This can be particularly helpful where the oils are degraded by bacterial activity as it becomes possible to determine the probable density (API gravity) and viscosity, key parameters to assess in development (Figure 6).

This approach has been used in many projects where core or cuttings from legacy wells have been utilized. It is to be noted that having access to high quality laboratory procedures enables us to establish a positive relationship between the measured gravity of flowed oils and proxy oils extracted from core or cuttings.

This method has also been employed in projects where oil in large, apparently pressure-related fields can be shown to be varying in quality because of the lack of sufficient time for diffusive mixing to homogenize the field charge. Figure 7 illustrates the results obtained using this approach in a large, low amplitude structure within a relatively low permeability carbonate reservoir. The results have been obtained using oil extracted from unwashed wet cuttings taken from long lateral wells and the density calculated using the bulk composition

Figure 7: Example distribution map of predicted API gravities across an oil field.

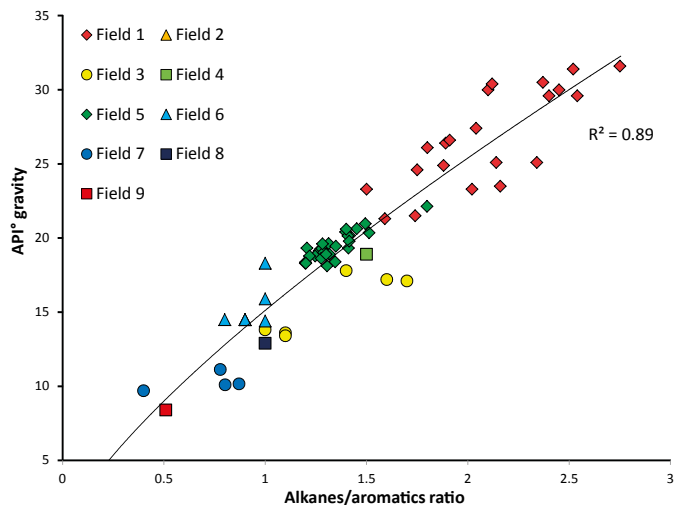
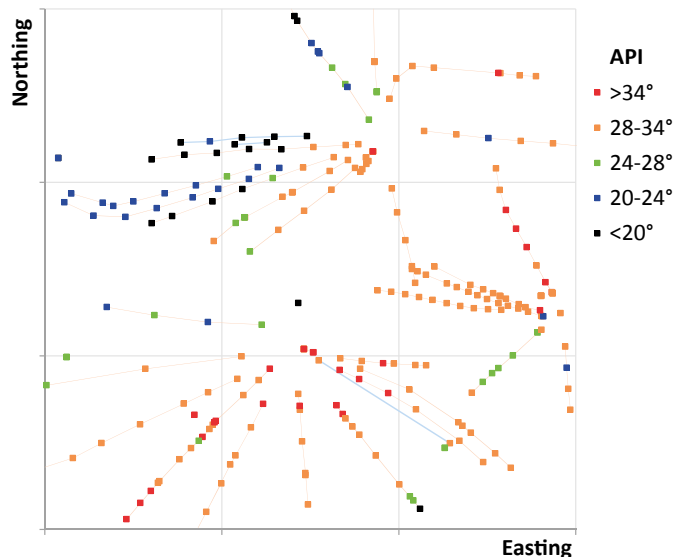


Figure 6: Correlation of API gravity with alkanes/aromatics ratios of flowed oils.

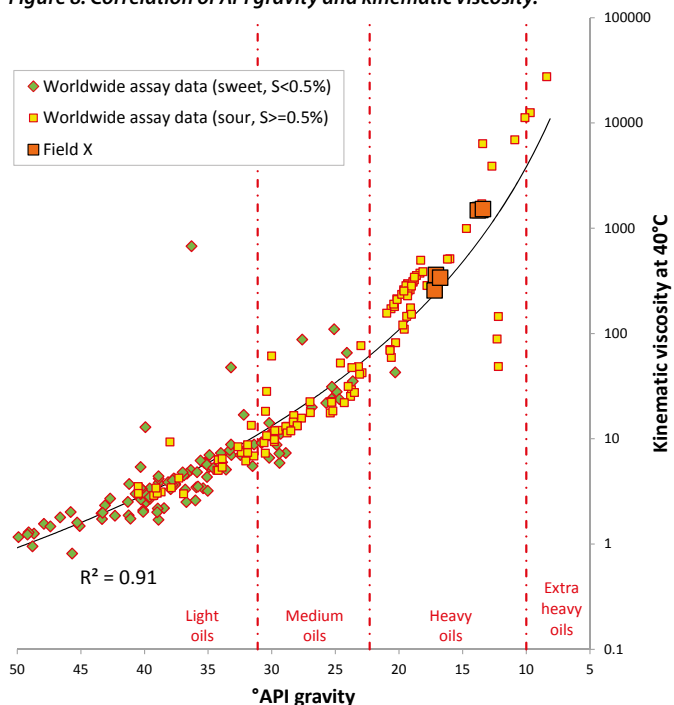
calibrated to the results from flowed oil samples.

These approaches can be taken even further where understanding how not just gravity but estimation of the often more important viscosity parameter is required. In these cases a range of parameters has been cross-correlated so that gravity and viscosity can be determined independently using high resolution biomarker analysis data (Figure 8).

Concluding Thoughts

The various tools available to a geochemist, particularly when integrated with basin modeling and geological analysis, can provide significant insights to multiple aspects of a petroleum system. The forensic investigation and analysis of shows provide a valuable and highly cost-effective set of observations that enable both constraint of established exploration models of the subsurface and perhaps the spark for the creation of new models and ideas which drive value creation in petroleum exploration. ■

Figure 8: Correlation of API gravity and kinematic viscosity.



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Hiding in the Basement

Basement reservoirs are recognized throughout the world as being oil-bearing and commercially productive, yet remain largely overlooked. Hurricane Energy's Robert Trice believes these rocks represent a huge, underdeveloped play for the UK and that the imaginative use of the plentiful available data could unlock the country's basement resource potential.

JANE WHALEY

"I first became interested in the potential of basement as a reservoir when I was working for Enterprise Oil in the 1990s," explains Dr. Robert Trice, CEO of Hurricane Energy, a company dedicated to identifying and exploiting such reservoirs. "We were drilling a well in Vietnam, investigating a typical clastic reservoir, when we decided to deepen the well to evaluate the basement – and it was oil-bearing. This sparked my interest and I began researching the subject of fractured basement reservoirs. The Vietnam story was fascinating, as in recent years the country's reserves have doubled, all due to fractured basement fields. The original discoveries in Vietnam were made by accident, and it took several years before the play was taken seriously.

"Could the same be true for the UKCS, I wondered? I believe it could. There have been several serendipitous

North Sea basement discoveries, including Cairngorm and Emerald and, of course, the West of Shetland giant field, Clair. However, the majority of companies stopped drilling as soon as basement was encountered. I did some research and decided there was considerable potential for exploration in fractured basement in the UKCS."

Untapped Resource

With a belief in this untapped and promising resource, Robert and a small staff of experts set up Hurricane in 2005. "Our aim was to seek out the right geological conditions in proven petroleum basins that will allow basement reservoirs to work, looking particularly for areas where previous drilling results indicated the presence of hydrocarbons in the basement but which were never followed up," he explains. "The relatively unexplored but prospective UKCS West of Shetland

area fits this description perfectly.

"The West of Shetland Basin has proven its petroleum potential, with the Clair, Foinaven and Schiehallion oil fields already in production. It also contains an estimated 17% of the UK's remaining hydrocarbon reserves. At Hurricane, we believe that the area remains underexplored for oil, and that new exploration concepts are required to unlock its remaining potential," he continues. "The Lewisian Basement, which is between 2.3 and 3.2 billion years old and composed predominantly of fractured, crystalline gneiss, forms extensive ridges and localized highs. These are charged by the prolific Kimmeridge Clay – the same rock which sourced much of the oil in the North Sea.

"Over the past eleven years we have tested this hypothesis and have outlined a number of prospects, drilled seven wells, and, most importantly,

This well-jointed granite on the Scottish Isle of Lewis provides a good analog for the fractured basement reservoirs in the West of Shetland Basin.



What are Basement Reservoirs?

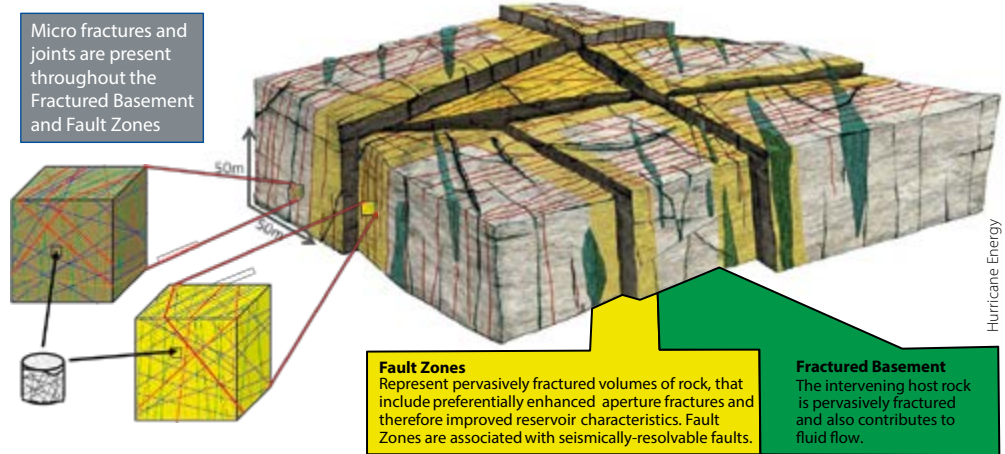
What is a fractured basement reservoir? According to Robert Trice, it is “a metamorphic or igneous rock in which geological processes have resulted in the creation of a hydrodynamic fracture network.”

The classic definition of basement is any metamorphic or igneous rock (regardless of age) which is unconformably overlain by a sedimentary sequence. According to Lands et al. (1960), “the only major difference between basement rock and the overlying sedimentary rock oil deposits is that in the former case the original oil-yielding formation (source rock) cannot underlie the reservoir”. It is important to note that in a basement reservoir the hydrocarbons are not held in pore space but instead are found within an extensive fracture network.

Basement reservoirs are variable and can be complex, both lithologically and structurally. Globally, however, basement reservoirs exhibit similar features that can be used as an ‘exploration template’ to aid in predicting their distribution and characteristics. They are typically very hard and brittle, and when subjected to initial cooling or tectonic activity, they

crack, forming an extensive faults and fracture network. They are also subject to modification due to processes like weathering and hydrothermal alteration. Basement reservoirs can be associated with either buried hill, fault block or hybrid structural trapping mechanisms and can be found in both compressional and extensional tectonic settings.

Fractured basement conceptual model.



validated our model for basement exploration. We have made two discoveries in the West of Shetland area and identified three further promising prospects for drilling, and as a result have 450 MMB of 2C contingent oil resources on our acreage, and we believe there is plenty more out there.”

How Does the Oil Get There?

By definition, basement rocks cannot overlie younger sedimentary source rocks, and so hydrocarbons will not have migrated directly upwards into them, as occurs in a classic petroleum system. However, in areas where basement has been uplifted so that it is adjacent to a deep source, a migration pathway can exist either through the basement itself or through a carrier bed that connects the source rock to the basement. An alternative migration route could be from a source rock that is draped over the basement high, allowing hydrocarbons to be expelled directly into the basement underneath.

“In the West of Shetland Basin, the basement plays we are chasing are all in

granitic rocks. The fracture networks develop from joint systems that exist as a result of the initial cooling of the granite. Subsequent tectonic events, which in the case of Lancaster include vertical uplift by as much as a kilometer, enhance the fracture network through the formation of ridges and domes,” Robert explains. “This movement importantly occurred during a key phase of hydrocarbon

migration, meaning that as the fractures were opening, hydrocarbons were being emplaced.

“One of the great attractions of fractured basement reservoirs is that they can be considered to be stratigraphic traps, in that oil can be found outside of structural closure, which can lead to extensive flank oil accumulations. This has been

Oil has been produced from fractured basement reservoirs for decades. In 1948 it was estimated that 1.5% of total Californian production came from this play (Eggleston, 1948), while in China the Yaerxia oil field, which produces from hard phyllite, slate and meta-sandstone basement rocks, was discovered in 1959. Oil was first found in basement in Siberia in the same year.

● Confirmed productive basement reservoirs.



Exploration

demonstrated in basement discoveries in Yemen, and the potential also exists for the same to occur on Hurricane's Typhoon Prospect.

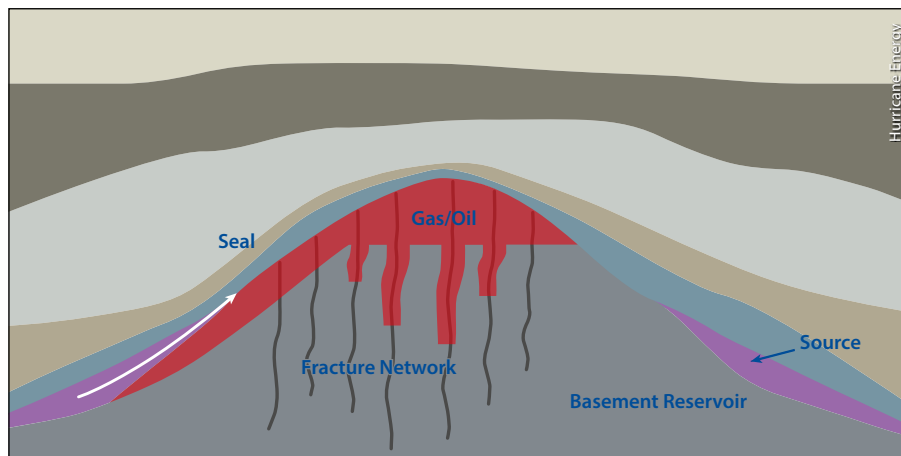
Exploring Basement Reservoirs

Although basement rocks are complex, the process and workflow involved in exploring for hydrocarbons in them is not greatly different from that applied to reservoirs with intergranular porosity, Robert believes. "It is important to gather and analyze a wide range of data, in particular to assess if an effective fracture system is present," he says. "By integrating a variety of technical information using off the shelf technology and proprietary techniques, the exploration potential of the basement can be comprehensively evaluated, geological risk minimized, and prospective well locations identified."

The most important recent technological development to assist in exploring basement reservoirs is probably the advent of 3D seismic data, which has allowed for effective imaging of fault networks. 3D seismic, combined with horizontal drilling and advances in both wireline and LWD imaging technology, has enabled fracture sweet spots to be targeted and effectively quantified by exploration and development wells.

"At the pre-drill stage, the detailed analysis of seismic data combined with 3D geological modeling is of particular importance in determining how fractured a basement reservoir target is likely to be," Robert continues. "The use of data obtained by previous licence holders can be crucial, especially 3D seismic, well data and cores, and we are fortunate to have a lot of that vital information for our assets, with many of the old wells drilled on our acreage having found indications of oil in the basement. Cores are useful as they provide definitive evidence of hydrocarbon presence as well as an insight into the basement lithology.

"Once drilling for oil is underway, we use a range of specific data-gathering techniques at the wellsite to enable the reservoir to be fully evaluated and explored. This includes the analysis of oil and gas through advanced gas



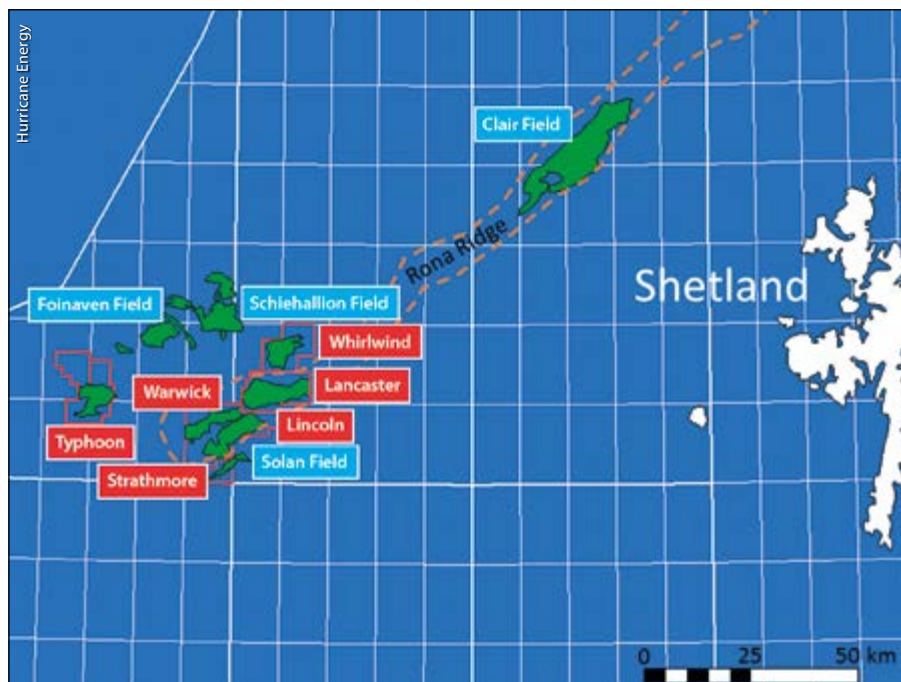
Stratigraphically trapped oil in the flanks of basement structures is a potential exploration target where basement is proximal to the source rock. An example of this is Hurricane's Typhoon Prospect, which has unrisked P50 prospective resources of 149 MMboe.

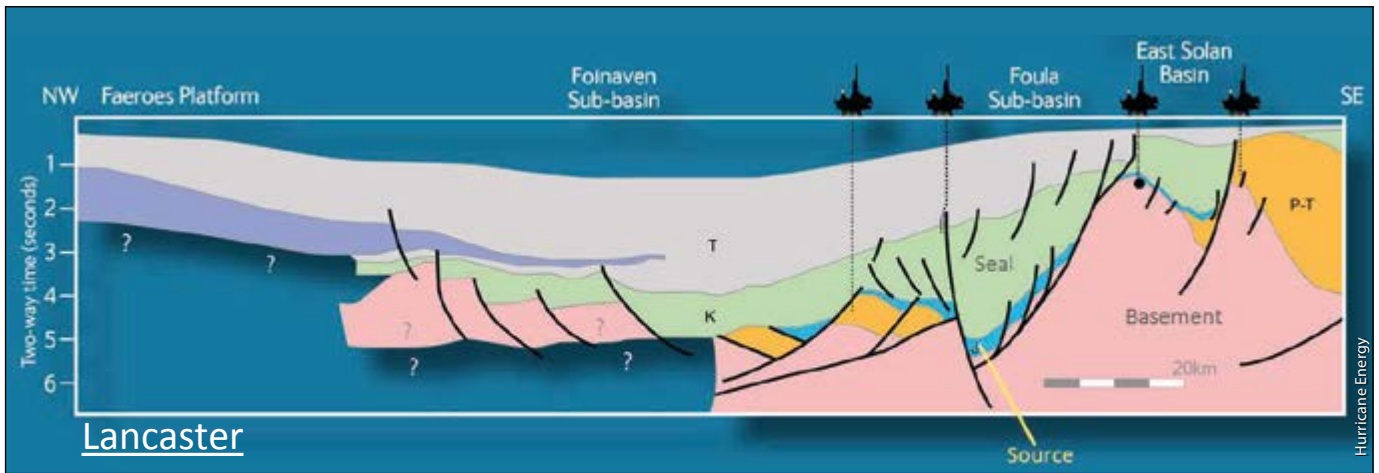
chromatography, as well as high resolution imaging acquired through the process of logging while drilling. Post drilling, we have utilized a range of wireline techniques including borehole image logs, sidewall cores and formation pressure and fluid sampling. A key factor in evaluating basement reservoirs is the determination of how well the hydrodynamic fracture network is connected, so we undertake well testing at the end of the drilling program. Obtaining production logging tool information and sufficient test data to carry out pressure transient analysis is key in detailing the effectiveness of the fracture network."

Prospects West of Shetland

The 1977 Clair Field discovery wells were the first to identify significant quantities of oil in fractured basement in the West of Shetland area, but subsequent tests were disappointing. The field is on production, mainly from the overlying Devonian, although there may be connectivity to the basement beneath. Clair lies on the Rona Ridge about 50 to 75 km north-east of and on-trend with Hurricane's assets. Basement oil at Clair together with oil shows elsewhere along the Rona Ridge provided plenty of evidence of oil presence and migration into the basement for Hurricane to investigate further.

West of Shetlands area map showing previously discovered fields (blue) and Hurricane assets (red).





Geological sketch section through the Lancaster discovery.

“The first prospect we drilled, in 2009, was Lancaster, where we had identified a four-way dip structural closure creating a conventional trapping mechanism,” says Robert. “We have now drilled five wells on the prospect and they have all identified oil within the structural closure. We also have oil well below the structural closure; our 2016 inclined well demonstrated that the Lancaster structure has an oil column height of some 670m. Our initial assessment of the 2016 well results suggest that the Lancaster Field reserves are likely to be significantly greater than 200 MMbo, our published 2C numbers. The second stage of our 2016 operations involved drilling a horizontal well, designed as a second future production well and also to provide additional information to help optimally plan field development. Early test results from this well have produced 14,500 bopd, which gives the company a great deal of encouragement.

“Our second basement discovery was Whirlwind, a large structure approximately 2,000m deeper than Lancaster, although charged from the same source. Initially drilled in 2010, the well flowed light oil/gas-condensate from an open hole test conducted over Lower Cretaceous limestones and underlying fractured

basement, although it was not possible to determine precisely which intervals were flowing hydrocarbons. 2C contingent resources of 205 MMboe (oil case) or 179 MMboe (gas-condensate case) have been assigned to Whirlwind.”

Just Use Imagination

“We have another two promising prospects to drill on the Rona Ridge – Warwick and Lincoln, both geologically similar to Lancaster – plus a number of other exciting prospects to follow up,” he continues. “For the moment, working on those and getting Lancaster into production will keep us busy. However, there are interesting

areas to investigate further south on the Rockall Ridge, which traverses both UKCS and Irish waters, and in the North Sea – and plenty more potentially prospective basement regions to consider beyond the UKCS.

“Basement plays offer massive potential throughout the world. They are considered by some to be more difficult and expensive to evaluate than clastic reservoirs, but I don’t agree. All that is restricting their exploration and exploitation is the procurement of good quality data – and imagination!” Robert concludes.

See online for references ■

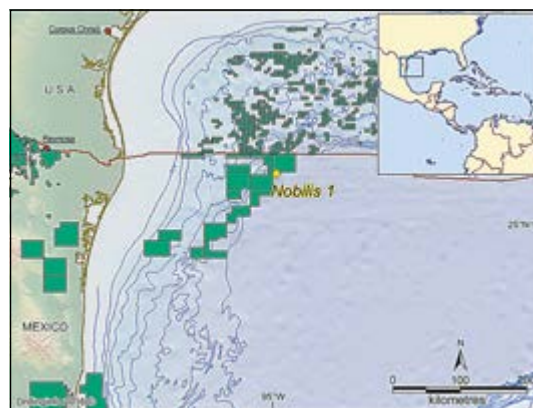
Dr. Trice during Spitsbergen operations. A senior manager is always on the rig drilling Hurricane’s wells during critical data-gathering phases.



Mexico: Thick Oil Column in Perdido Fold Belt

In September 2016 **Pemex** provided new data about the production potential of its exciting **Nobilis 1** new field wildcat in the AE-0077-Cinturon Plegado Perdido-03 contract, in the **Perdido Fold Belt**, located 220 km off the coast of the north-eastern state of Tamaulipas and close to the border with the US. The company announced that the well has the potential to produce 15,000 bopd, having previously reported that during tests the well produced 16,899 bopd and 27.7 MMcfcpd. It also noted that the well had encountered the greatest oil column thickness so far identified in this area.

Nobilis 1, drilled in water depths of around 3,100m, reached a TD of 6,115m in early May 2016. The well is believed to have discovered between 140 and 160 MMbo and was reported to have cost nearly US\$ 153 million. ■



Iraq: Two Important Wells

On 12 October 2016, **DNO** reported that it had spudded the **Peshkabir 2** appraisal well on the Zagros Foldbelt Basin **Tawke** block in the **Kurdistan Region of Iraq** in early October 2016. It is expected to be completed by the end of the year and, if successful, the Peshkabir field can be quickly brought on production using existing infrastructure.

The high-impact well has been located to appraise the Jurassic discovery up-dip from the Peshkabir 1 well location on the western part of the Tawke PSC area, in addition to testing additional prospectivity in the Cretaceous. This structure is a high-amplitude anticline, which forms a mountain range at the surface, with shallow layers outcropping to the surface on the flanks of the structure. Having already submitted a Notice of Discovery and Declaration of Commerciality to the Kurdistan Regional Government (KRG), it is understood that DNO submitted a Field Development Plan for the Peshkabir 1 oil discovery in October 2013. Designed to target a large undrilled feature to the west of the Tawke Field, Peshkabir 1 reached a final TD of 4,092m in April 2012 and encountered oil shows in Cretaceous, Jurassic and Triassic intervals. Six zones were tested, with the Jurassic Sargelu Formation flowing API 27-29° oil and water at varying rates of oil and water cut, while the remaining five zones (Triassic Kurra Chine 'A' and 'B' intervals and Cretaceous Mushora, Quamchuqa and Shiranish intervals) produced formation water.

The recent acquisition of 200 km² 3D seismic over the discovery area has significantly improved imaging of the northern and southern flanks of the structure, with early interpretations indicating significant bulk volume upside potential, with formations below the OWC possibly offering additional up-dip prospectivity, and confirming that Peshkabir 1 was drilled at structural closure.

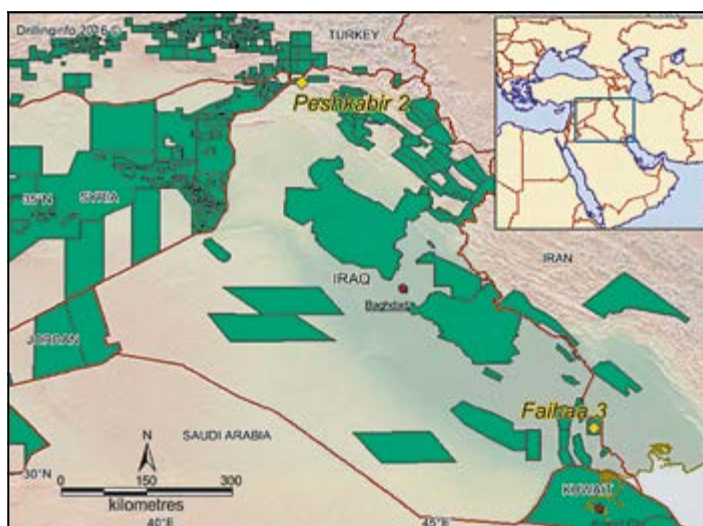
DNO Iraq AS holds a 55% interest in the Tawke block and is partnered by Genel Energy International Ltd (25%) and KRG (20%).

Meanwhile, in the far south of the country **Kuwait Energy** reported in mid October 2016 that its **Faihaa 3** appraisal/development well on **Block 9**, in the Zagros

Foredeep Basin, was spudded in August 2016. The well is the second of a two-well appraisal program to the Faihaa 1 oil discovery, located to the north of Faihaa 3, where Kuwait Energy announced in October 2015 that oil production had commenced after fast-track development, with output of about 5,000 bopd through a 32/64" choke. It was also announced in October 2016 that production had started at Faihaa 2, located in the north-western corner of Block 9, and that the well is now producing at a stabilized rate of 5,600 bopd.

The oil is reservoir in the Cretaceous Yamama Formation at a depth of around 4,000m and also in the shallower Cretaceous Mishrif Formation.

The exploration, development and production service contract for the block, which is located in the province of Basra, was awarded in Iraq's Fourth Licensing Round with an effective date of 3 February 2013, and has an initial five-year exploration period. Kuwait Energy Iraq Ltd holds a 60% interest and is partnered by Dragon Oil Holdings Ltd (30%) and Egyptian General Petroleum Corp (EGPC) (10%), the latter having formally farmed-in at the end of September 2015, with the asset becoming the Egyptian national oil company's first ever international investment. ■



US: Significant Light Oil Discovery in Alaska

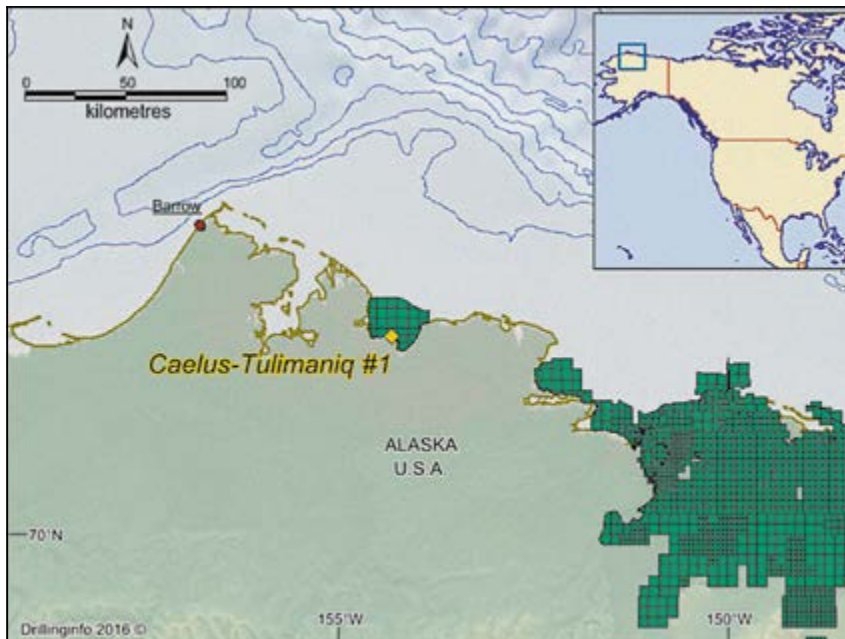
On 4 October 2016, **Caelus Energy Alaska** indicated that it has made a 'world class' oil discovery in **Caelus-Tulimaniq 1**, also known as **CT-1**, situated in Block ADL 392275 in the shallow waters of **Smith Bay** on the north coast of **Alaska**, about 500 km north of the Arctic Circle and 100 km south-east of Barrow.

CT-1 and step-out well Caelus-Tulimaniq 2 (CT-2) targeted a large Brookian submarine fan complex that covers over 777 km². The fan was successfully drilled and logged in both wells, with CT-2 encountering an extension of the accumulation 8.45 km north-west of the original CT-1 discovery. Gross hydrocarbon columns of over 305m were found in each well, with CT-1 and CT-2 logging 56m and 68m of net pay, respectively. Sidewall coring and subsequent lab analyses confirm the presence of reservoir-quality sandstones, containing light oil ranging from 40–45° API gravity.

The discovery is reported to hold in place reserves of over 6 Bbo and recoverable reserves of 1.8 to 2.4 Bbo and with Caelus expecting to achieve recovery factors in the range of 30–40%, the field could potentially provide 200,000 bopd. A field this size could increase

Alaska's rapidly diminishing oil reserves by as much as 80%.

Equity is shared between operator Caelus Energy Alaska Smith Bay (75%), L 71 Resources (10%), Nordaq Energy (10%) and Doyon (5%). ■



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The Value of International Campuses

After a career in industry, Prof. Mike Bowman moved to academia and is now Chair of Petroleum Engineering at the Qatari campus of Texas A&M University (TAMUQ) in Doha.

• **How easy was the move from industry to academia?**

I have really enjoyed the transition and the challenges it's offered, as well as the contribution I feel I have made, initially at Manchester and now in Qatar. I retired in 2011 but I had always hoped to return to academia. Throughout my career I had tried to keep hands on and as technical as possible, even in my latter years as VP Geoscience for BP. Geology is my passion and combining this with what I had learned over many years in upstream E&P, I felt I had something to give back to help future potential petroleum geoscience and subsurface practitioners. Fortunately, the University of Manchester felt the same way; I was offered a newly created Chair in Development and Production Geology, helping create a new Master's degree in Petroleum Geoscience and supporting the development of a range of university-wide strategic initiatives. I'm very grateful to the university for the opportunity, which I really enjoyed – I still have an Honorary Chair there and teach some classes.

• **When and how did you get involved with TAMUQ?**

The opportunity came out of the blue and was completely unplanned. My youngest son and his wife moved to Doha in 2015. When we visited them for a holiday they asked if we would be able to come over for extended periods if they were to start a family – Eloise is now 6 months old! I contacted a former colleague at BP, now a Professor at Texas A&M

Geologist Mike Bowman joined BP after completing a PhD and lecturing at the University of Wales. During 30 years with BP he had a wide range of roles, from specialist geologist to senior manager, with postings to the US and Aberdeen and periods working in Egypt, Russia, Azerbaijan and Kazakhstan. In 2011 he became Professor of Development and Production Geology at the UK University of Manchester, before moving to Qatar in 2015.



Mike Bowman

University, about giving a few talks at their new Qatar campus while I was in Doha. He put me in touch with the leadership there and the next thing I knew, I was offered the Program Chair in Petroleum Engineering. After some thinking (I hadn't intended to work full-time again) I accepted and I am now in my second year here.

I'm really enjoying it. The leadership both here and in College Station (Texas A&M main campus) have given me enormous support. We have recruited new faculty and staff and refreshed the curriculum, developing close links with both local industry and the regional education centers involved in subsurface teaching and research in the upstream O&G industry.

• **What brought Texas A&M to Doha; what do its programs cover?**

The TAMUQ campus is located in Education City together with a number of other international campuses, each chosen to bring expertise and capability in a range of core areas of education and research that Qatar believes are essential for its future success. This is the vision of Sheikha Mozah bint Nasser Al Missned, second wife of Sheikh Hamad bin Khalifa Al Thani, former Emir of the State of Qatar. Texas A&M was invited because of its world-class reputation in petroleum engineering, but we also offer programs in electrical, mechanical and chemical engineering, supported

by liberal arts and science foundation programs, enabling a fully US-style undergraduate degree to be offered. It is an excellent, exciting working environment. The small campus – about 1,000 undergraduate students – means a really high quality relationship between faculty, staff and students. The undergraduate programs are the same as those at the College Station campus, so our students get a fully-fledged engineering degree from Texas A&M – and the reputation that comes with this.

• **Is industry collaboration important?**

Essential. Overseas campuses are here to create a sustainable high quality capability for the benefit of Qatar. Keeping this in mind and working closely with local industry to ensure that we deliver what they need are vital for success, because our graduating



The Drilling Simulator lab, one of the top class teaching and research facilities at TAMUQ.

students will be taking jobs in these companies and our curriculum and research focus must be aligned to what industry needs. I have spent a great deal of time building closer links and relationships with Qatar Petroleum, the other national operating companies such as RasGas and QatarGas and local IOCs here in Qatar, as well as service and consulting companies. We have a strong, supportive industry advisory board with leaders from local companies who advise and guide us and offer support ranging from site visits to teaching assistance and career guidance. Overall, we have very good working relationships with our industry partners here in Qatar, and maintaining and growing these is a key to future success.

• What value do overseas campuses bring to their host country and what challenges do they face?

Overseas campuses offer local, in-country benefits and also broaden the perspectives of the home country campus. The key to success is effective leadership, organization and structure in the overseas campus to complement the imported curriculum. This demands high quality, dedicated faculty who deliver great teaching, research and service to the community. I believe that we have all of this at TAMUQ, which is why it is such a great place to work and is seen to be very successful from both local and home perspectives.

Making the strategic decision to set up an overseas campus is a major undertaking. The inaugural class of TAMUQ in September 2003 had 29 students, of whom 24 were Qatari and 15 were female. More than 600 engineers have graduated from Texas A&M at Qatar since 2007. Research activities addressing issues important to Qatar are valued at more than \$196 million and include, among others, environmental concerns, advanced water treatment technologies, petroleum reservoir studies, modeling and simulation. All of this demonstrates just how successful it has been.

To build and maintain such a successful track record the new site must uphold the quality of the home base university and ensure a comparably high level

of education for the local student body. These are not trivial undertakings, demanding continuous effort to set and maintain standards and to ensure comparability and compatibility in all aspects. I think the College Station and Qatar campuses of Texas A&M have worked hard and it has paid dividends; we have an excellent reputation locally and are seen as a core part of the education landscape here. However, you cannot stand still but must adapt to and foresee changing environments. The fall in oil and gas prices, for example, is putting pressure on locally available research funds. We are addressing these issues head on, working to attract the best students and building on the excellent track record of the last 13 years to shape a campus and program that meets future needs.

• How do you like living in Qatar?

My wife and I are really enjoying our time here in Doha. It is about the safest place in the world today, has great facilities and the Qatari people are generous, polite and welcoming. Doha is an amazing city, possibly one of the fastest growing in the world today, with great things to offer in all dimensions from local culture to food and sport. It also feels a tremendous privilege to be playing a part in helping create a sustainable legacy and capability in the country. We both agree it was a great decision and is a great experience – helped by our new grandchild who brings an extra burst of sunshine with her smile. ■

Texas A&M university campus in Doha.



The First Geological Map of Eastern Europe

Work done by Polish scientists in the early 1800s laid down the foundations of the modern oil industry.

Prof. PIOTR KRZYWIEC, Institute of Geological Sciences, Polish Academy of Sciences

In the late 19th and early 20th centuries the northern segment of the Carpathians (present-day south-east Poland and western Ukraine) was one of the most prolific hydrocarbon-producing provinces in the world. Before that, however, at the beginning of the 19th century, when modern geology was being born in Germany, France and Great Britain, an attempt was made to summarize field observations from the Carpathians in the form of a geological map, showing, amongst other things, the natural field occurrences of hydrocarbons such as oil seeps and gas leakages.

This map was prepared by Stanisław Staszic (1755–1826), a Polish priest, philosopher, statesman, geologist, scholar, poet and writer, and the leader of the Polish Enlightenment. Staszic graduated from a Jesuit school in Poznań, and then continued his studies in France and Germany, where he was taught by eminent scholars such as Georges-Louis Leclerc Buffon. Later, he translated Buffon's seminal work *Les Époques de la Nature* into Polish. Staszic was a very active supporter of industrial development in Poland, organized a mining school in Kielce, and served as president of the Society of Friends of Sciences (Towarzystwo Przyjaciół Nauk) in Warsaw for almost 20 years, from 1808 to 1826.

Map Shows Seeps and Hydrocarbons

His first geological publication, entitled *O Ziemiordztwie gór dawney Sarmacyi a później Polski* (*On Earth formation of previous Sarmatia, later Poland*), appeared in 1806. Staszic compiled this and several other essays into his geological opus magnum, a book published in 1815 and entitled *O Ziemiordztwie Karpatów i innych gór i równin Polski* (*On the Formation of the Carpathians and Other Mountains and Lowlands of Poland*). This book

was accompanied by an atlas containing a truly impressive map entitled *Carta geologica totius Poloniae, Moldaviae, Transylvaniae, et partis Hungariae, et Valachiae* (*Geological Map of the whole of Poland, Moldova, Transylvania and parts of Hungary and Wallachia*). Dated 1806 (nine years before the famous William Smith map of England and Wales), this map is relatively unknown to geologists and historians of geology, especially those from outside Poland, but it certainly deserves much better recognition.

Hand colored, the map was published on four large 66 cm x 45 cm sheets, and covers approximately a million square kilometers – a very large area which stretches from the Baltic Sea to the Black Sea. Staszic adopted the rock nomenclature used by the famous

German geologist Abraham Gottlob Werner, and used colours and numbers to indicate 150 different types of rocks and ore deposits. Of particular interest to petroleum geologists are the numerous oil seeps and the different rock types containing hydrocarbons, abundantly shown in the Northern Carpathians.

This geological map and other publications by Stanisław Staszic, together with the achievements of Ignacy Łukasiewicz (1822–1882), including the discovery of an efficient oil distillation process and the construction of a kerosene lamp, effectively laid the foundations of the development of the modern oil industry.

References available online. See *GEO ExPro* Vol. 11, No. 5 for more about the history of geological maps. ■



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Exploring Towards a Deficit

The oil industry is not able to find enough liquids on a global basis to replace what is being produced.

The good news is that a potentially supergiant discovery (i.e. > 5 Bbo recoverable) has been made on Alaska's North Slope. With an estimated 6–10 Bbo in place, Smith Bay possibly ranks as the world's largest oil find in recent years. In comparison, Prudhoe Bay, discovered in 1967 and the largest oil field ever found in the US, originally contained some 25 Bbo, of which close to 65% has been recovered. The largest field in the North Sea – Statfjord – just passed the production milestone of 5 Bboe.

The bad news is that Smith Bay is the only decent discovery on a global basis so far this year. Following nine months of exploration, only 5 Bboe (i.e. both oil and gas) had been found. And most of this is gas, according to Rystad Energy.

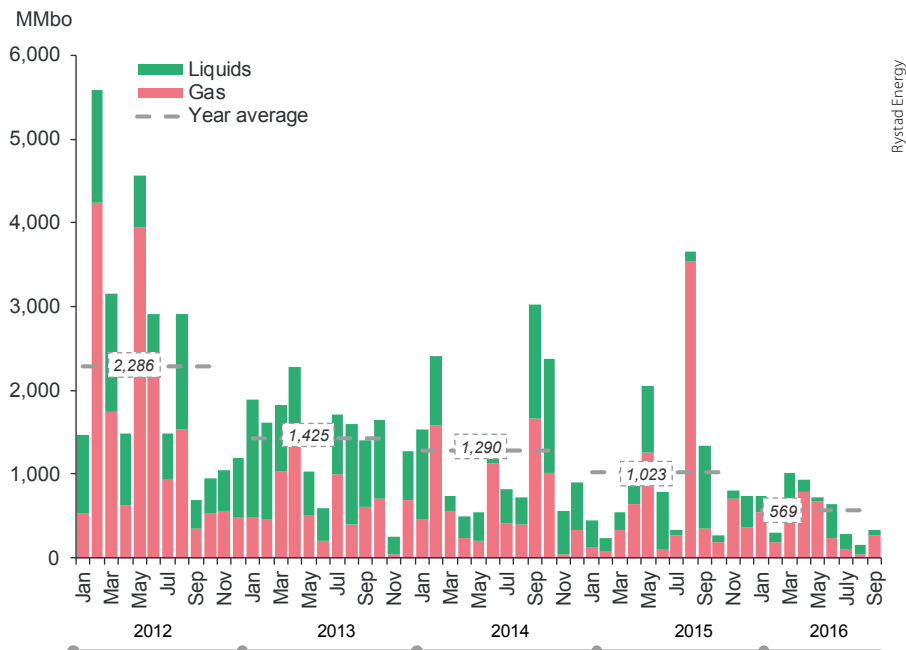
This comes on top of two other bad years, 2014 and 2015, when only 15 and 12 Bboe respectively were discovered. Moreover, in 2015 only 35% of that was oil. This trend seems to continue into 2016. Oil may not be plentiful any more.

By comparison, the consumption of oil (only) was approximately 33 Bbo in 2015 according to the *BP Statistical Review of World Energy*. In other words, for many years in a row we have found a lot less than we produce and consume. This is called the replacement ratio, and it does not take much to understand that we cannot continue with a ratio much lower than one if we want to avoid a deficit in the long run. That is, of course, good news for those who enjoy high oil prices, like the oil companies.

We certainly need more discoveries with reserves calculated in billions of barrels, like Smith Bay. The big question is where to look – and who will do the looking? In Alaska, all that was needed was a largely unknown privately held independent exploration and production company formed in 2011. ■

Halfdan Carstens

Global conventional discoveries.



Conversion Factors

Crude oil

- 1 m³ = 6.29 barrels
- 1 barrel = 0.159 m³
- 1 tonne = 7.49 barrels

Natural gas

- 1 m³ = 35.3 ft³
- 1 ft³ = 0.028 m³

Energy

- 1000 m³ gas = 1 m³ o.e
- 1 tonne NGL = 1.9 m³ o.e.

Numbers

- Million = 1 x 10⁶
- Billion = 1 x 10⁹
- Trillion = 1 x 10¹²

Supergiant field

Recoverable reserves > 5 billion barrels (800 million Sm³) of oil equivalents

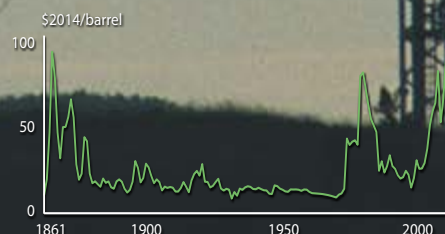
Giant field

Recoverable reserves > 500 million barrels (80 million Sm³) of oil equivalents

Major field

Recoverable reserves > 100 million barrels (16 million Sm³) of oil equivalents

Historic oil price



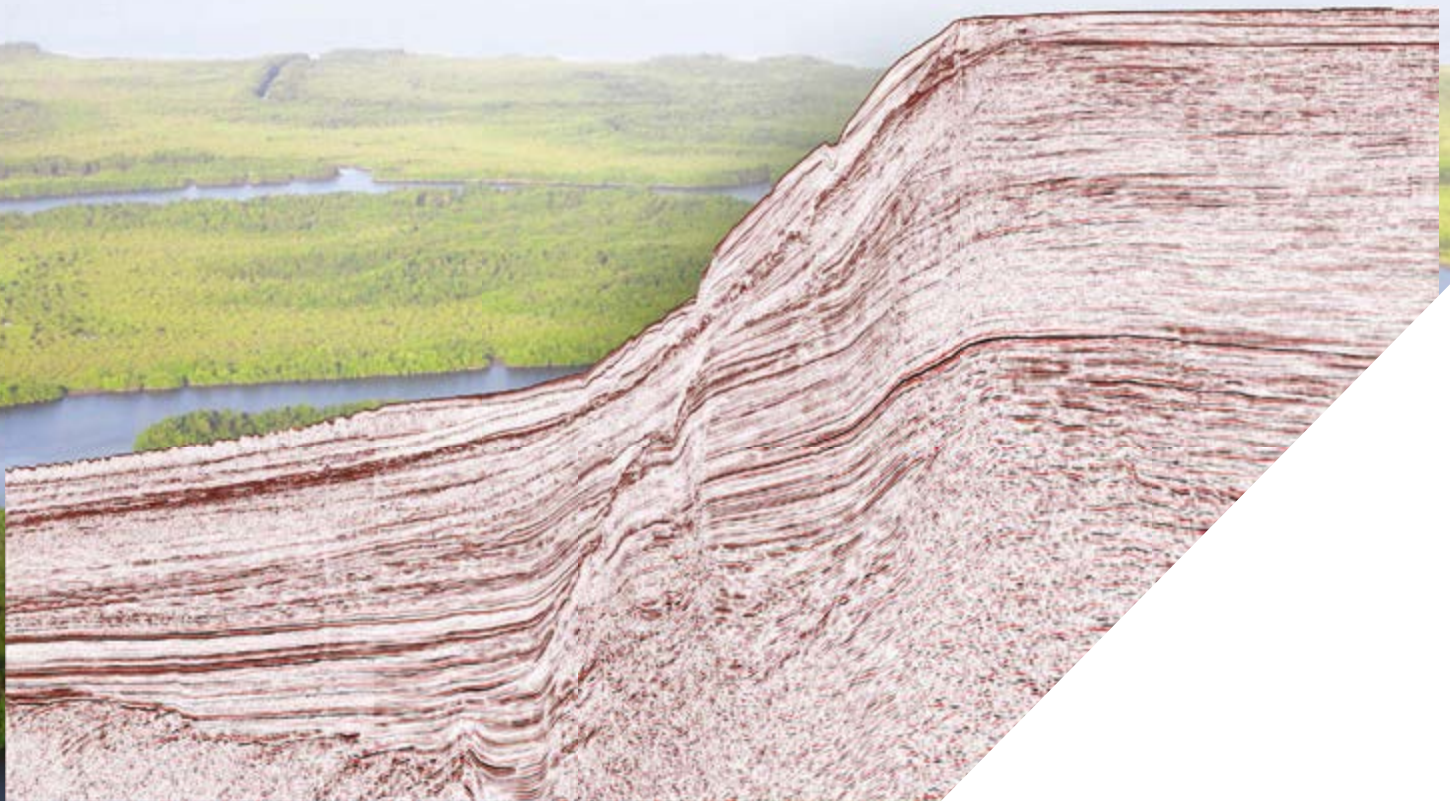
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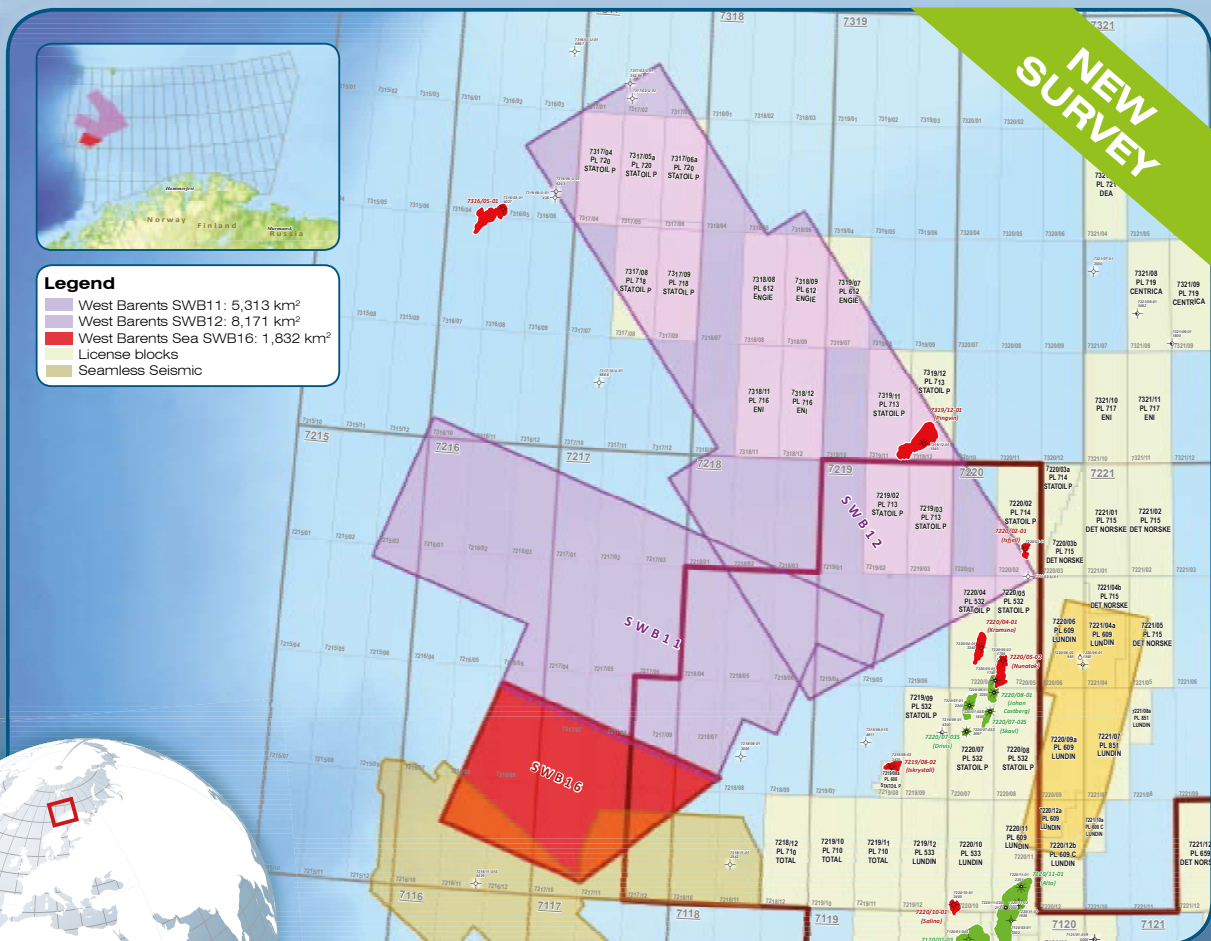


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Western Barents Sea

New Broadband Multi-Client Seismic Survey



The Western Barents Sea is the last frontier for the hydrocarbon exploration in the Norwegian offshore. In preparation for the 24th Norwegian License Round and including the recent extension of the APA area, Spectrum has begun the acquisition of SWB16, a 1,800 km² Multi-Client 3D seismic survey. Upon completion, a regional coverage of approximately 20,000 km² will be available.

The broadband fast-track volume will be available Q1 2017 to allow early participating clients to commence their initial interpretation and prospect screening. The final PSTM Broadband dataset and offset volumes will be available Q2 2017.