VOL. 11, NO. 2 – 2014

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

HISTORY OF OIL
Memories of Iraqi Kurdistan

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GEOTOURISM
Triassic Park:
Arizona's Petrified Forest

TECHNOLOGY EXPLAINED
Rethinking Regional Reconnaissance

GEOCHEMISTRY
Think Molecular – It Translates into Pay!

EXPLORATION
Shale Gas: A Commercially Viable Alternative?

NEW Interactive Website
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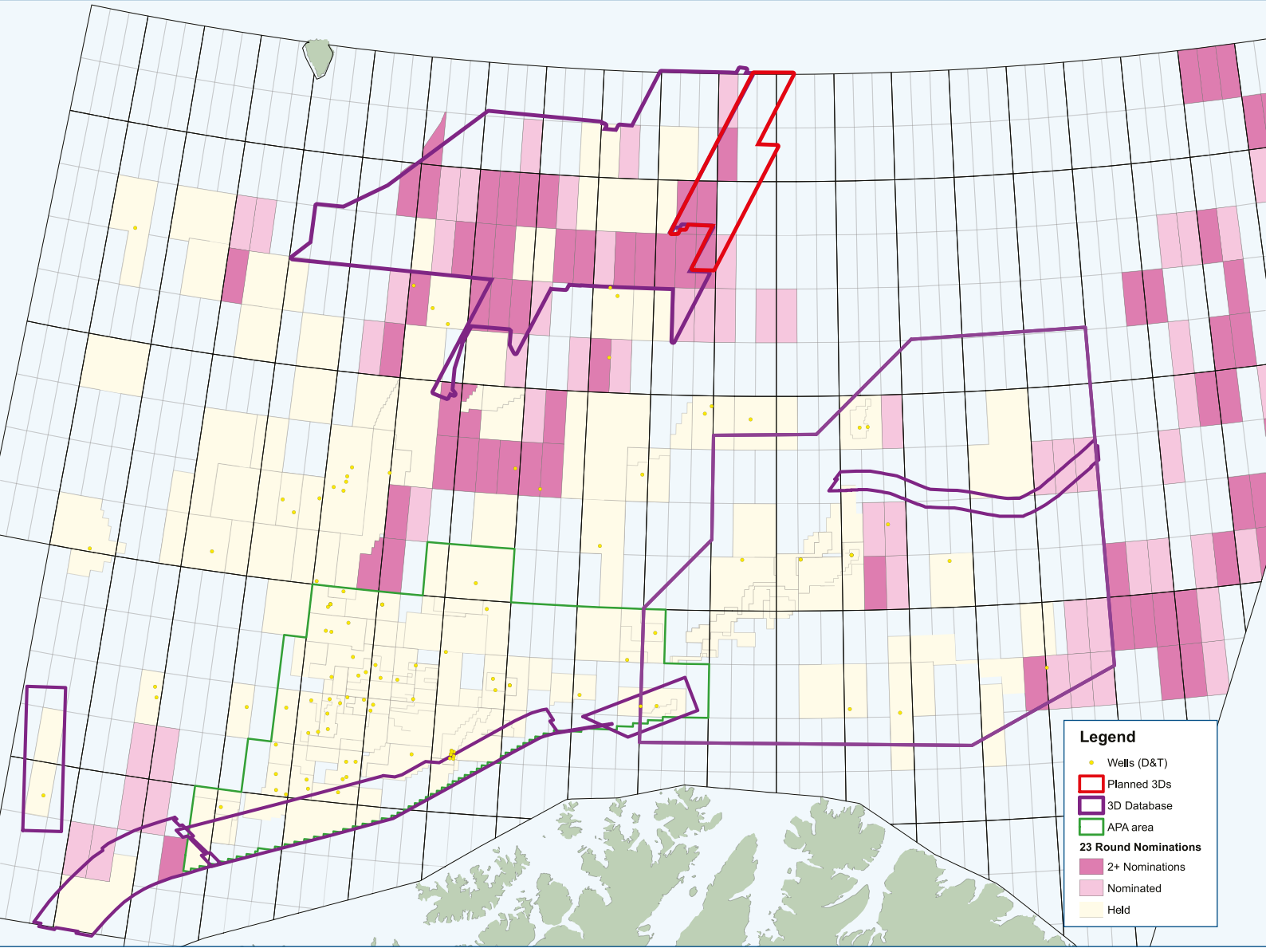
GEOLOGY GEOPHYSICS RESERVOIR MANAGEMENT



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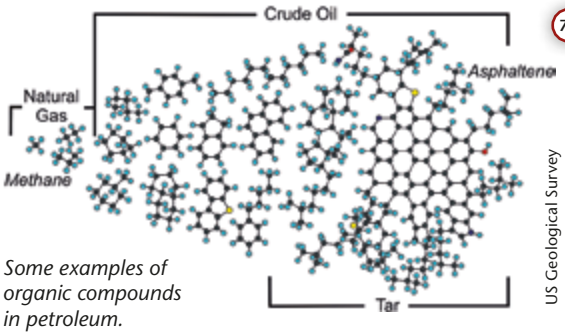
This edition of GEO ExPro Magazine focuses on the Americas, the Arctic and Frontier Exploration



Some examples of organic compounds in petroleum.

COLUMNS

FEATURES

Water for drilling mud, Oman – water is a global issue.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Many Different Frontiers

This edition of *GEO ExPro* magazine has a broad focus, as we shine the spotlight on the Americas, the Arctic and frontier exploration. We move from the very beginnings of the commercial industry – the 'geocity' of Titusville in Pennsylvania – to the future, and a discussion of what exactly constitutes an exploration frontier: a notion which encompasses geographical, geological, political and environmental concepts.

How can we best to communicate our science to the world?

As I write, frontiers are very much in the news, with saber-rattling along the Russo/Ukrainian border and Russia making its presence felt in Crimea. In common with many disputes around the world, the place of hydrocarbons and energy security cannot be ignored in this debate. Russia has the largest proven gas reserves in the world, and Ukraine is strategically located between it and one of its main markets, gas-hungry Western Europe, particularly Germany, which gets a large percentage of its energy through Russian gas. Many of the pipelines serving this market pass through Ukraine, which itself relies on Russia for 50% of its own supply.

The overthrow of the Ukrainian government in February by popular uprising was strongly driven by social media and other modern communication methods – as were the public demonstrations and revolutions of the 'Arab Spring'. There are now many different ways of getting a message out to the world, but as an industry we seem remarkably poor at harnessing them so that others can understand the facts, importance and excitement of what we do. With this in mind, the AAPG are including in their annual meeting in Houston in April a discussion forum on 'Communicating our Science' to debate how new media are changing our communications with each other and with the public. A panel of professional communicators, including university professors, government advisors, a television presenter and an industry communications expert, as well as the editor of your favourite geoscience magazine, will lead the discussion on how we can better communicate what we do – and its importance – to friends, colleagues, activists and the world in general.

JANE WHALEY
Editor in Chief

TRIASSIC PARK: Arizona's Petrified Forest

A cosmic array of colors explode from this polished section of a petrified log at the Petrified Forest National Park's visitors center. The park's badlands offer striking vistas and a peek back at life in the Late Triassic.

Inset: The exploits and adventures of the early explorers for oil in Iraqi Kurdistan make for fascinating reading.

GEO ExPro

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Maximizing Recovery

A new regulator and possible Scottish independence – interesting times for the UKCS.

In an environment of increasing uncertainty regarding sovereignty of lucrative UKCS resources, oil companies operating in the mature North Sea Basin are being urged to do what the London and Scottish parliaments seemingly cannot do, and work more closely together.

In June 2013 the UK government commissioned an independent review of offshore oil and gas recovery – led by industry stalwart Sir Ian Wood – with a remit to engage with companies holding interests in the UKCS, along with institutions such as HM Treasury, the Scottish government and regulators from the USA, Norway and Australia. The resulting report, published in February, suggests that the UKCS could deliver an additional 3–4 Bbo over the next 20 years, worth about £200 billion to the economy.

The report recommends that industry works closely with government to implement the UK Oil and Gas Industrial Strategy, and to develop the strategy for maximising the economic recovery from the UK Continental Shelf, by establishing a new sector regulator, focusing on six key areas:

- Exploration Strategy: ensure that economically recoverable resources are fully explored, appraised and exploited in a timely manner, by an appropriately tailored licensing regime and by encouraging data sharing.
- Asset Stewardship Strategy: ensure operators account for the proper stewardship of their assets, with consideration to adjacent resources.
- Regional Development Strategy: development on a regional, rather than a field basis, with the aim of maximizing economic recovery from clusters of fields. License holders should make their infrastructure facilities available to third parties.
- Infrastructure Strategy: prolong life of the existing infrastructure and achieve investment in new key infrastructure.
- Technology Strategy: ensure existing technologies are deployed to their full effect and that relevant new technologies are developed to maximize recovery.
- Decommissioning Strategy: achieve maximum economic extension of field life and ensure key assets are not decommissioned prematurely.

It is hoped that by implementing these strategies, operators will avoid unnecessary costs, delays and complexity in their dealings with one another. Key to the process is the need for industry to make available suitably qualified and experienced senior personnel.

Commenting on the present regulatory function, Sir Ian said it, "…has halved in size over the last 20 years and now lacks the broader capability and resources to perform the much more demanding stewardship role that is required…The (new) proposals and limited new powers are much more about stronger and better stewardship …as opposed to more regulation..." The UK government has accepted the key recommendations and Sir Ian is to chair an Interim Advisory Panel on setting up the new regulator. A CEO could be in place by the summer of 2014 and stakeholders are being invited to participate in the process.

Industry body, Oil & Gas UK, welcomed the report. Chief Executive Malcolm Webb said, "...We strongly welcome the proposal for a new arm's length regulator... The report is a game changer."

With the possibility of Scottish independence looming, UK Prime Minister David Cameron recently tweeted: "Broad shoulders of UK economy have got behind oil and gas and will stay there to get maximum benefit for all the UK, including Scotland".

It promises to be an interesting few months ahead as the new regulator emerges, the commitment of the industry to bear the costs is tested and the referendum on Scottish independence nears its climax – the outcome of which may provide the regulator with its first and potentially biggest hurdle. ■

WILL THORNTON

Reference:
UKCS Maximising Recovery Review: Final Report. Sir Ian Wood. 24th February, 2014, Crown copyright.

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

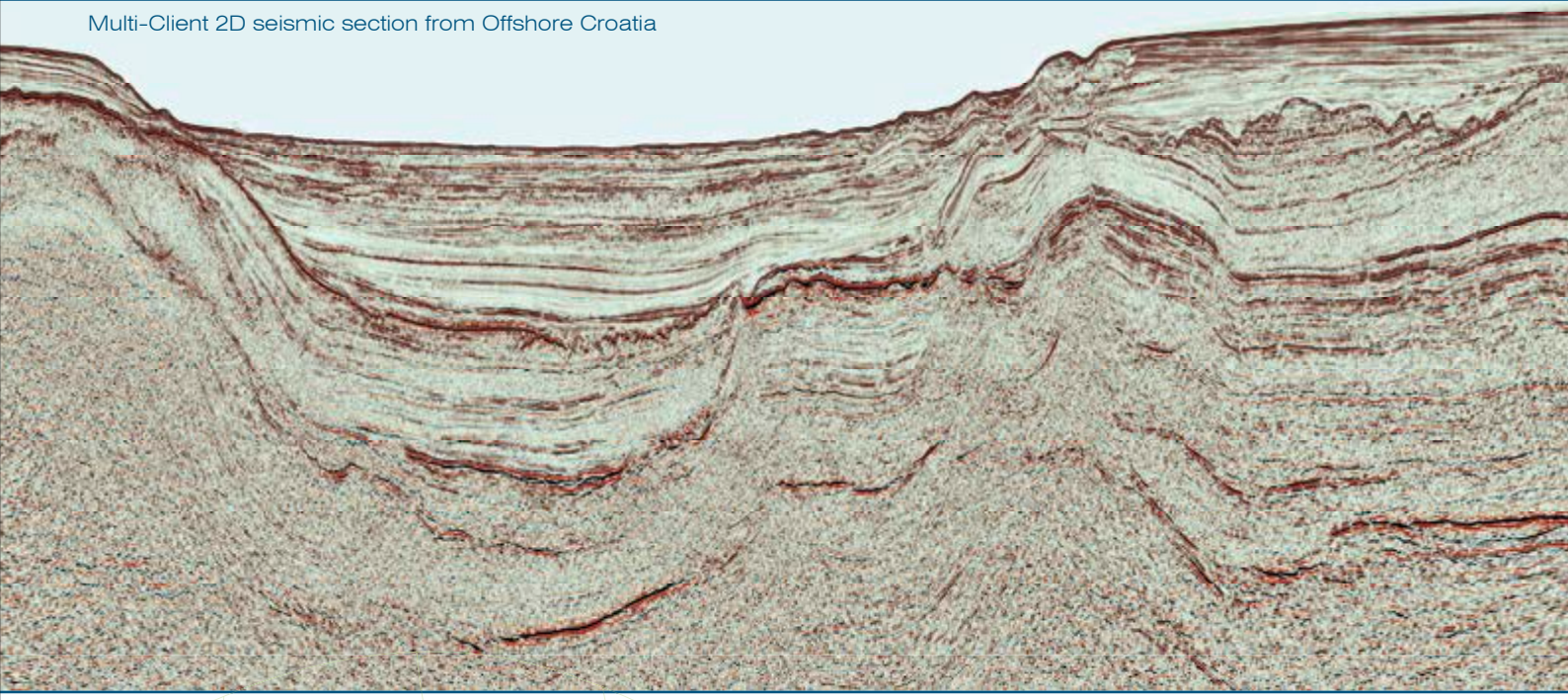
P3 reserves:
Quantity of hydrocarbons believed recoverable with a 10% probability

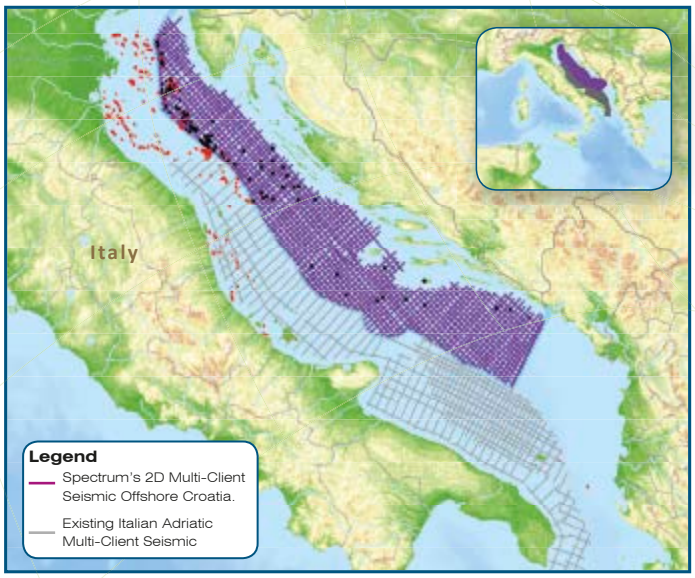
Oilfield glossary:
www.glossary.oilfield.slb.com

Offshore Croatia

A New Oil Province at the Heart of Europe

Multi-Client 2D seismic section from Offshore Croatia





Spectrum has acquired a truly unique Multi-Client seismic survey offshore Croatia. This is the only seismic data available to license in this hugely underexplored region which expects to see its first offshore licensing round this year.

The survey, acquired under contract to the Ministry of the Economy in Croatia, covers approximately 14,700 kilometres of long offset seismic data with a 5 km x 5 km grid. It extends across most of the Croatian Adriatic Sea and connects with Spectrum's reprocessed seismic data covering the Italian Adriatic Sea.

Final PSTM data has now been delivered and all processed data will be available in early April. The Government of Croatia plans to hold a licensing round over the country's offshore continental shelf in 2014.

Spectrum

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Better Together

Improving frontier exploration through content and software technology.

There are few known frontier regions that offer both opportunity and challenge in equal measure as the Arctic; the US Geological Survey estimates 13% of the world's undiscovered oil resources and 30% of its undiscovered natural gas reserves are to be found there. But exploration of these reserves, in difficult terrain that is covered in ice for much of the year and with a chequered political and economic history, is a risky venture for oil and gas companies of all sizes and stature. With 60% of the recoverable resources concentrated in six basins, and portions of eight countries contained in the Arctic, competition is high; oil and gas companies are in need of a competitive edge.

The Arctic is high-risk/high-cost, and any decision to look for resources in this region must be based on the most comprehensive and sound intelligence available. As such, much of the responsibility falls on the shoulders of exploration geoscientists, who must mitigate the risks associated with frontier exploration through having access to all the relevant data and high-quality map content available.

There is a perception that there is little Arctic data available to help this search, given its harsh climate, remoteness and inherent difficulties. But, in fact, this most final of final frontiers is surprisingly well documented. The Barents Sea region, for example, has extensive information available, including 2D seismic and even exploration wells. While this data is clearly essential, it is costly. Therefore, it is prudent at the outset of exploration activity to begin with a more comprehensive view into the geology and geologic evolution of a region; the kind of data found in scientific maps and literature, for example.

Structured Foundations

Published maps in geoscience literature, from scientific publishers such as Elsevier, Wiley, and Springer and professional societies like the AAPG, the Geological Society of London and the Geological Society of America, contain a wealth of information. A query of maps in the Barents Sea from geoscience publications using available scientific databases will likely return hundreds of results. The only caveat is that this crucial geospatial data from geoscience publications is unstructured, and extracting information from such sources is far harder than if it were numeric data in a spreadsheet or spatial data in a geographic information system (GIS).

For unstructured geospatial data in its published state to be helpful to exploration geoscientists and support the reliability of their interpretations, it must be in a format suitable for analysis; i.e. it must be GIS-ready. Integrating unstructured data from published maps into a GIS or modeling software is essential. Extracting and downloading maps that can then be overlaid into a GIS makes the content not only searchable and findable, but most importantly, usable. Crucially, this process allows for combining data from multiple sources into the same structure and context, making it easier to assess and validate the entire geological picture of an area.

The challenge is that making unstructured map data into GIS-ready content, and then integrating that into modeling software, represents distinct steps that are often addressed by using separate tools from separate vendors. For exploration geoscientists, this is an onerous and time-consuming process that hampers their ability to have the most comprehensive and holistic view to assess an exploration opportunity. Scientific information providers like Elsevier understand this challenge and are increasingly seizing the opportunity to make unstructured information searchable and usable in GIS platforms, through developing specialized products or partnering with GIS and geoscience software providers.

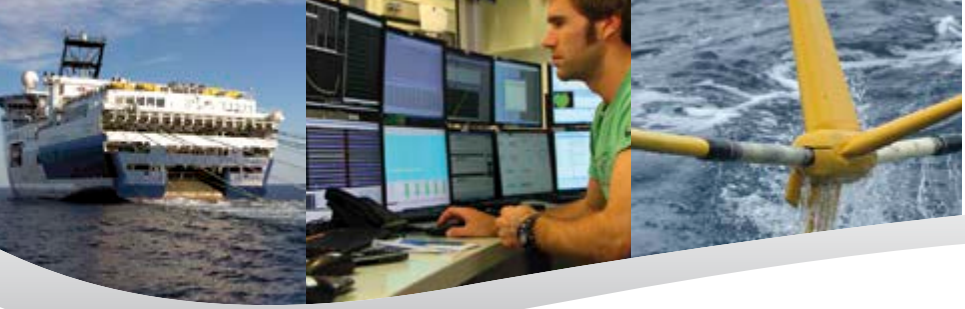
Meeting the Challenge

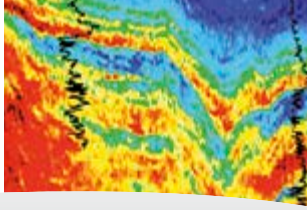
These kinds of industry developments, wherein content and software technology are combined, can stop information from being placed in silos, and allow geoscientists to make data from multiple sources, both proprietary and internal, comparable for analysis, greatly improving the efficiency with which they can work and gain insights for deeper analysis. These insights and the speed in which they can be uncovered are essential for companies competing for resources in frontier regions like the Arctic where the risk is great, but the reward high.

Synergies between content and software technology are on the rise, but still novel and infrequent enough that many geoscientists are struggling with multiple tools in an effort to make valuable data useful. The Arctic will remain a hotspot for some time to come, and even more data on the region will be created and published. Exploration companies should be looking for vendors who can offer comprehensive platforms with content that is easily discoverable and usable, allowing their geoscientists to work more effectively and thoroughly in these competitive and challenging regions. ■

PHOEBE McMELLON
Geofacets, Elsevier

Geofacets screenshot





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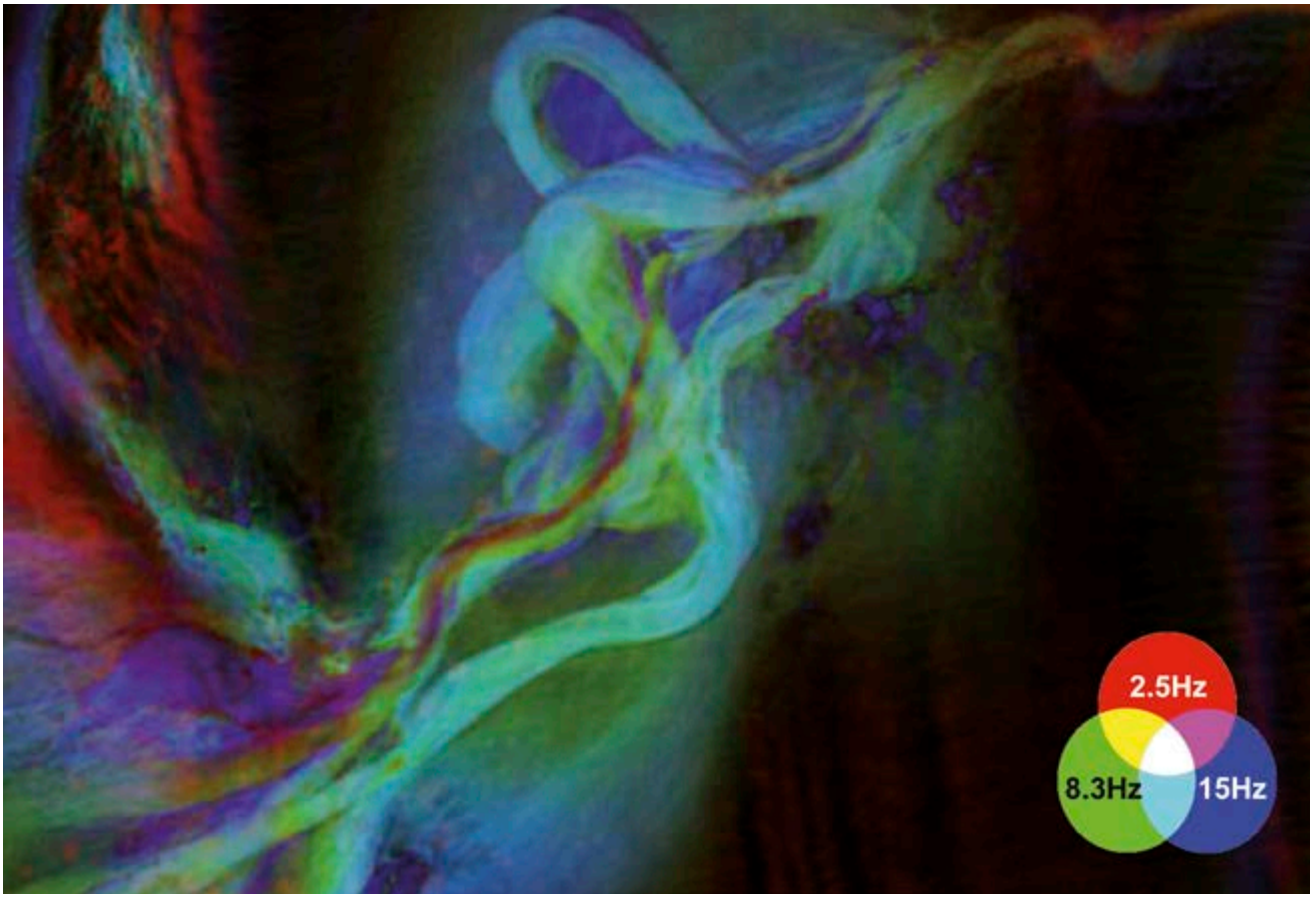

In this fast-track data from our offshore Angola multi-client survey, frequency decomposition of the ultra-low frequencies enables the different channels to be disentangled to produce a more accurate reservoir model.

The ultra-low frequencies (2.5Hz) of **BroadSeis**™ provide the stunning red channel in the image above. Without this broader bandwidth, it would not be possible to delineate the channel architecture properly.

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Whose Responsibility?

A recent decision by the government of Ecuador to abandon a pioneering conservation plan designed to prevent drilling in the Amazon rainforest has thrown the spotlight on the many issues surrounding the search for hydrocarbons in this unique part of the world.

The Yasuni National Park, a UNESCO Biosphere Reserve in the far north-eastern corner of Ecuador, about 250 km from the capital, Quito, is believed to be the most biologically diverse spot on the Earth, with more tree types in a hectare than in the whole of North America. There are 121 documented reptile species within the 10,000 km^2 of the park, as well as 382 fish species and at least 596 types of bird, a third of the total found in the entire Amazon region. And about 10% of the known insect species of the whole world can be found here. It is also reportedly home to two isolated indigenous tribes which have resisted contact with the outside world.

But Yasuni National Park also holds an estimated 909 MMb of proven and probable oil, discovered in 2007 by state oil company Petroecuador – about 20% of the country's known reserves. To somewhere as poor as Ecuador, where, according to the CIA World Fact Book, over a quarter of the population were living below the poverty line in 2012, this is a potential source of much needed wealth which could be used to improve housing, infrastructure, education and health care facilities. Since 2007, oil production has been near-stagnant in Ecuador at around 500,000 bpd, predominantly as a result of paucity of new developments.

Pioneering Plan

Knowing the potential risks involved in drilling and exploiting reserves in the rainforest – Ecuador has had a protracted 20-year legal battle over alleged pollution and environmental damage from Texaco's operations in the area to the north of Yasuni – the oil minister at the time of the discovery, Alberto Acosta, who himself worked in the oil industry for 20 years, came up with an unusual plan. He suggested that Ecuador would not permit exploration in the Yasuni, in perpetuity, if the rest of the world would agree to pay the country about US$3.6 billion – approximately half the estimated value of the oil. The money would be used to protect Yasuni and other Ecuadorian parks like the Galapagos, and in reforestation programs.

However, six years later, despite contributions from high profile individuals like Leonardo DiCaprio and Al Gore, and pledges from a number of countries, only $13 million had been collected. President Correa pulled the plug on the initiative in August 2013, saying "the world has failed us." From the start, he had insisted that the protection of the Yasuni area was the responsibility of all countries, particularly industrialized ones, rather than of Ecuador alone, stating: "It was not charity that we sought from the international community but co-responsibility." A number of countries and organizations, however, complained at the government's heavy-handed approach to negotiations, while Correa himself in 2010 rejected a deal with the UNDP and several other countries, which would have secured about half the money required, saying that donors were attaching too many conditions to the contributions.

The companies which were initially awarded the block that was the subject of the moratorium, led by Petroamazonas (a subsidiary of Petroecuador) and Sinopec, are now free to start exploring. They insist that any exploitation will be done in a way to minimize the environmental impact, including not building roads and taking precautions to protect the indigenous species and population.

China the Main Beneficiary?

If it had been successful, this could have been an interesting model for future conservation. But there seems an inevitability about the outcome when one considers the economic pressures on Ecuador since the initiative was announced in 2007, including the global economic crisis and Ecuador's default on sovereign debt in 2008–09. Ecuador has recently become increasingly dependent for financing on China, and in July the China Development Bank lent the Ecuadorians US$2 billion in exchange for nearly 40,000 bopd over two years. ■

JANE WHALEY

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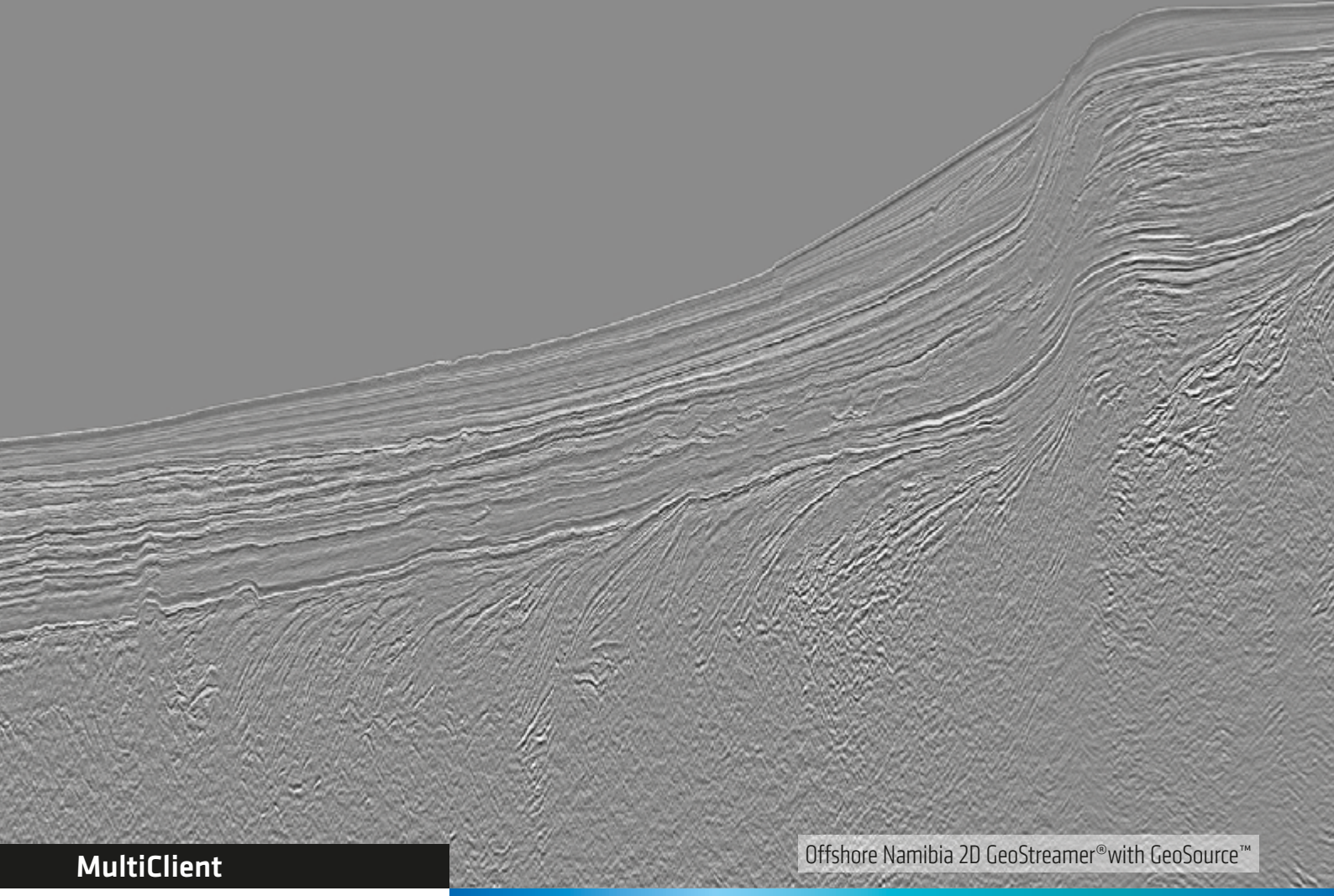
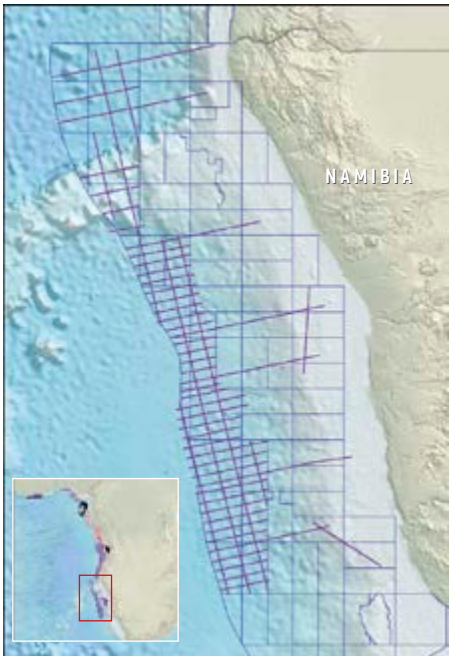


MultiClient

Offshore Namibia 2D GeoStreamer®with GeoSource™



NAMIBIA MC2D GEOSTREAMER®

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The extensive PGS MultiClient seismic dataset covers open deep-water blocks and provides the only modern technical database across this acreage.

This is the first comprehensive dataset to be acquired over these blocks highlighting the extensive and thick packages of post-rift sediment containing numerous channels, fans and source horizons and helping de-risk exploration in what is set to be the next West African hot spot.

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NAMCOR

PGS

Illuminating Challenging Areas

PGS's new full azimuth survey design can illuminate challenging deepwater areas of the Gulf of Mexico like never before.

No one has ever conducted a multiclient survey like this in the Gulf of Mexico.

Petroleum Geo-Services (PGS) has developed a unique survey design, which it has utilized in the most advanced MultiClient survey ever conducted in the Gulf of Mexico – its Triton survey. The survey design ensures that the most challenging, but also most promising areas in the Garden Banks and Keathley Canyon will now benefit from imaging of significantly better quality. The company has used an unparalleled full azimuth (FAZ) approach to acquisition and its industry-leading dual-sensor GeoStreamer® acquisition technology to optimize the results that can be achieved in this project.

Triton represents the next important advance in tailored acquisition design and state-of-the-art depth imaging. For this survey, a previously unseen approach to acquisition has been developed that utilizes a total of five vessels in the unique PGS Orion™ configuration. This combines two high-capacity streamer vessels, each towing ten 8 km GeoStreamer dual-sensor cables, in combination with three independent source vessels in a simultaneous long-offset (SLO) configuration, to achieve an effective far offsets in excess of 16 km.

GeoStreamer provides enhanced signal to noise and superior low frequency response for all offsets, and is particularly relevant for this survey because it helps to extend exploration options by enabling better geological modeling, as well as improved prospect definition and identification. Images generated from this data help place wells with greater precision through more accurate estimation of reservoir and overburden properties. Its unique ability to record complementary wavefields has enabled the development of revolutionary imaging technologies that exploit both primary and multiple energy, allowing the generation of reservoir images of unparalleled clarity and reliability.

The survey design and the use of unique PGS technology ensure that Triton will reveal the structures obscured beneath the salt with high fold, long-offset, dual-sensor full azimuth seismic data.

Exciting Areas

The survey in this exciting area of the Gulf of Mexico is progressing well – by the end of March, the company expects the survey to be approximately 60% complete. Acquisition began in November 2013 and Triton covers 10,000 km^2 and 390 OCS blocks, many of which are coming available for license or farm-in opportunities in the near future. Acquisition is expected to continue through Q3 2014.

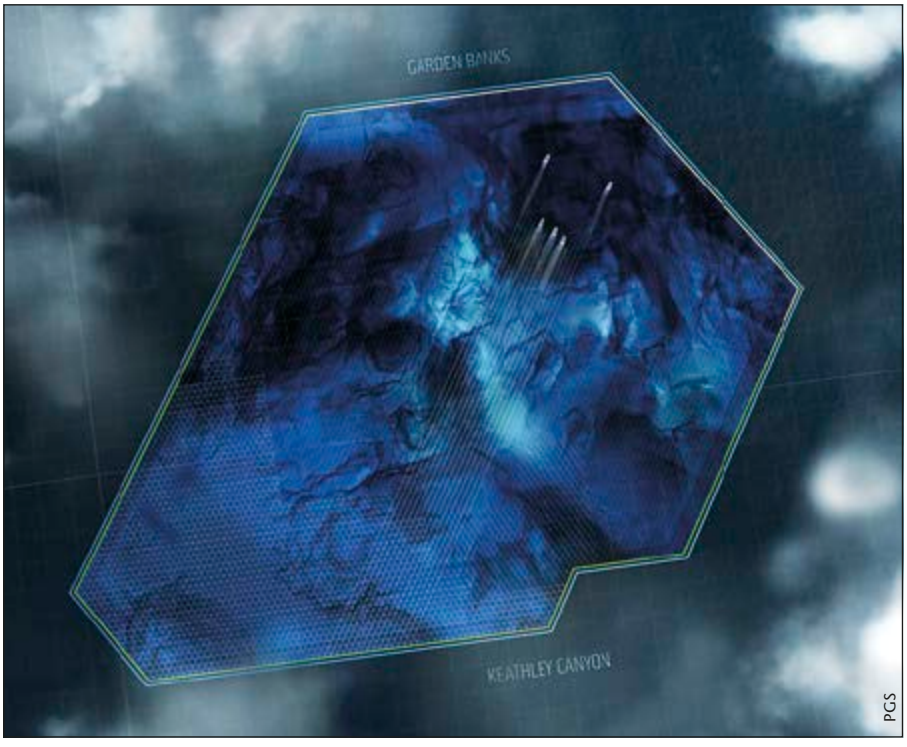
Triton is being acquired in the central western area of the Gulf of Mexico, a region which has proven to be highly prospective for hydrocarbons in recent years. The Keathley Canyon and Garden Banks areas, in particular, have hosted BP's sub-salt Tiber discovery in Keathley Canyon 102; several significant wildcat wells, including BP's Gila well in Keathley Canyon 93; and Cobalt's North Platte discovery in Garden Banks 959, to name a few.

Once the data has been acquired, the imaging workflow will include velocity model-building, leveraging the full suite of PGS model building tools, including the proprietary PGS hyperTomo technology. To create the best possible image, TTI RTM (tilted transverse isotropy reverse time migration) with 3D angle gather output will be used, allowing for image optimization and pre-stack data access throughout the model-building sequence and for final image optimization. The company is also in discussions with several clients about other aspects of imaging output as the survey progresses.

Triton represents a serious investment of intellectual capital for PGS and also an investment in the most effective application of technology given the structural conditions of the geology within this area. It is the next step forward in a long journey of industry-leading innovation for the company, with the aim of achieving the best image quality possible in the most exciting areas for exploration. ■

GREGG PARKER
Petroleum Geo-Services (PGS)

The design for the Triton survey uses a total of five vessels



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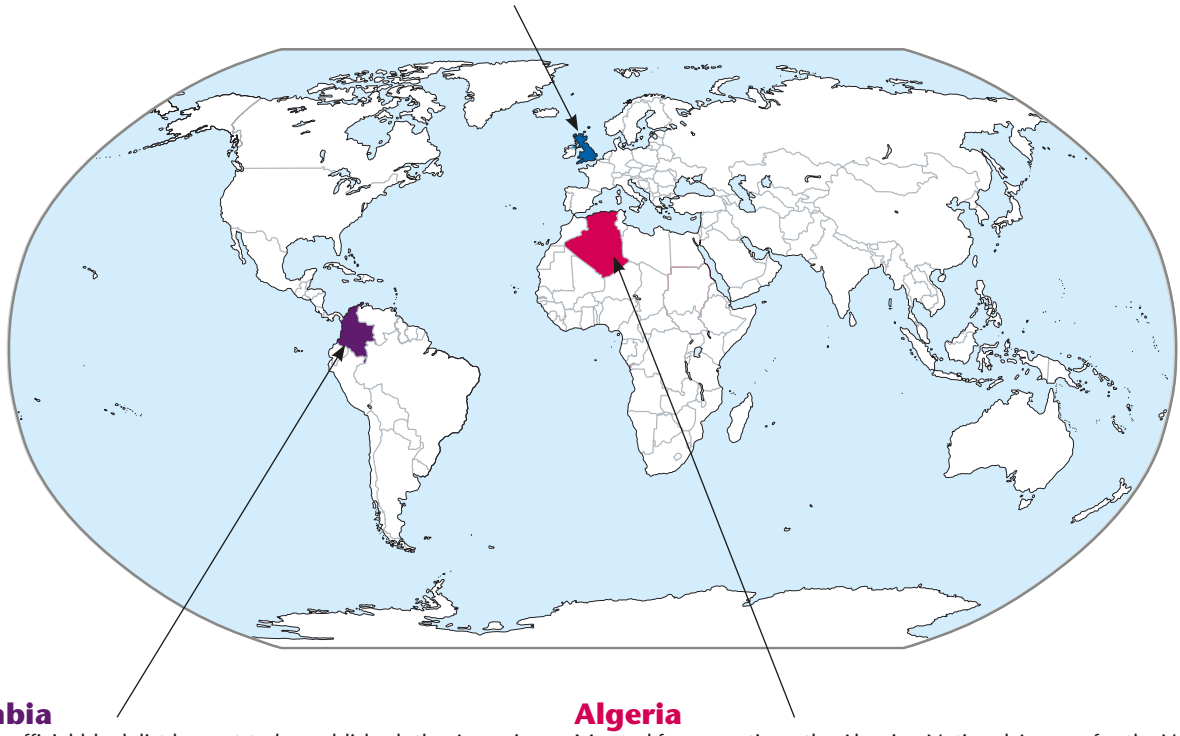
Unconventional Opportunities Gaining Momentum

United Kingdom

Amidst claims that 20 Bbo could still be in place, the UK government, seeking to stimulate a North Sea industry hit by falling production and rising costs, launched its 28th offshore licensing round offering 2,728 full and part blocks. Based on the conclusions of an environmental report, areas in the deepest waters of the South West Approaches are currently not being offered as part of the round because of inadequacy of data. In addition, a number of blocks previously excluded on the basis of recommendations of Strategic Environmental Assessments are still not being offered, including blocks in or overlapping with the boundaries of the Moray Firth and Cardigan Bay Special Areas of Conservation. Applications have to be submitted by 25 April. Michael Fallon, energy minister, said the government was hoping to maintain the level of interest evidenced in the previous round, which analysts believe was partly driven by tax incentives designed to improve the economics of commercially marginal fields and encourage exploration in once-unviable areas. These softened the effect of a £2 billion tax raid on the industry in 2011 but the inflow of spending has yet to translate into increased production.

Much investor interest has focused on the area west of Shetland, which holds about 17% of the UK's hydrocarbon reserves, and enough gas to meet 8% of the country's needs by 2016, but deep waters, hurricane-force winds and 4m waves present logistical challenges that make projects enormously expensive. In November 2013, Chevron said its £6 billion Rosebank oil project west of Shetland did not offer an 'economic value proposition' that justified proceeding with such an investment.



Colombia

While the official block list has yet to be published, the Agencia Nacional de Hidrocarburos (ANH) released the announcement and schedule for the Ronda Colombia 2014 on 20 February. Local media quoted minister of mines and energy, Amylkar Costa, as saying the round may be split into two phases, the first phase offering conventional blocks while the second phase will focus on blocks with unconventional potential. At that time the minister mentioned 57 conventional blocks and 40 for the unconventional. According to the published schedule, road shows will be held in Calgary, Houston and London with the publication of the official Terms of Reference due on 11 April. Interested companies will then have until 11 June to submit pre-qualification documents. The round will close on 23 July.

The Ministry of Mines and Energy seeks to generate around $2.6 billion by selling more than 22 million hectares for exploration and production in this auction. As it strives to sustain foreign investor interest in the sector, for the first time the ministry is offering areas potentially containing unconventional resources. The ANH road shows, in addition to promoting promising geological prospectivity, will also be underlining improved security following a decade-long military offensive, heavily backed by the US, although pipeline bomb attacks still take place. Two potentially large finds in late 2013 gave weight to Colombia's belief that there are large recoverable reserves in the central province of Meta.

Algeria

Mooted for some time, the Algerian National Agency for the Valorization of Hydrocarbons Resources (ALNAFT) has finally launched the fourth exploration bidding round following modifications to the oil and gas law passed in early 2013. ALNAFT is offering 31 blocks: six in the north of Algeria, seven in the center, six in the eastern part and 12 in the western part. Interestingly, with the government estimating unconventional gas resources at 700 Tcf, 10 of the blocks concern unconventional resources. The revised terms include the introduction of profit-based taxation and detailed terms for unconventional licenses, with an 11-year exploration phase set against seven years for conventional assets and a longer operating period. In making the changes, government sought to incentivize new investment in tight gas as well as shale. Applications are to be submitted by August 6, 2014.

Algeria's oil production has declined to 1.1 MMbpd, the lowest since 2003, while exploration has slowed in recent years following higher company taxation and a corruption probe at Sonatrach. Coming one year after the Islamist attack on the In Amenas gas facility, to which foreign personnel are only now returning, the licensing round is seen as a test of both the new terms on offer and confidence in the north African state's ability to manage security at its facilities. However, with an established infrastructure, access to European markets and significant resource potential, both unconventional and conventional, a number of companies have already indicated interest. Sonatrach remains a mandatory partner in all exploration projects, with a minimum stake of 51%.

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2D solid streamer long offset/Source vessel.

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

Osprey Explorer

2D Solid streamer long offset/Source vessel.

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

Harrier Explorer

2D Solid streamer long offset/Source vessel.

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

Northern Explorer

2D long offset/Source vessel.

Equipped with 12,000m of Sercel ALS streamer and 4 gun strings capable of very large source output.

Munin Explorer

2D long offset/Source vessel.

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

Hawk Explorer

2D Long Offset/Source Vessel.

Equipped with 12,000m of Sercel ALS streamer and four gun strings of Bolt 1900 LLXT.

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A Game Changer for Venezuela?

After President of Venezuela Hugo Chávez passed away last year, the risk of increasing political instability and the potential effects on the country's oil sector and global oil prices was recognized. This month, street protests against President Maduro's government flared into sporadic violence. Part of President Chávez's domestic popularity was due to the massive use of oil money to boost public spending and provide heavily subsidized fuel for the population, while he gained regional approval by providing a significant amount of crude oil and refined products to neighboring countries at below-market prices.

Vulnerable Economy

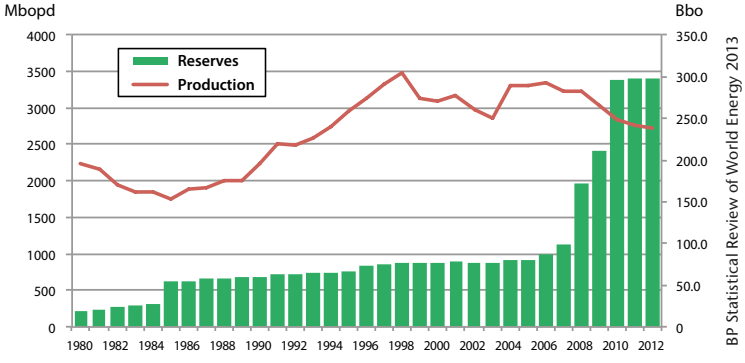
Oil accounts for around 97% of the country's total exports and Chávez benefited from high oil prices in recent years, but his expensive public spending programs redirected money away from the oil industry. Venezuela's production has dropped by 24% since Chávez came to power due to mismanagement, natural declines and lack of investment. Now the country needs an oil price of more than the current $110/barrel to balance its budget, versus $70/barrel just six years ago. This dependence on oil makes the economy highly exposed to a sharp fall in oil prices, which in turn could put political stability under pressure and increase the risk of further unrest, in a vicious circle.

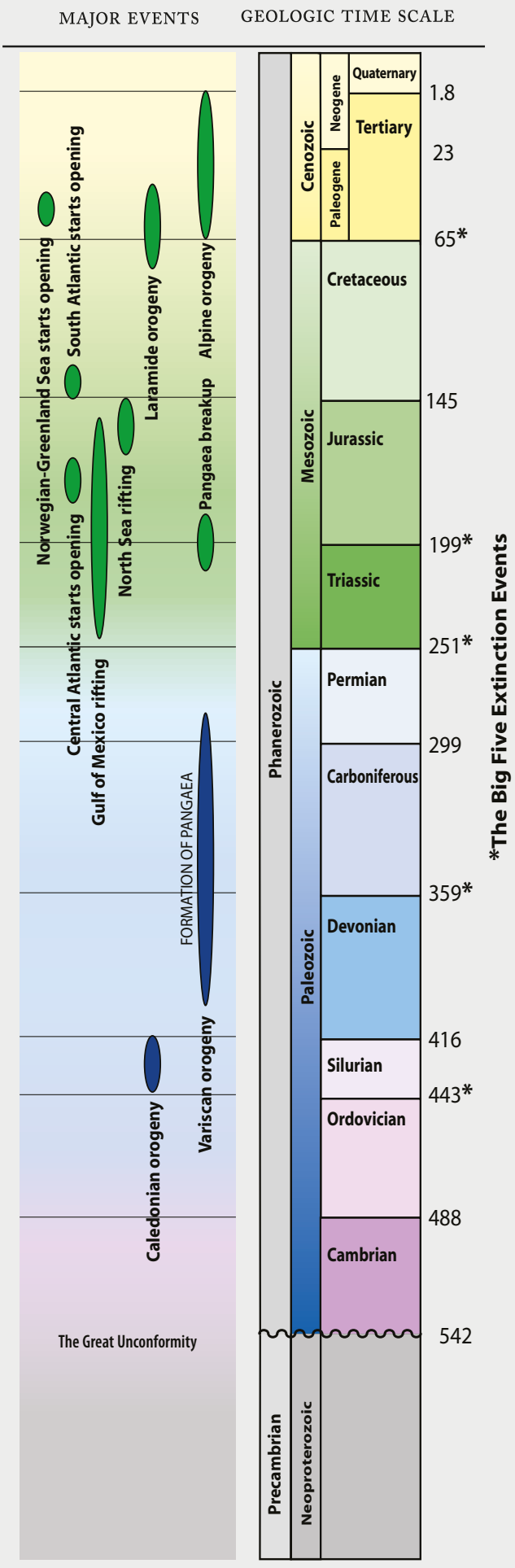
The death of Chávez could become a game changer for Venezuela in the longer term. A new president might lead to a new opening to the international market, helping PDVSA ramp up production once again. This does not seem very likely at the moment as the country has spiraling inflation, consumer goods shortages, power cuts and the world's highest crime rates. Much of Venezuela's future production has been sold to generate funds to help win the recent national election, maintaining the Chávez-era habit of treating PDVSA as a national piggy bank for financing social spending projects.

New Challenge from US Shale

Venezuela faces new challenges going forward. The country's conventional crude oil is heavy and sour by international standards, so much of its oil production goes to specialized domestic and international refineries. Today 40% of its oil exports go to the US, but with increasing shale oil production US import needs will fall, so Venezuela needs to find new buyers for its oil. One of the fastest growing destinations for its crude oil exports is China, which imported 230,000 bopd from Venezuela in 2011, up from only 19,000 bpd in 2005 (EIA). Expect to see more Venezuelan barrels moving eastward in the future. ■

THINA MARGRETHE SALTVEDT, Ph.D., Nordea





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Now Explore

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Adding Value

One of the major oil and gas industry conferences for 2014, **DEVEX**, is being held on the 6–7 May in **Aberdeen**. The event is run jointly by the Petroleum Exploration Society of Great Britain, Society for Petroleum Engineers Aberdeen, and the Aberdeen Formation Evaluation Society. Now in its eleventh year, this two-day event will host about 50 presentations, and feature around 35 stands where delegates are able to interact with exhibitors. This year's conference also sees the introduction of a new experience for delegates – a combined core workshop and field trip.

DEVEX 2014 focuses on **Adding Value by Accelerating Activity**. Speakers and exhibitors will share their experience and knowledge of projects, innovation and entrepreneurialism from within the oil and gas industry. The conference aims to help inform geologists, geophysicists, petrophysicists, reservoir engineers, petroleum engineers, production technologists, well engineers and drilling engineers. DEVEX has always attracted keynote speakers, and this year sees involvement from a variety of industry experts, such as Dominic McCormick from Shell, Rachel Jones and Tracey Flynn from Maersk, and Malcolm Pye from DECC. ■

Oldest Bit of Earth

A fragment of **zircon** from an outcrop in the remote Western Australian outback has been identified as **4.4 billion years** old, making it the oldest piece of the planet known. Researchers writing in the journal *Nature Geoscience* described how they used two different dating methods to determine the age of the crystal. They first used the radioactive decay of uranium, but fearing that the movement of lead atoms within the crystal may have produced a false date, they applied atom-probe tomography to determine the mass of individual atoms of lead in the crystal, which confirmed the initial finding.

This indicates that the crust started forming relatively soon after molten rock came together to create the earth 4.5 billion years ago. This early cooling of the earth also suggests that temperatures were low enough for liquid water and perhaps even life at a much earlier date that originally thought. ■

Zircon is used to determine the age of ancient rocks because it is exceptionally resistant to chemical changes

Rob Lavinsky, iRocks.com

Change of Venue

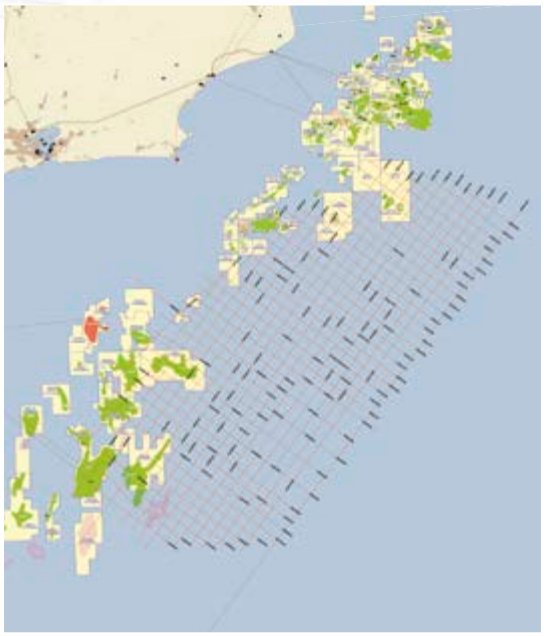
Shale Gas World is a great place to meet anyone concerned with the prospect of shale gas exploration in the UK. For the last couple of years it has been held in Manchester, but due to an increased level of interest from both attendees and exhibitors, this year it will be held in the NEC in **Birmingham**, UK, on May 13–14, 2014.

Topics to be discussed include commercialization of shale gas reserves, environmental and water management challenges, and how to optimize drilling and completions to maximize value. There will be key note talks from Cuadrilla Resources, the only company to have fracked a shale gas well in the UK, while the British Geological Survey will discuss the extent of resources, and representatives from Greenpeace and other environmental organizations will seek to find a common ground for the UK's energy future. A popular feature of these meetings are roundtable discussions hosted by community leaders, operators and license holders, where all attendees contribute. ■

Brazil Santos Campos New Multi-Client 2D data available

Dolphin geophysical

- Multi-Client Santos-Campos Basin, deep water Brazil
- 13,650km of Long-Offset (12,000m streamer) dataset provides industry with a 10 x 10km grid with line ties to several pre-salt discoveries, including Tupi and Libra
- Kirchhoff PSTM, Kirchhoff PSDM and Reverse Time Migration Phase 1 available
- Several large pre-salt leads identified with resemblance to existing giant discoveries. Post salt upside potential over large unlicensed areas.
- Interpretation study available



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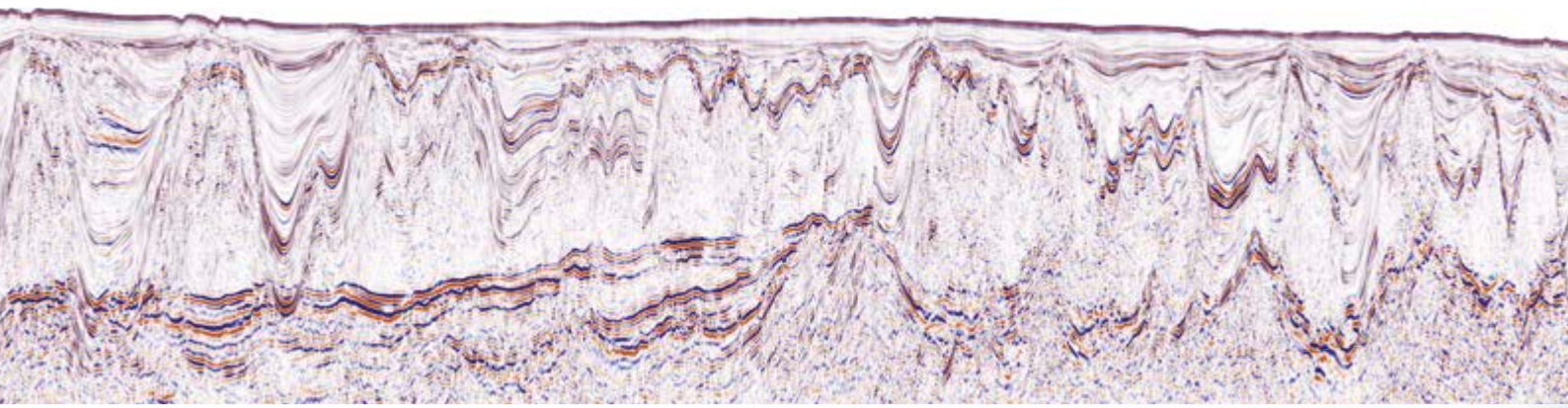

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Downhole Multi-Channel Photometer

Avo-produced multi-channel photometer inside the Weatherford sensor.

Downhole fluid analysis (DFA) prior to oil or gas production is essential in order to design production strategies and production facilities. DFA applications span deepwater, exploration, sample validation, fluid analysis between samples, where flow assurance is an issue, when mapping water floods, when determining reservoir connectivity, when determining compositional grading of reservoir and to see if fluids are changing. The Wireline R&D optical sensor group in oilfield services company **Weatherford** have collaborated with opto-electronic design and production specialist **Avo Photonics** to develop a downhole multi-channel photometer. The new **Reservoir Fluid Analyzer** sensor, which conforms to a 4.5 inch diameter space, can perform down-hole fluid analysis up to 5 km below the earth's surface, and perform high-quality photometric analysis while withstanding operating temperatures from -20 to 177°C with total differential pressures up to 30,000 psi. The sensor has completed several field trials and is being volume manufactured by Avo Photonics for Weatherford commercial deployment. ■

Uganda Edges Closer

Uganda took a step closer to becoming an oil-producing nation in February when it signed an MoU regarding the start of oil production with **Tullow Oil**, **Total** and **CNOOC**, which have formed a joint venture to develop a number of recently discovered fields in the Albertine Graben. The MoU provided a framework for commercial production, including providing fuel for power generation, supplying crude oil to a planned refinery with initial capacity of 30,000 bpd, and exporting crude by pipeline. Uganda will join a project to construct a pipeline to Kenya's planned new Indian Ocean port of Lamu, which is expected to become the regional export terminal. Ugandan production is not expected to start until 2016 at the earliest. ■

The Story Behind

The **Geological Society of Norway** invites explorationists to two beautiful days in **Oslo** in May. Surrounded by Cambro-Silurian sedimentary rocks of the Oslo Graben, recent discoveries on the Norwegian Continental Shelf will be the focus of a conference that reflects the new spirit in the exploration of the sedimentary basins offshore Norway.

The aim is for oil companies to share the background that led to their decision to drill a prospect: '**The story behind the discovery**'. Were there specific geological analyses behind the decision? Had someone done thorough research and re-analyzed the logs and samples from dry wells or technical discoveries? Or was there an observant geologist who spotted something interesting in the seismic data? The answers could be an inspiration to others, and thereby indirectly lead to other discoveries, large and small, on the Norwegian Continental Shelf. This conference will also feature the very first **prospect fair** in Norway. Service companies will get the opportunity to share prospects defined by seismic and EM data, while oil companies will be able to present promising prospects. ■

On the first day curious geologists are invited for a guided walk on the Fornebu peninsula, where Paleozoic sedimentary rocks are nicely exposed.

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Geophysical Services

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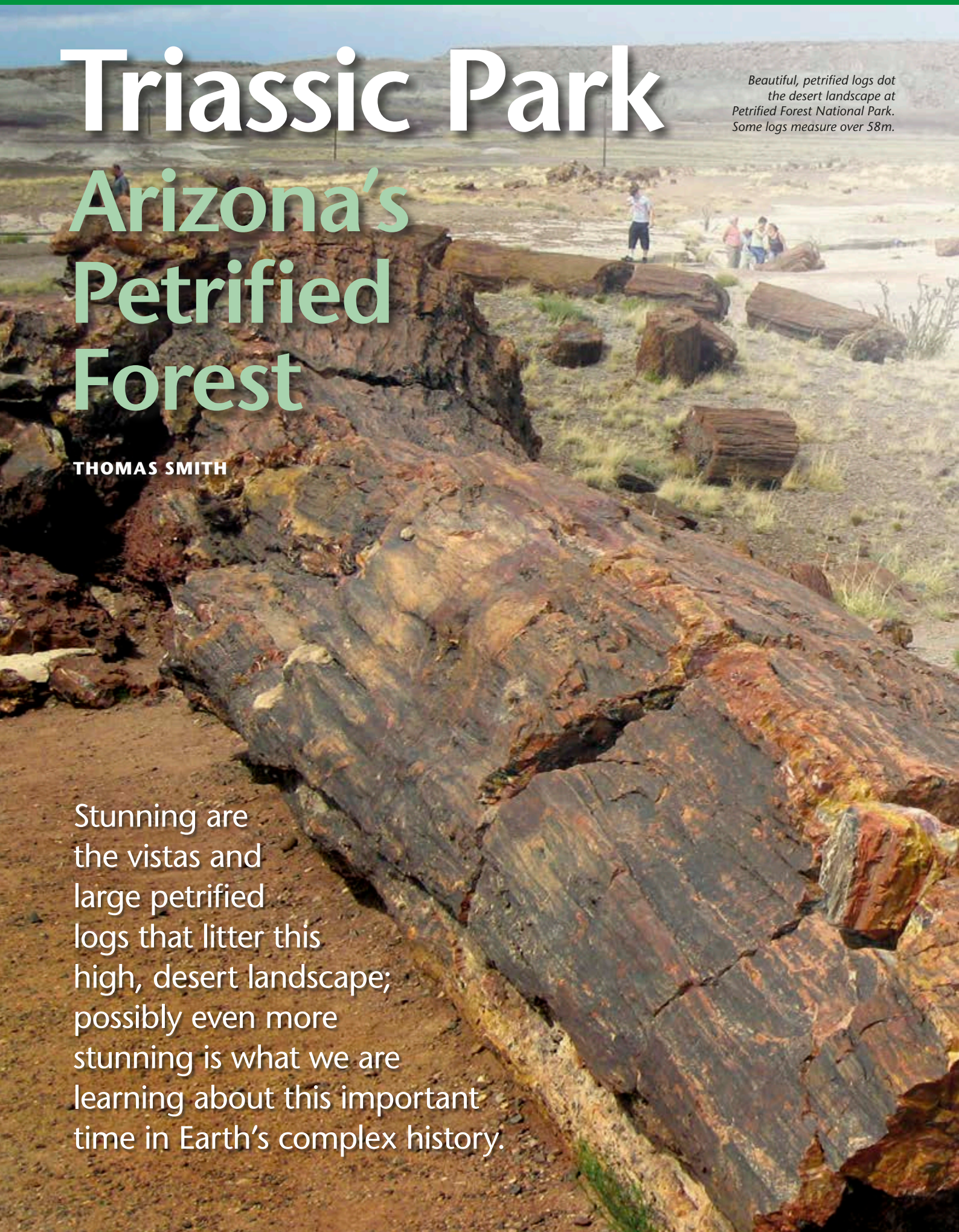
Triassic Park

Arizona's Petrified Forest

THOMAS SMITH



Beautiful, petrified logs dot the desert landscape at Petrified Forest National Park. Some logs measure over 58m.

Stunning are the vistas and large petrified logs that litter this high, desert landscape; possibly even more stunning is what we are learning about this important time in Earth's complex history.

Petrified Forest National Park (PFNP), located in north-west Arizona, is renowned for its brilliantly colored petrified logs scattered throughout the red, brown, and white hills and bluffs. Two hundred million years ago, when the climate was much wetter and warmer than today, conifer trees once lined ancient waterways. Periodic flooding would uproot and bury these trees and over time, the wood was replaced by quartz that is tinted into a kaleidoscope of rainbow colors. But what may be even more remarkable than the beautiful petrified trees is the historical narrative that other ancient animals and plants, well preserved in the park's strata, are telling us about the climate changes and evolution that took place in the Late Triassic.

The Chinle Formation, extensively exposed in the park and outcropping across much of the Colorado Plateau, is one of the most researched Late Triassic continental deposits in the world. Preserved in the strata of the PFNP is probably the best-studied terrestrial vertebrate faunas from this critical time in Earth's history. This period is situated right between the Permian and the end of the Triassic mass extinctions. Detailed mapping of the strata has led to a new interpretation of the biostratigraphy and a recent core drilling project may provide more information to the history and climatology of this 20 million-year time frame.

Park History

People have known about the Petrified Forest for over 13,000 years. Camp remains, tools, and projectile points made from petrified wood have been found in this area, dating from just after the last Ice Age to historic times. The Spanish were among the first Europeans to visit the area in the 16th century, but with no mention of the petrified wood; they were concentrating their efforts on finding routes between colonies along the Rio Grande River to the Pacific Coast. Within the park, Spanish inscriptions from the 1800s can be seen on some of the rocks.

The south-west became part of the US territories in the mid-1800s. In 1853, US Army Lt. Amiel Whipple was exploring a route along the 35th Parallel when he came upon a sandy wash in the Painted Desert that had deposits of colorful petrified wood along its banks. Whipple named it Lithodendron ('stone tree') Creek and was the source of the first published account of petrified wood in what would become PFNP. Settlers followed the 35th Parallel route and grazed cattle, sheep, and horses in the park until the mid-20th century. What started out as a wagon road in 1857 and a stage line in 1874, became the famous Route 66 in 1926. This route now is Interstate 40, a major US east-west connection, first crossing the park in 1958.

Once the area was discovered, the petrified wood began disappearing. In spite of regulations and fines, resource managers found that visitors could not resist taking these beautiful rocks. Congress turned down a bill to designate it a park in 1895. Conservationist John Muir explored the area in 1904 and 06. Whether or not Muir had any influence to protect this unique area, President Theodore Roosevelt established Petrified Forest National Monument in 1906 and in 1962 the US Congress made it a national park. More recently, the park boundaries have been expanded, more than doubling its size from 37,851 to 88,437 hectares.

Focusing on the Late Triassic

The Triassic Period in Earth's long history holds a particularly prominent position; it was a time of great change and rejuvenation after nearly 90% of the planet's species died off at the end of the Permian Period. New creatures that included rodent-sized mammals and the first dinosaurs became part of this new, growing diversity. It was also a time when its landmasses, originally linked as one supercontinent called Pangaea, had by the end of this period started breaking apart. The Late Triassic ends in a mass extinction that ushered in a time when dinosaurs would dominate the earth. Leading up to that mass extinction was an earlier faunal and floral transition, or even possibly a smaller extinction, that corresponds with a change in climate.

For over 50 years, many researchers in this area have focused on the Late Triassic. Interpretations concerning fossil transitions and climate change have been made that had regional and even global implications. However, one of the big questions that was not being answered was just when did this change occur?

This was just one question bothering William Parker, Chief Paleontologist at Petrified Forest National Park. "Despite over 150 years of study, the stratigraphic distribution of fossils in Upper Triassic deposits of the south-western United States

Thomas Smith

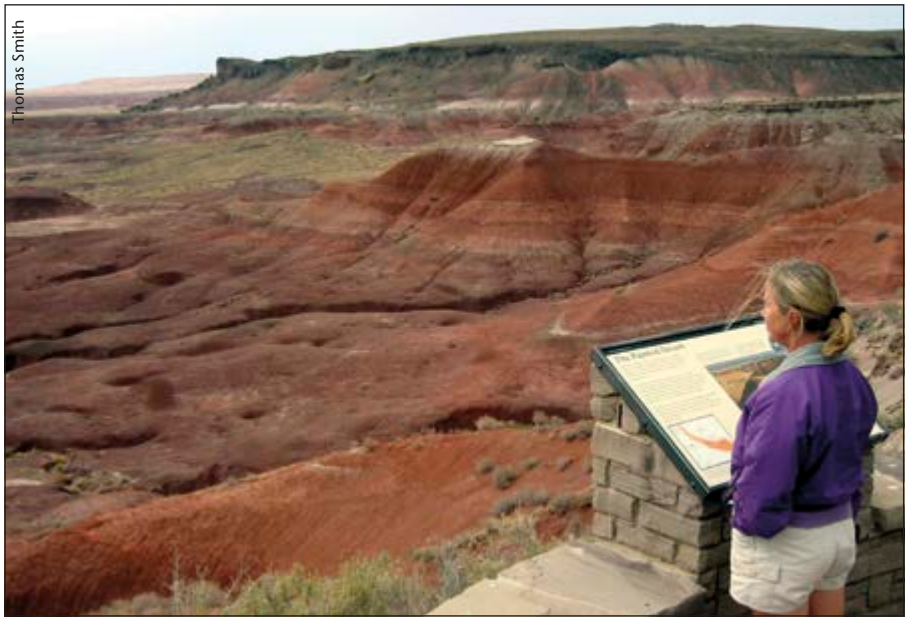

Thomas Smith

The petrified wood found in the park is almost solid quartz, with vibrant colors caused by impurities like iron, carbon, and manganese.

In a recent paper, Jeffrey Martz and William Parker, Petrified Forest National Park paleontologists, wrote: 'Geologists and paleontologists are ultimately historians whose objective is to construct an accurate narrative of the history of the earth and its living organisms, and to understand why these events occurred… Developing an accurate and detailed lithostratigraphic framework is the first and most essential step before anything collected from these strata can be used to construct a narrative.'

is still not well understood," says Bill. "When I started field work here in 2001, I found certain beds were incorrectly correlated, leading to errors in placing fossil and sampling localities within the stratigraphic framework. I knew that to make sense of what the fossils were trying to tell us, we needed to accurately relocate and plot all known Upper Triassic vertebrate fossil localities. We started our detailed remapping and relocation of fossil occurrences in the southern portion of PFNP."

Beautiful, scenic vistas like this one looking north across the Painted Desert, plus hiking, dark skies, intriguing history, and the colorful logs of petrified wood, draw visitors to Petrified Forest National Park.


Thomas Smith

Recognizing that there were multiple, look-a-like sandstones in this fluvial environment was one of the keys in helping Bill and Jeffrey realize that there were correlation problems with previous lithologic studies. Most of the previous researchers were content with the coarsely resolved stratigraphic framework when using the vertebrate fossils as biochronologic indicators.

Now, knowing that there were problems with the area's lithostratigraphy, and particularly correlation errors within the Sonsela Member of the Chinle Formation, they went back to the basics by 'walking outcrops and contacts, checking section measurements, and mapping the area in detail'. The process of getting 'back to the basics' can be difficult and sometimes forgotten when a lot of data already exists. Whether using outcrop or subsurface data, it is good to look back and make sure the basic data is sound (their premise in doing this work) so that the models made from that data are equally as sound.

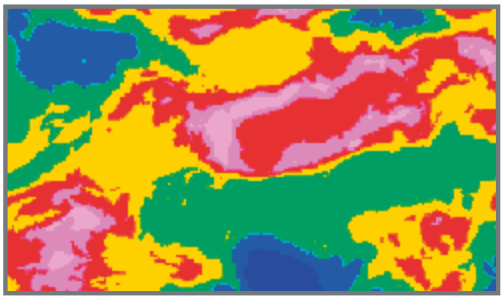
A new, comprehensive geologic map of the area was published in 2012. Armed with accurate sample localities, measured sections, and properly correlated beds, the two park paleontologists could begin to unravel the overall geology and history of the area in yet another 'revision'.

Re-Revising History

"If the basic superpositional relationships of the fossils, mag-strat samples, volcanic

The Neuquén you never knew

Uncovering the hidden secrets of one of the world's largest shale plays



Using predictive analytics, NEOS GeoSolutions combined hyperspectral, magnetic, electromagnetic (EM), gravity, and seismic datasets to determine optimal drilling locations. Warmer colors indicate higher prospectivity.

Argentina's Neuquén Basin is one of the world's most dynamic and underexplored hydrocarbon systems. Its two principal shale targets – Los Molles and Vaca Muerta – have been rich source rocks for the conventional reservoirs that have been produced in the basin for more than 50 years. With new technologies available for unconventional asset exploration and development, producers are taking a second look at these extremely thick oil- and gas-charged shales. While several seismic and non-seismic datasets have been acquired, the coverage lacks uniformity, and no one has been able to integrate the data into a single, actionable interpretation — until now.

NEOS GeoSolutions has acquired high-resolution, airborne geophysical data over 30,000 square kilometers of the Neuquén Basin. Using innovative, multi-measurement methodology, the company has integrated these new measurements with existing well, geological, geochemical, and seismic data available in the public domain, from third parties, and from the project's underwriters. NEOS designed the Neuquén survey to provide the project's underwriters with an enhanced basement-to-surface understanding of the basin and its potential.

Initially, high-resolution hyperspectral imaging was acquired to map the regional lithology, the total organic carbon (TOC) of the target shales, and oil seeps and indirect hydrocarbon indicators on the surface. A second work stream generated 3-D models constrained by the structural aspects of existing seismic lines, available well data, and newly acquired gravity and magnetic measurements. These models provided useful exploration insights by depicting isopachs, burial depth, depth-to-basement, and proximity-to-intrusives for all target shale horizons.

The team also developed a new hydrocarbon maturation model by combining the 3-D model, existing basin TOC models, and surface samples. This analysis identified new areas of opportunity previously considered to be overmature. By interpreting the locations of volcanoes and intrusives from airborne magnetic data, a new thermal gradient model was developed, refuting the misconception that intrusives had terminally degraded regional opportunities.

Finally, NEOS combined all datasets using a geostatistical data mining technique called predictive analytics. By analyzing key attributes – including shale thickness, a set minimum amount of overburden over the objective, a minimum of faults and fractures along the drill path or near the bottom-hole location, the potential for generated and retained liquid hydrocarbons, and a relatively flat topographic area for drilling – NEOS and client geoscientists highgraded acreage to identify optimal drilling locations and reveal the lucrative secrets of the Neuquén.

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

HIGHLIGHTS

KEY TECHNOLOGIES:

- MAGNETIC
- GEOCHEMISTRY
- GRAVITY
- HYPERSPECTRAL
- PREDICTIVE ANALYTICS
- SEISMIC REINTERPRETATION

AREA: Neuquén Basin, Argentina

CUSTOMER: Supermajor

FOCUS: Regional Mapping

TYPE: Unconventional

KEY INTERPRETIVE PRODUCTS:

- Regional 3D subsurface models
- Horizon-specific isopach maps
- Estimates of gas-in-place on an areal basis, developed using multi-variate analysis

CUSTOMER BENEFITS:

Reveals new prospectivity in the frontier portion of an established basin by integrating new airborne geophysical measurements with existing seismic, well, and geological and geophysical (G&G) data.

Ancient People

As well as being very scenic, the park is an open research laboratory drawing geologists, paleontologists, archeologists, historians, biologists and other scientists. It was chosen as the site for the first core drilling into the Late Triassic strata, part of the Colorado Plateau Coring Project. Once interpreted, the 548m of core taken late in 2013 will add to our knowledge of this critical period of the earth's history. Considerable ongoing archeological studies of the many sites located in the park is adding to the understanding of the ancestral past, while investigations into more recent faunal and floral changes are giving new insights over our more recent past. PFNP is truly a research park open to all disciplines.

People have inhabited the PFNP area for over 13,000 years. There are nearly a thousand recorded archeological sites and one of the most diverse collection of ceramics from northern Arizona has been found in the park as well.

Near the end of the last Ice Age, a highly mobile population moved into North America. They were focused on big game (Pleistocene mega-faunas such as mammoth and bison) and left behind lithic tool kits and highly diagnostic projectile points. The Clovis and Folsom people, during what is called the Paleoindian Era (13,000 to 8,000 B.C.), used the petrified wood for tools.

The Archaic Era (8,000 to 500 B.C.) followed with the transition from specialized hunters to a more broad-spectrum diet that included many different species of plants and animals. Corn arrived from the south late in this period and farming and sedentism began. These people left behind flaked tools, basin metates and one-handed manos used to grind corn, but no pottery from this period has been found.

Next came the Basketmaker Era, lasting from 500 B.C. to A.D. 650. These people lived in stone-lined pithouses and became increasingly sedentary. They grew corn, squash and beans and left behind beautifully made baskets and pottery. Most of the petroglyphs in the park were created by these people, including images of humans, animals, and solar events like the summer solstice.

The Pueblo periods followed, and these people started to build above-ground, masonry structures, first for food storage and then as places to live in. This was a stressful period as a major drought hit the region for about 50 years, ending in about 900 A.D. This is when artisans began decorating their pottery with black on white painted designs.

Agate House was constructed entirely from petrified wood during the Pueblo II period and was reconstructed in the 1930s. Located on a small hill within the Rainbow Forest, Agate House is an easy 2 km hike across badlands and a petrified wood-scattered landscape from the Rainbow Forest Museum.

PFNP has hundreds of petroglyph sites containing thousands of petroglyphs. Some, like this bird capturing a person, make you wonder what really happened.

The Pueblo communities increased throughout the III and IV periods of the Basketmaker Era – one of the ruins in the park has over 200 rooms. Some of the sites have been partially reconstructed while the Black Ax site, which may be the area's largest, has seen only preliminary exploration. By the end of the Pueblo IV period, about 1450, PFNP communities appear to have been depopulated and sometime later, Hopi, Zuni, and Navajo peoples began to use the region and continue to do so into the present.

minerals, and lithologic units used to acquire this information [that is used to derive a historical narrative] are misunderstood, the interpretation derived from them will be inaccurate," says Bill Parker. "The order and timing of events will be wrong, and any attempt to understand cause and effect will be in vain."

The well-exposed and studied rocks and fossils within PFNP have yielded interpretations that have been applied to regional and global climate and faunal changes. Previous studies of this area have hypothesized a Late Triassic (Tr-4) area-wide unconformity and put an important faunal transition, called the Adamanian-Revueltian transition, at this time point. Previous studies also concluded a significant overlap of the Adamanian-Revueltian faunas. Because of this faunal overlap, these same studies clearly reject the idea that a global tetrapod extinction occurred within the Late Triassic.

Martz and Parker recognized that previous studies relied on poorly documented correlations to make important biostratigraphic conclusions, so they concentrated their initial efforts on accurately mapping and correlating stratigraphic relationships in the park. This led to some interesting discoveries; they were able to clarify the local

Along with the fauna and flora that populated the area, one of the keys enabling Bill Parker and Jeffrey Martz to understand when the climate started to change was the location of the 'persistent red silicrete' bed marking the Adamanian-Rivueltian transition. They were able to place this within the lower Jim Camp Wash beds in the Sonsela Member, rather than at the Tr-4 unconformity as other researchers did.

Jeffrey Martz, paleontologist at PFNP, at one of the 'Flattops One sandstones' within the Sonsela Member of the Chinle Formation.

biostratigraphy with some profound regional and global implications. (It should be noted biostratigraphic 'revisions' from other areas have been shown to have comparable problems. Jeffrey Martz did a similar study of the Upper Triassic Dockum Group of West Texas that resolved conflicts in the lithostratigraphic and biostratigraphic correlations for that region.)

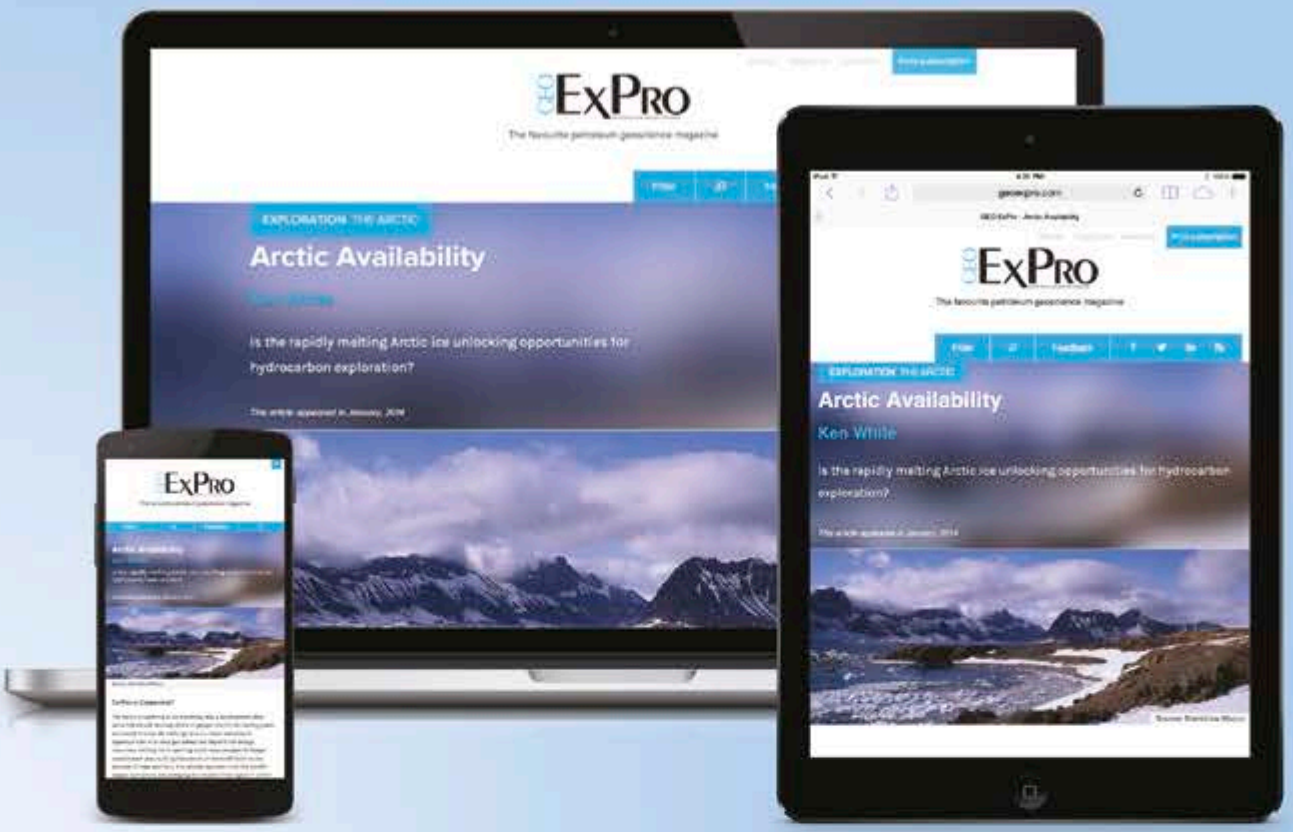
Now Parker and Martz can actually constrain where, in the strata, the changes happened. They showed that a single unconformable horizon within or at the base of the Sonsela Member, which previously was traced across the entire western United States (the Tr-4 unconformity) probably does not exist. The significant overlap between the Adamanian and Revueltian faunas has been rejected and does not occur at the Tr-4 unconformity. They know this by accurately locating samples and important boundaries within the correct stratigraphic levels.

These two paleontologists found a fossil turnover at the Adamanian-Revueltian boundary occurring at a time of climate change for the region, from relatively humid and poorly-drained to arid and well-drained. The vertebrate fossil transition occurs with the floral changeover based on recent palynology studies, and age constraints put this at about the same time as the Manicouagan impact event. The Manicouagan Crater is located near Quebec, Canada and is one of the oldest and largest impact craters on Earth dated at 214 million years ago, in the middle Late Triassic. Their studies also show that dinosauromorph diversity has held constant across the Adamanian-Revueltian transition, indicating it probably did not lead to the rise of dinosaurs in North America.

While these revisions may not seem major, in the realm of biostratigraphy they loom large. Attention to detail has paid great dividends to our understanding of the Late Triassic. In the oil and gas business, going back to basics and using constrained and accurate data to model a prospect is a foundation that can make the difference between a duster and a gusher. Remember, not all 'Flattops One sandstones' correlate.

Acknowledgements:

Special thanks to William Parker, paleontologist, and William Reitze, archeologist, for their help and information.



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New Insights on the Alaskan Chukchi Sea

Operationally challenging, environmentally sensitive and seasonally limited; the vast bounds of the underexplored basins of the Arctic region remain of significant long-term importance to the future of global energy demand. The offshore Chukchi region of Alaska represents significant untapped petroleum resources. The most recent assessment by the USGS suggests a potential 29 billion barrels of recoverable reserves.

BRAD TORRY, THANE STRANDBERG, ABU CHOWDHURY, JASON KEGEL, JAMES KEAY, TGS

The Chukchi Sea is part of the Arctic Ocean and generally considered part of the Alaskan Arctic Basin. It is bordered to the west by Russia's Wrangel Island and the East Siberian Sea, in the east by the Beaufort Sea, and in the south by the Alaskan mainland (Point Barrow to Cape Lisburn) and the Bering Strait. The Chukchi Sea is dominated by a broad, shallow continental shelf (the Chukchi Shelf) with water depths to 100m (330 ft).

Although oil production on Alaska's North Slope began in 1977 (see *GEO ExPro*, Vol. 7, No. 6), to date it has all been on state lands (North Slope Region) and in state inshore waters of the Beaufort Sea. The US government began offering oil and gas leases in th e Chukchi in the 1980s followed by an initial phase of exploration which identified active petroleum systems: however, there has been no development to date.

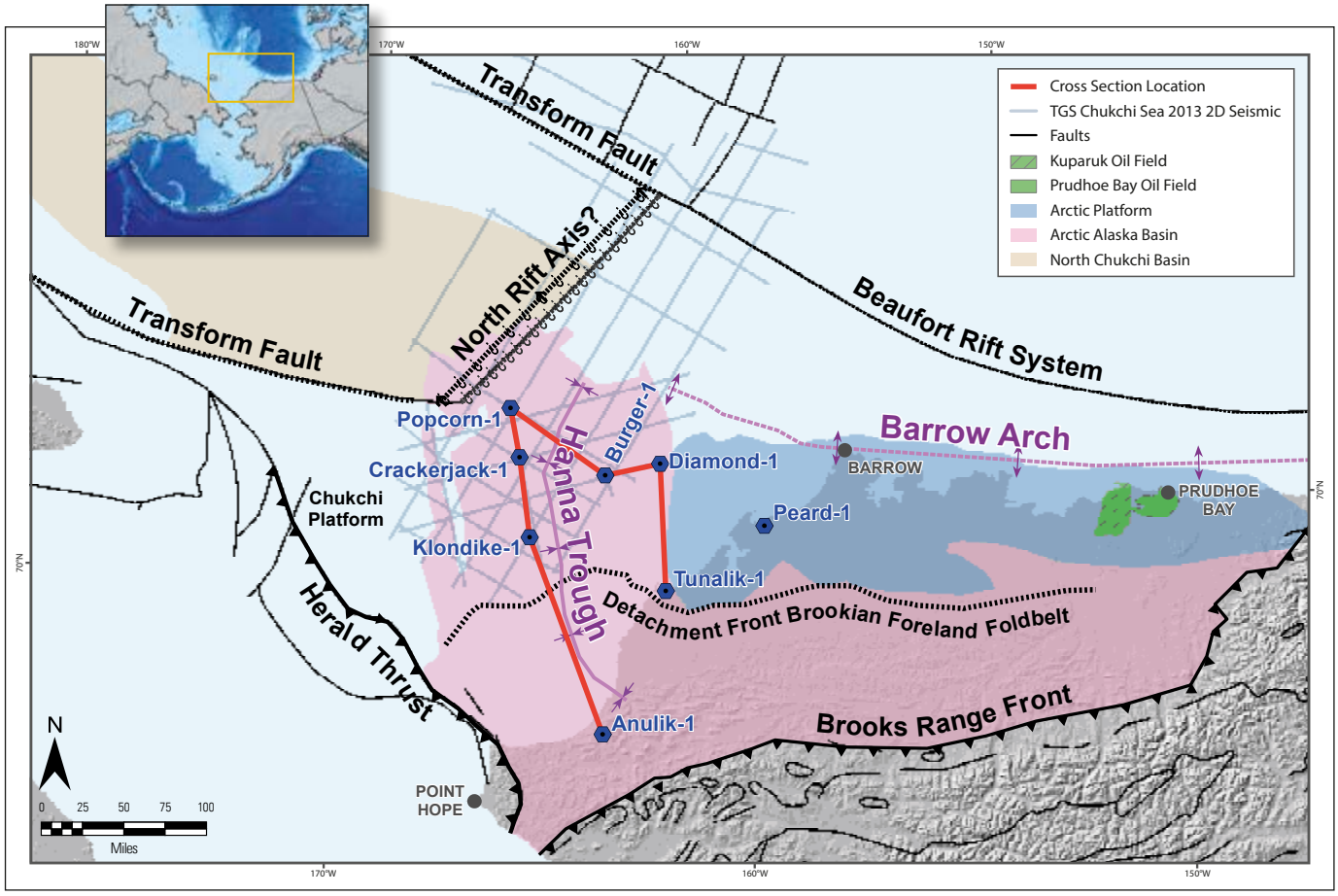
While the focus of this article is the Chukchi, it is important to note the global effort (including the USGS in Alaska, DMNG in Russia, Greenland, Norway, Finland, Iceland and Canada) as part of a circumpolar initiative to understand the basin-forming relationships, petroleum systems and hydrocarbon potential of the Arctic region.

Geophysics and Leasing Activity

Exploration along Alaska's North Slope (onshore) in the mid-1960s resulted in the Prudhoe Bay discovery in 1968. Extrapolating these results offshore, early geophysical assessments were made with potential fields' data followed by early 2D seismic. With the advancement of technology, longer offset, higher density 2D data continued to be acquired through the 1970s, 80s and 90s. In the Chukchi Continental Shelf area approximately 160,000 line kilometers of 2D seismic (offsets 6,000m maximum) were acquired between 1988 and 1991 in support of the lease sales and initial drilling activity. These efforts resulted in five exploratory wells (Klondike, Burger, Popcorn, Crackerjack and Diamond), the last of which was drilled in 1991. These early wells validated the presence of an active petroleum system, prospective reservoirs and both oil and natural gas potential, and established initial offshore reserves (Burger was estimated at 5

TGS

The coastline social, environmental and community responsibility are all issues to be dealt with in Arctic exploration.



General current sedimentary configuration with corresponding major structural elements, with the 2013 Chukchi seismic program and historical well locations.

TCF). Following a hiatus in activity, new longer offset 2D data was acquired in preparation for the 2008 lease round. 3D data was acquired in 2010 following the lease round. Since this time no new data had been acquired until TGS began its Chukchi Sea 2D program in 2013.

Land activity in the Chukchi region has occurred in three activity cycles. During the 1988–1991 period, four lease rounds were held in the Chukchi region which amounted to industry investment of $512 million on 483 blocks (2.7 million acres), none of which remain active today. Renewed interest followed the USGS assessment update in 2006 resulting in the OCS sale in 2008, which generated $2.7 bn and a new round of exploration activity. Following this lease round, certain oppositions to oil field activity resulted in a suspension of future lease rounds until agencies could produce a longer term plan for the region. This plan for the OCS region resulted in a five-year plan covering the 2012–2107 period. To enable time for more scientific studies the next lease round for the Chukchi is planned for 2016.

Structure and Petroleum Systems

As part of the Arctic Alaskan Basin, the Chukchi Sea region is generally considered a Mesozoic rift style basin consistent with its Arctic analogs: Russian Chukchi, Barents Sea, Greenland, and Beaufort. As identified on the map, the Chukchi is comprised of a number of structural terrains that define the basin/sub basin configurations. As new data is acquired and interpreted, these boundaries and our understanding of the tectonic events and implications to petroleum systems continues to grow. For the purpose of this article we have broken the basin into two regions: the Chukchi Shelf (area covered by current OCS leases bounded to the west by the Herald Thrust Zone and to the east by the Barrow Arch) and the North Chukchi Basin.

With only five offshore wells, understanding of the Chukchi stratigraphy has been constructed through extension of the highly petroliferous systems of the North Slope region with proven source and reservoir rock. The major stratigraphic sequences of the Chukchi are defined by four major unconformities; these sequences are the Franklinian (pre-Devonian), Ellesmerian (Triassic to Carboniferous), Beaufortian (Late Cretaceous/Jurassic) and Brookian (Cenozoic/Early – Mid Cretaceous). Work done in the late 1990s on Wrangel Island and onshore Alaska (Brooks Range) provides a key outcrop reference to these sequences and aids in our understanding today of the potential for hydrocarbon accumulations. Linking to the key structural events, these intervals may also be categorized as pre-rift sediments (Franklinian and Ellesmerian), rift sediments (Beaufortian) and post- rift sediments (Brookian).

The Franklinian (pre-rift) sequence is characterized from observations in the Brooks Range and Wrangel Island (outcrops) and a number of penetrations on the Alaskan North Slope. In the Chukchi, it is believed to consist of primarily carbonate, sand and shale sequences with areas potentially influenced by mafic intrusives and as yet poorly understood erosional boundaries. Considered a potential source and reservoir rock, true thickness and exploration potential remain to be determined.

Brute stack of 2013 Chukchi seismic – significant hydrocarbon potential can be identified in a complex structural setting, with a thick untested sedimentary section.

The Ellesmerian is the most prolific and understood sequence in the region. Production at Prudhoe Bay (and other fields of the North Slope) is attributable to this sequence, and it is the primary target for the current inventory of offshore wells. Production is generally from the carbonate facies of the Lisburn Group while secondary conventional production is from the interbedded sand/shale sequences in the Triassic interval. It should be noted that considerable unconventional potential exists in the marine shales over this interval, although offshore activity is currently focused on conventional production.

The Beaufortian sequence makes up the major infill from rifting and is largely comprised of marine and terrestrial sand and shale sequences. Understanding of spatial distribution of sands remains in its infancy with the limited offshore control. Many of the existing offshore wells did not encounter or encountered limited reservoir rock. Additional data should provide new information and ongoing prospectivity for this zone.

Brookian rocks make up the dominant section of the proven petroleum systems of the North Slope and Chukchi. Primarily thick marine and terrestrial shale and sand sequences, these sediments are considered excellent reservoir rocks with both structural and stratigraphic implications.

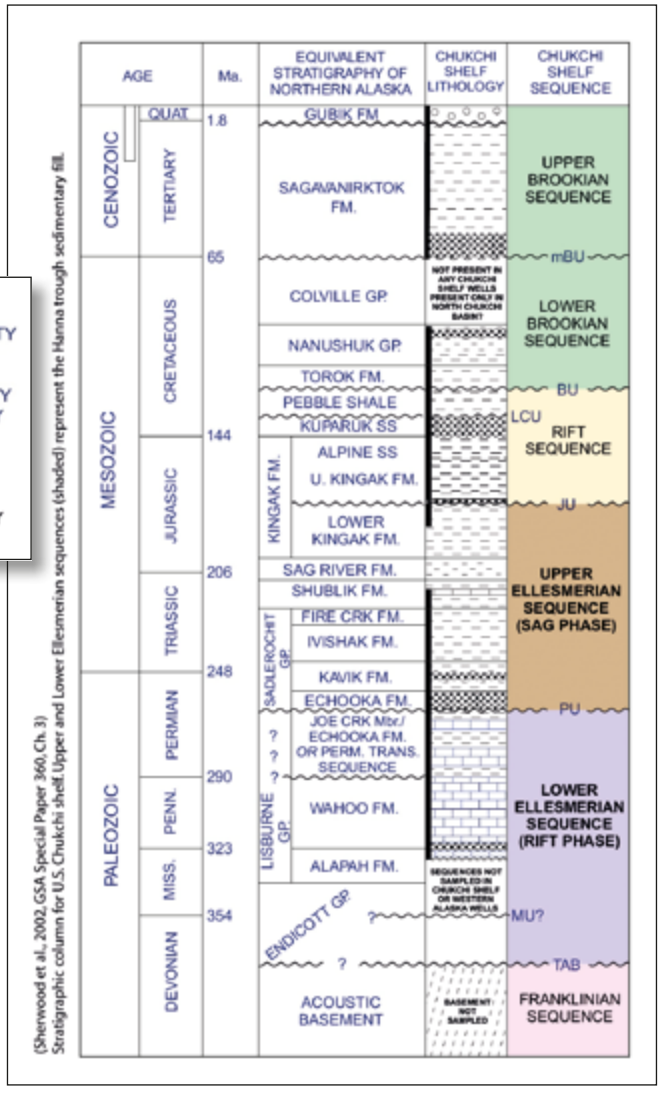
Trapping in the Chukchi is considered combined structural and stratigraphic. As with most early exploration, targets have been focused on large regional structures with four-way or fault-bounded closures. New work to identify AVO class anomalies or estimation of reservoir properties will enhance these interpretations. With new data, additional insight into stratigraphic boundaries may provide advance opportunities for early explorers.

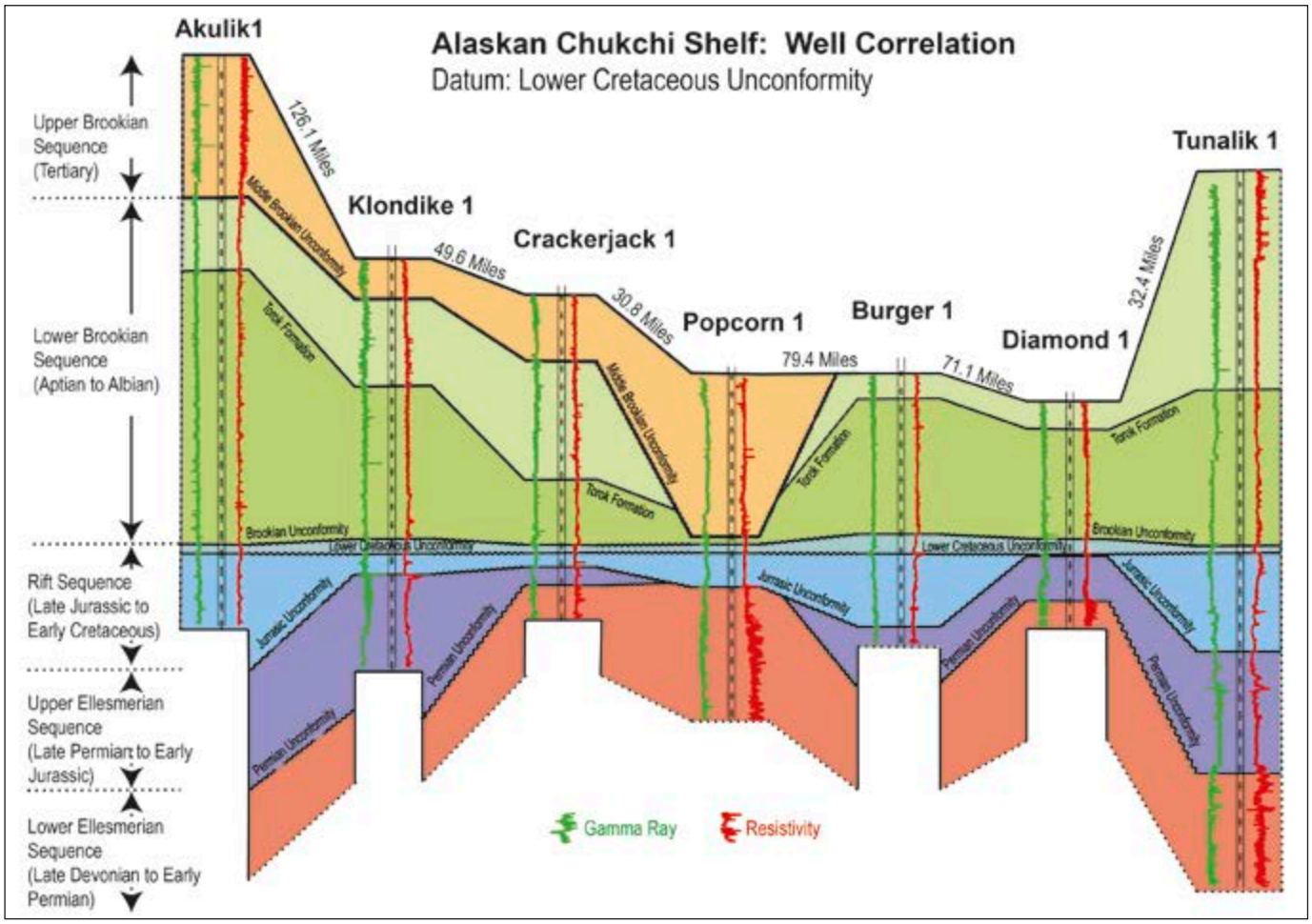
Exploration Risk Reduction

The objective of TGS's 2013/2014 seismic programs is to acquire new high resolution long offset 2D to image both the current OCS blocks in the Chukchi Continental Shelf region and extend our understanding further offshore into new exploration in the North Chukchi Basin.

The 2013 program was acquired during the open water season (July–October), and was conducted in water depths ranging from 100 to 3,500m. Early observations from the 2013 seismic program are provided in the seismic line shown on page 31 (example of data from the Chukchi Shelf). The new information, although preliminary, confirms existing

US Chukchi Shelf stratigraphic column.



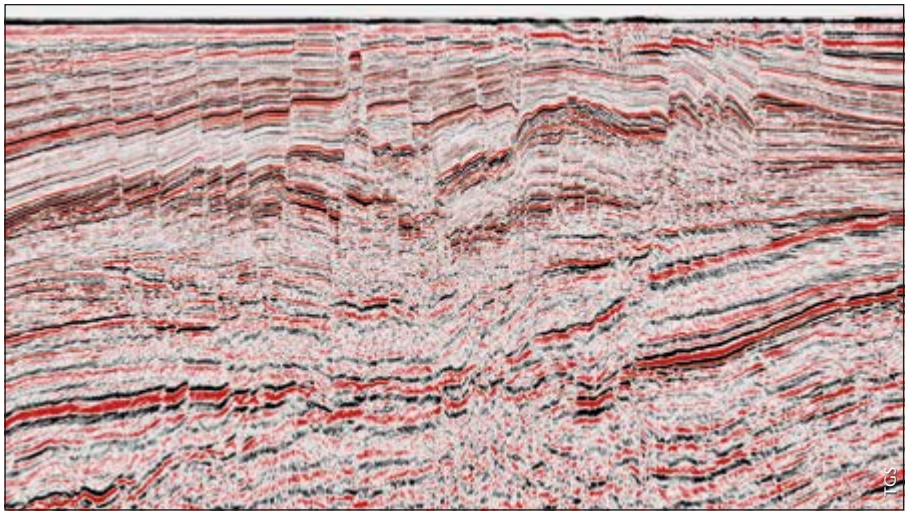


Representative section of LAS+ well curves extending from onshore to the offshore Chukchi wells. It provides a regional view of the general facies boundaries and the level of structural and stratigraphic. (Cross-section created using TGS data with reference to Sherwood.)

known structural elements and suggests the rift basin fairway may stretch beyond traditional thinking, while syn-rift/pre-rift sediments appear thicker and reach burial depths far in excess of those encountered on the shelf. The quality of the new data also enables advanced structural and stratigraphic imaging as can be observed in the line below. This level of detail provides new insight to understanding the prospectivity of the region.

Social responsibility remains a cornerstone of exploration activity and requires ongoing commitment to address and mitigate social, environmental and community impacts to enable the responsible co-existence of all activities. TGS has and will continue to engage local communities and agencies to address the requirements of all stakeholders and ensure sustainability and co-existence of our activities.

The new data reveals advanced structural and stratigraphic imaging.



Where Next?

The extension of the Mesozoic rift section throughout the survey area has led to the identification of genuine opportunities on the shelf and in the deepwater offshore Alaska. Further acquisition and renewed drilling activity will continue to expand and define the potential of the region.

Ongoing assessment of geotechnical data will advance understanding of petroleum systems in the Chukchi and the regional basin architecture. This information remains critical to the comprehension and prioritization of areas for future development and advancement of exploration in the circumpolar region. ■

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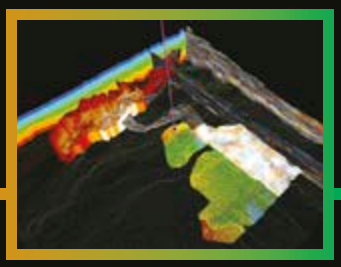

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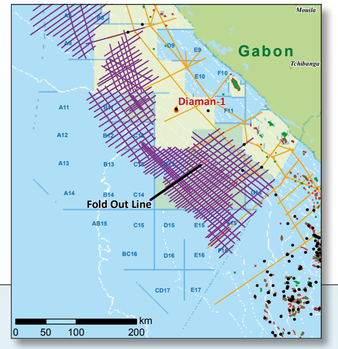
New Plays from Old:

Frontier Exploration at the Western Edge of Gabon's Salt Basin

Spectrum



Map over south Gabon's salt basin showing Spectrum's 2D dataset extending to the western limit of the salt basin.

In 2013 the Diaman-1 well was drilled by Total in 1,754m of water in the southern salt basin offshore Gabon, discovering hydrocarbons in the pre-salt section. The well is significant as it is the first in the salt basin to prove a working hydrocarbon system in the slope, deepwater, pre-salt play. It lies 120 km from the shore and 60 km further west than the adjacent oil discoveries on the shelf. However, the salt basin itself and its pre-salt prospectivity can be mapped extending another 120 km offshore from Diaman-1. At the edge of Gabon's salt basin a system of areally large horst structures are interpreted on seismic, presenting extraordinary pre-salt oil potential. The imaging of these horst suggests that, despite the Diaman-1 success, exploration has barely begun to unlock Gabon's deepwater plays.

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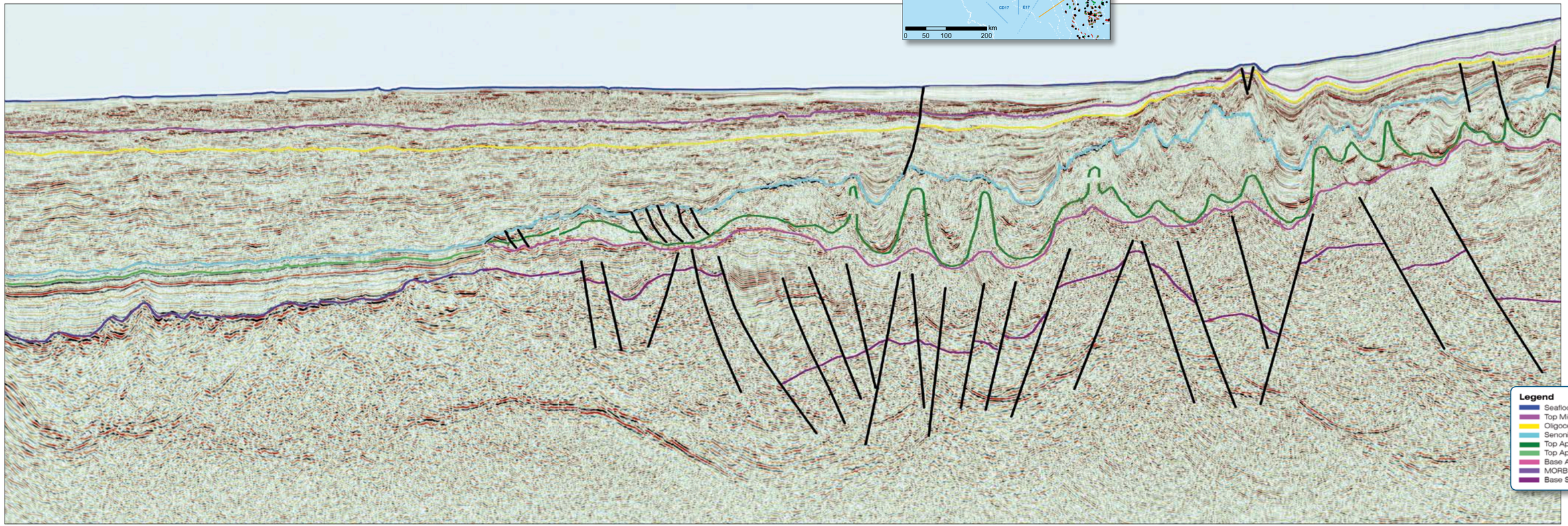


Long line (88km) showing the syn-rift outer high of Gabon.

Gabon

World-Class Frontier Exploration Targets

NEIL HODGSON, ANONGPORN INTAWONG, Spectrum

Seriously underexplored, the potential for deepwater Gabon to provide a spectacular future for sub-salt discoveries is very promising

Although Gabon's southern salt basin extends over an area of some 60,000 km^2, only 30% of it has been explored to date, predominantly in shallow water (jack-up drilling territory <200m water depth) or indeed onshore. Here, many large oil fields have been discovered below the Aptian salt (for example the Rabi Kounga and Gamba Fields), yet no discoveries have been made in the relatively thin post-salt Late Cretaceous and Tertiary sequences.

Until 2013 the progression of exploration from onshore sub-salt to offshore sub-salt in southern Gabon had not developed far beyond the shelf, primarily because of the lack of seismic capable of imaging the pre-salt section, and the lack of control in depth converting this section. Complex salt walls and diapirs, and even more complex velocity profiles within the Late Cretaceous sequences filling sediment pods between the salt had meant that structural imaging and trap integrity still carried an inherent risk. However, the first step into deepwater sub-salt was taken by Total in 2013, drilling the Diaman-1 well in the Diaba Block, in water depths of 1,725m, where they discovered gas and condensate in the syn-rift, Dentale Formation sandstone.

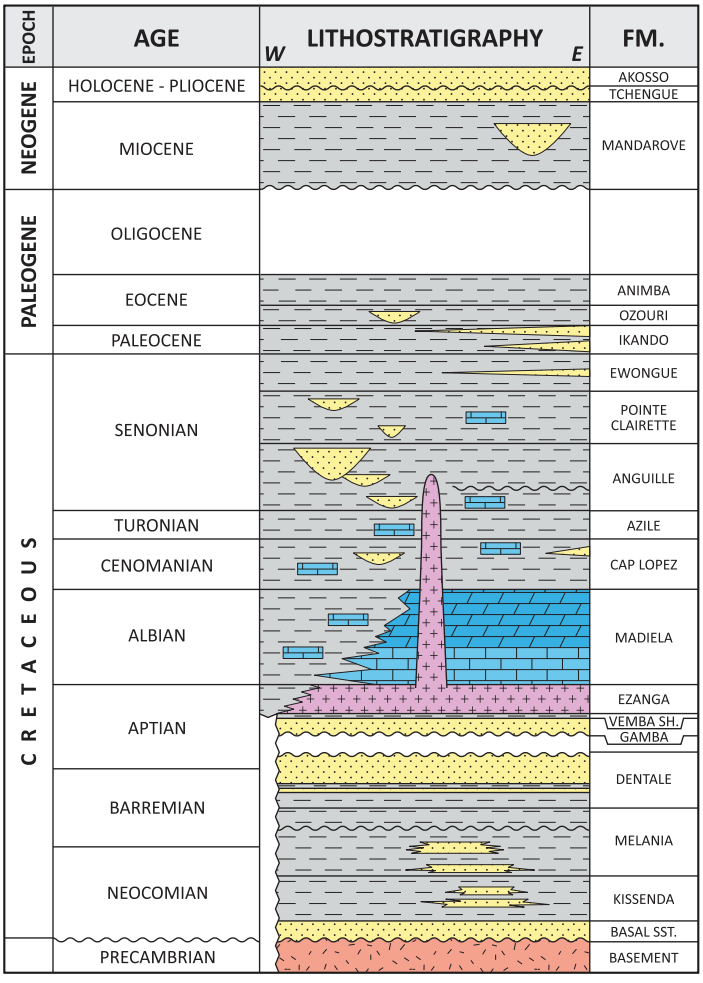
This has proved that a working hydrocarbon system is effective about 120 km from the shore. This is significant, as even cursory inspection of the available seismic indicates that the salt basin extends another 120 km offshore, to a transitional contact with marine spreading ridge (Mid Ocean Ridge Basalt). If Dentale and Gamba Formation (Gamba) sands are present across this whole pre-salt area, and these are underlain by Melania and Kissenda source rocks, the potential for deepwater Gabon to provide a spectacular future of similar sub-salt discoveries would be considered very promising. In fact, a more extraordinary feature exists at the far west of the salt basin that could surpass even this vision. This feature could also explain why this margin has a salt basin, whereas the conjugate Sergipe/Jaquipe Basins do not. To illustrate this, and consider some of the additional plays at the western margin of Gabon's salt basin, we need to consider the tectonic development of the rift, the syn-rift fill and the deposition of the Aptian salt.

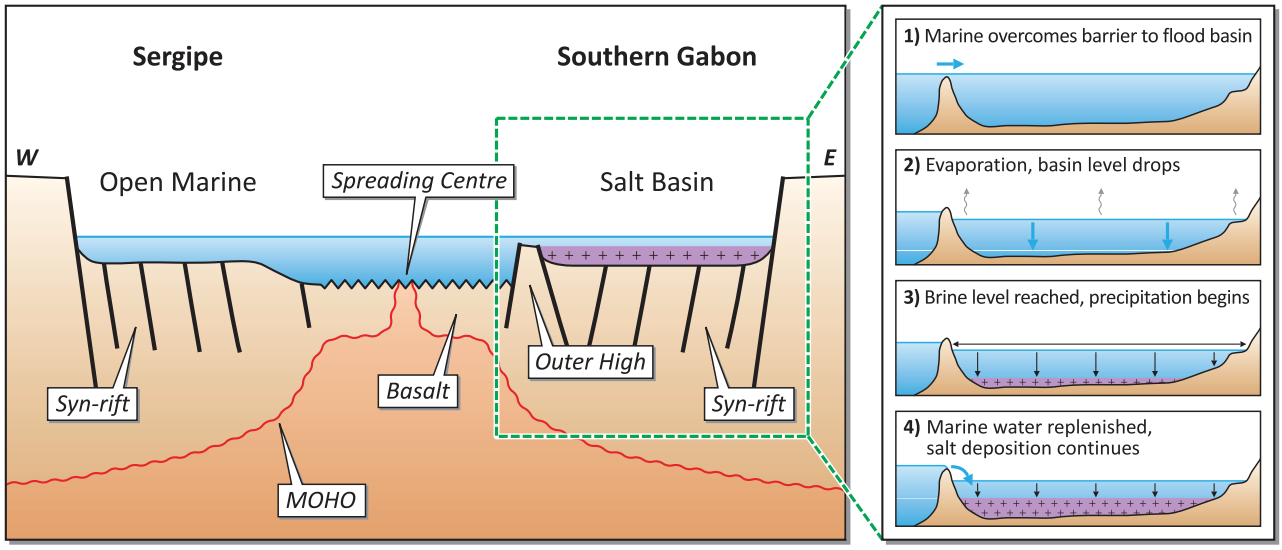
Syn-Rift Section

The syn-rift section that filled the nascent central rift valley in Gondwana during the early Cretaceous is comprised predominantly of clastic fluvial and lacustrine sediments. Within the section are two lacustrine source rocks, the Melania and the Kissenda shales, and interbedded syn-rift coarse and fine clastics of the Dentale Formation. At Diaman-1 the syn-rift section is very thick, as determined by full tensor gravity gradiometry (FTG) data, burying these source rocks into the gas-condensate mature window. South-west (down-dip) of Diaman-1 the syn-rift is thinner and the source rocks oil mature.

The provenance and drainage systems of the fluvial and lacustrine-deltaic sediments of the Dentale have been much debated, with little published evidence to guide the argument. However, the rift parallel organization of the syn-rift faults suggests a north-south depositional orientation, with fluvial systems probably distributed across the whole rift basin, a theory supported by detailed log and core-based sedimentological studies (Crossley et al., 2013). Success at Diaman-1 in the Dentale demonstrates the hypothesis that

A simplified stratigraphy of south Gabon's salt basin.





Cartoon sketch illustrating a model deposition of Gabon's salt sequence at the same time as deposition of marine Aptian source rock in the open ocean to the west. Inset showing the mechanism for salt water reflux after Monatron and Tapponier 2010.

fluvial-lacustrine systems are present across the whole rift basin (i.e. across the syn-rift in the conjugate Sergipe/Jaquipe Basins and Gabon), so it is very likely that syn-rift sands and source pairs will be present to the western edge of Gabon's salt basin too.

Towards the end of syn-rift, a marine transgression, presumably inundating the ~400 km wide rift valley from the south, reworked the upper syn-rift sediments, depositing the Gamba transgressive sandstone fairly ubiquitously. Transgression continued and a marine shale (the Vemba Shale) was deposited over the area and then the break-up rift episode was brought to a climax with the opening of a spreading center and the beginning of drift. No seaward dipping reflectors comprised of sub-areal lava flows that are common on other passive margins in the south Atlantic are observed on this margin, attesting to the sub-marine eruption of the spreading center. The outer-high horst could be comprised of a dyke swarm pre-cursor to spreading, although no sub-areal extrusive material is known from this section, and a syn-rift segment appears to be present over the high. A relatively narrow transitional crust zone is inferred from the candidate MOHO reflector observed on pull-out seismic line.

Following the start of spreading in the Aptian, minor uplift of the western margin of the basin created a barrier to marine ingress over the basin, as has been reported in analogous flooding rifts (e.g. Lake Assal, Afar, Djibouti). A variation of this model was discussed in detail by Montaron and Tapponnier, 2010, to account for salt deposition over syn-rift and oceanic crust between Brazil and Angola. This outer high barrier allowed a partial marine reflux system to develop depositing salt over the syn-rift sediments, whilst at the same time marine clastics were deposited on the open marine, western side of the barrier. This Aptian basin was relatively narrow and extended south to a narrow connection to the global ocean through the South Africa – Falklands plateau channel. As a result, the Aptian in this basin was restricted, frequently anoxic and has been proven by numerous penetrations to comprise a high TOC effective oil source, as shown in the figure above. Note the salt appears not to be present over the syn-rift of the Sergipe/Jaquipe Basin, suggesting that the outer horst on the western side of the rift failed as a marine barrier, allowing marine Aptian source to be deposited over the syn-rift in that basin.

New Plays Identified

With the inexorable increase in water depth in which drilling and more importantly development can be undertaken commercially, the large syn-rift structures at and around the outer horst of Gabon represent realistic targets for exploration in the next few years. Following the licensing of some of this play fairway in 2013, wide and full azimuth 3D seismic will soon be acquired over these features, allowing the internal character of the syn-rift to be imaged, identifying source rock and allowing sediment packages to be targeted.

However, even existing 2D PSTM and PSDM seismic, especially where the processing is informed by full tensor gravity gradiometry data, is sufficient to identify the existence of this structural trend and the key play elements, encouraging pathfinder explorers to lead the industry into this area.

The recent Diaman-1 discovery in Gabon opens up the slope setting for hydrocarbon exploration, proving that Dentale sands are present across the Gondwana break-up syn-rift. Significant structures remain on trend with Diaman although it may only be down-dip, towards the western edge of the salt basin that the source returns into the oil generative window. At the base of the slope, within exploration capability in the near future, lie large structures associated with the syn-rift plays around the outer horst, representing world-class frontier exploration targets providing the next orogeny in Gabon's long history of exciting exploration.

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Abstracts (~200 words) should be submitted as soon as possible to the technical committee, Africa2014@hgs.org. The program will be finalized by the end of April.

Currently, volunteers are being sought to be proactive Session Chairs and anyone interested should contact the Technical Committee as soon as possible.

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Memories of Iraqi Kurdistan

MICHAEL QUENTIN MORTON

In 2003, the fall of Saddam Hussein opened up semi-autonomous Kurdistan to foreign investment. It also revived the interest of oil companies in the region, which had been explored, but not developed, by the Iraq Petroleum Company (IPC) between 1946 and 1961. IPC surveys laid the foundation of our geological knowledge of Kurdistan and, for this reason, are still highly relevant to modern oil exploration. But these activities also involved IPC personnel living and working among the indigenous people of the region, and their memoirs of the time provide a fascinating insight into a forgotten aspect of oil exploration.

IPC in Kurdistan

The Turkish Petroleum Company, the forerunner of IPC, mounted an expedition to Iraq in 1925–6, which included a brief survey of Kurdistan. Following the discovery well at Baba Gurgur in 1927, the company's focus was on developing the massive Kirkuk oil field. It was not until 1946 that the region was opened up to oil exploration again.

As well as prospecting for oil, IPC was interested in the Kurdish mountains because their geology provided important clues about the structure of the region. But Iraqi Kurdistan had a troubled history as its people sought autonomy from Baghdad, and there were periodic outbreaks of unrest which made oil operations dangerous. Most of the area was accessible only on horseback and, apart from railway rest houses at Kirkuk and Mosul, a consulate house in Sulaimaniya and a few public works shacks elsewhere, company employees had to rely either on the hospitality of government officials or – more likely – travel with their own tents and assistants. Journeys usually involved a courtesy visit to officials en route, a lengthy process since custom demanded the killing of a chicken or a goat in a guest's honour.

Many of the scientists employed by the IPC group of companies worked in Kurdistan at some stage in their careers. Among the notable geologists and paleontologists who came and went was the enigmatic figure of Robert George Spencer 'Doc' Hudson. A man of craggy features

Mike Morton

A guard overlooking the Kurdish mountain range, 1952.

and exceptional academic ability, Hudson had been a professor of geology at Leeds University before joining IPC in 1946. His task was to study the fossils, mostly invertebrate, collected by the company's field parties. He brought with him years of experience of the fossils, stratigraphy and geology of northern England.

Although reluctant to accept his first eight-month assignment to Iraq, Hudson enjoyed it enough to spend a full year in the company's laboratories at Kirkuk. He stayed on with the company until 1958, writing extensively on the geology of the region and leaving to the company a 12-volume loose-leaf quarto 'Guide to Index Fossils of the Middle East'. He was considered a leading authority on the subject (and on the carboniferous geology of northern England and Ireland) when he died accidentally from carbon monoxide poisoning in his rooms at Dublin University in 1965.

The area of north-eastern Iraq that IPC geologists loosely called Kurdistan.

Kurdish Chieftains

It is remarkable how Kurdistan won the hearts of the IPC people who worked there. My father, geologist Mike Morton, often spoke of it as the finest place he had ever visited on his extensive travels around the Middle East. 'It's cold here now,' he wrote. 'I went up to the Persian frontier last week. It rained here too – and snow fell on the mountain peaks around the camp. It's a lovely part of the East – high mountains, trees, streams, wild birds, squirrels, and in the higher parts, wild pig, bears, and ibex. There are even a few leopards.'

Apart from the beauty of its natural landscape, this was a land of larger-than-life figures. Among its chiefs was Babekr Agha of the Pizhdar tribe. He was tall, gaunt and with a patch over one eye and a large aquiline nose. Dressed in baggy trousers, a brightly coloured cummerbund and wearing a turban, he presented an imposing figure. The men sitting around his *majilis* had all the charm and humor for which the Kurds are renowned.

In the 1950s, relations between the Kurds and the company were good. On one occasion, Babekr Agha arrived at the IPC hospital in Kirkuk for a medical operation. To the dismay of the British staff, a retinue of about 50 armed men, all of whom expected to sleep beside their chief, accompanied him. After much negotiation, staff persuaded them to camp outside in the hospital grounds. John Davies was the IPC surgeon, a man who was so devoted to his work that he stopped people in the street and, if they looked interesting enough, invited them to come for an operation. In the Agha's case, the operation was successful and the patient, on his departure, paid tribute to the IPC management while his

A geological camp near a village in the Kurdish mountains, 1952.

An IPC geological party at Chalki Camp in 1952. Back row, from second right to left: Tewfic Bey (headman of Barwar Country), IPC geologists René Wetzel, 'Doc' Hudson, Mike Morton and crouching, Sami Nasr. Among the mule men, guards and watchmen, the conical felt hats of the Assyrians contrast with the headdress of the Kurds.

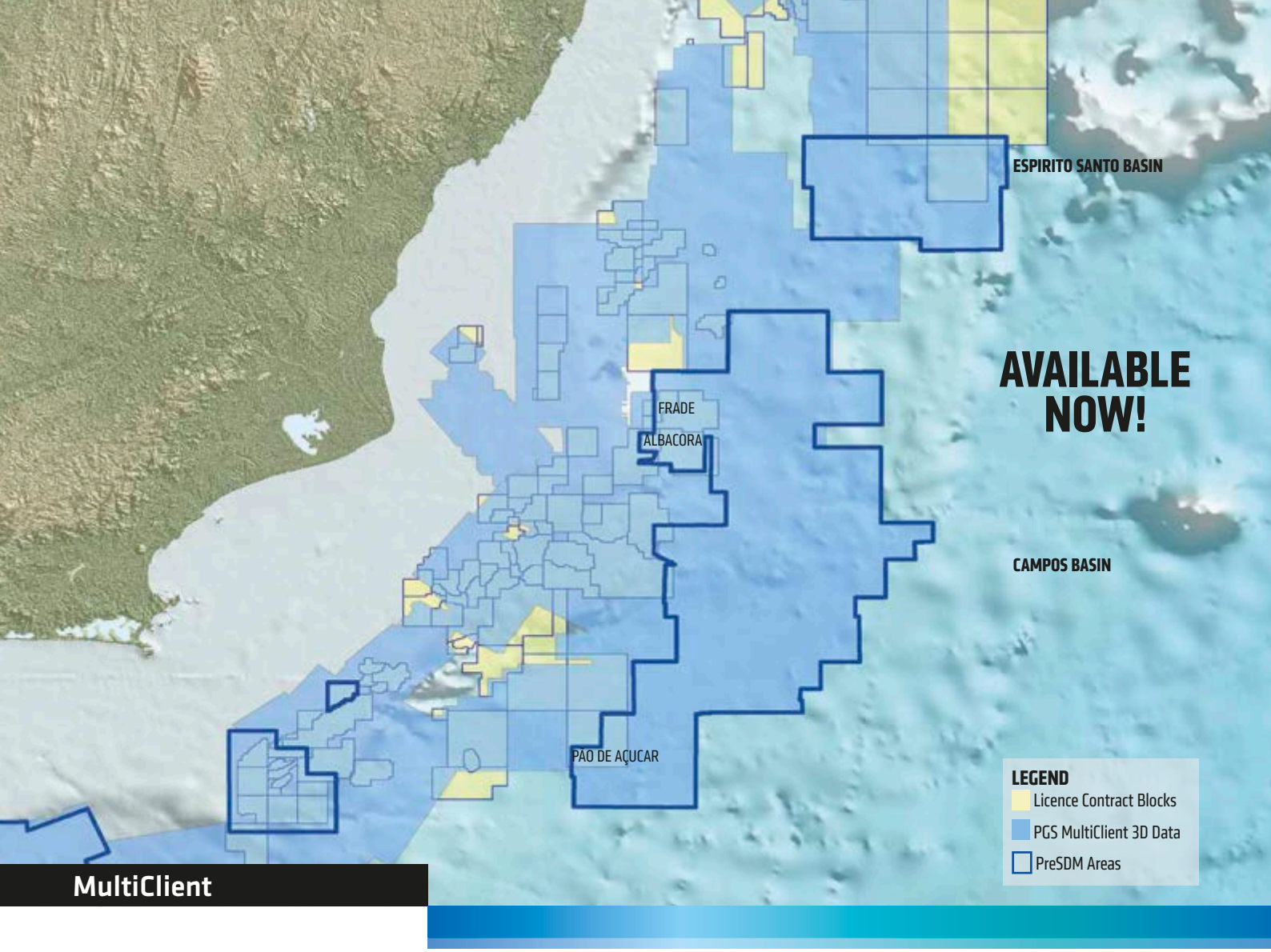
tribesmen jostled to get into the room.

Another prominent chief was Suleiman Agha of the Herki tribe. IPC liaison officer, Ian Macpherson, would often visit him to pay his respects. At one lunch thrown in his honor, Suleiman Agha provided the customary fare of lamb and rice cooked in the Persian style with apricots and walnuts. Unlike the Arabs, the Kurdish women were unveiled and moved freely around the gathering, although they did not eat with the visitors. They wore bright colors that clashed rather than matched but, as Macpherson observed, the effect could be dazzling in the strong clear light of an Iraqi spring. At the end of the lunch, the customary Kurdish gesture of approval – a series of energetic belches – followed. To judge by their efforts, they were well pleased, but Macpherson kept his counsel, prevented by company 'regulations' from making his own contribution.

At the center of Kurdish life was the town of Sulaimaniya, then a maze of narrow alleys and mud brick houses. For those houses built on a hillside, the roof of one formed the courtyard of the next row above – and so on. At the end of one of these alleys was the house where Macpherson stayed when recuperating from illness. Kerim, the young Kurd who looked after him, fed him well on kebabs and other local fare and, most memorable of all, breakfasts of preserved apricots, *mast* (smoky yoghurt), cornflakes and wild honey. It was a noisy house, surrounded by dogs, cats, small boys and donkeys. There was a small mosque, and storks on nearby roofs snapped their beaks all day, making a clattering sound that gave them the nickname 'lag-lag'. On the veranda, in the vine surrounding Macpherson's bed, hundreds of sparrows with piercing voices made sleep impossible after dawn.

The Kurdish tribesmen who assisted the survey parties were fierce yet intensely loyal. My father was accompanied by Kurds as guides, chain men, sample collectors and assistants. On one occasion, a tribesman appeared from behind a rock, demanding, 'Your money or your life!' Omar, a Kurd in the geological team and an ex-British army paratrooper, explained vehemently to the highwayman that the geologists were his guests and eventually the man let them pass safely. After they had passed by, Omar said, 'That man has insulted my nation, wait here, I am going back to kill him.' He was eventually persuaded otherwise.

A Kurdish tribesman at a geological camp in the mountains.



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A Case of Kidnapping

In July 1961 the Iraqi leader, General Abdul al-Karim Qasim, ordered his troops to begin military maneuvers against the Kurds, an action that precipitated a full-blown Kurdish revolt. Since most of the developed Iraqi oilfields were in the north, a cry went up that the Kurdish troubles 'smelt of oil'. One Baghdad newspaper reported that the government had found rebel maps printed with help from 'imperialistic quarters', and letters in English that the Kurdish leader, Mullah Mustafa al-Barzani, had written to British subjects. Mustafa had gone into hiding, the newspaper claimed.

In 1961, the rebels known as the Peshmerga raided an IPC exploration drilling camp at Taq Taq. They left the expatriates unharmed but the company suspended drilling operations and abandoned the well when Qasim confiscated the non-producing areas. In October 1962, the Peshmerga raided Ain Zalah and took a drilling superintendent prisoner. After a long walk to the Iranian border, they released him.

These troubles would have particular significance for one IPC employee. Frank Gosling had started with the company in the Geological Research Department in London in 1952 and transferred to Kirkuk in 1956. Here he worked on exploration wells and field surveys mostly in the Kurdish mountains. One day in November 1962, he phoned his wife, Pauline, to say that he was going to be late for lunch. He was showing an Iraqi geologist, Adnan Samarrai, the geology of an area some ten miles north-west of Kirkuk. Traveling in two Land Rovers, the party of five arrived at a spot in the Qarah Chauq hills and the two geologists began their inspection. Then four armed Kurdish tribesmen appeared. Initially, the atmosphere was tense – one of their drivers was convinced that the Kurds were going to kill them all. However, after some discussion, the Kurds decided to release the men at sunset and slip away.

But then they changed their minds. Thus began a lengthy trek through the mountains, arriving at the village of Bettwahta where they were held for four long weeks. This was a large village tucked under a large precipitous limestone cliff with caves at its base, providing the rebels with shelter from overflying Iraqi MIGs. The leader of the Kurds, Barzani, eventually arrived at the village to discuss Gosling's release. He was described as a 'fierce walnut-colored man of 59, with straight black eyebrows that almost met across an eagle's bill of a nose; a rough, obstinate old warrior'. After a long discussion, Barzani agreed that Gosling could leave, but via Iran, since the authorities in Kirkuk might accuse him of spying for the Kurds if he returned to Iraq.

Winter had arrived – the weather was cold with rain and sleety showers and icy water rushed down the mountain streams – and the next stage of the journey was hard. Presently, after setbacks and sickness, Gosling passed across the border into Iran, thence taken by train to Tehran. He arrived back in London on January 9, 1963, almost three months after his capture.

Kurdish leader Mullah Mustafa al-Barzani with men of the Peshmerga in the Kurdish mountains in 1965.

IPC geologist Frank Gosling.

Kurdistan Today

In 1972, the Iraqi government nationalized IPC's assets, effectively ending the concession. In 2013, however, a number of different oil companies had 24 drilling rigs in Kurdistan and this year there will be 40, with production expected to reach 250,000 bopd. A new pipeline to ship oil from Kurdistan to Turkey has opened, although it is opposed by the federal government in Baghdad, indicating that tensions between the regional and federal governments have not been resolved.

To read more about the history of the IPC, see *GEO ExPro iPad edition* App 6 'Once Upon a Red Line' .

Acknowledgements:

The author would like to thank Frank Gosling and Peter Morton for their kind assistance.

Quentin Morton's next book The Third River: Aspects of Oil in the Middle East, 1887–1979 *is being published in the spring by the National Center for Documentation and Research in Abu Dhabi, UAE.* ■

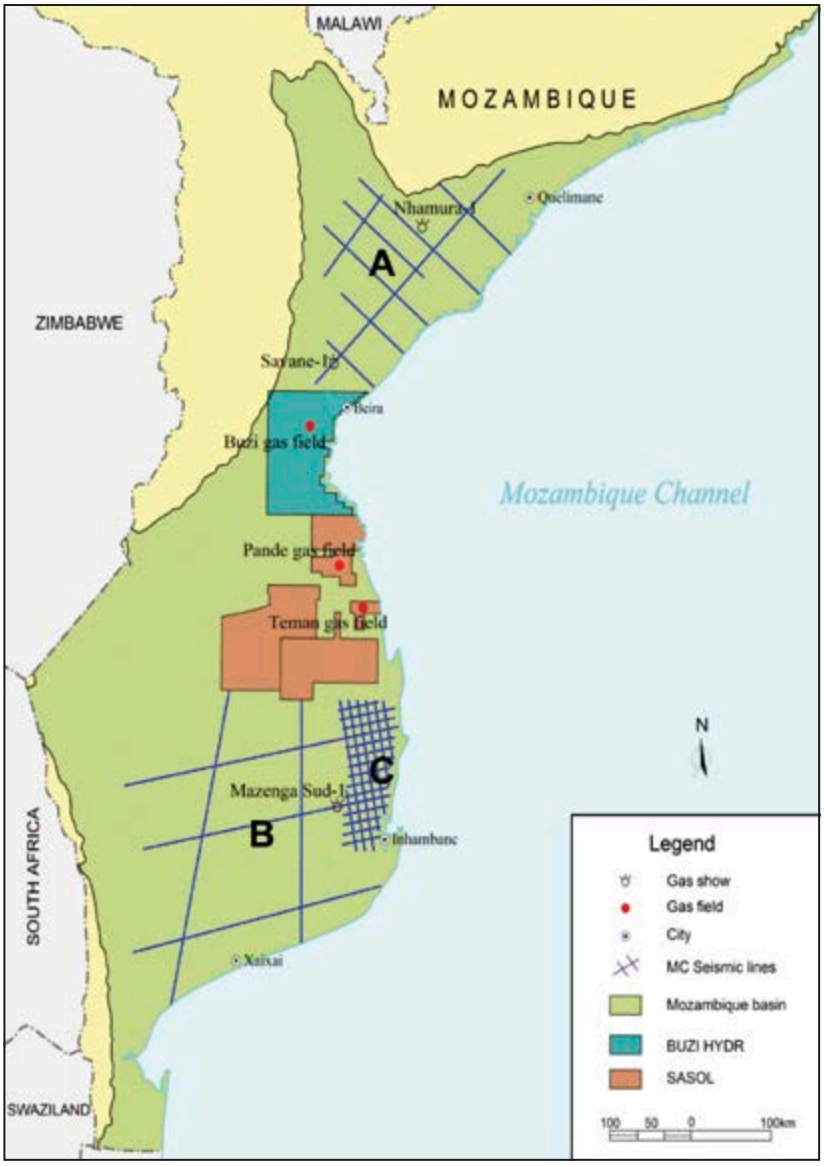
Multi Client Projects in Mozambique Onshore

With the recent large discoveries in the Ruvuma Basin, industry interest is turning again to the Mozambique Basin. Earlier exploration activities and leads suggest a high hydrocarbon potential in passive continental margin sedimentary deposits and rifted grabens/half-grabens systems within the area.

BGP MC has entered into an agreement with the National Petroleum Institute of Mozambique (INP) to exclusively carry out a 2D speculative seismic survey in onshore Mozambique. Covering a very broad area of coastal plain and continental shelf in the Mozambique Basin, the project area is believed to be a very prospective one for hydrocarbon exploration.

Lines are designed to map structure framework, sedimentary formations from ages, and to investigate hydrocarbon potential of the area. BGP will provide clients with high quality seismic data by utilizing powerful resources and state-of-the-art technology.

BGP plans to commence the project in Q2 2014, and a beneficial rate will be offered to early participants. INP is committed to launching a bid round based on the seismic data collected and oil companies should buy the data to apply for the concession blocks in the survey area.



Zambezi (area A): 1170 km
South Mozambique regional (area B): 1520 km
Mazenga (area C): 1775 km

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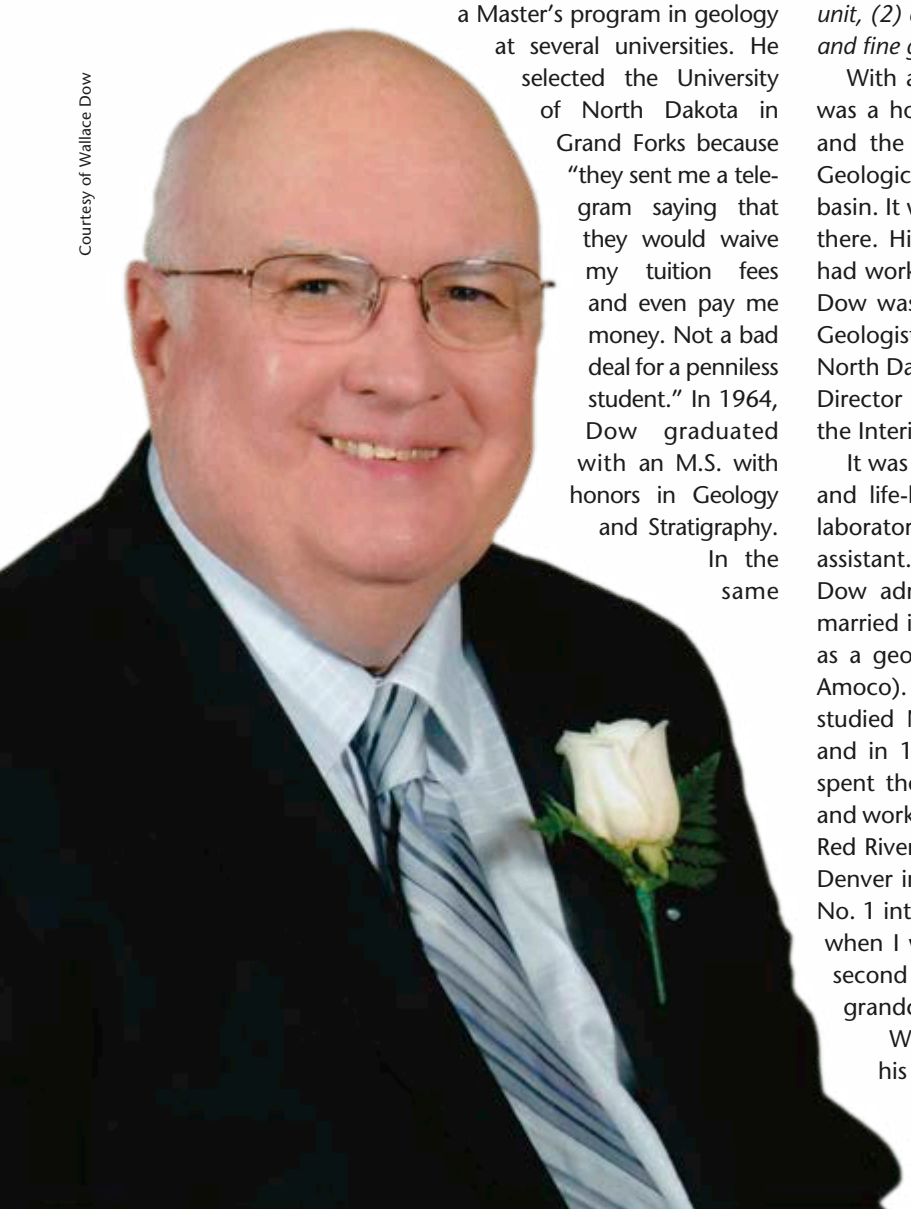
A Pioneer of Petroleum Geochemistry

RASOUL SORKHABI, Ph.D.

Geochemistry of petroleum source rocks was developed in relatively recent times. **Wallace Dow**, celebrating his fifth decade of professional life this year, played a pioneering role in the advancement of vitrinite reflectance and kerogen type studies as well as the concept of oil-source correlation, all paving the way to modern petroleum system analysis.

Wallace Gilmore Dow was born on June 4, 1937 in New Jersey and grew up in that state. He found his love for chemistry in high school. "In those days," Dow recalls, "there were four major science subjects in my high school: physics, chemistry, biology, and something called physiography, a combination of astronomy, meteorology, and geology, and two were required for graduation. Physics did not appeal to me and I did not fancy cutting up frogs in biology, so I chose chemistry and physiography which became my first introduction to geology." In 1955, Dow entered Rutgers University in New Brunswick, N. J. and graduated in geology four years later. After serving in the US Army for three years, Dow applied for a Master's program in geology at several universities. He selected the University of North Dakota in Grand Forks because "they sent me a telegram saying that they would waive my tuition fees and even pay me money. Not a bad deal for a penniless student." In 1964, Dow graduated with an M.S. with honors in Geology and Stratigraphy. In the same year, his first research papers were published: 'Effect of the salinity on the formation of mud cracks' in *The Compass of Sigma Gamma Epsilon*, and a paper on the Spearfish Formation (Triassic Red Beds) in the Williston Basin of North Dakota (in *Third Williston Basin Symposium Guidebook*), which was actually his Master's thesis and was formally published as the *North Dakota Geological Survey Bulletin 52*.



Courtesy of Wallace Dow

Williston Basin

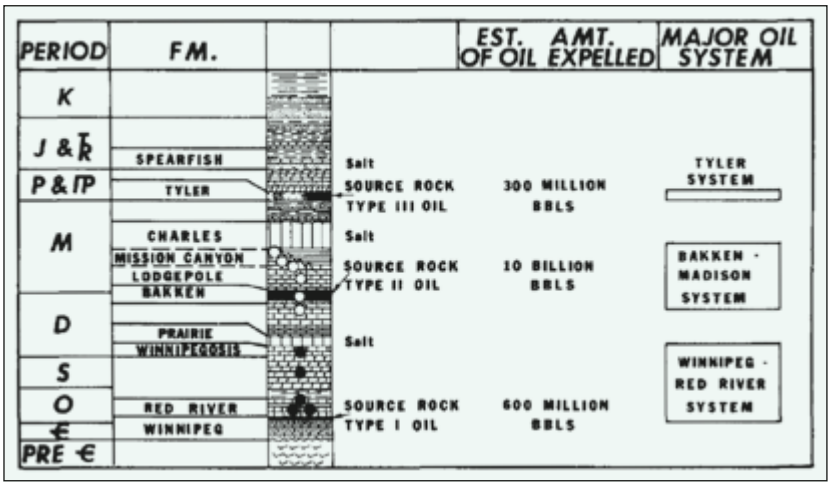
"In the subsurface of the Williston Basin in western North Dakota, the Spearfish Formation can be divided into three lithologic units. In ascending order these are: (1) a lower gray shale and red siltstone unit, (2) a middle salt unit, and (3) an upper red siltstone, shale, and fine grained sandstone unit." (Dow, 1964)

With a significant oil discovery in 1951, the Williston Basin was a hotspot for oil exploration during the 1950s and 60s, and the University of North Dakota and the North Dakota Geological Survey held a central position in studies of the basin. It was only logical for Dow to focus his Master's research there. His thesis advisor was Walter Moore, a geologist who had worked for Gulf Oil before joining the University in 1960. Dow was also supported by the department chair and State Geologist Wilson Laird (1915–1977), a prominent geologist in North Dakota who later served as the AAPG President as well as Director of the Office of Oil and Gas in the US Department of the Interior (1969–71).

It was also at North Dakota that Dow met his would-be wife and life-long companion Marlys, who had taken a geology laboratory class in 1963 for which Dow was a teaching assistant. "I needed someone to type my Master's thesis," Dow admits, "and she pretended to need tutoring." They married in August 1965, a year after Dow had got his first job as a geologist for Pan American Production Company (later Amoco). Initially, Dow worked in Casper, Wyoming where he studied Mesozoic sandstones of the Rocky Mountain basins and in 1965 the company moved to Denver, Colorado. He spent the next four years alternating as a well-site geologist and working on Paleozoic carbonates, especially the Ordovician Red River Formation. "When my first son Thomas was born in Denver in 1967, I was in the field drilling Pan American Hove No. 1 into naturally fractured Bakken Shale. I rushed to Denver when I was informed of his birth, eight weeks early." Dow's second son Kevin was born in 1968. The Dows now have five grandchildren.

What drew Dow to petroleum geochemistry was not only his interest in chemistry, but also his unique situation: "As

a well-site geologist I collected hundreds of oil samples for the new Amoco geochemistry lab in Tulsa, Oklahoma to analyze." In 1969, Dow was transferred to Amoco's Research Center in Tulsa where he was responsible for interpretation of geochemical data and prepared over 100 internal reports covering many US and overseas exploration blocks. There, he enrolled in the Ph.D. program in organic geochemistry and business management at Tulsa University (1970–1972) and took classes from legends like Colin Barker, Parke Dickey and Norman Hyne. In 1972, Dow left to work for The Superior Oil Company in Houston and never completed his Ph.D. degree.



Courtesy of Wallace Dow

'Oil systems' for the Williston Basin proposed by Wallace Dow in AAPG Bulletin in 1974. This was a germinal idea for what was later developed as the petroleum system analysis in the 1980s.

'Oil System'

"Most Williston basin oils belong to one of three basic types… isolated vertically by evaporates… All three oil types can be correlated to their source facies. Lithofacies maps of these source sequences, when combined with thermal alteration measurements, provide effective oil-source-area definition." (Dow, 1974)

While at Amoco Research, Dow and organic chemist Jack A. Williams developed the idea of oil-to-source rock correlation based on geochemical data from the Williston and several other basins and presented it to one of the company's vice-presidents who flew in from Chicago. "We basically handed him the concept of what later came to be known as 'the petroleum system', but he was unimpressed and declared it of little use in petroleum exploration! The bright side was that the company permitted us to present our work at the AAPG Annual Convention in 1972 in Denver in a session entitled 'New Ideas in Petroleum Exploration' which was later published in the 1974 AAPG Bulletin." Dow suggested "three major source-reservoir oil systems" for the Williston Basin: (1) the Winnipeg-Red River oil system below the Devonian Prairie salt; (2) the Bakken-Madison oil system between the Devonian Prairie and Mississippian Charles salts; and (3) the Tyler system above the Mississippian Charles salts.

Ten years later, Dow teamed up with Leslie B. Magoon (then at US Geological Survey) and formalized the original 'oil-system' ideas into the 'petroleum system' concept, culminating in AAPG Memoir 60 titled *The Petroleum System: From Source to Trap*, edited by Magoon and Dow. This volume, still the 'Bible' in its field, won the AAPG Robert H. Dott, Sr. Memorial Award for the best special publication of 1994. (See *GEO ExPro* Vol. 8, No. 5 for more about petroleum systems.)

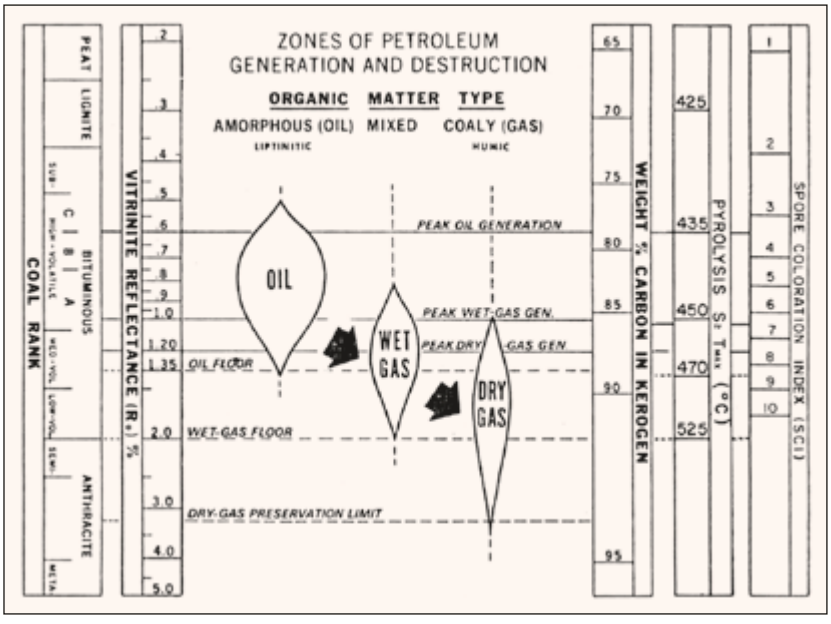
Thermal Maturity

"The primary purpose of kerogen maturation is to determine whether petroleum has been generated in source beds." (Dow, 1977)

Dow left Amoco to work for The Superior Oil Company in Houston because they had just begun using reflected light microscopy to study kerogen and Dow recognized it as an important new frontier in petroleum geochemistry. He hired Dolores O'Connor to do most of the microscopy work and together they advanced geochemical techniques and interpretations for the characterization of sedimentary organic matter including vitrinite reflectance (VR), which is now commonly used by oil explorers to assess the thermal maturity of source rocks. The VR technique was originally developed for ranking of coal with burial depth and temperature, but its application to petroleum source rocks revolutionized both the technique and petroleum geology. Dow and O'Connor's 1982 SEPM report is still a useful guide to the VR technique. Dow extended his studies to kerogen typing and published a seminal paper titled 'Kerogen studies and geological interpretations' in the *Journal of Geochemical Exploration* (1977), which remains one of his most cited works.

Dow and O'Connor left Superior Oil when management changed and after a short stint at Getty Oil joined Robertson

The famous droplet diagram showing the correlation of maturity indicators for oil and gas windows first presented by Wallace Dow in the Journal of Geochemical Exploration in 1977.



Courtesy of Wallace Dow

Research (US) Inc. in Houston. In the 1970s, through his interactions with international conferences like International Meeting on Organic Geochemistry, the Gordon Research Conference on Organic Geochemistry, and AAPG meetings and conferences, Dow was befriended by many of the pioneers in the field, including Alfred Treibs (the father of organic geochemistry), John Hunt (author of *Petroleum Geochemistry and Geology*, 1979, 1995), Bernard P. Tissot and Dietrich H. Welte (authors of *Petroleum Formation and Occurrence*, 1978, 1984). Hunt, Tissot and Welte, who wrote the first textbooks on petroleum geochemistry, cited Dow's papers. Dow regards the American geologist Parker Trask (1899–1961) and the German organic chemist Alfred Treibs (1899–1983) as two giants who began petroleum geochemistry during the Great Depression of the 1930s. Dow also wrote a biography of John Hunt (1918–2005) on his seventieth birthday in 1988, published in a proceedings volume, *Organic Matter* (Columbia University Press, 1992).

Deepwater Petroleum Source Rocks

"Continental slopes commonly are sites of high marine organic productivity and frequently contain reducing bottom conditions, quiet water, and intermediate sedimentation rates, all of which favor deposition of organic-rich sediments." (Dow, 1978)

The oil industry aggressively moved to explore deepwater basins in the 1970s. Although our knowledge of deepwater plays has increased over time, questions about petroleum source rocks in these basins is still hotly debated. It is, therefore, of interest to note Dow's 1978 *AAPG Bulletin* paper titled (far ahead of its time) 'Petroleum source beds on continental slopes and rises.' This paper resulted from Dow's involvement in the geochemical analysis of cuttings and cores from the offshore Gulf Coast and Atlantic coast (drilled as part of the US Continental Offshore Stratigraphic Test program) as well as those from several bore holes of the Deep Sea Drilling Project offshore North Atlantic. For the Gulf of Mexico, Dow found that the organic carbon content increases from shelf/neritic (0.23%) to bathyal/abyssal (0.60%) sediments.

DGSI and Recent Years

"My life philosophy is this: if you have a lemon, make lemonade. Faced with a failure and hardship, work hard and turn adversity into something even more successful. Publishing papers helps our professional career." (Dow in an interview with the author).

In 1983, when the global oil market collapsed, the Robertson Research (US) laboratory in Houston closed down, throwing many people out of work. Almost in desperation, Dow and his wife Marlys formed Dow Geochemical Services Inc. (later known as DGSI), which became one of the most active geochemical services companies for the oil industry during the following 16 years. It also trained a number of petroleum geochemists who later obtained leading positions in the industry. In 2000, DGSI was sold to Baseline (now part of Weatherford). During 2001–06, Dow was an independent geochemical consultant for several oil companies until one of these companies, EOG Resources in Houston, offered him the position of Chief Geochemist. Interest in petroleum geochemistry was literally 'born again' when oil source rocks became reservoirs in unconventional oil plays. In 2011, Dow retired, but ever a man in love with his job and science, he started another tenure as Chief Geochemist for Cimarex Energy Co. in Tulsa, Oklahoma where he and his wife currently live.

The 1970s witnessed the emergence of the geochemistry of petroleum source rocks. It is apt to end this essay with a statement Dow made in his 1977 paper: "As petroleum becomes more difficult to find and the search more expensive, the utilization of modern technology, including organic geochemistry, will play an increasingly important role in petroleum exploration." This statement is still valid and very much so for the unconventional shale gas plays such as those in the Williston basin where Dow began his fruitful career five decades ago.

In 2000, Wallace Dow was awarded the Arthur Gray Leonard Medal by the University of North Dakota for "outstanding achievement in the geosciences, especially in geochemical research and petroleum exploration and development." ■

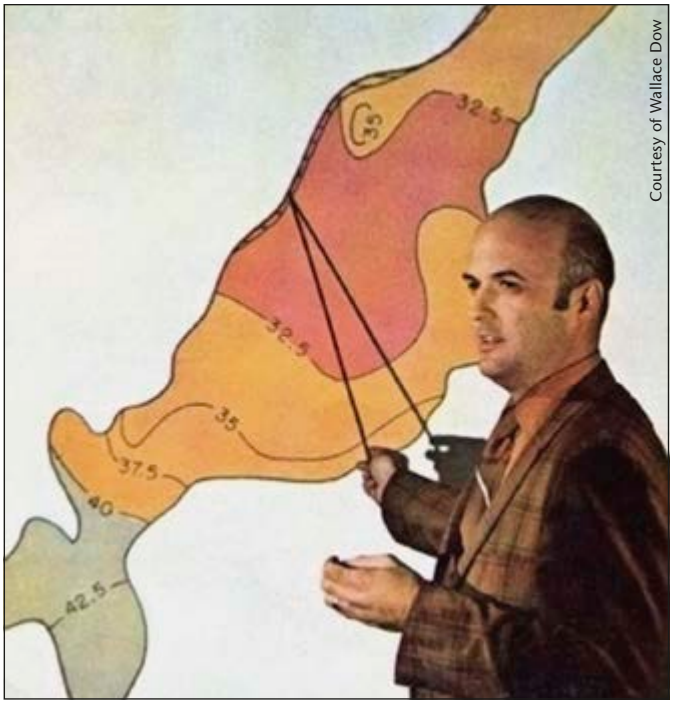
What is in a Word?

By Wallace Dow

Kerogen: "The portion of organic matter in sedimentary rocks that is insoluble in organic solvents; it is formed from formerly living organic materials by diagenetic processes in the first hundred meters of burial and is partially converted, under the influence of temperature and time, into petroleum." (1977)

Vitrinite: "The most common maceral group occurring in humic coals and also the most abundant constituent of most sedimentary kerogens. It is formed after sedimentation in the diagenetic environment by humification of lignin and cellulose of plant cells." (1982)

Wallace Dow during a presentation of his research work in 1971.



Broadband Seismic Technology and Beyond

PART VIII: BroadSeis in Exploration

Following on from the last issue of *GEO ExPro*, in which the change of thinking which produced BroadSeis was analyzed, we look at how this new technique can be effective in the search for oil. In this first part we consider its uses in exploration.

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

The advantages of broadband seismic have been demonstrated around the world at all stages in the exploration and production cycle, for many different geologies, and in various different environments. High frequencies produce sharp wavelets, while low frequencies reduce sidelobes, so that with broadband, seismic events are single peaks or troughs corresponding to genuine geological layers. This clarifies impedance contrasts and creates sharp images of small features as well as clear differentiation between different sedimentary packages.

The high frequencies enable detailed velocity modeling which can provide better deeper images. However, in many respects the low frequency end of the spectrum is more important than the high, as the low frequencies provide more quantitative and reliable reservoir inversion results, simplified interpretation and clearer facies discrimination. The low frequencies in BroadSeis are also crucial for Full Waveform Inversion (FWI), which is gaining popularity for velocity model building.

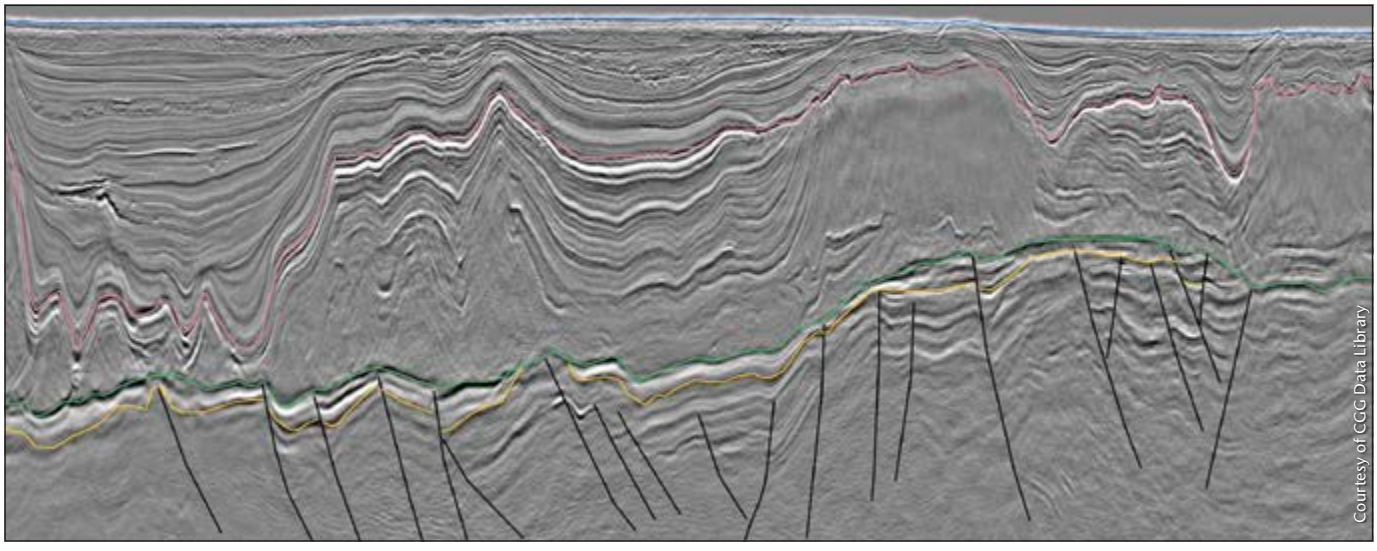
Benefits For Exploration

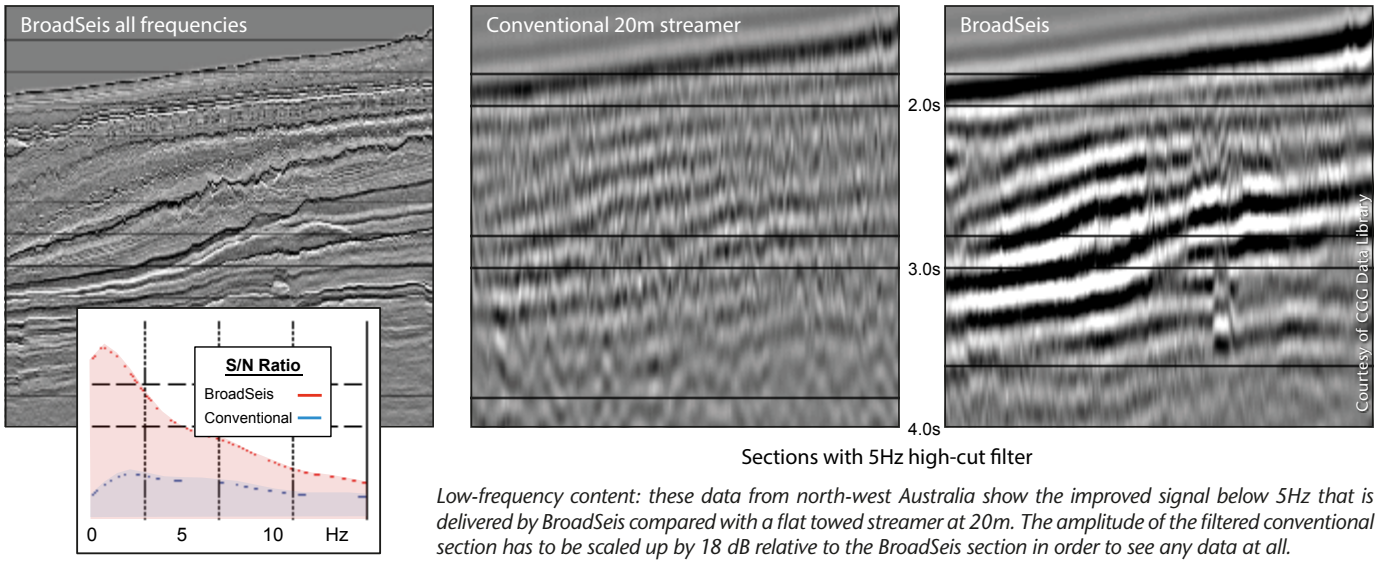
As broadband data provide both low and high frequencies they are ideal for exploration as potential targets at all levels can be imaged. The characteristic broadband 'texture' highlights stratigraphy as the additional low frequencies give an envelope to the seismic signal that shapes the larger-scale impedance variations, or in geological terms, the major lithology variations. This increases confidence in correlating seismic interpretation across faults and other major structural features, allowing layers to be easily distinguished. The Santos Basin data below demonstrate these advantages by providing clear differentiation of sedimentary packages and high-resolution shallow images, as well as clear imaging of the base of salt and the pre-salt sequences.

Three octaves of signal are generally considered necessary for adequate seismic resolution. Therefore, in order to achieve sufficient bandwidth in areas where high frequencies are limited, such as below salt where frequencies over 20Hz tend not to penetrate, it is necessary to extend the low frequencies, which are affected less by attenuation and provide greater accuracy and stability for seismic inversion. Conventional marine streamer acquisition usually lacks sufficient signal-to-noise ratio in the 2–7 Hz bandwidth due to streamer depth, streamer tow noise, source array configuration, source depth and source bubble. Using BroadSeis, it is possible to routinely record frequencies with good signal-to-noise ratio down to 2.5–3 Hz, providing three octaves below 20Hz as shown in the figure on the top of page 53.

The uses of broadband seismic in exploration are not limited to deep waters. CGG has acquired BroadSeis data in shallow

These BroadSeis data from the Santos Basin, Brazil, show clear imaging of the base salt and pre-salt sequence.





Low-frequency content: these data from north-west Australia show the improved signal below 5Hz that is delivered by BroadSeis compared with a flat towed streamer at 20m. The amplitude of the filtered conventional section has to be scaled up by 18 dB relative to the BroadSeis section in order to see any data at all.

water in the North Sea, offshore Vietnam and China, in water depths as shallow as 37.5m. In these areas the streamer shape is adapted to fit the circumstances, raising the deeper part of the streamer as the water gets shallower. The figure below shows data recorded offshore China in water depths varying from 85 to 115m, which provide excellent results, both in the shallow detail and in the fractured basement.

Ghost-Free Data

As discussed in *GEO ExPro*, Vol. 11, No.1, BroadSource is a synchronized source with two gun arrays deployed at different depths. The downgoing wavefields from these gun arrays will be synchronized while their respective ghosts are de-synchronized. The advantage of obtaining de-synchronized ghosts with well-tuned time delays lies in the resulting notch-free amplitude spectrum of the source (Siliqi, 2013).

A synchronized multi-level source is a compact solution for acquiring broadband data with variable-depth steamers. It can be deployed in the flip-flop mode necessary for 3D broadband surveys and has all the benefits of a standard marine source in terms of robustness, directivity and repeatability. In order to maintain the same directivity created by conventional source arrays, a 3D spatial distribution of airguns in two vertical levels is used and the resulting directivity pattern remains at the same quality range as that for a conventional source, even for frequencies corresponding to the single-layer source notch.

The multi-level source allows defocusing of the ghosts, but does not eliminate them. Nevertheless, the absence of notches in the spectra allows designature of the seismic along the full bandwidth. While the accuracy of pressure field modeling is sufficient for source array design it is not precise enough for building source designature operators. These can be more accurately designed using recorded near-field hydrophone measurements (Ziolkowski 1982, Poole 2013). This acquisition-based approach delivers a more accurate estimation of the bubble effect and low frequencies in general, which are fundamental for broadband acquisition.

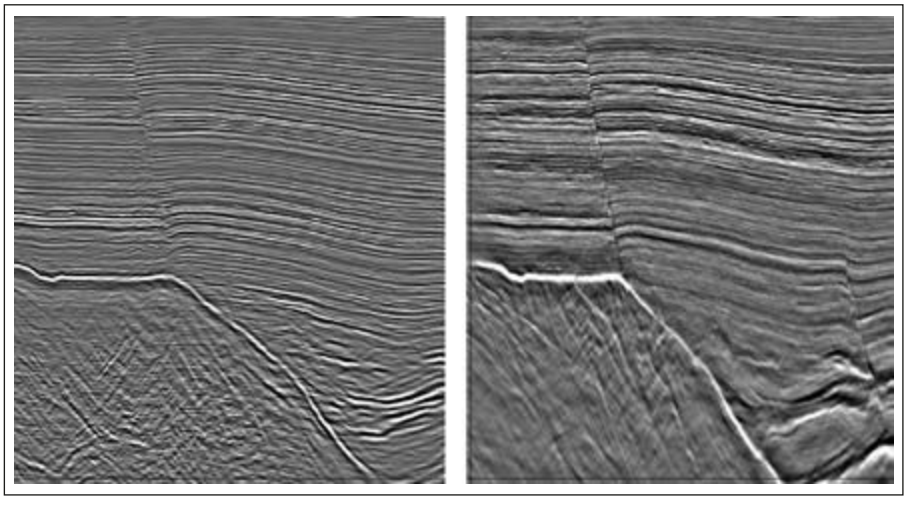
This allows an accurate designature process which encompasses residual de-ghosting, debubbling and zero-phasing in the same step. Several acquisitions worldwide have demonstrated the benefits of this technique in delivering ghost-free images with an extra-wide bandwidth from 2.5 Hz up to 200 Hz.

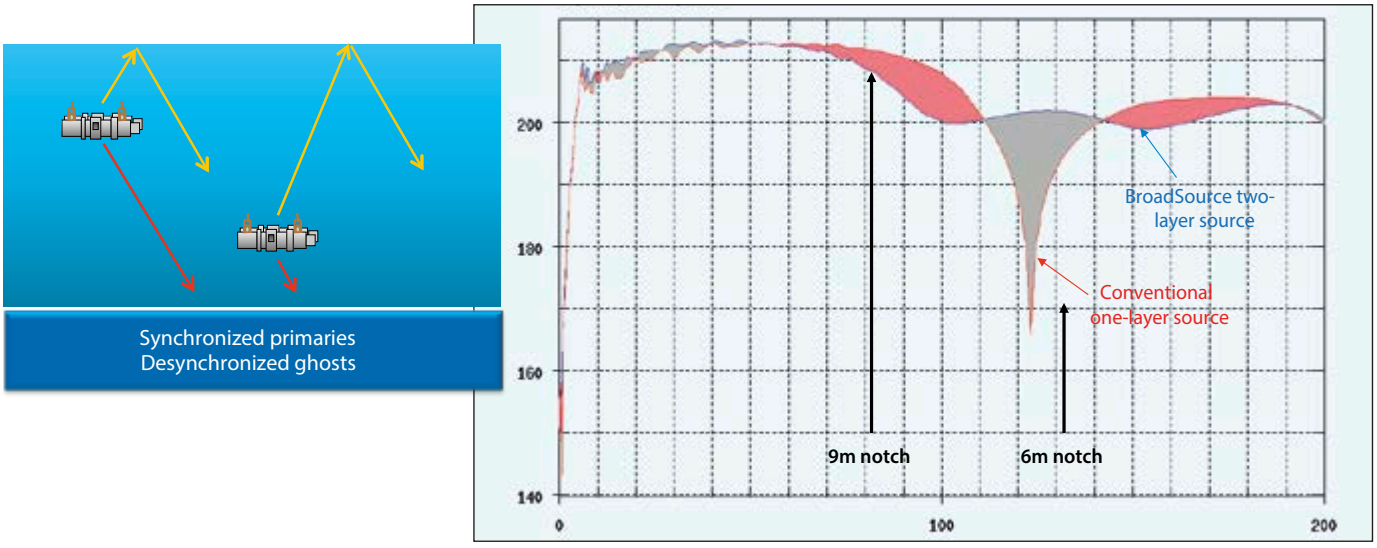
Combining BroadSeis and BroadSource

Combining BroadSeis variable-depth streamer acquisition with the BroadSource synchronized multi-level broadband source means that the receiver-side ghost-diversity philosophy has been extended by introducing ghost diversity on the source side as well. With this, ghost-free broadband data with more than six octaves of signal is achieved, from 2.5 Hz to 200 Hz, vital for the precise imaging of shallow data.

BroadSource provides the same low frequencies as a deep-towed conventional

Comparison of conventional (left) and BroadSeis data stacks (right). Variable-depth streamer data show better top of basement, better fault planes, clear indication of stratigraphic unit, and intra-basement reflections. From Zhang et al. (2013)



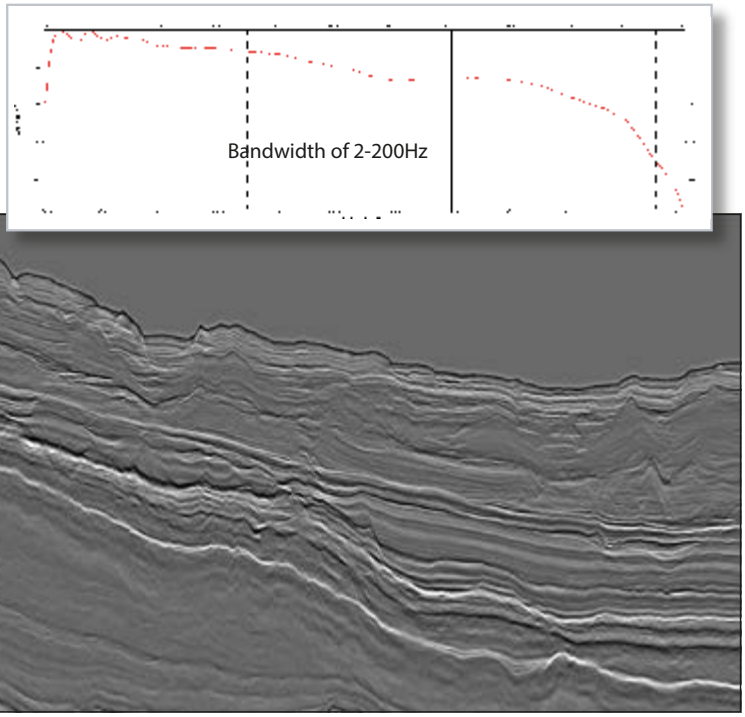


Amplitude spectra gain of a synchronized two-level source array with airguns at 6m and 9m, showing how the source ghost notch becomes filled in.

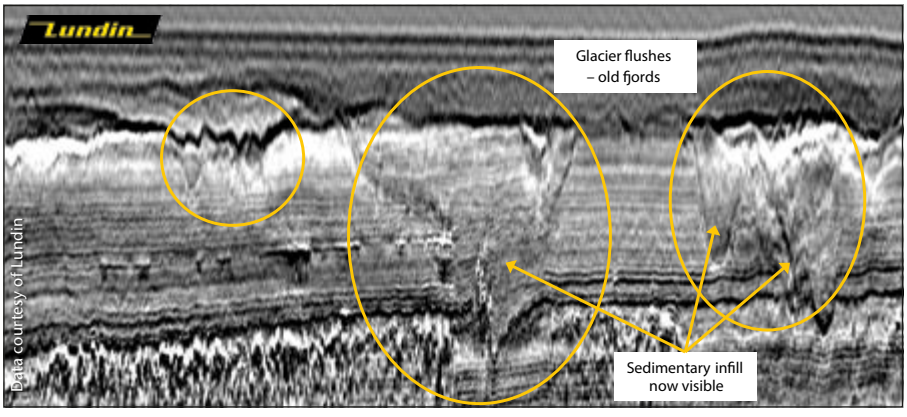
source, but fills the source ghost notch to extend the spectrum in the high frequencies. For the deeper parts of the section, the highest frequencies will vanish due to the inelastic attenuation of the earth and will not contribute to the image. However, the full bandwidth present in the shallow section enables precise imaging for shallow-hazard mapping and accurate velocity picking.

Over the last three years BroadSeis technology has established a strong position in the marine broadband market with over 25,000 km of 2D and 160,000 km^2 of 3D, wide- and full-azimuth data having been acquired. Part of its appeal is the routine acquisition of bandwidth of more than six octaves with excellent signal-to-noise ratio at low frequencies. In the next edition of *GEO ExPro*, the benefits of this bandwidth in relation to field development will be discussed.

By combining BroadSeis with BroadSource it is possible to achieve six octaves of ghost-free signal.



BroadSource provides incredibly high-resolution imaging in the shallow section (2.5 to 200 Hz), making the data highly suitable for use in site surveys, as shown in this Norwegian data where the sedimentary infill in old fjords is visible.



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Zhang Zhenbo, Wang Shoujun, Li Dongfang, Wang Ruiliang, CNOOC, Lin Dechun, Jason Sun, Xiao Yongdeng, Guo Yonghe, Conrad Judd, CGG. Review of the First Variable-Depth Streamer Seismic Survey offshore China. SEG 2013. ■

The Seismic Interpreter

Geophysicist **Alice Little** uses her geological knowledge and training as a seismic interpreter with Aker Solutions.

Although 'geophysicist' is a broad term covering many specialist areas of research and work, what we have in common is the recognition that different rocks and fluids respond differently to applied forces such as sound, gravimetric, magnetic and electrical. Exploiting these differing rock properties enables us to describe what is under our feet or indeed beneath the waves.

Geophysicists are involved at every stage of hydrocarbon exploration, development, production and at field 'end of life'. They can be responsible for data acquisition and processing, its interpretation, and integration of the data with information from other geoscience disciplines to construct a viable prediction of the subsurface. Geophysicists use many different types of data to assess the subsurface, including gravity, magnetic, seismic refraction, seismic reflection, electro-magnetic, induced polarity and resistivity. Each of these provides a piece of the puzzle. We never have all the pieces, so we will never see the complete picture of the subsurface – but then that's the challenge. The ultimate goal of any exploration team is to find reservoir rock trapping oil, gas or condensate in economic volumes.

Thinking in 3D

I am currently working as a seismic interpreter, part of a multi-disciplinary team putting together license applications for the Norwegian 23rd license round.

As with any interpretive process we have to make sure our base data is of the highest quality possible. We check the seismic data for polarity and phase according to the SEG standard being used. Where there are several seismic surveys overlapping, a harmonization process has to be performed, bringing together surveys of varying vintages and quality, to have the same phase and polarity. It may also be necessary to time shift surveys to ensure a good continuity on a regional scale. During this data quality assurance check and harmonization we use well data (sonic, density and gamma logs) as well as check-shots to tie the wells into the seismic. A synthetic seismogram is generated from the well data to aid this process – an incredibly important step as it connects the time domain seismic data to the well which is in the depth domain. The quality of this well tie is also dependant on good quality log data.

We can then take the interpretations the geologist has made from the well (formations, reservoir units, chronostratigraphy, etc.), and display these geological interpretations on the seismic, analyze the character of the seismic at points of interest (e.g. reservoir) and use this seismic character to interpret the lateral and vertical variations and limitations of the unit away from the well location. This link between geological facies analysis and seismic facies analysis enables us to 'predict' the extent of the unit concerned. In addition to the basic seismic data, we can derive attributes to see the variability of things like amplitude, frequency content, phase shifts, wavelet asymmetry and acoustic impedance. Combinations of attributes can be useful to identify and classify seismic facies, and if intercepted by a well they can be correlated with a specific geological unit.

We are also on the look-out for Direct Hydrocarbon Indicators (DHI or HCI): flat spots, polarity reversals and AVO anomalies, for example. However, these indicators are not unique to reservoirs filled with hydrocarbon. We need to use other investigations and information to confirm or negate whether the anomaly is due to hydrocarbons.

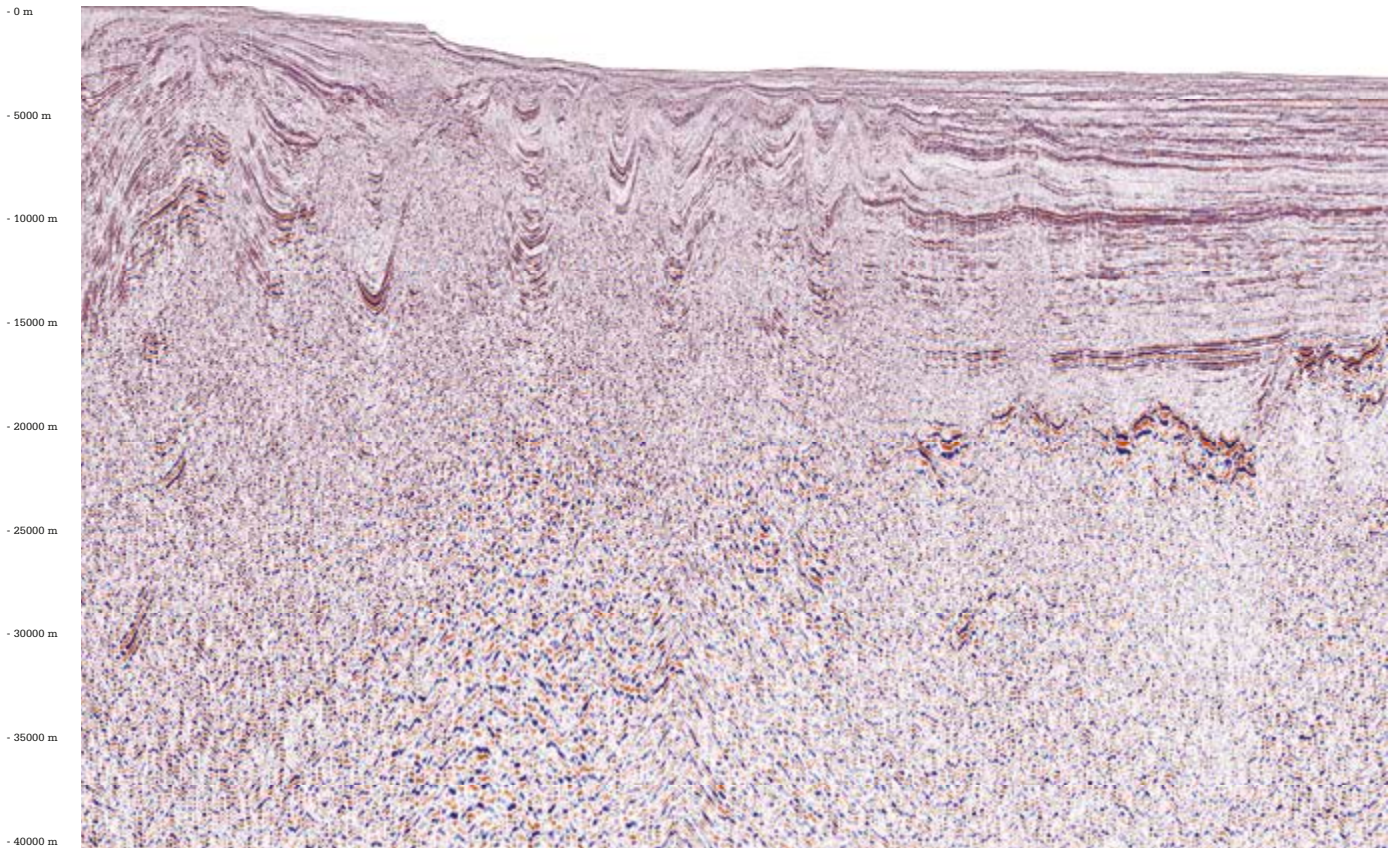
As things like volume calculations and drilling operations work in the depth domain, we have to convert the seismic interpretation from time to depth by generating a velocity model for the area of interest using velocity information derived from wells and/or from the seismic data. These conversions are generally QC'd at control points, often wells that have not been used to construct the velocity model.

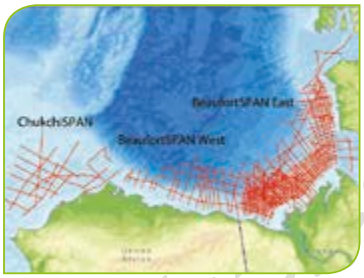
Presentation of our interpretations is often in map form, showing the depth and thickness of a predicted reservoir, the size of the trap and its spill points, and any potential drilling hazards (e.g. shallow gas). Maps of any attribute analysis in the area are presented, as well as seismic cross-sections to demonstrate the trap and the salient points of the interpretation.

Our work is very visual in nature; we look for patterns, make observations, thinking in three dimensions, image recognition and correlation with text book examples, problem solve and use our intuition on a daily basis. ■

Alice has a BSc Honours degree in Geology from the University of Leicester and an MSc in Basin Evolution and Dynamics from Royal Holloway University of London. She previously worked for Aceca-Geologica and TGSnopec and now works for Aker Solutions in Stavanger.

Regional insight into the entire Beaufort Basin.





BeaufortSPAN™ West includes nearly 2,500 km of newly acquired data and 3,000 km of existing data from the USGS. Spanning the Beaufort Basin and tying into ION's existing ArcticSPAN™ surveys, the program delivers an accurate and more comprehensive understanding of the geologic structure and evolution of this continental margin. Designed in collaboration with regional geoscientists and experts, and imaged by GX Technology using the latest processing techniques, BeaufortSPAN West provides a basin-wide context for this complicated, prolific region. To learn more, visit iongeo.com/BeaufortSPAN.

AREAS OF EXPERTISE

Unconventional Reservoirs

Challenging Environments

Complex Geologies

→ **Basin Exploration**

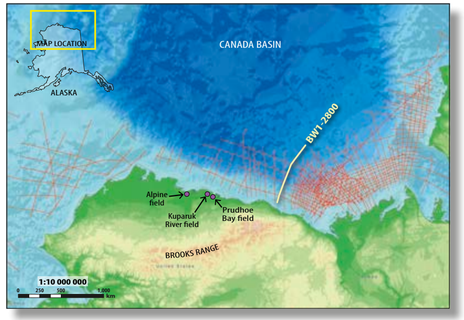
Reservoir Exploitation

Beaufort West:

New Insight into a Frontier Basin

The eastern Beaufort Shelf of Arctic Alaska – offshore from the Arctic National Wildlife Refuge (ANWR) – is a unique tectonic setting in an underexplored petroleum province. Previous questions surrounding this margin can now be addressed with the acquisition of new, long-offset seismic reflection data.

Stacked lithotectonic units at the south-western end of line BW1-2800 indicate the Belcher antiform may be cored by a hinterland dipping or antiformal stack duplex. The youngest horses are truncated by a large graben (~25 km wide) likely associated with the opening of the Canada Basin (D3), suggesting the duplex may be an Ellesmerian (D2) structure. Shortening produced by the Brooks Range orogeny (D4) was accommodated by inversion along D3 extensional structures, and detachment folding in the Beaufort fold-thrust belt. The position of the lower fold envelope (dark blue) above the duplex, but below an apparent imbricate, suggests D2 structures locally control the geometry of D4 deformation. Below the fold belt, a conspicuous series of landward-dipping reflections, which we interpret as exhumed subcontinental lithospheric mantle, forms a shallow, structural trough ~30 km wide (extended outer marginal trough). The north-eastern end of the trough steps up ~2 sec/8 km to a package consistent with oceanic crust and Moho, while to the south-west, faults inside the trough sole out and dip under continental crust along a surface we interpret as an outer marginal detachment (e.g. Pindell et al., 2014) associated with the opening of the Canada Basin (D3). If so, anastamosing subhorizontal reflections in the poorly imaged region below the trough may represent layered, mantle peridotite. (For explanation of deformation events D1–D4, see page 61.)



Location of foldout line BW1-2800 within the ION Geophysical BeaufortSPAN™ seismic program: Canada Basin, south-western Arctic Ocean. The Alpine, Kuparuk River, and Prudhoe Bay fields are located within the prolific North Slope producing area.

ANTIFORM

BEAUFORT FOLD–THRUST BELT

TWT (seconds)

10 km 50 100 150 200 240

SW NE

2 4 6 8 10 12 14 16

basalt flows

oceanic crust

Moho

outer marginal detachment

extended outer marginal trough

VE = 2.5:1

- Early Pliocene
- Early Miocene
- Upper fold envelope
- Mid. Eocene
- Mid. Eocene unconformity
- Lower fold envelope
- Franklinian basement
- Synrift deposits
- Subcontinental lithospheric mantle

continental crust — exhumed subcontinental lithospheric mantle — ocean crust

Beaufort West:
A Complete Wilson Cycle

New data reveals the deformation history of the Beaufort Basin through a complete Wilson cycle with implications for tectonic reconstructions and hydrocarbon potential.

ANN E. WALKER and **BRIAN W. HORN**, ION Geophysical

Strata within the BeaufortSPAN™ West survey area record a complete Wilson cycle, and at least four distinct phases of deformation, including the opening of the Franklin Basin (D1), Ellesmerian orogeny (D2), opening of the Canada Basin (D3), and the Brooks Range orogeny (D4), as described by the tectonic summary table below.

Similarities with Mackenzie Delta

The passive continental margin formed during Jurassic to Early Cretaceous time with the breakup of Pangea and opening of the Canada Basin (Sippel et al., 2013). Later overprinting by the Paleogene Brooks Range phase of Cordilleran deformation produced the arcuate Beaufort fold-thrust belt offshore (Helwig et al., 2011). During progressive oceanward migration beneath the shelf throughout the Cenozoic, the resultant tectonic wedge grew by deformation and incorporation of growth-faulted older deposits while simultaneously accommodating younger wedge-top strata that display a spectacular array of stratal geometries. Although the shallow veneer of this extant wedge has been known for decades, its structure at depth remains enigmatic due to limited seismic imaging.

The petroleum geology of the US eastern Beaufort Shelf shares many common elements with the more maturely explored Mackenzie delta of Canada, where a significant volume of hydrocarbons (1.5 Bbo and 10 Tcf) have been discovered. Fewer than a dozen exploration wells have been drilled on the 100 km-wide shelf of north-eastern Alaska, and only two were drilled more than 30 km from the coast. Active petroleum systems on the shelf are indicated by oil seeps along the coast, oil and gas shows in most exploration wells, and at least two oil discoveries estimated to exceed 100 million recoverable barrels. In addition, the giant Point Thomson gas, condensate, and oil accumulation straddles the coastline on the south-western margin of the deformed shelf.

Proven reservoir rocks are mainly Paleogene sandstones, including both deltaic and turbidite facies. Reservoir potential also exists in Cretaceous, Jurassic, and pre-Mississippian strata in a spectrum of structural, stratigraphic, and combination traps that is observed on seismic data.

Shelf to Basin Geology

The geology of the north-eastern Alaska Arctic margin is revealed by a 240 km seismic line (see main foldout line on preceding page) that extends from the inner Beaufort Shelf to the Canada Basin. The line ties to the

AGE			DEFORMATION EVENT		SUMMARY
Paleocene–L. Miocene			D4	Brooks Range orogeny	The Brooks Range orogeny (North American Cordilleran orogen) occurred in pulses produced by the collision of an island arc terrane with the southern margin of Alaska, and progressive accretion of continental terranes.
Cretaceous	Late				
	Early				
Jurassic	Late		D3	formation of Canada Basin	The dominant phase of rifting occurred ~195–170 Ma, and produced attenuated continental crust, exhumed subcontinental lithospheric mantle, and ocean crust ~130–128 m.y. old.
	Mid.				
	Early				
L. Devonian–E. Carb.			D2	Ellesmerian orogeny	Low-angle subduction and/or the collision between Siberia and Laurussia produced NE–SW trending structures.
Cambrian–Devonian			D1	formation of Franklin Basin	The Franklinian basement assemblage is comprised of carbonates, shales, and turbidites deposited over a failed rift basin and passive margin related to the breakup of Rodinia.

After Grantz et al. (2011); Helwig et al. (2011); Sippel et al. (2013)

easternmost exploration well on the US Beaufort Shelf, the Amoco Belcher No. 1 completed in 1989.

The stratigraphic interpretation of the data is based from different sources on the shelf and in the deep basin. Stratigraphy beneath the shelf is tied to the ANWR (Arctic National Wildlife Refuge) coastal plain, the near-shore Canadian Beaufort shelf, and biostratigraphic data from the Belcher and other exploration wells. Stratigraphy beneath the deep basin represents the distal slope of the Mackenzie delta and is tied to the stratigraphic framework of Helwig et al. (2011). The structural interpretation is consistent in style and scale with published interpretations of onshore outcrop and seismic studies to the south (e.g. O'Sullivan & Wallace, 1992), and east (e.g. Helwig et al., 2011).

The predominant structure beneath the shelf and upper slope is a broad (~80 km), duplex-cored antiform with the Belcher well located at the crest. The approximate top of acoustic (Franklinian) basement is both thrust and normal faulted. These two fault generations accommodated at least three phases of deformation, including duplexing, followed by rift-related extension, and minor inversion associated with Brooks Range compression.

The structural style in the upper slope to proximal basin floor region is defined by upright detachment folds in the Beaufort fold-thrust belt. Unconformities on fold hinges and growth strata in adjacent synclines indicate these structures formed during the Oligocene and Miocene. We interpret the deep, landward-dipping structures imaged below the fold belt to be exhumed subcontinental lithospheric mantle in a wide or extended outer marginal trough (e.g. Pindell et al., 2014). Faulted blocks within this trough are overlain by well-imaged syn-rift to early post-rift strata. A deep detachment is interpreted to ramp up from acoustic basement beneath the middle slope and continue northward near the base of Cenozoic strata, separating the extensional structures below from the detachment folds above.

Displacement on the detachment underlying the Beaufort fold-belt dies out toward the north-east as the sediment thickness increases to ~6 sec on the foldout line. Mass transport deposits are common in the upper 2–3 sec in Neogene to Quaternary strata, and were likely initiated by slope failure on the Mackenzie delta fan.

Perhaps most significant is the apparent truncation of the antiformal stack duplex below the Belcher antiform by extensional faults associated with the opening of the Canada Basin – a relationship that suggests duplexing may have occurred during the Ellesmerian orogeny. If so, this structure would not only represent a new structural tie- or piercing-point between the Alaskan and Canadian conjugate margins, but would also be the closest known tie-point to the inferred rotational pole of rifting.

Acknowledgement:

The author would like to thank David W. Houseknecht, US Geological Survey, for assistance with this article.

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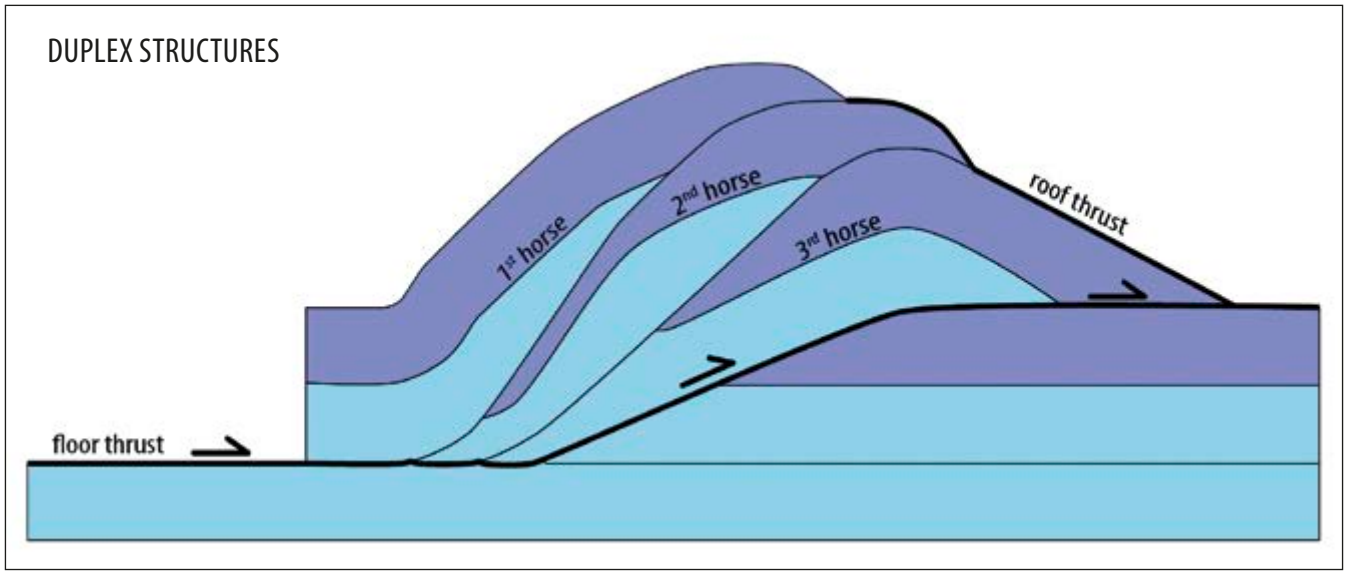
Thrust systems in which a series of thrust sheets are stacked like shingles between a roof and a floor thrust are known as duplexes. The individual fault-bound thrust sheets that compose a duplex are called horses (here they are numbered by the order in which they formed). Modified from Mitra, S. (1986). Duplex structures and imbricate thrust systems, geometry, structural position, and hydrocarbon potential. AAPG Bulletin 70: 1087–1112.



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Rethinking Regional Reconnaissance

A multi-method approach for exploring Argentina's Neuquén Basin, one of Latin America's most dynamic and underexplored hydrocarbon systems.

CARLOS FERNANDEZ, NEOS

The Neuquén Basin, which was first explored for hydrocarbons a hundred years ago, lies just east of the Andes deformation. Sedimentation was triggered by the inception of a late Triassic rift system characterized by large tilted blocks that were filled by both marine and non-marine clastics and volcanics. A collision of continents in the Jurassic added further structural complexity to the region as the two principal shale targets in the basin – the Los Molles and Vaca Muerta – were deposited.

These black shales are widespread throughout the basin and have served as rich source rocks for the conventional reservoirs that have been producing in the area for more than 50 years. Both are extremely thick oil- and gas-charged shales that have taken on a new importance as new technologies have become available for unconventional asset exploration and development.

Argentina's shale formations are considered to comprise the largest shale gas resource outside the US and are often compared to the Eagle Ford play in Texas, where horizontal drilling and hydraulic fracturing have enabled engineers to turn source rocks into reservoirs. The shallower of the two, the Vaca Muerta, is proving to be more oil prone than the Los Molles, which tends to produce dry gas. There have been a series of discoveries in the Vaca Muerta at reportedly good flow rates and, as a result, companies are taking notice.

Single Interpretation Needed

The Neuquén Basin has emerged as a high-potential arena for hydrocarbon exploration. The Argentinian government has estimated that the basin contains more than 250 Tcf (40 Bboe) of unconventional natural gas in both tight sands and shales. Activity in the Neuquén Basin has increased recently as a series of international oil and gas firms have leased acreage throughout the play. One of Argentina's dominant local players has announced several discoveries in the last couple of years, and analysts now believe the basin could produce several billion barrels of oil equivalent in the decades ahead. More recently, other international E&P companies have made moves to secure acreage as part of their global strategic expansion into unconventional shale plays.

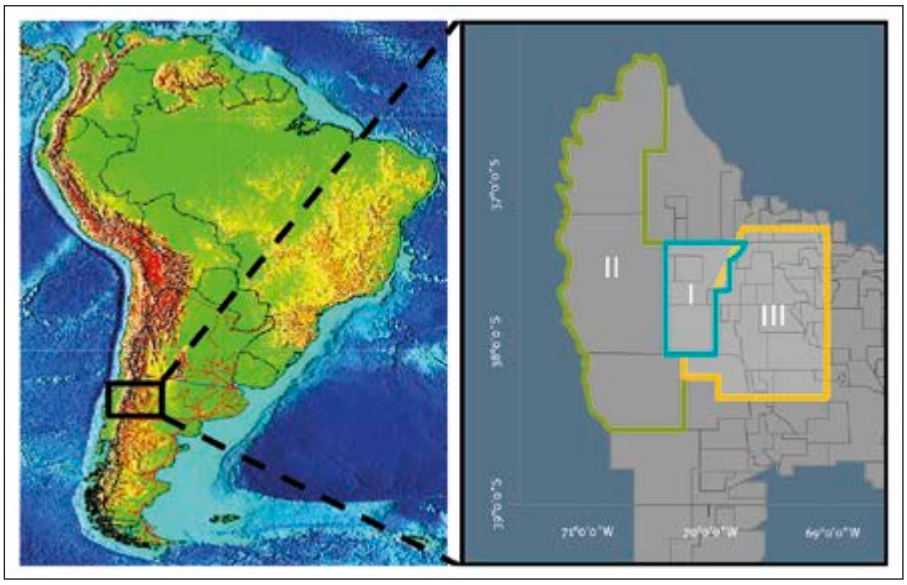
Although several seismic and non-seismic datasets have been acquired in the area, the coverage is not uniform and no entity has yet integrated all of the available data into a single, cohesive interpretation. While many geoscientists might think 'seismic first' when exploring the Neuquén, the sheer expanse of the basin, challenging topography (especially as one moves west towards the Andes),

The Andean Cordillera del Viento lies in the northern part of the Province of Neuquén and rises to over 4,700m. The challenging topography is one reason why E&P companies have been looking beyond seismic to assess the potential of the region.

NEOS

and the region's subsurface imaging objectives (which frequently require long-offset seismic surveys) dictate a more expensive and time-consuming program than many companies can tolerate.

As a result, several operators in the region began to look 'outside the box' for a fast and efficient exploration method in which the target shale intervals could be mapped and the most prospective 'sweet spot' locations identified. These operators turned to NEOS GeoSolutions – a Houston-based provider of surface and subsurface imaging solutions – to recommend a different approach. The alternative that NEOS proposed – trade-named neoBASIN™ – involves acquiring, integrating, and simultaneously interpreting as many geological, geophysical, and geochemical datasets as possible. In 2011, the company began to acquire data for its Neuquén neoBASIN project.



Neuquén neoBASIN Program Phases I-III.

Improved Understanding

On a neoBASIN project, NEOS gathers unique, high-resolution geophysical data using its proprietary airborne sensors over a known or potentially prospective basin. Measurements from these systems are combined with additional geological, geochemical, geophysical, and well data available in the public domain, from third-parties, and from NEOS's clients, and are then simultaneously interpreted to render a more accurate, cross-correlated, 3D depiction of the subsurface Earth.

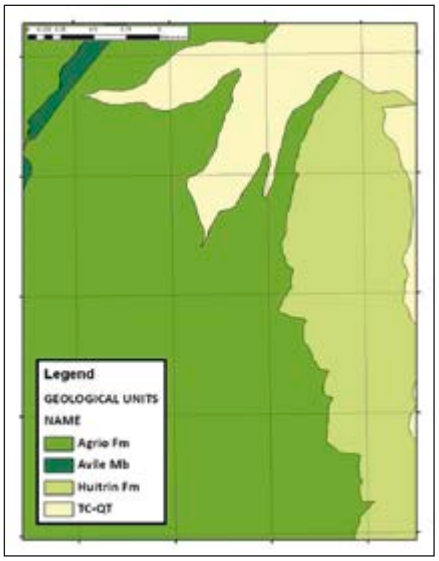
For the Neuquén project, the survey was designed to provide the project's underwriters with an improved understanding of the basin's geologic context, including maps of the location, depth, and thickness of potential source rocks; assessments of the basin's sedimentary, tectonic, and thermal history; and 'sweet spot' maps that highlighted the most prospective areas for hydrocarbon exploration using a cutting-edge, statistical data mining technique called predictive analytics.

To date, NEOS has acquired 30,000 km^2 of non-seismic data over the Neuquén Basin, including high-quality gravity, magnetic, and hyperspectral datasets. In addition, significant on-the-ground work has been completed, including 'ground truthing' to validate the airborne measurements as well as field-based geochemical studies. As a team of geoscientists began an intensive field sampling program, legacy seismic and potential fields' datasets were re-processed and reinterpreted, and a new airborne acquisition program was launched to obtain modern gravity, magnetic, and hyperspectral data. In December 2012, several of the project's original sponsors underwrote a 10,000 km^2 expansion adjacent to the original survey area, as shown in Phase III above.

The project focused on assessing the relative prospectivity of the Neuquén Basin, including the regional liquids-generation potential of the various shale targets within the basin and the tectonic, structural, thermal, and depositional factors that directly affected relative well productivity. By applying its proprietary geostatistical interpretation methodology to all of the G&G datasets that were acquired or accessed, NEOS sought to:

- Identify structural and geochemical anomalies on the surface that may indicate lithological and hydrocarbon-bearing sweet spots in the subsurface;
- Map major sedimentary layers, fault systems, volcanic intrusives and other basin-scale structural features;
- Create 2D structural and lithological cross-sections and 3D subsurface models;
- Map the distributions of hydrocarbon accumulations, fracture systems, and certain rock properties, including the TOC of outcropping shales;
- Integrate and simultaneously interpret all G&G measurements to highlight potential exploration targets and to high-grade acreage;

Airborne hyperspectral data (right) compared to legacy geologic map (left).



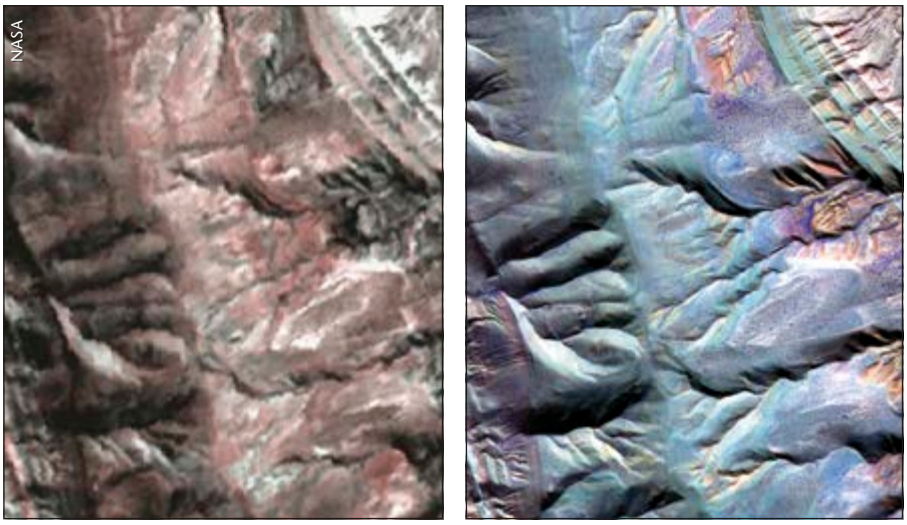
- Identify the most prospective acreage worthy of further investigation and analysis.

Early Results

One of the first aspects of the study was to improve the geologic maps within the area. Airborne hyperspectral data played a key role in this regard. Various government agencies had mapped the area of interest historically, noting only four outcropping geologic horizons in the relatively large area shown on the previous page. As the hyperspectral image shows, the area appears to have far more going on geologically than the legacy government maps might have suggested.

Although public data options for several geophysical datasets existed, NEOS determined that new data acquisition would be advantageous given the program's imaging objectives. To highlight an example of the data quality improvement that was possible, the left-hand image above was acquired using NASA's ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) satellite. ASTER data is readily available to geoscientists, although it doesn't cover all regions of interest to natural resource explorers. Although these datasets are acquired from space, they don't have the resolution you see on publicly disclosed spy photos or Google Earth. Interestingly, ASTER serves as one of the more common sources of data for geoscientists undertaking airborne remote-sensing projects, and ASTER data was, in fact, available over this portion of the Neuquén Basin. By comparison, the other image was acquired using hyperspectral sensors flown aboard NEOS-owned and operated fixed-wing aircraft. Even to a layman, the difference in resolution is readily apparent, a difference that ultimately translates into the utility of the data.

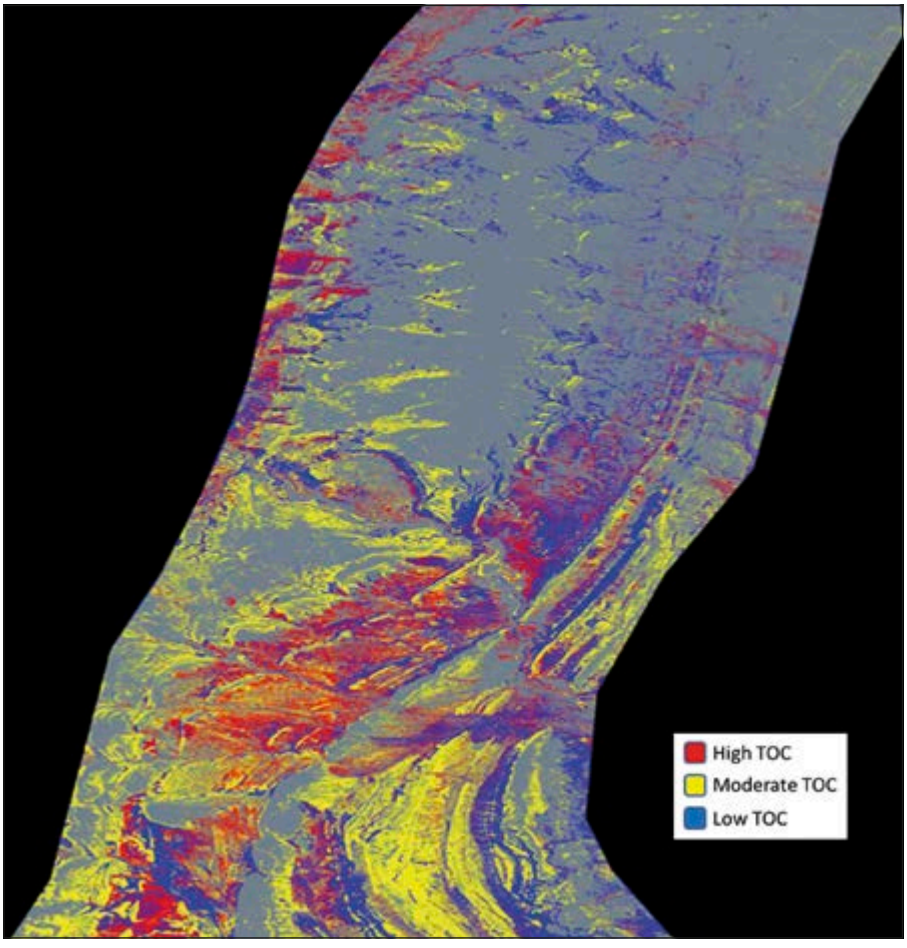
This high-definition imagery was analyzed to classify and categorize the data and to identify direct and indirect hydrocarbon indicators on the surface, including the presence of specific minerals that indicate the presence and maturity of source rocks outcropping at the surface in this structurally complex region at the foothills of the Andes. Airborne, field, and laboratory analyses of hyperspectral and rock sample data were combined to create a map of TOC variations in the outcrops of target shale horizons throughout the survey area.



Publicly available satellite multi-spectral data (left) vs. new, fixed-wing aircraft-acquired hyperspectral data (right).

Following the basic hyperspectral processing efforts, the Neuquén ground-sampled spectra and existing spectral library were employed to classify the hyperspectral data in order to produce a surface lithology map, a hyperspectral geologic map, an altered clay and mineralization map, a surface hydrocarbon seep map, and the TOC map of outcropping shales shown below.

Map of TOC (total organic carbon content) in ~200 km² area of the Neuquén Basin, created by analyzing hyperspectral, field, and laboratory data.



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Area-Wide Models

A second workstream involved the generation of area-wide 3D models that included and reflected the structural aspects of existing seismic lines, existing or new geologic cross-sections, structural and lithologic data from surface geologic maps, and available well data. A series of 2D profiles were made from these available data sets and then carefully adjusted to conform to the newly acquired and processed gravity and magnetic data along the individual profile surface tracks.

These 2D profiles were then combined to create the area-wide 3D depth model, which provided very useful exploration insights by depicting isopachs, burial depth, depth-to-basement, and proximity to intrusives for all target shale horizons; basin-scale structure, including basement topography, sediment thickness, intrusives, and fault systems; and data inputs to other regional exploration tools, including thermal maturity and TOC models. By interpreting the various maps and models, NEOS was able to segment the Neuquén survey area into regions more likely to contain liquids vs. dry gas and to identify those areas with multiple or repeat sections, a factor that derisks drilling.

In addition, the team developed a new hydrocarbon maturation model by integrating the 3D model, existing basin TOC models, and surface samples. This new maturation model identified additional areas of opportunity that were previously considered to be overmature. By interpreting the locations of volcanoes and intrusives from airborne magnetic data, a new thermal gradient model for the area was developed, refuting the previously dominant concept that intrusives and extrusives had seriously degraded most opportunity in the region. The 3D model greatly assisted in predicting the thickness of the objectives and the depth below surface, a critical factor in picking drill sites in the region.

The final analytical step in the evaluation of the Neuquén Basin was to combine all measurements, maps, interpretations, and data bases into a 'sweet spot' map showing the recommended targets for initial exploration drilling. Several maps were generated by focusing on the entire basin and then the specific individual objectives of the various program underwriters.

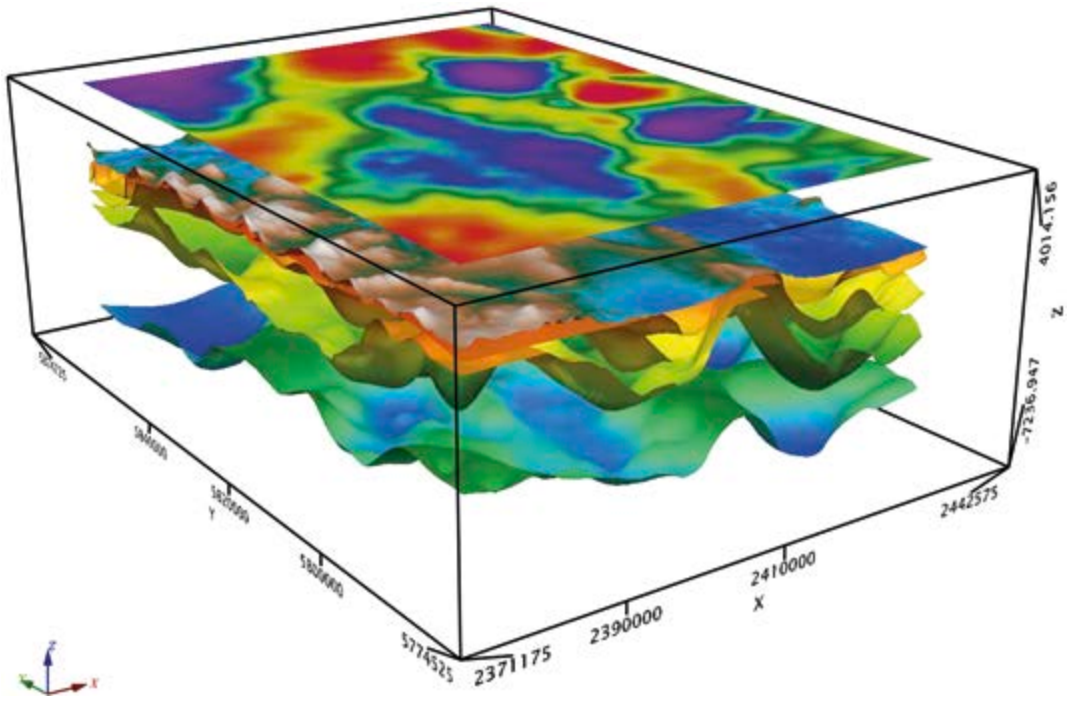
The data integrations or fusions were performed mathematically using a geostatistical data mining technique called predictive analytics. Several different predictive analytics methods were applied, including, for example, the Phase I project underwriters identifying their optimal drilling locations based upon key attributes such as minimum thickness of the target interval; minimum amount of overburden over the objective; a minimum of faults or fractures along the drill path; possibility of having generated and retained liquid hydrocarbons in the objective(s); and a relatively flat topographic area from which to conduct drilling operations. The predictive analytics algorithms then searched for these attributes, with different colors used to indicate where the most desired suite of attributes appear.

Program Expansion Plans

At present, NEOS is planning to acquire deeply penetrating, airborne-acquired electromagnetic data over a large part of the program area. It has had great success acquiring and interpreting passive source EM (magnetotelluric) data in North America, and believes that this data in the Neuquén Basin may provide additional insights into the distribution of hydrocarbons.

To date, the multi-measurement approaches applied in the Neuquén Basin have delivered new and unexpected exploration insights in a relatively under-explored portion of this promising shale gas basin. NEOS continues to refine the multi-measurement interpretation methodologies that are most applicable to the Neuquén and believes that their application throughout South America – from the interior basins of the Brazilian Amazon region to the Andes foothills in Colombia – are very promising indeed. ■

3D subsurface model, from which isopachs, burial depth, and depth-to-basement can be extracted at the basin scale.



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Shale Gas
A Commercially Viable Alternative?

What's to stop Europe from repeating the US shale gas success story?

EPI Ltd

The use of horizontal drilling in conjunction with hydraulic fracturing has greatly expanded the ability of producers to profitably produce oil and natural gas from low permeability geological formations, particularly shales, all over the globe. The application of fracturing techniques for oil and natural gas production began to grow in the 1950s and the application of horizontal drilling to oil production began in the early 1980s. By this time, the introduction of improved downhole drilling motors and the invention of other important supporting equipment, materials, and technologies meant more prospects have become commercially viable.

The US Shows How

Large-scale shale gas production started around 2000 when it became a commercial reality in the Barnett Shale in north-central Texas. As the success of this formation became apparent, other companies started drilling wells so that by 2005, the Barnett Shale alone was producing almost half a trillion cubic feet per year of natural gas. Similar success was seen in the Fayetteville Shale in northern Arkansas, so then they began to develop other shale formations, including the Haynesville, Marcellus, Woodford, and Eagle Ford shales.

In 2000 shale gas provided only 1% of US natural gas production; by 2010 it was over 20% and the US government's Energy Information Administration predicts that by 2035, 46% of the United States' natural gas supply will come from this source. Since shale gas has become an increasingly important source of natural gas in the US over the past two decades, potential gas shales in the rest of the world are now becoming of interest. Some analysts expect that shale gas will greatly expand worldwide energy supply and China is estimated to have the world's largest shale gas reserves.

The success of shale gas developments in the US resulted from a number of factors: the need to find an alternative method to release the remaining gas reserves onshore; a very competitive industry under pressure to offer good prices; tax incentives; private mineral right ownership; and the natural gas price was on an upward trend. The US economy in general is the most productive and innovative in the world, and the oil and gas industry is a very competitive sector of the economy.

Can Europe Follow US Success?

The US success proves that although the technology may not be immediately applicable in other parts of the world, shale gas could be produced at very competitive rates. European countries such as Poland, France, Germany and now the UK are considered to have very significant shale gas resources.

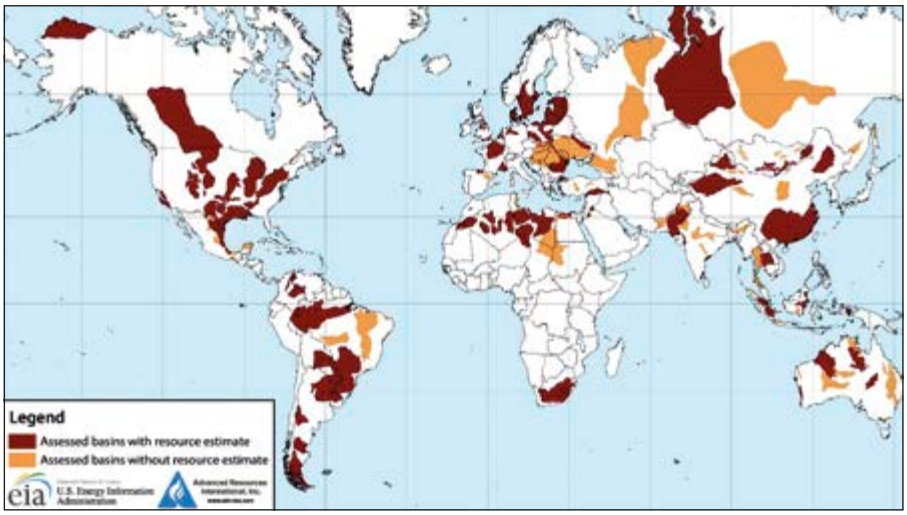
However, it is not as straightforward as one would have hoped. To start with, many of the gas reserves are to be found in highly populated urban areas, and the European onshore oil and gas industry is very small and uncompetitive. Also, in Europe, state authorities control the licensing of exploration acreages, which means that mineral rights are publicly owned. Local communities are politically aware and perceptive to the ongoing anti-fracturing campaigns. Compound this with EU policies such as market liberalization, renewable energy targets, expensive environmental regulations and safety standards and the road to success seems very rocky indeed.

Looking specifically at the UK, while

Henry Faulkner, EPI

Where is Shale Gas Found?

Conventional gas reservoirs are created when natural gas migrates from an organic-rich source formation into permeable reservoir rock, where it is trapped by an overlying layer of impermeable rock. In contrast, shale gas resources form within the organic-rich shale source rock. The low permeability of the shale greatly inhibits the gas from migrating to more permeable reservoir rocks.



Basins with assessed oil and gas formations.

shale gas geological prospects look very good indeed there are still significant technological and cultural challenges to overcome. Within the country there is little social acceptance of shale gas production amongst the public, with negative publicity following the possibility of small-scale earthquakes being triggered by fracking and landowners disputing the right to drill under their properties coupled with the fear of changing the character of the countryside.

But, given that Britain has had recent success in developing its offshore industry by adopting and improving US technologies in the North Sea, plus the fact that there is little resource nationalism in Britain and the government is trying to create good business conditions for the shale gas services industry, so onshore shale gas is likely to develop like its offshore counterpart.

Many senior members of the UK government have spoken out in favor of shale gas exploitation as a form of indigenous energy that could bring down energy bills and an alternative to investment in renewable energy. The Prime Minister, David Cameron, recently announced that the government was going 'all out' for shale gas. But others are less positive, with Vince Cable of the Liberal Democrats telling the UK newspaper *The Guardian* in February this year that: "Shale gas is a long-term possibility – no more than that."

Lord Browne, former chief executive of BP and now chairman of Cuadrilla, the only company to have used modern hydraulic fracturing techniques in the UK, has also said he is cautious about the timescale because of planning objections. When he spoke to the same newspaper he said it could take five years to discover whether the shale gas reserves of the UK could be profitably exploited.

Shale Gas Exploration for Dummies

So, the UK market at least is there for the taking for any company brave enough to take the plunge but, with worldwide gas shale exploration still in its relative infancy, it can be a steep learning curve for many oil and gas companies looking to get into this market. With extensive experience in this area from projects around the world, the EPI Group offer some pointers for improved gas shale exploration techniques within the seismic phase of operations.

Planning: Land surveys in urban/populated areas bring with them their own unique set of logistical problems. Ideally seismic programs need to be planned so they do not interfere with local agricultural activities, especially during crop planting or harvesting phases. In urban areas consider planning your survey timing to ensure minimum disruption to local activities – it may seem simple but don't run your vibroseis down the main highway in rush hour traffic if you don't want to upset the locals!

EPI's experience has also shown that ground stability is extremely important, affecting source performance into the higher frequencies above 50Hz, non-uniform power spectra and the generation of high amplitude, low frequency noise trains (i.e. ground roll). Typically ground conditions are found to be most stable during the winter months, assuming little or no snow cover, or throughout the summer between periods of high agricultural activity. Clearly, successful seismic operations would have to be closely coordinated with the farming community.

Contracts: Review and update all bid request documents – many performance specifications have been found to be out of date. Typically, contracts are poorly formed and unclear in areas such as allocated parameter testing time and weather days.

Shale gas surveys are unlikely to be in empty areas like this in Oman. Urban areas offer a different set of challenges.

It is important to consider equipment transportation and storage pre-survey.

Source fidelity: The vibratory source is typically used in shale gas exploration, but beware – local governmental agencies have placed weight limits and other operational restrictions on urban surveys, thus precluding more modern-day vibroseis technology, as most local contractors are still operating 20-tonne vibrators manufactured in the mid-'90s. In addition, until recently local seismic contractors have only had to contend with state-supported competition and so, due to the lack of outside competition, source maintenance is typically below recognized industry standards and the importance of source fidelity was not viewed as a real issue.

Vibrator design and mechanical/hydraulic fitness should be areas of major concern, and companies should exercise due diligence to ensure that they conduct independent pre-audit source evaluations prior to awarding seismic programs, and also specify in the bid document the vibrator of choice or equivalent, vehicle options, source controller and firmware.

Geophysical considerations: Conventional wisdom applies when conducting shale gas exploration but very few operators actually take the time to observe fundamental geophysical requirements: looking at effective noise attenuation, spatial sampling and holes in their stack arrays, for example. Many operators are faced with undesirable compromises that inevitably adversely impact on the data quality and therefore the successful illumination of a shale-gas play.

If you are operating in an area for the first time, it is highly recommended to construct a super sampled (5m potted geophones) test spread to establish the following parameters:

i. Effective offsets to properly image the deep targets
ii. Optimal spatial sampling
iii. Sweep type (linear vs. nonlinear), usable bandwidth
iv. Characterize in-line and cross-line noise trains – depending on local terrain, determine if there is a requirement for an aerial geophone array to attenuate ground roll, side-swipe from hills, etc.

Also consider effective source parameterization – source effort (number of sources, drive level, etc.), drag vs. standing sweeps, number of composites and modeling of source/receiver array responses to minimize source generated noise and reduce high frequency smear – to assist in generating a reliable static solution.

Take it From Us!

Experience has taught us a few things: here are a few operational tips to consider.

Firstly, depending on the results from the test spread, there may be a requirement to permit a wider 2D line swath to accommodate a staggered geophone array. Another point that may seem simple (but staggeringly easy to get wrong!) is that, when in production mode, make sure the vibrators do not drive over the spread. Other points to consider are making sure to establish realistic spread noise tolerances and good geophone planting-coupling practises and carefully considered wiring configurations.

And finally – make use of others' experience. Using a highly experienced consultancy to assist you with the survey planning, pre-survey auditing, the acquisition phase and beyond can make all the difference.

References available on www.geoexpro.com

Think Molecular

It Translates into Pay!

Being able to predict gas-oil ratio and bulk petroleum phase volumes ahead of drilling is a crucial yet very poorly constrained element of exploration strategy. The organic matter in petroleum source rocks is able to tell the story; we simply need to read it.

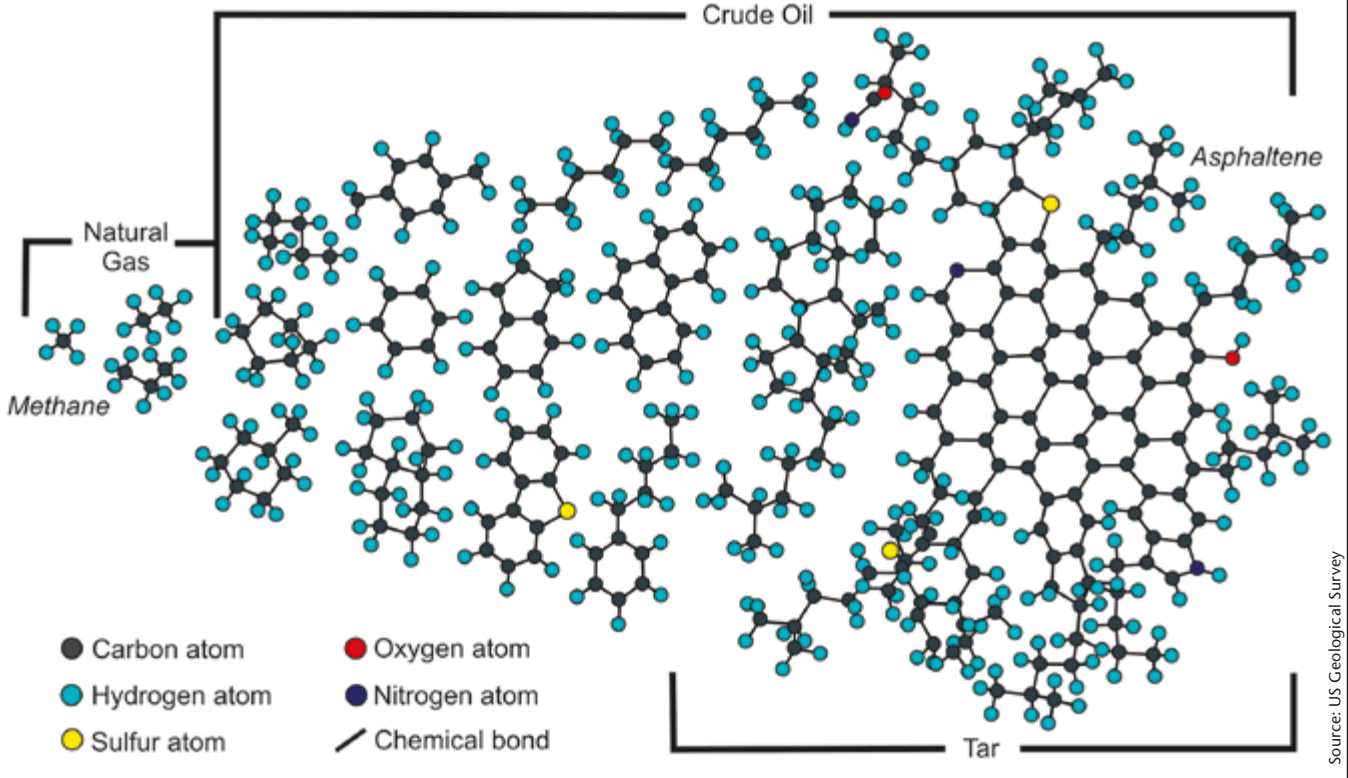
NICOLAJ MAHLSTEDT, ANDREAS HÜBNER, ROLANDO DI PRIMIO, and **BRIAN HORSFIELD**
GEOS4, Germany.

Petroleum source rocks can be formed in a variety of depositional environments. Key controls are organic matter production and preservation in the sediment. The organic matter deposited can be of algal, bacterial, or planktonic origin, or stem from terrestrial land plants. In any case, preserved organic matter assemblages can be variable in source rock sequences, depending on input and preservation conditions. Figure 2 (opposite page) shows the macroscopic lithologic variability observed in the Jurassic Posidonia Shale, and indicates variability in depositional environment and diagenetic overprint, which in turn can result in organofacies variability. The first step in source rock assessment is thus the detailed investigation of organic facies using pyrolysis techniques.

The molecular structure of the petroleum generative part of organic matter within a source rock is the key parameter, and directly controls the bulk petroleum properties of fluids encountered throughout the sedimentary column. The bulk composition of the first-formed petroleum is therefore of paramount importance because all subsequent processes occurring in the source-carrier-reservoir system – for instance, phase separation during secondary migration or uplift or fractionation during reservoir leakage – simply act upon this original composition.

Insights into the bulk-chemistry of kerogen and petroleum are required and can be easily gained by cost- and time-effective laboratory methods such as pyrolysis gas-chromatography, in which the sample is heated under an inert atmosphere leading to decomposition of the organic matter into smaller molecules which are separated using a

Figure 1. *Some examples of organic compounds in petroleum (schematic), from the simplest (methane) to the most complex (asphaltene). Pyrolysis gas-chromatography of kerogen, the precursor of petroleum in source rocks, directly translates to petroleum composition and properties and is used for predictions ahead of drilling.*



gas-chromatographic column. Knowledge of the traditionally determined generative potential alone, i.e. the hydrogen index (HI) derived from Rock-Eval pyrolysis, neither allows prediction of gas-oil-ratios nor prediction of the composition of the liquid phase. The former controls phase behavior and the latter is critical because chemistry – sulfur contents, wax contents and TAN – all directly affect physical properties – viscosity, recovery – and therefore price per barrel.

To gather molecular information on live kerogen within a source rock is furthermore of great relevance, especially in unconventional systems as the liquids and gas are 'reservoired' in the matrix/fracture porosity and sorbed on the surface of the 'source' organic fraction itself.

In this article we will show later how the molecular structure of this organic matter not only defines how much petroleum will be retained within the rock but also how much gas can be stored via sorption. We will also illustrate, using a backcloth of source rocks from all over the world, how the chemical structure of macromolecules influences petroleum composition and thus phases behavior of hydrocarbon fluids within the sedimentary column and during production.

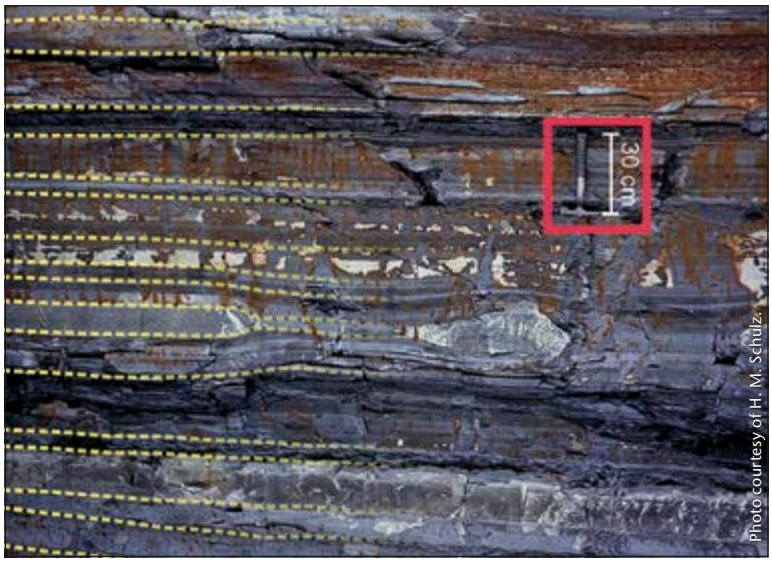


Figure 2. *Jurassic Posidonia shale – typical of what shales often look like. Small scale vertical heterogeneities, as visualized with the yellow broken lines in the left of the photo, indicate variable depositional conditions and hence, likely variability in organic matter contents and preservation.*

Defining Kerogen Quality

As already explained, the total organic hydrogen budget, or HI, is inadequate for assessing oil or gas generating potential, and the bulk components of kerogen and petroleum, as revealed by pyrolysis gas-chromatography, have to be taken into account for compositional kinetic modeling and bulk petroleum properties prediction. This has been demonstrated by the liquid hydrocarbon-prone nature of Type III source rocks in South East Asia and Australia (Durand and Paratte, 1983; Horsfield et al., 1988) and proposed for the gas-condensate-prone Type II kerogen from the Alum Shale of Scandinavia (Horsfield et al., 1992).

The need for the application of molecular typing schemes is demonstrated in Figure 3, using organic-rich, immature shales from all over the world and of all geological ages. Depositional environments are described as fully lacustrine (full circles) or marine (different symbols), demonstrating that higher land plants as the main precursor for Type III kerogen do not significantly

Figure 3. *Rock-Eval 'Pseudo-Van Krevelen' diagram: This classification is excellent for predicting yield. But that is all! It is too simple.*

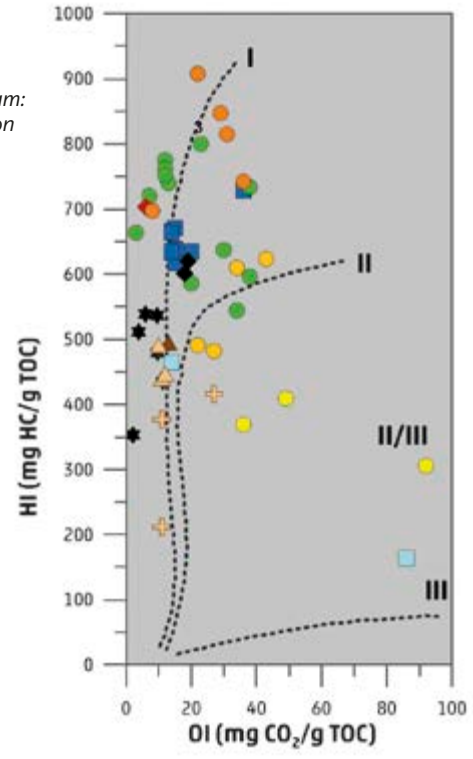
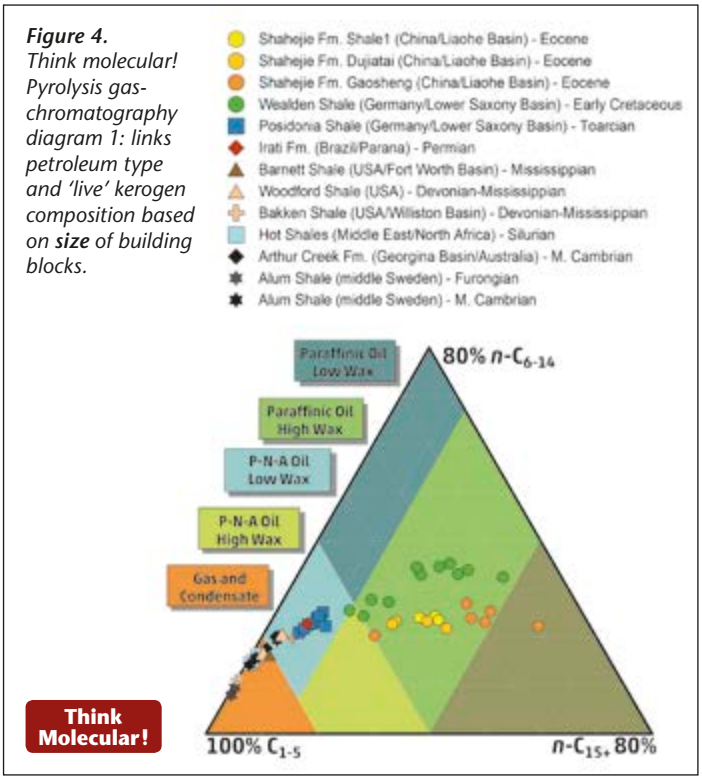


Figure 4. *Think molecular! Pyrolysis gas-chromatography diagram 1: links petroleum type and 'live' kerogen composition based on **size** of building blocks.*



contribute to the organic matter. Nevertheless, one can see at first sight in the Pseudo-Van Krevelen diagram (Figure 3) that generative potentials are characteristic for all kinds of classical kerogen types, including Type III, and that samples cannot be clearly separated into marine Type II and lacustrine Type I sources. Classical kerogen typing is therefore misleading and prediction of bulk petroleum properties impossible.

Instead, open-system pyrolysis gas-chromatography (PyGC) provides a very convenient solution to define kerogen quality. In Figure 4 the pyrolysate composition is displayed in the ternary diagram of Horsfield (1989) which has at its apices the proportions of total gaseous products in the C_{1-5} range, summed C_{6-14} n-alkanes and n-alk-1-enes, and summed C_{15} n-alkanes and n-alk-1-enes. This diagram allows correlation of pyrolysates and petroleum composition on the basis of the average chain-length distributions of alkyl-moieties and enables us to obtain information about the source depositional environment.

The results are convincing. For all samples of the Cretaceous Wealden (Germany) and the Shahejie Formation of Eocene age (China), generation of paraffinic, wax-rich oil can be inferred which is characteristic for lacustrine source rocks (full circles) deposited under alkaline to freshwater conditions. Similarly, marine source rocks (different symbols) typically generate mixed-base oils, i.e. a more paraffinic-naphthenic-aromatic low wax oil which can as well be inferred for the here displayed shales of Jurassic through Cambrian age. Interestingly, pyrolysates of many marine shales of Paleozoic age tend to intercalate into the gas and condensate organofacies field characteristic for the presence of more short-chain dominated, aromatic precursor structures within the kerogen. In any case, whether the first-formed petroleum is rich in gas or rich in wax compounds exerts a strong control on the petroleum fluid properties and thus phase behavior.

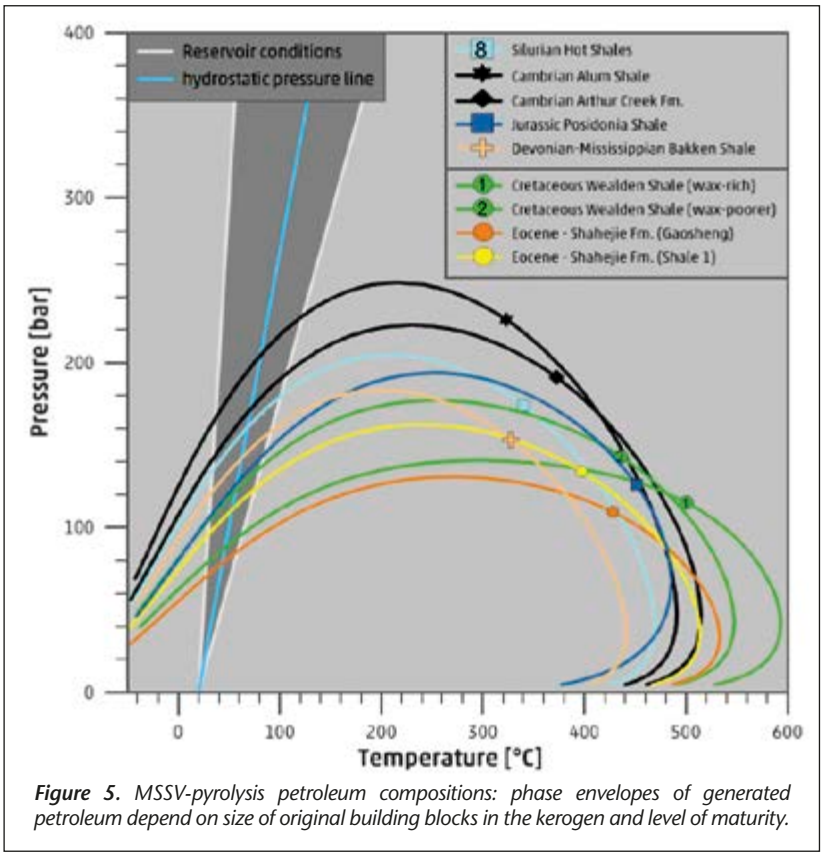


Figure 5. *MSSV-pyrolysis petroleum compositions: phase envelopes of generated petroleum depend on size of original building blocks in the kerogen and level of maturity.*

Differing Physical Properties

In Figure 5, phase envelopes of selected marine and lacustrine samples are shown and illustrate the physical properties of cumulatively generated fluids at 70% kerogen conversion (using closed-system Micro-Scale-Sealed-Vessel pyrolysis following the PhaseKinetics approach of di Primio and Horsfield, 2006). Strong differences in physical properties even within organic matter type groups are revealed. Generally, the phase envelope describes the changes in phase state as a function of pressure and temperature and its shape is mainly controlled by the gas content (GOR) and dryness (methane content) as well as by the amount, density and molecular weight of the so-called plus fraction (~C_{6+} compounds) of the fluid. Thus, the higher the GOR and dryness of a generated fluid, the higher is the cricondenbar and saturation pressure (upright envelopes). The examples in Figure 5 demonstrating this come from marine, Cambrian shales from Sweden (Alum Shale) or Australia (Arthur Creek Formation). Vice versa, the higher the amount, density, and molecular weight of the plus-fraction, the higher is the cricondentherm and the lower is the saturation pressure (flat, 'loaf' shaped envelopes), with examples in Figure 5 coming from lacustrine shales from Germany and China.

It should be kept in mind, though, that only a small part of the shown pressure-temperature conditions are realized within geological subsurface to surface systems, here indicated by the darker shaded, triangular area comprising a hydrostatic pressure line for a 30°C/km geothermal gradient. The intersection of the different bubble point curves with, for instance, the hydrostatic pressure line is diagnostic for the depth level at which phase separation (i.e. exsolution of gas from the liquid phase) could occur in the source-carrier-reservoir system during migration or uplift. For the given samples, gas would exsolve from volatile oil sourced from the Alum Shale already at 2 km burial depth (~200 bar), whereas gas would not exsolve from waxy black oil sourced from the lacustrine Shahejie Formation until 700m burial depth (~70 bar).

Consequently, the quantitative determination of bulk composition for petroleum first formed in source rocks is a requirement for modeling the migration and storage of petroleum using a petroleum system engineering approach.

Aromaticity of Kerogen

Quantifying the gas stored in shale-gas reservoirs in 'free' and 'sorbed' states is critical for the assessment of gas-in-place (GIP) and the design of effective production strategies. Keeping in mind that Type II kerogen in marine shales may be similar according to Rock-Eval parameter definition but can comprise very different structural organic matter units, we would like to point out that gas retention behavior seems to be closely

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linked to kerogen structure, besides maturity. That means that it is not the amount of 'dead' carbon or simply the carbon content which is crucial for the overall sorption capacity of a source rock, but the structure of the 'live' (i.e. petroleum generative part) of organic matter. For this, kerogen aromaticity is the key: aromaticity and sorption capacity are positively correlated.

In Figure 6a the pyrolysate composition is displayed in the ternary diagram of Eglinton et al. (1990), with which the sulfur richness or aromaticity of kerogen can be assessed. It can be deduced from Figure 6b that the more aromatic and short-chain dominated kerogen in Cambrian Alum Shale or Mississippian Barnett Shale exhibits higher sorption capacities than the less aromatic and short-chain dominated kerogen in the Jurassic Posidonia Shale from Germany.

Most important for unconventional petroleum systems, increased organic matter aromaticity leads not only to the formation of petroleum with higher gas-oil-ratios but generally to a much higher sorption capacity at all maturity levels. In extreme cases, as shown for the gas-condensate-prone Type II kerogen from the Alum Shale of Scandinavia (Horsfield et al., 1992), aromatization upon maturation can significantly lower the expulsion efficiency, causing retention of the major part of the generated hydrocarbons and finally formation of refractory carbon. In addition, this preservation of TOC was recently shown to increase the absolute late gas potential, which seems to range around 40 mg CH_4/g TOC for source rocks at maturity levels prior to metagenesis (R_o ~2.0%) (Mahlstedt and Horsfield, 2012).

Control of organic matter characteristics on sorption behavior.

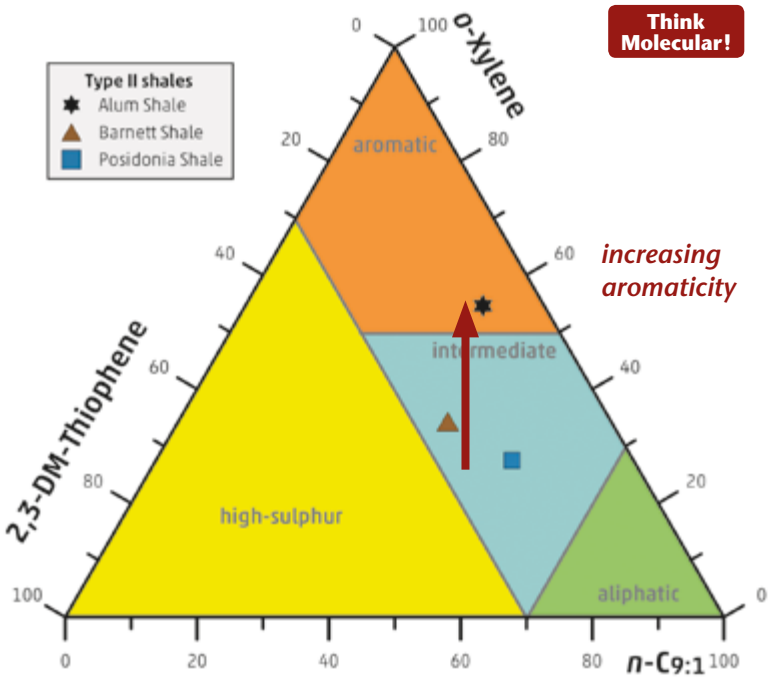

Figure 6a: *Pyrolysis gas-chromatography diagram 2: recognizes **types** of building blocks: paraffinic, aromatic, sulfur-based.*

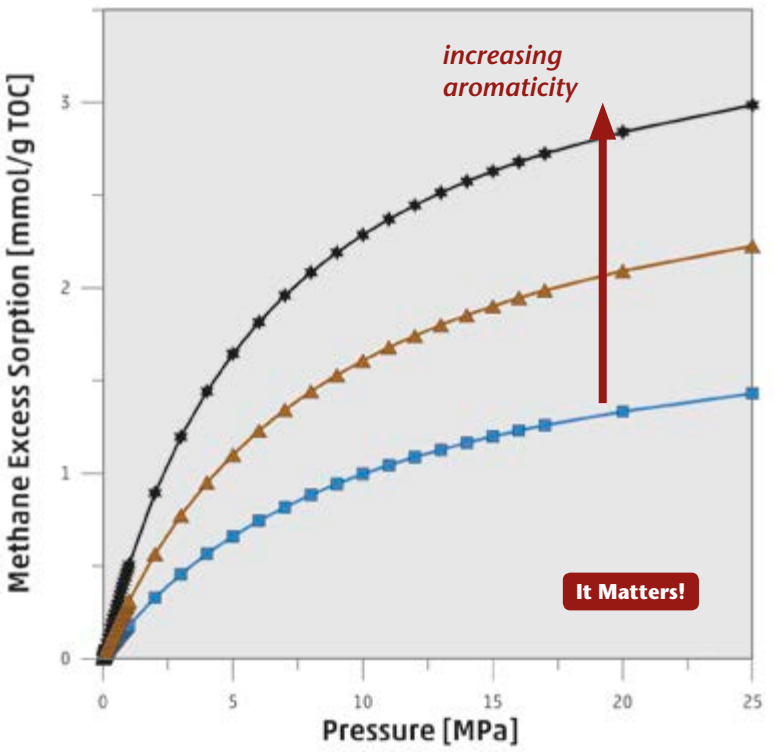

Figure 6b: *Petrophysical Analysis Excess Sorption Isotherms: Adsorption capacity is controlled by the size and types of building blocks of kerogen.*

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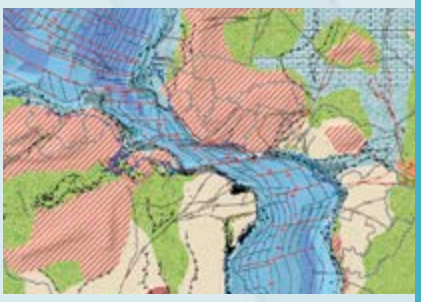

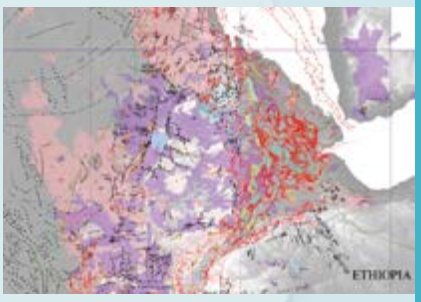

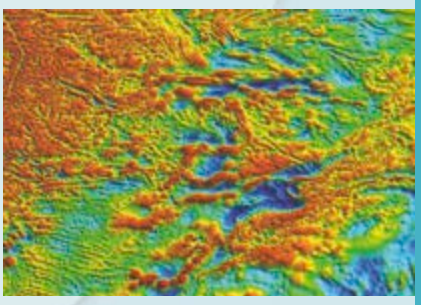

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Around the World in 59 Stages

Building a portfolio of global models for all of the 59 stratigraphic stages from the Permian to Present Day requires a layered approach – from the lithosphere to the atmosphere.

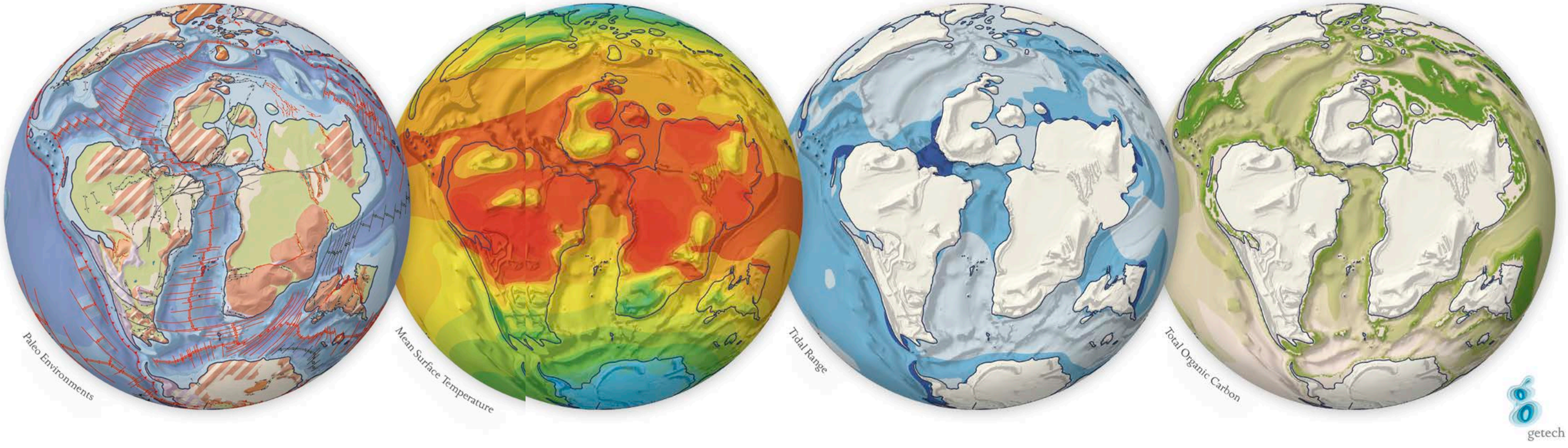
Getech build these state-of-the-art models from the very bottom to the top. The foundation is an understanding of the Earth's structural framework and crustal architecture constrained from the most comprehensive collection of gravity and magnetic data available, together with remote sensing analysis, seismic and geology.

These data enable Getech's geoscientists to reconstruct the tectonic histories of each crustal element, which together define their global plate model. This model provides the globally consistent framework and set of accurate base maps on which are superimposed gross depositional environments, base-level variations, sediment source areas (uplift), transport pathways (paleo-rivers) and elevation. Conditioning these data sets with present day analogs and geological data allows detailed modeling of the evolution of landscapes through time.

The paleobathymetric and paleotopographic grids resulting from this work, together with the defined paleo-river systems, provide the key boundary conditions for a coupled ocean-atmosphere climate model that is used to generate quantitative oceanographic, climatic and vegetation results. These results yield insights into the processes that affect deposition of source, reservoir and seal facies: from landscape development and sediment fluxes that determine the composition and character of clastic sediments, to the distribution of upwelling zones, ocean currents, and watermass stratification that influence organic matter production, preservation, and dilution.

Paleobathymetric models also provide the necessary input for detailed, variable mesh tidal modeling which is used to reconstruct transport capacity and the probable nature of coastal bedforms.

Getech's models of lithofacies distribution are not simply based on averaging and masking of pre-defined cut-off values for selected variables; they use an quantitative approach. This defines their understanding of not only the location of reservoir and source facies, but also the variation and sensitivity of the systems themselves. This is key to being able to fully assess exploration risk in frontier areas.



Reducing Exploration Risk through Modeling

Building Tool-Sets for Global Exploration: Paleogeography, Paleoclimatology and Source Rocks

RICHARD TYSON and **AMANDA GALSWORTHY**, Getech

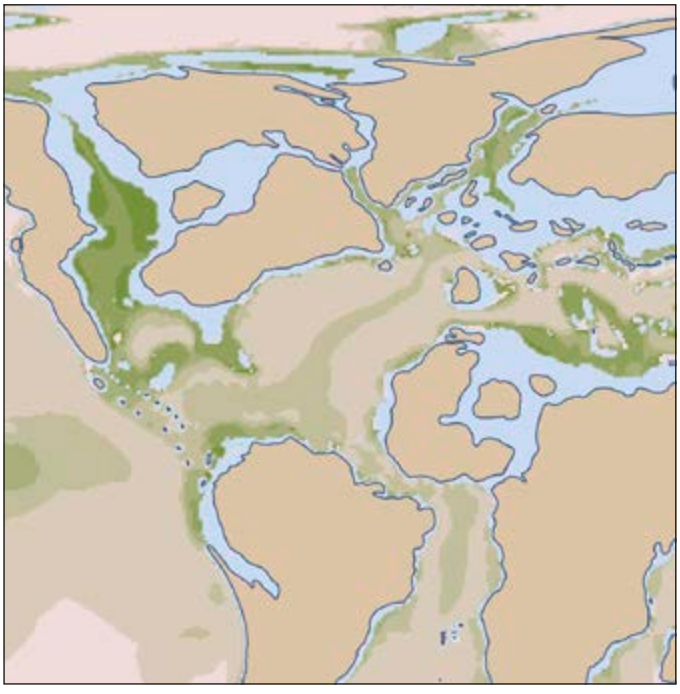
Source rocks are a pre-requisite of any petroleum system. Whilst the deposition of a potential source rock facies does not guarantee either the presence or effectiveness of a petroleum system, it at least establishes the possibility of one. Frontier basins inevitably have little or no analytical source rock data prior to exploration, and the occurrence and quality of a source rock may be inferred only from regional or theoretical analogs. Additionally, data that are available may be unrepresentative of the facies in the potential kitchen areas, therefore extrapolation and interpolation are often required. Exploration risk is thus inevitably high; anything that can help to screen basins and thereby reduce risk is crucial.

Getech's approach to reducing source rock risk is via modeling and prediction of the initial depositional distribution of organic-rich sediments. This is based on its stage-level paleogeographic reconstructions plus, for marine facies, algorithms for parameters such as primary productivity and sedimentation rate. The paleogeographies provide inputs for atmospheric and ocean circulation modeling and tidal modeling, which in turn assist with lithofacies prediction, including some parameters directly relevant to source rock development. These include paleoclimate, runoff, clastic sediment flux, upwelling, ocean circulation or stratification, oxygen solubility, oxygen demand, tidal bed shear stress, and tidal mixing regimes. Modeling of organic matter input, preservation and dilution allows both qualitative and quantitative predictions of source rock occurrence and properties. In particular, it is possible to predict initial total organic carbon (TOC) and kerogen type, both fundamental inputs for basin modeling. As in most things, the truth is more commonly grey rather than black or white, so Getech's quantitative models are designed to permit an assessment of degrees of source rock potential.

Fueled by Data

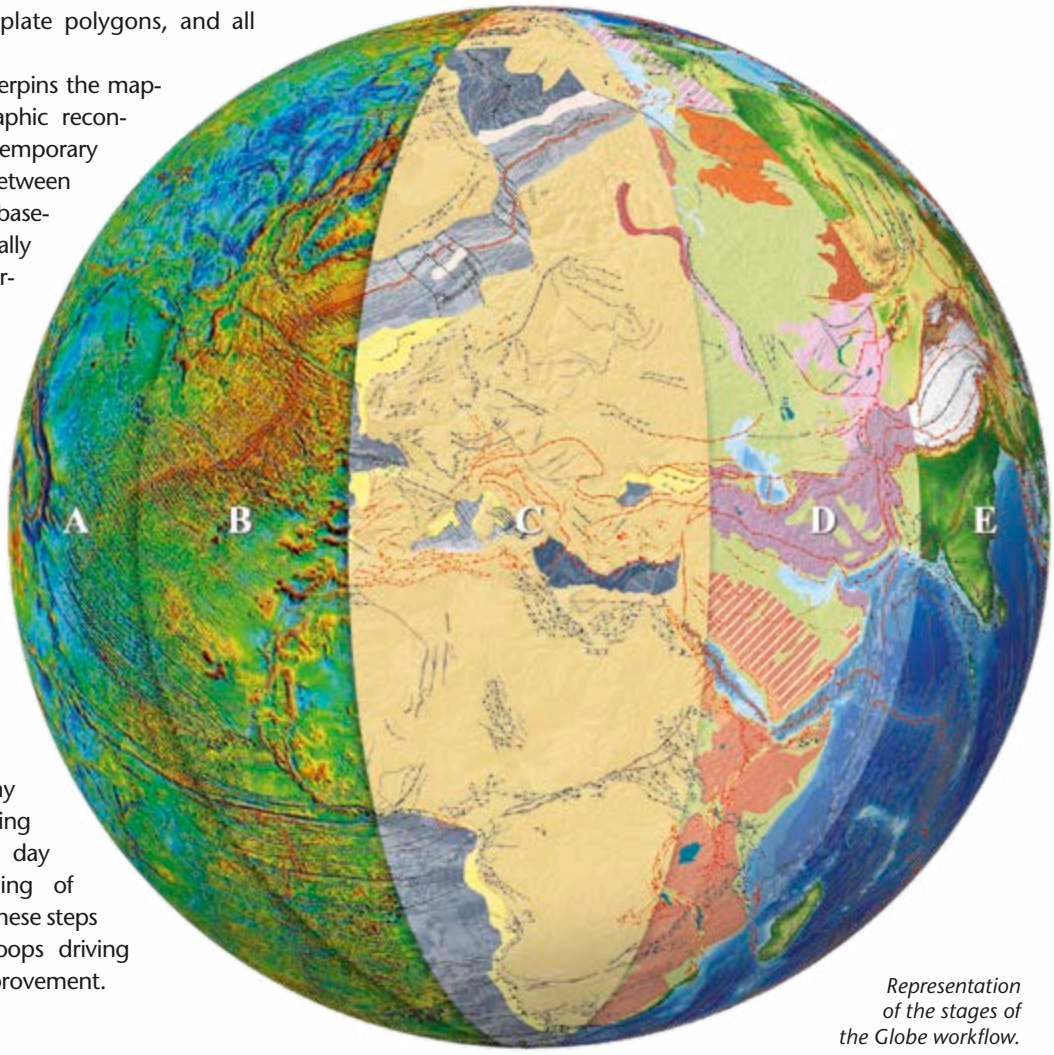
As the paleogeographic reconstructions underpin the whole modeling exercise, it is appropriate to briefly review the Globe workflow on which they are based. Mapping of the present day distribution of geological structures is based on our comprehensive global gravity and magnetic data library (Layers A and B on image on page 84) coupled with other data. Each structure is classified and fully attributed with information on its nature and activation history. This, in turn, helps constrain the plate model (Layer C). Plate rotations and hierarchies are synthesized from an analysis of diverse datasets, including Euler poles, paleomagnetism, relative plate motions, fossil distributions, orogenic histories, basement ages and accretion timings. The initial global plate model forms the fundamental crustal framework evolving through ongoing, focused testing and modeling of regional crustal classification and composition. The base maps created from the plate model include rotated

Turonian paleogeography with TOC predicted on primary productivity, water depth, and distance from land. Darker colours indicate higher predicted TOC values. No TOC estimate is possible for inner shelf depths where carbon flux equations are not meaningful.



cultural and structural data, plate polygons, and all compiled constraint data.

The key paradigm that underpins the mapping of Getech's paleogeographic reconstructions is the use of a contemporary base-level to distinguish between depositional 'sink' areas below base-level, and tectonophysiographically defined sediment 'source' terranes above base-level (Layer D). Sediment facies and lithology are compiled and mapped within the sinks. The paleogeographies also enable analysis of drainage networks: for younger timeslices this can be informed by a careful analysis of modern day drainage and topography, while for older timeslices, provenance analysis is used to infer the source to sink relationships. Digital elevation models (DEMs) of paleotopography are created using the prevailing tectonic conditions, modern day analogs and an understanding of surface processes (Layer E). All these steps are iterative with feedback loops driving continuing refinement and improvement.



Representation of the stages of the Globe workflow.

Refining the Models

In compiling paleogeographies, it is important to take account of sea-level variations throughout the stage being mapped. Whilst marine reservoir facies are most likely to be deposited during low-stand, marine source rock facies will tend to be deposited during transgressive phases. Defining the coastline for highest stand for each timeslice thus allows us to utilize the most appropriate bathymetry as an input to our models. Additionally, organic rich, oil-prone sediments occupy a broad environmental envelope in terms of water depth, paleoclimate and lithology; there is no single combination of factors which results in their development. In different regimes, high input (productivity), enhanced preservation (dysoxia-anoxia), or low dilution may be the predominant factor explaining organic-richness. Getech's initial focus has been mainly on marine shelf and slope source rocks where the prevalent pattern appears to be one of enhanced preservation coupled with low dilution in deeper, distal and low energy facies.

By changing the assumptions and algorithms used in the source rock models, it is possible to test different scenarios and hypotheses and thereby appraise the relative or absolute impact of different parameters on the modeled outcomes. Predictive success can be improved when real data is available and can be substituted for modeled inputs. Monte Carlo modeling can then be used to address levels of uncertainty at a more local level.

As the late statistician George Box observed, 'All models are wrong, but some are useful.' Modeling is necessarily an iterative process and initial models must always be refined in order to produce a convergence between predictions and observations. Algorithms based on modern data analogs provide an initial 'blind test' prediction, resulting in a quantitative approach that is independent of actual source rock observations. Such models, utilizing mean productivity, water depth, distance from land, and latitude, can predict much of the global scale pattern of organic-rich sediment distribution, and an even closer fit with observations is possible when upwelling and dysoxia-anoxia are taken into account.

Applications for Exploration

A quantitative approach built on carefully compiled and interpreted data via the Globe workflow means that consistent, objective predictions of global source rock distribution become an accessible goal. By utilizing Getech's predictive paleolithofacies modeling to understand how source rock distribution and quality are influenced by paleolandscape/bathymetry and paleoclimate (and the influence of the underlying plate tectonics), explorationists can better evaluate the risks associated with the source rock component of the petroleum systems in frontier areas. ■

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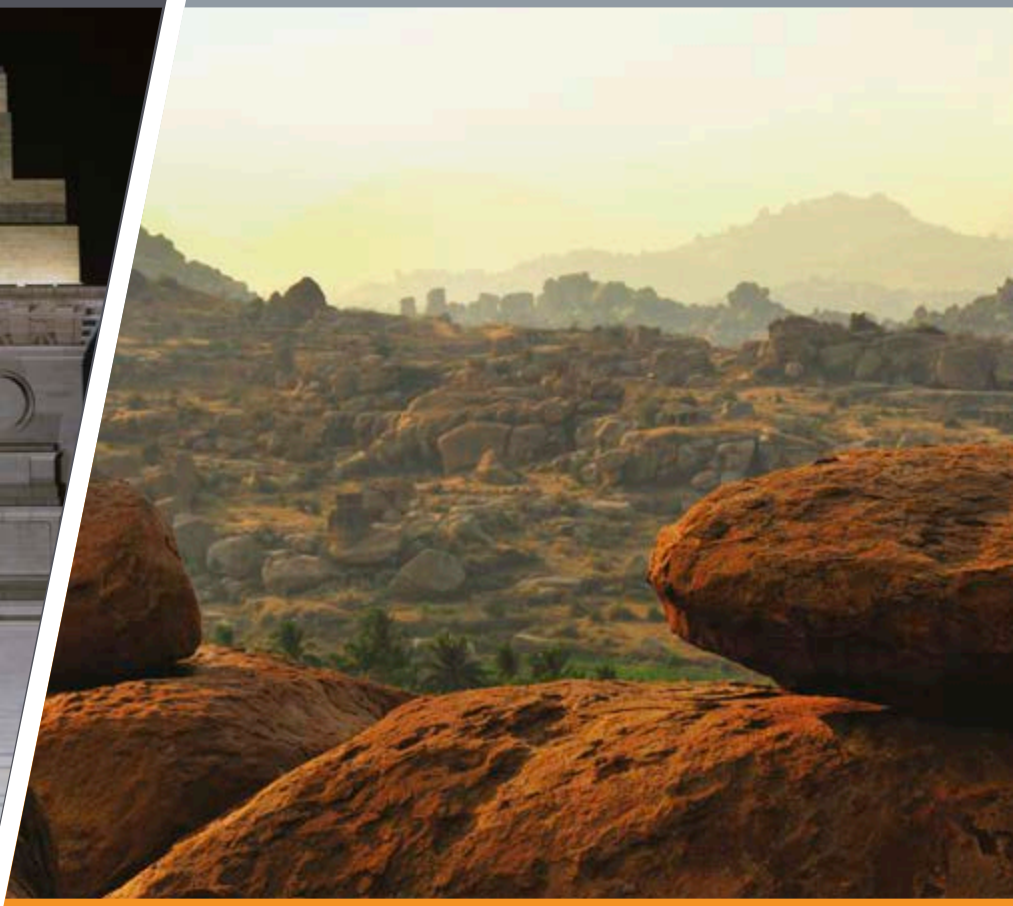

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ALLWORLD EXHIBITIONS

Water Truths, Damn Truths and Statistics

What do we all understand about the use of water in the energy industry?

JOHN SIMMONS, ON Communication

Since Mark Twain introduced the phrase 'lies, damn lies and statistics', it has been applied in situations as varied as Prime Ministerial speeches and the title of an episode of TV's 'West Wing'. One situation where we badly need truths, damn truths and statistics is in the public understanding of water use, especially water used in the energy industry.

The press and other media regularly offer statements such as, 'On average, a vegan indirectly consumes nearly 600 gallons of water per day less than a person who eats the average American diet' and 'A gallon of gasoline takes nearly 13 gallons of water to produce'*. This type of statement is woven into many of the debates about water and combining 'statistics' with the misuse of verbs such as 'consume' and 'takes', results in chronic misinformation which negatively influences the development of onshore oil and gas and other energy projects.

The Energy Sustainability Challenge

The sustainability of an industry depends on recognizing risk and for that, facts are essential: real facts, gathered from research, set in a logical context and tested for their veracity and relevance to real world settings. Gathering such data was at the heart of an initiative that BP has been running since 2010 – the Energy Sustainability Challenge (ESC) driven by BP's Chief Scientist, Professor Ellen Williams. "We recognized concerns about global resources being able to support the world's growing population, let alone raise the living standards to acceptable levels across the globe," she explains. "To meet those concerns actions must be prioritized and finite financial and physical assets assigned in a planned manner. Prioritization needs understanding, and understanding has to be based on facts. The ESC's aim is to gather facts and organize them in ways that can be accessed readily by policy makers. With water there were particular challenges: understanding the language around water use, appreciating the different ways in which volumes are measured and recorded and making reasonable extrapolations from the data available in developed countries to take account of data gaps in less developed nations."

The results to date of the research carried out by researchers at 15 of the world's leading universities are the publication of many peer reviewed papers and the production of three new handbooks: *Water in the Energy Industry*; *Materials Critical to the Energy Industry* and *Biomass***. They are available for free online at www.bp.com/energysustainabilitychallenge.

The challenge of producing the books, undertaken by Oxford-based energy industry communicators, ON Communication, started with the review of the research data produced by the academics. Next came the task of structuring the information and creating appropriate technical illustrations to enhance and complement the text in order to provide a valuable resource for both specialist and non-specialist readers. ON's MD, Martine Benoit, reflects, "Publishing data tables is one challenge, but making the data come to life has been the aim of everyone at ON involved in the writing and production of these books. We

Cooling towers at a coal-fired generating plant.

wanted them to be not just accurate and informative, but also pleasurable to read and memorable."

Clear Water

As Professor Williams mentioned, gathering real data about water and the nexus of water and the energy industry required tenacity on behalf of her team and researchers across the globe, partly because of the language associated with water. It is essential to be cautious of verbs like 'consume' and 'take', and in addition to be clear about what type of water is being discussed. The *Water* book offers definitions that differentiate brackish and saline water. Water withdrawal, consumption, use, discharge and disposal are also defined. This lexicon underpins the descriptions and arguments carried in the book and the authors exhort readers to base examination of water in their own industry on these definitions.

Another requirement for examination of the impact of the energy industry on water resources is to compare volumes of water to the amount of energy produced – water intensity – in a uniform manner. This allows for direct comparisons across energy sources and processes.

Energy Versus the Rest of the World

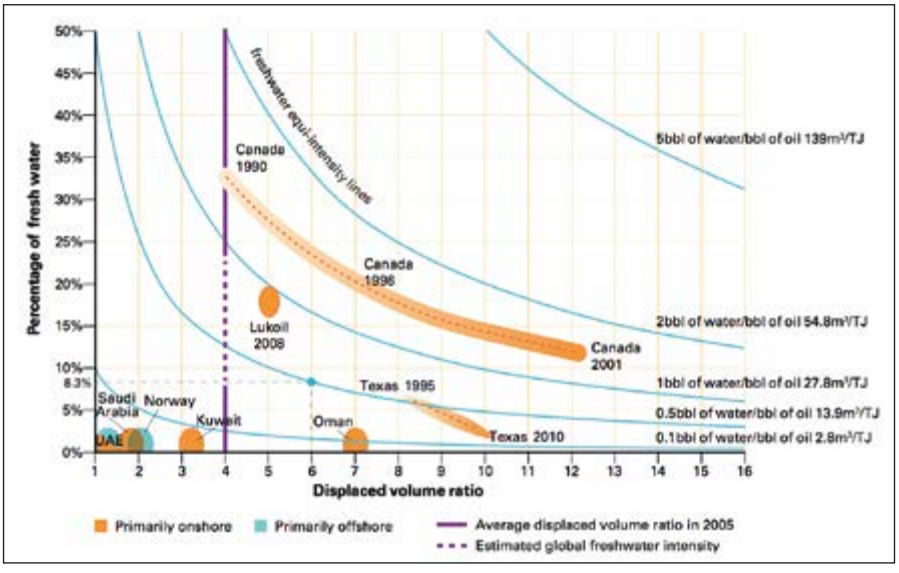
The present day total withdrawal of freshwater is estimated at around 4,000 cubic kilometers (km^3) per annum, some 10% of the total renewable freshwater available. Agriculture accounts for 70%, some 2,700 km^3 of this extraction, compared with the energy industry's 470 km^3 or 12% of the annual total. Most of the energy industry withdrawal is for cooling and is ultimately evaporated or returned to the hydrological cycle as warmer water. The rest is exposed to variable levels of contaminants, treated post-use and either returned to the environment or disposed of as waste.

Understanding how freshwater is used in the energy industry is the first step in reducing both withdrawal and consumption. Reduction can benefit the industry in many ways. Every liter costs money to obtain and treat pre- and post-use. Energy companies have to compete for water in many areas with agriculture, other industries and municipal needs. Public perception that energy production requires vast amounts of water may constrain activities. Furthermore, concerns that companies pollute water systems can, as is the case in the nascent European shale gas sector, literally be a showstopper.

Who Uses What, Why and Where?

Making the best choices about how we invest to protect the world's water resources requires improved water-use understanding. The book covers water in oil, gas, coal and uranium extraction, and also examines water in biofuel crop production, refining, electrical power generation and energy in water systems.

Freshwater consumption in conventional oil production for different regions and at different stages of field maturity.



The discussion on conventional oil focuses on waterflood and produced water. The historical situation where some waterflood required large volumes of freshwater is countered by data indicating that today, in most fields, the re-injection of produced water and the injection of saline or brackish water significantly reduces the demand for fresh water. The impact of water injection is captured in the displaced volume ratio, which is the sum of the volumes of produced oil and water divided by the volume of produced oil. The figure on the previous page shows data plotted from a range of fields and clearly indicates that the use of seawater and brackish water in offshore fields and the Middle East greatly reduces freshwater consumption to levels close to zero. It also shows the effect, on fields in Texas and Canada, of using alternatives to freshwater for injection. Extrapolating the data summarized in this figure leads to a global average for freshwater consumption intensity for conventional oil of about half a barrel of water per barrel of oil.

As waterflooding is not normally carried out in conventional gas fields, intensities are typically less than 3/100 of a barrel of water per barrel of oil equivalent (boe). The shale gas revolution has sparked controversies around fracking, many of them concerned with water. The industry has responded rapidly to public and legislative concerns by evolving practises to use less freshwater. Early fracking operations used mainly freshwater, as the chemicals needed to enhance the process were sensitive to saline water. The drilling industry is developing additives that can be effective with brackish water and this, combined with the recycling of the water that flows back to the surface after fracking, should have a marked effect on reducing freshwater consumption. Consumption intensities are hard to estimate, as the production life of fractured wells is often lengthy. Figures from 400 wells in the Barnett shale in the USA range from about a tenth to half a barrel of water/boe.

The oil and gas industries need to be aware of these intensities and how they compare to other energy sources. The table below offers a summary situation from the data gathered during the ESC program. The intensities for conventional oil and gas and even unconventional gas compare favorably with coal, but they are certainly not grounds for complacency.

Energy source	Share of world's primary energy produced (IEA, 2010 data)		Global average consumptive water intensity	Annual freshwater consumption volume
	%	Million TJ	m^3/TJ	km^3
Conventional oil	30.7%	145.0	15	2.18
Unconventional oil	1.7%	8.28	100	0.83
Conventional natural gas	18.3%	78.6	<1	0.08
Unconventional natural gas	2.6%	13.1	17	0.25
Coal	27.3%	137.0	40	5.50
Uranium mining and processing	5.7%	28.5	2.5	0.07
World		500.0		8.9

Note: 1 km^3 = one billion m^3

Estimates of consumption intensities and corresponding annual global water consumption for different primary energy sources.

Four Rs for Progress

Pressure is growing from all sides to reduce water intensity for energy production. It makes sound economic sense, increases the likelihood of continued licenses to operate and improves environmental performance. Reduction, as summarized by Ellen Williams in her introduction to the *Water* book, relies on the four Rs:

- **Replacement:** the use of non-freshwater sources such as seawater, brackish water, produced water and wastewater in place of freshwater.
- **Reuse:** using the same water multiple times in an industrial process.
- **Recycling:** treating wastewater to make it a usable replacement for freshwater in another application.
- **Regional responsibility:** adapting practises to suit the local availability and demands on renewable freshwater.

Directing action towards any of those requires understanding of where and how water is used in the energy industry and reliable data. Professor Williams believes, 'The ESC's *Water In The Energy Industry* book is a good starting place to gather both understanding and data. The work to-date has given clarity on water use in the energy industry and shown how water use can be significantly reduced.' ■

** Statements from the National Geographic website: http://environment.nationalgeographic.com/environment/freshwater/water-conservation-tips*

*** Available from May 2014.*

Water being trucked hundreds of kilometers to seismic crews exploring for oil and gas in the Algerian Sahara.

Titusville, Pennsylvania

America's First Oil Town

Long before Houston, it was the little town of Titusville which was at the heart of America's oil industry. In fact, when the Drake well hit oil in 1859 in Titusville's Oil Creek, it triggered a chain of events that led to the modern oil industry. Titusville is described as 'the valley that changed the world.'

RASOUL SORKHABI, Ph.D.

> "The city of Titusville in the south-east corner of Crawford County… has a population of about 8,000 persons. The principal industries are oil refining, and the manufacture of heavy forgings and internal combustion engines. The city is served by the Pennsylvania and New York Central railroads… A heavy sandstone, occasionally pebbly [Pottsville Series of Mississippian age], caps a few of the higher hills in the eastern part."
>
> *'Oil Geology of the Titusville Quadrangle, Pennsylvania', Parke A. Dickey (1941), Pennsylvania Geological Survey, Mineral Resource Report 22*

Today, Titusville has lost its key position in the oil industry. But a visit to this little town of 5,600 people in the northwestern corner of Pennsylvania is a chance to travel back in time to the early history of the oil industry. Moreover, as the Marcellus shale gas revolution is sweeping through the northeastern USA, the historical oil towns in that region, including Titusville, are drawing increased attention.

Titusville gets its name from Jonathan Titus, who first settled there in 1796. Over the years, other people built houses in the area along the banks of a creek that later came to be called Oil Creek because of the presence of oil seeps. For decades, lumber was the main industry in the area until August 27, 1859, when 'Colonel' Edwin Drake (1819–1880) and William Smith ('Uncle Billy'), working for The Seneca Oil Company of New Haven, drilled the historic oil well at Titusville to a depth of 69.5 ft (21m) into Devonian sands. The area rapidly developed as oil drillers settled along the Oil Creek. Currently, Titusville has an area of 2.9 mi^2 (7.5 km^2). (For more information see 'The Birth of the Modern Oil Industry,' *GEO ExPro*, Vol. 6, No. 3).

Oil Heritage Region

The 2.3-mile Titusville historic walking tour, along the Main, Central and Diamond streets, comprises nearly 20 sites including Western New York & Pennsylvania Railway Station

A replica of Drake's 1859 well (built in 1945) housed in the Drake Well Museum and Park, Titusville. A reproduction of the steam engine was added in 1986.

Rasoul Sorkhabi

(built in 1860 and renovated in 1988), Titusville Iron Works Company (1860), St. James Episcopal Church (the city's oldest church, built in1863), Titusville Oil Exchange (built in 1881), Benson Memorial Library (1904), the house of John Mather (1829–1915), whose photographs preserved in sight Pennsylvania's oil history, and the house of Ida Tarbell (1857–1944), author of *The History of the Standard Oil Company* (1904).

Some other places of interest in Titusville include Titusville Historical Society, the University of Pittsburgh's Titusville Campus, the building of the Titusville Herald, the 'First Daily Newspaper in the Pennsylvania Oil Region,' launched in 1865, and Edwin Drake's grave and memorial in Woodlawn Cemetery.

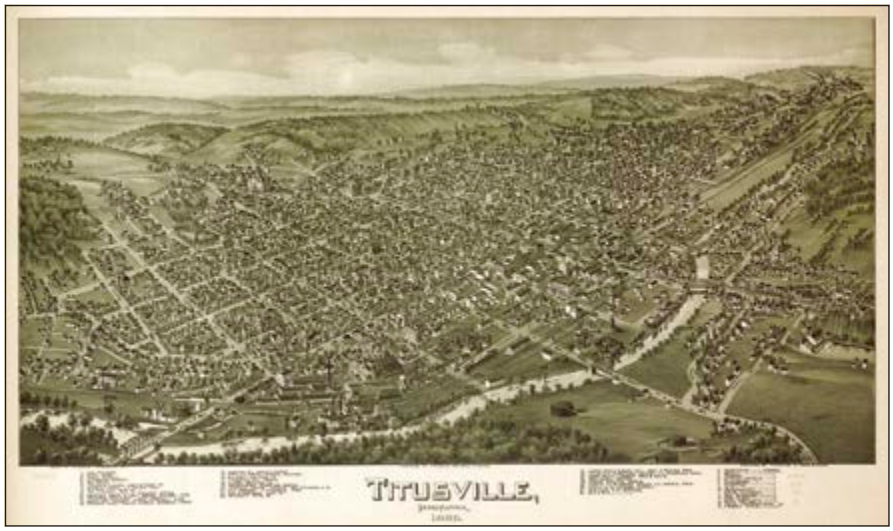
Rasoul Sorkhabi

The Tarbell House (324 East Main Street) in Titusville, where oil historian Ida Tarbell grew up. For more information on this amazing woman, see 'Ida Tarbell: Pioneering Oil Industry Journalist,' GEO ExPro, Vol. 8, No. 2. The house was purchased and renovated by the Oil Region Alliance.

Titusville is the northern portal of entry into the Oil Heritage Region that contains the earliest sites of American oil activities. It is administered by the Oil Region Alliance based in Oil City (see www.oilregion.org). The Drake Well Museum and Park (http://drakewell.org) lies just south of Titusville and is a popular sight for tourists and students. Oil Creek State Park can be visited by car on state highway 8, by a two-and-a-half-hour train ride (Oil Creek and Titusville Railroad, which runs from mid-June through October) or by walking along the Oil Creek Trail, all of which lead to Oil City, some 16 miles (25.8 km) to the south of Titusville. Also at Oil City, Oil Creek flows into the Allegheny River which drains much of the southern parts of Pennsylvania.

In 2009, Titusville City, Drake Well Museum and Park, and Oil City held a number of events celebrating the 150th anniversary of the Drake well, including the annual symposium of the Petroleum History Institute. For more information about Titusville, visit the website http://titusvillepa.com. ■

Titusville, Pennsylvania in 1896 drawn by T. M. Fowler (1842-1922).



KEN WHITE

Peru: Success for CEPSA

Drilling its first well in Peru since starting operations in the country in 2007, **CEPSA** has confirmed its **Los Angeles 1XST** wildcat in Block 131 in the **Ucayali Basin** as an oil discovery. Drilled to a total depth of 3,791m, the well encountered 19m of net pay in the objective Aptian Cushabatay Formation. Three drill stem tests were conducted over two intervals in a sidetrack that kicked off from 3,200m and yielded a cumulative flow rate of 3,422 bpd of 44–45° API oil. CEPSA has applied for a 30-day initial production test to further understand the reservoir drive mechanism, which, subject to government approval, is to be followed by an extended production test beginning mid-2014.

Los Angeles 1XST is the first exploration well of a proposed four-well program. CEPSA operates the block with 70% interest, and partner Pan Andean Resources (Pacific Rubiales) holds the remaining 30%. While reserves may not be huge, the find is considered significant as it supports the potential of the underexplored basins in Peru. ■

China: Major Gas Find

Having drilled a number of wells in the area over the last two years, **PetroChina** has now established one of the country's largest gas discoveries in more than a decade. Located in the central **Sichuan Basin**, the **Moxi** field has proven geological reserves of **15.5 Tcf** and technically recoverable reserves of **10.8 Tcf**. The play target is the Longwangmiao Formation of the Cambrian, which studies indicate extend over 20,000 km^2. Apart from the Longwangmiao Formation, the Dengying Formation of the Sinian is also a play in this area. In July 2011, PetroChina confirmed Gaoshiti 1 as an important gas find, testing 36 MMcfgpd in pre-Cambrian. The success demonstrated that there might be great exploration potential in the Gaoshiti-Moxi paleo-high area which has a large structural closure of 1,015 km^2 at the Sinian Top layer.

Moxi is an important find given China is the world's fourth-largest consumer of gas. With demand forecast to nearly quadruple in the period to 2030, the country is implementing a strategy to increase supply of the cleaner-burning fuel by boosting domestic exploration and raising imports. At Moxi, PetroChina is now building a production facility able to pump 140 Bcfpy under phase-1 development, which is to be followed by another 211 Bcfpy in a second phase. ■

With a population of 1,390 million people and rapidly rising demand, China is urgently looking for gas reserves.

Angola: Third Pre-Salt Discovery

With its **Bicuar 1A** exploratory well **Cobalt International** has confirmed a fourth pre-salt discovery in the **Kwanza Basin**, and a third in deepwater Block 21. The planned depth of the well was 6,241m with objectives to evaluate potential pre-salt mound facies and deeper stratigraphic intervals. Drilling was expected to last between 130 and 150 days but instead the well was completed in 59 days to a depth of 5,739m. Approximately 56m of net pay from multiple pre-salt intervals was encountered, with data analysis confirming the existence of both oil and condensate in multiple intervals. No free gas zones or water contacts were observed. Suspended without testing, the well was described by Cobalt to be of particular significance, as it is the first discovery of mobile hydrocarbons in the deeper pre-salt syn-rift reservoir. The next step in the evaluation of the prospect, currently estimated to have a resource potential of around **300 MMboe**, will be an appraisal well or a drill stem test. Cobalt also believes the well encountered characteristics that have been present in similar features in the Campos Basin of Brazil and will be key to expanding the potential of the broader Angola Kwanza Basin pre-salt. It may also stimulate wider industry interest in the seven Kwanza Basin blocks being offered in the onshore bid round for which pre-qualification starts on 25 March. ■

Halfway to the Promised Land

Promised Land (2012)
Director: Gus Van Sant
Producers: Chris Moore, Matt Damon, John Krasinski

Just out on DVD, *Promised Land* is a low-key, thoughtful drama that aims to unpick some of the human realities driving the US fracking social and economic phenomenon. It manages this with an admirable even-handedness and even sensitivity – but is let down by a truly unexpected plot twist that is likely to leave audiences head-scratching at best, but more likely questioning what message exactly they are supposed to take from the film.

Produced, co-written and acted by Hollywood's Matt Damon, it prompted a somewhat knee-jerk reaction from the American Petroleum Institute who, in the run-up to the film's 2012 release, orchestrated a discrediting campaign that focused heavily on the fact that the film was funded by Abu Dhabi Media (and therefore *ipso facto* biased). Given that the film is absolutely not a propaganda rant – both sides of the debate are given a good airing – and that a strong plot sub-theme is the skulduggery of big corporations and their misuse of public relations, audiences may conclude that the API actually shot itself in the foot here.

Matt Damon co-wrote, produced and starred in Promised Land

Seeing Both Sides

The strength of the film is that the story is told through the eyes of two gas company reps (Matt Damon, Frances McDormand), two good people who have been given the job of signing up the rural folk of a recession-struck community in Pennsylvania. Matt Damon's character, in particular, is convinced of the 'rightness' of his mission, having seen his grandfather's home town decimated by poverty after the closure of one agriculture-related plant. "You all see it coming and you just don't get out of the way… When all the help stops coming, you'll remember this day," he argues in frustration with a group of resistant farmers.

In fact fracking is accepted by both sides of the debate as the only alternative to rural poverty and loss of community: "I'm lucky to be old enough to have a shot at dying with my dignity," says the retired, activist teacher with heart-felt resignation. Disempowerment and social inequality are ever-present themes, providing a sombre backdrop to the film. "How many wells you got up there in Manhattan?" asks one farmer. "The only reason you're here is because we're poor."

The film touches on the other 'no alternative' argument, so rarely discussed. "You can't be neutral here," states Matt Damon's character. "If you are against this, you are for coal and oil… unless we talk about cutting consumption and that's a conversation none of us want to have." Unfortunately, apart from a reference to "running everything on rainbows and happy thoughts" there's no further investigation of this line of thinking – this is a Hollywood film, not a documentary, after all, but it leaves the two sides of the debate as polarized as ever: if you want to drive a car, you have got to live with the technology.

Many of the 'issues' surrounding fracking are not dealt with – not methane release, earthquakes, water or infrastructure requirements, nor the longevity (or not) of wells. Water contamination is the focus of just one scene, where the 'environmentalist' attempts to explain fracking to a class of school children using a plastic bag, a spear and a toy farm. The anti-fracking argument is instead implied in Damon's character's journey from confident, motivated salesman, to "I'm not a bad guy" assertions, coupled with heavy drinking, to the rather oblique, mumbled admission that "We might be betting more than we think".

Plot Twist

But even this message is lost in the bigger story of corporate venality and 'just a job' sales techniques. The plot twist that brings Damon's character to his theatrical final change-of-heart can only leave an audience perplexed. It is a comment on corporations, not fracking, and depending on your personal take regarding big business, it either discredits the film greatly – or confirms your worst fears.

On the whole, this film is a watchable attempt to explain the down-on-the-ground realities of America's shale boom to those of us who are far removed. Interestingly, in January this year Qatar announced that it will no longer seek to fund Hollywood films, so possibly the API criticism hit one of its marks – with no benefit to the US public. ■

NIKKI JONES

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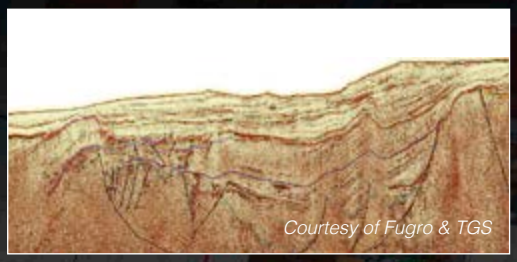

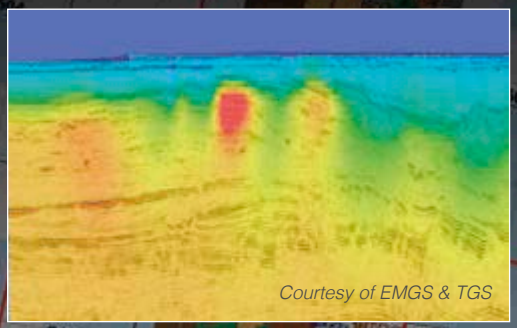

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The Next Frontiers

Where is the oil industry going next – and what exactly do we mean by a frontier? **Alastair Fraser**, EGI Professor of Petroleum Geoscience at Imperial College, London, sheds some light on the matter.

How do you define an exploration frontier?
An exploration frontier is somewhere or something that answers the question 'how and where will we find more oil and gas?' With that viewpoint, we need to look not only at geographical and geological issues, but also technological, environmental and even political frontiers.

Are any true geographical frontier areas left?
Well, the real 'final frontier' geographically is the virtually unexplored Arctic, particularly off northern Russia, but that involves all the other frontier categories. Geologically we are pushing the boundaries from the known shelfal petroleum systems into deepwater plays, while the technology has not yet been developed to cope with production from wells which are icebound for half the year and permanently in danger from ice and ferocious Arctic storms. The environmental issues in this pristine wilderness are immense, and since Russia holds two-thirds of the Arctic continental shelf, exploration there is fraught with political questions. So – a true frontier!

Tell us about technological frontiers.
In the Arctic we have the technology to explore for hydrocarbons within a 4–6 month weather window, but year-round production from a rig frozen-in for half the year and which can be hit by vast wave-borne slabs of ice – that's still to be resolved. The key will be to take the ice out of the equation by placing all production facilities on the seabed, but there are still major issues around this, plus all pipelines will need to be buried to avoid ice damage.

Away from the Arctic, after Macondo we need to ensure that we can safely drill in ultradeep water. As the distance between the seafloor blowout preventer and the topside facilities gets longer, communication between these two must remain at the forefront of technology.

Excluding the Arctic, where are the geographical frontiers?
The majors have always pursued frontier strategies – it is the basis for their very existence. In the beginning of the last century they were chasing the Middle East, whereas when I first entered the industry in the '70s, we were moving offshore into the North Sea and Gulf of Mexico. Since then, we have covered much of the globe – the Atlantic conjugate margins and East Africa have now moved from frontier to mainstream. Areas which may have significant potential include the South Australian Bight, offshore India and deepwater southern South America.

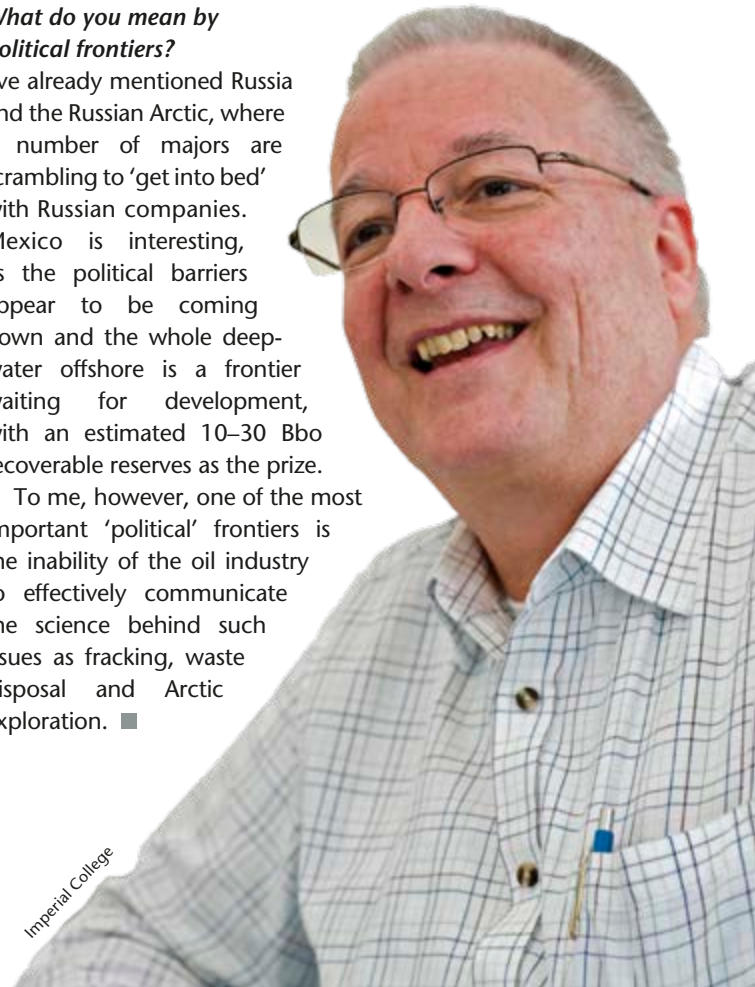
How about geological frontiers?
We are following the geology into deeper and deeper water and I think that will continue. Another example of 'new' geology is the sub-salt of the South Atlantic. We have been producing from the Tertiary and Upper Cretaceous plays off Angola for decades; if we'd bothered to drill deeper, below the salt, we would have discovered a whole new set of plays, as initially revealed through exploration in the Brazilian Santos Basin. The geology also leads us to ignore areas; due to the break-up of Gondwana, the whole of the southern Atlantic, including Antarctica, is considered to lack a good regional source rock but we occasionally get surprises, like the recently discovered lacustrine source in the Falklands Basin.

But there is an important 'geological frontier' which we cannot ignore – unconventional resources.

Which leads us to environmental frontiers?
Indeed! I think the amount of shale gas and oil and other unconventionals we have identified, and the technological advances already made in their extraction, mean that we have enough short- and medium-term global reserves to allow us to leave the Arctic, at least until we can be sure that we can produce there safely both environmentally and technologically. For that to happen we have to address the fears of the environmentalists over shale gas and oil, and I believe that we can extract this resource safely and with minimal and manageable environmental risk. We should be asking the question 'would you rather we did fracking or explored in the Arctic?' The shale gas frontier is here – we need to make it happen.

What do you mean by political frontiers?
I've already mentioned Russia and the Russian Arctic, where a number of majors are scrambling to 'get into bed' with Russian companies. Mexico is interesting, as the political barriers appear to be coming down and the whole deep-water offshore is a frontier waiting for development, with an estimated 10–30 Bbo recoverable reserves as the prize.

To me, however, one of the most important 'political' frontiers is the inability of the oil industry to effectively communicate the science behind such issues as fracking, waste disposal and Arctic exploration. ■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An Attractive Upstream Destination

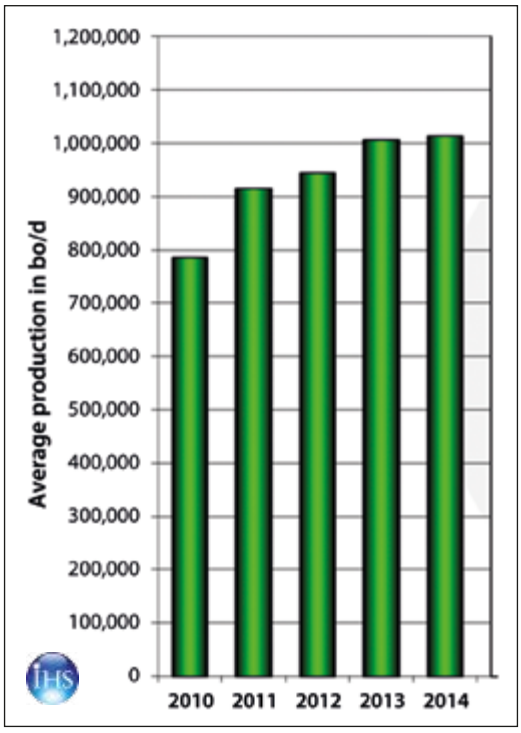
Colombia: seductive potential but security issues remain

The enactment of a series of regulatory reforms to make Colombia's oil and natural gas sector more attractive to foreign investors has led to a steady increase in both exploration and production. The turnaround is attributed to the implementation of market-oriented policies during the Uribe administration, aimed at fostering competition. These comprised firstly, the cutting of royalties from a flat 20% to a sliding scale of 8 to 25%, depending on production levels, so overall, the state's share of revenue through royalties and taxes was reduced from 70% to 50–55%. Secondly, Ecopetrol was freed from government budgetary constraints and allowed to attract and manage its own financial resources. The final innovation was the 2003 creation of the National Hydrocarbons Agency (ANH), an independent hydrocarbon regulator in charge of allocating and managing petroleum concessions in the country. Consequently, the oil and gas sector has evolved as one of the most attractive upstream investment destinations and Colombia is rated as the third best place to do business in Latin America.

A Number of Challenges

Prior to 2008, Colombia's oil production had been flat for many years, following a period of steady decline that started in 1999, when production peaked at 830,000 bpd. The principal causes of the fall were natural reduction at existing oil fields and a lack of new discoveries. Despite strong interest from private companies, and the return to Colombia of some of the largest oil companies, the majority of current activity remains focused on areas with the best geological information. International studies indicate that between 10 and 20 Bbo of crude could be found in Colombia in the coming years, but the future of the oil industry is playing out in areas that are increasingly challenging, like the Amazon. In addition, after nearly a half-decade of relatively secure operations, attacks on oil and natural gas pipelines have increased. More exploration success and improvements to infrastructure safety are critical to further increases in oil production.

Colombia's oil production exceeds its existing pipeline capacity and the resulting transportation bottleneck is a significant challenge. The issue is being addressed as a series of pipeline projects are being advanced and are expected to begin operations in the next couple of years. This proposed pipeline expansion, however, continues to focus on the Caribbean/North American market, and many observers believe this poses a problem for Colombia's export outlook in the medium term. The US is still the main destination for Colombia's oil, but is becoming less dependent on foreign oil supplies due largely to the shale oil and gas revolution, and could even become a net exporter of oil. Analysts fear that Colombia's oil infrastructure, therefore, is expanding to continue supplying a declining market. However, as with the existing infrastructure, securing the integrity of new pipelines will require significant efforts and costs. Analysts have also expressed some concern that uncertainty surrounding the current oil boom poses a serious challenge to policy makers, believing that fiscal and trade balances have become 'addicted to oil' and as a result, non-oil exports have lost competitiveness.



Shale Gas and Offshore

Policies aimed at increasing domestic natural gas consumption and exports, combined with increased demand from the power sector as a result of weather-related hydroelectric shortages, have made expanding natural gas production a priority for the government. The Ministry of Mines and Energy recently published a decree announcing that it plans in the next six months to present a final technical terms and procedure document, which will serve as a guideline for unconventional exploration. This will specify the requirements regarding financial, technical and operational, legal, environmental, and corporate social responsibility for companies interested in unconventionals. The selection of areas for inclusion in the 2014 Bid Round (see page 18) will reflect the priority that the ANH is giving to the unconventional hydrocarbons and offshore areas (shale gas potential estimated at 17 to 20 Tcf), hoping that they will deliver the larger finds the country needs to improve its proven oil and gas reserve to production ratios and secure Colombia's medium- to long-term supply security.

The ability of the state to maintain security is a big factor going forward. Guerrilla fighters continue to dog the national government and an increase in pipeline bombings will discourage some private companies from investing in the oil sector. President Juan Manuel Santos, who is seeking re-election as President in 2014, hopes to secure long-term peace with the militants in a second term. Successful negotiations would open up more territory to exploration, but if the government is to encourage new exploration with the aim of boosting reserves, it also needs to speed up the approval of environmental permits. ■

KEN WHITE

Norway Barents Sea

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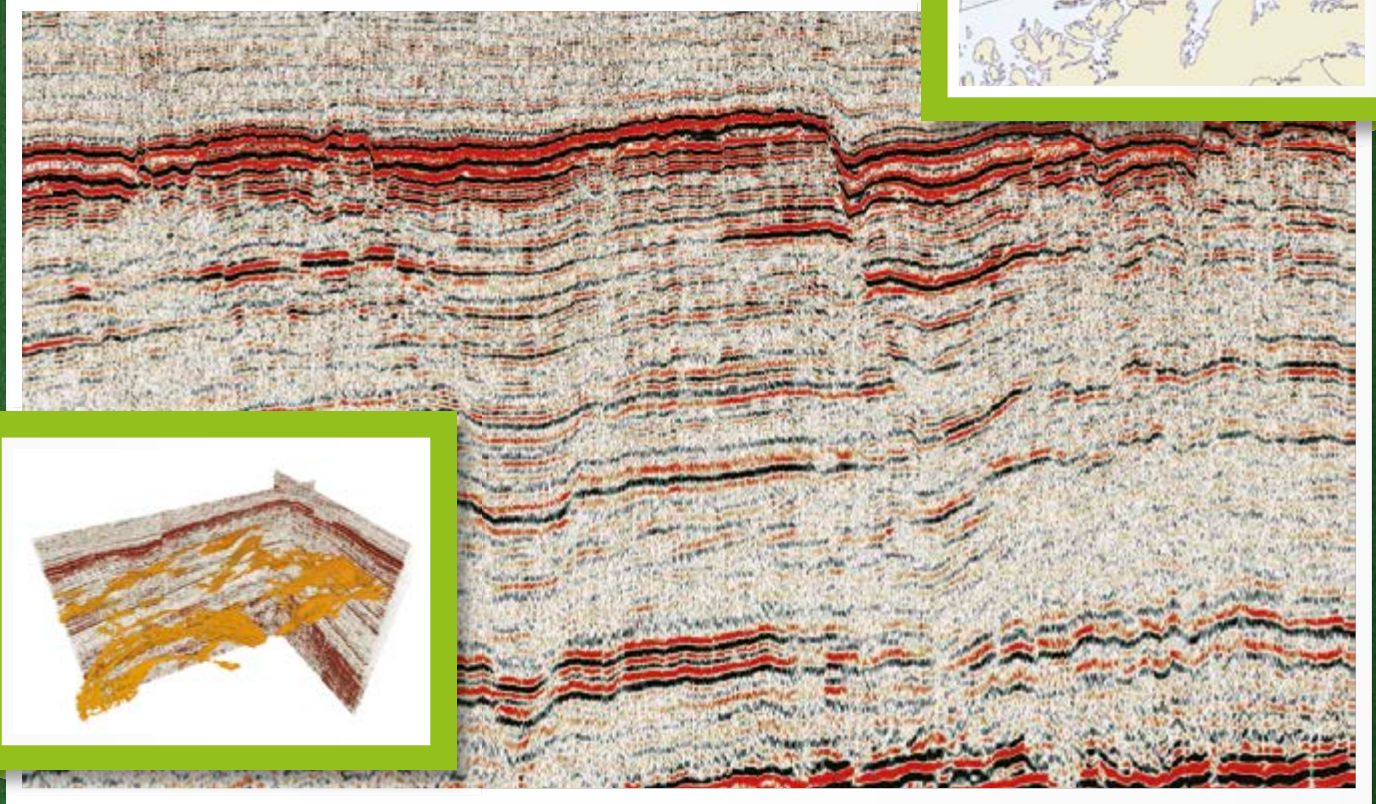

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The Oil Curse

The oil industry is making a lot of money from nations that are infected with corruption. It appears that very few people care.

It is well known that some of the world's most corrupt countries are amongst the world's largest oil producers.

Let's look at Angola. The West African country produced about 1.8 MMbopd in 2012 (2.1% of the world's total), and thus ranks as the 15th largest producer in the world. Some of the money generated from the sales of these barrels obviously goes into the wrong pockets, as Angola is looked upon as extremely corrupt according to Transparency International (TI). Out of 177 countries listed, with Somalia and North Korea at the bottom, Angola ranks 153. While oil is flowing from multiple fields offshore Angola, the people remain poor, the reason being that a significant part of the revenue is not used to improve the economy. Individuals with close connections to the government, however, are flush with money that belongs to the country.

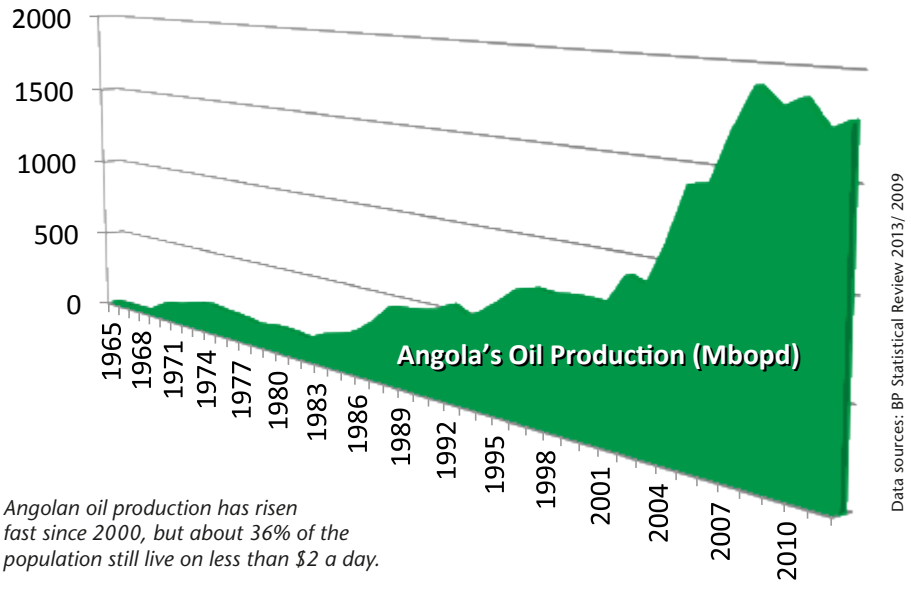
Venezuela, far down on Transparency International's list (160), also serves as a good example of an oil-producing country (2.7 MMbopd) with an advanced level of corruption. Things started to turn bad when oil started flowing in large quantities. And in South Sudan, a country which is almost at the bottom of TI's list (no. 173), development into an oil-producing nation (roughly 200,000 bopd) has certainly not created riches for the extremely poor people of that country.

This is known as 'the oil curse'. According to Michael L. Ross (*The Oil Curse: How Petroleum Wealth Shapes the Development of Nations*, 2012), professor of political science and director of the Center for Southeast Asian Studies at the University of California, Los Angeles, countries that are rich in petroleum have less democracy, less economic stability, and more frequent civil wars than countries without oil.

Since 1980, Ross says, the developing world has become wealthier, more democratic, and more peaceful. Yet this is only true for countries without oil. The oil states are no wealthier, or more democratic or peaceful, than they were three decades ago – some are worse off. Important exceptions are countries like Norway (no. 5 on TI's index), Canada (no. 9), and Great Britain (no. 14), which have high incomes, diversified economies, and strong democratic institutions, and have extracted lots of oil with few ill effects.

Ross also warns that the global thirst for petroleum is causing companies to drill in increasingly poor nations, which could further spread the oil curse. The heritage generated from corruption is very difficult to get rid of, so difficult that the nations will be affected for generations to come. It is very sad that the international oil companies do not unite to try to reduce the problem. ■

HALFDAN CARSTENS



Angolan oil production has risen fast since 2000, but about 36% of the population still live on less than $2 a day.

CONVERSION FACTORS

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

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

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

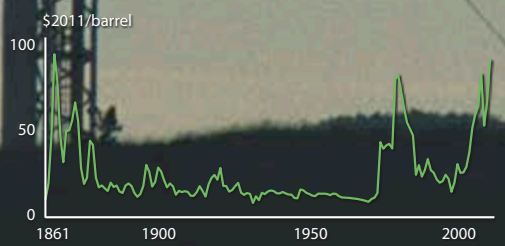
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

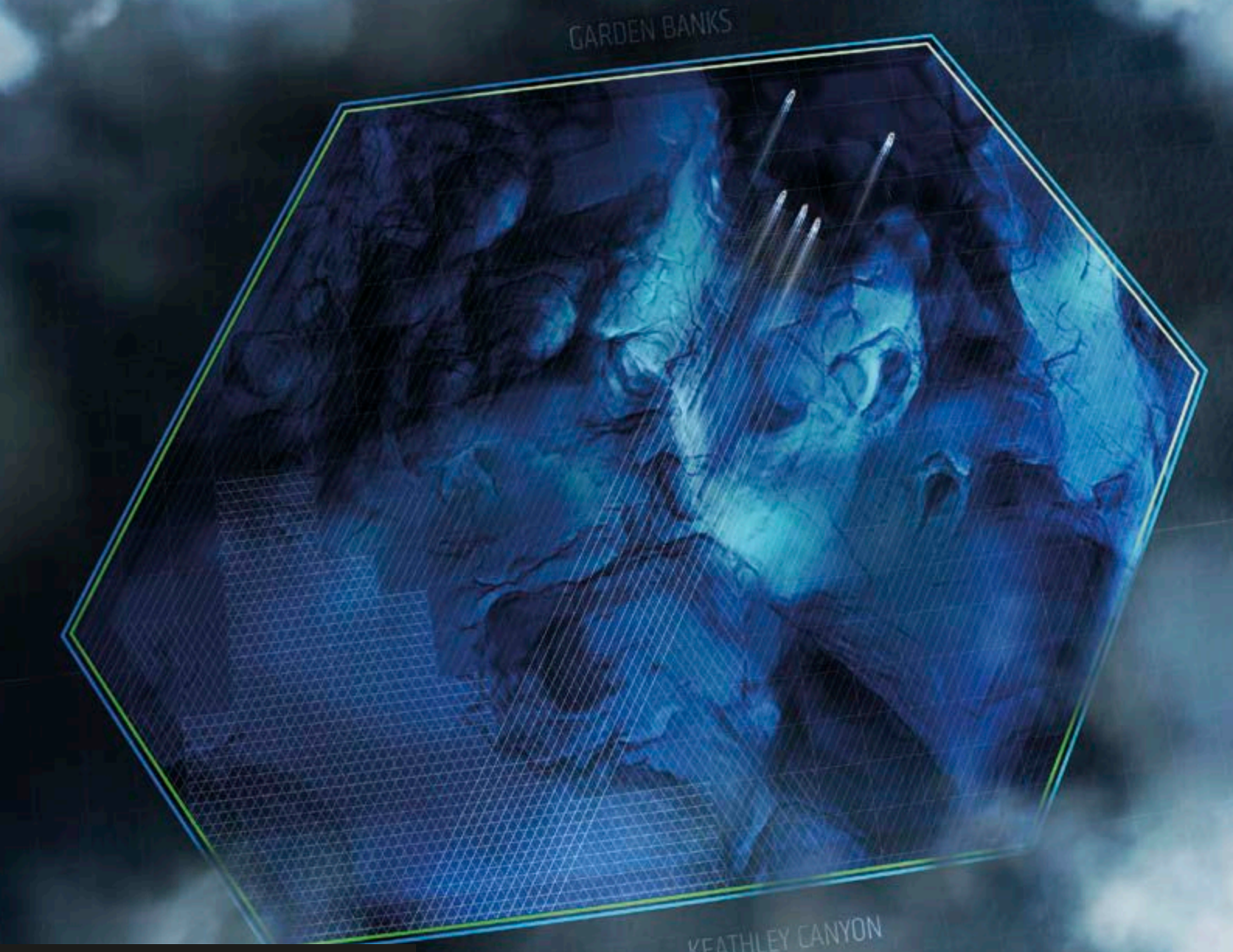
Supergiant field
Recoverable reserves > 5 billion barrels (800 million Sm^3) of oil equivalents

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

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

Historic oil price





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