VOL. 10, NO. 2 – 2013

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

geoexpro.com

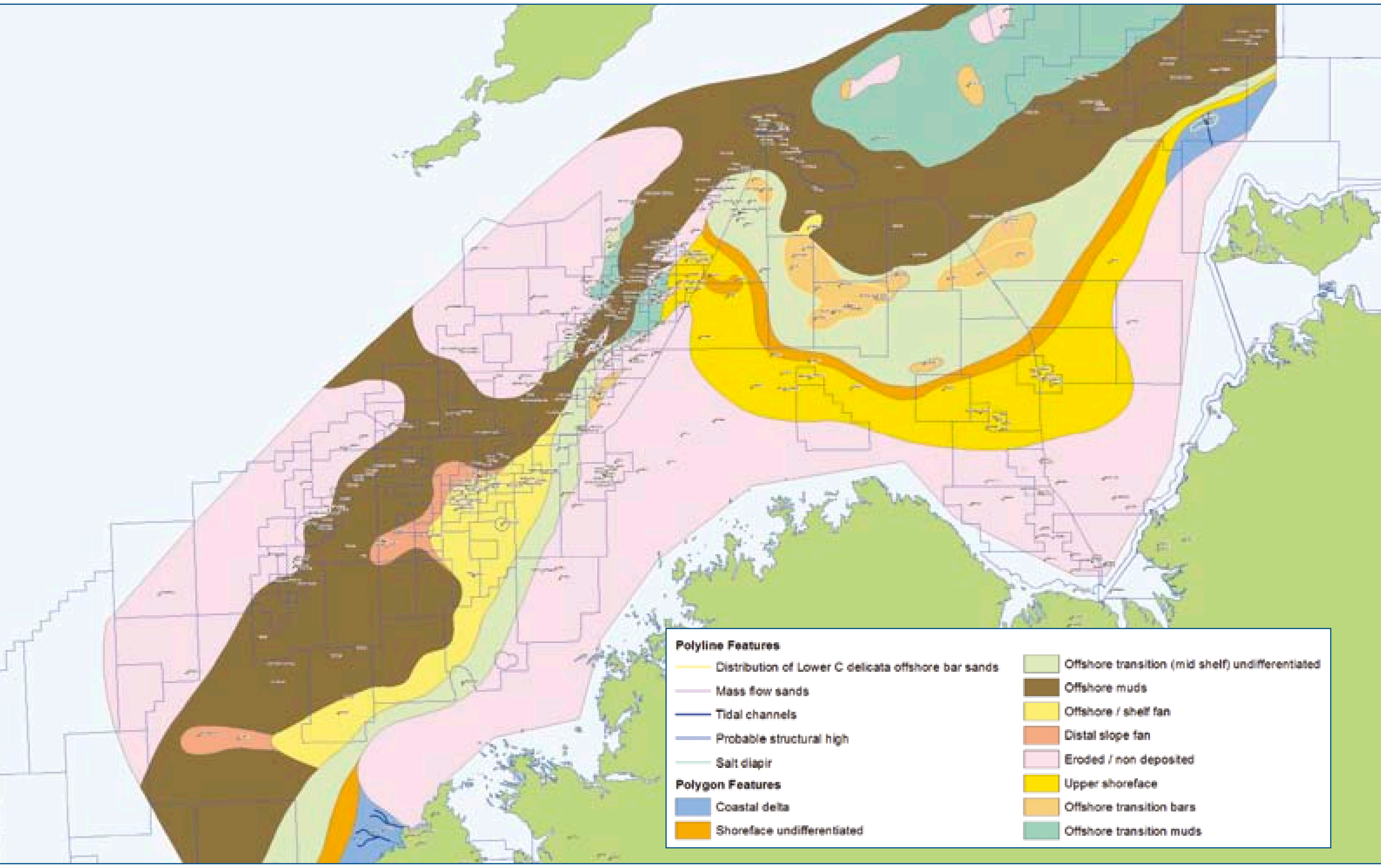
GEOTOURISM
The Icefields Parkway

GIANT FIELDS
Unleashing the Mad Dog

RESERVOIR MANAGEMENT
A Simple Guide to Seismic Inversion

EXPLORATION
South Atlantic: New Deepwater Frontiers

GEOLOGY GEOPHYSICS RESERVOIR MANAGEMENT



Example Facies Map covering the Browse and Bonaparte Basins

NORTHWEST SHELF SEQUENCE STRATIGRAPHIC STUDIES

TGS has expanded its regional sequence stratigraphic studies to include two basins in Australia's prolific Northwest Shelf. These studies are delivered through the Facies Map Brower (FMB). The FMB aims to be the primary tool for exploration across each hydrocarbon province. It is regularly updated with newly released wells and revisions to the subsequent facies maps provide an ever increasing level of detail. Thus, the whole product is designed to provide both an extensive data repository of wireline and interpretive stratigraphy plus a detailed regional basin understanding constrained within a robust geological model.

The Bonaparte Basin study was completed in 2012 and includes over 160 wells. The Browse Basin study, originally completed in 2010 with 76 wells, has now been fully updated to include all recently released wells. There are 35 gross depositional environment maps across the two basins providing a consistent framework upon which to base ideas and play concepts.

The projects can be licensed individually or as the combined, fully consistent study.

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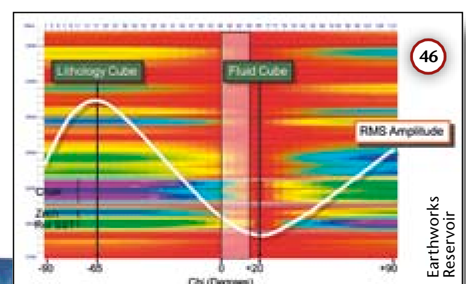
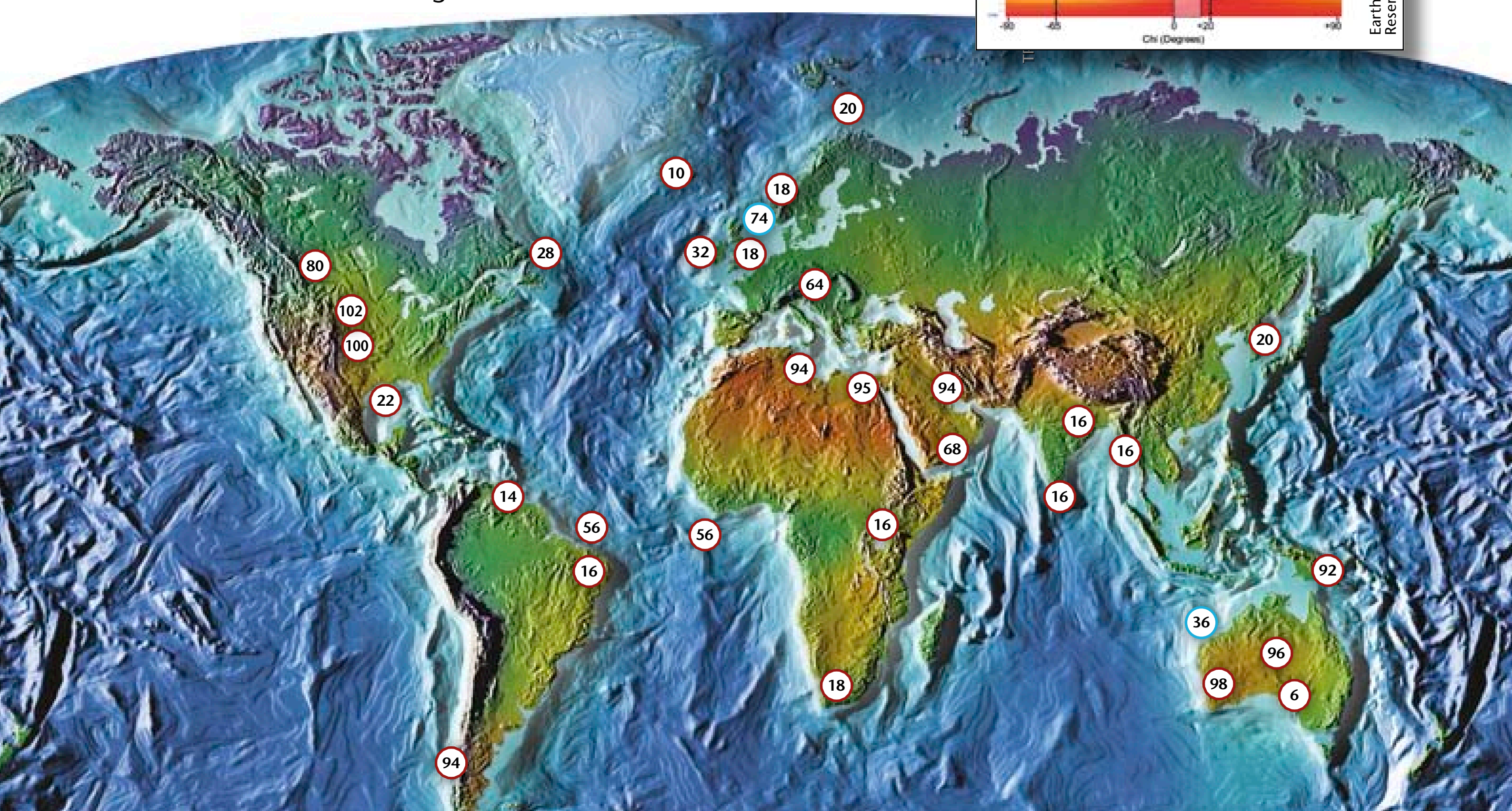


Seismic inversion – a complex topic with many different methodologies



Geology is Cool!

Getting the message across: the audience at the PESGB Stonely lecture clearly enjoyed comedian Hugh Dennis's approach to geology

I think I can safely assume that anyone reading this has at least a passing interest in the geosciences, while for a fair number of you, geology and related subjects are not just a means of earning a living, but topics of abiding fascination.

We are, however, in a minority, with many people having either no interest, or at worst, thinking that it is a 'dirty' subject, associated with despoiling the planet through the extra ction of minerals and oil. Considering what an important place the subject takes in the economy of the world, it is often not taken seriously. There was a recent furore in the British media when a Member of Parliament asked whether a geologist or a person stacking supermarket shelves was more important. Would he have used the same comparison with a physicist or a biologist?

So how can we improve the general perception of our profession and encourage more young people to join it and fill the much discussed void which will be created by the 'great crew change'? By employing all methods at our disposal, I suggest, from using social media to explain controversial aspects such as fraccing to the general public, to promoting geosciences in schools and colleges through visits, courses and sponsorships.

The UK's PESGB recently came up with a very original and successful approach to this challenge. The speaker at its annual public 'Stoneley Lecture' was popular comedian Hugh Dennis, a well-known television star – also a geography graduate and geology enthusiast. The approach appeared to work, as the lecture hall was full, with an audience excited to hear Hugh talk in a very entertaining manner about his passion for the outdoors and describe geology as the basis of so much of importance in our lives. He did admit that his initial interest in landscape and rock formations was developed on long family walks in the wet British countryside, as he trailed a long way behind his family and looked at everything around him – pretending he was nothing to do with his father (a bishop), who carried the family cat inside his coat, with its head poking out for all to see!

Well, it worked. Whatever the route, we need to get more people understanding the excitement and fasciation of our subject at all levels. Geology *is* cool!

JANE WHALEY
Editor in Chief

UNLEASHING THE MAD DOG

The Mad Dog production truss spar is permanently moored in a water depth of 1,311m in the Gulf of Mexico, 320 km south of New Orleans, Louisiana. Pictured in the forefront is the Saipem 7000 heavy lift vessel approaching the Mad Dog spar (on the left in the distance) for the installation of a new Drilling Rig Module (DRM) in March 2012.Technological imaging advances and a phased development in the 15 years since discovery have begun to unlock the full potential of the field, increasing its known oil-in-place to 4 Bboe.

Inset: The drive along the Icefields Parkway through the Canadian Rocky Mountains is a scenic delight, with plenty of opportunities to see mountains, lakes, waterfalls, bears – and impressive geology.

GEO ExPro

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

Cover Photographs:
Main Image: Rocky Kneten
Inset: Anne Hargreaves

Layout: Bookcraft Ltd.
Print: NXT Oslo Reklamebyrå

issn 1744-8743

South Australia's Unconventional Resource

A newly published guide outlines the opportunities and risks involved in exploiting unconventional reserves in South Australia

Once regarded as something that would happen in the future, recent exploration results achieved in the South Australian Cooper Basin by companies like Santos, Beach Energy, Origin Energy and Senex Energy are leading towards unconventional gas being used in households across south-east Australia. Australia's first unconventional gas production was achieved by Santos and its Cooper Basin joint venture partners Beach Energy (Delhi) and Origin Energy on October 19, 2012, when commercial natural gas production commenced from Moomba 191 shale gas well. Explorers have been accelerating appraisal of Cooper Basin unconventional gas plays.

The South Australia Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) formed a South Australian Roundtable for Unconventional Gas in May 2010. A total of 240 organizations are participating in this, including individuals, peak representative bodies, companies, universities, media outlets, and key agencies from all states, the Northern Territory and the federal government. The roundtable was tasked with producing a roadmap for unconventional gas projects in South Australia to identify opportunities and risks in order to: inform markets; inform people and enterprises that may someday compatibly co-exist with unconventional gas projects; and reduce critical uncertainties that may impede efficient, profitable and welcomed investment.

South Australia became the first Australian state to finalize a comprehensive approach to developing its vast unconventional gas resources on December 12, 2012, when Minister Koutsantonis released the Roadmap for Unconventional Gas Projects in South Australia. The roadmap lays out the priorities for attention that, once addressed, will lead to more unconventional gas being extracted from South Australia.

The roadmap lays out the opportunities to develop South Australia's gas resources in a sustainable way and options for reducing uncertainties that may act as a disincentive to investment. The 125 recommendations cover the full life cycle of unconventional gas projects – from exploration to production and possible liquefied natural gas exports, as well as related supply chains and infrastructure. To progress the recommendations, the roundtable will come together early in 2013 to develop action plans to implement agreed priorities. ■

ELINOR ALEXANDER

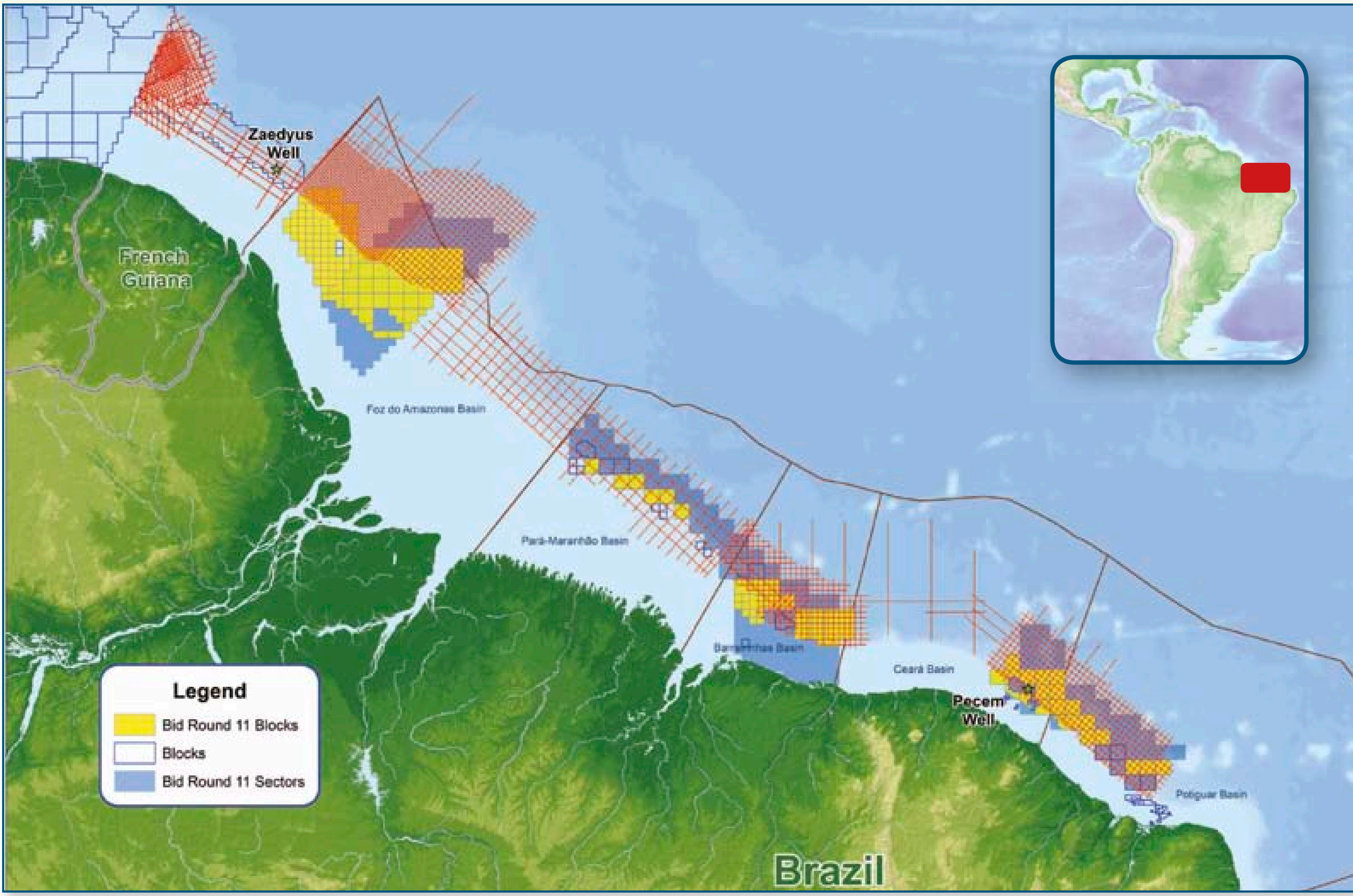
The roadmap can be downloaded from DMITRES's Petroleum website www.petroleum.dmitre.sa.gov.au. Go to Prospectivity, Basin & Province Information, Unconventional Gas, Unconventional Gas Interest Group.

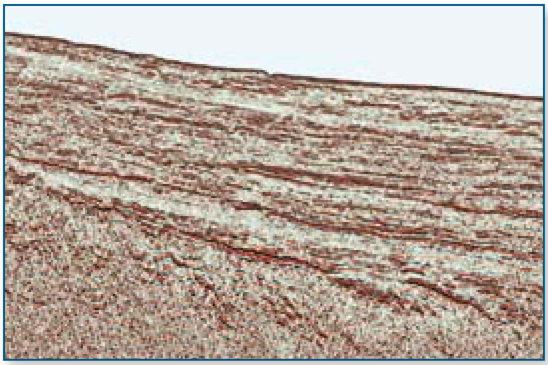
http://www.petroleum.pir.sa.gov.au/prospectivity/basin_and_province_information/unconventional_gas/unconventional_gas_interest_group/roadmap_for_unconventional_gas_projects_in_sa

Premier of South Australia, Hon. Jay Weatherill MP, turning the valve to start production from Moomba 191, Australia's first commercial shale gas well, in the Cooper Basin.

Equatorial Margins Brazil

Multi-Client Seismic - Data Available for Brazil Round 11





Seismic section from the Potiguar Basin data

Spectrum is active in five basins along the Equatorial Margins of Brazil that are on offer in Round 11. We have new PSTM and PSDM data available for each of the Foz do Amazonas, Barreirinhas, Ceara and Potiguar surveys, all of which were acquired with 10,000 m offsets and 13 second record lengths.

Two reprocessing efforts are underway along the Equatorial Margins, one a 9,600 km program in the Para-Maranhao Basin that links the Foz do Amazonas Basin to the Barreirinhas Basin. The second project is an 7,783 km project in the deep waters of French Guiana, which will link the Zaedyus discovery with the recently acquired data in Brazil. The well tie data will be available in late March and the remaining data in April.

Our Multi-Client team is committed to delivering high quality data in advance of the upcoming Round 11. Companies participating in Spectrum's programs will have a competitive advantage in this round.

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Barrel Award Time Again!

Every year, geoscience students from throughout the world battle to win a coveted place in the finals of the AAPG Imperial Barrel Award competition (IBA). To get there they have to beat other teams in their university, and then take part in regional finals, with this year 110 teams from 31 countries taking part. What drives them to take on such an intense program? We spoke to participants from Southampton University in the UK, which has been participating in the competition for several years.

"Each year we run an optional module for Master's level geology and geophysics students, based around the AAPG's IBA competition," explains Professor Martin Sinha, who organized the program at Southampton last year. "We split the students into teams, who compete in an internal competition. Entry to the module is competitive, based on academic performance. The team who win then represent Southampton in the AAPG Europe section competition in Prague."

Professor Sinha believes that the process is immensely valuable for all the students who participate. "A key feature is that it requires students to draw on the areas of knowledge and skills that they have studied in the past, forcing them to integrate their understanding from different areas of earth science in a way that few other modules do. Secondly, it exposes them to working under pressure as a team in a highly competitive environment and to an immovable deadline. Thirdly, it provides contact with industry professionals, and a realistic simulation of the way that exploration groups operate in the commercial world.

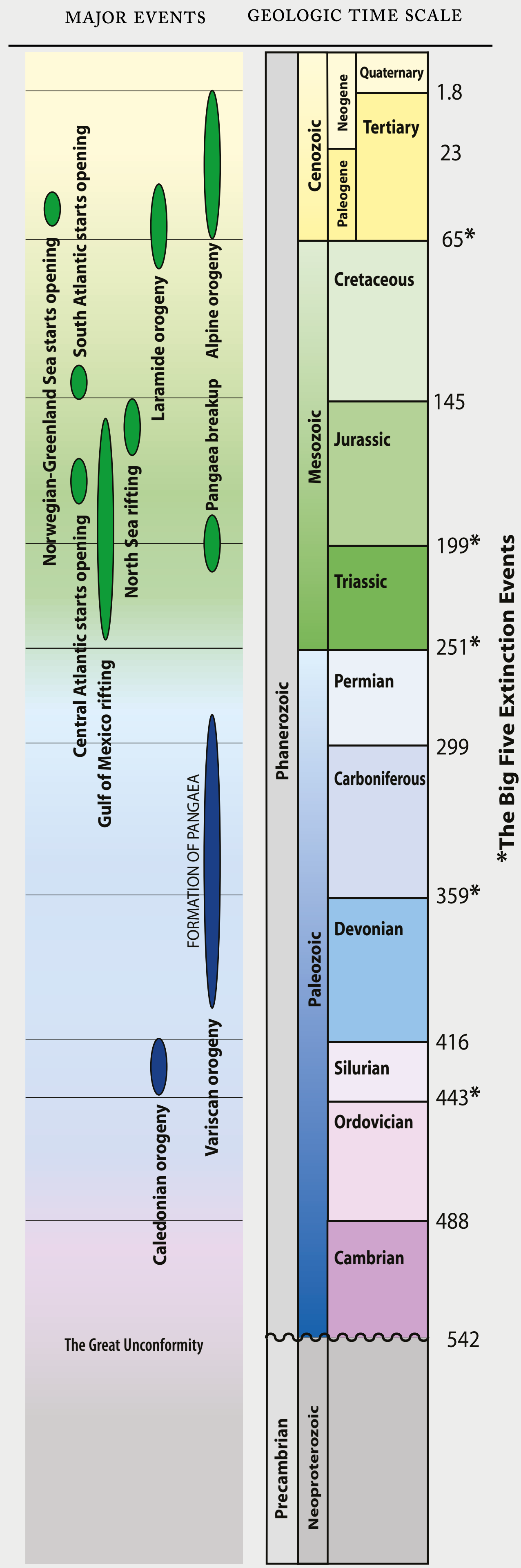
"All the students start off nervous and in awe of the task they face – and of the compressed time scale," Professor Sinha continues. "In the end, they are often inspired and motivated to produce the best work of their university career and to exceed their own expectations. This, and the maturity and self-confidence which the program generates, is the real benefit of the competition."

Valuable Experience

Louise Moorhead, now a geophysicist with CGG, understands just how important this experience is, having been in the 2011 Southampton team which won the regional finals and were runners-up in the International competition. "The IBA, with its format of investigating the hydrocarbon potential of a particular area, was a great experience and an opportunity to see how my geophysics degree could be applied in practice," she explains. "I saw how all elements in the process of evaluating hydrocarbon potential of an area are brought together through teamwork. I made some great contacts, and got feedback about working in the industry. The experience helped me decide where I wanted my career to go.

"The IBA helped me build up presentation and communication skills, vital for the working environment, but it was also an eye-opener to what the industry is like and how theory is put into practice. I would definitely recommend it – a very rewarding experience."

"I decided to do the IBA because it is practical and job-focused and I wanted to learn some of the skills I will need to work in the oil industry," explains Alex Gillespie, one of this year's Southampton University team going forward to the regional finals at the end of March. "What was amazing was how all the teams came up with different conclusions from the same data and training," adds his team-mate, Alexandra Cookson. "It has definitely made me excited about a career in the oil industry." ■



Iceland Exploration Revived

Recent license awards suggest that active exploration may soon resume in Iceland's freezing waters

Iceland is currently not producing oil or gas. However, the very first oil and gas offshore licensing round of some 40,000 km^2 on the Jan Mayen Ridge, which lies between Norway and Iceland, was announced in 2009. In October 2011 the second licensing round was announced, which has resulted in the award in January 2013 of the country's first exploration and production licenses, to operators Faroe Petroleum and Valiant Petroleum. A third application was also received from Eykon Energy, and the applicant has been given until May 1, 2013 to find an additional participant in order to undertake the licensed activities.

Promising Geology

Following the opening of the Atlantic between Norway and Greenland in the Early Eocene, the Jan Mayen Ridge itself detached from Greenland in the Early Miocene, and now lies east of the mid-Atlantic spreading center as a discrete micro-continent. The Mesozoic and early Tertiary of the Jan Mayen Ridge has strong affinities to the sections of eastern Greenland, where oil is known to have been generated and trapped, as well as the petroleum systems west of Shetland, the Norwegian Sea and the northern North Sea of the UK.

The hydrocarbon play system of Jan Mayen comprises Middle and Upper Jurassic source rocks, charging Jurassic to Late Cretaceous sandstones within the Mesozoic sequence. Amplitude anomaly 'bright spots' and possible gas chimneys observed on the seismic, as well as pockmarks on the seafloor, indicate the presence of hydrocarbons in the basin.

Structural traps mappable on high quality reprocessed 2D data available in the area comprise both extensional rotated fault blocks, and very large inversion anticlines. Stratigraphic traps consisting of onlap pinchouts and constructional fan geometries have also been identified at several levels providing additional prospectivity.

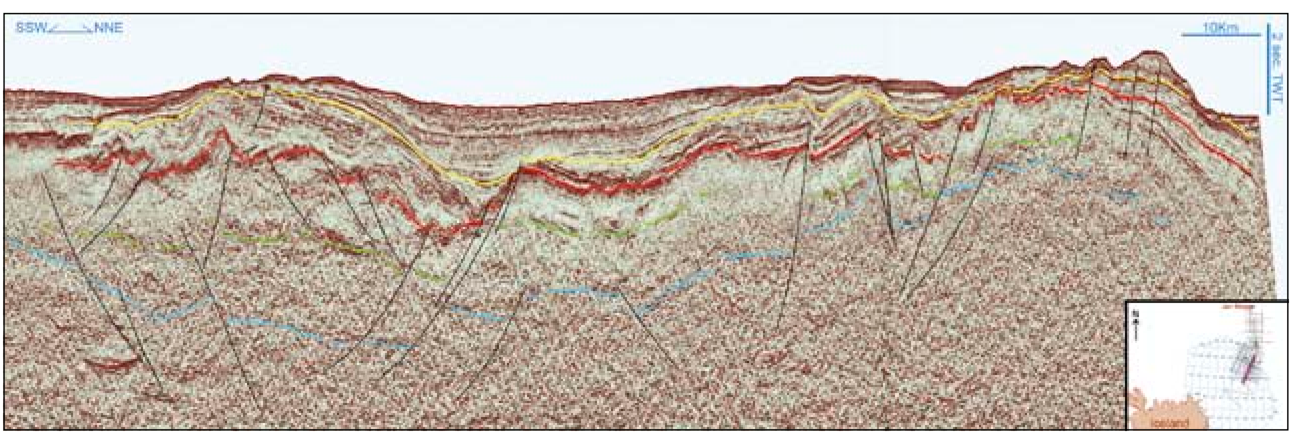
Prospectivity has also been highlighted in a sampling survey that was conducted by the Norwegian Petroleum Directorate and the University of Bergen using a remotely operated vehicle, uncovering good quality sands and rocks of Mesozoic age, similar to the main source rock on Greenland. TGS has also acquired ten gravity cores and two dredges in 2011, indicating active seepage of Jurassic oil and the existence of a petroleum system on the Jan Mayen Ridge.

What's Next?

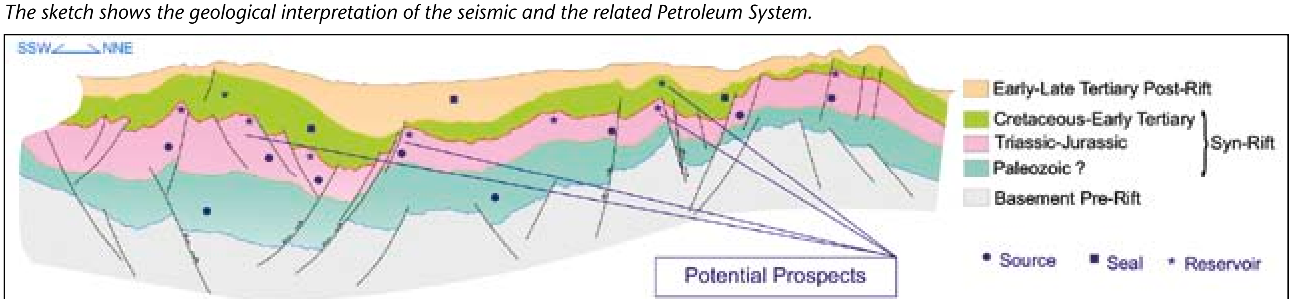
Even though no deep wells have been drilled on the Icelandic Shelf for the purpose of exploring for hydrocarbons, exploration activity and data acquisition has been ongoing since the 1970s, with seismic data being acquired by different geophysical companies. With the license awards further exploration activity will take place to unravel the Icelandic Continental Shelf. ■

KIM GUNN MAVER and **PAOLO ESESTIME,** Spectrum

Seismic section across the licensed blocks of Iceland.



The sketch shows the geological interpretation of the seismic and the related Petroleum System.

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Demand and Salaries Rising

An Oil and Gas Global Salary Guide sheds insights on the employment situation

With the geosciences and subsurface industry constantly growing with further exploration and development worldwide, the demand for skilled technical subsurface professionals has increased. Over the last 12 months permanent salaries within the geosciences discipline globally have risen 5.25% to an average of US$100,689. (Respondents were asked to provide their base salary only in US dollars equivalent, converting foreign currency into US dollars at the time of responding.)

Within the subsurface market, we have seen talent being exported from the UK to the Middle East, the biggest importer of talent. The Asia-Pacific region is also importing personnel, with contractors chasing more favorable day rates and expatriate opportunities. The UK has seen a large increase of imported talent from India and western Africa.

Fewer Benefits

Focusing on the industry overall, a significant finding when looking at the salaries and benefits year on year, is the number of people not receiving benefits. This has dropped to just less than 35%. We know from our own activities that benefits and allowances are a vital part of successful recruitment within the industry, where tailoring to the individual, the project and the business are increasingly commonplace. Benefits enable companies to actively engage with individuals they are looking to employ and retention rates can also be bolstered.

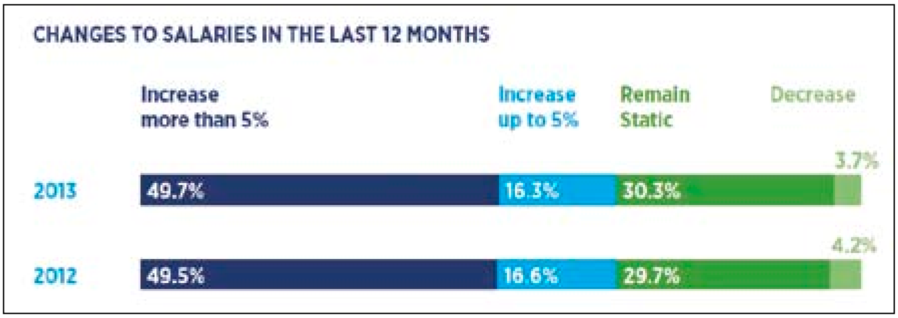
The main mechanism by which employers are engaging with candidates is through bonuses and this is where we have seen the largest growth. Bonuses have risen by 7.8% since 2011 to a total of 42.8% of employees receiving some sort of bonus in 2012. Healthcare and home leave allowances were the two other movers in 2012, rising by 3.16% and 2.56% respectively. In terms of what these benefits were worth to individuals in 2012, there was not a great deal of change from 2011. Tax assistance rose slightly as a percentage of what it is worth; however, slightly fewer were receiving it so it has not made much of an impression on the overall remuneration pool.

Disappointingly, there has not been an increase in the number of women working in the industry. With skill shortages as they are it appears to be the ideal time to take advantage of what should be a sizeable proportion of the workforce; unfortunately it appears this is a missed opportunity. Regionally the Americas are faring better than others, as the only two continents with more than 10% of female workers. The Middle East, Africa and Asia are once again at the lower end of the scale.

There was little change in tenure within subsurface businesses, the average stay being 3.7 years. Many E & P organizations are offering more challenging opportunities and the option to relocate overseas through inter-company transfers.

The Oil and Gas Global Salary Guide 2013, produced by recruiting experts Hays Oil & Gas and leading jobsite Oil and Gas Job Search, is based on data from 25,000 respondents and more than one million items of data. ■

ZAK MARKLEW
Hays Reservoir and Petroleum Engineering Manager



ABBREVIATIONS

Numbers
(US and scientific community)
M: thousand = 1×10^3
MM: million = 1×10^6
B: billion = 1×10^9
T: trillion = 1×10^{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

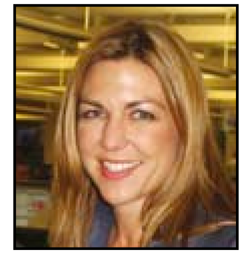
P2 reserves:
Quantity of hydrocarbons believed recoverable with a 50% probability

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

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

Challenges Ahead for Venezuela

What difference will the death of President Chavez make to the oil industry?



THINA MARGARETHE SALTVELT, PH.D

Oil prices did not react sharply to the news that Venezuela's President Hugo Chavez passed away in March after 14 years in office. Now an election will be held within 30 days and there is considerable uncertainty. Short term, growing political unrest in Venezuela could drive oil prices higher as the global supply/demand balance is still tight. Longer term, however, the new regime will hopefully ensure that the country fulfills its enormous potential and produces more oil. Although this may help to dampen sharp upward movements in the oil price in the long run, there is a long way to go.

One important reason why the president gained domestic popularity is the massive use of oil money to boost public spending and provide heavily subsidized fuel for the population. Chavez also gained regional approval as Venezuela provided a significant amount of crude oil and refined products to its neighboring countries at below-market prices and has a separate supply agreement with Cuba.

Venezuela's Economy Highly Exposed

Oil accounts for around 97% of the country's total exports and the popularity of Chavez benefited from high oil prices in recent years, but this came at a cost. The expensive public spending programs redirected money away from the oil industry. Venezuela has reportedly the largest oil reserves in the world, with proven oil reserves at the end of 2011 of 296.5 Bb, compared to Saudi Arabia's 265.4 Bbo and Canada's 175.2 Bbo (BP). Nevertheless, the country's oil production has dropped by 22%, due to mismanagement, natural declines from mature fields and lack of investment since Chavez came to power in 1998/99. Now the country needs an oil price of more than the current US$110/barrel to balance its budget, versus US$70/barrel just six years ago. High and increasing oil prices have so far compensated for the decline in oil exports.

The country's dependence on oil makes the economy highly exposed to a sharp fall in oil prices, which in turn could put political stability under pressure. Chavez has contributed to keeping prices high by not maintaining investment and production. Through the declining production in Venezuela, the oil market has become tighter.

The death of Hugo Chavez can become a game changer for the Venezuelan oil industry in the longer term if the new president opens up the oil industry. When Chavez took control of the industry, several oil companies withdrew from the country. A new president might attract more foreign investors, lead to a new opening to the international market and help PDVSA ramp up production once again. The changes will not happen overnight, but increasing the country's production capacity will help to balance the global oil market in the long run. In the meantime the country will be a price-taker and remain dependent on its fellow OPEC members to balance the market to support the oil price. OPEC's unofficial oil price target is US$100/barrel.

Challenge from US Shale Oil

Venezuela will also face new challenges going forward. The country's conventional crude oil is heavy and sour by international standards. As a result, much of its oil production must go to specialized domestic and international refineries. Today 40% of the country's oil exports go to the US, but with increasing shale oil production there we expect US import needs will fall in the future. Venezuela needs to find new buyers for its oil. One of the fastest-growing destinations of Venezuelan crude oil exports has been China. In 2011, China imported 230,000 barrels of crude oil a day from Venezuela, up from only 19,000 barrels a day in 2005 (EIA). We expect to see more Venezuelan barrels moving eastward in the future.

José Cruz/ Agência Brasil


Dolphin
geophysical
POLAR DUCHESS

Frontier and Deepwater Take Center Stage

This new feature throws the spotlight on countries around the world where key licensing opportunities have recently been announced.

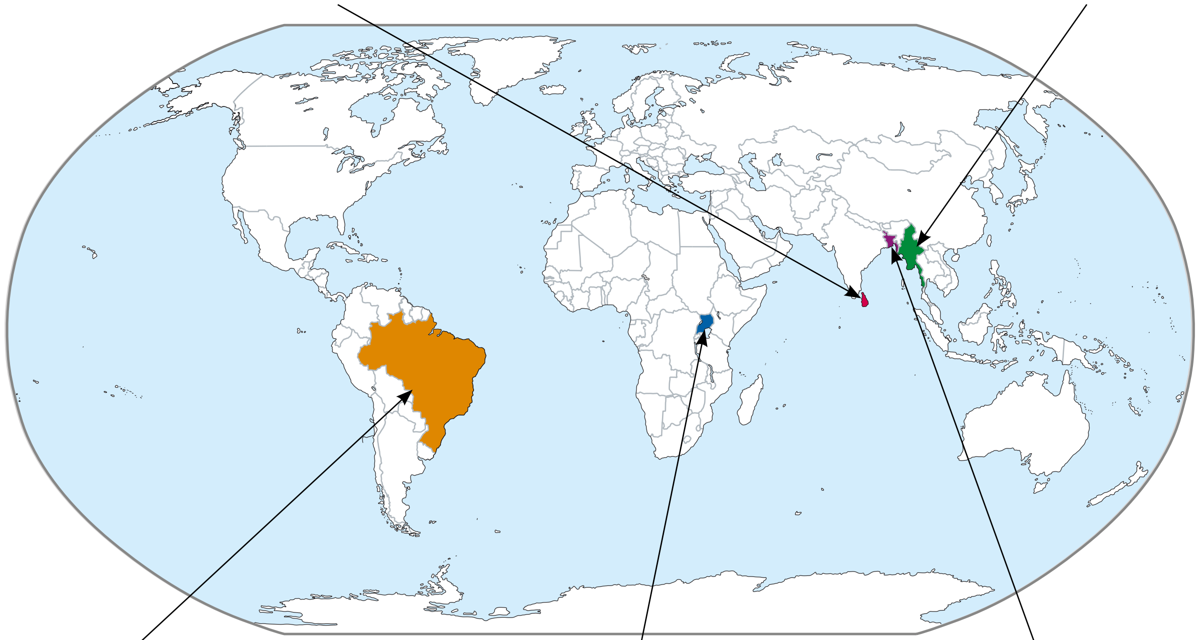
Sri Lanka

At the IHS CERAWeek conference in Houston, the Sri Lankan government opened the country's second bidding round, offering 13 offshore blocks in the Mannar and Cauvery basins, located in water depths of between 10 and 3,000m. The blocks on offer in the Cauvery basin range in size from 2,403 km^2 in the shallow waters of the Palk Straight, between Sri Lanka and India, to 4,566 km^2 in deepwater areas to the north-east of Sri Lanka. The blocks in the Mannar basin are larger, ranging in size from 2,714 km^2 to 8,120 km^2 in the deep to very deep waters of the Gulf of Mannar. Exploration licenses will be awarded for an eight-year period (3+2+3) with a biddable work program for each phase that will include the drilling of one well. Bid deadline is September 30, 2013.

The government is also introducing the concept of joint study acreage, for which it has earmarked several very large areas off the south and east coast in which there is no data at all and very little knowledge of subsurface conditions.

Myanmar

The Ministry of Mines is inviting international exploration companies to submit sealed bids for a total of 18 onshore blocks that it is tendering. Fifteen of the blocks are being offered under production sharing contracts, while the remaining three are offered as improved petroleum recovery contracts. Companies wishing to take part must submit a 'letter of expression of interest' no later than two months after the date of the announcement (January 17, 2013), subject to which potential bidders will be pre-qualified and selected. Selected bidders must partner with at least one Myanmar-owned company from a list held by the Ministry of Energy. It is predicted that the onshore round is unlikely to draw attention from major foreign players as most are awaiting the more promising but largely unexplored offshore tracts to become available. In this regard the ministry has hinted an offshore round comprising 29 blocks could be launched in April. No decision has yet been made as to whether foreign players will be allowed to take a 100% interest in the technically more complex deepwater blocks, according to Zaw Aung, the director of planning at Myanm ar Oil and Gas Enterprise. The open bidding round process is part of the government's drive to show transparency in doing business with international companies (see *GEO Expro* Vol. 10, No. 1).



Brazil

The country's National Hydrocarbons Agency (ANP) said President Dilma Rousseff has signed off on the plan to hold a long-awaited ANP Round 11 following the resolution of a royalty dispute. The round will total 172 blocks, comprising 85 offshore covering 59,460 km^2 and 87 onshore covering 61,834 km^2. It was later reported that the ANP and the Ministry of Mines had agreed, subject to formal approvals, to expand the round by including an additional 117 blocks: 65 offshore and 52 onshore. ANP Round 11 will therefore total 289 blocks covering 155,712 km^2. Set to be held May 14–15, 2013, this is the first bid round to be held in Brazil since 2008.

Uganda

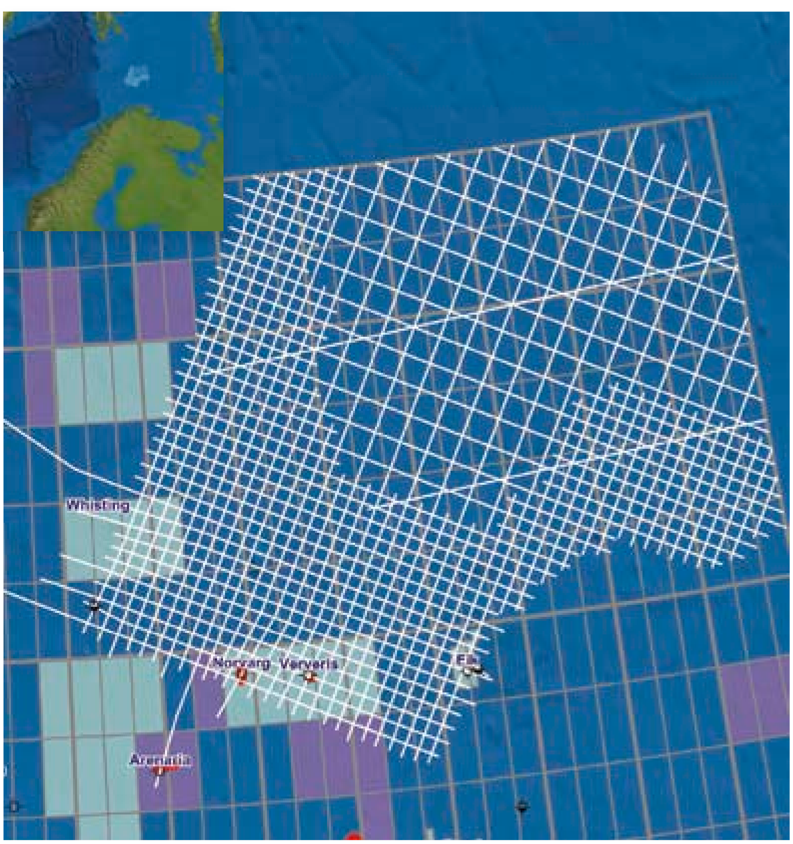
Uganda is planning to o ffer 13 blocks in its upcoming licensing round, which is planned following the passage of a new law aimed at improving accountability and transparency on revenues. The law has been approved by parliament but is awaiting sign-off by the president. The round, possibly late 2013 or early 2014, is significant as it will be the first since Uganda's remarkable successes in the Albertine Rift Basin.

Bangladesh

The government has extended the deadline for the submission of bids as part of the Bangladesh Offshore Bidding Round 2012 from March 18 to April 2, 2013. The round comprises 12 blocks, nine in shallow water (less than 200m) and three in deepwater (down to 2,000m). Shallow water blocks SS-04 and SS-10 contain the Kutubdia and Teknaf structures and winning bidders for these will be required to allocate an additional 10% of profit gas to the government. Terms require that at least one member of the consortium must have daily offshore production of at least 15,000 bo/d or 150 MMcfg/d to qualify for bidding.

Snøspurv 2D Seismic Survey

12,000KM - Barents Sea - Norway



The Snøspurv 2D

High Resolution Seismic Survey

- Searcher Seismic and Seabird Exploration have allocated a 2D seismic vessel for a 12,000 km regional seismic survey covering the Bjarmeland Platform in the Norwegian Barents Sea. The survey is scheduled to commence early 2013.
- The Snøspurv Seismic Survey is designed to enhance the seismic resolution of the prospective Triassic-Jurassic sections of the southern and western part of the Bjarmeland Platform. The Carboniferous/ Permian in addition to the Triassic section are the main exploration targets at the northern part of the survey area.
- Data will be available from Q3 2013 for participating companies.

SeaBird Exploration

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Successful IP Week

The UK Energy Institute recently held its very successful annual **International Petroleum Week**, which is a leading forum for discussion for decision-makers from around the world. Topics discussed ranged from upstream, midstream and downstream, to finance and investment, technology and gas as well as outlooks on specific regions, such as Africa, the Middle East, Asia and Russia. With a theme of 'Meeting today's challenges – investing in tomorrow's opportunities', the event is unusual in that it has a number of seminars which feature talks from key note speakers followed by panel and floor discussions, leading to a number of lively debates. Topics covered in seminars included global energy security, the role of technology in delivering successful upstream projects, financing oil and gas in the future and managing international risk. The event always culminates in the IP Week dinner, which attracts over 1,200 guests wanting to hear from industry leaders and network with their peers. ■

Delegates at the International Petroleum Week enjoyed a reception at the Houses of Parliament, overlooking the Thames.

DEVEX Celebrates 10 years

Now in its 10th year, the **DEVEX** conference continues to go from strength to strength and is now firmly established with 490 delegates and 33 exhibitors attending in 2012. This year there is a comprehensive and stimulating program spanning two days, with contributions from many of the largest, smallest and independent organisations in the industry. There will be 44 high quality presentations and 20 posters from a range of disciplines – all with the aim to educate and inspire. The theme of 'Maximizing Our Diverse Resources' is immensely important to the future success of the oil and gas industry, and the presentations will show just how healthy the industry is in that respect.

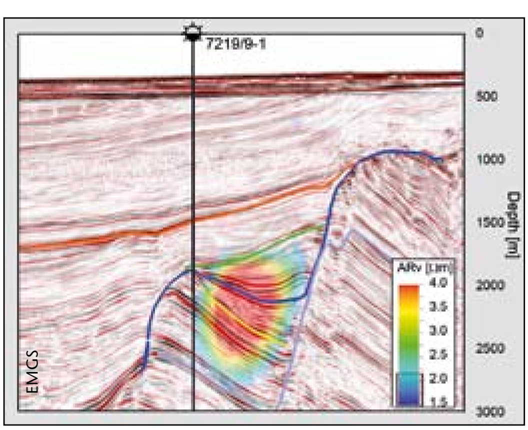
Organized jointly by the PESGB, SPE, AFES and DECC, DEVEX is a not-for-profit conference run by industry professionals. It offers tremendous value, a first rate technical experience and a great opportunity to hear the latest industry opinions. ■

GEO ExPro Free Online

GEO Expro Magazine is pleased to announce that all its digital editions are now available free of charge, in line with its policy of making information about the oil and gas industry available to all who are interested. This includes the **iPad App** editions, which are freely available from the AppStore, and the **pdf magazine**, which can be downloaded from the GEO ExPro website (www.geoexpro.com), where registration and log-in are no longer required. ■

20th Africa Oil Week

As excitement over gas discoveries in East Africa and oil in the West African transform margin continues, attendance at the annual **Africa Oil Week** is expected to be at an all-time high. This event is the world's leading meeting on Africa for corporate deal-making, roadshows and senior-level networking across the oil/gas industry in and on Africa. It will be held in Cape Town in November this year, and over 1,000 delegates are expected to attend, including many ministerial delegations from a range of countries, plus a record number of exhibitors. Africa Oil Week is a meeting with a global reputation, designed to help build the African continent's economic future. ■



EM anomaly, Havis discovery in the Barents Sea.

CSEM Experts in Oslo

The Geological Society of Norway (NGF) is repeating its success from 2009 and hosting the **2nd International CSEM Conference** in Oslo, May 14–15, 2013. Since the inception of the technology in 2002, the market has grown significantly, with increased competition leading to rapid advancements in technology, visualization and interpretation.

Leading scientists and EM-experts from around the world are meeting up in Oslo to learn from each other and discuss recent developments in CSEM technologies and case studies from around the world, and look at how to integrate CSEM and other geophysical information to maximize the potential in the data. The 2013 international conference should therefore also be ideal for geologists who are concerned about the application of this method. ■

First Extraction of Methane Hydrate

As discussed in a recent series in *GEO ExPro*, methane extracted from hydrate deposits is a potential source of energy, albeit one which is very hard to recover. The likelihood of this becoming a resource for the future moved a step closer in March 2013 when the Japanese company **JOGMEC** produced methane gas from offshore hydrate deposits for the first time. Having spent several years conducting seismic surveys and exploitation drillings in the Nankai Trough, off the country's Pacific coast, in Phase 1 of Japan's Methane Hydrate R&D Program, JOGMEC moved to Phase 2 in 2009, looking to develop a technology to extract natural gas through the dissociation of methane hydrate. For this first offshore production test JOGMEC is using depressurization to turn methane hydrate to methane gas and is also hoping to obtain information on the dissociation behavior of methane hydrate under the sea floor and the impact of extraction on the surrounding environment.

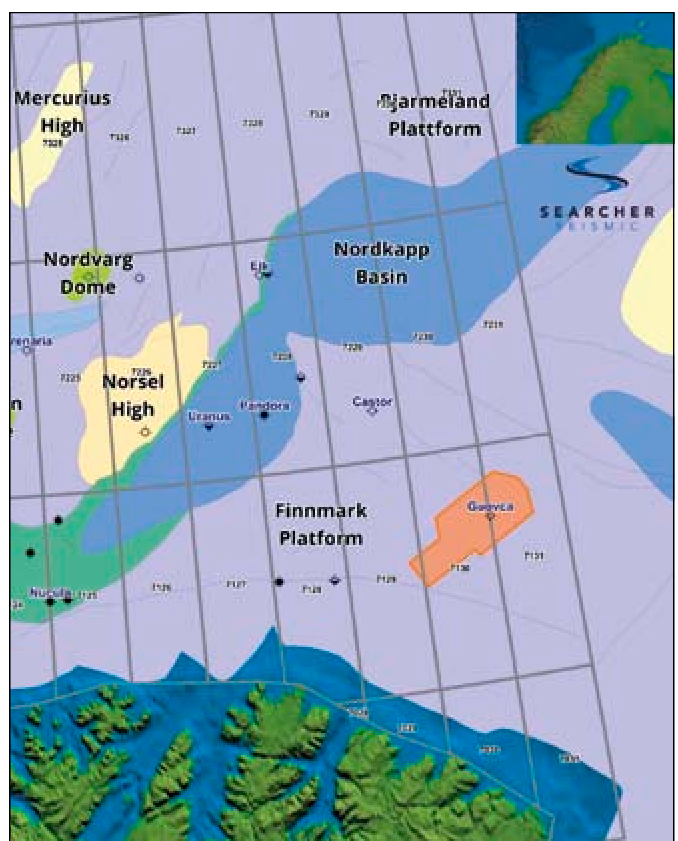
Since the Fukushima nuclear crisis, Japan has redoubled its efforts to find alternative energy sources. A Japanese study has estimated the existence of at least 40 Tcf of methane hydrates in the eastern Nankai Trough. ■

A sample of gas hydrates collected from Mallik, Canada

Finnmark Platform Survey

After a number of discoveries in recent years, the **Barents Sea** is one of the hottest areas in north-west Europe, but although interest was high in the recent licensing round, where 72 blocks were on offer in the Barents Sea, there has been little exploration in the eastern region of the Sea. A recent study by the Norwegian Petroleum Directorate suggests that the south-eastern Barents Sea area, near the Russian border, could hold as much as 1,887 MMboe and suggests that the Finnmark Platform is a combined oil and gas province. It is expected that this part of the Barents Sea will feature in the next round, so data covering the area will be much sought after.

In a timely move, **Searcher Seismic** in partnership with **Dolphin Geophysical** have recently announced a 1,407 km^2 non-exclusive 3D seismic project on the Finnmark Platform, the data for which will be available to participating companies from Q3 in preparation for the 23rd Round nomination process. Data processing has commenced in Dolphin's UK center, aimed at enhancing the imaging of the Jurassic sequence and to improve definition of deeper Triassic and Permian clastics. ■



UK Shale Gas in Spotlight

After the ban on fraccing in the UK was lifted in December last year, companies have started looking at how to make the most of the shale gas opportunity in the country. **Shale Gas World UK**, which is being held in **Manchester** in June, should be a good opportunity to learn more, from understanding the real potential of the resource from the British Geological Survey to reviewing how companies already involved plan to commercialize shale gas reserves. Proven unconventional operators like Talisman, Hutton and Falcon will be discussing how to manage environmental and water management challenges and how to work effectively with the planning authorities, while the impact of shale gas development on local economies, job creation and energy security will be another interesting topic. ■

Unleashing the Mad Dog

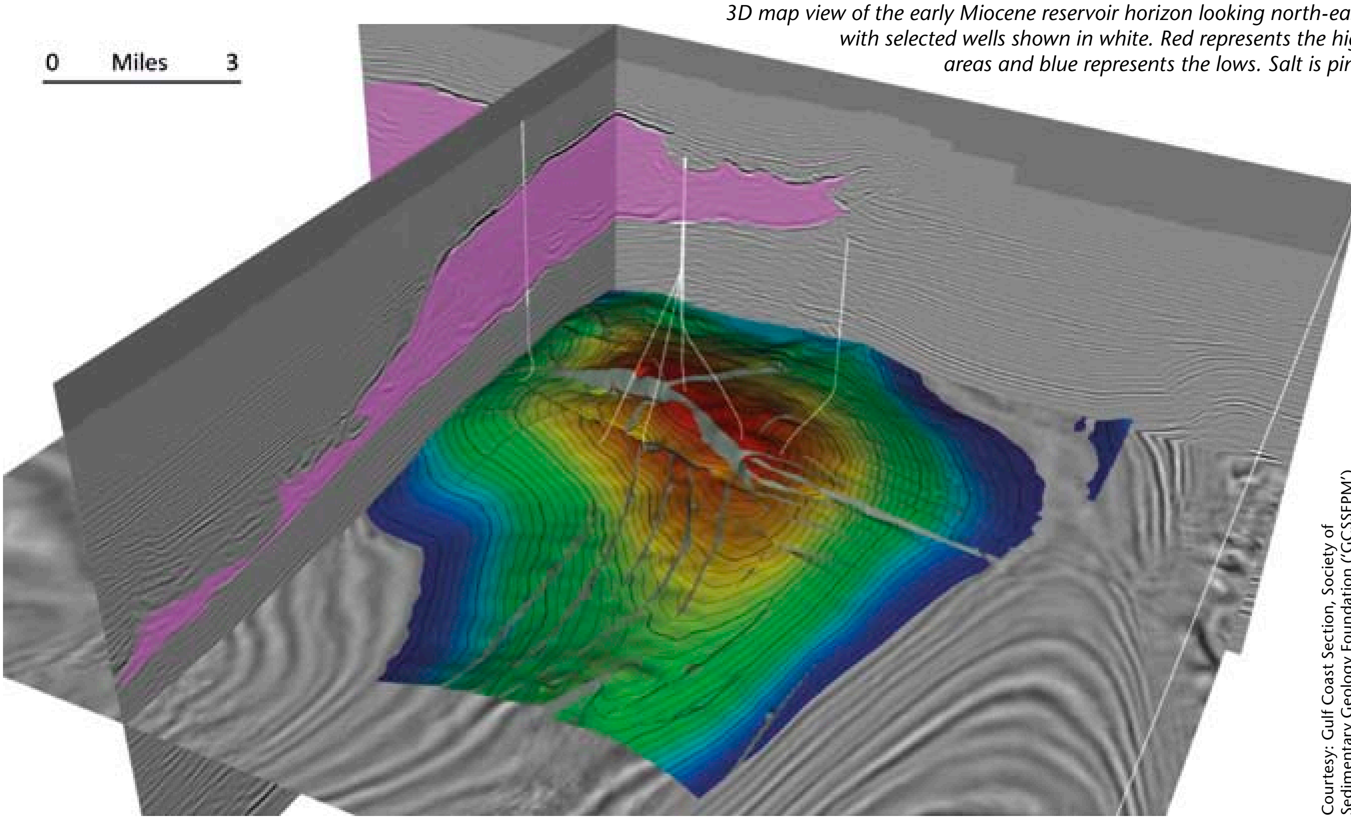
Technological imaging advances and a phased development in the 15 years since discovery have begun to unlock the full potential of the Mad Dog Field, increasing its known oil-in-place nearly tenfold to up to four billion barrels of oil equivalent.

THOMAS SMITH

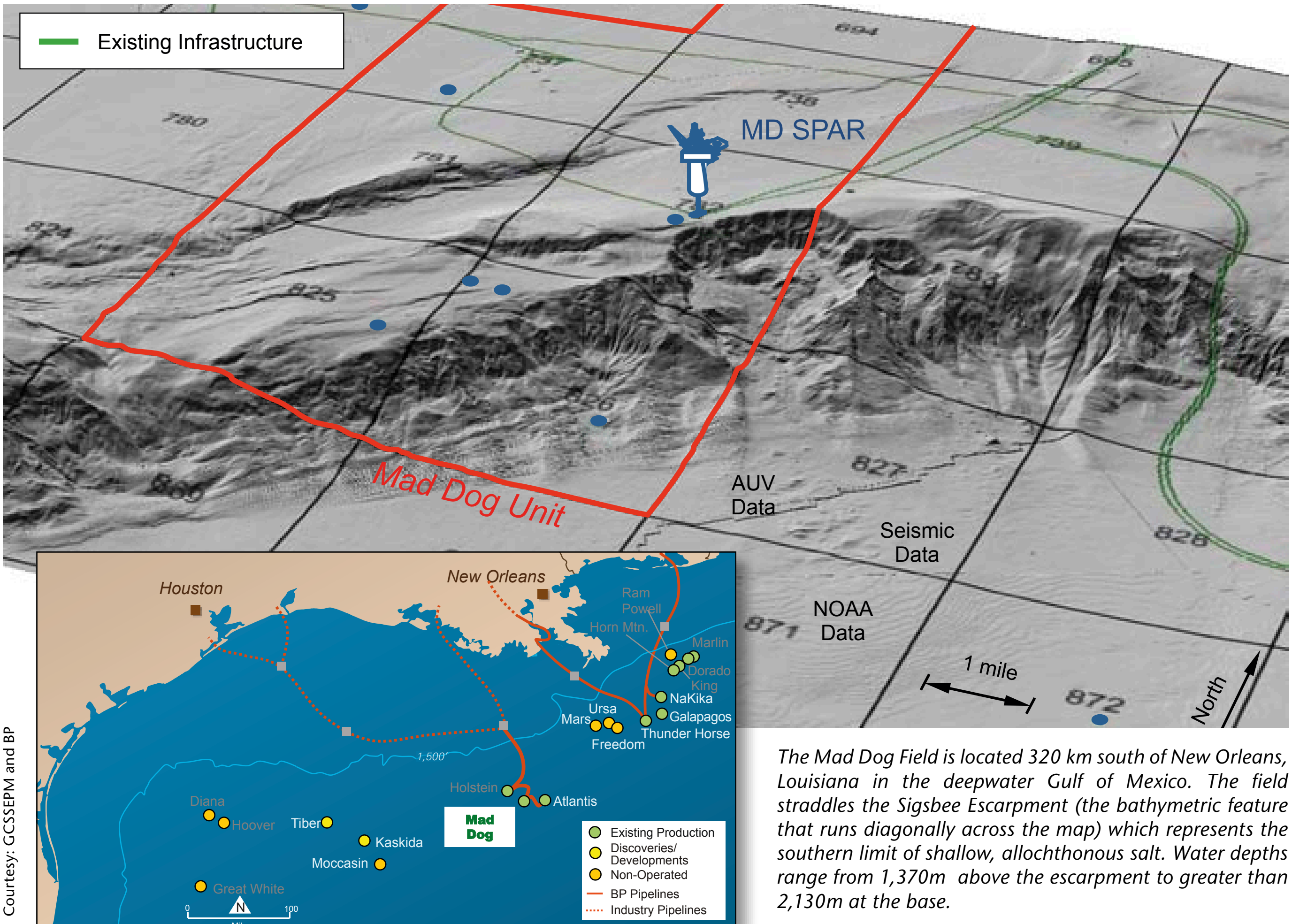
Mapping on a 1996 vintage 3D seismic survey over the southern Green Canyon area of the Central Gulf of Mexico revealed a broad, simple, anticlinal high. Reflectivity was very poor over the structure's crest, which was located beneath the main salt body. Imaging showed good reflectors outboard of the salt to the south and fair reflectors beneath the thin salt on the north side of the structure. In 1998, the first well on this structure was drilled seaward of the Sigsbee Escarpment through the good reflectors and finally into the crest, encountering 66m of hydrocarbon-bearing Miocene reservoirs. The Mad Dog Field had been discovered.

Early appraisal wells would soon confirm an economically developable resource of about 450 MMbo in-place but also illustrated to the subsurface appraisal team the need for better seismic imaging. These wells encountered fault blocks not seen on seismic data. Some of these fault blocks were not hydrocarbon charged, adding risk to the development over the crest. Also, drilling problems arose from the significant amounts of mobile tar deposits encountered in the overburden section. The early drilling results led BP and its co-owners, BHP Billiton Petroleum ('BHP') and Union Oil Company of California ('Unocal', owned by Chevron), to take a very calculated and incremental approach in developing this field. The results have been outstanding, turning a relatively small, deepwater field into a giant that is expected to produce significant oil for the next 40 years.

3D map view of the early Miocene reservoir horizon looking north-east, with selected wells shown in white. Red represents the high areas and blue represents the lows. Salt is pink.



Courtesy: Gulf Coast Section, Society of Sedimentary Geology Foundation ('GCSSEPM') and BP Exploration & Production Inc. ('BP')



Courtesy: GCSSEPM and BP

The Mad Dog Field is located 320 km south of New Orleans, Louisiana in the deepwater Gulf of Mexico. The field straddles the Sigsbee Escarpment (the bathymetric feature that runs diagonally across the map) which represents the southern limit of shallow, allochthonous salt. Water depths range from 1,370m above the escarpment to greater than 2,130m at the base.

From Simple to Complex

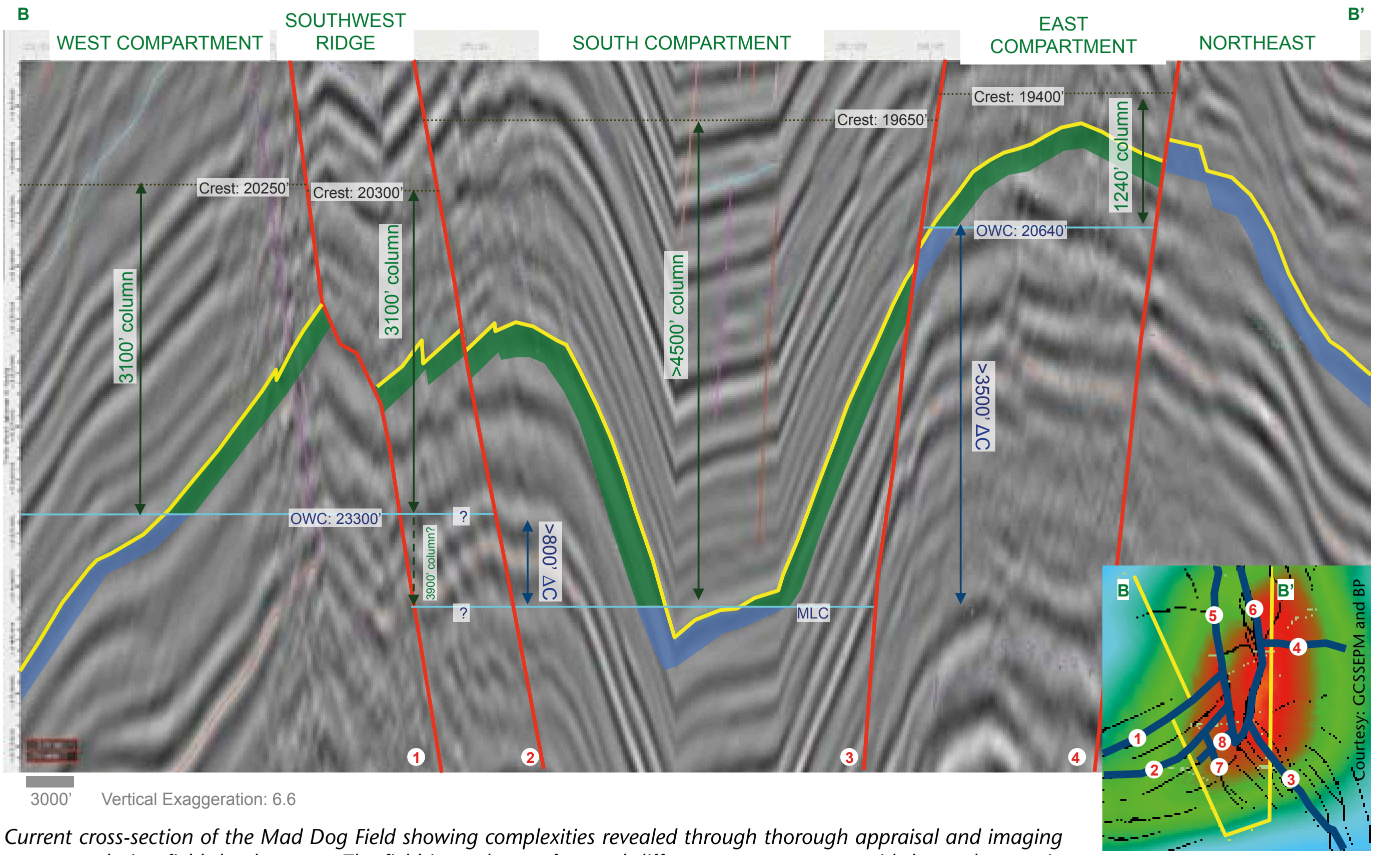
When appraisal wells drilled between 1999 and 2001 showed the presence of enough hydrocarbons to develop, planning for production began. In February 2002 a truss spar equipped with an integrated drilling rig that included 16 slots was approved by the project co-owners. The overall development would cost around $1.5 billion. The truss spar would be permanently moored in 1,311m of water and capable of processing 80,000 bopd and 60 MMcfgpd. The first production commenced on January 13, 2005.

Immediately after the first production, south-west ridge appraisal wells drilled by Unocal extended the oil column 245m deeper on the west side of the structure. They drilled an updip sidetrack to the well and found a wet compartment. Drilling problems arose on additional deep tests when several six meter-thick, mobile tar intervals flowed into the wellbore and proved impassable. The subsurface picture was now becoming more complex. A wide-azimuth towed streamer (WATS) seismic survey was consequently commissioned (see Improved Seismic Imaging section on page 24).

"We interpreted that the A5 producer was connected to a large volume of fluid from pressure transient analysis but were unable to place a follow-up well because of poor data quality," recalls Dr. Christopher Walker, structural geologist for Mad Dog Phase 2 with BP. "The map generated from the WATS data revealed a large undrilled compartment. We planned the #11 well to test the projected oil/water contact (OWC) in this block, but at our target depth the sands were still full of oil. The team was able to chase the OWC down dip, using real-time biostratigraphy, real-time azimuthal density and gamma ray information and other logging-while-drilling (LWD) data to geo-steer until the OWC was finally tagged at 7,111m. This deeper OWC on the west side now increased the hydrocarbon resource beyond the designed capacity of

The Mad Dog Platform

BP plc



Current cross-section of the Mad Dog Field showing complexities revealed through thorough appraisal and imaging programs during field development. The field is made up of several different compartments, with large changes in hydrocarbon column height across the major sealing faults illustrated in red. Yellow is the top of the early Miocene reservoir, green is oil and blue is water. Insert map shows location of cross-section with sealing faults in blue.

the current truss spar."

The successful west appraisal wells indicated to the team that before updating the strategy to optimize recovery, the other untested flanks of the structure needed to be fully appraised. Thus, the Mad Dog South well was planned. A previous well in that area had hit water-bearing sand updip of the planned south appraisal target, reducing the probability of finding hydrocarbons on the south flank of the structure. "This is where the 2009 reprocessing of the 2005 WATS data proved valuable," explains Dr. Walker. "Vertical Transverse Isotropy (VTI) depth migration was applied to the data to reveal an intricate web of faults on the crest of the south flank. This allowed us to interpret the wet penetration as a sealed fault block, and opened up the possibility of an accumulation down dip. The #5 well drilled by BHP in May 2009 greatly exceeded pre-drill expectations by discovering 85m of net MD pay in the early Miocene sands still full to base. A side-tracked well extended the lowest known oil another 40m deeper than on the west flank, which led to another large increase in the oil-in-place resources."

The most recent field extension drilling took place in 2011 when BHP drilled the Mad Dog North appraisal well. This well was again successful, finding 50.6m net pay. They were also able to collect conventional core for the entire reservoir section for the first time in the 13-year history of investigation of the field. The core information would help refine the design parameters for the next phase of field development.

Improved Seismic Imaging

"The first appraisal wells clearly indicated we needed better seismic imaging to safely and economically develop this field," says Dr. Walker. "The water depths over the field vary from 1,200m to 2,100m across the 610m high Sigsbee Escarpment and the reservoir is at depths greater than 5,800m beneath a layer of allochthonous salt. This salt layer varies greatly in thickness, with steeply dipping edges, overhangs and a rugose base and top, creating challenges for seismic imaging of the reservoir. Such irregularities create illumination gaps where reflected seismic energy cannot be adequately acquired using narrow azimuth 3D seismic methods.

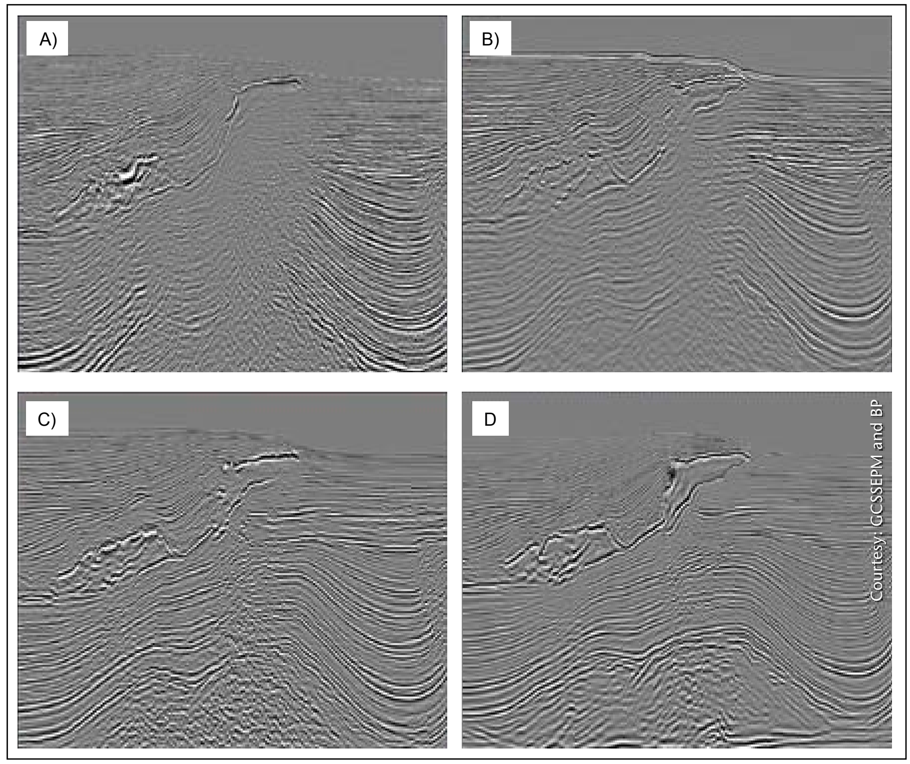
"The progressive development of the field can be intimately tied to advances made in seismic data acquisition and processing technology," Dr. Walker explains. "The first major imaging improvement was achieved when we were able to merge the original data with new narrow azimuth towed streamer (NATS) data acquired in a different orientation in 2000, creating a multi-azimuth image. New subsurface density information from the wells allowed us to build a better velocity model which further improved the image quality. However, between 2001 and 2005, the appraisal and development wells that were drilled for the first production facility continued to encounter subsurface surprises, including the largest fault in the field, with over 305m of missing section.

These surprises, along with the potential for additional hydrocarbons, led BP to commission the industry's

first large-scale, wide-azimuth towed streamer (WATS) program across the field in 2004. "The new wide-azimuth data would prove to be a real game changer for imaging the field," says Dr. Walker. "This method allowed the collection of longer offset data compared to conventional NATS acquisition. The method increased the illumination of the reservoir by recording data from a range of azimuths that have taken complex paths through the overburden. Much better reflectivity of the structure's crest and the mapping of additional faults revealed for the first time the potential size of the trap and allowed more challenging wells to be planned. This data was reprocessed in 2009 resulting in additional clarity over the structure."

The Development

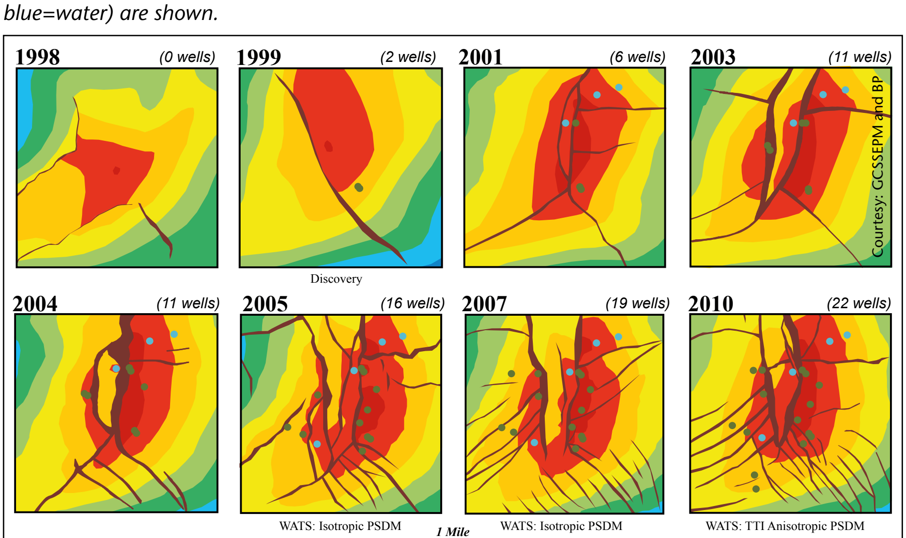
With new volumes found shortly after the first oil was produced and the additional success of subsequent appraisal wells, Mad Dog's in-place resource estimates exceeded the capabilities of the original truss spar. For the operators to safely and efficiently produce these resources, a Phase 2 project was initiated. An all-subsea development was recommended which was to be tied back to a second spar host facility with a capacity of 130,000 bopd. A water-flood project was also planned to enhance flank oil recovery. The second truss spar called 'Big Dog Spar' is expected to be sanctioned by the co-owners in 2013.



Improved seismic imaging through new technologies over time enabled geoscientists to have a better look at the structure beneath the salt. Pictured along the same line: (A) the 1998 narrow azimuth towed streamer data; (B) the 2003 reprocessing of that data with a second survey shot in a different orientation; (C) the 2005 addition of the wide azimuth towed steamer data; and (D) the 2009 tilted transverse isotropy (TTI) reprocessing of that data.

Dr. Walker explains that, "By starting small and developing known hydrocarbons, investing in technology to improve the seismic imaging of the field and a continuing appraisal drilling program, the team of geoscientists and engineers assigned to the field was able to evaluate resources while simultaneously unlocking their value. Our early oil-in-place estimates were 450 million barrels. Integrating production data with the improved seismic imaging and appraisal wells has allowed the second phase of evaluation to proceed with greatly reduced subsurface uncertainty. The estimates of the field have grown substantially since the first single spar development in 2005 because we were able to accurately locate additional appraisal wells that greatly extended known OWC in different compartments of the structure. The oil in-place is now up to 4 Bboe. We are currently planning the second phase of development that will involve the design and construction of a new production facility, which will make the Mad Dog Field a major Gulf producer for decades to come."

With improved imaging and additional wells, structure maps gradually improved. Red represents the high areas and the brown polygons represent fault heave gaps. Not all well penetrations (green=oil, blue=water) are shown.



Acknowledgements:

This article was written from information presented at the 32nd Annual Gulf Coast Section, Society of Sedimentary Geology (GCSSEPM) Foundation Bob F. Perkins Research Conference (2012). Special thanks to GCSSEPM and to BP, BHP and Unocal for the information and illustrations. Special thanks to Dr. Walker for his help in preparing this article. ■

Beneath the Labrador Sea

A new seismic dataset helps clarify the deepwater hydrocarbon potential offshore Newfoundland and Labrador in Canada

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RON BORSATO, PGS, Weybridge, UK
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First oil was produced on the Grand Banks in 1997 from the Hibernia Field and since then the world-class oil-producing fields Terra Nova, White Rose and North Amethyst have come on stream in the Jeanne d 'Arc Basin, and the Hebron field is going into development in the same basin. It is estimated that recoverable reserves of 4.6 Bbo and 18.8 Tcf of natural gas exist in the Mesozoic basins of Grand Banks alone. The 2009 Mizzen oil discovery in the Flemish Pass Basin, estimated at 200 MMbo recoverable reserves, proved the extension of a working petroleum system, sourced by the prolific late Jurassic source rock into an area where it was previously only postulated to exist. The extent of the nascent Labrador Sea in Late Jurassic-Early Cretaceous, north-west towards the Davis Strait, was previously unknown and has now been partially delineated with the new 2D seismic data. This confirms the presence of a continuous Mesozoic rift section throughout the slope and deepwater regions of the Labrador Sea.

Recent work along the western Greenland margin also confirms extensive Mesozoic rift basins, as well as Turonian-aged source rock in outcrop and in offshore exploration wells (Knutsen *et al.*, 2012).

The major period of exploration on the Labrador Shelf was in the 1970s and 1980s, when more than 200,000 km of 2D seismic were recorded and 30 wells were drilled (21 in the Hopedale Basin and 9 in the Saglek Basin) with the last well drilled in 1983. Five discoveries were made in Hopedale Basin of which the Bjarni H-81/North Bjarni F-06 complex is the largest, estimated to contain more than 3 Tcf of natural gas in a Bjarni Formation sandstone of Early Cretaceous age (see dip line, page 29). The three other natural gas discoveries are Snorri J-90 within a Gudrid Member sandstone reservoir (Paleocene age), Hopedale E-33 in a Bjarni Formation sandstone reservoir, and the Gudrid H-55 discovery which has an Ordovician carbonate reservoir. The only discovery in the Saglek Basin is the Hekja O-71 natural gas discovery which is estimated to contain 2.3 Tcf in a Gudrid Member reservoir. It is important to note that all wells were drilled on the shelf and they achieved a 25% success rate.

Significant Hydrocarbon Source Potential

Rifting in Labrador began approximately during the Lower Cretaceous Berriasian and resulted in extensive peneplanation of the basement with earliest syn-rift deposits encountered in shelf wells comprising the Alexis Formation volcanics and the fluvio-lacustrine Bjarni Formation. With expanding section observed on seismic in southern regions, the possibility exists for preservation of older Mesozoic sediment over deepwater regions of the Labrador offshore.

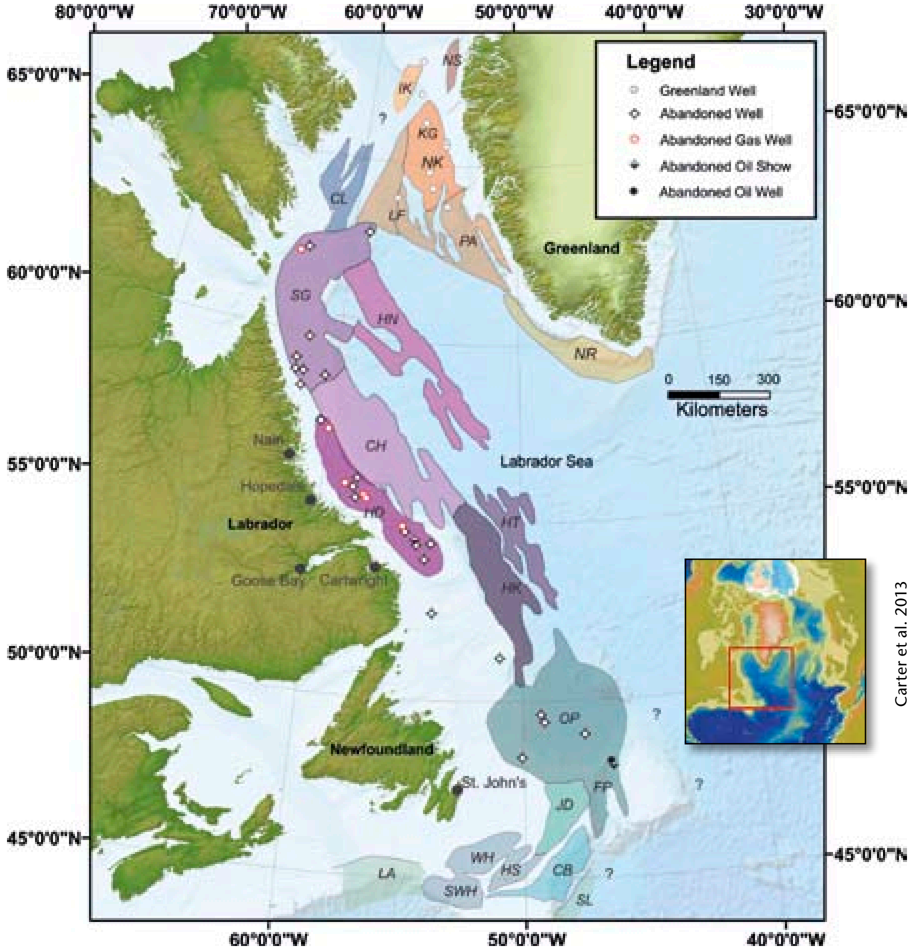
The Avalon unconformity (Cenomanian age) marks the transition into late- to post-rift sediments, which consist principally of marine shales and their more proximal sand equivalent (the Freydis Member). Seafloor spreading commenced in the Late Maastrichtian or Early Paleocene and is marked by the Bylot unconformity (base Tertiary). These syn-rift sediments are mainly marine shales with some submarine fan and shallow marine sandstone deposits (Gudrid and Leif Members). Seafloor spreading ended in Late Eocene-Early Oligocene and is represented by the Baffin Bay unconformity with post-rift sediments comprising terrestrial and marine shales, siltstones, sandstones/siltstones and glacial beds.

The total organic carbon content of the Lower Cretaceous to Eocene shale deposits is considered sufficiently high to yield significant hydrocarbon source rock potential. Turonian-Cenomanian marine shales of the Markland Formation are immature on the shelf, but are buried at greater depths in the slope and deepwater regions. The younger marine deposits are immature on the shelf, but these shales

The rugged and pristine coast of Labrador in north-east Canada.

Newfoundland and Labrador Department of Natural Resources – Geological Survey

Distribution of Mesozoic basins on Grand Banks offshore Newfoundland. The Labrador Sea stretches from the Davis Strait in the north-west and includes the Hawke Basin (HK) in the south-east. There are six main sedimentary basins on the Labrador Shelf: the shelfal Hawke, Hopedale (HD) and Saglek (SG) Basins, and the deepwater Holton (HT), Chidley (CH) and Henly (HN) Basins. The Orphan Basin (OP) is located north-east of Newfoundland, and the Flemish Pass (FP) and Jeanne d'Arc (JD) Basins are located almost directly east of Newfoundland.



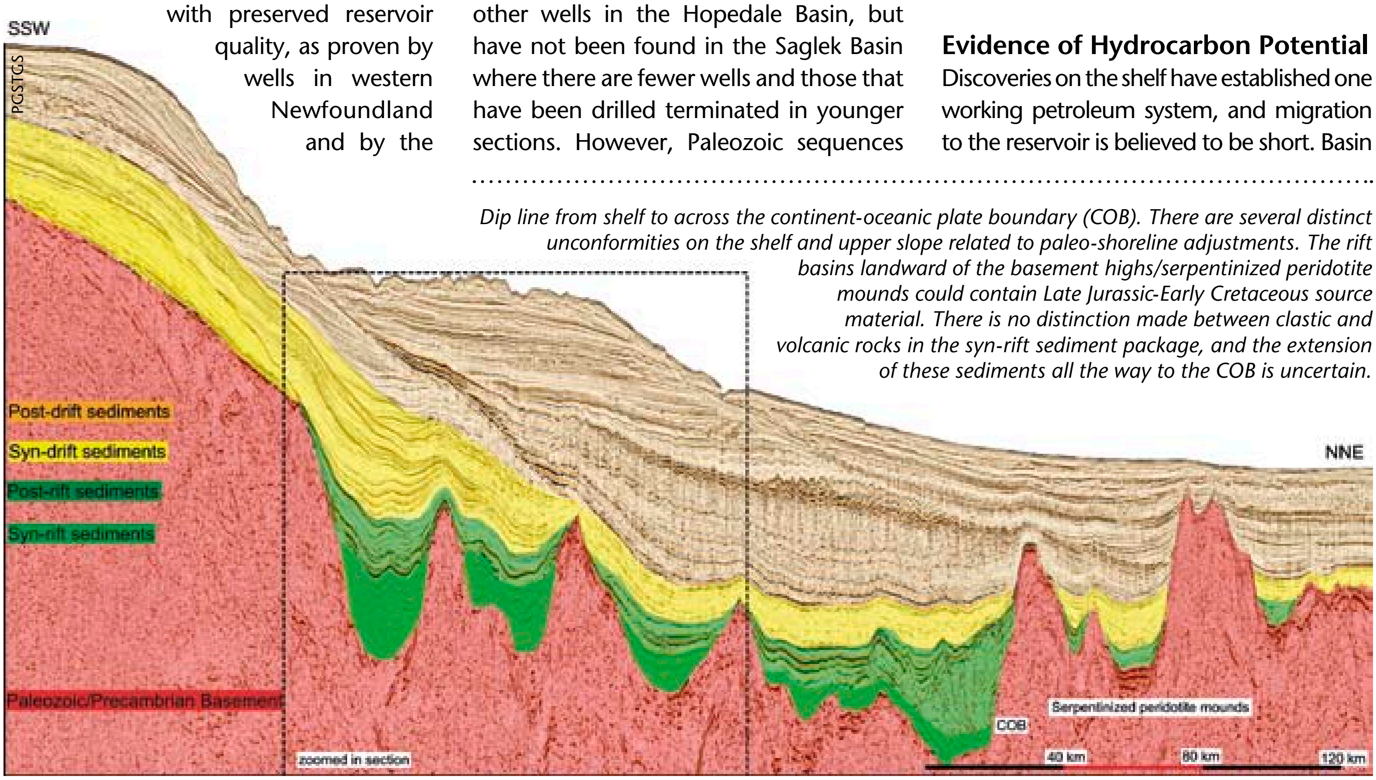
may reach adequate burial depths in slope and deep water regions, and act as excellent regional seals.

On the shelf the Bjarni Formation sandstone is the most widespread reservoir with both structural traps related to the rift topography and combination structural-stratigraphic traps. The deepwater Bjarni Sandstone onlaps rotated Paleozoic to Precambrian fault blocks and is draped directly over the fault blocks creating 4-way dip traps and the structural highs associated with fault blocks form 4-way dip closures in younger sediments. On the slope and rise the early syn-rift Bjarni is likely similar in depositional character, while the distal equivalents of the Freydis, Gudrid and Leif Member sands are expected to occur as basin fans with trapping mechanisms being stratigraphic and structural, as well as combination traps of both types.

Lower Paleozoic Ordovician rocks include carbonates and dolomites with preserved reservoir quality, as proven by wells in western Newfoundland and by the Hopedale E-33 well and the Gudrid H-55 well in Labrador. Carbonates with reservoir quality were also encountered in a few other wells in the Hopedale Basin, but have not been found in the Saglek Basin where there are fewer wells and those that have been drilled terminated in younger sections. However, Paleozoic sequences are present on Baffin Island and probably offshore West Greenland and may be present in the Saglek Basin.

Evidence of Hydrocarbon Potential

Discoveries on the shelf have established one working petroleum system, and migration to the reservoir is believed to be short. Basin



Dip line from shelf to across the continent-oceanic plate boundary (COB). There are several distinct unconformities on the shelf and upper slope related to paleo-shoreline adjustments. The rift basins landward of the basement highs/serpentinized peridotite mounds could contain Late Jurassic-Early Cretaceous source material. There is no distinction made between clastic and volcanic rocks in the syn-rift sediment package, and the extension of these sediments all the way to the COB is uncertain.

modeling of the Hekja discovery shows that the reservoir has barely reached the oil-window and the Gudrid sandstone reservoir deposited directly on basalt suggests that the gas in Hekja must have had a lengthy vertical and lateral migration route. This indicates the existence of a source rock located outside the shelf and suggests that there are at least two gas prone source rocks capable of charging large reservoirs.

An oil-seep survey showed several active seeps in an area east of the Hekja discovery, and since gas is the only proven hydrocarbon in this area these slicks indicate another working petroleum system in the region. This is further supported by evidence of a Mid to Late Cretaceous oil prone source rock off of Western Greenland in the Disko Island region (Bojesen-Koefoed *et al.*, 1999, 2004, Knutsen *et al.*, 2012) and the northern tip of the Saglek Basin trend.

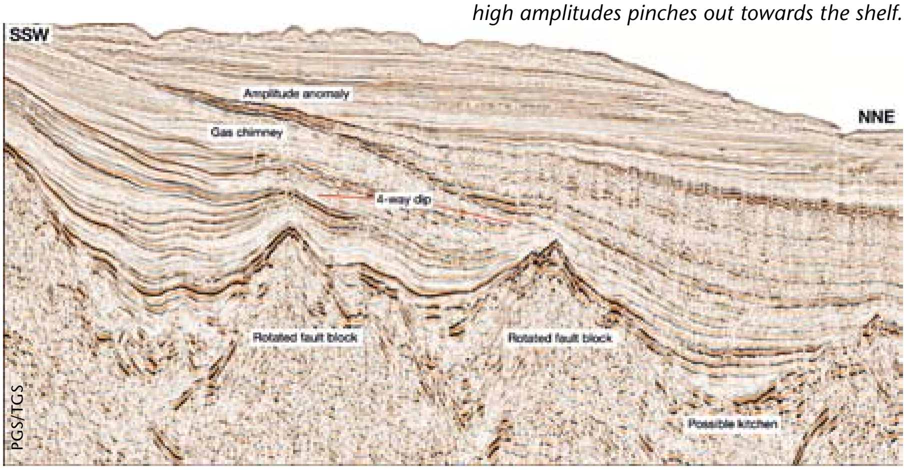
A 2010 satellite oil slick mapping survey of the Labrador Sea revealed numerous slicks in the deepwater regions, which were used to optimize positioning of the long-offset GeoStreamer seismic survey lines. Although it is early in the analysis of the new data, there are seismic amplitude anomalies in some of these frontier basins with AVO character consistent with hydrocarbon signatures in analogous basins of similar age. A maturity study conducted in the Hopedale Basin indicate that a depth of 3,300m is sufficient to reach the HC window, while observed sediment thicknesses of 3.5 seconds in the rift-basins close to the COB suggest sufficient burial of the potential Mesozoic (Late Jurassic and Turonian) source material to reach maturity. In some regions, long range migration from these pools to the reservoir may be required, which we know has happened in the Hekja well, decreasing the uncertainty of the play.

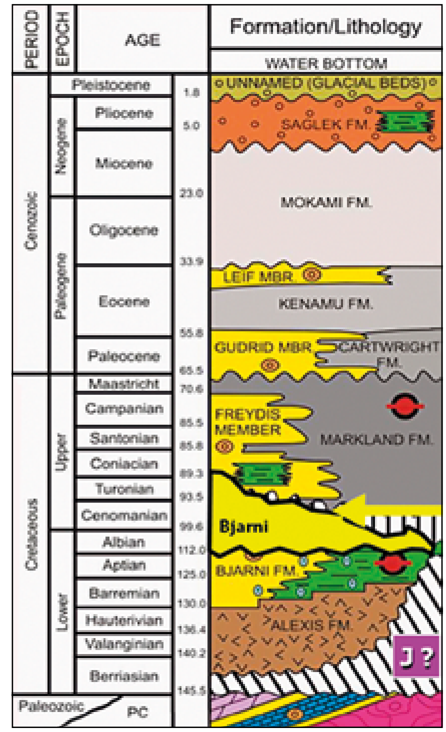
De-Risking Exploration

Exploration in Labrador has been somewhat dormant for well over two decades, with no deepwater tests ever conducted. The new seismic dataset acquired over slope and deepwater regions will help de-risk future exploration models and provide a much better understanding of the petroleum system. Early indications suggest a Mesozoic rift basin fairway that stretches from the Orphan Basin in the south through to the Saglek Basin in the north, with syn-rift sediments reaching burial depths far in excess of those encountered on the shelf.

Could there have been an early seaway passage between Greenland and Canada providing the correct environment for deposition of high quality marine source rocks in restricted rift basins in Late Jurassic and similarly in the Late Cretaceous? The question is still unanswered, but by covering the failed rift-arm, this dataset provides a unique opportunity to search for these rift basins close to the COB in the hunt for a potential Jurassic and Turonian-Cenomanian source rock. The extension of the Mesozoic rift section throughout the survey area has led to the identification of genuine opportunities on the slope and rise offshore Labrador. Further acquisition will continue to test the potential of the region, with positive insights suggestive that now may be the opportune time to re-engage exploring for hydrocarbons in the deep waters of the Labrador Sea.

Synrift sediments onlapping large rotated fault blocks which creates potential 4-way dip closures in younger strata. There are several gas chimneys seen over the fault blocks. A wedge of anomalously high amplitudes pinches out towards the shelf.





Modified after Enachescu, 2011

Stratigraphic column for offshore Labrador.

Acknowledgement

The authors want to thank PGS, TGS Nopec, and Nalcor Energy for permission to publish this work, and the different contributors from within the PGS organization.

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Ireland's Porcupine Basin: The Dream Comes Closer

Michael Hanrahan

The vertiginous interbedded sandstones, siltstones and claytones of the cliffs of Co. Clare look towards the wild deep waters of the North Atlantic.

Buoyed by new thinking and a high oil price, the industry readies itself to once again take on the technical, environmental and financial challenges of operating on the frontier Atlantic margin.

KEN WHITE

Over the years estimates of hydrocarbon resources in Irish waters have ranged from 10 Bboe to 50 Bboe, but at present little exploration work exists to substantiate either figure. Indeed, in nearly half a century, almost 200 wells have been drilled around Ireland but there have only been four commercial discoveries. Shell's problems with the Corrib gas field off western Ireland, when some local landowners refused to allow construction work on the onshore section of pipeline, have been well documented, and that and other environmental issues have been addressed; the project is now due on stream late 2014.

The lack of exploration is not surprising, as many of the Atlantic Margin plays involve operating in water depths of between 500 and 2,000m, in the challenging Atlantic Ocean. These are not hospitable conditions at the best of times and present unique and costly challenges to drilling. However, with an oil price consistently over US$ 100 per barrel, drilling here is now more widely accepted as being economically viable and the situation is changing. Historically, exploration of the Porcupine Basin has focused on Jurassic targets based on similar plays in the northern North Sea but, unlike the North Sea, no wells have been drilled in the basin over the past decade.

Success in different types of reservoirs elsewhere on the Atlantic margin, such as offshore West Africa and South America, have led to fresh ideas that have prompted a re-examination of the whole basin. Couple this with improving technology, sustained high oil prices and competitive terms, and a number of explorers are finding Ireland now offers an attractive opportunity. Supporting this renewed interest, the Petroleum Affairs Division of Ireland's Department of Natural Resources (PAD) has contracted BGP to acquire a mega-regional 2D long-offset seismic survey of some 18,000 km, covering all the basins west of Ireland. Acquisition should start early April 2013 and be concluded by the end of the year.

The Challenging Porcupine Basin

Recent interest offshore Ireland has focused on the shallow North Celtic Sea Basin, off the south coast, where Providence Resources grabbed the headlines in the final quarter of 2012 declaring it has established a potential of up to 1.6 Bbo in-place at its Barryroe discovery in around 100m of water off the south coast. The company is now planning operations in the more challenging Porcupine Basin.

This basin is a large north–south oriented structure lying 150 km south-west of Ireland that contains up to 10km of Upper Palaeozoic to Cenozoic sediments in water depths ranging from around 350m in the north to 3,500m in the far south. 13 wells have been drilled so far in the key area of Jurassic deposition which covers about 10,000 km^2. The PAD consider that a number of major plays can be recognized, with significant potential expected to be located in Jurassic and pre-Jurassic reservoirs in tilted fault blocks developed along the margins of the Porcupine Basin. There is additional potential in post-rift stratigraphic and structural plays in Cretaceous and Tertiary sediments. Further indications of hydrocarbons are the presence of gas chimneys and seeps in areas not yet explored. Potential sources included Upper Jurassic Kimmeridge

Clay equivalent mudstones, which are known to be present and mature for hydrocarbon generation in the Porcupine Basin.

Given the size and complexity of the basin it remains underexplored. Flows of hydrocarbons from wells in the basin in the 1980s and 90s, although deemed uneconomic at the time, indicate the presence of a number of working petroleum systems. Few of these wells were drilled on quality seismic data; current thinking is that the basin holds the potential to reveal opportunities that the advent of modern 3D seismic data brings and just about all of the players have revealed structures with massive potential reserves. While this has worked wonders for respective share prices, a sense of reality beckons as a new wave of wildcat drilling is about to commence.

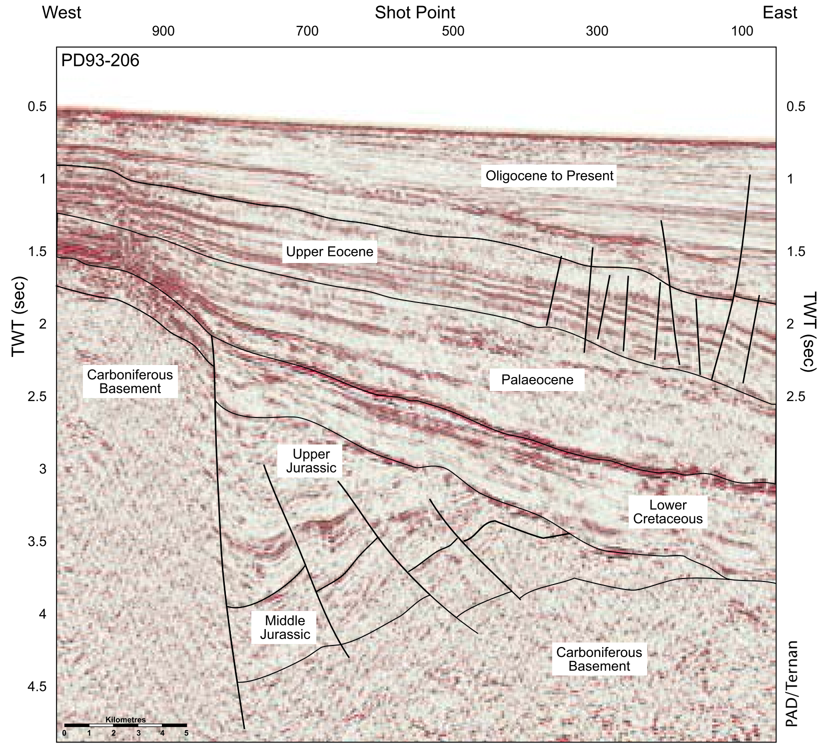
Here Come the Boys!

ExxonMobil has signed a letter of intent to use the Eirik Raude S/S to drill the huge Dunquin gas/condensate prospect during the second quarter of 2013. Located in 1,524m of water, the Dunquin project consists of two main Middle Cretaceous carbonate prospects, Dunquin South and Dunquin North; combined resources are estimated at 1.7 Bboe recoverable, a staggering resource for Europe if proven.

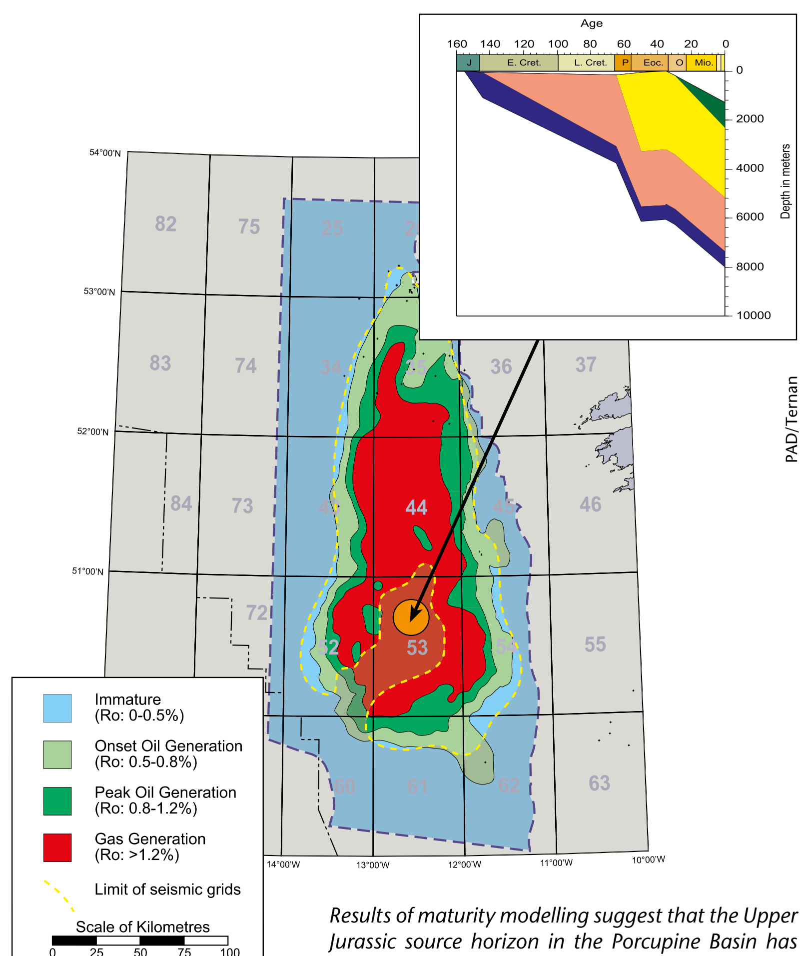
Providence and partner Sosina Exploration were awarded Licensing Option 11/9 as part of the 2011 Irish Atlantic Margin Licensing Round, which contains the southern Porcupine Basin Drombeg prospect in around 2,500m of water, 220 km off West Cork and around 60 km from the Dunquin exploration prospect. According to Providence, preliminary analysis has indicated a recoverable P50 prospective resource potential of 872 MMbo, based on an oil-in-place volume of 2,970 Bbo. However, further technical data, including 3D seismic, will be required in order to better assess the ultimate resource potential. A number of similar Lower Cretaceous seismic anomalies have been identified both laterally offset to, as well as vertically stacked with, the Drombeg prospect, providing further resource growth potential.

In the main Porcupine Basin, Providence is relinquishing operatorship of Frontier Exploration License (FEL) 2/04, which contains the Lower Cretaceous Burren oil discovery, and FEL 4/08 to Chrysaor ahead of a two-well program in around 400m of water which is designed to appraise the 1981 Spanish Point gas condensate discovery, due to spud in the third quarter of 2013. Some 300 km² of 3D seismic data was acquired in 2009 which firmed up a resource level of up to 510 MMboe with around 200 MMboe recoverable.

Two other Porcupine Basin players, Europa Oil and Gas and Petrel, have identified what they describe as previously unknown and significant prospects. Europa has identified two large prospects



Jurassic tilted fault blocks against basin margin fault on the western margin of the Porcupine Basin, with thick Cretaceous and Tertiary cover.



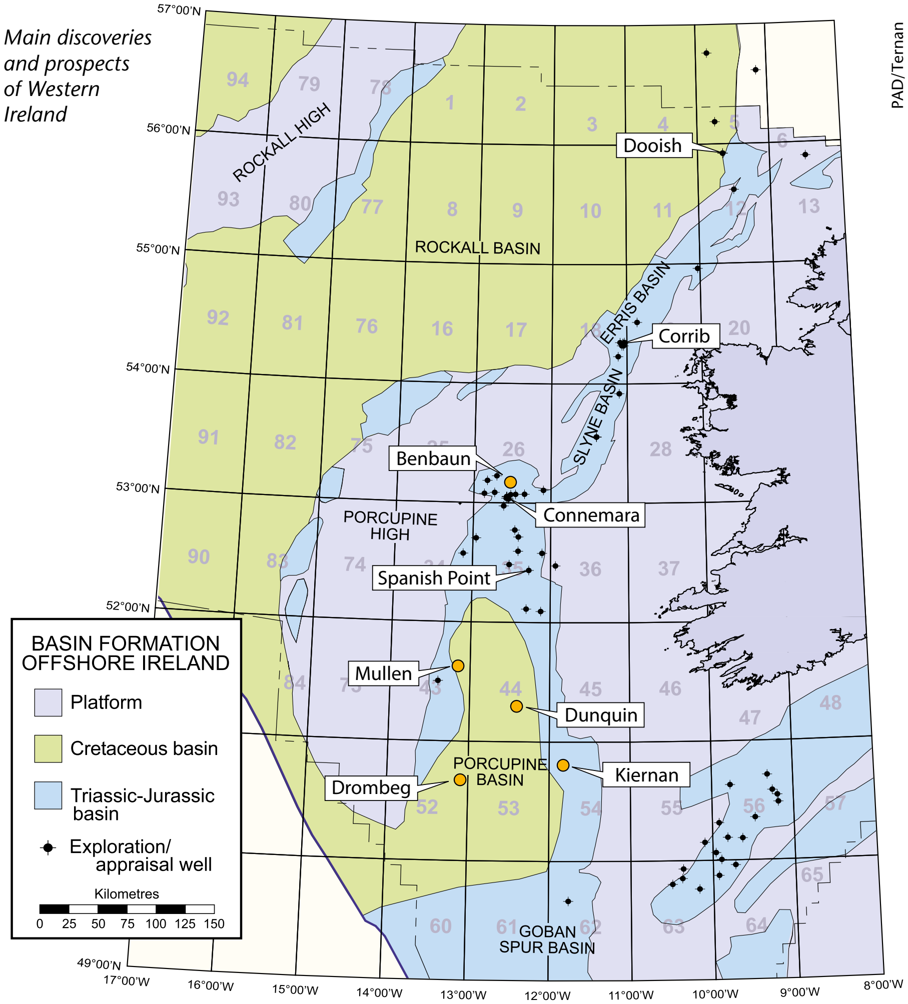
Results of maturity modelling suggest that the Upper Jurassic source horizon in the Porcupine Basin has generated large quantities of mobile hydrocarbons, and it is still generating today.

in the South Porcupine Basin: Mullen and Kiernan. Mullen, in water depth of about 1,000m, has a P50 resource of 482 MMbo, with plays identified in the Paleocene, Lower Cretaceous and Pre-rift Jurassic. First pass seismic mapping over the Kiernan prospect, which is in deeper waters of about 1,700m, has identified three reservoirs with total mean unrisked indicative resources estimated at 1,612 Bbo and 10 Tcfg. Europa anticipate drilling in the second phase of their frontier exploration license.

Petrel Resources has concluded a technical study of its six option blocks in the Porcupine Basin, revealing that 'encouraging prospects at the Lower Cretaceous and Tertiary levels' are evident in both sets of blocks, with those blocks in Quadrant 35 looking 'particularly promising'.

Other players firming Porcupine Basin plans include San Leon Energy, operating a Frontier Exploration Licence at the northern limit of the North Porcupine Basin, where it has mapped the 180 MMb Benbaun prospect. This is a combined structural–stratigraphic Upper Jurassic prospect analogous to the UK Buzzard Field. Elsewhere, Bluestack has mapped a well-defined Upper Jurassic stratigraphic trap on Licensing Option 11/3 with a PMean of 8.3 Tcf gas in-place.

Two Seas Oil and Gas, meanwhile, have identified two large Paleocene fan prospects on their license area to the west of Spanish Point, which have potential in-place volumes of over 500 MMbo, as well as Jurassic and Cretaceous leads. Another interested party is Antrim Energy, with acreage just north of Dunquin which has promising Cretaceous play fairways.



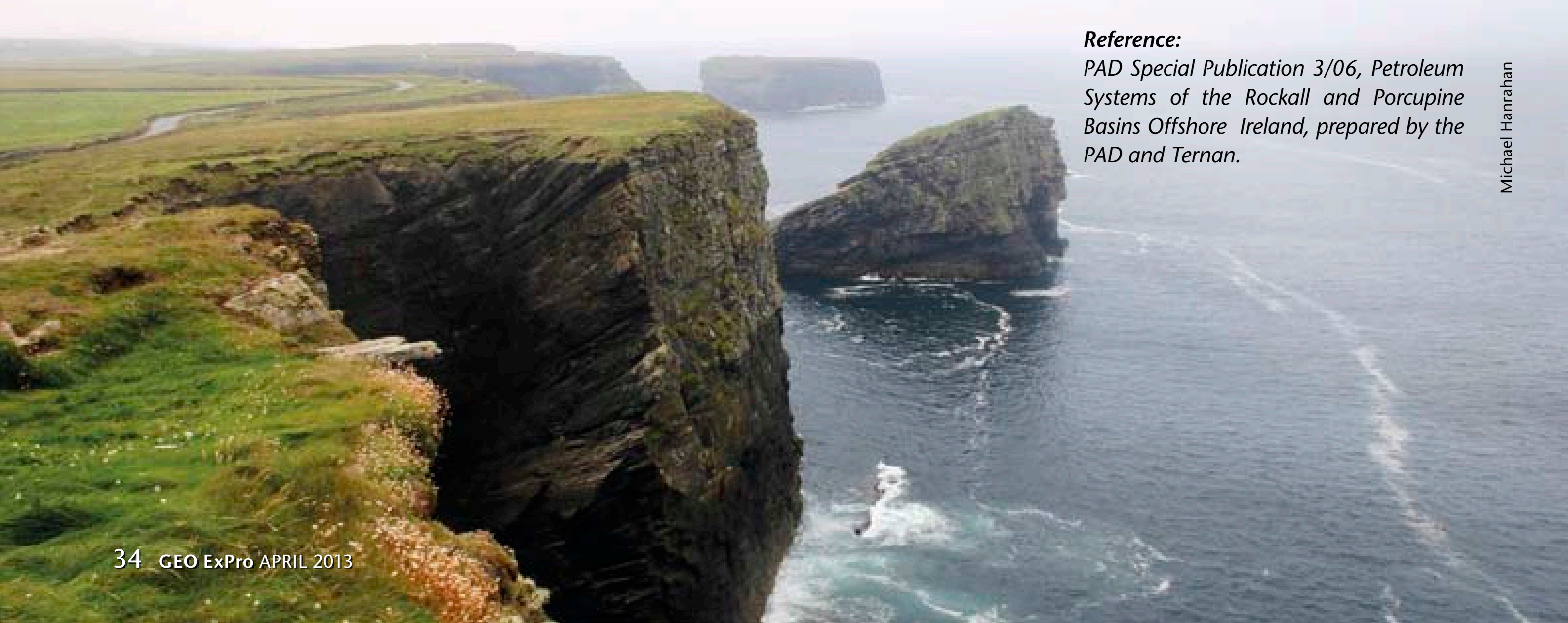
Main discoveries and prospects of Western Ireland

PAD/Ternan

Exciting Prospects

Excitement is rising in the Atlantic Margin west of Ireland. This year the area will see the shooting of the largest ever seismic survey offshore Ireland and the drilling of one of the most exciting wildcats in a new play. The majority of the companies who were awarded acreage in the area in the recent licence round have worked up their prospects and are now actively looking for partners to progress exploration on their blocks. Ireland has been one of those places where promise is always just around the corner, tantalizingly close yet so far away. With recoverable reserves for the offshore west of Ireland estimated to be in the region of 10 Bboe, it looks as though 2013 could be the year that the dream finally becomes a reality. ■

Reference:
PAD Special Publication 3/06, Petroleum Systems of the Rockall and Porcupine Basins Offshore Ireland, prepared by the PAD and Ternan.



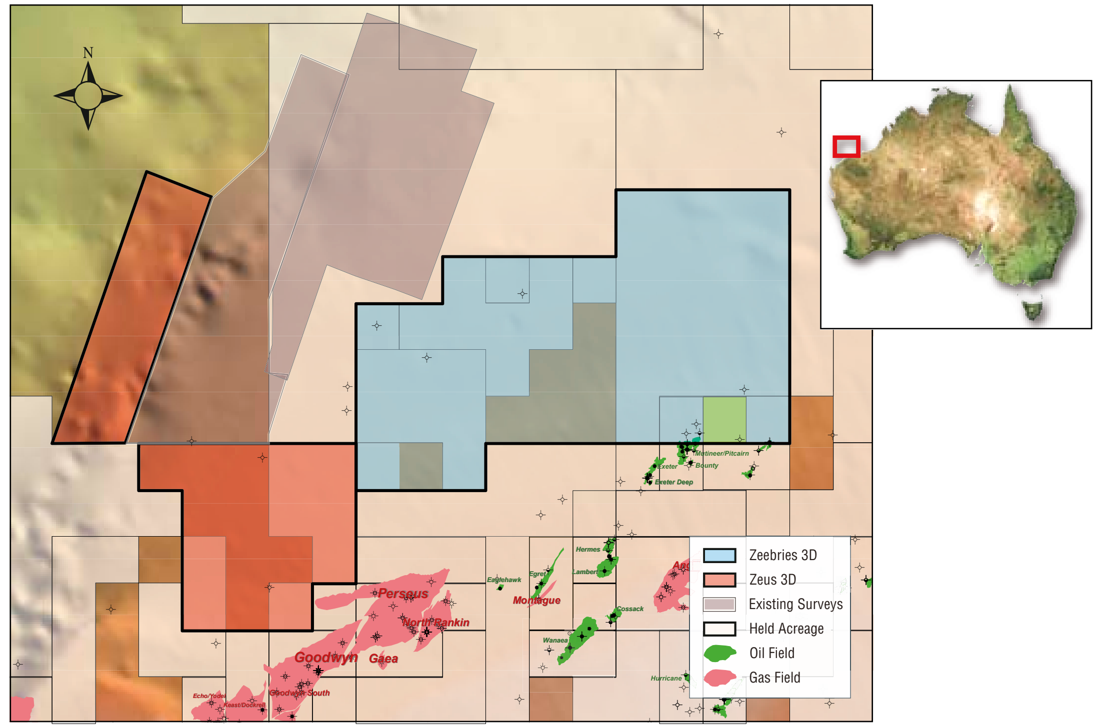
Michael Hanrahan

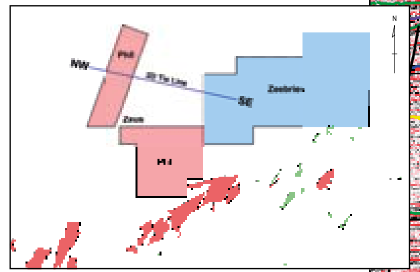
Zeus and Zeebries:

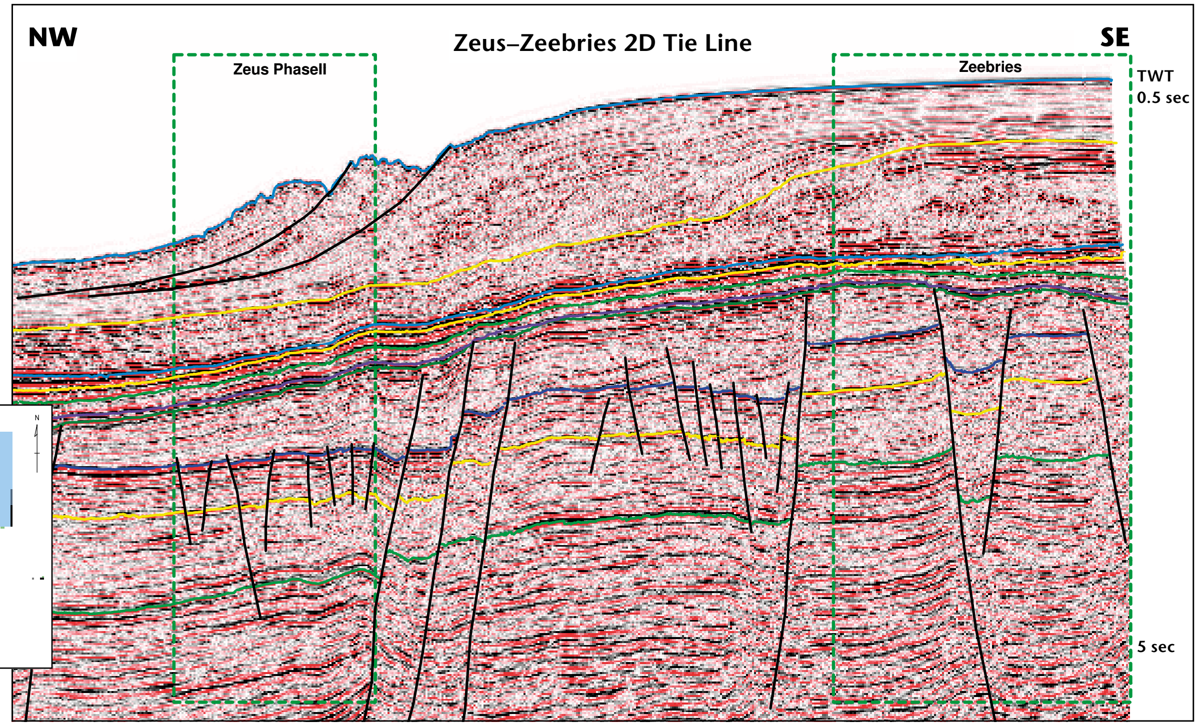
Enhanced exploration potential from new high-quality 3D data acquired by Fugro in the Northern Carnarvon Basin – Australia's most prolific hydrocarbon-producing basin.

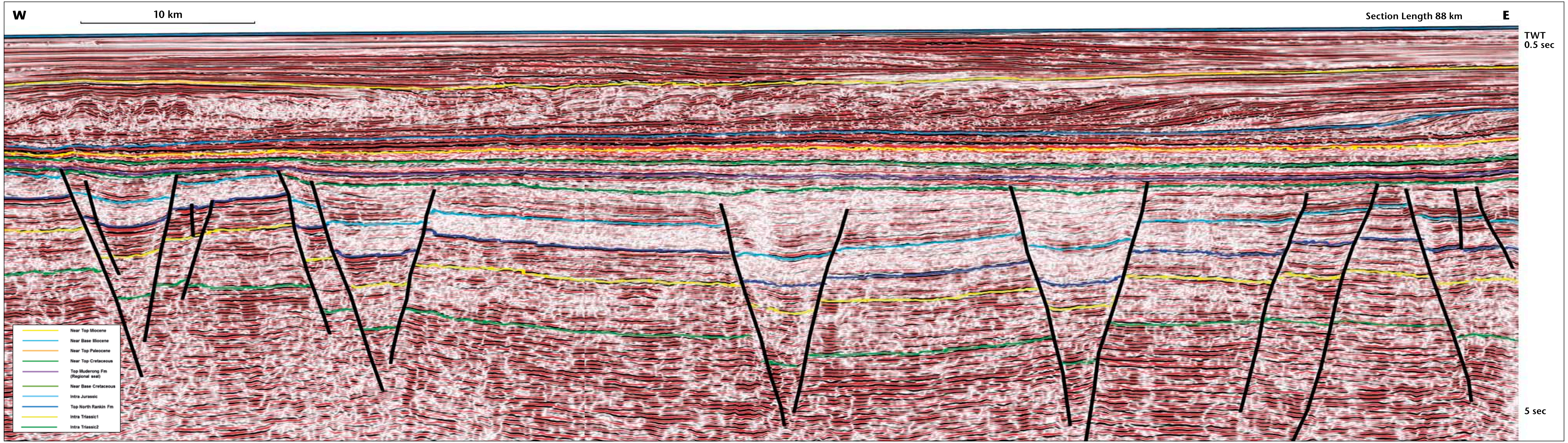
These survey areas are within Australia's premier hydrocarbon province, adjacent to producing fields and existing infrastructure. The surveys aim to clearly define play levels in the area, including the Triassic Mungaroo fault blocks to the south at the Goodwyn gas field and the Jurassic-Triassic horsts and wrench-controlled troughs to the east.

The data is owned by Fugro and marketed by CGG.









West-East oriented Zeebries 3D seismic line. The Zeebries survey was acquired by the M/V Geo Atlantic and M/V Geo Celtic with ten solid streamers of 6.6 km in length. Regional seismic events include the main reservoir units of the Triassic to Lower Cretaceous fluvio-deltaics and marginal marine clastics.

Zeus and Zeebries: Significant Exploration Insights

High-quality 3D data could provide new exploration opportunities in this highly prospective part of the Northern Carnarvon Basin, where underexplored areas exist within close proximity to producing fields.

JARRAD GRAHAME and **PATRICIO SILVA-GONZALEZ**, CGG

The Zeus and Zeebries 3D surveys are located in the Northern Carnarvon Basin, Australia's premier petroleum province. The surveys were acquired north-north-east of the Goodwyn, North Rankin and Perseus gas fields, which lie along the Rankin Trend, forming part of the eastern boundary of the basin. The main objective of Zeus and Zeebries is to clearly define play levels within Jurassic-Triassic uplifted blocks, horsts, drapes and anticlines, which represent the main structural trapping mechanisms throughout the area.

A full bandwidth simultaneous inversion, including lithology probability volumes, was carried out for the Zeebries 3D by Jason (a CGG company). The inversion volumes were produced to aid interpretation and provide predictive rock and fluid distributions to better constrain subsurface reservoir models. Time and depth migration is being conducted for the Zeus Phase II 3D.

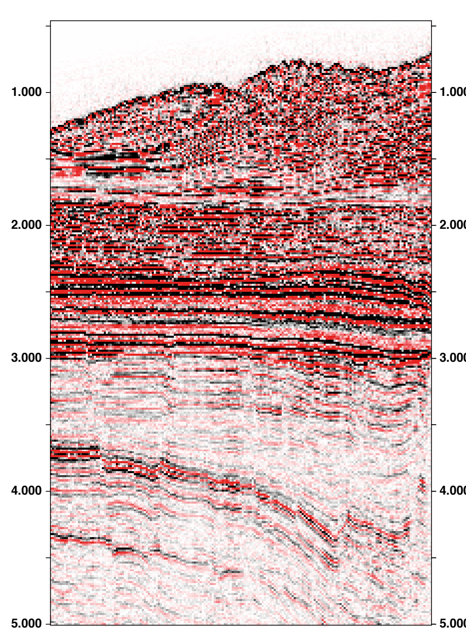
Geological Overview

The offshore depocenter of the Northern Carnarvon Basin contains a thick succession of late Paleozoic to Cenozoic sediments. The main reservoir units are dominated by Triassic to Lower Cretaceous fluvio-deltaics and marginal marine clastics, deposited during multiple phases of syn-rift extension. The offshore basin, which covers approximately 535,000 km², evolved from Late Paleozoic pre-rift, to tectonically active Mesozoic syn-rift, followed by subsidence (post-breakup of Gondwana), and finally to a Cenozoic passive margin carbonate shelf (*Geoscience Australia*, 2012). Sediment thickness in the Northern Carnarvon Basin is known to reach up to 15 km in the Exmouth Plateau (west of the study area).

Regional tectonics produced structural trends oriented north-eastwards, which control the basin architecture and to a large extent the distribution of sediments within the sub-basins of the North Carnavon Basin. Secondary north-oriented structuring is presumed to have developed as a continuation of a Paleozoic onshore trend (Purcell, 1988). The local structural elements throughout Zeus and Zeebries are characterized by a series of complexly-faulted broad anticlines and synclines. Structural traps created by these extensional cycles consist of uplifted blocks, horsts, drapes and anticlines. Mapping of structures throughout the surveyed areas reflects the interplay between underlying basement architecture and syn-rift structuring (*Geoscience Australia*, 2012).

The interdependent processes that contribute to generation, migration and accumulation of hydrocarbons within the basin are largely controlled by tectonic activity occurring in the Jurassic through to the Early Cretaceous. Petroleum system development can be attributed to syn/post-rift structuring and sedimentation, followed by post-rift reactivation. These cycles produced the necessary elements for the occurrence of hydrocarbon accumulation, within the thick successions of late Paleozoic to Cenozoic sediments.

Zeus 3D west–east line.



Hydrocarbon Sequences

The main hydrocarbon generative sequences consist of gas-prone source rocks of Triassic-Jurassic marine and fluvio-deltaic successions. Geochemical studies undertaken in the area indicate that gas accumulations along the Rankin Trend originate from Triassic source rocks deposited in fluvial to marine environments. The studies further indicate that accumulations in adjacent areas to the east of the project area were sourced from Jurassic fluvio-deltaic and marine successions (Boreham et al., 2001, Edwards and Zumberge, 2005).

Pre-rift to active margin reservoirs within the Northern Carnarvon Basin consist of fluvial and shoreline sandstones of the Triassic Mungaroo Formation and fluvial-marine sediments of the

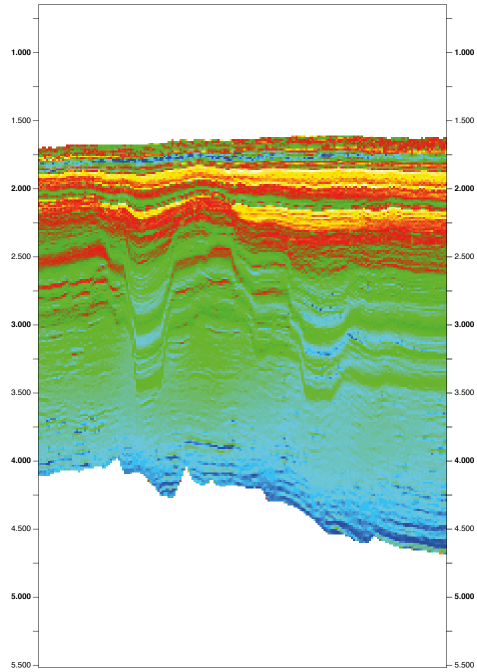
Late Triassic-Early Jurassic Brigadier and North Rankin Formations. These formations are also known gas-prone source rocks. Early syn-rift reservoirs consist of Middle Jurassic deltaic sandstones of the Legendre Formation, which is also a potential hydrocarbon source at distal margins. The main syn-rift reservoirs comprise Late Jurassic to Early Cretaceous reservoir-quality turbidites, submarine fans, shoreline sands and fluvial sandstones at sub-basin margins. The Lower Cretaceous Muderong Shale provides a regional top seal throughout the Northern Carnarvon Basin. Additional intra-formational sealing units occur in the Cretaceous Barrow Group sediments and Forestier Claystones, the Jurassic Athol and Legendre Formations and the Triassic Mungaroo Formation.

Exploration Insights

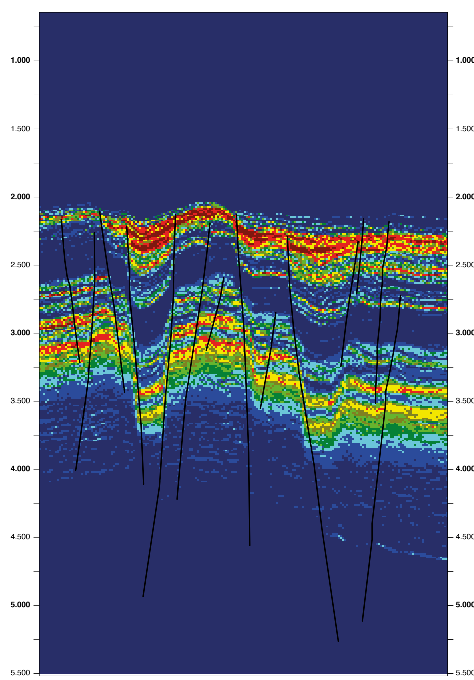
Several wells are located within Zeebries along structural trends to the south-east, adjacent to the Mutineer and Exeter oil fields, and to the north-west along the Brigadier Trend. The wells intersected good-quality reservoir sands at target levels, primarily within the middle to late Jurassic sands of the Angel and Legendre Formations, and the late Triassic to early Jurassic sands of the North Rankin and Brigadier Formations. Preliminary interpretation confirms that similar potential hydrocarbon-bearing closures, at these target levels, can be mapped extensively throughout the survey.

With the added benefit of full bandwidth inversion volumes, the distribution of potential reservoir sands can be mapped more effectively by extending well information throughout the entire volume. The impedance and lithology probability volumes provide valuable information where reservoir sands can be identified with more effective access to hydrocarbon charge than previously known. Discrimination of reservoir sands with intra-formational seals enables the interpreter to more clearly define additional stacked reservoir potential. This is critical where intra-formational claystones are below vertical resolution, or too acoustically subtle to be imaged on reflectivity data alone.

The Zeus surveys provide significant exploration insights to the west of Zeebries, where under-explored areas exist within close proximity to producing fields. Greater understanding of the local distribution and geographic extent of resource plays, made possible by these surveys, could provide the basis for further exploration in this area.



Zeebries full bandwidth simultaneous inversion P-Impedance.



Zeebries full bandwidth simultaneous inversion sand probability estimate. Red indicates high probability.

Acknowledgements

The authors would like to thank Fugro for granting approval for publication of the data contained within this article. ■

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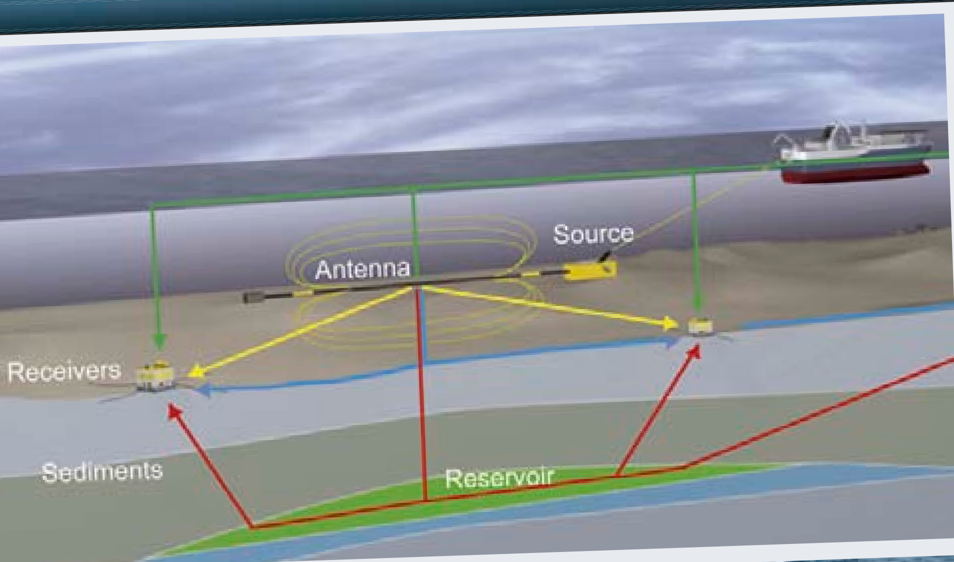
Zeebries and Zeus Surveys

Covering approximately 3,800 km², the Zeebries survey was acquired by the M/V *Geo Atlantic* and M/V *Geo Celtic* vessels with ten solid streamers, 6.6 km in length, spaced at 100m, utilizing Fresnel Zone Binning to minimize infill. Processing was undertaken by Fugro Seismic Imaging (prior to acquisition by CGG) in Perth, Western Australia, utilizing techniques to enhance visualization of the structurally complex Jurassic and Triassic fault blocks. The north-east-trending structures of the Brigadier Trend, the Victoria Syncline and the northern tip of the Rankin Trend comprise the main structural elements throughout Zeebries.

The Zeus Phase I and II surveys cover approximately 1,320 km² and 760 km² respectively, adjacent and to the west of the Zeebries 3D. The surveys were acquired by the vessel R/V *Seisquest* with eight solid streamers, 6 km in length, spaced at 100m. The surveys were undertaken to further understand play levels within Jurassic-Triassic fault blocks, and to confirm the presence of potential hydrocarbon traps to the west of significant gas and oil discoveries along the Rankin Trend.



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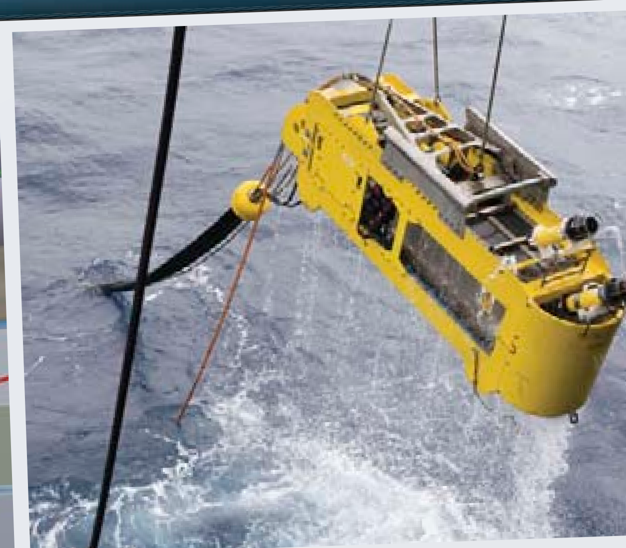
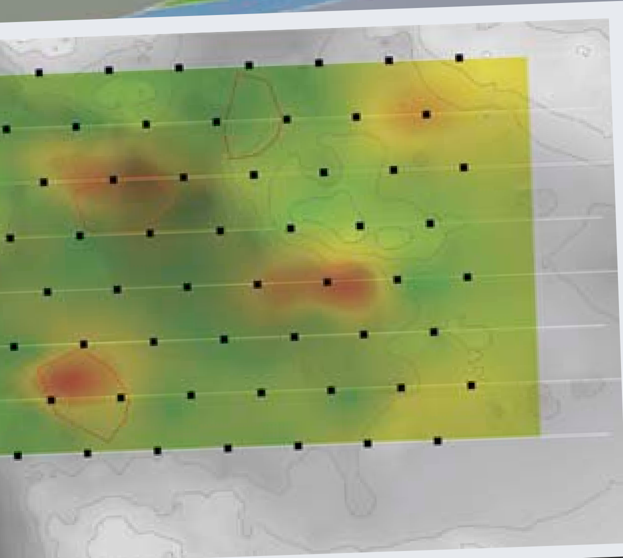




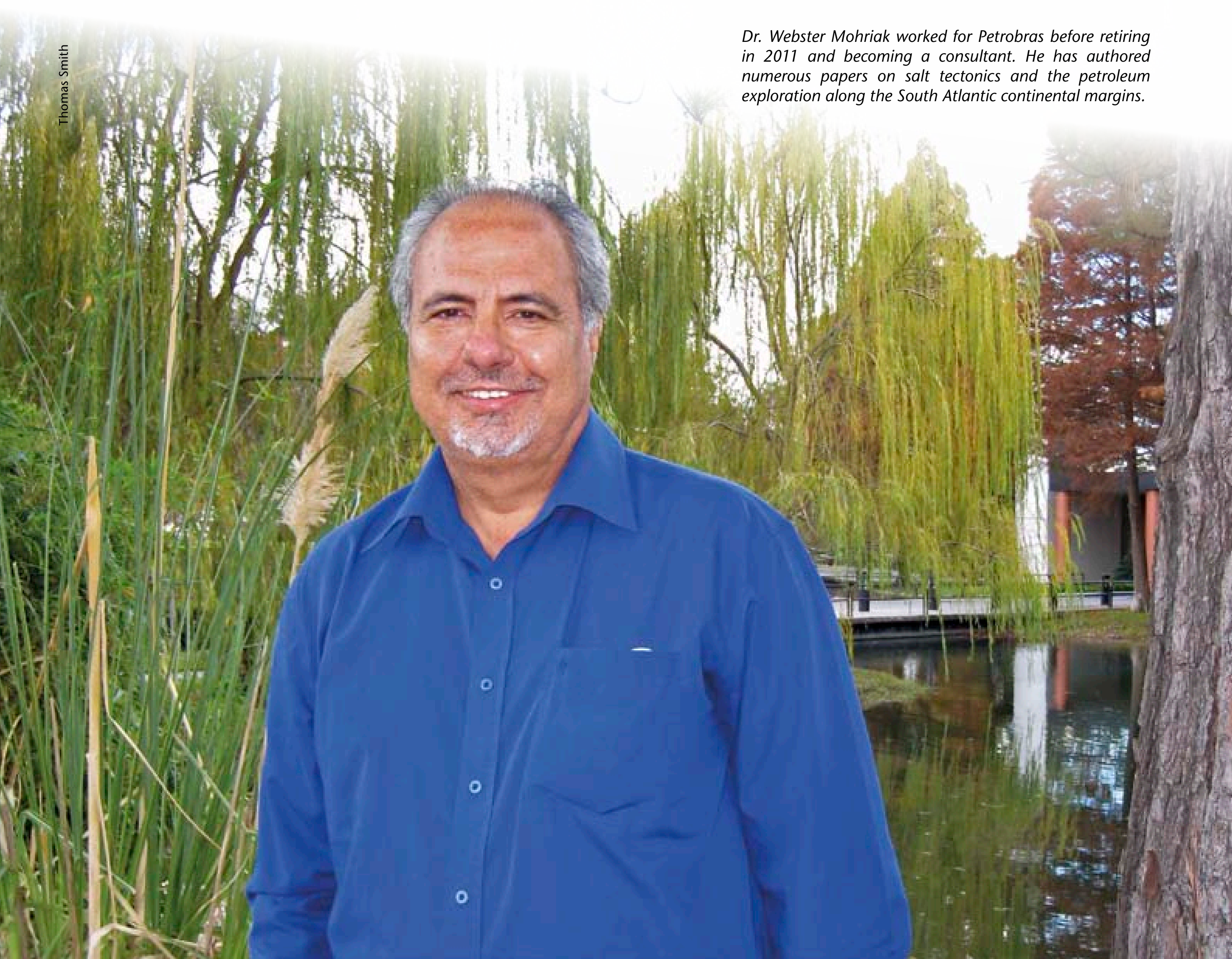
Mr. Conjugate Margin

Early in his career, geologist Dr. Webster Ueipass Mohriak analyzed 'the whole crust' along Brazil's continental margin to become one of the world's leading experts on conjugate margins.

THOMAS SMITH

Webster was working in a bank in São Paulo, Brazil, at the age of 16 where he enjoyed writing international reports for the bank manager. The manager's secretary translated German documents and had a 'world of experience' that impressed the young Webster, including experience in commercial analysis for the bank's investment portfolio.

She sparked Webster's interest in the sciences and encouraged him to 'look to geology for good jobs and adventure'. Later that year he took the required exams to enter Brazil's university system; the dreaded rite of passage, informally known as 'the funnel,' is a series of ferociously competitive exams that are must be passed before students can be accepted into a university. With only 50 slots in geology open to the country's top-rated school, Webster secured part of his future by being accepted into the geology program at the University of São Paulo.



Thomas Smith

Dr. Webster Mohriak worked for Petrobras before retiring in 2011 and becoming a consultant. He has authored numerous papers on salt tectonics and the petroleum exploration along the South Atlantic continental margins.

Inspiring Times

Subsequent to earning a degree in geology, Webster began working for Brazil's state owned oil company, Petrobras, in 1980. After taking another national exam a few years later, he was picked by Petrobras higher management to study geology abroad. At Durham in north-east England, he started working on a PhD project under John Dewey. This move proved to be very influential in Webster's development and geologic thinking. A year later, Dr. Dewey was appointed department head at the prestigious Oxford University where many of his students, including Webster, soon followed. At Oxford, "we (the students) worked in a basement across the road from the geology department," says Webster. "Here, most of us acquired a cosmopolitan view of the geosciences, given the fantastic atmosphere of scientific research ongoing at Oxford with students from all over the world. The lectures, given by renowned geoscientists, inspired us to broaden our knowledge base from a local to a more regional approach."

Indeed, in the late 1960s, John Dewey virtually grew up geologically with the then-newly accepted plate tectonics theory. While on sabbatical in New York, Dr. Dewey plotted the geologic details of the entire Caledonian orogenic belt that resulted from the closure of the Iapetus Ocean and the collision between north-western Europe and a North American-Greenland continent. The remnants of this once-prominent mountain range now curve from the eastern United States, up through Greenland, Norway, Scotland and Ireland. From these studies, he realized that there existed mountain belts of different types that could be explained only by the opening and closing of ocean basins.

In the early 1980s, concepts such as rifting and the ideas of existing conjugate margins were widely accepted by the geologic community but still poorly understood. One pioneering researcher, Bruce Rosendahl of Miami University, was trying to change our geologic understanding of rifts and continental margins and would become another major influence on Webster's career.

While Webster was in graduate school at Oxford, Bruce Rosendahl was doing some of the first research on a nascent rift in East Africa, where great lakes such as Tanganyika and Malawi covered the deep structures beneath the water. Project PROBE took Rosendahl and his research vessel onto the great lakes of the East African Rift. He conducted seismic surveys along these lakes, making the first ever profiles of an embryonic rift system. Rosendahl was also one of the first to use ultra-deep, multichannel seismic techniques, in another PROBE Project, to image down to 40 km along the West African continental margin. The acoustic profiles offshore Gabon imaged the upper mantle, the rifted crust and the overlying sediments, revealing the segmented nature of how continents break up and how the South Atlantic Ocean was created.

Oceans Apart

While Bruce Rosendahl was looking at deep seismic records off the West African coast, a group of Petrobras researchers had their own 'Crustal Project' offshore Brazil. The Petrobras group, led by Webster after he finished his PhD, was analyzing the first deep seismic profiles acquired offshore Brazil.

This work would be pivotal for not only Webster, but in helping researchers realize the importance of looking at 'the whole crust' to understand the structure of Brazil's most important producing basin since the 1980s, the Campos Basin. Again working with Petrobras, Webster and his fellow researchers soon became aware that the rift basins of eastern Brazil and West Africa would be better analyzed when integrated before the continental breakup and the formation of the South Atlantic Ocean that now separates the two continents.

"Once I realized how important it was to look past our own margins to understand the geology, I started exchanging technical communications with Bruce (Rosendahl) in the mid-1990s," explains Webster. "He actually sent me several of the works he was doing with other colleagues that I used to analyze and compare with the continental margin work I was doing at Petrobras."

Webster was now even more convinced of how important it was to see the big picture, even if some of the answers to questions lie across an ocean basin. He was driven to integrate and exchange knowledge from each side of the Atlantic Ocean margins. To this end, he organized one of the first sessions devoted to continental margins at the 5th International Congress of the Brazilian Geophysical Society held in São Paulo, Brazil, in 1997.

"This was one of the first technical meetings where the deep structure of the continental margins was analyzed and compared," says Webster. "We had the opportunity to invite geoscientists from different research groups who were exponents in continental margin studies. The meeting exceeded all expectations and the American Geophysical Union proposed to have several of the presentations written as chapters for a book planned on continental margins. *Atlantic Rifts and Continental Margins* was then published, and it included some of the most referenced articles on West African margin geology."

Unique Company Experience

"Petrobras is a company that provides incentives for its employees to search for solutions in-house by using the best science available worldwide," explains Webster. "Specialists from many branches of the oil industry, from basic geology to ultra-sophisticated 3D visualization techniques, participate in projects either in the exploration or research groups. A tradition in the company is to have geoscientists and engineers visit classical basins around the world and participate actively in training programs abroad while working with other renowned specialists. This way, some of our solutions for geoscience and engineering questions have come from the analysis of worldwide analogs."

Webster explains that, "For nearly 30 years, the focus at Petrobras has been on turbidites as the main reservoirs for fields found along the continental margins, not only in Brazil but in many other exploration areas. Now, the company has shifted toward the pre-salt carbonates which are becoming the primary target in deepwater drilling. This has led to research projects and PhD studies in Brazil and abroad. Again, the company and several of the exploration partners are applying the best technologies available in order to fully unlock the production capacity of these carbonate (microbialites) rocks."

Webster's own experience at Petrobras reflects the company's philosophy of applying the 'best' science available to their producing basins. He started out in the 1980s working on a project aimed at analyzing the factors that controlled the occurrence of hydrocarbons in the Campos Basin. "We investigated why this relatively small basin was so prolific when compared to other basins," says Webster. "The answers started to appear by integrating all the data. This basin has a very rich source rock, an evaporite layer that created both seals and windows for migration from the pre-salt source rocks, and a Late Cretaceous to Tertiary uplift forming coastal mountains, the erosion of which deposited widespread turbidites into the deep waters of the basin."

At this time, Giuseppe Baccocoli (see *GEO ExPro* Vol. 5, No. 4), a senior Petrobras geologist renowned for early studies in the Campos Basin that led to the first commercial discovery in that basin, inspired Webster to learn more about the salt layer and its deformation. Webster was asked to analyze one of the first AAPG volumes on salt diapirs in the Gulf of Mexico. This seeded a particular interest in his career, which was devoted to understanding salt tectonics in the Campos Basin.

Webster furthered his research and understanding of continental margins with Petrobras in the early 1990s by participating in the Cabo Frio Project. "This would be the first project to integrate the regional datasets from the southern Campos and northern Santos basins," Webster explains. "We identified the Cabo Frio fault zone that extends from the central Santos Basin into the Campos Basin. The fault zone is a major antithetic fault that is associated with salt flowing basinwards above a regional high. This created one of the largest structures in the South Atlantic, 'the Albian gap,' a region devoid of the Albian carbonates. The study was presented at an international conference on salt tectonics, in Bath, England, in 1993. Specialists were amazed with that intriguing structure and the paper is still considered one of the landmarks on salt tectonics. As a matter of fact, several research institutions worldwide have tried to simulate physically and numerically the development of that structure."

Another example of 'applying the best science' occurred at a meeting in Houston in the early 1990s, the GCSSEPM conference 'Salt, Sediment and Hydrocarbons.' Webster attended the presentation on the Mahogany discovery in the Gulf of Mexico, the first sub-salt commercial find. "This made us wonder if we had similar structures offshore Brazil," Webster recalls. "We came away from the conference analyzing some deep blocks in the Espirito Santo Basin. Several years later we interpreted an allochthonous salt tongue with possible Tertiary reservoirs below the Aptian salt, which we called a sub-salt play. Similar structures have proven productive off Africa and, who knows, we may find out in the coming years if the structures off our coast will bear hydrocarbons as well. This is just one more example of how regional studies and analogs from different areas can be used for exploring less known or even frontier regions elsewhere in the world."

Webster participating in field studies on an island off the Espirito Santo Basin (Abrolhos region), where he freely shares his knowledge of, and learns more about, the tectonics of continental margins.

Webster Mohriak

International Focus

Since his recent retirement from Petrobras in 2011, as a consultant Webster has continued to apply his vast knowledge of continental margin geology to places like the Solimões Basin in the upper Amazon region of Brazil and to new exploration off the coast of Namibia, West Africa. "I am working to integrate datasets in order to propose viable models for future prospects," says Webster. "We [geoscientists at HRT Oil & Gas] are fine tuning our structural models for known fields to be used as analogs for structures to be drilled. One of those, the Castanheira prospect, resulted in one of the best gas discoveries in the Solimões Basin."

He is also pursuing more academic collaboration by contributing as one of the editors and co-authors in a book that will be published by the Geological Society of London in 2013, *Conjugate Divergent Margins*. In one chapter in the publication, Webster and his co-author make comparisons between the Red Sea-Gulf of Aden and the South Atlantic.

I finally met Webster in 2012 at the most recent Perkins Conference in Houston, entitled *New Understanding of the Petroleum Systems of Continental Margins of the World.* He was certainly in his element, conversing with experts who study the continental margins of the Gulf of Mexico, Australia and New Zealand, South America, Africa, Europe and Asia. Our interview was punctuated by interruptions from other well-wishing geoscientists. It was clear Webster's focus for the future is to expand the existing knowledge of basins and their petroleum systems around the world and encourage mutual collaboration. He truly believes that: "Allowing university geoscience students to work with Brazilian datasets as well as data from the West African margin and ongoing projects involving international teams with specialists from Germany, England, United States and many other countries, will result in a better understanding of the petroleum systems for the rift basins. This and future cooperative efforts will usher in a new stage of exploration when the concepts developed in one segment of the margin can be immediately applied to other segments across an ocean." ■

A Simple Guide to Seismic Inversion

ASHLEY FRANCIS ● Earthworks Reservoir

Seismic inversion is a complex topic with many different methods. This can make it confusing for the non-specialist to understand the various flavors of seismic inversion and choose the most appropriate tool for a particular interpretation task

Seismic inversion is essentially a very simple procedure. In a seismic inversion the original reflectivity data as typically recorded routinely is converted from an interface property (i.e. a reflection) to a rock property known as impedance, which itself is the multiplication of sonic velocity and bulk density. In a conventional seismic reflectivity section the strong amplitudes are associated with the boundaries between geological formations, such as the top reservoir. This type of data is most suited to structural interpretation. In an inverted dataset the amplitudes are now describing the internal rock properties, such as lithology type, porosity or the fluid type in the rocks (brine or hydrocarbons). Inverted data is ideal for stratigraphic interpretation and reservoir characterization.

Figure 1: *Conventional seismic reflection data (top) compared with colored impedance data (bottom). The sand intervals are shown as the blue/purple colors.*

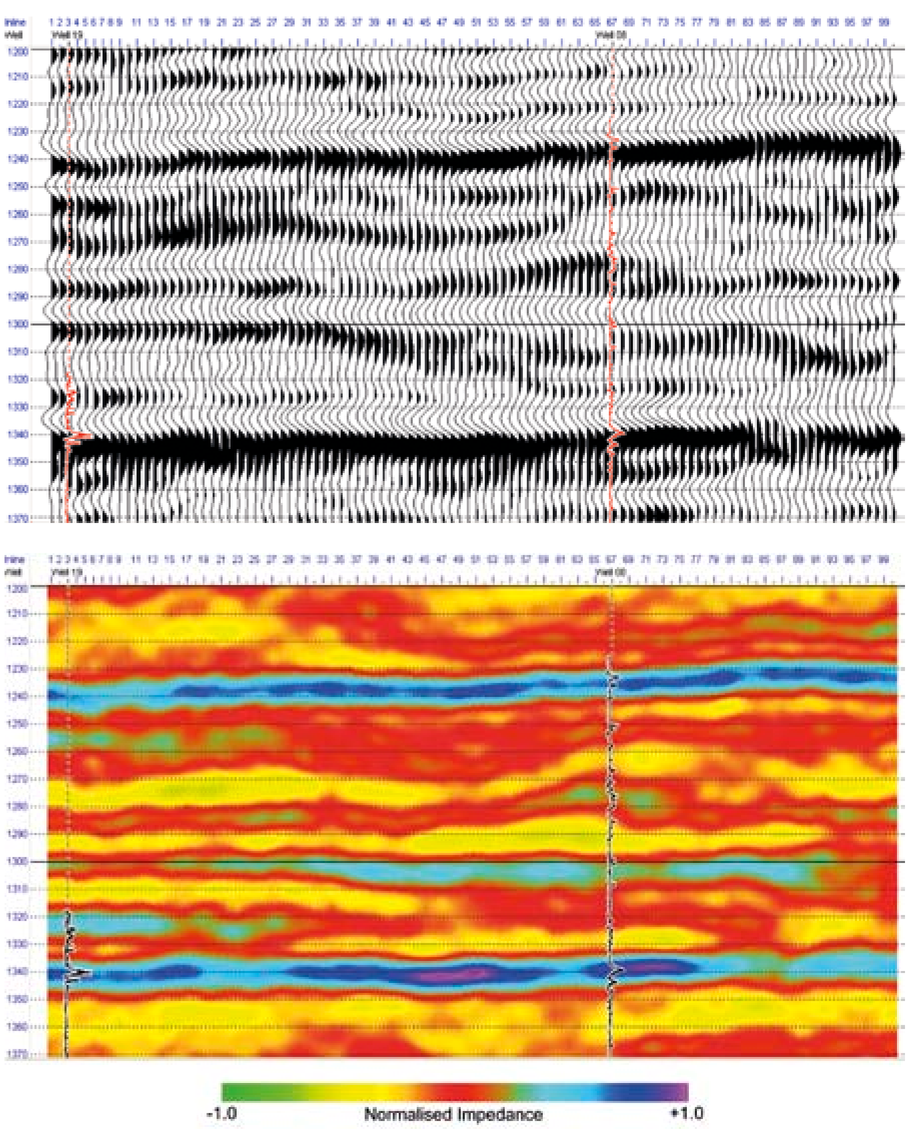


Figure 1 compares a conventional seismic reflectivity section with the simplest form of inversion, known as a relative impedance, which is directly estimated from the seismic with no model inputs and so is a robust and reliable seismic property. This particular example uses a method developed by BP known as colored inversion, which is the best type of relative impedance currently available.

One feature of a relative inversion such as colored inversion is that the data is trendless. For example, because porosity decreases with depth we would expect impedance to increase with depth as the geological formations become harder and faster with compaction. However, a relative impedance seismic volume is trendless both vertically and laterally, because trends are by definition very low frequency features of the data and seismic does not record very low frequencies. Therefore an important rule to understand about relative impedance is that it does not inform us about trends.

Deterministic Inversion

In a deterministic inversion the missing low frequency is introduced to the inversion, thus giving the appearance of trends. However, in effect, the missing low frequency trend is simply modeled and added to the relative impedance result, so a deterministic inversion is really just a modeled trend plus a relative impedance. The result can look like it has strong vertical and lateral trends present but great care must be taken when interpreting this data because these trends are not from seismic reflections but are from a smoothly interpreted model.

A demonstration of the influence of the model is shown in Figure 2. You will note that the deterministic inversion without model is essentially identical to the relative inversion, hence the general statement that deterministic inversion = relative inversion + model.

Although great care must be taken in interpreting trends from deterministic inversion, if the model is carefully constructed and if the seismic response is comprised of strong amplitudes at the target reservoir then a deterministic inversion may be used for mapping and lateral prediction. Some examples of mapping porosity in this way are illustrated in Figure 3.

Simultaneous Inversion

Pre-stack seismic data contains additional information about the rock properties of the earth and these can be inverted for, using several different methods. A common one is simultaneous pre-stack inversion, a form of seismic inversion which inverts for several rock property parameters simultaneously using the pre-stack gather (or partial stacking of this data, such as angle stacks). Usually simultaneous pre-stack inversion is a deterministic inversion, so as noted above great care must be taken with the results to ensure that what is interpreted is seismic data and not the model. After pre-stack simultaneous inversion it is often safer to filter the model out of the results using a high pass filter.

If sufficient angle ranges in the seismic gathers have been successfully processed then it may be possible to invert seismic data for three properties, sometimes called three-term inversion. This requires good quality seismic including processed angles above 40° and is not always possible. More commonly and very routinely seismic is inverted using a two-term approach, which is quite reliable and possible with most seismic reflection datasets where pre-stack data is available. This method of inversion gives two output rock properties, typically P-wave (sonic) impedance and S-wave impedance. These can be combined to create two further properties known as lambda-rho and mu-rho. In general P-wave impedance (IP) and lambda-rho properties inform us about pore space effects such as porosity and hydrocarbons (presence or saturation). S-wave impedance (SI) and mu-rho inform us about lithology with the effects of the pore space and fluids removed. By comparing a rock property anomaly between each type of output it is possible to get a better understanding as to whether the anomaly may be caused by porosity/saturation changes or by lithology changes.

If three-term inversion is possible then the result will be sonic, shear and density parameters. These are usually in the form of P-wave (sonic) impedance, S-wave impedance and bulk density. The additional bulk density term is quite difficult to invert for from seismic as its contribution to the overall seismic amplitude is small and only present on large angles (greater than 40°).

Seismic inversion results are very often calibrated to some other rock property. The calibration can be after the inversion, for example to convert a seismic property to estimate porosity. An example is shown in Figure 3 of a stratigraphic horizon slice from a deterministic seismic inversion, calibrated to porosity. Two different stratigraphic levels are shown, with red corresponding to high porosity. Although this is a good quality inversion and is controlled by many wells, we should note it is a deterministic inversion and so care should be taken not to over-interpret trends which may be coming from the imposed model and not the seismic data. One way to guard against this problem is to request the model to be supplied with the final deterministic inversion and check that the trends interpreted are not artefacts from the model building.

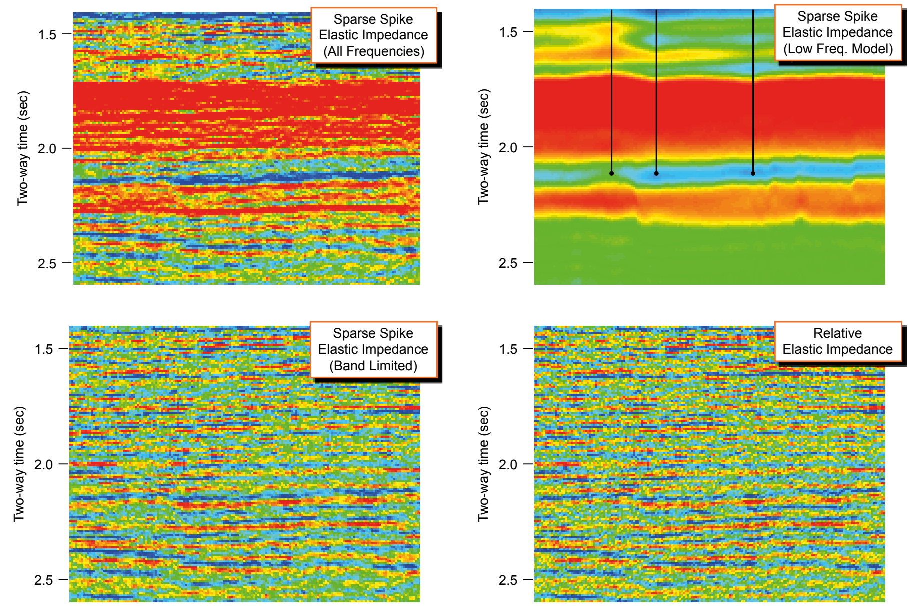
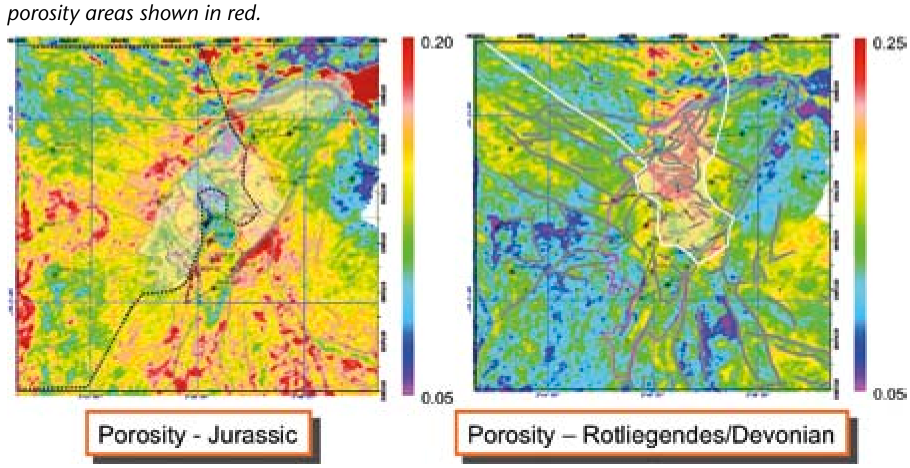


Figure 2: *Top left panel is the result of a deterministic inversion, while top right shows the low frequency model used to create the deterministic inversion. The lower left panel shows the deterministic inversion after the model has been removed and the lower right panel shows the relative inversion only of the original seismic. Note that the deterministic inversion without model (lower left) is essentially identical to the relative inversion (lower right)*

Figure 3: *Stratigraphic slices through a deterministic inversion result calibrated to porosity. Good porosity areas shown in red.*



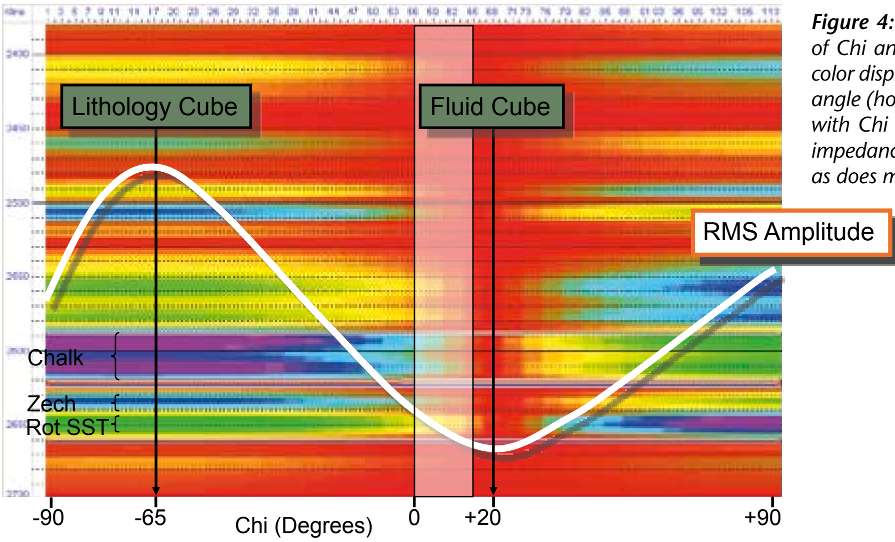


Figure 4: A modeled example of EEI impedance as a function of Chi angle using well logs. The vertical axis is time and the color display is of the relative impedance as a function of the Chi angle (horizontal axis). Note how the amplitude strength varies with Chi angle. Zero Chi angle corresponds to P-wave (sonic) impedance and around -45° corresponds to S-wave impedance, as does mu-rho. Lambda-rho is typically about +30°.

EEI Inversion

It is also possible to perform a type of calibration before inversion. This is where the pre-stack data is combined to create new seismic properties which are most closely related to properties such as petrophysical quantities like porosity or shale volume. A robust and natural way to achieve this is to use a method called Extended Elastic Impedance or EEI, again invented by BP. An extended elastic impedance uses the angle gather information (the same information required by a pre-stack simultaneous inversion) and projects the data across new angles using standard AVO intercept and gradient analysis. The new angles required as output are chosen to correspond to rock or petrophysical quantities of interest, such as porosity or shale volume, usually by analyzing well log data. EEI uses a special angle term called Chi which can have a continuous projected range from -90° to +90°.

A modeled example using well logs is shown in Figure 4. The beauty of EEI is that it gives a continuous range of possibilities from 90° to +90°, not just properties that correspond to geophysical parameters such as the ones described above. This makes it possible to select a seismic property volume for a Chi angle that corresponds to a petrophysical quantity such as shale volume, making the result much more interpreter friendly. Alternatively, two characteristic angles can be found for seismic datasets, one of which corresponds to the Chi angle at which the largest amplitudes occur and is referred to as the 'lithology cube' and one at the Chi angle associated with the minimum angles. This is often called the 'fluid cube', although a better description would be the 'pore space cube' as it is generally sensitive to both fluid types and porosity.

EEI results are often presented as relative or colored impedance, and can also be output as a deterministic inversion.

Inversion and Reservoir Modeling

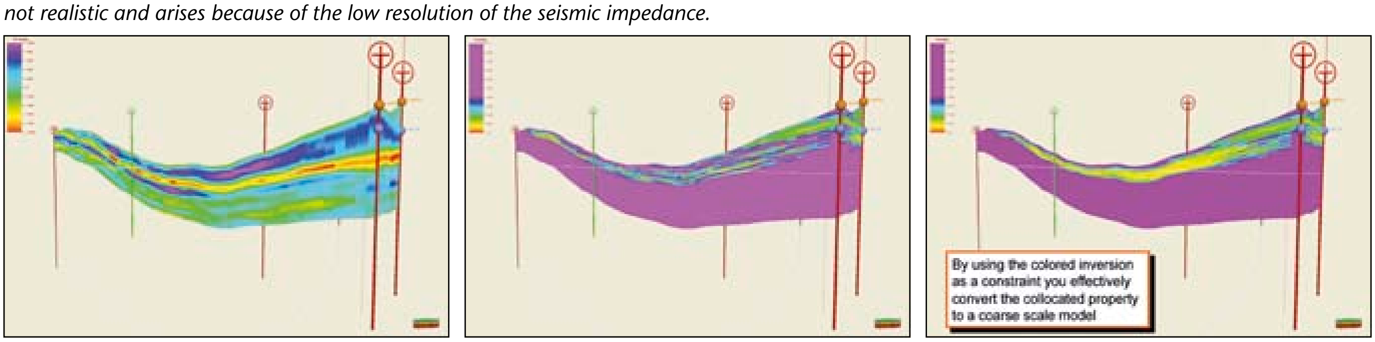
Seismic inversion output is quite attractive for guiding the mapping of properties like facies distribution or porosity in reservoir modeling. However, great care should be taken in using inversion data in this way.

One problem is the effect of seismic 'tuning', where the amplitudes of the inversion respond not just to the rock properties but also to the thickness of the bed. If the thickness is close to the 'tuning' frequency of that particular seismic then the amplitude can appear much brighter than it really is, possibly causing thickness changes in the beds to be misinterpreted as rock property changes. This problem affects relative and colored inversion. It is sometimes claimed that deterministic inversion removes the effects of tuning, but in general this is not the case. Tuning effects must be removed before inversion data can be used in reservoir models.

A second problem with using seismic inversion data in reservoir modeling is the large difference in vertical resolution between the model and the seismic impedance. A model typically has a vertical cell resolution of 1m, but seismic inversion is more typically a vertical resolution of 20m. Constraining the reservoir property at 1m scale to a seismic property at 20m scale is incorrect and can lead to poor models which can give misleading fluid flow characteristics. An example of this is shown in Figure 5.

An additional problem is the model in a deterministic inversion. If this model is left in the seismic property used to map

Figure 5: In the left panel a seismic colored impedance is displayed in the reservoir model cells. In the middle panel the shale volume property has been simulated in the model using only the wells – note the detail in the layering. In the right panel the shale volume has been simulated in the model using the wells and the seismic impedance from the top left panel. Note how the good reservoir (not purple) is smooth and strongly connected. This is probably not realistic and arises because of the low resolution of the seismic impedance.



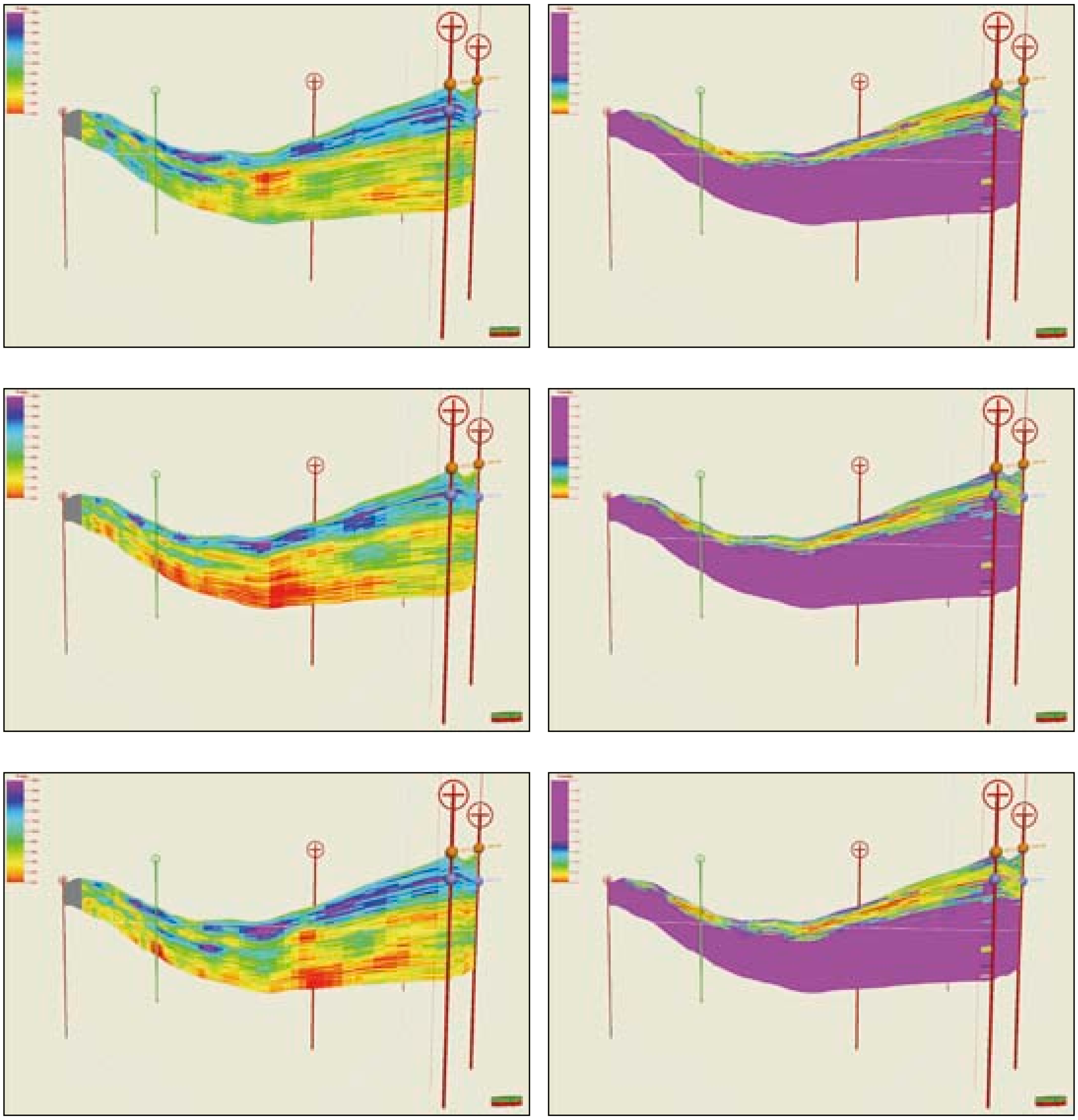


Figure 6: The left panels are different geostatistical realizations of impedance generated from a stochastic inversion. The differences between these realizations highlights the uncertainty in a seismic inversion that is modeled in a stochastic inversion. Note also how much more detailed and realistic they are than the smooth colored impedance result shown in the left panel of Figure 5. On the right are shale volume simulations in the reservoir model, each constrained by the stochastic inversion realization to its left.

properties in a reservoir model, then we are in danger of making our reservoir model follow the trends of another model we have created! This is clearly a serious problem and so the model part should be removed from a deterministic inversion before it is used in a reservoir model.

Stochastic Inversion

Stochastic inversion (or geostatistical inversion) is the technique of simulating possible rock property models using the seismic. This has many technical advantages for use in reservoir modeling and uncertainty analysis: it removes tuning effects, it models the uncertainty and it can be computed at fine scale; but these advantages must be weighed against its higher cost and the large data quantities that must be managed. A comparison of a stochastic inversion used in a reservoir model is shown in Figure 6.

There are many flavors and variants of seismic inversion and only the most general ones have been compared here. As a quick guide, the following table provides comparison showing the good features (green ticks) and the bad features (red crosses) of the various methods.

For more details see: www.earthworks-reservoir.com ■

	Removes Tuning?	Correct Scale for Reservoir Model?	Low Frequency Model	Uncertainty	Reservoir Connectivity
CI	No - needs correction ×××	No ×××	None ✓	Point Uncertainty Only ✓	No ×××
DI	No – needs correction ×××	No ×××	Model Interpolation ×××	Point Uncertainty Only ✓✓	No ×××
SI	Yes ✓✓✓	Yes ✓✓	Simulated ✓✓✓	Yes ✓✓✓	Yes ✓

From Core to Pore

PAUL WOOD

Advanced technology can now be taken into remote field environments to make lithology description much more detailed and accurate than was possible before

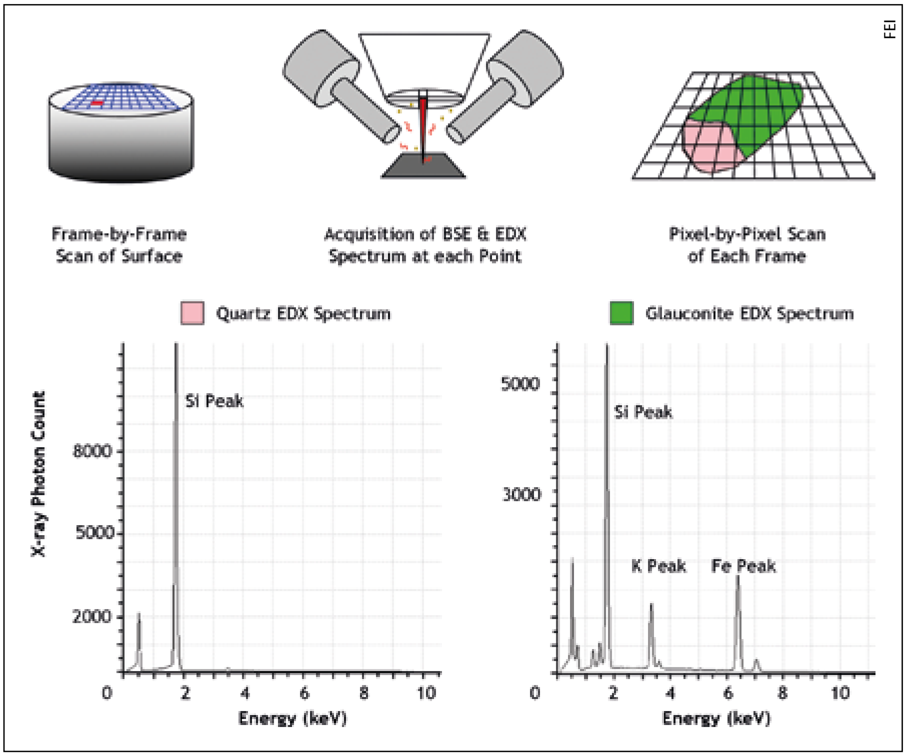
From the early days of hydrocarbon exploration, right up to the present day, the 'traditional' method of finding the geological or stratigraphic position of a well while drilling has been to look at the rock samples or ditch cuttings that come to the surface. Drill bits grind up the rock they are penetrating and the cuttings are carried up by the returning drilling mud. Geologists called mudloggers extract the samples from the shaker tables, the sieves that separate solid particles from the mud, calculate their depth of origin in the well and analyze them under a microscope. From this they can determine the overall mineralogy of the samples and, combined with other data such as the presence of micro-fossils, work out the overall lithology and geological age of the samples.

In many cases, these measurements are supplemented by rock property information from measurement while drilling (MWD). These direct views of the rocks that are being penetrated are often the only way to determine the stratigraphy unless more costly techniques like coring are employed. But there is a limit to the accuracy and detail that can be obtained by looking at the samples under a microscope. The results are also highly dependent on the knowledge and experience of the mudlogger and well site geologist, as they are essentially from visual observation backed up by some basic analysis of the drilling parameters.

The lithology description provided by mudloggers is essential while a well is actually being drilled, but it is often not sufficient to provide the detail of the mineralogy and other rock properties needed by, for example, petrophysicists, geologists and geophysicists studying detailed reservoir behaviour. So the samples from the well site are not discarded, but bagged up and sent to specialist geological laboratories for further analysis. Often, this analysis may be done in great detail, at a submicron level, using a Scanning Electron Microscope (SEM). As well as providing very detailed images, these devices also make other measurements of the samples such as their BSE (back-scattered electron) and characteristic X-ray signals (energy-dispersive X-ray or EDX spectrum). These signals are distinct for different chemical compositions and so can

FEI

The portable scanning electron microscope can be transported to the well on a truck.



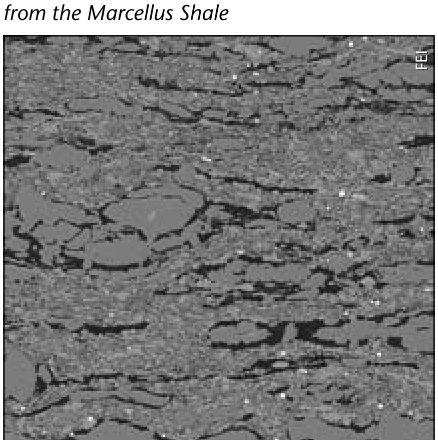
Schematic of the sample measurement process. The electron beam is scanned across the sample surface; at each measurement point (also called a pixel) the BSE and x-ray signals are used for mineral identification by analyzing the EDX spectrum for chemical composition and subsequent classification based on known mineral chemical compositions.

provide the basis for automated and very accurate mineralogy and lithology determinations.

SEM analysis can provide valuable information about rock properties, though in most cases this comes too late to influence operational decisions, as the measurements are made using bulky and sensitive equipment in labs, usually long after drilling is complete. But now it is possible to take a ruggedized SEM to the most remote well locations to provide fast and accurate lithology descriptions while a well is drilling, using a system called QEMSCAN® WellSite™ developed by FEI.

FEI is a leading developer and manufacturer of electron and ion beam microscopes. It has a business unit, 'Natural Resources', that is dedicated to the geoscience sector, including the oil and gas business, and has developed a suite of applications based on an SEM with resolution down to 1 micrometer called QEMSCAN (quantitative scanning electron microscope) which uses a proprietary 'Spectral Analysis Engine'. This 'engine' first analyzes the elemental composition of samples by comparing the measurements to standard reference sets and then uses a statistical analysis method (Species Identification Protocol – SIP) to identify and quantify the mineral composition. This method has proved to be effective in the identification of minerals including clay minerals and is also able to distinguish between, for example, minerals lining pores and intergranular cements.

Scanning Electron Microscope (SEM) image from the Marcellus Shale

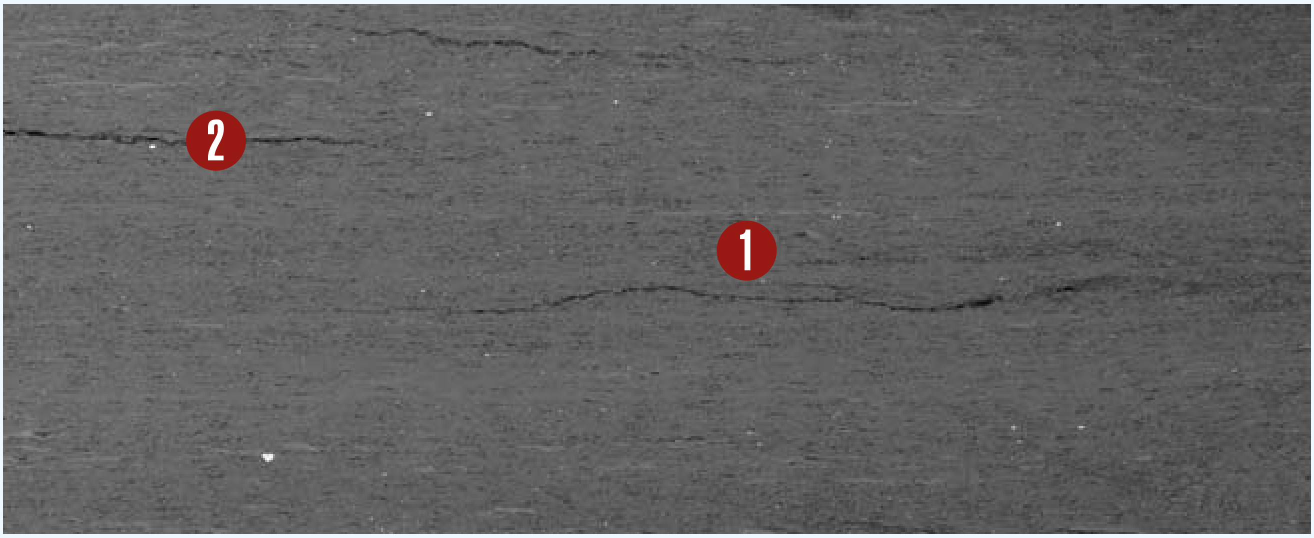


Taking SEM to the Well

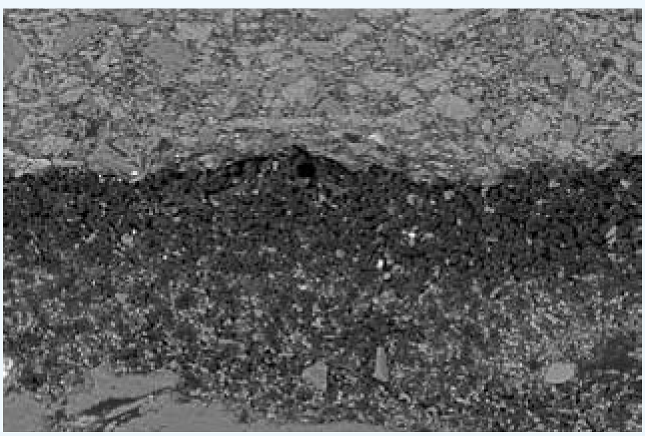
FEI has made a portable version of the QEMSCAN that can be taken to remote locations by helicopter or even on the back of a small pickup truck. A specially optimized sample preparation workflow has also been developed that is suitable for field use, rather than standard SEM techniques that require laboratory conditions. Cuttings samples are sieved to the required size, for example between 2mm and 63 microns, washed and dried with a microwave oven. The samples are mixed with epoxy resin, which is cured into a cylindrical block that is then cut into sections by a diamond saw. The samples are coated with a thin layer of electro-conductive carbon to prevent charging by the electron beam of the microscope. Each sample section is scanned by the microscope on a grid at a rate of up to 200 measurements per second, building up, over a measurement time of some 30 minutes, about 400,000 measured points per set of samples.

Data processing on the measurements using the Spectral Analysis Engine and SIP method then takes place offline and produces images of the results together with a detailed mineralogy log and lithology log based on standard classifications. One of the advantages of this QEMSCAN WellSite system is that it can identify and remove the effects of contaminant and additive particles automatically so that the results are based only on genuine geological samples. In a field test conducted recently in a remote location in Papua New Guinea, the system was able to keep up with drilling, averaging 23 sample sets a day, with the most continuous run being 728 samples in 34 days.

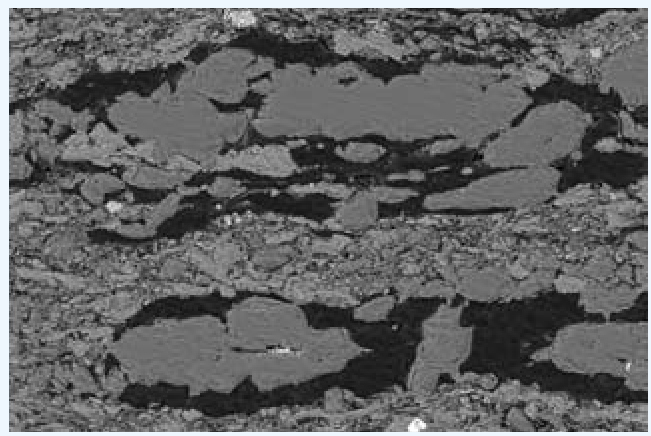
Wet cuttings sample, direct from a shale shaker, with a resin impregnated block of the same sample for comparison.



0.7 inch (ca. 1.7 cm) wide core sample of Marcellus shale. This image consists of 585 SEM images and is about 31 gigabytes in total.



1 (zoomed in) matrix of clays, quartz and calcite with non-porous organics.



2 (zoomed in) fractured organics observed in one of the fractures.

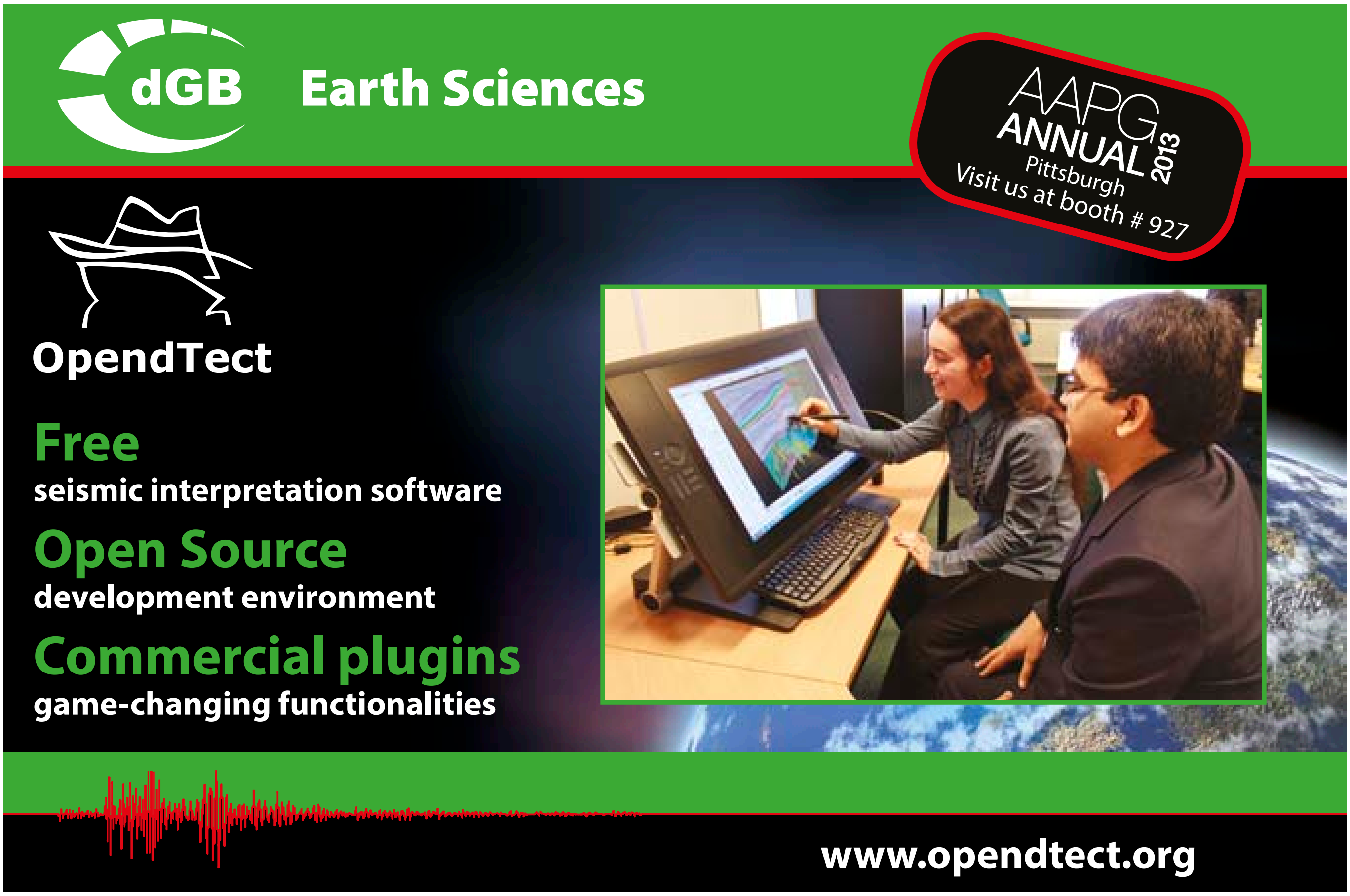
MAPS Tiling and Stitching allows users to look at the whole fabric picture (top image), or zoom in to look at the detail of specific areas (bottom images).

Nanoscale Resolution

The concept of taking a scanning electron microscope into remote field locations and producing a detailed mineralogy log in real time is certainly impressive. But there are situations where even micron-scale resolution is not enough. These may be when analyzing unconventional 'tight' reservoirs such as the Marcellus Shale in the north-eastern US. Here, to achieve resolution down to a few nanometers, which is necessary to look at detailed 3D pore geometry and the fine details of mineralogy, new high resolution microscopes such as Field Emission or Focused Ion Beam Scanning Electron Microscopes (FEG-SEM and FIB/SEM) are required. FEI manufactures these devices too, with the FIB/SEM technology produced under the name DualBeam™.

These complex devices are still for laboratory, not field work. But in looking at the results, FEI also addresses the problem of how to go back to the basics of a representative wellsite core from an image that may be only 10 microns across. When analyzing such data, perhaps ten images may be chosen at random, but it is difficult to see that these minute samples provide a representative view of the rock fabric. The company has developed automatic SEM imaging software called MAPS Tiling and Stitching. Thousands of DualBeam images of a sample (each image of maybe 4,000 x 4,000 pixels) are acquired over a period of several days in an automated and unattended process. As many as 10,000 such 'tiles' are then 'stitched' together by the software to provide, for example, a 400,000 x 400,000 pixel image that may comprise tens of gigabytes. Viewing software then allows the user to zoom in and out, looking at individual detail or the whole fabric picture. The images can also be compared and overlain with images from larger scale methods, such as the QEMSCAN mineral maps.

FEI is principally a specialist microscope manufacturer. By addressing the needs of the oil and gas business with a dedicated natural resources business unit, the company has been able to take advanced technology, hitherto reserved for the lab, into remote field environments to make lithology description much more detailed and accurate than was possible before. With specific solutions aimed at unconventional reservoirs, FEI is able to extend geological analysis from core to pore at the finest detail required today. ■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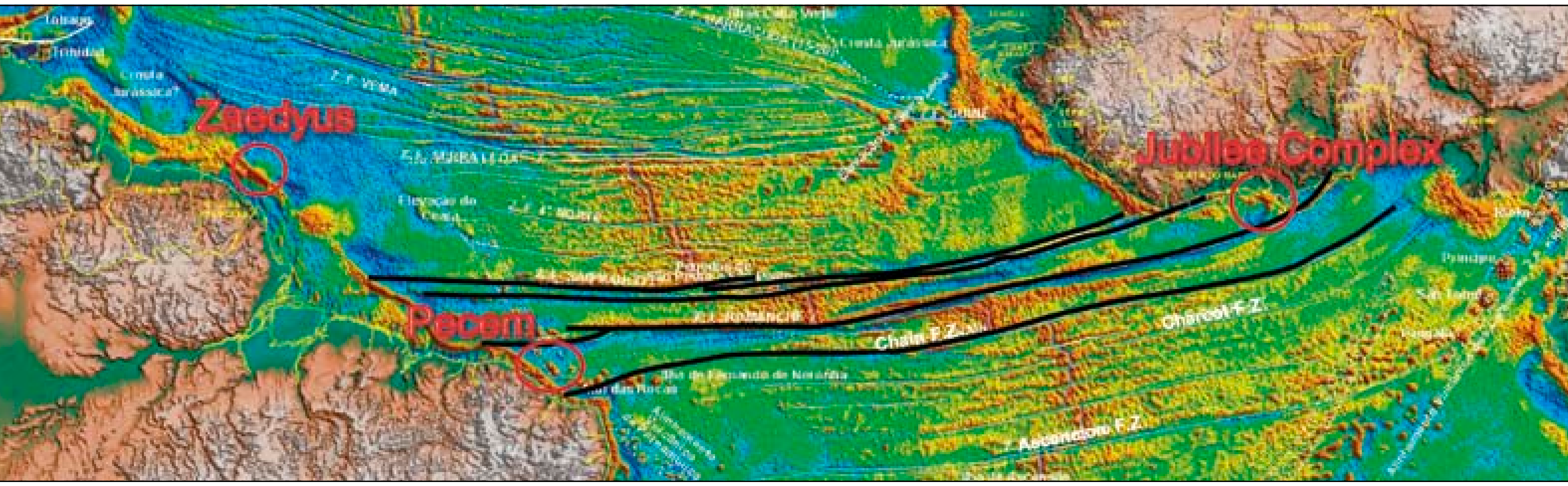
New Deepwater Frontiers an Ocean Apart

Large oil finds in the African Equatorial Margin have led to recent oil discoveries along the South American Equatorial Margin. Similar geologic and geochemical characteristics suggest analogous petroleum systems with enormous potential in both conjugate margins.



MARCIO ROCHA MELLO, NILO CHAGAS AZAMBUJA FILHO, ANDRÉ BENDER, HRT Oil & Gas
SILVANA MARIA BARBANTI, TIKAE TAKAKI, IPEX
CARLOS ALBERTO FONTES, GeoHub
WEBSTER MOHRIAK, Consultant, WMGC

Topographical-bathymetric map of the South Atlantic Equatorial Transform Margin. The major transform fault zones that offset the oceanic spreading centers are shown in black. Recent deepwater discoveries include Jubilee in the Tano Basin offshore Ghana, Zaedyus in the Guyane Maritime Block offshore French Guiana, and Pecem in the Ceará Basin offshore Brazil.

The South Atlantic Equatorial Margin represents new, deepwater exploration frontiers. The 2007 Tullow Oil discovery of the **Jubilee** Field off the West African margin, located 60 km offshore Ghana in 1,100m of water, was the first for the region. The first oil was produced in December 2010 from recoverable reserves estimated to be over 600 MMbo. In the area that was once connected to the equatorial West African margin, but is now separated by the Atlantic Ocean, two discoveries have been recently announced. In 2011, Tullow Oil, drilling to test a 'Jubilee play' on the other side of the South Atlantic, announced that their **Zaedyus** well encountered 72m net oil pay in turbidite sandstones. Petrobras and BP announced the discovery of oil from the Ceará Basin **Pecem** well in 2012, which encountered 140m of net pay 76 km off Brazil's coast in 2,129m water.

These three discoveries have characteristic tectono-stratigraphic evolution, source rock facies and oil types, suggesting that similar petroleum systems may occur across the conjugate margin. By applying, in a paleogeographic context, a unified model for this hydrocarbon province, new geologic details are revealed about these underexplored petroleum systems an ocean apart.

Plate Tectonic Reconstructions

The application of plate tectonics reconstructions aims to restore the basins, now separated by an ocean, to their previous pre-breakup and drift locations.

The Gondwana breakup in the Early Cretaceous (125 Ma), as the South American plate separated from the African plate, resulted in transtensional and transpressional rift basins in the South Atlantic Equatorial Margin. The rifted margins developed continental lakes and fluvial systems, which were infilled with siliciclastic and carbonate rocks. The initial rift phase was followed by a transitional phase of subsidence in the Late Aptian to Early Albian (110 Ma). This was associated with the early stages of oceanic crust formation and seawater ingression which allowed local accumulation of late Aptian evaporites in some basins, such as the Ceará Basin, and a rapid subsequent deepening of the depositional environment. After continental breakup and total separation of the plates by inception of oceanic crust in the Late Albian (100 Ma), the deepening of the sedimentary environment resulted in an oceanic basin influenced by worldwide sea level rises and falls. During the Late Albian to Turonian (Late Cretaceous), organic-rich shales and marls were deposited in maximum sea level-rising episodes that gave origin to the global Oceanic Anoxic Events. By Late Santonian to Early Campanian (85 Ma) the divergent margins were totally separated by the active spreading centers. Previous sedimentary successions were deformed by extensional and compressional forces.

Reservoir Rocks

Erosion of the granites and gneisses from the cratons and from the uplifted rift flanks along the continental margin resulted in deposition of deltaic to shallow marine sands on the platform. Episodes of sea level falls gave rise to the development of erosional incisions of the deltaic and coastal sand deposits stored on the platform and in shallow marine environments. The steep continental slope favored the growth of canyons which acted as pathways for sand-rich turbidite currents and hyperpycnal flows into deepwater marine environments during sea level low-stands. These sands were deposited as amalgamated channel-lobe reservoirs as found in the Jubilee Complex. Similar deposits have also been identified near the French Guiana/Amazon Cone area, as testified by the Zaedyus discovery.

During the deposition of these turbidites, sea bottom topography played a significant role in creating important sedimentary facies variations. These are characterized by onlap and pinch-out seismic features, especially when associated with structural highs in the transition from distal rift border to oceanic crust. The facies variations of the sand-prone stratigraphic sequences resulted in stratigraphic plays which have been successfully tested in West Africa, particularly in the Tano Basin, Ghana, and more recently at the Zaedyus discovery off French Guiana.

Source Rocks and Oil Types

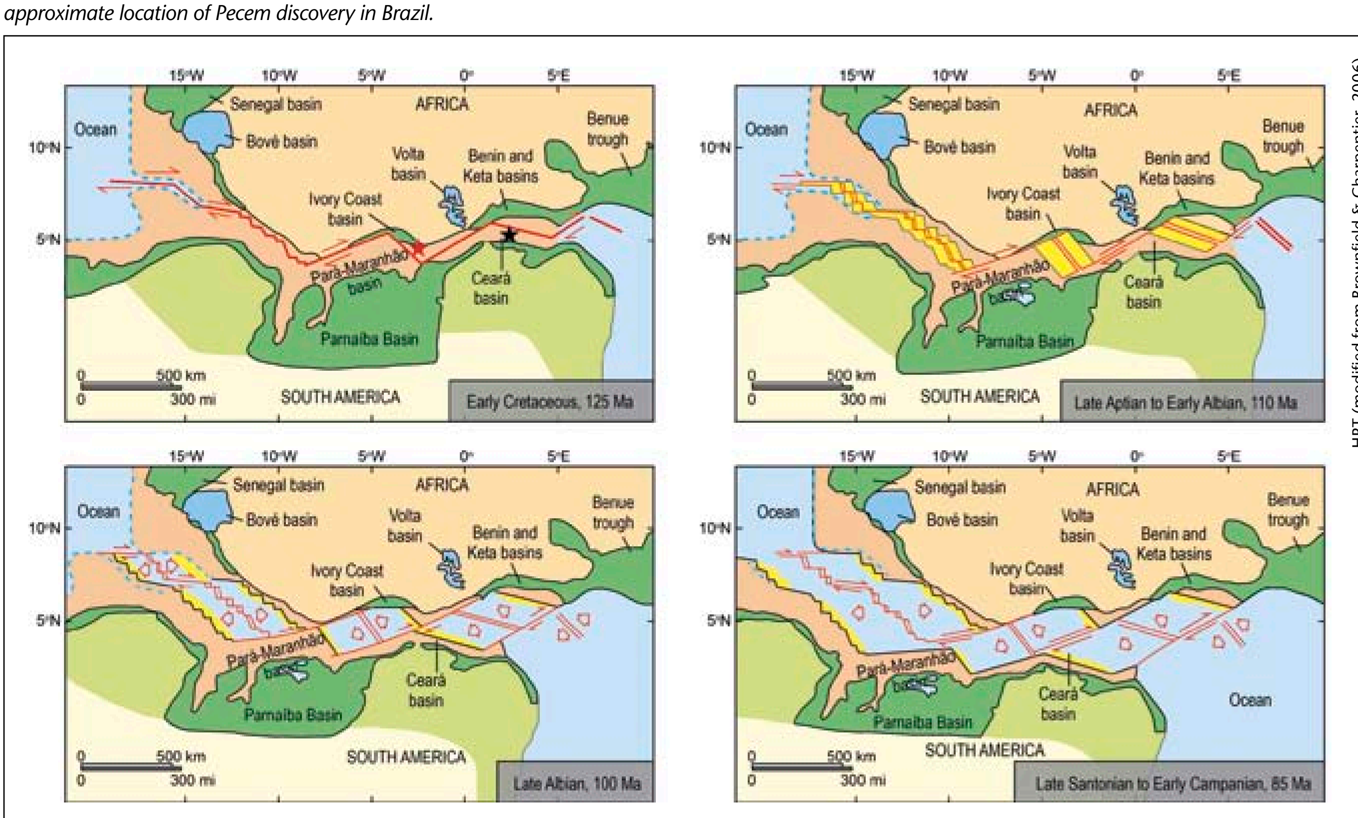
Based on analysis and studies of oils recovered from exploratory boreholes offshore of the Brazilian Equatorial Margin undertaken by the Integrated Petroleum Expertise Company, (IPEX), Brazil, four separate petroleum systems have been identified using biological markers and high resolution geochemical technologies. This advanced geochemical approach aims to refine the play analysis based on geological and geophysical interpretation.

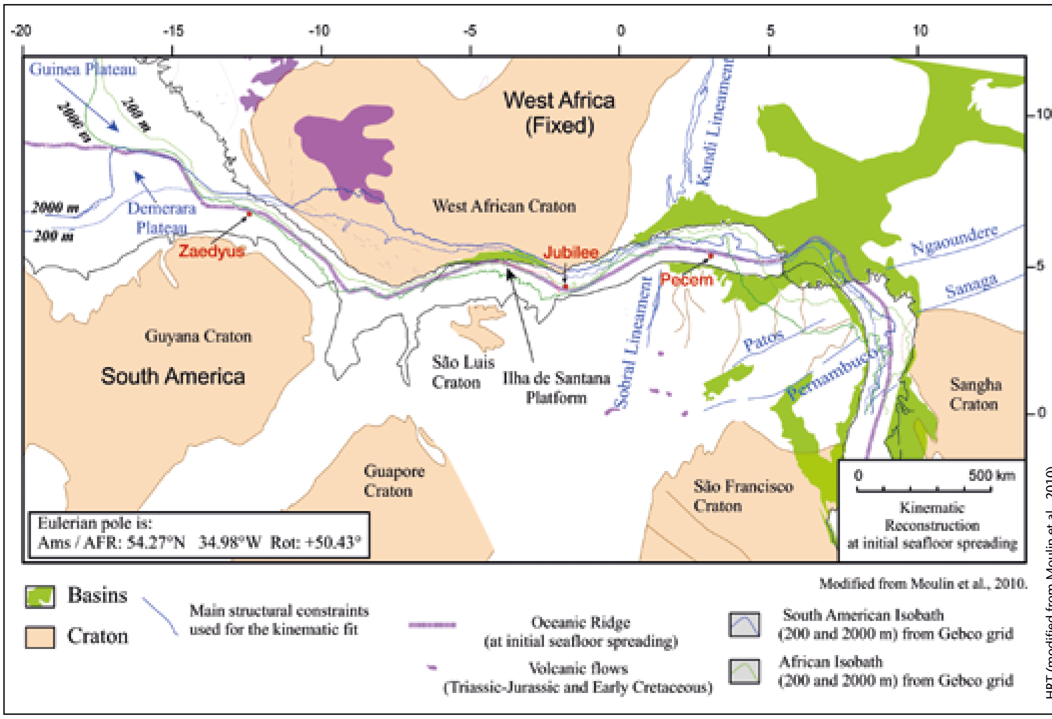
The oldest oil system is characterized by highly cracked, very mature oils and condensates sourced by a saline to alkaline, calcareous black shale deposited in a lacustrine brackish to saline anoxic environment. This Aptian/Barremian petroleum system is responsible for 90% of the oil generated offshore Brazil. Late Aptian salt plays an important role as well and has been identified in the most important producing basins on both sides of the Atlantic.

The second oil system is characterized by transitional environments, as found in the Ceará and Potiguar Basins, with the Late Aptian source rocks in the early to peak oil window stage. Most of the Equatorial Brazilian and West African transform continental margin basins are characterized by lack of massive salt in the transition from continental to marine environments. However, the exception may be Ceará Basin, where a few boreholes encountered evaporites in the Late Aptian stratigraphic interval, indicating a restricted depositional environment. Moreover, geochemical data from hydrocarbons recovered from oil fields in the Ceará and Potiguar Basins in northern Brazil indicate the presence of oil types similar to the ones that are present in the salt basins south of the equatorial transform fault zones. Consequently, the transform margin basins may share similar source rock systems.

The third petroleum system consists of Albian/Cenomanian/Turonian marine black shales, which are a major source for

Equatorial Atlantic Margin: plate reconstruction of sedimentary basins from rift to drift. Red star: approximate location of Jubilee Field in Africa; Black star: approximate location of Pecem discovery in Brazil.





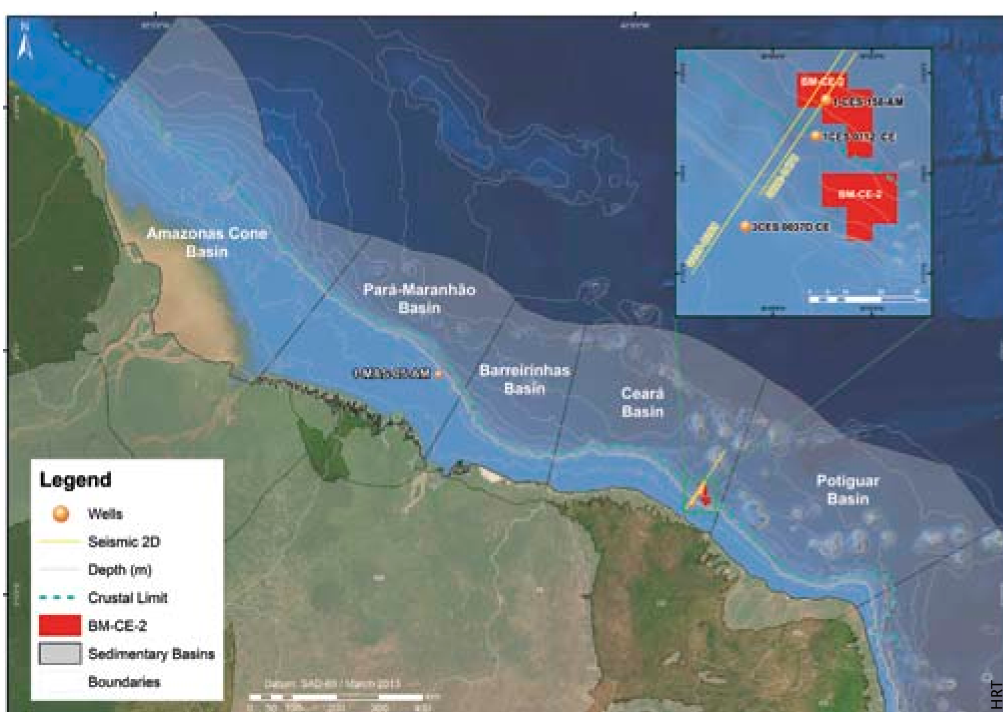
Reconstruction of the plates to pre-breakup stage indicates that the Jubilee discovery in the Tano Basin correlates with the segment of the Brazilian margin located eastwards of the Ilha de Santana platform. The Zaedyus discovery offshore French Guiana is located in the segment of the margin facing the Guyana and West African cratons, west of the Amazon Cone. Both discoveries have sand-rich Upper Cretaceous turbidite reservoirs. The Pecem Ceará Basin discovery is related to the late syn-rift Aptian siliciclastic reservoirs, which are equivalent to the reservoirs in small discoveries in the Tano Basin offshore Ghana. The Niger Delta province in West Africa partially overlies the oceanic crust and corresponds to the offshore Ceará/Potiguar Basins on the Brazilian side of the conjugate margin, a region characterized by several seamounts and volcanic plateaus.

the oils in the West African salt basins, particularly in the deepwater settings of the Cabinda region, Angola. Similar oils have also been registered in the Amazonas Cone and Pará-Maranhão basins, and recently in five ultra-deep water discoveries in the Sergipe Basin. The oils in the Jubilee Complex are also sourced by the same marine black shales, deposited in deepwater settings. The origin of the marine hydrocarbons in these areas is related to Late Cretaceous global Oceanic Anoxic Events, which occurred when the two plates were totally separated and the basins were influenced by worldwide sea level rises and falls.

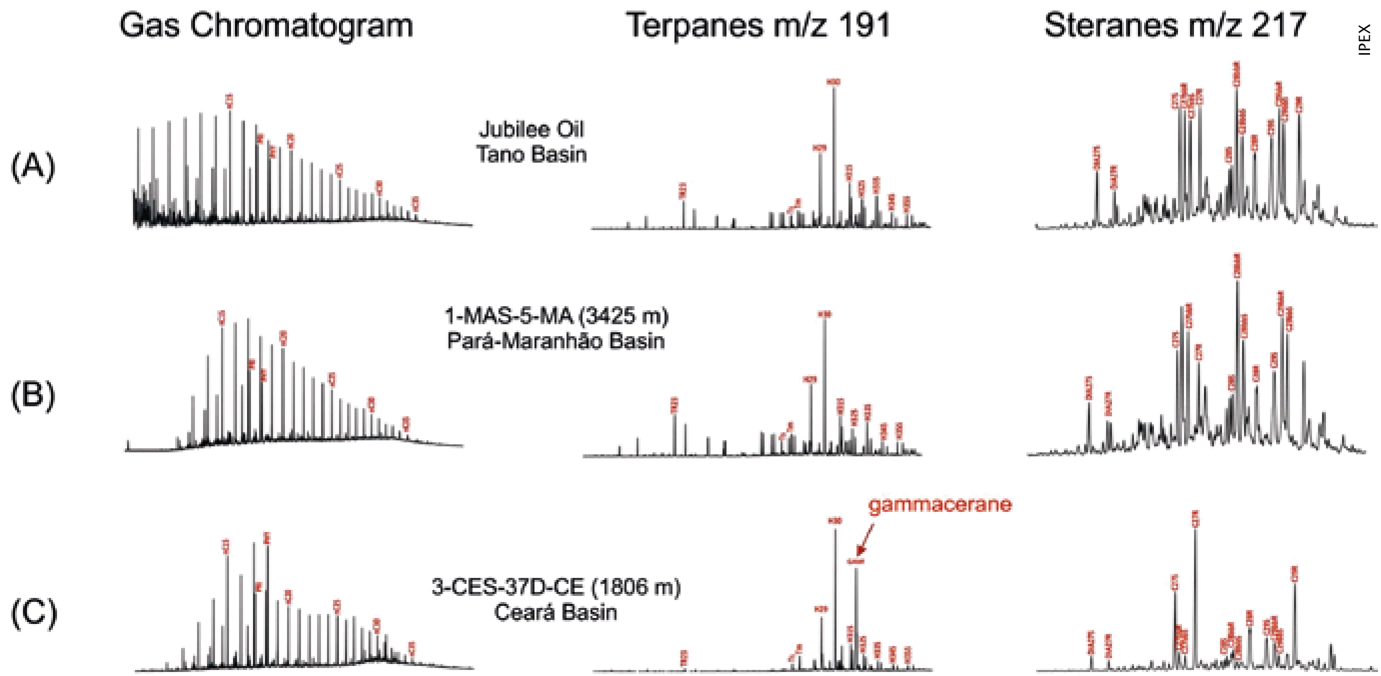
The fourth petroleum system consists of Tertiary source rocks that occur in deltaic environments in the Pará-Maranhão Basin. The 1-PAS-9 and 1-PAS-11 sub-commercial discoveries, as well as the gas accumulations in a number of wells drilled in the past decades, were sourced by these Tertiary source systems.

The geochemical components of the oils analyzed suggest that the lacustrine and marine source rocks which are extremely prolific in the Brazilian margin north of the Florianópolis Fracture Zone/Rio Grande Rise (Santos and Campos Basins) and north of the Walvis Ridge in West Africa (Namibe and Kwanza Basins), also occur in the South Atlantic Equatorial Transform Margin. The oil discovered in the Pecem well indicates a transitional environment source but could also include contribution from the same Albian-Cenomanian source rock system present in the equatorial margin of West Africa.

The implication is that simply matching recent discoveries in the conjugate margin basins, for example the Tano Basin offshore Ghana with the Ceará Basin in northern Brazil, does not necessarily yield the entire story. There is a great deal of contrasting sedimentary and structural development peculiarities from basin to basin and margin



Regional map of the Brazilian Equatorial Margin showing the primary sedimentary basins. The recent Pecem discovery in the deepwater Block BM-CE-2 of the Ceará Basin is shown in red. The location of the seismic profiles on page 62 are shown in yellow.



Detailed geochemical characterizations, including gas chromatography-whole oil and biomarker profiles, of three oils recovered in the South Atlantic Equatorial Margin, conducted by IPEX. The oils from the Jubilee Field and from the Pará-Maranhão Basin are very similar, suggesting that both were derived mainly from anoxic Late Cretaceous marine shales. The Ceará Basin oil analysis, with the presence of high gammacerane, is very different from the other two. The presence of high concentrations of this biomarker indicates stratification and high salinity, which signals that oils in the shallow water portion of this basin (Xaréu Field) are derived from transitional sequence source rocks rather than the Late Cretaceous marine shales.

to margin. The application of detailed geochemical analyses and integration of geological and geophysical methods can lead to better exploration models for these basins and provide clues on the best strategy for drilling any new prospects identified in the South Atlantic Equatorial Margin.

Offshore Equatorial Brazil

Five large sedimentary basins border the 2,200 km north-eastern Brazilian coastline. The westernmost, the Amazonas Cone Basin, is characterized by a thick Late Tertiary sequence with shale diapirs and thrust faults forming a deepwater gravitational foldbelt. Moving east, the Pará-Maranhão Basin has a thick carbonate platform and foldbelt in the transition from continental to oceanic crust. The Barreirinhas Basin is also characterized by a very thick sedimentary succession and deepwater foldbelts. The Ceará Basin is marked by a thinner Tertiary sedimentary succession but with a thicker syn-rift trough in the platform and deep water. Finally, the Potiguar Basin is characterized by several intrusive and extrusive igneous rocks affecting the sedimentary succession in the platform and in the deep basin. IPEX and Geohub reports indicate that these basins have several elements that point to the potential presence of large hydrocarbon accumulations in areas sourced by local syn-rift and by early post-rift source rock pods, as suggested by high-resolution geochemical evaluations of the margin.

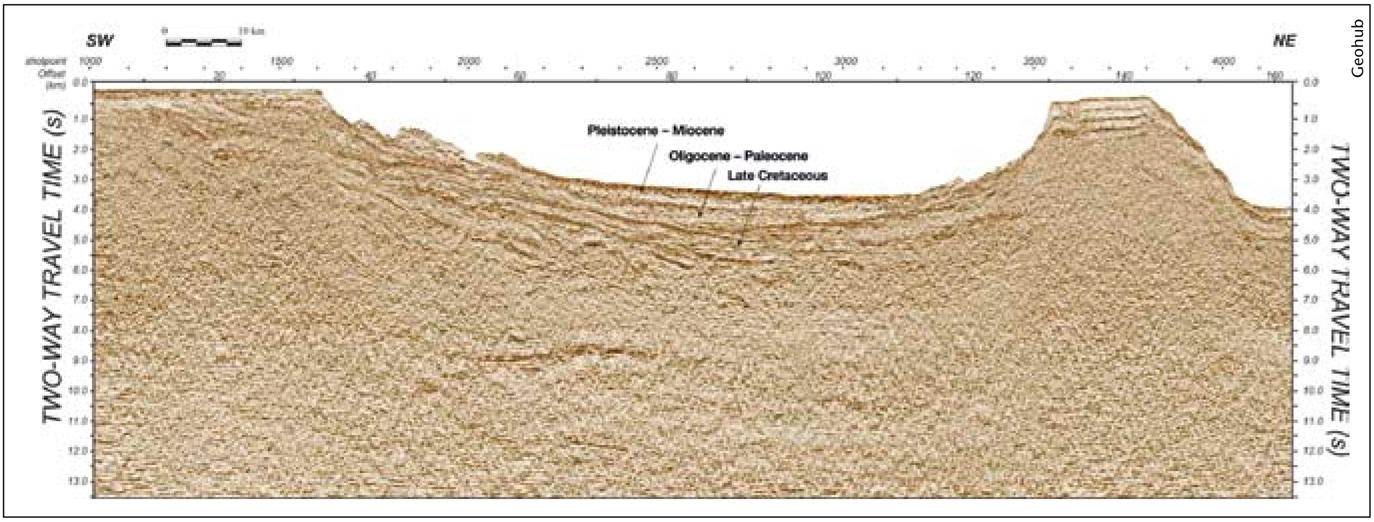
Integrated Approach and Forecasts

Only a few deepwater exploratory wells have been drilled in the South American Equatorial Margin from the Amazonas Cone to the Potiguar Basin. Significant shallow water discoveries have been made in both the Ceará and Potiguar Basins, with the largest oil-producing region in Equatorial Brazil being the onshore portion of the Potiguar Basin. Production is from the syn-rift to transitional successions.

By contrast, the West African Equatorial Margin has been subjected to more intensive exploration activity. This resulted from insightful basin analysis projects conducted by companies such as Kosmos, Tullow and Anadarko, culminating in successful drilling in the deepwater province of the Tano Basin. Mahogany-1, drilled in 2007, was the first borehole to prove oil in the Turonian-age low-stand fans that form stacked reservoirs in the Jubilee Field Complex. Successful exploration concepts derived from these turbidite fans offshore Ghana have been applied to the western extension of the West African Transform Margin. The Late Cretaceous episodes of sea level falls that resulted in development of these reservoirs in the Jubilee Complex were also recognized in seismic profiles in other basins. Several prospects have been successfully tested by exploratory drilling, extending the oil trend from Ghana to the Ivory Coast and Sierra Leone.

The play concept developed in North West Africa was applied in a similar way to the conjugate margin in South America. By extrapolating their interpretations to the opposite side of the ocean, exploration geoscientists have developed prospects in ultra-deepwater settings offshore French Guiana and northern Brazil that shared similar stratigraphic and structural play characteristics with the Jubilee discovery. One of the first tests resulted in the discovery of Zaedyus, which found light oil in Late Cretaceous turbidite reservoirs, duplicating the success story obtained in the African Margin. This prospect successfully tested a genuine frontier region which had no deepwater wells, and confirmed the petroleum systems conjectures developed by the exploration teams.

New and better seismic imaging and

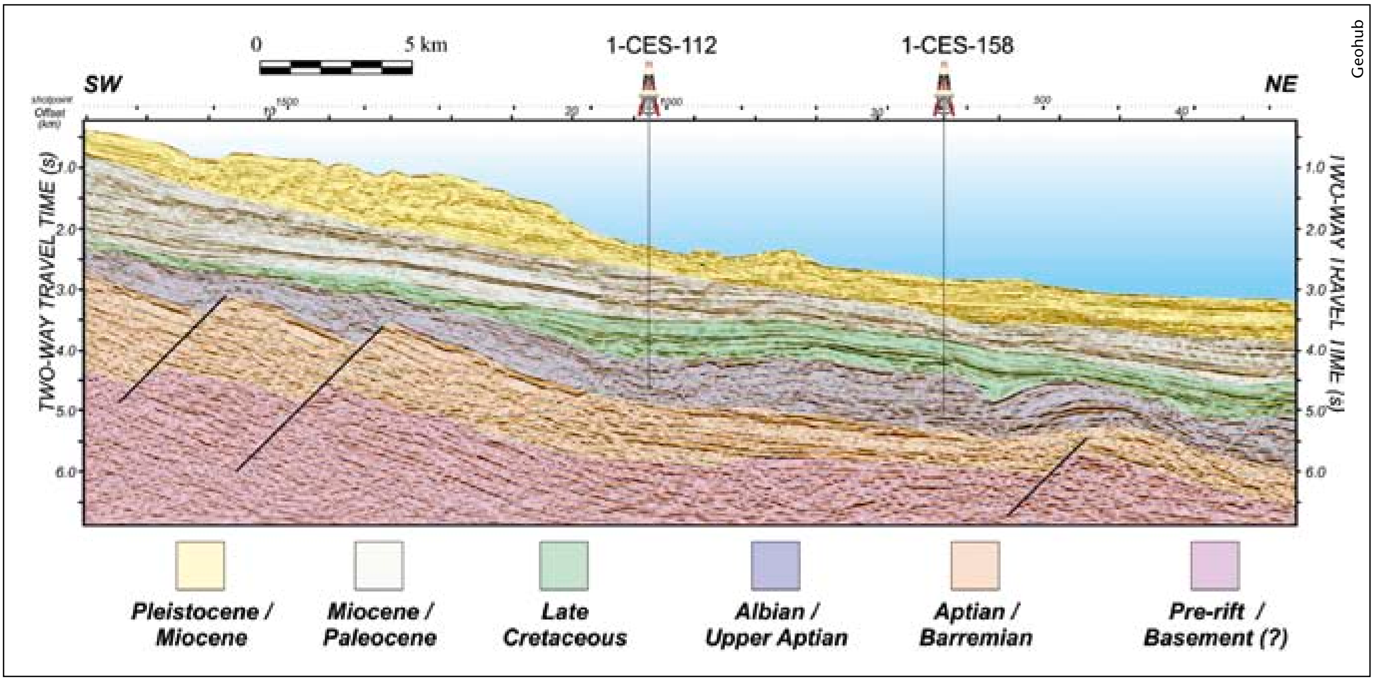


A regional deep seismic profile extending from the Ceará Basin platform toward the oceanic crust, showing a relatively thin Tertiary stratigraphic sequence across the basin, and a much thicker Late Cretaceous succession thickening towards the ultra-deepwater province. Influence of the volcanic seamounts (north-east side of seismic line) developed on oceanic crust is characterized in the Cretaceous to Early Tertiary stratigraphic sequences. The transition from continental to oceanic crust is marked in regional deep seismic profiles by a high-reflectivity zone in the lower crust (8-9 seconds TWTT), suggesting a transition to the upper mantle in a highly-thinned continental crust.

3D visualization software have enabled geoscientists to establish an unprecedented stock of leads and plays yet to be tested for this vast region. The recent successful tests in conjugate margin analogous plays provide the interpretation teams with calibrated results. The new geochemical data analysis and integrated modeling for the ultra-deep areas of the northern Brazilian margin have also resulted in a better evaluation of risks and exploratory criteria for the selection of viable prospects even in lightly explored and remote areas.

The next bid round in the Brazilian Equatorial Margin will be offered by the National Petroleum Agency in May 2013 and will mark a return to this frontier region. Diamondoid and biomarker analyses of oil from the Ceará Basin and from the Jubilee Complex prove that both the transitional and the marine source rocks may reach maturation levels for feeding giant turbidite fans in deepwater settings of the South Atlantic Equatorial Transform Margin. Over the next few years, drilling should test innovative approaches and hopefully extend production to the ultra-deepwater province of the Brazilian Equatorial Margin. ■

Seismic profile through the first deep-water exploratory well (1-CES-112) in the Ceará Basin, drilled in 1993, and the Pecem discovery well (1-CES-158). The image shows syn-rift faults extending up to Albian times, and development of Late Cretaceous mini-basins probably associated with salt or shale flow. Compressional tectonics resulted in interesting compressional structures overlying basement highs which are yet to be tested. Similar structural and stratigraphic plays can be found along Brazil's equatorial margin.

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60 Years of Innovation

KEN WHITE

Emerging through privatization of state entities, Romanian company **Prospectiuni** has developed into the leading geophysical and geological service company in south-east Europe, and now operates in the Middle East and Africa as well as throughout Europe.

Romania is one of the oldest hydrocarbon-producing countries in the world, with initial production recorded in 1858. At one time it was the largest petroleum producer in Eastern Europe but the reality now is that domestic oil and gas production are both in long-term decline. That said, the country appears to be positioning itself for a renaissance in exploration as the offshore, particularly the deepwater, is generating widespread industry interest while the onshore is thought to hold significant tight oil and shale gas reserves. With the government committed to boosting domestic production to reduce a reliance on imports, both opportunities are attracting strong interest from a host of international players. The latest initiative involves a new round of bidding due to take place in April 2013, in which the government is offering 15 blocks onshore, mainly on the Moesian Platform in the south of the country, and 15 offshore.

Since the 1950s, geophysical surveys for hydrocarbons in Romania were carried out by 'The Enterprise for Geological and Geophysical Survey of Hydrocarbons' (IPGGH), a function within the Ministry of Mines, Oil and Geology. By the mid-1970s this enterprise had established a strong reputation for using the most up-to-date technology and for keeping abreast of progress in all aspects of geophysical acquisition and processing.

Romania began its privatization process in 1991 when the economic transformation committee implemented expansive general economic reform measures and called for a thorough and speedy privatization of most state-run enterprises, large and small. These ambitious proposals were, however, quickly bogged down by the new democratic process. IPGGH was one of the jewels to emerge from the 1991 privatization program as it became Prospectiuni and in 2000, Prospectiuni became a privately owned company, retaining its base in Bucharest.

Reform to Perform

In 2008 Prospectiuni formed a top management team of international and Romanian experts and specialists, to implement a new strategy of investing in people and in cutting-edge technology and equipment. The main goals were to target new territories and clients and stay ahead of competitors through cost-effective services, complying with the highest international HSEQ standards. Just two years later the company's aggressive growth strategy had seen a marked expansion of its global market, undertaking projects not just in Romania but also in Bulgaria, Georgia, Morocco, Portugal, Senegal and Tajikistan.

At the end of 2008, the employees in Prospectiuni comprised just two nationalities, Romanian and American, while the company now has specialists from 33 countries. Since 2008, 700 international employees have joined the company, which now boasts 2,500 employees. "Most of our employees are Romanian, but we have been recruiting extensively in countries such as Senegal and Morocco. We try to employ local people from countries where we operate. Every year, we have operations in 8 to 10 countries," states Gehrig Schultz, CEO of Prospectiuni in an interview for *Ziarul Financiar* (the most prestigious business publication in Romania).

Today, Prospectiuni is the largest geological and geophysical services company in Romania, maintaining a portfolio of works in Europe, Africa and the Middle East. It also provides services for important Romanian entities, such as Petrom, Romgaz and Rompetrol. "Even though the contracts with these strategic clients are bigger than in the past, their contribution to our

Prospectiuni

Survey underway in Tajikistan

Romania has a long history of hydrocarbon exploration

overall turnover has diminished in the last couple of years. We consider this a great accomplishment because it proves that we have achieved a sustainable growth through new lines of businesses and a wider offer of services, gaining new clients and at the same time keeping our traditional major clients, who remain as important as ever", declared Gehrig Schultz.

Prospectiuni was the first company to deploy Sercel's eUnite cableless recording units in Europe, and recently acquired a further 600 channels, increasing the company's inventory to 4,500 channels and a total channel count of over 30,000. It now has the largest cableless recording capability in Europe, ideal for urban or other areas of difficult data acquisition. The company also established a professional development center in 2012 to train future managers and specialists as it plans to double its size within the next four years.

At the beginning of November 2012 Prospectiuni appointed Andrew Clark to the newly created position of President to manage the day to day business activity of the company. In taking on the new responsibilities Clark commented that the company had a "wealth of growth opportunities in our core petroleum geophysical services business and in emerging areas such as environmental monitoring, mining exploration services and other services to the petroleum industry". The company's competitive advantage will be particularly apparent to the industry in the current bidding round, as a number of geological and geophysical studies are available for some of the open blocks. The process will also offer Prospectiuni new business development opportunities with regard to seismic data acquisition, processing and interpretation.

Important Core Strengths

Seismic services are a core strength of Prospectiuni, with the company able to provide field seismic crews fully equipped for 2D, 3D and 4D seismic data acquisition, seismic surveys planning, data quality assurance, in-field processing for data quality, and recording and surveying equipment and maintenance. These crews have a vast experience in operating through various terrain types and deploying a variety of energy sources. The company offers a full range of 2D and 3D seismic data processing and interpretation services using the most advanced equipment and software, along with highly qualified and trained personnel, who have experience in processing both new and old 2D/3D seismic data, applying standard processing in time, as well as in special processing such as AVO Analysis and Attribute Stacks, Horizon Velocity Analysis and 3C Data Processing and Depth Migration.

As Andrew says, "A client from anywhere in the world can be set up with remote access to the company's processing system with the possibility not only for data visualization but also for running different jobs or performing specific tests.

"Due to our proven track record and vast expertise in the region we often act as an advisory service to companies interested in moving into the country," Andrew explains. "Based in Bucharest, we can offer them presentations on Romanian geology and information about regional data, as well as very useful general information on costs and timelines for acquiring data in Romania."

Geology to Environmental Studies

"Another core strength is the provision of geological services, both domestically and internationally, including geological mapping and various prospecting and exploration projects in different lithological and structural contexts," Andrew adds. "We can provide preliminary assessments of resources and reserves and offer expertise in the field of mineral resources potential in areas less geologically investigated."

Promediu is the environmental division of Prospectiuni, and carries out environmental laboratory analysis, impact

Prospectiuni has performed seismic data processing for over 60 years, from the early graphical methods through to the most advanced, modern digital techniques, manipulating large datasets.

assessments, waste management studies, risk evaluations for contaminants and monitoring programs.

In the geophysical arena, the company is fully equipped to conduct a range of geophysical surveys using non-seismic techniques for hydrocarbon and mineral exploration, as well as environmental and geotechnical studies such as magnetotelluric surveys, DC electrical surveys, gravity surveys and magnetic surveys. These datasets can either be used to map a specific geophysical characteristic to determine a prospective area of interest or can be integrated with seismic, geochemical and other data to provide a complete subsurface model.

From a geochemical perspective the company has established parameters to enable prospecting for hydrocarbons and geothermal water and can provide processing and interpretation of raw geochemical data.

Looking to the Future

"Currently, we are fully engaged in terms of operational capacity, and major investments are underway aiming to increase our working capacity. We plan to double the turnover of the company in the next three years and for this we have to make significant investments and hire more people. We have just signed contracts with Sercel to invest 20 million euros in 2013 alone," declared Gehrig Schultz. "Our range of services is expanding and at the same time, companies demand better images of the subsurface. We realised that it is more cost-effective to buy equipment rather than rent it," he added. Based on the investments planned for the next two years, the number of employees is estimated to rise to between 3,000 and 3,500.

One of the biggest achievements for Prospectiuni in 2012 was the growth of the Professional Development Center, as Andrew Clark explained. "Developing people is a prime concern for the company and a prime objective for the management team. Prospectiuni has huge potential, and a solid foundation to build on; this facility is helping us to develop new capabilities and specialists for the future." Gehrig Schultz, commenting on the significant role of Prospectiuni in building future specialists in the G&G worldwide industry, added, "We have invested in both Prospectiuni's future and in the geophysical industry's strength by creating opportunities for geoscientists to develop their skills and knowledge. We actively support student professional societies in Romania, Serbia, Bulgaria and Croatia. Our international teams are working to provide the same opportunities across Africa and Asia."

Another big challenge is to maintain and continue developing the HSEQ system. Andrew Clark notes: "All Prospectiuni's management systems are ISO certified, a huge achievement unequaled in the geophysical industry. The next step in developing our HSEQ culture will be the implementation of the Behavior Based Safety Process."

The company intends to have ten crews in 2013 (up from eight at present), four of which will operate abroad, building to 12 by 2014. "The market for G&G services has been shrinking, especially in Poland, and this means that some of our competitors are targeting the southern Europe countries where we operate. Globally, the market continues to be pretty fragmented, but the niche market we operate on still looks good. We remain focused on South Europe and the Middle East," says Gehrig Schultz.

Andrew Clark sees prioritization as one significant challenge for the future: "There are so many opportunities for our company to pursue. Selecting the best business opportunities represents a key factor in our future success." ■

Wide range of services: applied geophysics surveys and geological laboratory analyses.

Oil Exploration in Yemen

MICHAEL QUENTIN MORTON

Yemen is a land of physical contrasts, bounded by mountains, desert and sea. It includes the Socotra archipelago and various islands in the Red Sea. At the heart of the south, like a deep gash across the land, is the Hadhramaut Valley. The geology of the region intrigued the early explorers, as it continues to do today. They had to overcome considerable political and physical difficulties as well as grapple with a complex geological puzzle that had its origins in the breakup of Gondwanaland.

"It is melancholy to find this interesting coast, which in former times was probably fertile and prosperous, now almost entirely desolate and the few inhabitants that remain nearly always at strife with their neighbors." Thus wrote the commander of the survey ship *Palinurus* which, in 1846, carried Dr Henry Carter on the first geological survey of the land now known as Yemen. Carter, a medical officer in Bombay, was also a naturalist and geologist. Commissioned by the government of India to conduct the survey from the ship and on brief excursions, he published *Memoir on the Geology of the South-East Coast of Arabia* (1852), the first systematic account of geological observations of the region. Although a trickle of explorers followed in his wake, most notably an Austrian expedition in 1898–9, they did not advance far into the interior but produced some useful reports.

Al-Mukalla harbour in the 1950s

Mike Morton

Today's Yemen was then three separate political entities. To the north, the territory was under Ottoman occupation, and remained so until 1918. It was then ruled by Imams until 1962 when there was a revolution and a lengthy civil war. To the south, the town of Aden, a British colony since 1837, was primarily a strategic coaling station and later an oil refinery. In the south-eastern hinterland there were a number of small emirates that evolved into a British protectorate. The British withdrew in 1967 and the whole country – north and south – was united as the Yemen Republic in 1990.

The steep cliffs of the Wadi Hadhramaut posed difficulties for the early oil explorers.

Between the World Wars

In 1921 rumors of oil seepages led the British government's Petroleum Department to report: "Petroleum is also said to occur at many points in the interior of Yemen." Although the main focus of the oil business was elsewhere in the Middle East at this time (see 'The Emergence of the Arabian Oil Industry', *GeoExpro* Vol. 5, No. 6), a few of its main players made cameo appearances. The ubiquitous Frank Holmes was interested in the oil prospects of the Farasan Islands, which belonged to the neighboring emirate of Asir, and in the Salif salt mines on the Red Sea coast. In 1929, the American millionaire Charles Crane sent mining engineer Karl Twitchell to Yemen to assist with water supply and agriculture, and investigate mineral prospects. Harry St. John Philby, an adviser to the Saudi king, visited Shabwa in 1936. Driving a station wagon and accompanied by a small detachment of Saudi guards, he swept out of the desert and caused much consternation among the British authorities. Although not a geologist, Philby kept a record of interesting geological features, such as oil seepages around Shabwa, and drew maps.

The Qu'aiti Sultan of Mukalla and Ash Shihr showed a keen interest in the mineral possibilities of his sultanate. This led to surveys around the port of Al-Mukalla which was, according to one British eccentric, the site of King Solomon's Mines. In 1918, geologists Beeby Thomson and John Ball reported on coal and oil prospects. The following year, Dr Little of the Geological Survey of Egypt arrived to carry out a six-month mineral survey. His report was the first attempt to describe the stratigraphic and paleontological features of the area. Subsequently Shell, through their agent Anton Besse, discussed a concession for Ash Shihr, but their partners in the Turkish Petroleum Company (the forerunner of IPC – see next section) were against it.

Later explorers of the Hadhramaut in the 1930s were Von Wissman and Van der Meulan, and the great Arabian explorer Freya Stark, whose party included a female geologist, Miss Elinor Gardiner. These expeditions provided information and maps that would be useful to later surveys.

IPC and the Search for Oil

The oil strike in Bahrain in 1932, and the subsequent loss of the Saudi Arabian oil concession to Standard Oil of California, triggered the interest of the Iraq Petroleum Company (IPC) in the region. This company, a consortium of oil majors and Calouste Gulbenkian (see 'Oil from Babylon to Iraq', *GeoExpro* Vol. 6, No. 2), sought to pre-empt its rivals by obtaining oil concessions along the fringes of Arabia.

In 1936, Petroleum Concessions Limited (PCL), an associate company of IPC, obtained an exploration permit for the Aden Protectorates. In 1937, an IPC survey party working in neighboring Saudi Arabia obtained the Imam's permission to survey to the north of Al-Hudaydah but

The author's father in a Dodge Power Wagon with an assistant sitting on the running board, Hadhramaut, 1949

the results were unpromising. In 1938, while Freya Stark was exploring the interior, Messrs Pike and Wofford were in the skies above, carrying out aerial surveys for PCL. They did some structural mapping of the Hadhramaut and around Al-Mukalla; but otherwise their work was restricted by the 'local objections' of tribesmen.

In 1946, IPC liaison officer Major Tony (Tadeus) Altounyan arrived with a box of Maria Theresa dollars (the currency of the time) and explored the Mahra country, the easternmost part of the Aden Protectorate, on camel. He returned in the autumn of 1947 with two geologists – the author's father, Mike Morton, and René Wetzel. This party carried out a detailed surface examination of the Mahra country, retracing Altounyan's footsteps of the previous year.

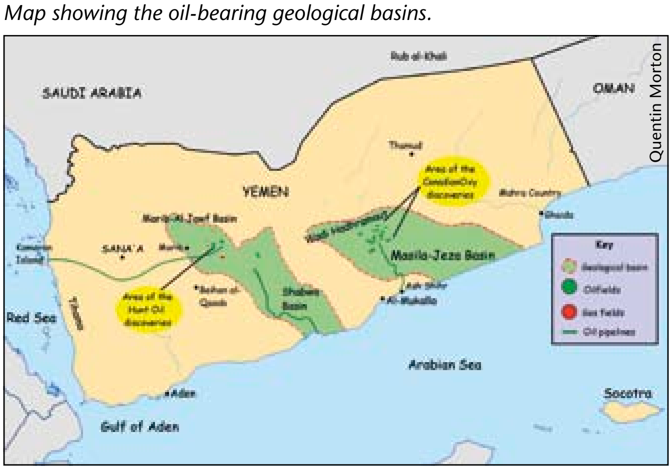
Rumors of oil shales and seepages persisted. In late 1949, the same geologists caused much excitement among the authorities in neighboring Yemen, who accused them of preparing an 'invasion'. However, their reception in Beihan al-Qasab was friendly: the Emir of Beihan and his family, encouraged by stories of Saudi oil wealth, accompanied the geologists on all their excursions. Although the area generally lacked sufficient rock exposures to justify extensive geological work, the possibility of geophysical surveys around the northern border was left open.

In 1953, PCL established a geological base near the bedouin well at Thamud. For the next six years, Lebanese geologist Zaid Beydoun led a series of geological surveys which were supplemented by aerial and magnetic seismic surveys. Beydoun was a remarkable figure: as well as conducting a one-man survey of Socotra, he wrote extensively about the geology of south-western Arabia. In 1968, he co-authored a special report in which the geological nomenclature of the region was formalized. In 1994, the Geological Society of London awarded him the William Smith Medal for his 'outstanding achievement in petroleum geology'. He noted that it was good to receive the award while he was still alive.

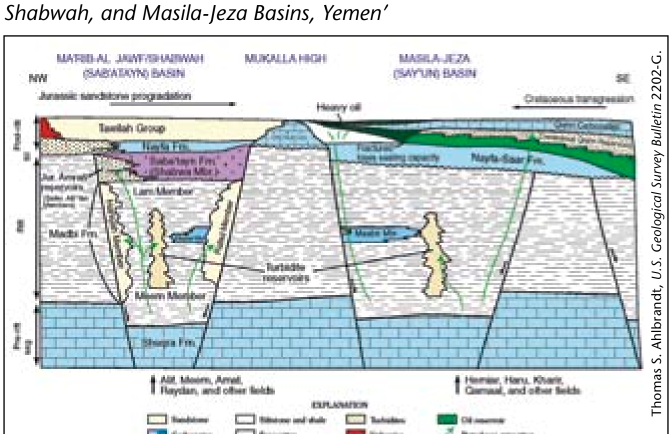
IPC's search for oil ultimately proved fruitless. In 1959, the Company abandoned the Hadhramaut after failing to agree terms with the Sultans and, in the following year, withdrew from the Protectorate altogether. BP, which had separately investigated Kamaran Island in the Red Sea, also withdrew.

Zaid Beydoun in a 'Swiss Cottage' tent with the necessities of life: notebook, Tilley lamp, aspirin and cigarettes!

Map showing the oil-bearing geological basins.



Schematic diagram of the petroleum systems in the two basins from 'Madbi Amran/Qishn Total Petroleum System of the Ma'rib-Al Jawf/ Shabwah, and Masila-Jeza Basins, Yemen'



Success at Last

In the 1960s and 70s, as the overall geology of the Middle East was unraveled, the existence of some deep localized rift-related Jurassic basins was revealed. These were postulated to be associated with the breakup of the Gondwana supercontinent. The associated restricted basinal conditions had proved favorable for the development of good quality oil source rock. These in places had been buried sufficiently deeply to generate hydrocarbons, which in turn had subsequently migrated into accessible reservoir rocks. Younger Tertiary rifts in the Gulf of Suez also proved interesting.

After the departure of IPC, the first commercial drilling began in 1961 when the Mecom group drilled a number of dry holes on the Red Sea shore, followed by Shell between 1976 and 1980. In 1964, Pan American (Amoco) drilled a number of dry holes in the Aden Protectorate. Algerian and Russian groups also showed an interest, with the latter making some promising findings in the Shabwa area. In 1982, the Italian firm Agip made a marginal offshore discovery some 170 km east-north-east of Mukalla.

In the early 80s, at the instigation of Syrian geophysicist Moujib al-Malazi, Hunt Oil instituted a seismic program, predicated on aeromagnetic indications of a rift in the north-eastern part of North Yemen. Field indications of Jurassic

instability, together with the presence of petroliferous shales, added significantly to the area's attraction. Based on al-Malazi's analysis of the seismic data, four prospects were drilled in the Ma'rib-Al Jawf Basin in 1984. Hydrocarbons were found in well-developed sands below a salt formation in three of those prospects, including the Alif No. 1 well, which tested at 7,800 bopd, the first discovery of oil on a commercial scale.

Since Beydoun's outcrop studies had described Jurassic outcrops on the western flank of the Al-Mukalla high, there was a good possibility that the Jurassic rifting extended farther to the east. This prompted CanadianOxy and its original partner, Consolidated Contractors International, to acquire the 37,200 km^2 Masila Block. In 1991, the existence of a second petroleum basin, the Masila-Jeza basin, was confirmed when CanadianOxy struck oil at Sunah No. 1. This was soon followed by more discoveries at Heijah, Camaal and Hemiar. By 2011, Yemen had twelve main producing blocks, operated by nine international oil companies.

Yemen Today

Yemen had proven oil reserves of around three billion barrels as of January 1, 2012, and petroleum accounted for roughly 25% of GDP and 70% of government revenue. However, the country's infrastructure, particularly its pipelines, has suffered from sabotage, leading to serious interruptions to the flow of oil. Piracy has curtailed offshore activity. If the difficult internal situation continues, the immediate future of oil exploration in the country looks uncertain.

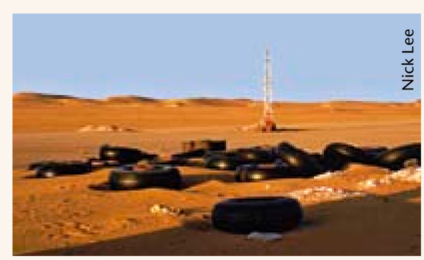
Acknowledgement: *the author wishes to thank Nick Lee, Ian Maycock and Peter Morton for their assistance.* ■

Production test at Alif No.2 in September 1984

Abandoned in the Sands

In the mid-1950s, the American company holding the main Saudi Arabian concession, Aramco, was sending survey parties deeper into the desert. One day, a PCL surveyor was laying down magnetometer and gravimeter lines on the edge of the Rub al-Khali – one of the remotest places on Earth – when he was astonished to see through the eye-piece of his theodolite the outline of a drilling rig only a few hundred meters away. He reported it and a patrol of Arab levies led by a British officer found an Aramco party in what was claimed to be British-controlled territory. After a brief discussion, the Aramco party abandoned its camp and left its mobile rigs in the desert. The equipment remained *in situ* for many years and provided a popular attraction for visiting geologists.

This photograph shows one of the abandoned Aramco rigs. Bedouins siphoned petrol from the tanks of the abandoned vehicles and removed the inner tubes from their tyres, hence the pile of discarded tyres in the foreground. Filling the tubes with the petrol, the bedouins then transported them to the Hadhramaut Valley to sell on the open market.



In 1957, a field party with trucks and water tankers pass the mud skyscrapers of Shibam in the Wadi Hadhramaut en route for the northern desert.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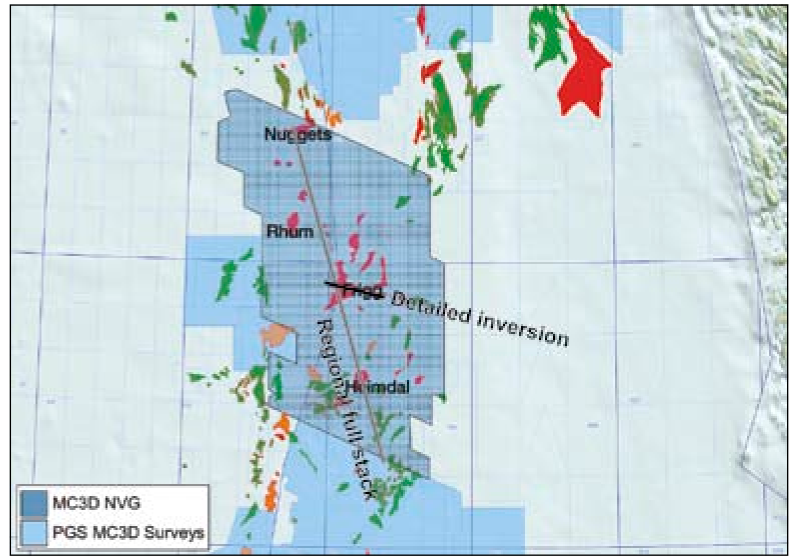
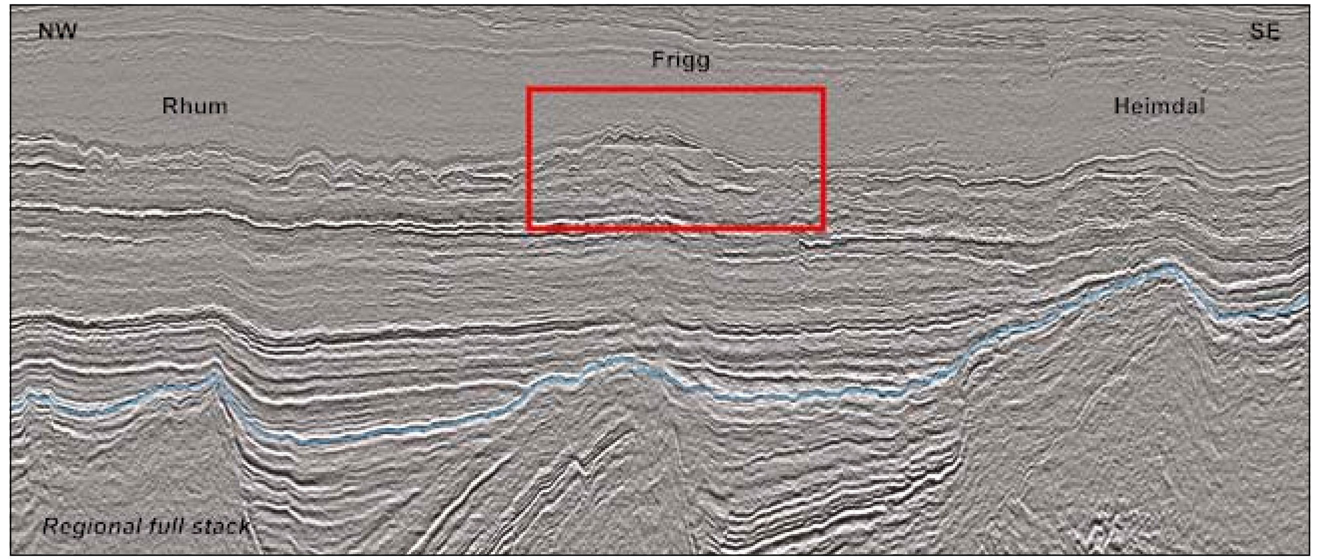
Recorded Broadband 3D:

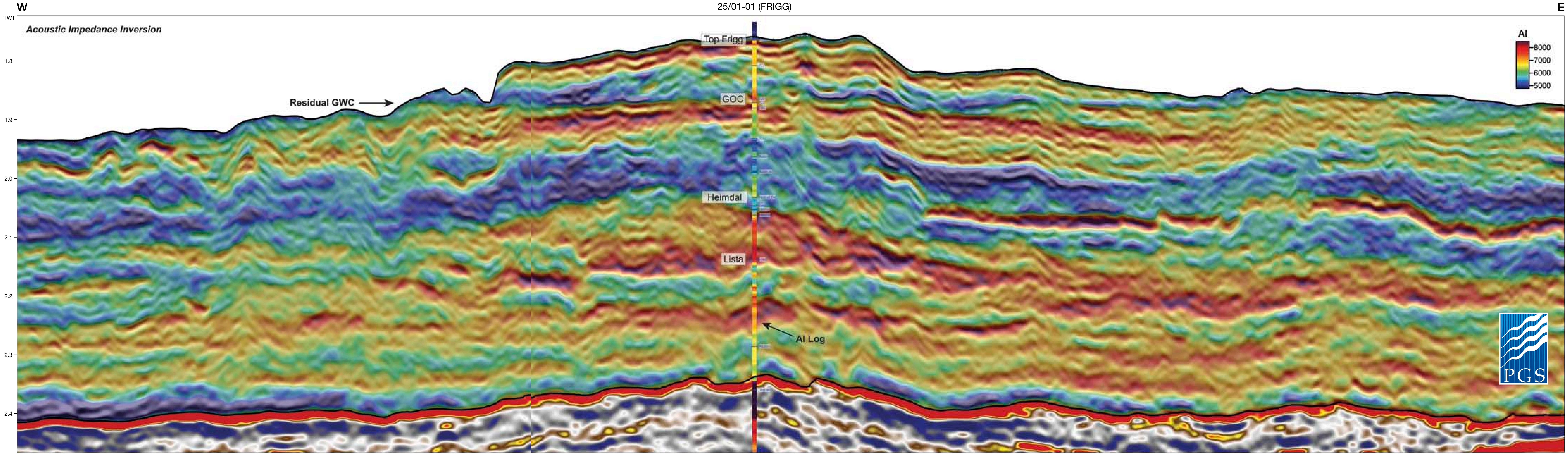
Improving reservoir understanding and characterization with recorded broadband seismic

The seismic line below is the result of pre-stack seismic inversion (acoustic impedance) across the Frigg field. The residual Gas Water Contact can be clearly seen using the GeoStreamer dataset and not to the detriment of the resolution. Low and high frequency are both enhanced.

Lately, the marine seismic industry has witnessed a big shift in application of broadband seismic data acquisition techniques. Common to all methods is an approach to increase the frequency bandwidth of acquired data in comparison to data acquired by conventional means. The main goal is to extract more from the earth than mere frequencies. This article is a continuation of the journey explained recently in *GEO ExPro* Vol. 9, No. 5, which introduced the exploration potential of this North Viking Graben dataset.







Extracting More Than Mere Frequencies

Recorded broadband data can have a huge impact on the reliable prediction of reservoir properties.

CYRILLE REISER and **TIM BIRD**, Petroleum Geo-Services

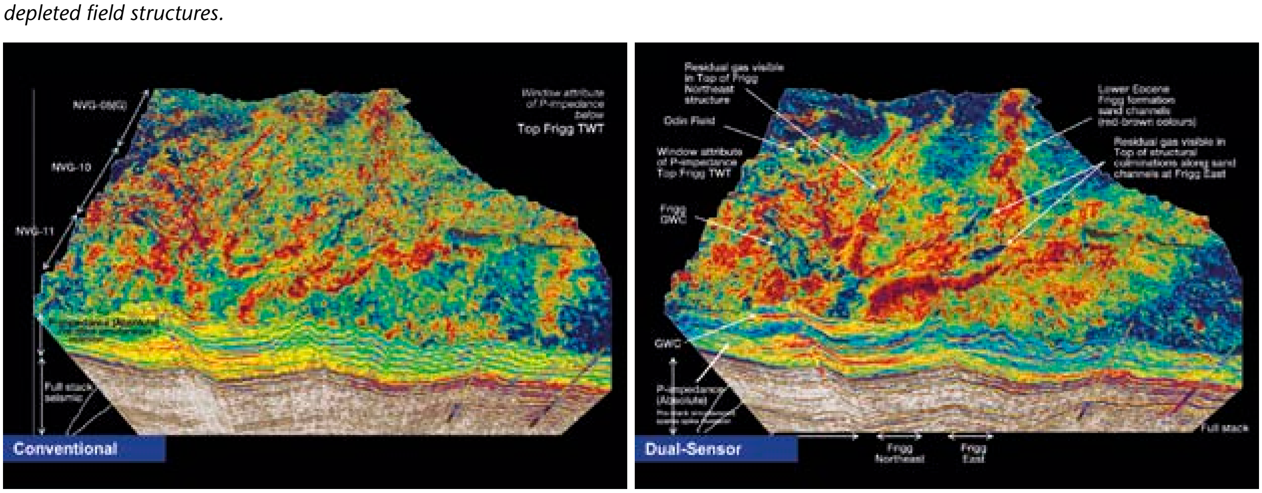
The most obvious benefits of broadband techniques relate to the increase in resolution on offer from the wider bandwidth, in addition to improved penetration due to signals richer in lower frequencies. The arguments for broadband are so compelling that there is good reason to believe that all new acquisition will be broadband before too long. The image of the fold-out area from the North Viking Graben on the previous pages illustrates the improved resolution available from the GeoStreamer dataset. Can you work without it? That's ultimately the question that every explorer should ask him/herself. This type of seismic also amply demonstrates the improvement in interpretability – but there is value beyond merely improved resolution.

What is perhaps less well known and less publicized are applications in addition to pure imaging, where recorded broadband data has a huge impact on the reliable prediction of reservoir properties. The case study presented in this article highlights these benefits.

Deriving physical rock properties from seismic data offers great value to geoscientists. After all, it is rocks that we are drilling, not acoustic signals. Seismic inversion in combination with rock physics analysis is the most common workflow to derive rock or elastic properties from seismic data. A fundamental bias of all inversion methods is that a particular seismic dataset can lead to a number of alternative inversion results. With narrow band seismic data there is a lack of information on the high side and low side of the amplitude spectrum, so the geoscientists tend to constrain the number of possible solutions to reach the most reliable one. Normally, they do this by incorporating a background trend model based on known or 'a priori' information, usually nearby well data or other geological values. As a consequence, the uncertainty of the results away from these constraints, i.e. away from well control, increases significantly. Using broadband seismic data, with its greater frequency content, substantially reduces the amount and potential bias of 'a priori' data input – we can rely more on the 3D information content from seismic data away from well control. Recorded broadband data makes the inversion or any quantitative interpretation solution less dependent on what we already believe, and increases its usefulness in areas where a priori information may be scarce or uncertain. In other words it is a more data-driven inversion.

This case study from the North Sea area demonstrates how the use of broadband seismic fundamentally helps delineation of targets in the first place, and more importantly describes the internal structure of reservoirs and quantifies key reservoir properties, that in turn increases the probability of discriminating lithology and fluid facies.

The left-hand image represents the result of the acoustic impedance from a conventional dataset, whereas the seismic inversion coming from the dual-sensor streamer data is represented on the right-hand side. The background blue tones correspond to shale lithologies, while the red tones represent the sands and the localized blue areas along the sand channel axes represent sand with residual gas saturation in depleted field structures.



Stretching Ambitions

GeoStreamer acquisition and processing was recently performed over a 3D area in the North Viking Graben in the vicinity of the Heimdal and Frigg fields. Based on the results of the seismic processing, a complete reservoir characterization or quantitative interpretation project was carried out over the Frigg area (more than 1,000km^2).

The Frigg field comprises a clastic reservoir of early Eocene age deposited in a deep marine environment and exhibits characteristic prograding submarine fan geometries on the seismic. The gas was discovered at a depth of around 2,000m and a clear flat-spot signature is evident on the seismic. Production ceased and decommissioning of the field started in 2004, however residual gas is still present which can be analyzed and mapped on this seismic dataset.

On this dataset a full quantitative interpretation has been performed including wavelet extraction, low frequency model generation and pre-stack simultaneous inversion. The figure below illustrates the inversion results by comparing the acoustic impedance from the conventional and the recently acquired and processed dual-sensor seismic or 'recorded broadband'. The contrasts between the results for the two co-located datasets eloquently summarize the previously described benefits of broadband seismic in terms of interpretability improvement and better delineation of the geological feature.

The main results of the comparison between the conventional and broadband seismic after pre-stack inversion are:

- Interpretability improvement: by being able to delineate the various stratigraphic units, for instance the prograding foresets are better delineated on the broadband seismic data;
- Better delineation of the main geological features by separating the sands and shales responses with the inversion results. More low frequencies and better signal-to-noise improve the stability and resolution of the inversion results.

The improvement in results from dual-sensor pre-stack analysis gave encouragement that a better understanding of the lithology and fluid distribution in this dataset could be achieved by lithology-fluid classification. Elastic attributes have been classified based on a rock physics analysis performed for the area. The lithology fluid classification highlights all the main geological features and field architecture and differentiates channel sands, hydrocarbon sands, and the shale layers forming the reservoir seal. By overlaying the various field outlines on the 3D lithology fluid classification, the residual gas in the Frigg, Frigg East, Odin and other hydrocarbon accumulations can be seen clearly, located on the structural culminations of discrete localized channel fairways.

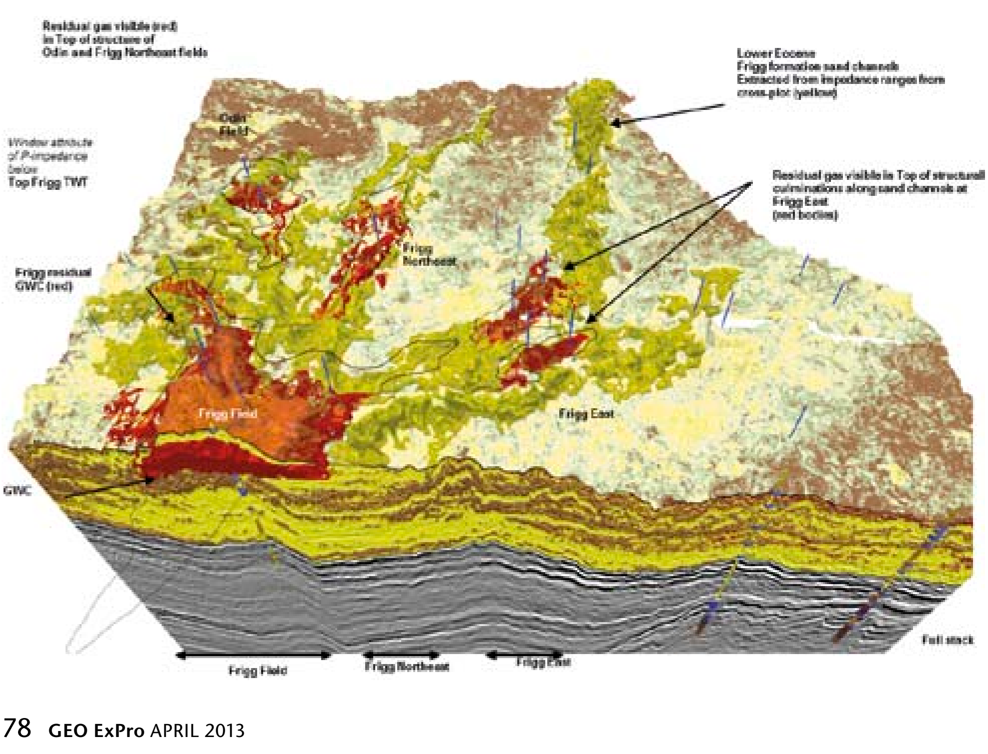
Improving Accuracy

This is one of many recent case studies of recorded broadband seismic, highlighting that the extended seismic bandwidth of over an octave on both the low and high side noticeably improves the accuracy in the extracted elastic properties away from well control. The greater reliability of inversion results from dual-sensor seismic, with less reliance on local well bias, plays an important role in the evaluation and de-risking of prospects and optimizing well placement, through accurate lithology and fluid prediction.

Broadband seismic without receiver and source ghosts opens even more the possibility of interpreting and analyzing the true earth response with significantly less filtering and interference effects. The potential benefit of broadband seismic is therefore across the asset life from the exploration stage to production optimization and resource estimation with better constrained uncertainty.

We are just at the beginning of realizing the full potential of such data and many more examples will be revealed shortly, demonstrating the power of such recorded and measured broadband seismic. Watch this space…

3D lithology fluid classification based on the Rock Physics Analysis. The results of the classification match the various field outlines like Frigg, Frigg East and Odin (north-west of Frigg).



Acknowledgements

We would like to sincerely thank all our colleagues in PGS for all the fruitful discussions during the last few years and also PGS for permission to publish this work and the many contributors within the PGS organization.

Scenic Geology of the Icefields Parkway

ANNE HARGREAVES

The drive from Lake Louise to Jasper on the Icefields Parkway, through the Banff and Jasper National Parks, Alberta, Canada, is a scenic tour that attracts people from all over the world. Cliffs and glaciers are visible along this three-hour drive, which is best stretched over at least a day, allowing time to stop often for photos, hikes and wildlife viewing. This article will focus on the area north up Highway 93, called the Icefields Parkway, between Lake Louise and the town of Jasper.

View of highway coming through the Big Bend after which it climbs to Sunwapta Pass. Palliser Limestone cliff is visible in the center topped by Exshaw and the recessive Exshaw shale, which is a marker bed seen in many well logs from the Interior Plains. The south summit of Cirrus Mountain is composed of the Rundle Formation. Across the valley to the right is also Palliser Limestone but from this angle resembles exfoliating granite.

Geological Setting

The Canadian Rocky Mountains rise majestically from the interior plains of Alberta. Let's ponder the general geological setting of Canada. In a nutshell, where the central craton of the North American continent is exposed it is called the Canadian Shield, which occurs in northern Saskatchewan, Manitoba, Ontario, Quebec, Nunavut and the Northwest Territories. The gneiss underlying the Rockies as basement is of this same Archean age and is part of this craton. The shield area in the Archean was a mountainous uplifted area and shed sediments towards the future Interior Plains and future Rocky Mountain areas while at the same time lying in the southern hemisphere. At times underwater, most notably during the Cambrian when the famous Burgess Shale was deposited, and at times exposed, for example during the Silurian, the sediment layers built up with mostly shales and carbonates interlayered with some quartz sandstones and silt layers. Of economic importance today, during the Devonian a significant warm inland sea developed, creating reef deposits that later became viable oil- and gas-producing formations in Alberta. There is also evidence of glacial activity in the Proterozoic and Carboniferous as well as during the most recent cyclic Neogene and Quaternary glacial episodes.

Mother and cubs near the Icefields Parkway – be sure to leave time for wildlife viewing!

The Canadian Rockies extend from the US border in the south, trending north-west for almost 1,500 km following the Alberta-British Columbia (BC) border, crossing into BC and terminating just shy of the Yukon Territory. It is a long, narrow range, 180 km wide at most, and was created by thrust faulting from west to east, when older Cambrian rocks were thrust up and over younger Mississippian and even Cretaceous rocks. The Rockies consist of the Foothills, the Front Ranges and the Main Ranges, and end abruptly at the Rocky Mountain Trench which lies just inside the BC border. The Trench, visible from space, came into being about 60 million years ago as a huge downward trending fault and has the youngest sediments in the Rocky Mountain area.

Thrust faults occur in fold and thrust belts which are associated with orogenies, or periods of mountain building due to collision of plates. In this area, the Rockies were raised due to collision with terranes to the west of the central craton which collided, causing thrust faults which propagated themselves laterally and upward through the section. By definition, thrust belt faults move upward through the section and always result in older rocks overlying younger ones. Movement is usually along weaker shales and the uplifted rocks are often the hard, resistant cliff-forming carbonates from the Cambrian thrust over soft clastics from the Mesozoic. Glaciation and water erosion deepened the less resistant shale-filled valleys. The fault lines trend south-east to north-west. Complex folding and faulting associated with the thrust faults include drag folds and break thrust faults, where the anticline-syncline pair rupture leaving steeply dipping formations in either direction and occasionally sometimes backwards.

The most recent glaciation in the area was the Wisconsinan, which brought the Cordilleran ice sheet from the mountain areas over the city of Calgary, where it lay probably 1 km thick, approximately 31,000–14,000 years ago.

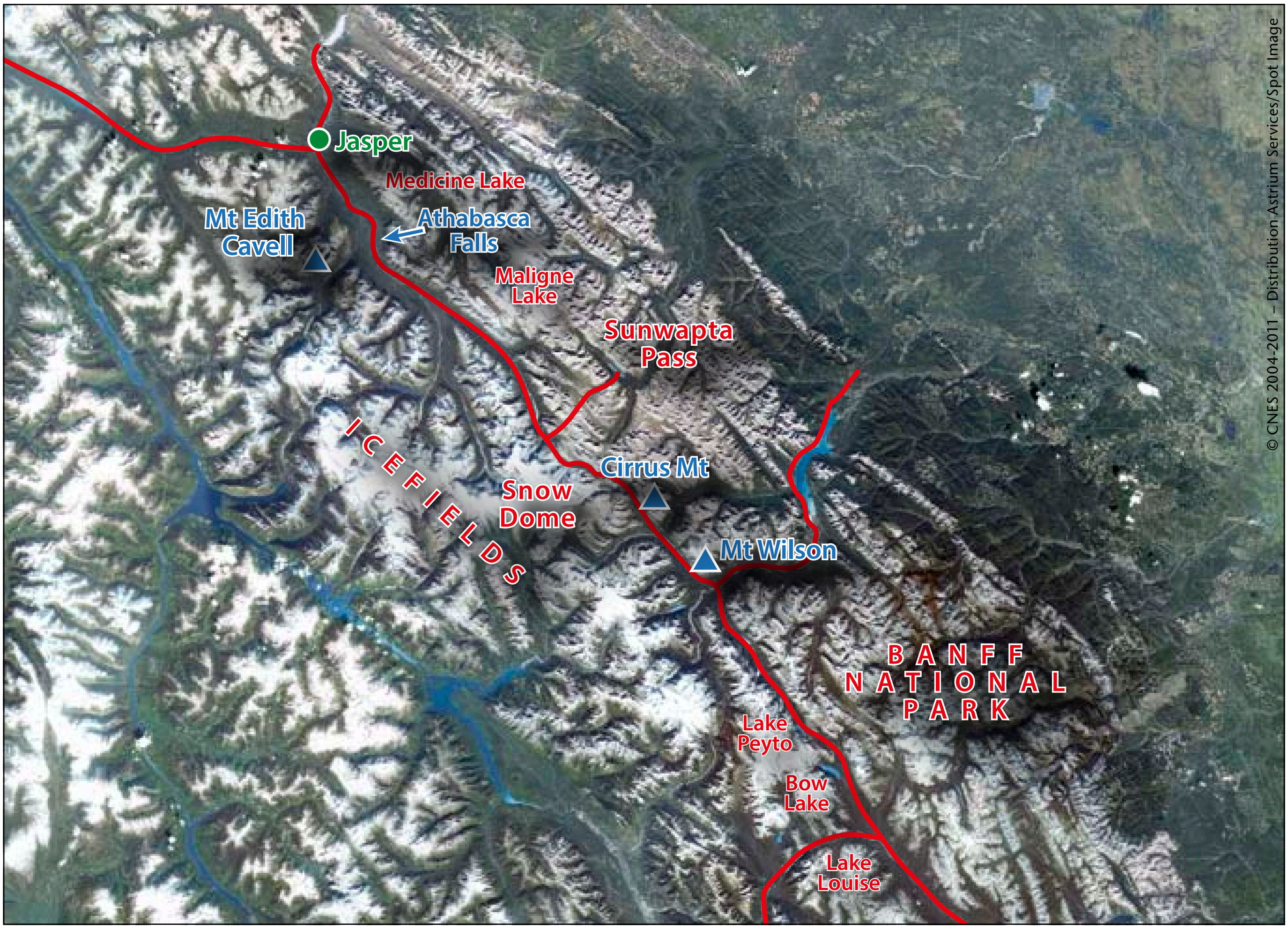
Glaciers and Hikes

From this point we will travel back in time on our trip to Jasper. It is highly recommended to grab a copy of Ben Gadd's *Canadian Rockies Geology Road Tours* for much greater detail than is offered in this article.

This beautiful highway follows the Icefields Parkway along the trace of the 330 km long Simpson Pass fault and the valley bottom, consisting mostly of shale, shaly limestone and gritstone of the Proterozoic Miette group. The Icefields, or glaciers, high up on the watershed, feed valley glaciers and these are visible along the route. The Icefields themselves are supported by the hard resistant rock of the main ranges, the relatively flat thrust sheets of resistant Gog quartzite and the Middle Cambrian carbonates and dolomites such as the Cathedral, Stephen and Eldon Formations.

Bow Lake near the headwaters of the Bow River is fed from the Bow Glacier. An excellent half-day hike along the lakeshore takes you to Bow Falls. For the best information on all hikes in the National Parks, consult Patton and Robinson's *Canadian Rockies Trail Guide.*

Continuing on the highway, take the turnoff to the Peyto Lake viewpoint, and see the beautiful blue color of the water. Glacial



runoff feeds this lake, and from the viewpoint you can see how the gray load is being dumped. A large delta has filled about a third of this lake since the Wisconsinan retreat 14,000 years ago.

From here we follow the Mistaya River, and peaks on the left-hand side of the highway are in the Gog, Mt Whyte, Cathedral, Stephen and Eldon Formations. Next, the Upper and Lower Waterfowl Lakes offer camping and two hikes with little elevation gain to Cephran and Cirque Lakes. Fishing is allowed with a proper fishing license.

At Saskatchewan River Crossing the North Saskatchewan River exits the valley and heads east to Edmonton, and of course, Saskatchewan. There is a tephra bed with two distinct layers visible by the highway bridge. One was from Mt Mazama, which blew in Oregon about 8,000 years ago creating the well-known Crater Lake; this layer is actually also visible in Calgary. Above it, the upper Bridge River tephra is from an eruption 2,700 years ago near Lillooet, BC. The huge mountain just north of and towering over the rest stop area is Mt Wilson, with rocks from Bison Creek, Mistaya, Survey Peak, Outram, Skoki, Owen Creek, Mount Wilson and Beaverfoot Formations; a thick carbonate succession of Middle Ordovician age.

Continental Divide

Further along we climb the magnificent Sunwapta Pass. As the highway crosses a large glacial outwash plain with a sharp curve called the Big Bend, the road climbs and the view back down the valley shows Cirrus Mountain on the right-hand side. It is made from the familiar Mississippian Rundle and Banff Formations and the Devonian Palliser Formation package underlain by rocks of the Fairholme Group. Stop here for photos!

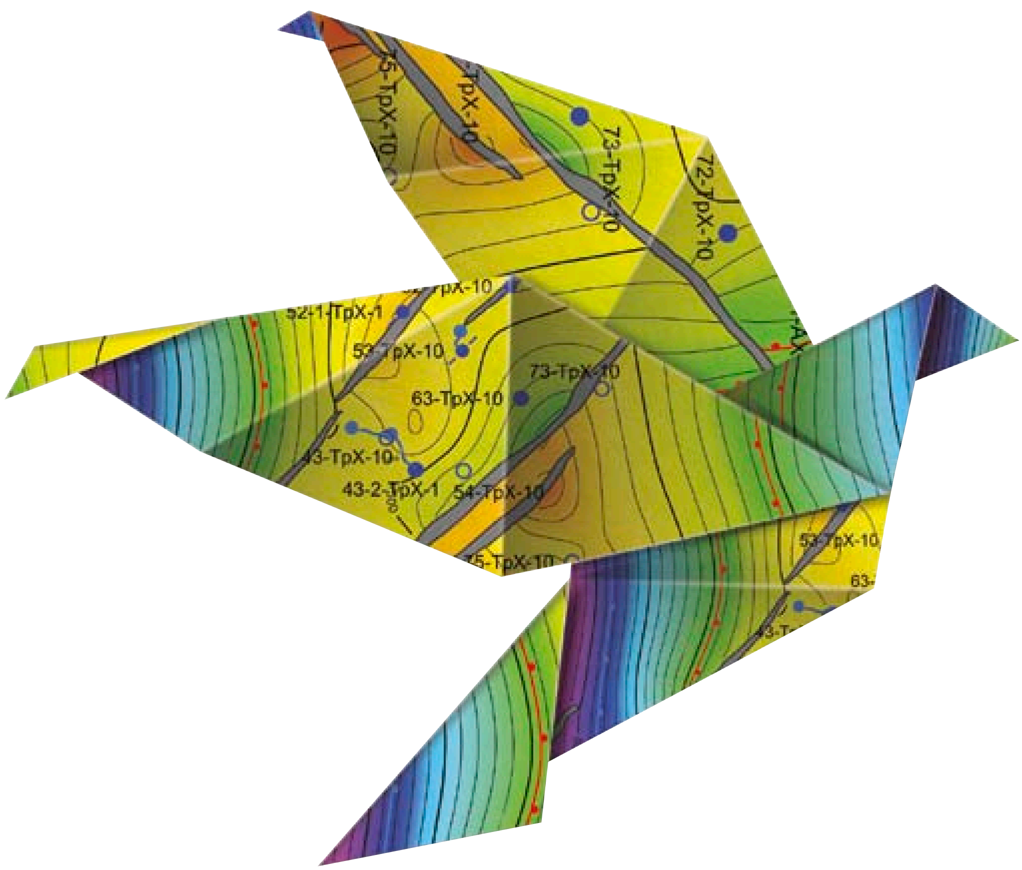
Carrying on up the pass, you will see a sign for Parker Ridge, which is an excellent place to stop and hike up the ridge and see the surrounding glacier as well as some fossil corals buried in dark dolomitic lime mudstone of the Devonian Southesk Formation – but remember that fossil-collecting is not allowed in National Parks. The view from the top of the ridge to surrounding peaks and rock formations is breathtaking.

The Icefields Information Center is worthy of a stop, and visits can be made to the Icefield proper and to the Snow Dome. This is a special place because it is the center of the Continental Divide: to the west, all water drains to the Pacific, to the north via the Athabasca and Sunwapta Rivers it drains to the Arctic, and to the south-east via the North Saskatchewan River to the Atlantic Ocean.

Carrying on past the Icefield Center you lose elevation on a winding road with breathtaking views, passing through a 'shooting gallery' of random blocks of pink Gog quartzite boulders which are shed from the above outcrops.

Many Photo Opportunities!

Following the Sunwapta River, you eventually reach a stop for the Sunwapta Falls, where the river drops about 100m in stages down through the resistant limestone and dolomite of the Snake Indian Formation into the Athabasca River valley.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Maligne Canyon, a 55m deep gorge carved through Palliser Limestone, possibly a cave prior to glaciation.

Further along, you can stretch your legs at Athabasca Falls where large volumes of glacial melt water pound down 13m of McNaughton (Gog) quartzite.

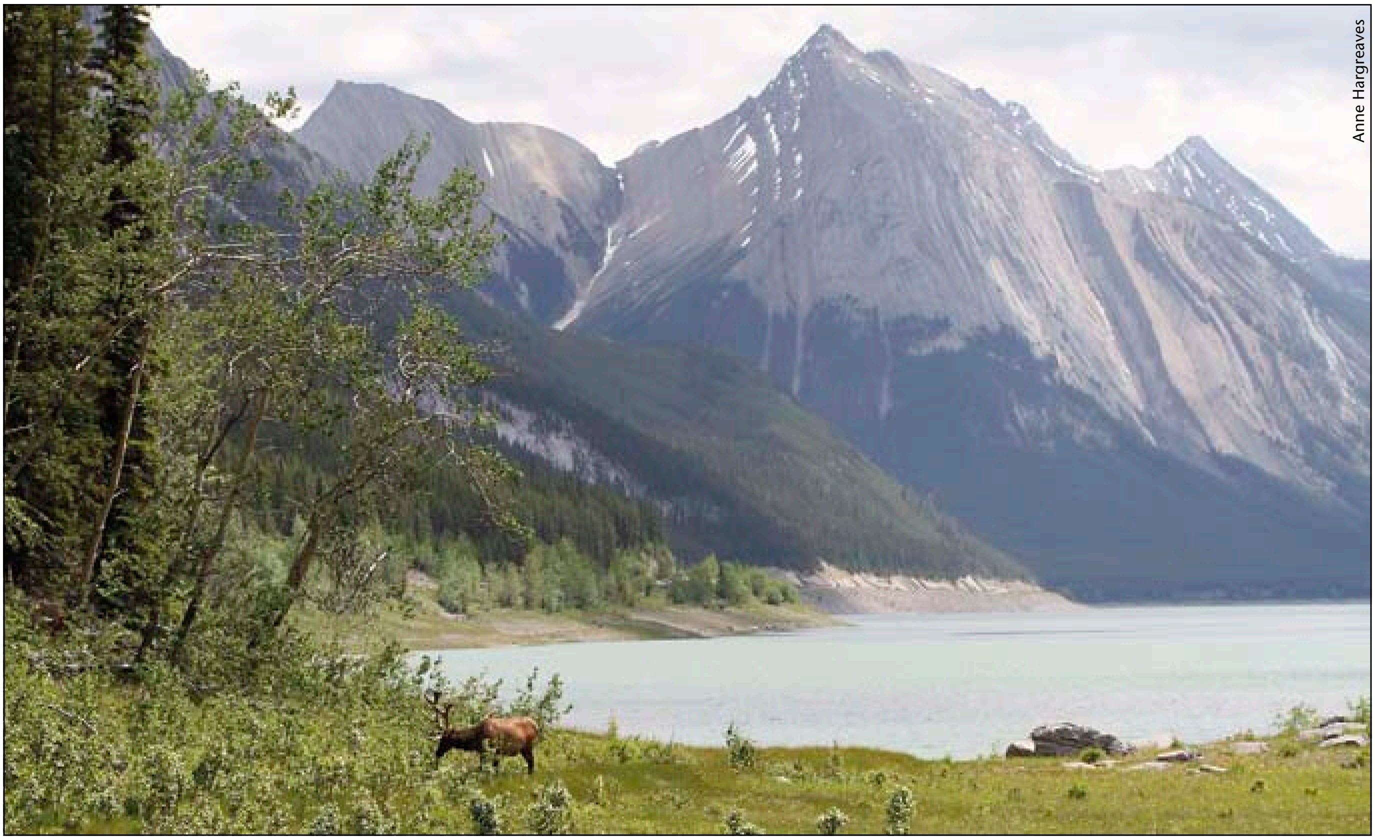
As you near the town of Jasper, keep an eye out for the exit to Mt Edith Cavell and Angel Glacier. They are located approximately 14 km south-west of Jasper following a switch-backed paved road up an alpine cirque. The massive quartzite McNaughton Fm, part of the Gog group, towers 1,400m above you. You can hike around small icebergs in Cavell Pond, which have calved from the Cavell Glacier nearby.

Approaching Jasper, the valley lies in Miette group deposits. The Fairmont Jasper Park Lodge is worth a visit as it dates back to the early part of the previous century and has a beautiful setting and excellent restaurants, although it is several kilometers east of the Jasper townsite.

After passing the turn to the lodge, carry on up to Maligne Canyon. Maligne Canyon is a 55m deep canyon carved in Palliser Limestone. It is fed by underground rivers flowing out of some type of cave karst river system flowing from Medicine Lake as well as Maligne River at surface. Medicine Lake is a

Anne Hargreaves

Icefield immediately north of the Columbia Icefield, with Snow Dome and the Dome Glacier. The Continental Divide, from which water flows in three different directions, peaks from a point on the Dome Glacier.



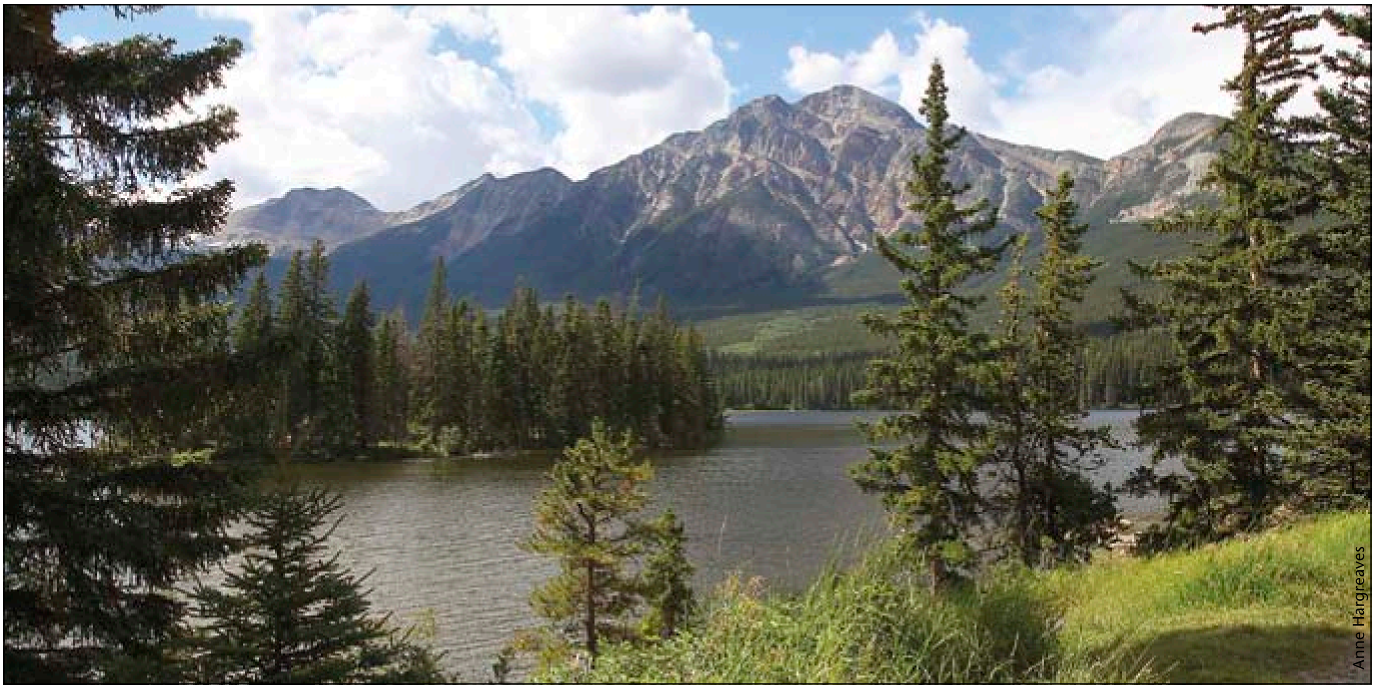
Elk at Medicine Lake, which was dammed by a rockslide. There is no visible exit for the water as it disappears below the surface into a karst system.

beautiful lake in the spring and summer, but low water flow in the fall and winter means that it dries up, refilling when the spring meltwaters begin to flow.

Other options for stunning views in the Jasper area are to take the Jasper Tramway up to the top of the Whistlers Mountain, or to drive to Pyramid Lake just north of Jasper with the Gog quartzite Pyramid Mountain rising above it.

There are so many boat and bicycle routes in the area to explore as well as hiking trails, a week could easily pass by. Jaspar has a very unique flavor, as most of the shops, restaurants and cafés are locally owned and operated. VIA Rail Canada has a station in Jasper, allowing you to take a scenic train ride to Vancouver, Prince Rupert or even out of the mountains and across the prairies and Canadian Shield to Toronto. ■

Pyramid Lake and Pyramid Mountain, comprised of the Gog Group.



Broadband Seismic Technology and Beyond

PART II: EXORCIZING SEISMIC GHOSTS

LASSE AMUNDSEN, Statoil and
MARTIN LANDRØ, NTNU Trondheim

"I wouldn't describe myself as lacking in confidence, but I would just say that – the ghosts you chase you never catch"

***John Malkovich** (1953–)*
American actor, producer and director

The ghostly Brown Lady of Raynham Hall, caught in a (possibly not authentic) photograph in 1936.

Country Life Magazine

Ghosts have always held some degree of fascination, thanks to hundreds of books and movies devoted to the subject. One of the scariest films of all time is The Exorcist, a 1973 horror film which deals with the demonic possession of a young girl and her mother's desperate attempts to win back her daughter through an exorcism. Ghosts are also present in seismic recordings and must also be exorcised.

To understand how geophysical priests exorcize seismic ghosts, either through developing sensor technologies or new data processing methods, you need to understand what ghosts are and how they band-limit seismic data. Like John Malkovich, geophysicists do not lack confidence, but we believe our profession may never be fully successful in catching and exorcizing the seismic ghosts. The real-world problem is too tough. We give you the history.

Broadband Seismic Towed-Streamer Methods

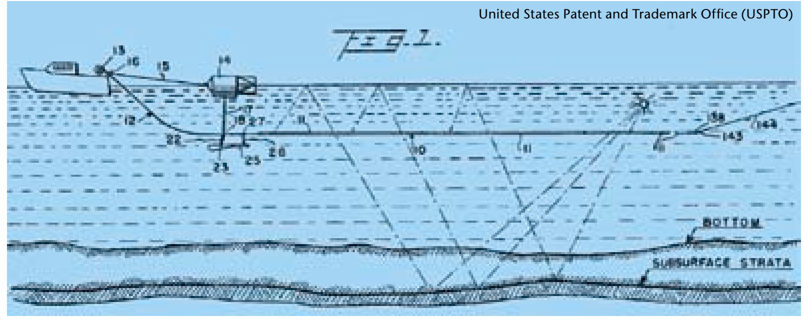
Conventional marine seismic acquisition techniques record data over a useable frequency range of typically 8 to 80 Hertz. A seismic section with this bandwidth can resolve reflectors separated by about 20–25 ms. This resolution is adequate for mapping medium to large geological structures with simple stratigraphy. However, in areas having complex geological features, conventional data hide the details required to fully assess the exploration potential.

One of the major factors hampering marine seismic resolution is the ghost effect – the result of reflections from the sea surface. Ghost reflections interfere constructively or destructively with the primary reflections, thereby limiting useable bandwidth and data integrity due to notches at particular frequencies. The notch frequencies depend on the respective depths of the source and receiver. For example, a depth of 6m produces a notch at 0 and

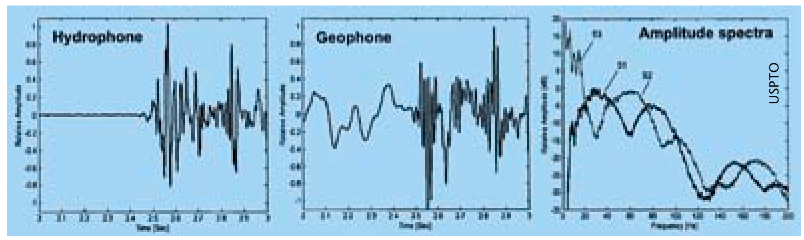
125 Hz, while a 20m depth produces notches at 0, 37.5, 75, and 112.5 Hz (*See figure on page 91*). Some control can be exercised in acquisition by varying the depth of the source and streamers, but the full bandwidth remains compromised.

Acquisition and processing solutions to address the receiver ghost problem were introduced in the mid-1950s, with significant technological progress having been made over the last five years. Major developments include the hydrophone-geophone (P-Z) streamer; over/under streamers; slanted streamer; GeoStreamer, P-Z; BroadSeis, variant of slanted streamer; and the multicomponent streamer, IsoMetrix.

Hydrophones measure pressure (P) changes, while geophones and accelerometers are sensitive to particle motion. The hydrophone is omni-directional and measures the sum of upgoing and downgoing pressure waves. The vertically oriented geophone (Z) has directional sensitivity and measures their difference.



Drawing from Pavey and Pearson (1966), who proposed combining hydrophone and geophone measurements to attenuate the effect of ghost reflections from the sea surface.



Hydrophone and geophone measurements at 13m depth with amplitude spectra from Vaage et al. (2005). The noisy low-frequency part of the geophone signal (53) is recalculated from the recorded pressure signal below ~18 Hz using the Z-P model (see box) and merged with the non-noisy geophone signal before deghosting.

Significant Developments

By 1956, Haggerty from Texas Instruments had patented methods for canceling the ghost reflections and reverberations in the water-layer by deploying hydrophones and geophones, and over/under streamers. His analysis was based on the theory of standing waves. Today, history shows that Haggerty was 50 years ahead of time.

Pavey and Pearson from Sonic Engineering Company described in 1966 how the frequency components that are canceled on hydrophone recordings due to the ghost can be replaced by the use of geophones. However, it was found that the combination of P and Z signals tended to degrade the S/N-ratio of the lower frequencies in the seismic band. The Z-sensor had high noise caused by the specific mounting of the sensor and the rotation of the towed cable.

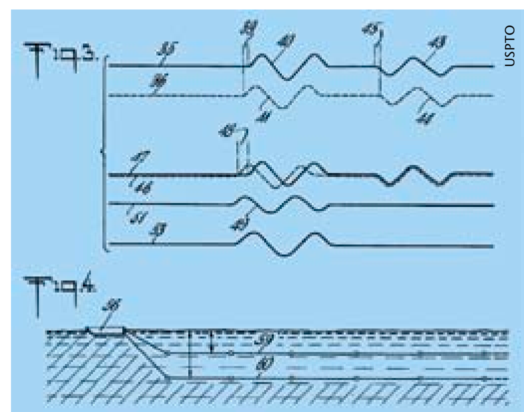
Berni in Shell Oil (1982–85) developed the geophone principles further. The first successful P-Z marine streamer, PGS' GeoStreamer, was described by Vaage *et al.* (2005). In addition to the deghosting advantage, the GeoStreamer reduces weather noise and increases acquisition efficiency by extending the weather acquisition window.

In 1976 Parrack from Texaco patented the use of streamers that are spaced apart vertically to cancel the downgoing ghost signals from the sea surface. The first practical 2D applications of the over/under streamer method started in 1984 in the North Sea, driven by ideas from Sønneland in Geco. The method was introduced as a means to reduce the weather downtime by deploying two streamers on top of each other at large depths, such as 18m and 25m, to minimize the effect of swell noise. In addition, it allowed deghosting. The over/under acquisition, however, had limited applications during that period due to deficiencies in marine acquisition technology related to lack of streamer control in vertical and horizontal planes.

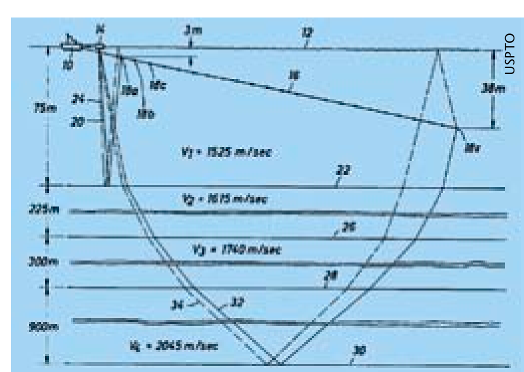
With the introduction of new marine acquisition technology that has accurate positioning and advanced streamer control, the over/under method has been used for the last six years, mainly for 2D applications.

Slant streamer marine acquisition was first proposed by Ray and Moore (1982) from Fairfield Industries. The novel idea of this method was to have variable receiver depths along streamers and, inherently, variable ghosts from receiver to receiver, and to take advantage of this in the stacking process. However, slant streamer acquisition was not successful at that time due to inadequate data processing algorithms, particularly for the ghost-removal process.

Today, variants of the slant streamer idea have been implemented by



Drawing from Parrack (1976), who proposed using over/under streamers to cancel the downgoing ghost signal. The two upper traces show that the ghost (45) arrives first on the upper cable (35) then on the lower cable (36). By aligning the ghost arrivals and subtracting, the trace (51) is ghost-free.



Drawing from Ray and Moore (1982), who proposed a 'high resolution, high penetration marine seismic stratigraphic system' where a slanted cable gathers seismic reflections so that the primary and ghost reflections from a common interface are gradually spaced apart.

CGGVeritas (BroadSeis) and by WesternGeco (ObliQ).

The concept of multicomponent towed streamers was introduced by Robertsson *et al.* (2008). The system, now called IsoMetrix, measures pressure with hydrophones, and particle acceleration in y- and z-directions with micro electromechanical systems (MEMS) accelerometers. Based on these measurements crossline wavefield reconstruction and deghosting can be performed (*GEO Expro* Vol. 9, No. 5).

Ghosts

The effect of the sea or land surface is a well-known obstacle in seismic exploration and has been addressed since the outset of reflection seismology (Leet, 1937). Van Melle and Weatherburn (1953) dubbed the reflections from energy initially reflected above the level of the source, by optical analogy, 'ghosts'. Lindsey (1960) presented a ghost removal or deghosting solution by observing that a downgoing source signal of unit amplitude followed by a ghost with time lag $\tau_0=2z/c$, here represented in frequency domain by the function $G = 1 + r_0 \exp(i\omega\tau_0)$ can be eliminated theoretically by applying the inverse filter $D = 1/G$ to the data: $D\,G = 1$. Here, r_0 is the reflection coefficient at the overlying boundary, $k = \omega/c$ is the wavenumber, $\omega=2\pi f$ is the circular frequency, f is the frequency, c is the propagation velocity, and z is the source depth.

In marine seismic surveying, the time domain pressure pulse that is emitted by the single airgun in the vertical direction is called the pressure signature. The pressure pulse that travels upward from the source is reflected downward at the sea surface and joins the initially downward-traveling pressure pulse. This delayed pulse, reflected at the sea surface, is called the source ghost.

Also on the receiver side the sea surface acts as an acoustic mirror, causing receiver 'ghost' effects in recorded seismic data. While the reflections from the subsurface move upward at the receiver, the receiver ghosts end their propagation moving downward at the receiver.

Ghost Effect on P

In the following, we discuss receiver ghosts – source ghosts were discussed in *GEO ExPro* Vol. 7, No. 1 on Marine Seismic Sources. We assume that the reflection coefficient at the sea surface is $r_0=-1$.

Consider conventional pressure recordings at depth z. As seen from the illustration on the page opposite, the ghost is delayed with travel time $\tau = \tau_0/\cos\theta$ relative to an incident plane wave that has a propagation angle θ to the surface. The composite signal (primary and ghost), that is the ghost function, in the frequency domain then can be written $G_-=1-\exp(i\omega\tau)$.

The frequency spectrum of this composite signal, $|G_-(f)|=2\sin(2\pi fz\cos\theta/c)$, has zeroes or 'notches' at frequencies $f_n=nc/(2z\cos\theta)$ $(n=0,1,2,\ldots)$, where the interference between signal and ghost is destructive. The first notch is always at 0 Hz. The second and following notches are steered by the depth z. As a result there is a strong loss of useful low-frequency energy in pressure seismic data, in addition to similar losses at the second and higher notch frequencies. On the other hand, constructive interference occurs at frequencies intermediate adjacent notch frequencies, leading to maxima in the amplitude at these frequencies.

One of the goals in broadband marine seismic acquisition is to deliver data rich in both low and high frequencies. The challenge of increasing low-frequency while maintaining high-frequency content is caused by the receiver ghost effect. Towing streamers shallowly favors the higher frequencies at the expense of attenuating the low frequencies, while towing streamers deeper favors the lower frequencies, at the expense of attenuating frequencies within the seismic bandwidth.

Ghost Effect on Z

Today's most advanced streamer technologies record both particle velocities and pressure. The hydrophone is omni-directional and measures the sum of upgoing and downgoing pressure waves. The vertically oriented geophone has directional sensitivity and measures their difference. Therefore, in *Z*-recordings the ghost has opposite sign compared to that in *P*-recordings: $G_+ = 1 + \exp(i\omega\tau)$. Its frequency spectrum reads $|G_+(f)|=2\cos(2\pi fz\cos\theta/c)$, and has notches at frequencies $f_n = (2n+1)c/(4z\cos\theta)$, lying mid-between the notches in the *P*-recordings. Thus, hydrophones and geophones give complementary information. Where the hydrophone has zero sensitivity due to the ghost, the *Z*-geophone has its maximum sensitivity, and vice versa.

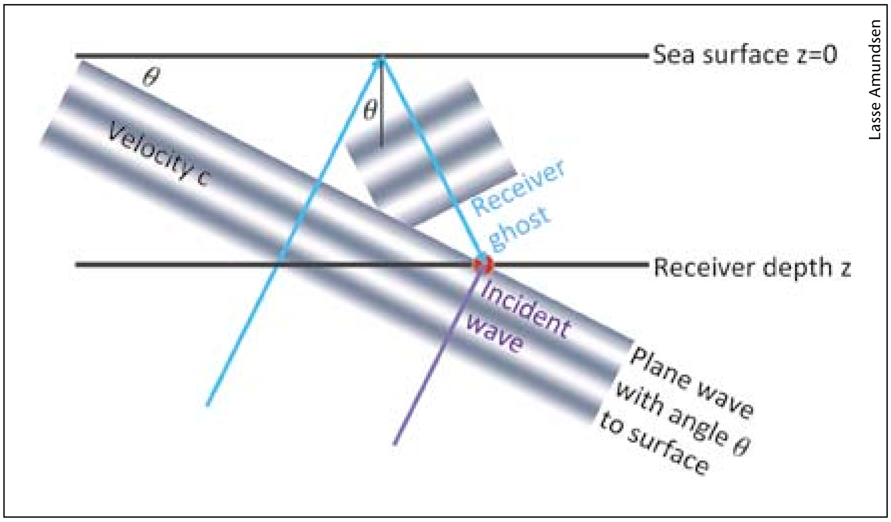
Let *R* denote the 'reflection response' of the subsurface (including the source ghost). Then $P\sim R\,G_-$ and $Z\sim R\,G_+$. It now follows that you can exorcize the receiver ghost by summing *P* and *Z* (when *Z* is properly scaled to *P*) since $(1/2)(P+Z)=R$. Thus, receiver side deghosting, equivalent to computing the upgoing component of the pressure field, can be done from *PZ* measurements. This is a fundamental basis of both PGS's GeoStreamer solution and WesternGeco's IsoMetrix solution.

Deghosting by PZ Summation

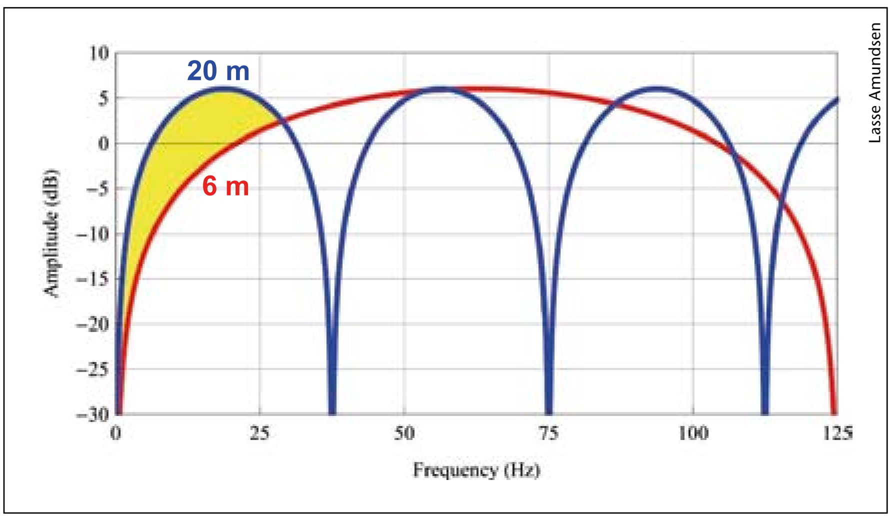
However, for low frequencies, below 15–20 Hz, depending on the particular acquisition system and weather, the *Z* recordings are too noisy to be used in *PZ* summation. The solution to this problem was developed and implemented by PGS in the GeoStreamer. The straightforward combination of the two equations, $P\sim R\,G_-$ and $Z\sim R\,G_+$, gives the *Z-P* relationship, first published in *Geophysics* by Amundsen (1993): $Z\sim(G_+/G_-)P$.

Thus, for the low frequencies where *Z* is noisy, *Z* can be estimated from P by deghosting the pressure (multiplying *P* by $1/G_-$) and ghosting the result (multiplying by G_+). Then, this estimate of *Z* is used at low frequencies whereas the *Z* measurements are used at higher frequencies in deghosting. The *Z-P* model is used also in 3D deghosting of WesternGeco's IsoMetrix measurements, not to replace low-frequency *Z* data but rather to further constrain the cross-line reconstruction problem.

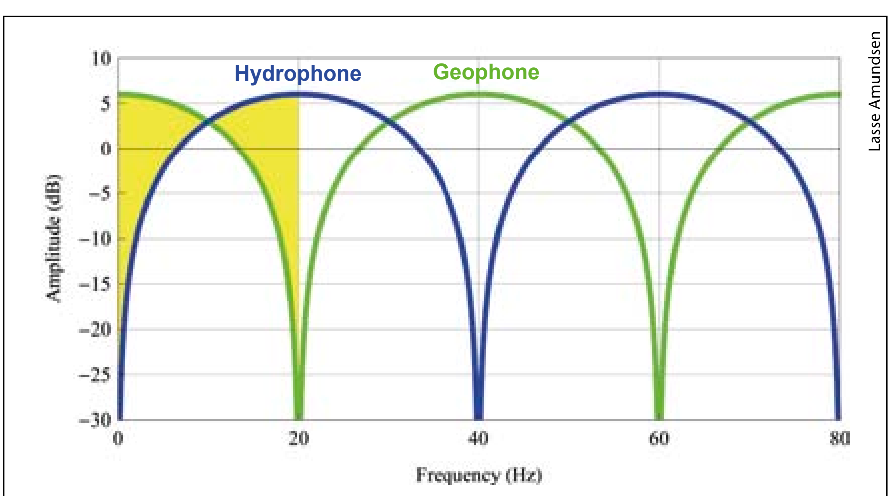
We observe that *P-Z* sensor streamers have no direct benefits for low frequency recording as they use only the hydrophone at low frequencies; the geophones are used to infill the higher frequency ghost notches. To get high-quality pressure measurements at low frequencies, the cables must be towed deep where the pressure ghost notch has minimum effect and the *S/N* ratio is good. ■



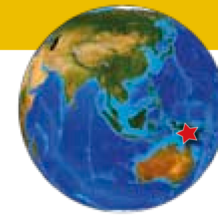
A plane wave with angle θ to the surface is incident at the receiver (red circle). The ghost is delayed with time $\tau = 2z/(c \cos\theta)$. The rays that are normal to the plane wave denote the direction of the wave.



Ghost responses that modulate pressure recordings for deep-tow at 20m and shallow-tow at 6m. The ghost amplifies some frequencies (amplitude >0 dB) and attenuates other frequencies (amplitude <0 dB). By towing deeper the pressure signal is improved below ~30 Hz. Although deep-tow yields nice low-frequency characteristics, the second notch at 37.5 Hz has a detrimental effect on resolution.



Receiver ghost responses for hydrophone and geophone at 18.75m depth. The geophone has maximum response (+6 dB) where the hydrophone has notch, and vice versa. For the low frequencies, the real geophone signal is too noisy, and deghosting is achieved using the geophone-hydrophone model.



Port Moresby
Colorful but Troubled

Despite having a dangerous reputation, Port Moresby, the capital of Papua New Guinea, is expanding fast, principally as a result of a major LNG project

ELEANOR ARCHER

Repeatedly finding itself in the not-so-coveted category of the top five least liveable cities in the world, according to the Economist Intelligence Unit, Port Moresby has not made a good name for itself. The capital of Papua New Guinea, it has become infamous for robbery, rape and murder, with low stability, poor health care and lack of infrastructure. 'Raskol' gangs control vast areas, and the murder rate is, according to the UK Home Office, three times that of Moscow, and 23 times that of London. Yet despite this ominous overview, there is much more to Port Moresby than statistics and gang culture.

Colorful History

Port Moresby lies on the south-eastern coast of the Papuan Peninsula of New Guinea, separated from the northern parts of the island by a cordillera which runs the length of the New Guinea Mainland. The country is made up of the mainland and around 600 offshore islands, and is home to about 5.1 million people. With over 800 languages spoken, Papua New Guinea has a rich and diverse culture, with Port Moresby at the center of its colorful history.

The native people of Port Moresby, the Motu and the Kiotabu, were sea-going people, who lived in houses built on stilts in the harbor. The men sailed across to the Gulf of Papua in what was called the Hiri voyages, trading Motu cooking pots with the Erama (Gulf) people in exchange for sago, a major staple food in New Guinea. The expeditions were huge and highly dangerous; up to 20 canoes, holding around 600 men and laden with 20,000 clay pots, would brave the treacherous journey to bring back food for their families. These voyages are still commemorated today in what is called the Hiri-Moale festival.

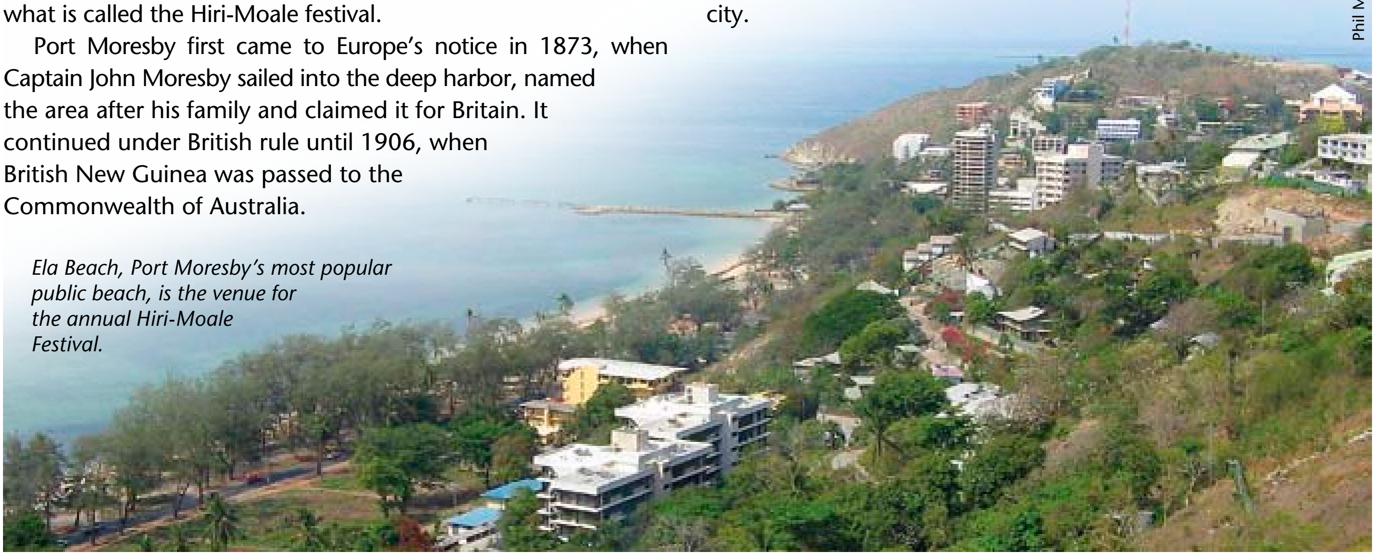
Port Moresby first came to Europe's notice in 1873, when Captain John Moresby sailed into the deep harbor, named the area after his family and claimed it for Britain. It continued under British rule until 1906, when British New Guinea was passed to the Commonwealth of Australia.

Port Moresby played an important part in battles during WWII. Its position on the south-eastern coast made it a prime objective for the Imperial Japanese forces, as a staging point and air base to cut off Australia from South East Asia and the Americas. Despite air raids and attempts at invasion, the Japanese ultimately did not succeed, and in 1945, Port Moresby became the capital of the newly combined Australian territories of Papua and New Guinea. In 1975 Papua New Guinea claimed independence, choosing Port Moresby as the capital of the new state. The population of the Port Moresby area expanded rapidly after independence. In 1980 the census registered 120,000; by 1990, this had increased to 195,000 and it now reaches over 300,000.

Major LNG Project

The population of Papua New Guinea is as diverse as the terrain.

In recent years, Port Moresby has come to play an important role in LNG export. A new project was set up in the city, championed by ExxonMobil, after three large gas discoveries, Hides, Angore and Juha, were found in the southern and western highlands of the country, with reserves approaching 4 Tcf. A two-train LNG facility is being constructed at Napa Napa, near Port Moresby, with cargoes due to start in 2014, and the PNG LNG project is expected to produce 9 Tcfg during its 30-year life span. The project claims to have the potential to transform the economy of Papua New Guinea, boosting GDP and export earnings and providing a major increase in government revenue, as well as creating employment opportunities during construction and operation. Only time will tell what impact these developments will have on the world's 'least liveable' city.

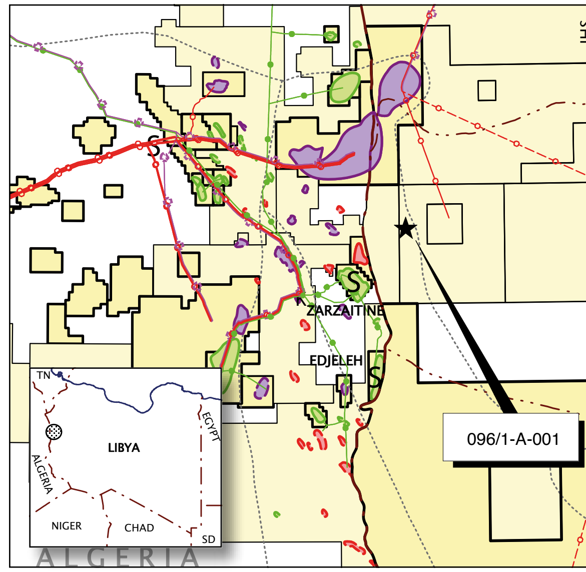


Ela Beach, Port Moresby's most popular public beach, is the venue for the annual Hiri-Moale Festival.

LIBYA: First Success for Sonatrach

Sonatrach's first well on what is highly prospective acreage has been completed as an oil and gas discovery. Wildcat **A1-96/1** is in Area 96 in the Ghadames Basin, about 650 km south-west of Tripoli and very close to the border with Algeria. The well, drilled by its SIPEX subsidiary, was tested flowing 2,188 bpd of 45° API oil and 1.5 MMcfgd between 1,881 and 1,884m in the Devonian Tahara Formation. Area 96 was awarded in Dec 2007 with a work obligation that includes the acquisition of 2,600 km² of 3D seismic, 2,000 km of 2D seismic and the drilling of eight wells within the first five years.

Sonatrach resumed exploratory operations in Libya in June 2012, following a suspension for more than a year due to security concerns caused by the February 2011 uprising. The country's oil production had come to a virtual standstill by the summer of 2011 but bounced back to about 1.4 MMbpd in January 2013, according to official data. With the oil sector the mainstay of the economy, Libya aims to increase its oil production to 1.7 MMbpd by the end of 2013, even though recent events would suggest security remains precarious. Interests in Area 96 are held by SIPEX (operator, 50%), Indian Oil Corporation (25%) and Oil India (25%). ■



QATAR: First Gas Discovery in 42 Years

Operating the 544 km² offshore Block 4N (Khuff) concession, Wintershall has successfully appraised its **WIQ4N-1** gas discovery of 2011 and has established the find as a major gas field with in-place resource of around 2.5 Tcf. The first appraisal, **WIQ4N-2**, is believed to have been suspended early in 2013 after an extensive testing program that lasted for much of the second half of 2012. A second appraisal is due to get underway shortly to further define the country's first gas discovery in the 42 years since it established the North Field, with reserves in excess of 850 Tcf, as the world's largest gas field. Energy Minister Mohammed bin Saleh Al-Sadah, who is also managing director of Qatar Petroleum, said the Wintershall discovery was part of an effort by the country to "prudently explore for and develop our natural resources" and that it will contribute to the country's economic prosperity.

Block 4N is located in around 70m of water to the north of Qatar and is in direct proximity to the North Field. Interests are held by Wintershall (80%) and Mitsui (20%). Wintershall is also operator for the 1,665 km² offshore Block 3, which was awarded in 2007. The first 3D seismic surveys in this area were completed in summer 2010 and two wells are due to be drilled in 2013. ■

The new find is the first gas discovery in Qatar since the vast North Field. Gas from this is processed at the Pearl Gas-To-Liquids plant, the largest GTL project in the world.

CHILE: Gas Find

GeoPark Holdings says its **Palos Quemados 1** wildcat in the Tranquilo Block, Magallanes (Austral) Basin in the far south of the country is a gas discovery that has major implications for the area. The well was drilled to a total depth of 1,600m and a test conducted in the El Salto Formation, at approximately 805m, yielded a flow of 4 MMcfgpd through a 10 mm choke and with a well head pressure of 1,050 psi. Longer term production testing will be required to determine stabilized flow rates and the extent of the reservoir. The Palos Quemados 1 well is located approximately 6 km from a regional gas pipeline and studies are underway to assess facilities needed to connect the gas to market.

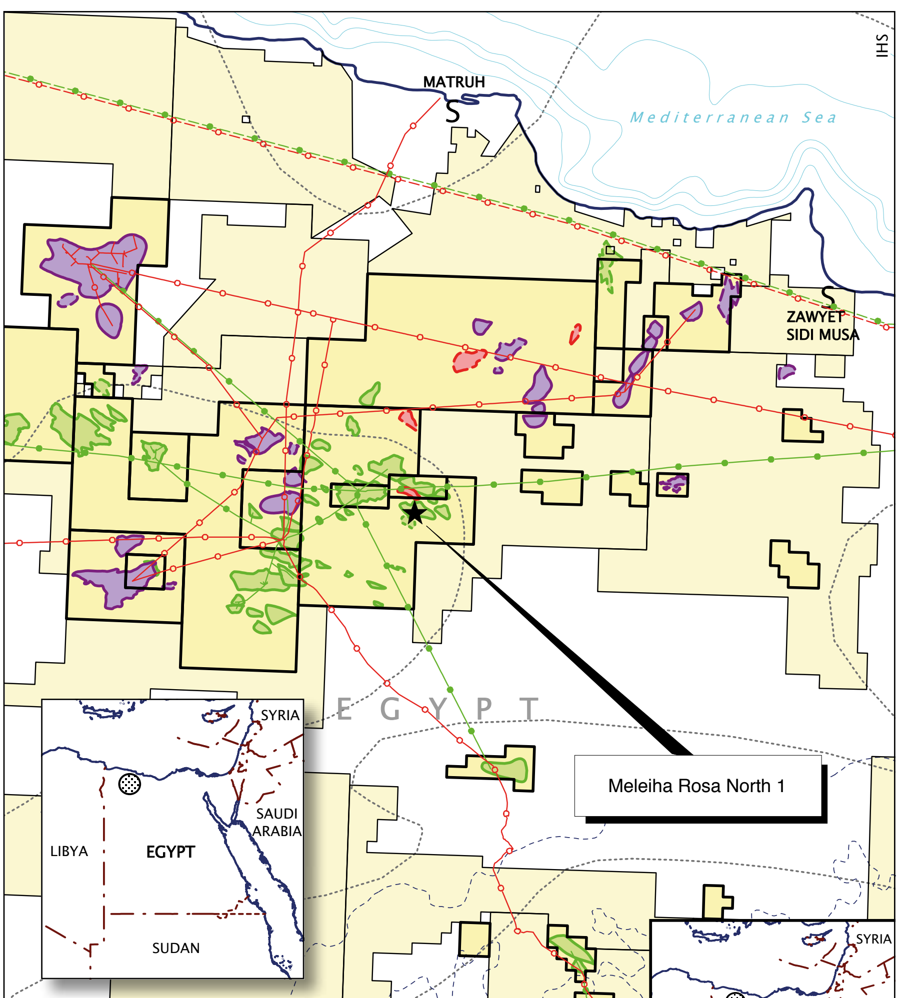
Significantly, Palos Quemados 1 is the first gas discovery in the Magallanes Fold and Thrust Belt in more than 40 years, prompting the GeoPark's chief executive officer, James F. Park, to say, "The result from this new gas field discovery in Palos Quemados is significant because it confirms the exploratory potential and prospectivity of the western part of the Magallanes Basin where additional opportunities have been identified." Prior to this result GeoPark, the largest privately owned producer in Chile, had formally advised the Ministry of Energy that the partners in the Tranquilo block had elected to not proceed with the second exploratory period, relinquishing all but a 374 km² area that consists of protected exploitation zones for the Cabo Negro, Marcou Sur, Maria Antonieta, and Palos Quemados prospects.

GeoPark Magallanes Ltda. operates the Tranquilo Block with 29% interest on behalf of its JV partners Pluspetrol Chile Corp (29%), Wintershall Chile Ltda. (25%) and Methanex Chile SA (17%). ■

EGYPT:
Deeper Western Desert Play

Eni has made a new oil discovery with its **Meleiha Rosa North 1X** wildcat located in the Meleiha Concession, in the Western Desert of Egypt, a second success in the company's strategy to refocus exploration activities in Egypt by targeting deeper oil plays in the area. Located in the Meleiha block, onshore Shoushan sub-basin, the well encountered a total pay of 80m of multiple good quality sandstones of the Bahariya, Alam El Bueib, Khtatba (Upper and Lower Safa) and Ras Qattara formations. Tests have yielded a 43°–48°crude at good rates and at least two development wells are planned in 2013. Each is expected to yield 2,000 bopd with output delivered to the nearby processing facilities at the Meleiha field.

The Western Desert's deeper potential has been boosted over the past year with the company also scoring another sizable discovery in May 2012 with the Emry Deep 1 wildcat. Drilled to a total depth of 3,628m it encountered over 76m of net pay in multiple sandstones of the Lower Cretaceous Alam El Bueib Member. The company estimates the resource at 150–250 MMbo in place with production now exceeding 18,000 bopd. The short time to market of these discoveries is in line with Eni's strategy to focus on fast-track development of conventional oil assets. This latest result confirms that the Meleiha Concession still holds significant un-tapped deep exploration potential that has been enhanced by the recently acquired 3D seismic and the new geological models derived from it. ■



SHAPING A NATION: A Geology of Australia

Shaping a Nation: A Geology of Australia. Geoscience Australia, 2012, Richard Blewitt, Chief Editor, 571 pages

Australia's defining moment came 34 million years ago when the continent rifted from Gondwana. The separation released it from cold high-latitudes, allowing it to drift northward into the subtropical high, where it has been for the last 10 million years.

The continent itself is, however, home to some of the oldest rocks in the world, some dating back to 3.7 billion years. Even more intriguing, a detrital zircon grain from Western Australia has an age of more than 4.4 billion years. (The Earth is close to 4.6 billion years.)

This voluminous book about the geology of (mostly onshore) Australia is not another book about rocks, minerals and fossils catalogued through time. It is thus not only about how the geological history has shaped the continent where the Aussies live, it is also about how the geological history has influenced Australia's human history and the way they live. It is about how underlying geology has created a nation and a society.

We therefore totally agree with Martin Ferguson, Minister for Resources, Energy and Tourism, who says in the introduction that this book 'demonstrates the fundamental importance of the study of Earth sciences to our society'.

For this reason, this well-illustrated book is quite different from many other popular geoscience books, just because it emphasizes why geology is important to our society – which also explains why it does not start with the birth of the Solar System, continue with the Precambrian and end up in the Quaternary. While geological time is key to the understanding of geological history, it is even more important to realize that we study geology because we can make use of geological knowledge to shape a nation. This is what makes this book unusual. And – above all – interesting to read.

Wide Range of Topics

Consequently, the eleven chapters deal with topics like 'Groundwater – lifeblood of the continent'; 'Foundations of wealth – Australia's major mineral deposits'; and 'Deep heat – Australia's energy future'.

True to its intentions, the book starts with a chapter about the demography, history and culture of 'Australia and the Australian people', including geography (nicely illustrating that its size is equivalent to the US lower 48), landscape ('the flattest on Earth'), climate (flush with ultraviolet light resulting in the highest skin cancer rates in the world), flora (certainly a lot more than the plentiful fossil record), fauna (of the 869 reptiles, 773 are found nowhere else), resources (utilization started with the aboriginals, while the discovery of copper saved the colony from early ruin) and geohazards (largely cyclones, floods, droughts, heatwaves and bushfires).

Chapter 4 – Out of Gondwana – will probably be the favourite for petroleum geoscientists who want to know more about the Australian petroleum systems. Above all, it shows how Australia

Weathering has resulted in the formation of abundant iron oxides, giving the Australian landscape its distinctive red colour. Ayers Rock (Uluru) is probably the most famous landform in Australia. It consists of steeply dipping sandstones of Cambrian age and stands some 348m above the surrounding plane. Australia is largely covered by weathered rocks (regoliths), and Ayers Rock can be looked upon as an erosional remnant.

Ingvild Carstens

Old – Very Old

The closest we get to a geochronological order is Chapter 3 that deals with 'Living in Australia'. We learn about the evolution of life based on a Gondwanan legacy, but with a flora and fauna made largely unique because of the continent's separation from others over most of the Cainozoic.

Australia has large areas of undeformed crust, and in the Pilbara Craton (Western Australia) stromatolites have been found that may be 3.5 billion years old. These stromatolite fossils set a minimum age limit for the origin of life on Earth.

In the same area, spectacular modern examples of stromatolites can be studied in Shark Bay. This is also what makes Australia a great place to visit.

Stromatolites in Shark Bay.

emerged from the supercontinent of Gondwana, but the breakup process is closely linked to where coal, oil and gas are found. While Paleozoic basins contain some fossil fuels, the Mesozoic marginal basins, which were created as Gondwana broke apart, contain 90% or more of Australia's conventional oil and gas. Most of the oil was originally in the Gippsland Basin (between Australia and Tasmania). The majority of the gas accumulations are on the North West Shelf.

Petroleum exploration in Australia began in earnest in the 1860s, resulting in a few modest shows. Surface oil seeps are not common, meaning low activity for almost hundred years, and it was not until 1953 that the first flow of oil occurred (Rough Range 1 in the onshore Carnarvon Basin). By the early 1960s, the momentum on exploration had been built and discoveries came along with increased drilling. By 1972, all the major basins and petroleum systems that are today producing hydrocarbons had been found.

Australia is certainly a fascinating country: huge, by any standard, and tons of geology to offer that can be studied in a warm and pleasant climate. No one with an interest in geology should, however, ever consider going there without having spent considerable time on this book. It is a valuable trip planner for the curious geoscientist. ■

HALFDAN CARSTENS

Australia Booming

Australia's LNG and unconventional gas industry is booming – a good time for ION Geophysical, a leading provider of geophysical technology, services, and solutions for the oil and gas industry, to open their first GX Technology (GXT) processing center in the country. We talk to **Kelly Beauglehole**, Managing Director of GX Technology Australia Pty Ltd about this move.

Describe the O&G exploration industry in Australia at the moment.
The Australian O&G exploration industry is taking a substantial position in the world energy market, driven by the massive resources of the North West Shelf and by the enormous potential for unconventional hydrocarbon reserves. Conventional oil and gas exploration, development and production are booming due to investors' perception of abundant resources, proximity to major markets, and low sovereign risk. It was reported in 2012 that Australia is set to become the world's biggest liquefied natural gas producer by the end of the decade, with seven of the world's ten major LNG projects currently under construction.

There is a large unconventional resource in the country: is there a good appetite for exploring for this?
Exploration for unconventional hydrocarbon resources such as shale gas and oil, tight gas and oil, and coal seam gas has seen a resurgence with the maturing of technologies such as horizontal drilling and fracture stimulation. Geoscience Australia estimates that unconventional gas resources are likely to be considerably more than estimated conventional gas resources. This potential has prompted major oil companies such as Chevron, Total, Shell, Hess, and British Gas to commit to major onshore exploration programs. This international interest augments the existing work being done by Australian companies such as Santos, Beach, Origin, Buru, Finder, AWE and many others.

ION is in the process of opening its first office in Australia – why now?
We are responding to industry demand and also acting to fill a gap in ION's global coverage. Until now, ION was well represented with major centers in Houston and London supported by smaller centers in 18 other locations – but without a significant presence in South East Asia. Customer demand drove us to rectify this omission and, after an analysis of the region, Perth was selected as the optimum site to establish an office to represent ION's entire business profile, with special emphasis on the GeoVentures multi-client BasinSPAN products, and on GXT's processing capabilities. A formal opening ceremony is planned for June 2013.

We have been involved in the seismic technology industry for over 40 years, originally designing and manufacturing seismic equipment, but in recent years we have transformed our business so we now also provide a full range of seismic imaging services, technologies, and products such as depth imaging. As a result, ION's GXT group is well positioned to provide services through the exploration and development cycles for both conventional and unconventional hydrocarbon reserves in Australia.

What are the most significant recent geophysical developments for Australian exploration?
Viewed through the prism of my experience in the seismic imaging business, enormous improvement in data processing capability has been realized in the time since I joined GSI as a seismologist in 1980. I sympathize with the geophysics graduates joining the industry today who need to assimilate these extra 30 years of technological advances in their initial orientation. Some recent developments of note are the advances in offshore acquisition and processing strategies for broader bandwidth seismic resolution and effective amelioration of the source and receiver ghost, Reverse Time Migration for enhanced depth imaging in complex settings, and Waveform Inversion for development of high fidelity velocity models. In many cases with emergent seismic data processing technologies, the fundamental research was performed long ago but only the development of high performance computing has facilitated usage in routine exploration.

What are the most important factors and issues for the future development of the industry in Australia?
The North West Shelf LNG industry is in transition from an exploration to development phase, and investment in the production infrastructure is expected to peak in 2014. Production from these fields will continue for decades and the challenge will be to monitor and manage field development for optimum recovery. Technologies such as 4D seismic monitoring via permanent installations of ocean bottom nodes are important in this process, and here GXT can play a role with its expertise in seabed systems, 4D processing, and multi-component, full-wave imaging.

Onshore environmental sensitivities are important, and if we wish to emulate the US success story in the development of unconventional resources then strategies to reduce drilling costs need attention.

I have to ask – where does your unusual surname come from?
Unfortunately there aren't any colorful stories about my surname. My father's ancestors migrated to Australia in the mid 1800s from England and I am unsure whether their passage was assisted by the English government! I would like to think that there are some French or aristocratic origins to the name, but refrain from investigating in case the reality is less romantic. ■

ION GXT

Kelly Beauglehole is an Australian geophysicist who has been in the oil and gas industry for over 30 years, working for a range of geophysical service companies including GSI and Fugro.

The United States: Top Gas Producer

The International Energy Agency's (IEA) 'World Energy Outlook' for 2004 stated: "OPEC countries, mainly in the Middle East, will meet most of the increase in global demand. By 2030, OPEC will supply over half of the world's needs…" Now, fast forward eight years to their 'World Energy Outlook 2012' which now states: "The global energy mix is changing, with potentially far-reaching consequences for energy markets and trade. *It is being redrawn by the resurgence in oil and gas production in the United States…* [emphasis added]."

The US has passed Russia as the world's top gas-producing country and is projected to be the top oil producer by overtaking Saudi Arabia in four to seven years. This turnaround is largely driven by the technologies developed in the US that have unlocked tight oil and shale gas resources.

Increasing Production in Known Plays

Production from the known shale plays such as the Eagle Ford in Texas, Bakken in North Dakota, and a portion of the Marcellus in Pennsylvania and West Virginia continues to rise sharply. Production from nine Eagle Ford Shale fields increased from 183,000 bopd in October 2011 to over 323,000 bopd exactly a year later. The same can be said for the Bakken, where operators have more than doubled production in the past two years. Just over the last year, through to October 2012, production has increased from 488,000 bopd to over 747,000 bopd. Gas production from the Marcellus has also doubled over the last year at now over 7 Bcfpd, about 25% of the total US shale gas production. These one year production increases are impressive and drilling activity is expected to increase in 2013, exceeding the 2012 totals.

These known plays are expanding in areal extent as well. The North Dakota Bakken play is now heading west into Montana, back to where it began at the Elm Coulee Field. This play is also moving into new areas in North Dakota, as well as into South Dakota (Red River Play) and north into Saskatchewan and more recently Alberta, Canada (referred to as the Alberta Bakken). It is estimated that about $30 billion will be spent on the Eagle Ford shale play in 2013, a new record for the area. The Eagle Ford extends south-west into Mexico and east into Louisiana, where companies are starting to exploit the Tuscaloosa Marine Shale (TMS). This shale underlies the Eagle Ford (Eutaw in Louisiana) but the similarities make the two formations nearly indistinguishable. The Marcellus and other related shale plays in the north-east US are so big that only a very small portion has been exploited thus far.

Let us not forget conventional plays doing their part in US production resurgence. With newer production methods and better imaging, much more oil is being pumped out of old existing fields. Then there is the deepwater Gulf of Mexico; this area continues to yield new discoveries and production is increasing each month.

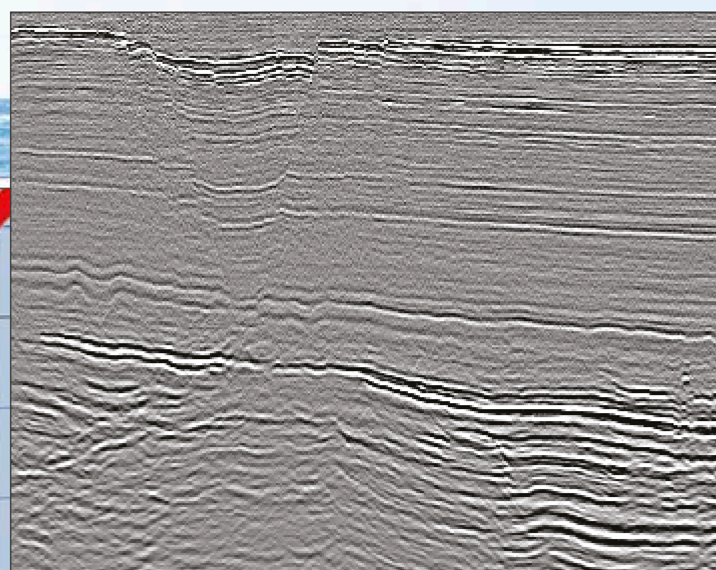
Emerging Oil Plays

Three new shale oil plays could make the Bakken and Eagle Ford look like small potatoes when all is said and done. In west Texas and eastern New Mexico, new shale plays blanket the 400 km wide by 480 km long Permian Basin. The Wolfcamp Formation is the source rock for much of the area's conventional productions. This shale ranges from 245m to over 600m thick and underlies huge areas. Estimated Ultimate Recovery (EUR) for wells in this interval is up to 37 MMbo. Pioneer Oil and Gas has several wells, still early in production, delivering 800 to 1,000 bopd. The Cline Shale, sometimes also referred to as the Wolfcamp, underlies an area covering roughly 25,000 km². The oil interval in this shale is up to 170m thick and is estimated to contain more than 30 Bb of recoverable oil, dwarfing the Bakken Shale estimates of 3.4 Bbo. Finally, there is the Bone Springs-Avalon (also called the Leonard) shale play that is very complex; however, some companies (Concho Resources to name one) have achieved outstanding results.

Moving on to the West Coast, the Monterey Shale has sourced most of the oil found in the very productive Los Angeles and San Joaquin basins. Most of the production from this shale to date has been from conventional reservoirs; however, that might be changing. With the EIA estimating that over 15 Bbo is at stake, oil and gas leasing in these areas is at a fast pace, with new companies opening offices in southern California.

A final shale play worth noting is being explored on the North Slope of Alaska. Great Bear Petroleum currently has over 2,000,000 km² under lease south of the Prudhoe Bay oil fields. They core-drilled two wells through the Shublik Formation, one of the primary source rocks for North Slope oil, and are evaluating results. If the play pans out, it could keep the Trans Alaska Pipeline System (TAPS) going for many years and create a new oil boom for Alaska.

THOMAS SMITH



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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.

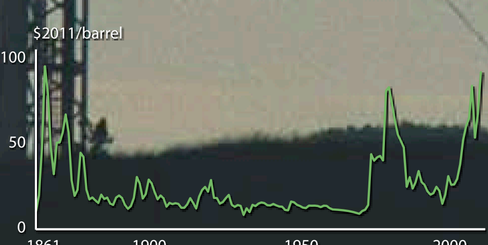
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

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

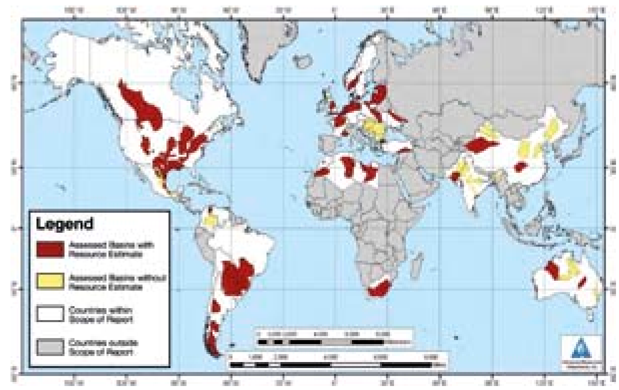
Historic oil price



A World of Plenty

Shale gas resources are potentially huge, but so far only the US that has taken advantage of this low permeability reservoir rock.

Shale gas has rejuvenated the natural gas industry in the US, starting in the 1980s and 1990s when engineers experimented with making deep shale gas production commercial in the Barnett Shale in Texas. By about 2005 output had reached 0.5 Tcf per year, and several other plays were being pursued in the lower 48 (e.g. Fayetteville, Haynesville, Marcellus and Eagle Ford Shales).



IEA has evaluated shale gas resources in 48 basins in 32 countries worldwide, concluding that this unconventional resource has gigantic potential, with a low CO_2 footprint compared to other fossil fuels.

Shale gas is nothing magical: it is natural gas trapped within its own source rock. Due to low permeability it cannot escape and migrate to nearby reservoir rocks. This is also why a combination of horizontal drilling and hydraulic fracturing is necessary to extract large volumes of shale gas. It is the development of these techniques that has made shale gas production a valuable venture, and which has increased US shale gas production by a factor of ten from 2000 to 2010. As a result, 23% of US gas production came from shales in 2010. The future also looks good: in 20 years' time shale gas production may constitute almost 50% of US natural gas production.

The US is no doubt in the lead. Driven by huge resources, innovative companies, dedicated people and a wish to be self-sufficient with respect to gas, it has transformed the world gas market. Shale gas is now also being explored and exploited in other parts of the world. But exactly how much can be produced is unclear – the only certainty is that the number of countries with potentially large resources grows steadily.

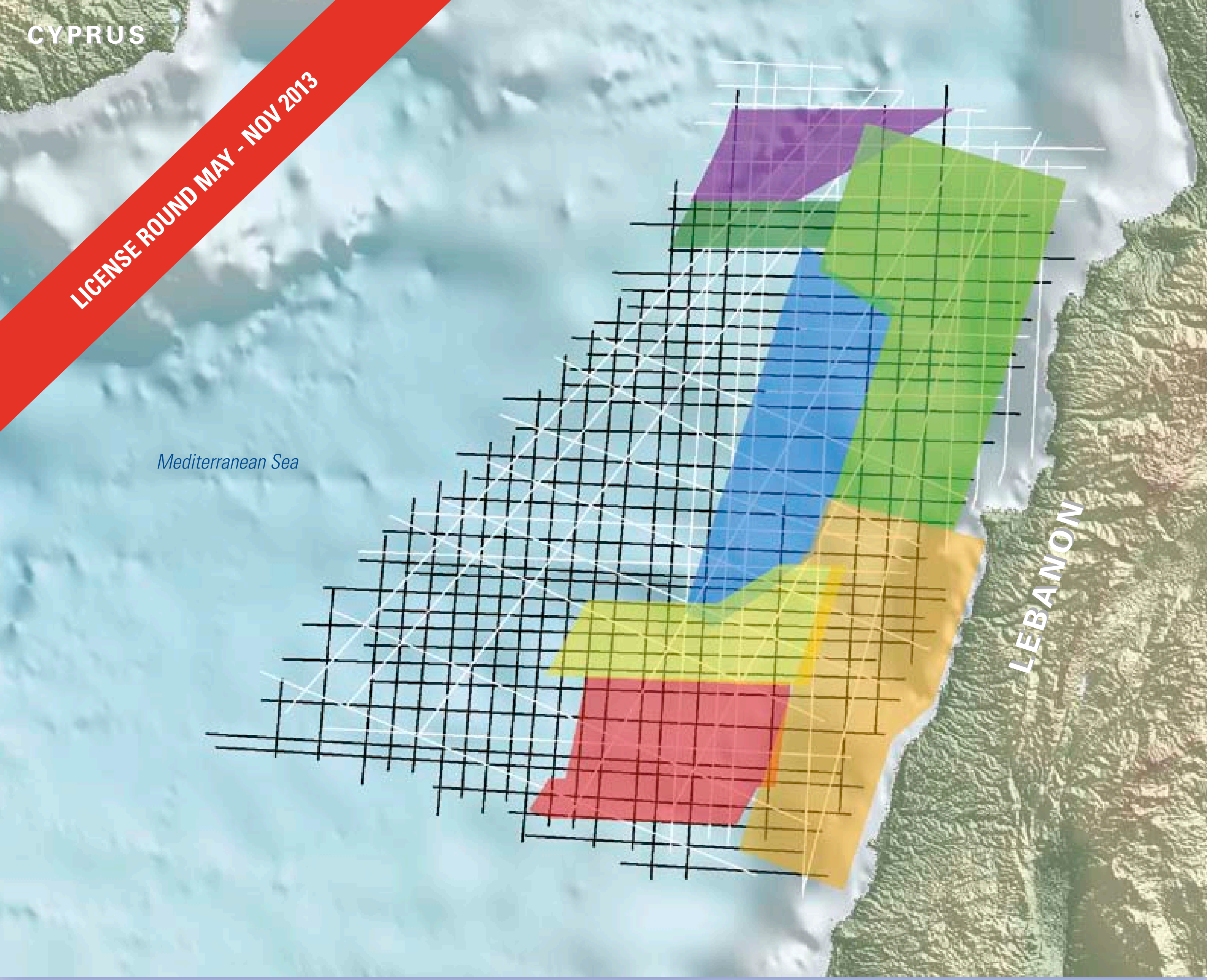
Shale gas has been discovered on all continents except Antarctica. In Europe, Poland in particular may have significant resources, with the International Energy Association (IEA) suggesting the technical resources for shale gas to be 187 Tcf (35 Bboe). However, while 109 shale gas concessions for prospecting and exploration have been granted so far, no single shale gas field has yet been fully documented in Poland.

The biggest reserves in a world-wide perspective may be in China, which according to IEA may hold total recoverable resources in excess of 1,275 Tcf (242 Bboe). However, while China already produces lots of coal bed methane, the shale gas adventure has not taken off yet. According to *The Economist*, China is pushing shale gas exploration by encouraging domestic producers to form partnerships with foreign oil and gas companies, and several of the supermajors, like BP and Chevron, are already involved in joint ventures with Chinese partners.

With respect to world reserves, the US is second with technical resources of 862 Tcf (163 Bboe), Argentina third with 774 Tcf (147 Bboe) and other countries with potentially significant resources are Mexico, South Africa, Australia, Canada, Libya, Brazil and France. The world's total shale gas resources are estimated at 6,622 Tcf (1,258 Bboe).

Interestingly, IEA has listed both Norway and Sweden on their technical resources list, although you cannot find a single Norwegian geologist who believes in shale gas production from Cambrian Alum shales in the Oslo Graben. In Sweden, Shell withdrew a couple of years ago after drilling three non-commercial wells in Lower Paleozoic rocks. The numbers from IEA therefore need to be regarded with scepticism. The shale gas venture is by no means mature yet. ■

HALFDAN CARSTENS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