VOL. 14, NO. 1 – 2017

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

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GEO PHYSICS:
The Future of Marine Seismic Acquisition?

EXPLORATION

The Geological Treasure of the Sierra Madre

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This edition of *GEO ExPro* magazine focuses on the Arctic, the Caribbean, Mexico and the Gulf of Mexico; and New Technologies for Cost Efficiency.

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Spring is Nigh?

There seems to be a distinct air of optimism developing in the oil and gas industry since we turned the corner into the new year. Faint buds of hope and indicators of new growth are beginning to show, the oil price has stabilized, albeit around $55 rather than the over $100 it was a few years back, and the US rig count rose by 17 in the first week of February, 27% higher than it was in 2016*. Even exploration in the highly expensive Arctic has had some boosts, as we report in this edition of *GEO ExPro*. Some, though not all, oil company results for the last quarter of 2016, while not rebounding strongly, showed promising indications that the slump may have bottomed out.

There are also indications that oil companies of all sizes are beginning to raise their heads above the parapet and think about exploring again, realizing that, with the 2016 replacement ratio for liquid hydrocarbons falling below 10%, they have to start finding more reserves. To help them do it, we now have a much leaner industry, with a strong emphasis on cost efficiency, the application of integrated new technologies and 'doing more with less'. This means that in many places exploring for oil should now be profitable even at today's crude prices.

But have we learnt any lessons, or will we keep on following the boom and bust cycles? The jury is out: if we scurry to increase the pace of production too quickly, we risk increasing the supply glut which was at the root of this downturn. OPEC members appear to have stuck to their self-imposed reduction in output so far, but in December 2016 Russia is reported to have had its highest monthly production for 30 years. Already, into just the second month of 2017, the oil price has taken a couple of knocks on hearing that crude stockpiles continued to build up in the US.

We still have a long road ahead of us. ■

* Baker Hughes

Jane Whaley
Editor in Chief

THE GEOLOGICAL TREASURE OF THE SIERRA MADRE

Geologist David Jiménez is looking at an outcrop of the Chicontepec Formation in the southern part of the Tampico-Misantla Basin near the town of Filomena Mata, Veracruz State, Mexico. The photo shows a very contorted slump which formed in a slope environment, moved from right to left and is underlain and overlain by thin, undeformed turbidites. This indicates it is a synsedimentary slump and is not tectonic. The outcrop is informally named in Spanish *Culebra*, or snake.

GEOExPro

www.geoexpro.com

GeoPublishing Ltd
15 Palace Place Mansion
Kensington Court
London W8 5BB, UK
+44 20 7937 2224

Managing Director
Tore Karlsson

Editor in Chief
Jane Whaley
jane.whaley@geoexpro.com

Editorial enquiries
GeoPublishing
Jane Whaley
+44 7812 137161
jane.whaley@geoexpro.com
www.geoexpro.com

Marketing Director
Kirsti Karlsson
+44 79 0991 5513
kirsti.karlsson@geoexpro.com

Subscription
GeoPublishing Ltd
+44 20 7937 2224
15 Palace Place Mansion
Kensington Court
London W8 5BB, UK
kirsti.karlsson@geoexpro.com

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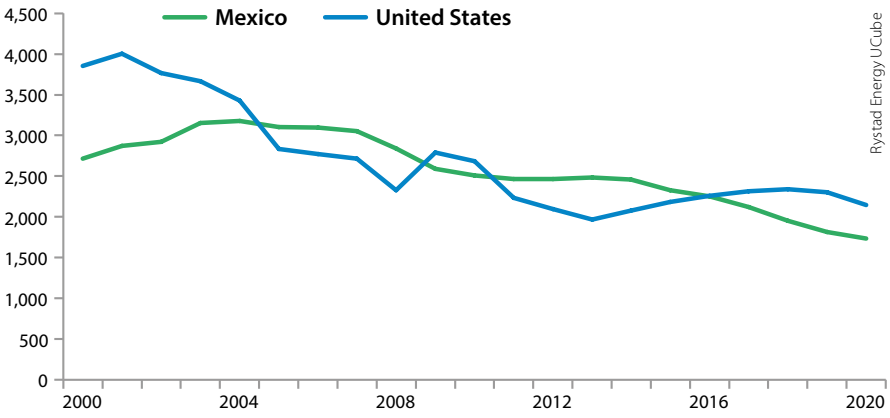
US Back as Largest GoM Producer

The Mature Gulf of Mexico Continues to Thrive

The Gulf of Mexico is currently one of the largest offshore producing areas globally. Despite it being a mature province, there are still high activity levels and plenty of interest in the region.

During 2016, 125 new licenses were awarded in the Gulf of Mexico. Of these, 116 were awarded from the US side, and the remaining eight were on the Mexican side through the continuation of the first license round there. This round had mixed success, with offshore deepwater experiencing the largest level of interest among the international oil companies.

In 2016, operators drilled about 100 exploration wells in the Gulf of Mexico, most of which were located in the US deepwater areas, with only 15 wells on the Mexican side. The 2016 activity was lower when compared to previous years, which saw an average of ~120 spudded exploration wells per year. In addition, the discovery results were disappointing, yielding only 450 MMboe of new volumes, compared to an average yearly discovered volume of 1,200 MMboe from 2010 to 2015. The largest 2016 US discoveries were the Shell-operated Fort Summer and Chevron's Gibson, and the largest discovery in Mexico was Nobilis, operated by Pemex.



Total Gulf of Mexico production split between US and Mexico, Mboepd.

Total Gulf of Mexico production was around 4.5 MMboepd in 2016, with 80% liquid content. Since 2012, US production has remained relatively flat, compared to an average production decline of 2.5 MMboepd in the ten years leading up to 2012. New developments are the main reason behind the flat production. However, new projects such as Lucius, Jack/St Malo and Delta House have caused US deepwater production to grow almost 0.5 MMboepd over the last two years. On the Mexican side, the increased decline in production over the last two years was mainly driven by the Cantarell project. Due to the different trend for the two countries over the last few years, 2016 was the year when the US once again became the largest producer in the Gulf of Mexico. Rystad Energy expects the country to hold this position going forward.

In terms of investment, the province has seen lower activity over the last two years, in line with the rest of the global E&P industry. In 2014 just under US$ 50 billion were invested in the Gulf of Mexico. This number dropped to just above US$ 30 billion in 2016, and in 2017, Rystad Energy expects it to fall further to about US$ 25 billion. One of the key reasons for lower activity going forward is the paucity of sanctioning activity during 2016.

Espen Erlingsen, Senior VP Analysis, Rystad Energy

ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids
barrel = bbl = 159 litre

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

Gas

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

Ma: Million years ago

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

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

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

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

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

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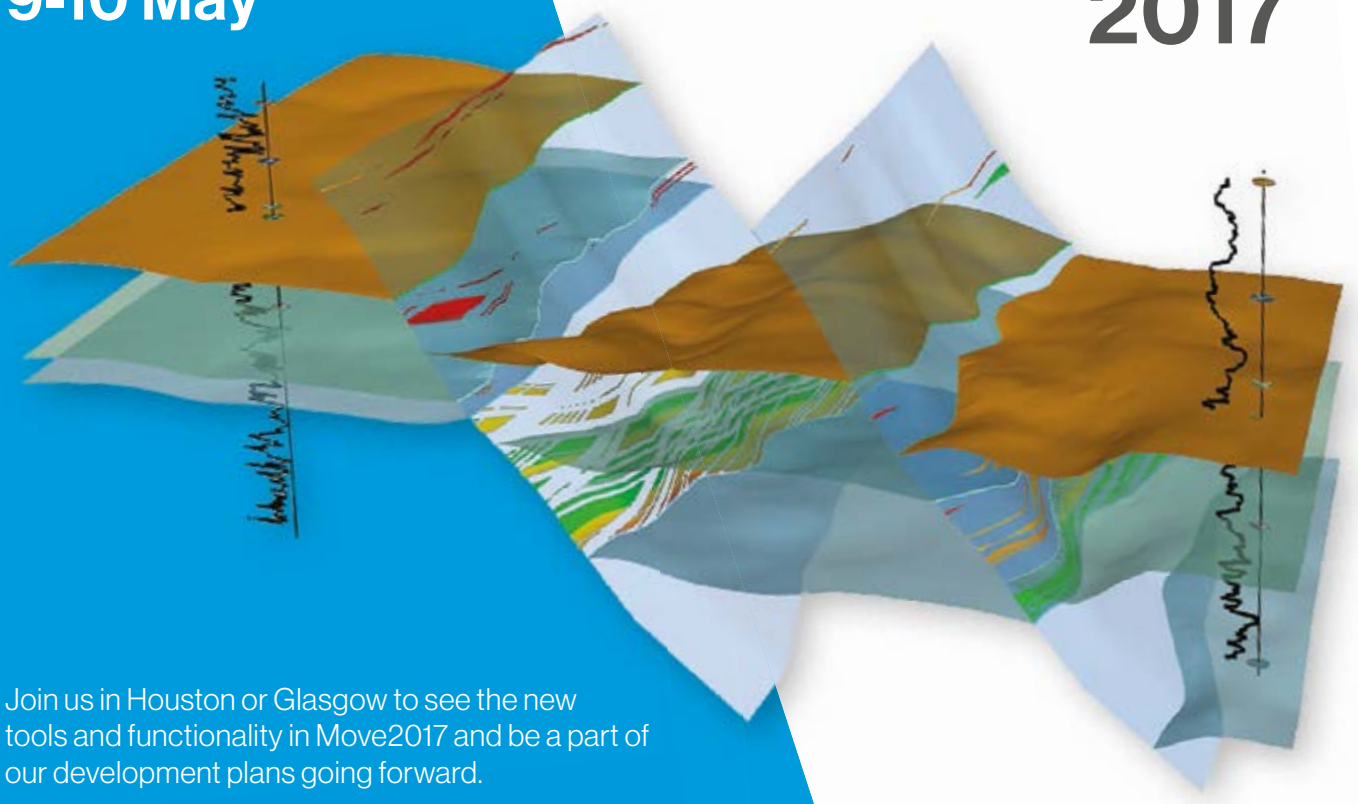

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Variety of Opportunities

Lebanon: Levantine Basin Blocks

In January 2017 Lebanon relaunched the licensing round which has been on hold for three years pending a resolution to the political crisis which had left the country without a president for much of that period.

In 2013, 46 companies had qualified to take part in bidding for oil and gas tenders in Lebanon, 12 of them as operators. These companies will remain qualified and there will be a second prequalification round for other interested companies, which will close at the end of March, with the list of qualifiers to be announced on April 13. Bids must then be submitted by September 15, and the awards will be announced in November 2017.

Five offshore blocks (1, 4, 8, 9 and 10), covering a total of 8,575 km^2, are open to bids. The majority of the offered area is in relatively shallow water, although water depths in Block 8 exceed 2,000m in places. The three southern blocks, (8, 9 and 10) are partially in territory which is disputed by Israel. Lebanon's offshore area is located in the Levant Basin, where in recent years a number of giant gas fields have been discovered in Israeli, Egyptian and Cypriot waters.

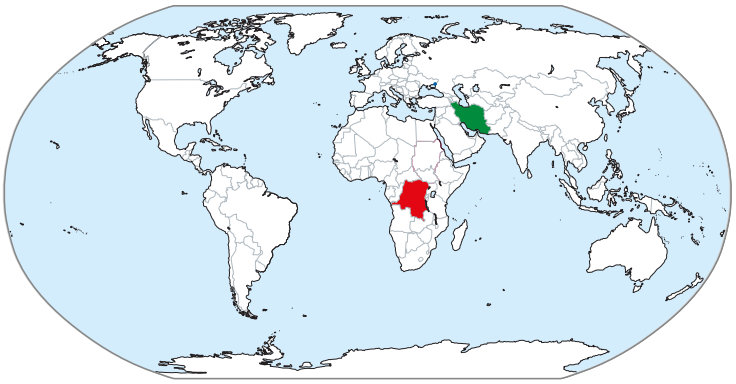
According to President Michel Aoun, Lebanon hopes to start production in 2018 and will deposit the revenues in a sovereign wealth fund.

Iran: New IPCs

Despite the recent imposition of fresh sanctions by the US, Iran will launch new contracts to develop its hydrocarbon resources in February 2017, its first such tender since the lifting of the original international sanctions a year ago. So far, 29 companies from more than a dozen countries are reported to have pre-qualified, but others may still apply. The list to date includes Shell, Total, Eni, Petronas, Gazprom and Lukoil, as well as companies from China, Austria, and Japan. The launch of these contracts has been delayed several times due to opposition from hardline rivals of President Hassan Rouhani.

Iran's leaders hope that the new Iran Petroleum Contracts (IPCs) offered for development deals will encourage foreign companies and boost output after years of underinvestment, but some analysts believe that the contracts are not attractive enough at a time of low oil prices, especially when compared with those offered by neighboring Iraq. International investors must team up with local partners, but the new contract model gives investors a share of the oil they produce and lets them sell it on the global market, unlike the previous buy-back deals.

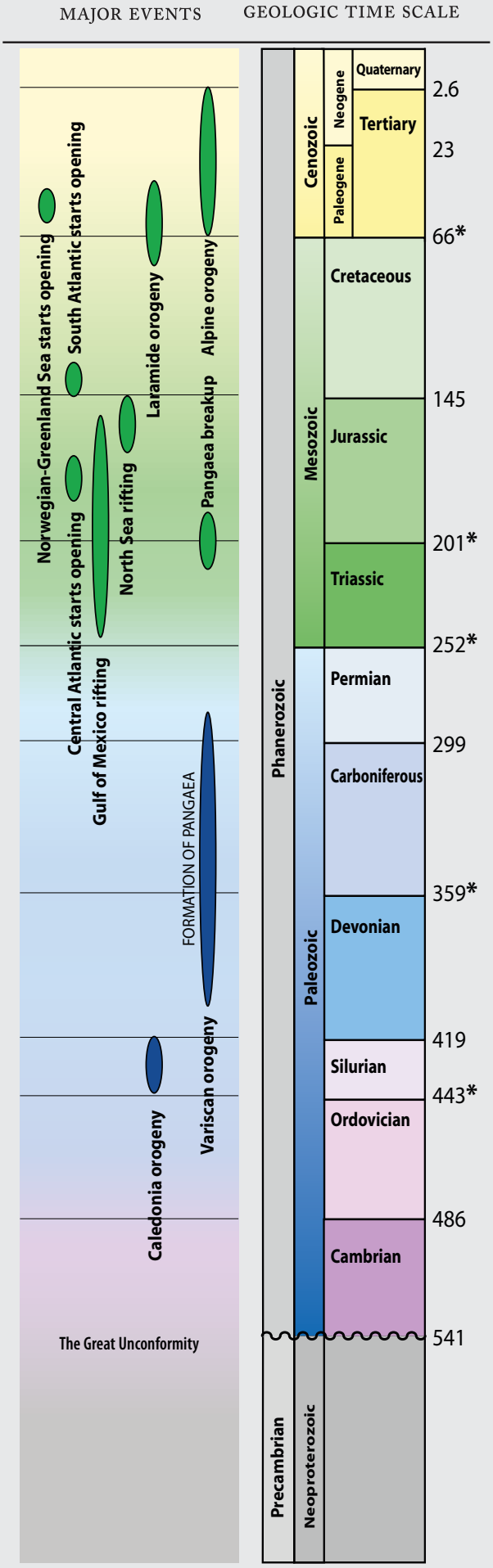
A total of 40 exploration projects are available, which according to Wood Mackenzie could help recover 28 Bboe, with gas fields being the biggest projects on offer.



Congo: Round Closing

Thirteen blocks are available as part of the 2016 Congo License Round, for which the final submission date is March 29, 2017. Eight of the blocks are offshore, in water depths varying from 100m to over 3,000m, and which vary in size from the relatively unexplored deepwater Block XXII, which is over 3,500 km^2 and has not been drilled, to the 539 km^2 Block XXVII, with eight wells, including one discovery. The other five blocks are in the onshore Cuvette Basin, which lies close to the border with the Democratic Republic of Congo and is essentially virgin territory as no wells have been drilled since the 1980s in the entire basin, and there are no discoveries to date. However, it is believed that a number of potential reservoirs are present, representing a range of depositional environments, as well as possible source rocks.

Results of the appraisal of the bids submitted by companies will be announced at the end of May 2017.



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In a complex and uncertain global environment,

GeoConvention promotes collaborative approaches and multidisciplinary integration to help optimize the efficient and responsible development of oil and gas resources. Join us at the GeoConvention 2017 on **May 15–17, 2017** in **Calgary**, Alberta Canada – 'Early Bird' discounted registration is now open. ■

GEO ExPro Contributor Honorary SEG Lecturer

Geophysicist **Martin Landrø**, who with Lasse Amundsen writes the long-running *GEO ExPro* column 'Recent Advances in Technology', has been appointed an SEG (Society of Exploration Geophysicists) **European Honorary Lecturer** for 2017. The title of his lecture is 'New trends in marine seismic acquisition – possibilities and impact on data quality'. In this he will look at advances in source technology and discuss why it is so challenging to generate very low frequencies in seismic acquisition. A key objective will be to show significant improvements within seismic data acquisition and to discuss potential directions for further improvements, related to efficiency and data quality.

Geir Morgan

Dr Landrø, who has a PhD in physics, has been a professor at the Norwegian University of Science and Technology since 1998, having previously been a research geophysicist in a number of organizations including Statoil. He has been awarded many prizes for his research and contributions to the seismic industry, including the SINTEF award for outstanding pedagogical activity (2009) and the EAGE's Conrad Schlumberger award.

The lecture tour will visit ten European countries between January and May. To see the full itinerary visit the SEG website. ■

Celebrate 100 Years!

When was the last time you were at someone's 100th birthday party? **AAPG** will give you that opportunity on April 2–5, 2017 at the **George R. Brown Convention Center** in **Houston**, as they host **ACE 2017** and commemorate **100** years of AAPG geoscience stewardship. The event will be a blend of the historic past of the profession, the industry's technical present, and a hard look at the changes in energy development coming in the 21st century.

AAPG began planning this event back in 2006 – and that shows in the many opportunities available at ACE this year, which include 117 sessions over 12 themes, 430 oral presentations, 800 poster presentations and 1,228 speakers from 41 countries.

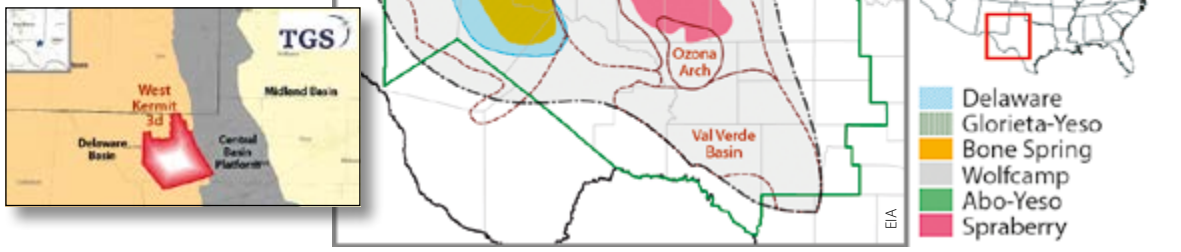
In addition to the technical program, AAPG will also be working with PROWESS to present a forum honoring **100 Years of Women in Petroleum Geology**, and will host its first **Pitchapalooza**, an event aimed at connecting ideas with the dollars to fund them. ACE also offers many field trips to rekindle your passion for your profession. Finally, ACE will host AAPG's 100th Anniversary Gala, featuring Daniel Yergin as keynote speaker. ■

Wolfcamp Shale: Largest Ever USGS Estimate

According to a recent **USGS** assessment, the **Wolfcamp Shale** in the **Midland Basin** portion of Texas' **Permian Basin** province contains an estimated mean of **20 Bb** of oil, **16 Tcf** of associated natural gas, and **1.6 Bb** of natural gas liquids. This estimate is for continuous oil, which USGS defines as 'an oil resource which is dispersed throughout a geologic formation rather than existing as discrete, localized occurrences', i.e. unconventional hydrocarbons. The figures represent the undiscovered technically recoverable resource and is the largest estimate of continuous oil that the USGS has ever assessed in the United States, **nearly three times larger** than that of the 2013 USGS Bakken-Three Forks resource assessment.

"The fact that this is the largest assessment of continuous oil we have ever done just goes to show that, even in areas that have produced billions of barrels of oil, there is still the potential to find billions more," said Walter Guidroz, program coordinator for the USGS Energy Resources Program. "Changes in technology and industry practices can have significant effects on what resources are technically recoverable, and that's why we continue to perform resource assessments throughout the United States and the world." ■

Selected oil-producing formations in the Permian Basin.



TGS Permian Basin Seismic Project

On the topic of the **Permian Basin**, multi-client seismic company **TGS** recently commenced field operations for a 3D survey in of the Delaware Basin part of the Permian Basin. This project, the first onshore seismic project in the Permian Basin for TGS, will encompass approximately 400 km^2 in the **West Kermit** area of Texas, about 100 km west of Midland and close to the border with New Mexico.

This high resolution 3D survey is designed to assist in the evaluation and development of multiple zone potential including highly productive Wolfcamp (see left) and Bone Spring intervals. Data acquisition is expected to begin in early Q2 2017, with final data available to clients in Q4 2017. The data will be processed by TGS utilizing its modern land imaging technology to provide clients with greater reservoir understanding. West Kermit 3D is complemented by TGS' extensive geologic products database with data from over 425,000 wells and multiple interpretive products in the Permian Basin. ■

New Marine Geophysical Company

There is a new 'kid' on the seismic block – marine geophysical company **Shearwater GeoServices AS**. Established in 2016 and with a head office in Bergen, Norway, Shearwater is an integrated provider of marine geophysical services to oil and gas and multi-client companies worldwide and operates a fleet of four modern, high capacity seismic vessels, as well as offering advanced processing and software services in offices in the UK, US and India.

Built by a joint investment from GC Rieber Shipping ASA and Rasmussengruppen AS, Shearwater will receive technical and crewing support from GC Rieber Shipping for marine operations, with the organization being established in part on former **Dolphin Geophysical** staff and in part on new hires. It was launched at the SEG Exhibition in Dallas in October 2016 and aims to be the most cost-efficient company in the industry.

Why the name Shearwater? According to the company: *"Shearwaters are magnificent long-winged seabirds that fly very close to the water and seemingly cut or shear the tips of waves. This efficient shearing technique enables them to move across wave fronts with the minimum of active flight. Not unlike our vessels, Shearwaters spend their lives on the open ocean, covering immense distances in their regular seasonal migrations from pole to pole."* ■

The Geological Treasure of the Sierra Madre

STEPHEN P.J. COSSEY
Cossey and Associates Inc.

This is a classic geological detective story, set in remote eastern Mexico, full of unique characters, mystery and intrigue. Like all geological stories, it is incomplete, but may turn our understanding of the Gulf of Mexico literally upside down, and could possibly answer the question of what caused one of the greatest climate changes in geological history, the Paleocene/Eocene Thermal Maximum.

The story starts in 2004 when I visited the turbidites of the Chicontepec Formation in the Tampico-Misantla Basin in the foothills of the Sierra Madre Oriental in eastern Mexico – a wild and timeless area and setting of the famous movie *The Treasure of the Sierra Madre* starring Humphrey Bogart.

I was accompanied by Mark Bitter, who had done his MSc fieldwork here in the 1980s. He showed me the photos and descriptions of his original outcrops, many now overgrown, including a small outcrop of what he and others described as a 'coal' within a sequence of turbidites in the Paleocene/Eocene Chicontepec Formation. His original photos revealed a steeply dipping section of thin-bedded sandstones with a variable thickness black bed in the middle. Mark did not remember its exact location, but knew it was close to the village of Chicontepec. Initially, I did not think this outcrop significant in the overall story of the Tampico-Misantla Basin, but finding it soon became an obsession, because any coal in a turbidite sequence is anomalous. I drove all the roads near Chicontepec comparing the outcrop dips to those in the photograph and finally discovered it, set back about 100m from the road and very overgrown. The black 'coal' bed was clearly visible, recessed somewhat by erosion.

Over the next eight years I regularly visited the outcrop, including it on field trips that I led to the basin, always explaining that it was a 'coal' overlain and underlain by turbidites, but I said little about its environment of deposition, suggesting it was probably a raft of waterlogged trees carried out

Figure 1: (a) The author is pointing to the steeply dipping black 'coal' bed as it was in January 2006. Compare the vegetation to the photo in (b), the 'coal' outcrop in 1984. Note the apparent rapid thickness changes and sandstone on strike with the black bed in the foreground.

into the deep basin, sunk, buried and converted to 'coal'. I was not happy with this interpretation, but it seemed the only logical explanation at the time and no one ever offered an alternative.

Collecting the Puzzle Pieces

In 2006 colleague Lynne Goodoff alerted me to the presence of several unconformities in the Chicontepec Formation, clearly visible on seismic. I had not found evidence of these in outcrop, but was intrigued by their number and basinwide nature. From cores I realized that high gamma ray features interpreted as shales overlying the unconformities were actually pebbly mudstones, probably deposited as debrites. Whenever high-resolution biostratigraphy was present in the wells, they confirmed the large hiatuses across the unconformities.

In February 2010, I collected samples from either side of the 'coal' bed, which were dated by foram specialist Peter Thompson as Foraminiferal Zone P5, spanning the Paleocene/Eocene boundary (Gradstein et al., 2004; Pearson et al., 2006).

Fast forward to 2012 when I was involved in a study for Pemex, building a basinwide stratigraphic framework for the Chicontepec Formation and thus identifying the sequence boundaries in about 99 wells. One of the team members, Dr. Don Van Nieuwenhuise, was using graphic correlation to identify sequence boundaries from well data. At the end of the study, one of the major boundaries was recognized at about 54–55 Ma, close to the Paleocene/Eocene boundary – the same unconformity which had been designated Discordancia (Unconformity) "A" by Pemex geologists for many years. We now had several pieces of the puzzle needed to put together the complete story of the basin.

The mystery of the 'coal' bed still baffled me. I knew it was approximately at the Paleocene/Eocene boundary and I had recently read the 2003 paper by Rosenfeld and Pindell on the possible isolation and drawdown of the Gulf of Mexico, in which they propose that the Gulf could have been isolated from the world's oceans in the Paleogene, evaporated and then catastrophically refilled, rather like the Messinian crisis in the Mediterranean in the Miocene (Vai, 2016). However, they did not know exactly when it happened or how long it lasted, proposing only that it was close to the Paleocene/Eocene boundary.

Figure 2. Outcrop excavation in 2015 showing the bitumen bed thickening along strike and containing large clasts.

The mysterious 'coal' bed was close to the Paleocene/Eocene boundary and overlain and underlain by turbidites – but where were the shallow marine facies we would expect in a normal regression and transgression? Could this so-called coal at approximately the P/E boundary be the 'smoking gun' that would prove Rosenfeld and Pindell's theory?

The Search is On!

Determined to solve this, I returned to Mexico in March 2015. I obtained more detailed samples from above and below the 'coal' bed for age dating, to see if the results coincided with the sequence boundary we had identified in 2012. I also took samples of the bed itself, and asked specialists to determine their origin and environment of deposition. To my surprise, the samples were not coal; they contained no macerals or minerals and the 'coal' was, in fact, some form of fossil bitumen. It had no stratification, showed conchoidal fracture and immediately released oil and gas when exposed to fluorescent light.

The 14 samples from above and below the bitumen bed were again confirmed to be Foraminiferal Zone P5, spanning the Paleocene/Eocene boundary (Gradstein et al., 2004; Pearson et al., 2006). Peter Thompson also noted that there were variable quantities of fragmentary limonite tubes in the samples below the bitumen bed, but none above it, which from his experience suggested evidence of rooting. He also noted that there were no shelf-restricted foraminifera in the samples immediately surrounding the bed. Meanwhile, Dr. Van Nieuwenhuise had graphically correlated the same samples and confidently concluded that the bitumen bed represented a hiatus of 850,000 years (54.95–55.8 Ma).

So, is this bitumen layer a fossil oil seep, a depositional bed or injected into a void? And what was the depositional environment? I was convinced it was a bed and not injected because of thin clay layers observed above and below it. Small clay clasts found within the layer could also be seen in Mark Bitter's 1984 photograph, when the outcrop was about 5m further forward than it is today. Mark's work provided other clues. His measured section of the outcrop in 1984 recorded the bed as 60 cm thick, but today it is only about 12 cm. Why such big thickness changes over such a short distance?

There was only one way to answer these questions and get some fresh samples of the bed: we must core the outcrop and determine its lateral extent and thickness changes. A coring program was organized for September

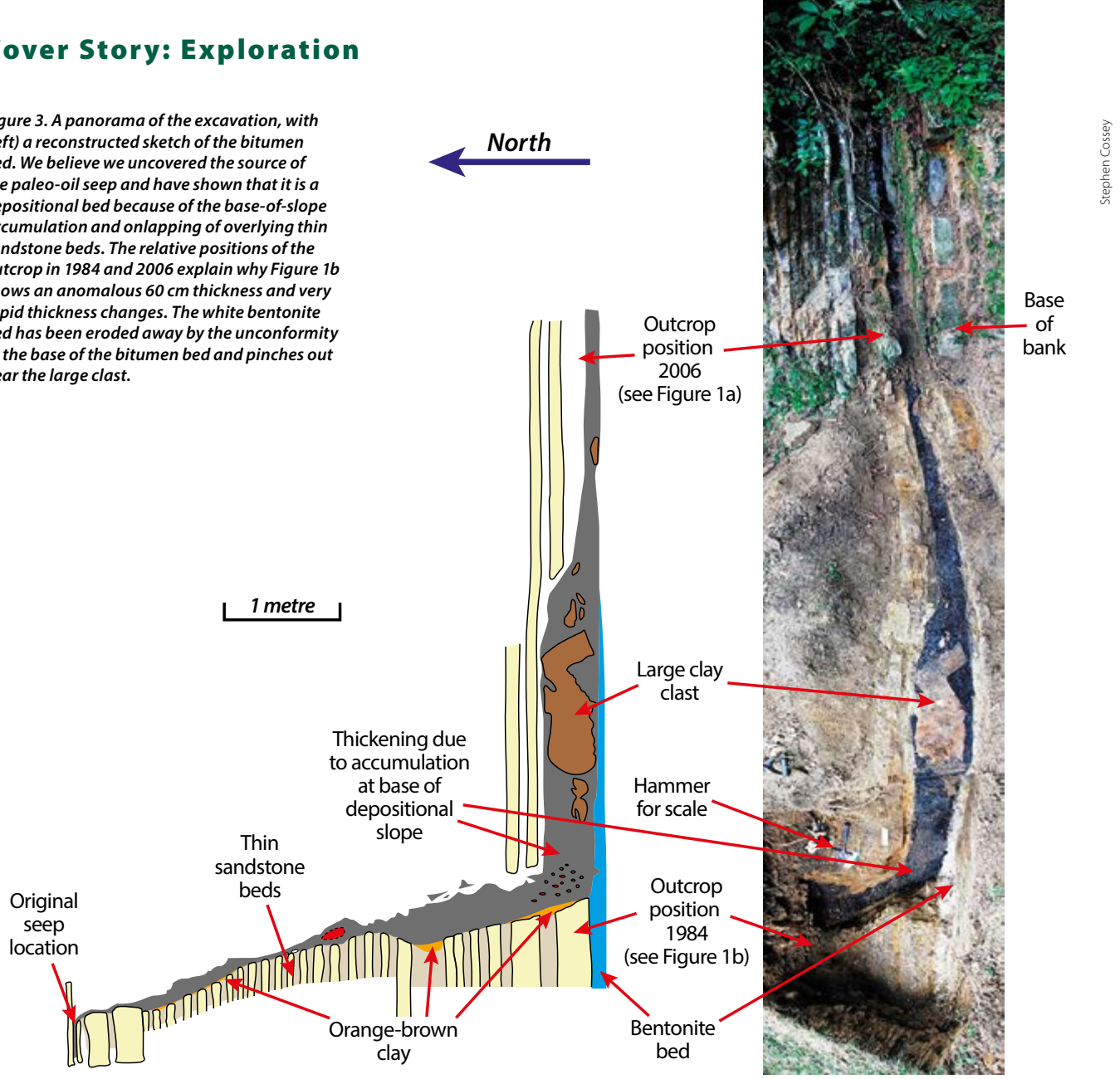


Figure 3. A panorama of the excavation, with (left) a reconstructed sketch of the bitumen bed. We believe we uncovered the source of the paleo-oil seep and have shown that it is a depositional bed because of the base-of-slope accumulation and onlapping of overlying thin sandstone beds. The relative positions of the outcrop in 1984 and 2006 explain why Figure 1b shows an anomalous 60 cm thickness and very rapid thickness changes. The white bentonite bed has been eroded away by the unconformity at the base of the bitumen bed and pinches out near the large clast.

2015 and a cast of actors assembled for the adventure, including lecturers and students from UNAM in Queretaro. Mark Bitter also decided to return to the area with us.

Coring and Excavating

We arrived in Chicontepec on a wet September evening and the next day we chose the core locations and started drilling. In case the core recovery was unsuccessful due to weathering, we also started digging out the bitumen bed by hand, following it along strike away from the bank, and soon began to see some unusual features. Initially we thought the bed split along strike but then we discovered a large deformed clay clast within it, along with smaller clasts. The bed got deeper the further we moved away from the natural outcrop; by the end of the first day we had dug about 5m along strike, but were now about 1m below the surface (Figure 2). At the end of our excavation pit something strange was happening; the bitumen bed seemed laterally discontinuous because we could see a thick sandstone on strike with the part of the bitumen bed that we had exposed – as we'd seen on the 1984 photo. This mystery would have to wait until tomorrow.

We returned next day feeling more like archeologists than geologists! Extending the trench, we discovered that the bitumen bed was not discontinuous, but turned and headed north; we were excavating along an erosional unconformity, confirming the hiatus that Dr. Van Nieuwenhuise had predicted from the earlier samples. By the time we could no longer hand-dig we had discovered that the bed thickened along strike, took a 40° turn along an erosional unconformity (Figure 3) and continued in a more northerly direction. The two boreholes, 16m apart, showed that the bitumen bed was present 10m down dip, below the present outcrop face, but was absent in the subsurface along strike and 16m behind the outcrop face – evidence that it was pinching out eastwards.

Proving the Drawdown Theory

With this new evidence and more samples we returned home to analyze everything and discuss this unique outcrop and its possible relevance to the Gulf of Mexico drawdown theory. In our first paper (*Interpretation*, Cossey et al., 2016), we described the bitumen bed in detail, proposing that it was

Figure 4: Oil seeps near Carpenteria, California. Note that the thickest part of the 'fan' is at the base of the cliff, similar to the Chicontepec bitumen bed.

direct evidence for the Gulf of Mexico drawdown, but also hinting that the drawdown of the Gulf was somehow connected to the Paleocene/Eocene Thermal Maximum (PETM). After its publication I was contacted by Dr. Jerry Dickens at Rice University in Houston, who was intrigued by the hypothesis connecting the bitumen bed outcrop to the Gulf of Mexico drawdown and to the PETM, which he had been studying for 20 years. He was keen to follow it up.

We needed to go back to Mexico to continue the excavation northwards and trace the bitumen bed to its source to prove that it was a seep, not an injection feature. A small team, including Jerry Dickens, returned in May, 2016. This time we would excavate mechanically, since the fresh outcrop was going to be too deep for hand-digging!

We marked out the area to be excavated based on the previous year's results and by the next morning the hole was almost completely excavated. Unfortunately, our excavation up the side of the unconformity showed that the bitumen bed only continues for about 5m, thickening in places to 30 cm, before it disappears, presumably at the source of the paleoseep (Figure 3). Jerry collected about 50 samples from the entire outcrop for nannos, forams and palynology analysis.

A modern-day analog to the Chicontepec bitumen bed might be the oil seeps from an unconformity seen along the cliffs near Carpenteria, California (Figure 4). The scale is about the same, and features such as small bitumen 'fans' are preserved at the base of the cliff.

An Ongoing Story

Our focus switched to a long, clean road cut near the village of Acatepec, about 10 km west of Chicontepec. Its importance is that we interpret it as a submarine canyon-fill sequence overlying Unconformity "A" – the same unconformity we had been excavating at the bitumen bed outcrop. I believe that this canyon fill represents the post-PETM sequence overlying Unconformity "A", which formed when the Gulf of Mexico drawdown occurred. Jerry took more samples through this section and about 100 samples from the two outcrops are now being analyzed for forams, nannos and palynology and we await the results eagerly.

What we know for sure is that this is not the end of this adventure or the story, but just the beginning. The pieces of the puzzle will come together and the Sierra Madre will once again reveal some of its secrets – but only when it is ready.

Acknowledgements:
Thanks to all the people who have contributed to this story, especially the Tectonic Analysis Ltd. Consortium-funded Cordilleran/Gulf of Mexico Research Program for supporting aspects of the 2015–2016 field campaigns and ongoing analyses.
This article is dedicated to the memory of David Jiménez.

References available online ■

Figure 5. The Acatepec outcrop near Chicontepec.

Integrating Seismic Imaging and Inversion

Combining depth imaging and inversion workflows into a single consistent process has the potential to provide more accurate models in a shorter time than achievable to date.

FRANCISCO BOLIVAR, RICHARD COOPER and LUCY MacGREGOR, Rock Solid Images;
JACQUELINE O'CONNOR, JEFF CODD and DAVID KESSLER, SeismicCity Inc.

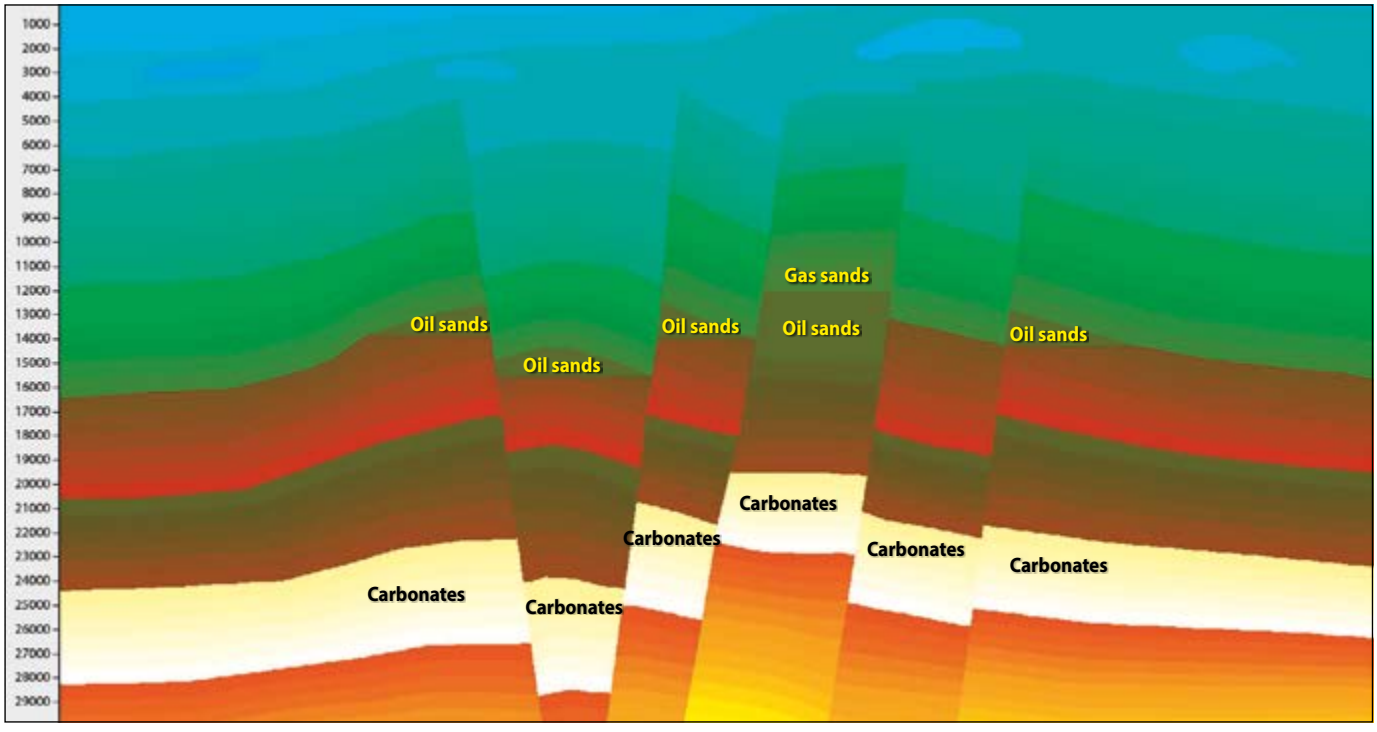
The hydrocarbon industry is exploring in ever more complex environments, and the demands for efficient extraction of identified reserves require accurate imaging of reservoir architecture and robust characterization of rock and fluid properties. Depth migration algorithms exist to assist in determining reservoir architecture; however, these are often applied in isolation from the subsequent seismic inversion and reservoir characterization steps required to build static reservoir models. The result is in many cases a disconnect between structure and properties, i.e. between rock properties provided in the time domain and well planning as required by engineers in the depth domain. Addressing this disconnect has the potential to improve reservoir models, and can also lead to a significant improvement in efficiency and reduction in turn-around time as duplication of steps is avoided.

Using PSTM Gathers in Inversion

Today depth imaging is at the core of seismic data processing. PSDM volumes are used for interpretation and prospect generation and, if accurately created, will consist of seismic events imaged at the correct depth and spatial location. However, although seismic imaging is done in depth, in many cases impedance inversion is still done using pre-stack time (PSTM) gathers. There are a number of disadvantages to inverting PSTM data. Firstly, if the gathers input into the inversion process are not migrated to the correct spatial location, then the inversion results will also be incorrectly positioned. Secondly, incorrect imaging will lead to erroneous impedances, particularly true for pre-stack inversion when positioning errors will induce erroneous AVO effects. Moreover, when impedance inversion results are delivered in the time domain they need to be converted to depth for comparison with well log or other geophysical data, and to build reservoir models for resource development and management. Without a valid model, which is developed during depth imaging, there is no reliable way to correctly convert time domain seismic data to depth.

The reason for the use of PSTM gathers in inversion is historical. In the past, PSDM used to be of lower frequency and due to variations in illumination, amplitude was not preserved. Over the years PSDM technology has been greatly improved

Figure 1: Geological model used for the study. Lithology and fluid properties were assigned to each layer, and from these, elastic parameters were calculated using standard rock physics relationships. The result is a five parameter elastic model consisting of Vp, Vs, density, delta and epsilon.



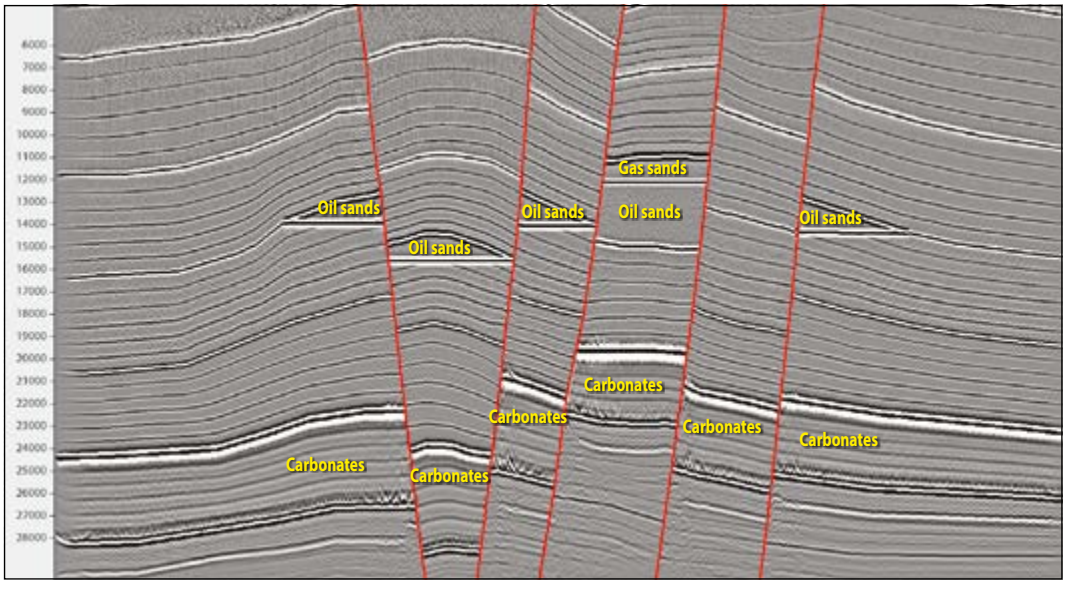
and today's PSDM data is as high frequency as any PSTM data. Amplitude is preserved in areas of uniform illumination and the industry is working to produce amplitude-balanced PSDM even in areas of variable illumination. The study presented here examines the accuracy of rock properties computed from impedance inversion undertaken using PSDM gathers.

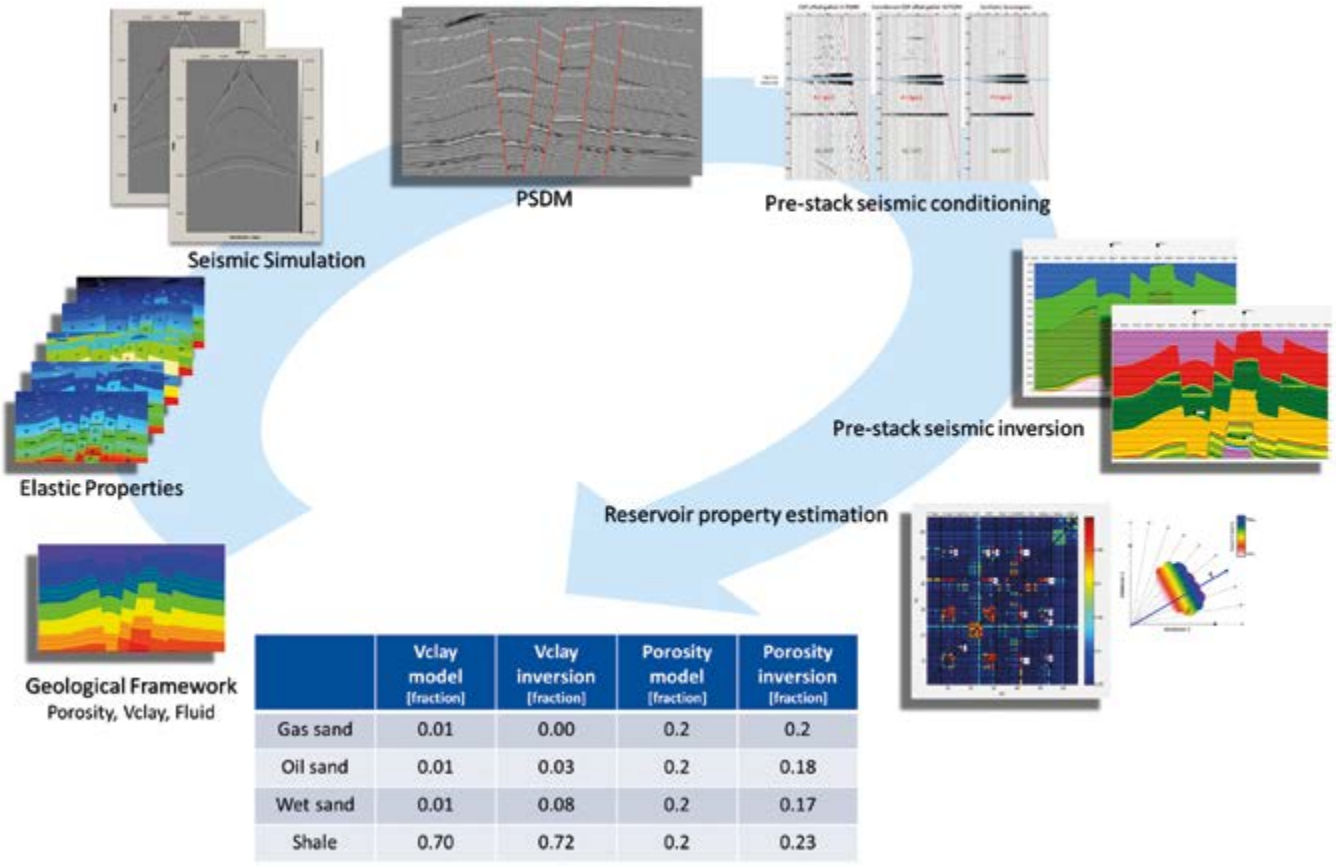
Testing Seismic Depth Imaging

In order to test the accuracy of seismic depth imaging combined with impedance inversion, simulated seismic data generated from a synthetic model (i.e. when the answer is known) was used. An elastic model was developed and seismic simulation using the full elastic wave equation was undertaken to generate a realistic seismic dataset. The faulted geological model used consists of a series of normal and reverse faults (Figure 1). The elastic parameters were calculated from porosity and clay content values provided for each layer using standard rock physics relationships. Porosity in the oil sand and gas sand was set to 20% and the clay content set to 1%. Using these values, a five parameter anisotropic elastic model was built.

A non-dispersive recursive migration operator application (Kosloff et al., 2008) was used to generate simulated shot gathers from the anisotropic elastic model. The simulated shots were then migrated using an amplitude-preserving Kirchhoff summation PSDM algorithm. The results of PSDM are migrated image

Figure 2: Amplitude-preserving Kirchhoff summation PSDM stack.





	Vclay model [fraction]	Vclay inversion [fraction]	Porosity model [fraction]	Porosity inversion [fraction]
Gas sand	0.01	0.00	0.2	0.2
Oil sand	0.01	0.03	0.2	0.18
Wet sand	0.01	0.08	0.2	0.17
Shale	0.70	0.72	0.2	0.23

Figure 3: Workflow applied in this study and numerical results from reservoir property estimation through the multi-attribute rotation scheme (MARS).

gathers at the correct spatial location, and a stack of these gathers produces the final PSDM stack (Figure 2).

The PSDM gathers formed the input to the simultaneous elastic impedance inversion, which operates in the time domain and therefore required the PSDM gathers to be stretched to time prior to inversion. The gathers were conditioned to remove residual noise (such as multiples) in preparation for inversion, and a low frequency model was constructed based on the input model at brine-saturated conditions. The conditioned gathers and low frequency model were next input to a simultaneous elastic impedance inversion (Tonnellot et al., 2001), from which P impedance and S impedance were obtained. These were stretched back to the depth domain, using the same velocity model that was used to stretch the depth domain PSDM gathers to the time domain. Note that the depth to time conversion and time to depth conversion steps, applied respectively before and after the impedance inversion, are robust, and are required as the seismic inversion assumes a stationary time-domain wavelet.

Calibrating with MARS

As the final step, the seismic inversion results were used to calculate rock and fluid properties using the multi-attribute rotation scheme (MARS) (Alvarez et al., 2015) and compared to the values used to construct the model. Observed misfit of the predicted reservoir property values in comparison with the actual model are small (Figure 3) and are mainly due to the limitations resulting from using only elastic measurements to predict rock properties. Fluid and lithology responses move in non-orthogonal directions when only seismic inversion derived attributes are used. Therefore, there will always be a fluid imprint on the lithology measurements and vice versa. In this case, the transform used was estimated with reference to all fluid phases (wet, oil and gas). As a consequence, the volume of clay predicted in a location with only two fluid phases, wet and oil, will trade off the lack of separation from the background with a decrease in reservoir rock quality (i.e. an increase of volume of clay).

However, results indicate that PSDM preserved the relative amplitude of the data and therefore rock properties can be successfully predicted and positioned in the correct spatial location and depth using a robust seismic reservoir characterization technique.

A Step-Change

Combining depth imaging and inversion workflows into a single consistent process has the potential to provide more accurate models in a shorter time than achievable to date. Although simple, the synthetic example presented illustrates that amplitudes can be preserved in depth imaging, and the resulting PSDM gathers can be used to robustly determine reservoir properties in depth. Work is on-going to extend this principle to more complex geological models and environments. The results will represent a step-change in the quality of sub-surface information available to explorers and reservoir engineers, and the efficiency with which it can be provided.

References available online. ■

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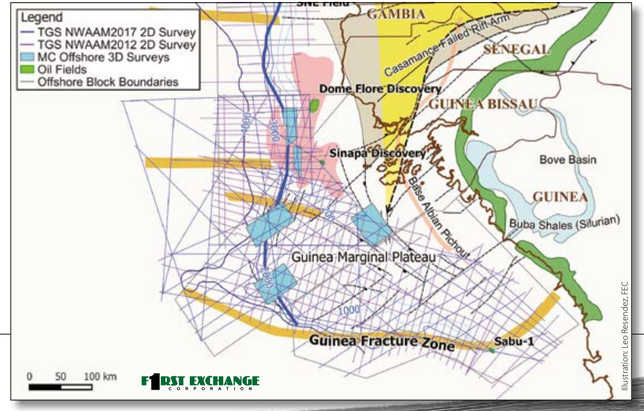
Revealing Future Opportunities Within the Southern MSGBC Basin



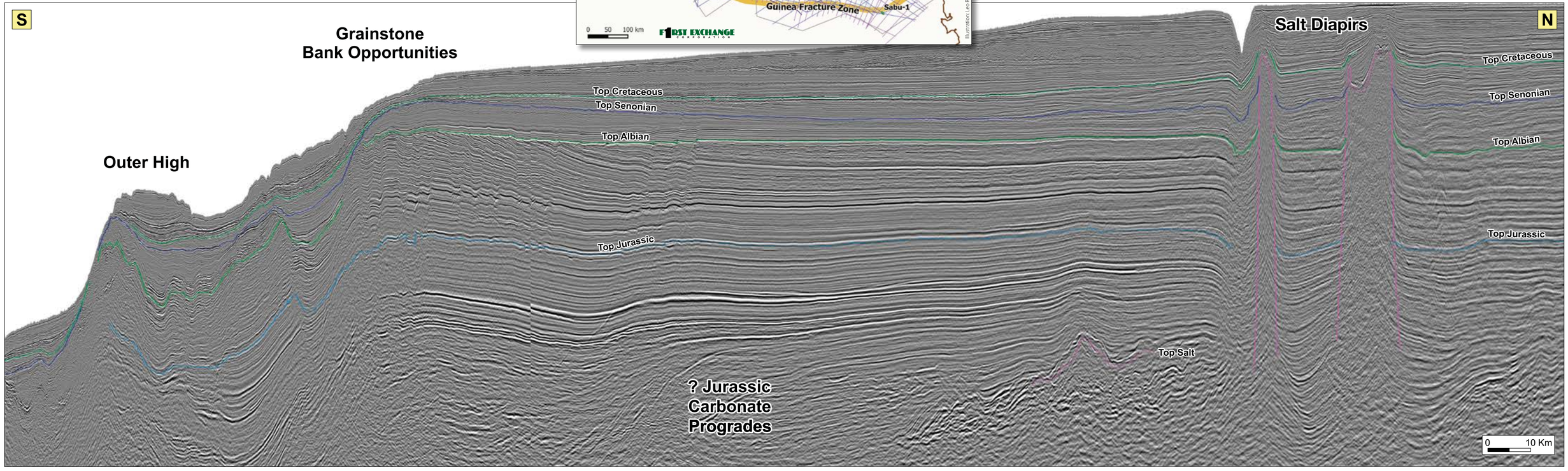
The fabric of the Guinea Marginal Plateau is illustrated here using a 360 km-long line that runs south-west from the Sinapa diapirs to clip, at its far end, the south-east edge of the Outer High.

Near the northern end of this line Sinapa encountered oil in Albian sandstones draped against a diapir. The source of the oil remains to be confirmed, but previous modeling by FEC indicated a Cenomanian and/or Albian origin.

To the south-west, provisional interpretation shows agrading and prograding sequences building upwards and outwards. These developed within the older Jurassic, reminiscent in their form to those in the Tarfaya region of Morocco, and are beyond a deep domal rise positioned directly below the crest of the carbonate bank. Eastwards sloping progrades, located below an unconformity, suggest the bank's crest here is a grainstone whose build-up was perhaps controlled by the rise of the deep structure. As such, it could be analogous in terms of its setting to the carbonates positioned above Domes Flore and Gea.

The origin of the Outer High remains to be established. It could be a collapse structure or have been a delta, introduced from the south and located between the Guinea Marginal Plateau and the Demerara High of Suriname. Diapirs are suggested on some lines.

TGS



Exploration Potential in the Southern MSGBC Basin

A new study reveals the plays and opportunities that abound in this exciting region.

NICK CAMERON and ANDY CARR, First Exchange Corporation; **BEN SAYERS**, TGS

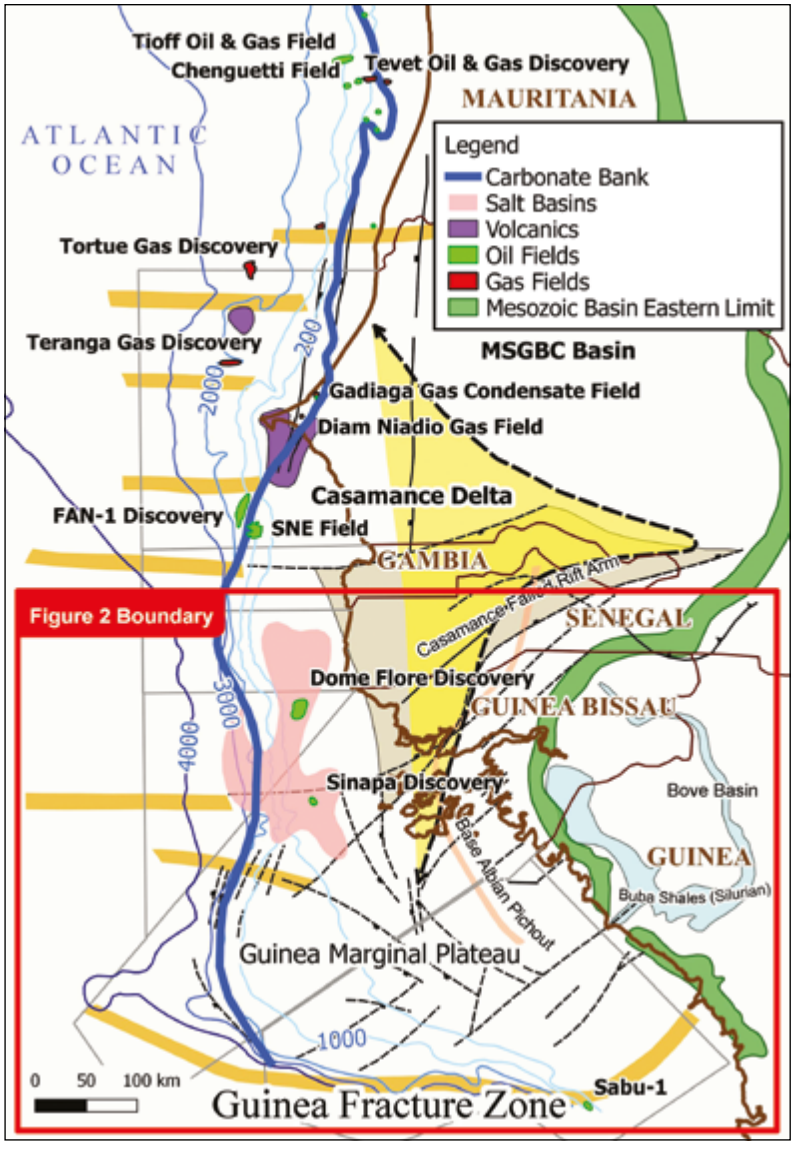
This article supplies the geological rationale for the review, at present being undertaken by First Exchange Corporation (FEC) in Houston and TGS in the UK, of the exploration potential of The Gambia, southern Senegal (Casamance), the AGC, Guinea-Bissau and Guinea (primarily north of the Guinea Fracture Zone). This work will complement the 2016 review by FEC of Senegal from Casamance northwards to the Mauritanian border, in which a new, oil-prone source of Lower Jurassic age was identified. The factors determining whether oil and gas would be found in deepwater wells were also established.

Following the giant heavy oil (11–13° API) discoveries in the Dome Flore and Dome Gea region of Casamance in the late 1960s/early 1970s, with estimated in-place volumes of 2 Bbo, followed by the 1975 discovery of world-class, oil-prone, mid-Cretaceous source rocks in DSDP boreholes 367 and 368, it was evident that the southern Mauritania-Senegal-Guinea-Bissau-Conakry (MSGBC) Basin should offer multiple opportunities for significant hydrocarbon discoveries. This potential began to be realized following the discovery of the oil and gas fields north-east of Dakar (Tullow and Fortesa) and, more recently, the Sinapa find (Premier Oil) in Guinea-Bissau. However, it was not until 2014 when the Cairn Group drilled their FAN-1 and SNE-1 discovery wells that the magnitude of this potential was confirmed. These successes were followed shortly afterwards by giant finds by Kosmos Energy, though these were of gas rather than the expected oil. The ongoing Guyanese discoveries by ExxonMobil lie on trend across the Atlantic. In 2012 Hyperdynamics discovered a sizeable residual oil accumulation on an Equatorial Atlantic trend in their Sabu-1 well in the far south-east of Guinea.

Geology, Plays and Opportunities

The pre-rift section includes Devonian and Silurian source rocks, plus reservoir and seal. Triassic rifting initiated the final break-up of Laurentia from Gondwana with salt accumulating below the break-up unconformity in the Casamance failed rift arm. Drift commenced at about 190 Ma (Middle-Lower Jurassic). Growth of a shelf margin carbonate bank, 4–5 km thick, dominated the subsequent Jurassic and early Cretaceous histories. In complete contrast, the younger Cretaceous is characterized by deltaic progradation into the (by then) deepwater settings present west of the carbonate bank.

Figure 1: The geological fabric of the southern MSGBC Basin. Included are the blocks, Sinapa, Sabu-1 and for Senegal the Cairn and Kosmos discoveries, plus the onshore fields.



This period is associated with the opening of the Equatorial Atlantic.

Slower rates of deposition define the Tertiary, and from the Eocene onwards onshore uplift began to influence sedimentation. Diapir growth was renewed in the Dome Flore and Dome Gea region, leading to the development of the cap 'foraminiferite' reservoirs. The resulting exploration fabric is summarized in Figure 1.

Nine plays are recognized, as illustrated in Figure 2. The SNE discovery occupies play 5 and, where there is salt, play 3. FAN-1 lies in plays 7 and 8, while grainstone bank possibilities are present within play 5. The giant 60 km-long by 20 km-wide closure provided by the Outer High (play 6) offers multiple possibilities.

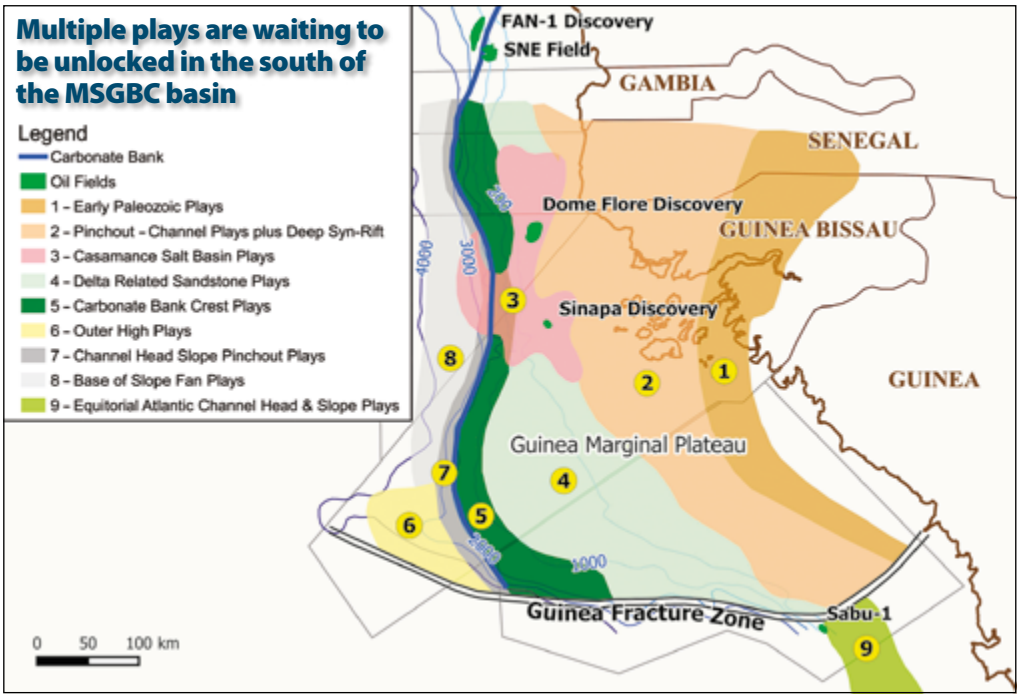


Figure 2: Casamance and Guinea Marginal Plateau plays.

An interpreted line from the TGS NWAAM 2012 2D seismic survey has been used to illustrate a variety of opportunities, some of which are established, and some of which are either emerging or new. This line is presented as the foldout on the previous page.

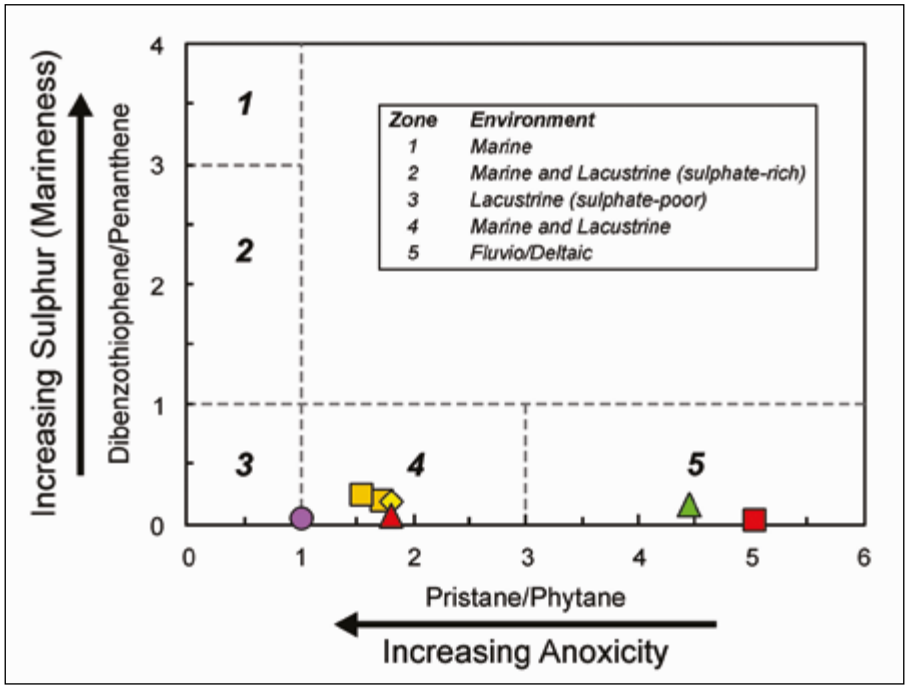
Source Rocks

In relation to the established mid-Cretaceous sources of Senegal, oil is located in interlobe settings of the Casamance Delta, and gas sources are associated with depositionally thicker lobe settings. In addition, biomarker evidence for a Lower Jurassic source system was encountered in the onshore wells north-east of Dakar (Figure 3) and indirect evidence was found for the continuation of this source system northwards into Mauritania and southwards into Guinea. A further objective for the new project is to determine whether a Lower Jurassic source exists under the Guinea Marginal Plateau and, if it does, to establish its maturation history in relation to the new and emerging play possibilities. Its existence there would open multiple new opportunities.

Over the past 20 years FEC and its authors, in conjunction with Petroguin, have undertaken substantial geologic studies, including seabed coring and petroleum systems modeling. FEC have recently completed a study in Senegal to help reveal the play concepts further north and are presently working with modern TGS seismic data to publish a new 2017 petroleum systems overview, carrying the knowledge southwards to Guinea-Bissau and Republic of Guinea.

TGS, together with GeoPartners and PGS, are currently acquiring their 12,529 km NWAAM2017 grid (see map on previous page). A fast-track seismic PSTM will be available from June 2017 and will be integrated into the new petroleum systems overview. ■

Figure 3: Biomarker environmental evidence from Senegal for a Lower Jurassic source system.



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Independents Rockin' on Alaska's North Slope

With recent oil discoveries potentially exceeding 10 Bbo, independents and their partners are opening up plays that could reshape exploration in a large portion of the Arctic.

THOMAS SMITH

Recent discoveries in formations once thought to have limited potential may have unlocked two huge new plays for the Arctic. These discoveries alone will reverse an alarming downward oil production trend on Alaska's North Slope once they come on line. The 2014/2015 Nanushuk discovery in the Colville Delta area was made by Repsol and Armstrong Energy, LLC. According to Bill Armstrong, founder and company president, "We have multiple other horizons that we plan to develop: at least six different zones. The Nanushuk (middle Cretaceous) and the Alpine (Jurassic) sandstones are the biggest at this time and will be developed first." Former Alaska Department of Natural Resources Commissioner Mark Myers said the field "has the potential to be second in size to Prudhoe Bay [passing the supergiant Kuparuk Field]."

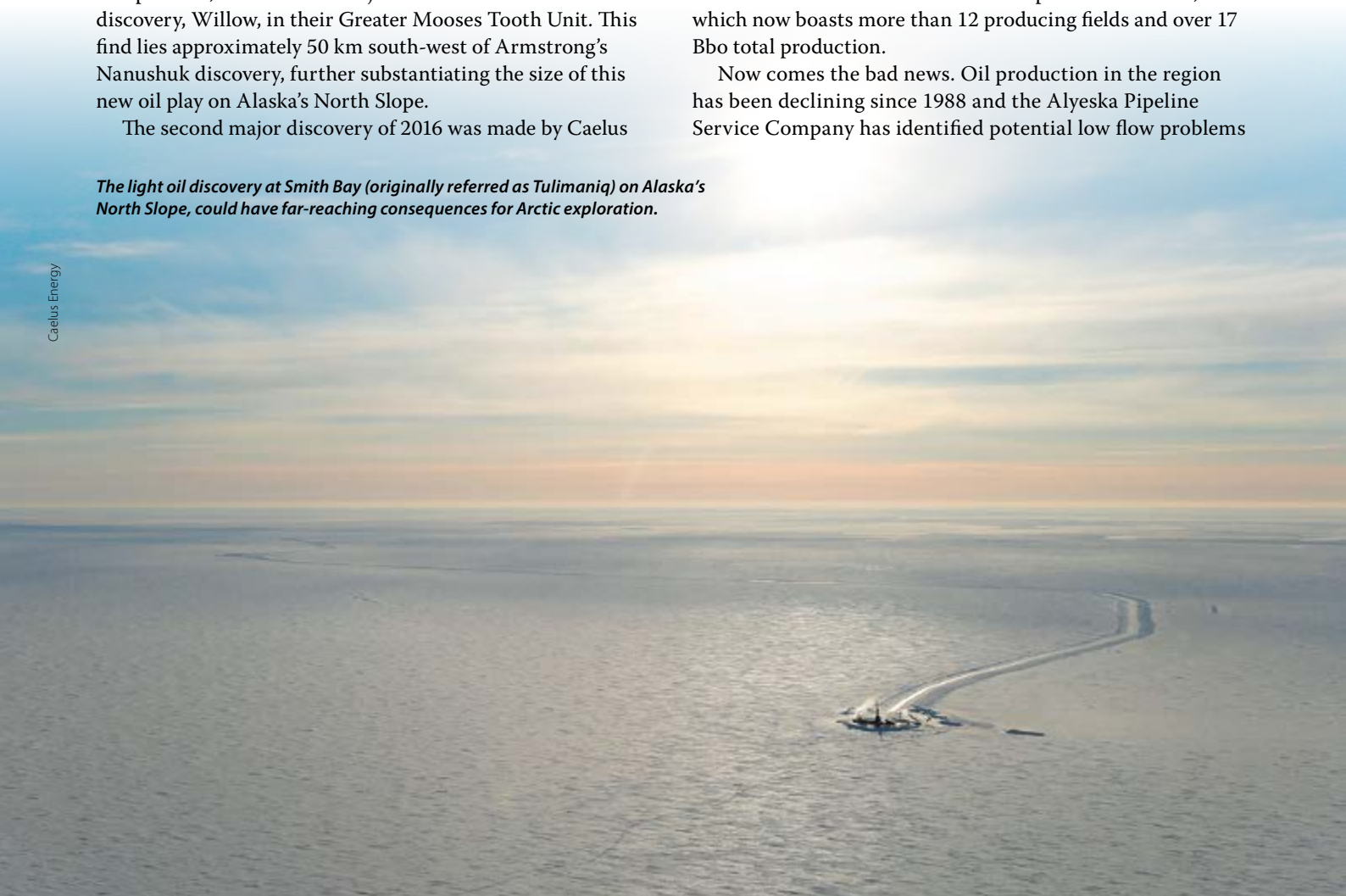
On January 13, 2017, ConocoPhillips, the world's largest independent, announced a major Nanushuk Formation oil discovery, Willow, in their Greater Mooses Tooth Unit. This find lies approximately 50 km south-west of Armstrong's Nanushuk discovery, further substantiating the size of this new oil play on Alaska's North Slope.

The second major discovery of 2016 was made by Caelus Energy Alaska in the Smith Bay area in the Cretaceous Torok Formation that lies directly below the Nanushuk Formation. Caelus claim the fan structure spans more than 777 km^2 and possibly holds over 10 Bbo. Both plays could extend well beyond the current discoveries and provide new exploration targets along the Arctic coast.

Needing a Big Find

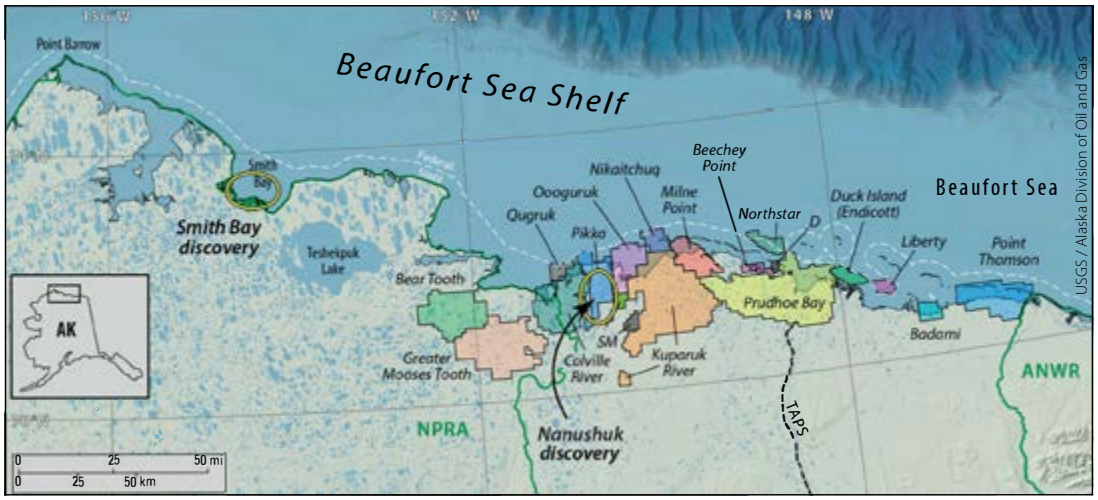
Mention Alaska's North Slope, and Prudhoe Bay, North America's largest oil field, will certainly come to mind. Discovered in 1968, the field and its primary reservoir, the Triassic-aged Sadlerochit Formation, came on stream on June 20, 1977. The greater Prudhoe area has now produced over 13 Bbo. North America's second largest oil field, Kuparuk, was discovered in 1969 with production commencing in 1981. These two fields have anchored development of the area, which now boasts more than 12 producing fields and over 17 Bbo total production.

Now comes the bad news. Oil production in the region has been declining since 1988 and the Alyeska Pipeline Service Company has identified potential low flow problems



The light oil discovery at Smith Bay (originally referred as Tulimaniq) on Alaska's North Slope, could have far-reaching consequences for Arctic exploration.

Caelus Energy



Alaska's North Slope showing existing fields and units and the location of two major discoveries. The Nanushuk (Qugruk wells) discovery and the newly formed Pikka Unit is located close to existing fields and infrastructure near the Colville River and is already slated for development. The Smith Bay discovery is approximately 150 km from existing facilities and will require much higher development costs to bring production on line.

with the 48-inch (1.2m), 800-mile (1,287 km) Trans-Alaska Pipeline System (TAPS). The 2016 average throughput was 510,000 bopd, slightly up from the prior year. However, the US Energy Information Administration sees continued declining production from the North Slope and in a low oil price case, if the throughput goes below 350,000 bopd, TAPS could be decommissioned in less than 10 years.

Early production estimates for the Nanushuk discovery and the recently formed Pikka Unit (a unit is a group of leases covering all or part of a hydrocarbon accumulation) indicate an output of 120,000 bopd by 2021. The Smith Bay discovery is much further from infrastructure and will take longer to come on line but Caelus estimate production from this field could be about 200,000 bopd. If all pans out, these fields will give TAPS throughput a much needed boost.

Astounding Nanushuk Discovery

Repsol E&P USA, as operator for Armstrong Energy, LLC and GMT Exploration, drilled the initial Qugruk wells, two with encouraging production tests and a third with hydrocarbons identified in multiple zones. These wells, drilled during the short 2013 winter season when the terrain is frozen, reached depths of over 3,000m. Subsequent delineation drilling the following years confirmed the development potential of the area. A total of 16 positive wells were drilled during four winter drilling seasons. Good quality 30° gravity oil at rates as high as 4,600 bopd and relatively shallow depths make this find particularly attractive.

Late in 2015, Armstrong acquired a majority interest in their joint holdings (303,000 hectares) with Repsol and became operator. A third-party report released by Armstrong estimated C-1 (contingent) reserves at 497 MMbo, C-2 at 1,438 MMbo and C-3 at 3,758 MMbo. Armstrong said these contingent reserves would be converted to Proven, Probable, and Possible where appropriate upon the final investment decision.

Mark Myers, then Alaska Department of Natural Resources Commissioner, said "the discovery was amazing… the possible contingent number makes the discovery the largest since Prudhoe Bay."

What makes this discovery possibly even more amazing is the primary reservoir, the Nanushuk Formation, and where the oil was generated. David Houseknecht said, "with 150 ft [46m] of net pay sandstones in a 650 ft [200m] oil column covering more than 10,000 hectares, reservoir rocks with a porosity of 22% is pretty astounding. In most other explored areas, the topset beds of the Nanushuk do not form reservoirs this prospective. Much of the North Slope's oil has been generated south of current production and migrated north. North of the Barrow Arch, seismic data show similar source rock intervals dipping steeply north and oil could have migrated south into this trap."

As Houseknecht explains, "This clinoform deposition system filled the Colville Basin from west to east, eventually spilling north over the Barrow Arch. In the area of the Colville Delta where the discovery was made, sediment flow was slowing down, sedimentation changing, and a marine

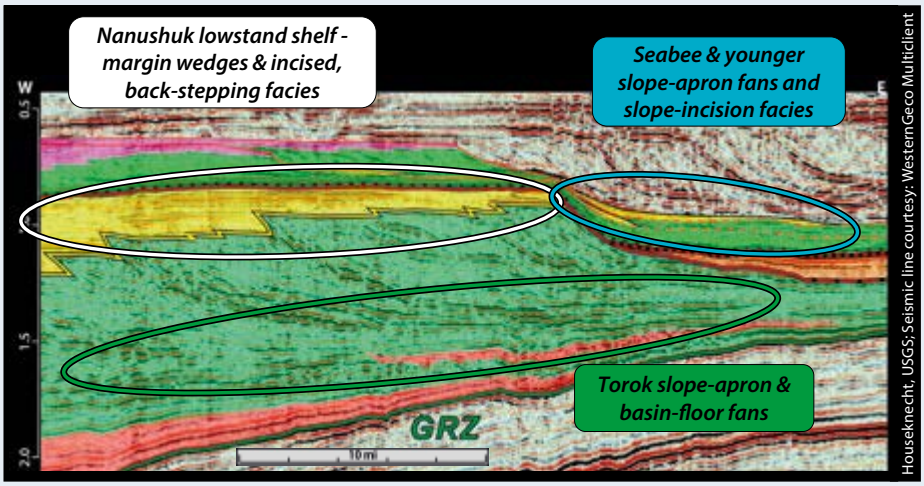
The Trans-Alaska Pipeline System conveys oil from Prudoe Bay on the north coast of Alaska to Valdez, 1,287 km further south.

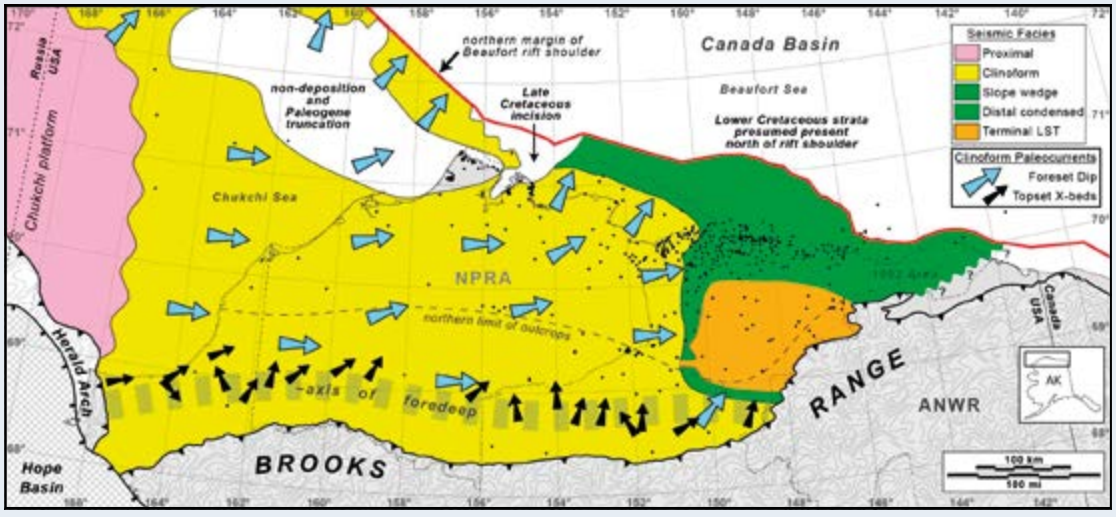
The Depositional System

North Slope stratigraphy is divided into four depositional sequences: from oldest to youngest, Franklinian, Ellesmerian, Beaufortian, and Brookian. Most of Alaska's oil has been found in the Carboniferous to Triassic Ellesmerian reservoirs, including at Prudhoe Bay and seven other North Slope fields. Beaufortian strata record a rifting event and dates from early Jurassic to early Cretaceous. Reservoirs in this sequence are found at the Kuparuk and about ten other North Slope fields.

The Cretaceous through Tertiary Brookian sediments prograded across Alaska North Slope, filling the Colville Basin. According to David Houseknecht, senior research geologist for the US Geological Survey and expert on Arctic Alaska petroleum systems, "It forms one of the world's largest clinoform systems." While oil and gas have been discovered in Brookian reservoirs, the only production has been from late Cretaceous and early Tertiary discoveries near existing infrastructure close to the Prudhoe Bay and Kuparuk fields. Before the recent oil finds in the Torok and Nanushuk formations, successes in these formations had been very limited. In exploring the National Petroleum Reserve Alaska (NPRA), the US Navy found a couple of small oil fields, one near the Simpson Bay oil seeps and another at Umiat in the Brooks Range foothills. Several small gas discoveries have also been made in the foothills. More recently, new oil pools have been found in existing fields in both the Torok and Nanushuk formations along with several discoveries near existing fields.

Seismic line showing stratigraphic and combination trap potential near the Torok-Nanushuk shelf margin. The Nanushuk discovery would be in the Nanushuk lowstand shelf-margin wedges and incised back-stepping facies. The Smith Bay discovery would be located in the Torok slope-apron and basin-floor fans.





Map of Alaska's North Slope with paleocurrent data from the Lower Cretaceous sequence, including the top sets of the Nanushuk Formation showing a north dip with a general west to east progradation as indicated by the foreset dips (blue arrows).

shelf was forming. Just north of the current Colville Delta area the shelf margin changes from a south to north orientation to a west to north-west direction. I believe the change in the relict shelf margin is a key to this oil play. Another key is the deposition of a condensed shale over the reservoirs as a consequence of a rise in sea level that forms a seal as well as a potential oil source. The prospective middle Cretaceous shelf margin play may extend 100 miles [161 km] west of the Colville Delta and remains almost untested."

Smith Bay Discovery

Approximately 170 km up the coastline north-west from the Qugruk discovery, Caelus discovered a massive oil deposit in the Torok Formation that directly underlies the Nanushuk. Its two Smith Bay wells encountered 305m of oil with net pays ranging from 56m to 68m. The wells were not flow tested but extensive sidewall coring confirmed quality reservoirs with oils ranging from 40 to 45° API gravity. They estimate between 6 and 10 Bbo in-place.

According to Jim Musselman, Caelus CEO, "This field is

roughly equivalent in scale to the Kuparuk River field. It lies in an ancient submarine fan structure that spans more than 300 mi² [777 km²] in the Smith Bay area. The reservoirs sit at a depth of 5,000 ft [152m] at this base of slope in the Torok fan complex. A third well is being planned to flow test the reservoir but I remain confident, based on core and seismic data, in the overall scale of this find. In fact, the submarine fans in the Torok extend well beyond the area encompassed by our seismic surveys so this discovery may be much larger than originally estimated."

The oil occurs in multiple sand bodies and compartmented reservoirs, common in similar submarine systems, and will be challenging as well as expensive to develop. "We're confident that the rocks here are fine [good reservoir quality]," says Musselman. "Development will require horizontal wells and fracking."

The company has been focusing on Brookian rocks in their exploration and development efforts on the North Slope. They have found Torok reservoirs at the Nuna development in the Oooguruk field located just east of the Pikka Unit, and have identified Brookian targets in their acreage holdings east of Prudhoe Bay near the Canning River. However, their Smith Bay discovery remains a major step out of the true and trusted reservoirs that have anchored North Slope production for so many years.

The Next Steps

Caelus officials admit development of the Smith Bay field will be expensive because of its remote location. "It will cost $8–10 billion to bring this field on line," says Musselman. "Field viability would require sustained mid-$60 oil prices and a future stability of Alaska's fiscal system." The company has not given a time line for development but state that once started, first oil is possible within five years.

Being much closer to existing infrastructure, Armstrong is preparing to accelerate development of its Nanushuk discovery. The company is working on an Environmental Impact Statement and construction is expected to begin on its completion. Oil could start flowing in 2021. Development will include 150 wells drilled from three gravel pads, an operations pad, access roads, and various pipeline and connections to existing facilities.

These two discoveries have both State and federal officials excited about the future. A joint State and federal oil and gas lease sale was held December 14, 2016. High bids for federal leases totaled $18.8 million compared to last year's total of $790,000. ConocoPhillips bought most of the federal leases but had to outbid Armstrong Energy, LLC to get some of them. The State fared equally as well, seeing one of the most significant sales in nearly two decades. They received 402 bids and winning bids totaled nearly $17.8 million.

As witnessed by the bidding, the companies are equally as excited as State and federal officials about the prospects offered by two new, potentially very extensive plays in spite of the current low oil prices. Certainly Alaska's North Slope has not seen this kind of optimism for a long time.

Acknowledgment:
David Houseknecht of the US Geological Survey was an invaluable source of information for this article. ■

The Armstrong and Repsol Nanushuk discovery wells Qugruk 1 and Qugruk 6 that have opened up an exciting new play on Alaska's North Slope.

The Future of Marine Seismic Acquisition?

A new marine seismic acquisition method offers full azimuth, full offset coverage, excellent quality data and repeatability, all in a very efficient manner.

LUC HAUMONTÉ, Kietta

Over the past 50 years developments in marine seismic acquisition have progressed in leaps and bounds. From the early days of oil exploration, when sound waves from dynamite explosions were recorded on a single hydrophone, through to the advent of 3D and 4C seismic obtained by increasing numbers of streamers and the introduction of ocean bottom systems, technology has tried to keep pace with the evermore demanding needs of the industry.

In recent times, however, there appears to have been a stagnation in development. The exponential growth in the amount of data acquired confirms the need for better quality and efficiency. The industry, as well as the price environment, has changed and it is essential that we develop new technologies that address the complexities of offshore operations and increasingly challenging geological settings. The big question is how to deliver data better suited to advanced quantitative interpretation methods while controlling costs. A new acquisition system, FreeCable™, attempts to address and resolve these issues.

Marine Acquisition Techniques

The trend in recent years has been to tow ever-increasing numbers of streamers in order to increase the volume of data coverage. The PGS Ramform vessels, for example, are giants – 100m long and 70m wide – designed to tow up to 24 streamers, each several kilometers long. But because of the level of hydrodynamic forces involved, the possible number of streamers is approaching its limit, plus there are inherent noise issues through wave motion and towing movement. A massive amount of data is obtained from this equipment; however, surveying in a standard grid pattern is single azimuth, which results in considerable limitations in coverage.

To overcome this, multi-azimuth surveys are undertaken, using a standard array of towed streamers but different shooting azimuths – but the initial cost is approximately multiplied by the number of azimuths, and full azimuth sampling is still not obtained. Alternatively, using several seismic vessels and source vessels, a wide azimuth survey can be acquired, which yields better coverage, though still not full

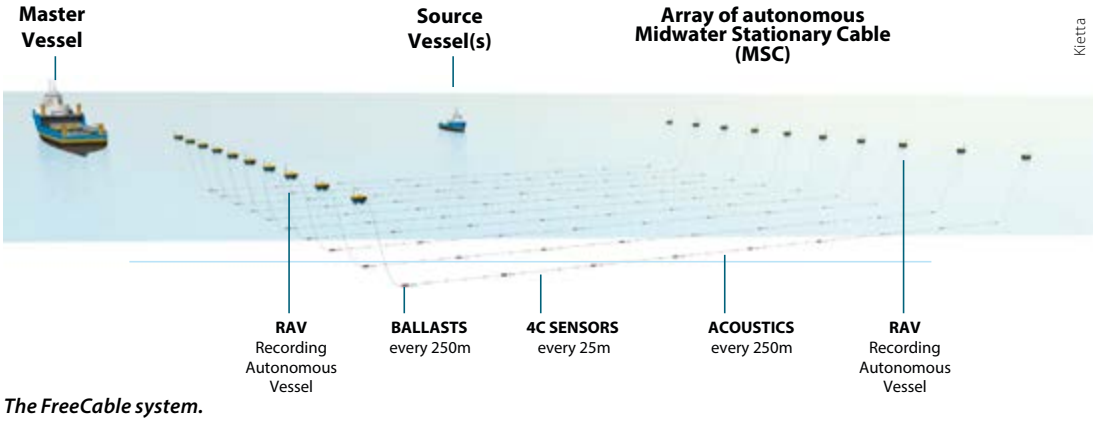
The new acquisition system being tested at sea.

Kietta

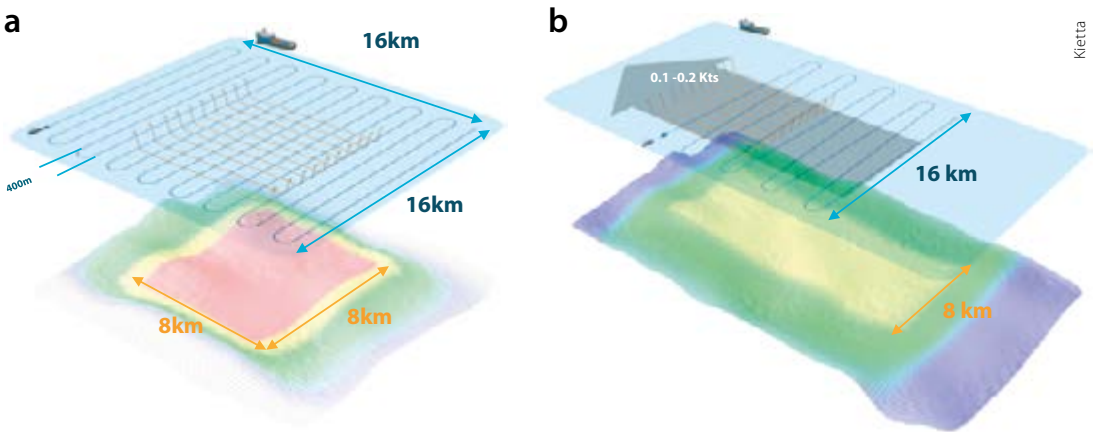
azimuth and with the disadvantage of shorter offsets and logistical complexity – and more expensive again.

Noise reduction has been a continuing area of research. Most noise is generated through swell, towing, and the strumming related to the mechanical tension in the streamer, which are hard to eliminate with present acquisition methods. The post-processing noise level is also a function of the processing gain, which can be improved with a higher coverage.

Another area of improvement over the years is signal spectrum enlargement. The industry has developed different solutions to overcome the ghost problem, such as the over-under technique, the slant streamer technique or the multi-sensor streamer. However, these advantages remain limited since measurements are corrupted by noise, linked to the fact that streamers are still towed at about 5 knots.



The FreeCable system.



Acquisition methods tested include (a) patch and (b) progressive shooting.

Improving bandwidth and resolution has been a priority since the early days of the seismic method – to see thinner beds, to image smaller faults, and to detect lateral changes in lithology. Broadband seismic acquisition is now an integral part of the process.

Ocean bottom technologies, involving nodes or other receivers static on the seabed, are currently the only solutions that address all the azimuth and offset issues. However, they have significant drawbacks, including seabed-related noise, low productivity and high costs, particularly in deeper water, and they are not suitable for many seafloors, such as pinnacles or corals.

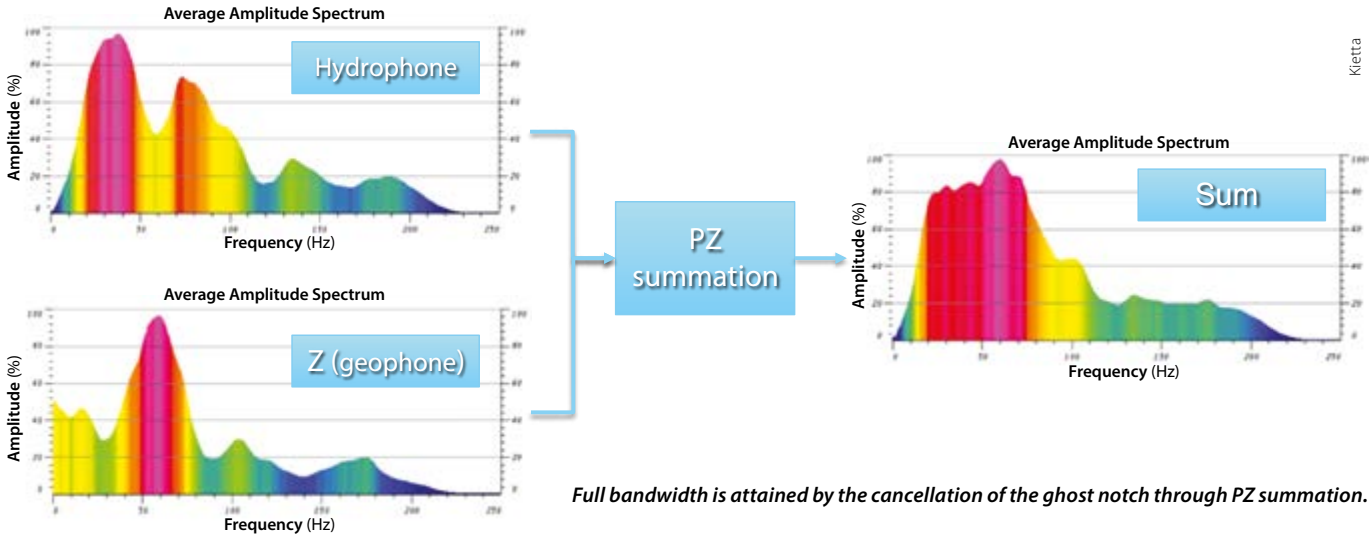
Enter FreeCable

This new method of seismic acquisition, developed by French company Kietta, is the result of six years of discussions, designs, prototypes and trials. It is based on the classical principles of reflection seismology: one or more vessels provide a sound source and a large number of seismic sensors attached to submerged cables measure the reflected waves. There are, however, some very significant modifications in this system, and all the components used have been specifically designed for it.

The main difference lies in the receiver array and the way it is operated. The 8 km-long streamers in the 20-cable spread are independent and autonomous, each controlled by a pair of robot vessels which regulate the position. They float in the mid-water, where there is much less ambient noise than at shallower depths or on the seafloor, with 4C sensors every 25m, each with a hydrophone and geophone measuring wave pressure and velocity. The signals from these are combined to cancel out the reflection ghost, leading to a flat spectrum and full bandwidth over the seismic frequency range, regardless of depth. Very significantly, since there is no towing vessel, the noise resulting from water flow and tension in the cables is completely eliminated.

Data can be acquired using a number of acquisition methods, with the two tested so far being 'patch' and 'progressive' shooting. In the former the spread is stationary at a fixed location with respect to the seabed. The shooting vessel sails perpendicularly to the cables, ensuring high-fold recovery, shooting every 25m, with an inter-line spacing of 400m and an overshoot of 4 km on each side. Once an 8x8 km zone is covered, the array moves to the next contiguous zone. In progressive shooting the cables and sensors, guided by the autonomous vehicles, move very slowly (~ 0.1 knot) along a pre-determined route. The shooting vessel again sails crossline, shooting every 25m with a 4 km overshoot. The speed of the cables allows them to move 400m in the time it takes the shooting vessel to shoot a complete line.

This level of precision in navigation and timing is possible through the patented navigation techniques used by the



Full bandwidth is attained by the cancellation of the ghost notch through PZ summation.

autonomous source and the recording vessels. These ensure that the effects of sea currents and mechanical tension and vibrations along the cables are negligible and that the center of the spread stays as close as possible to the target while maximizing the seismic data quality. All operations are supervised from a control room onboard a master vessel communicating with the various components wirelessly, with real time QC of the data.

Full Azimuth and Other Advantages

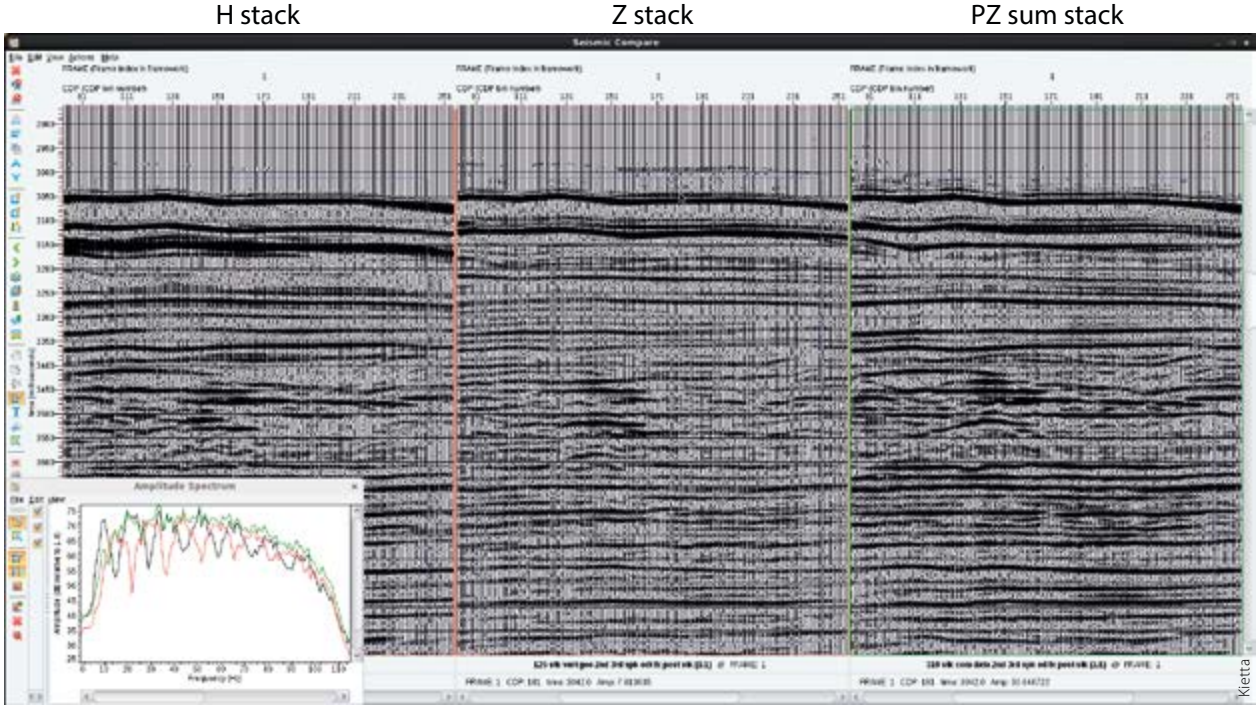
With this system it is possible to obtain the 'holy grail' in seismic acquisition: 3D high fold seismic data with both full azimuth and full offset across the full fold area of 8 km x 8 km. It has high coverage per bin (12.5m x 12.5m in the typical configuration), which greatly improves the post-stack signal-to-noise ratio (+26dB), while the geometry produces a completely isotropic response since full offset, full azimuth data is obtained in every bin: the response is independent of the azimuth.

One of the most significant applications of this full 3D acquisition is that in complex subsalt geological structures it may allow for the illumination of zones which are in 'shadow' for other technologies. In addition, it provides richer data for amplitude versus offset and azimuth reservoir characterization studies.

With the inline geophone signal recording useful seismic energy which can be exploited to give a 3D vector measure of the particle velocity, and positional accuracy better than 1m (2D-RMS radial error), allowing for accurate repeatability, this methodology is ideal for 4D and 4C investigations.

This method shows improved productivity over other seismic acquisition methods in a number of ways. Without

Sea trials proved that full bandwidth is obtained, with the ghost notch eliminated through PZ summation.



a cable-towing vessel time is not wasted on wide U-turns. As a result continuous acquisition is obtained when using the progressive method, while the patch survey is ideal for cost-effective 4D. In addition, there is far less weather downtime, as the method is not as sensitive to bad weather and high sea states. In fact, when compared to same data quality surveys acquired by traditional methods over a 900 km^2 area, FreeCable is twice as productive as multi-azimuth acquisition and six times more productive than OBC.

Flexibility is another key feature, as it is easy to mobilize and operate this system in any environment and the geometry and survey design can be tuned to each individual project. From the environmental viewpoint, operations leave a small footprint, with very low fuel consumption, no impact on sea bottom, and a low level power source with respect to marine fauna, while the reduced number of offshore personnel required to run such a survey is advantageous from the safety perspective.

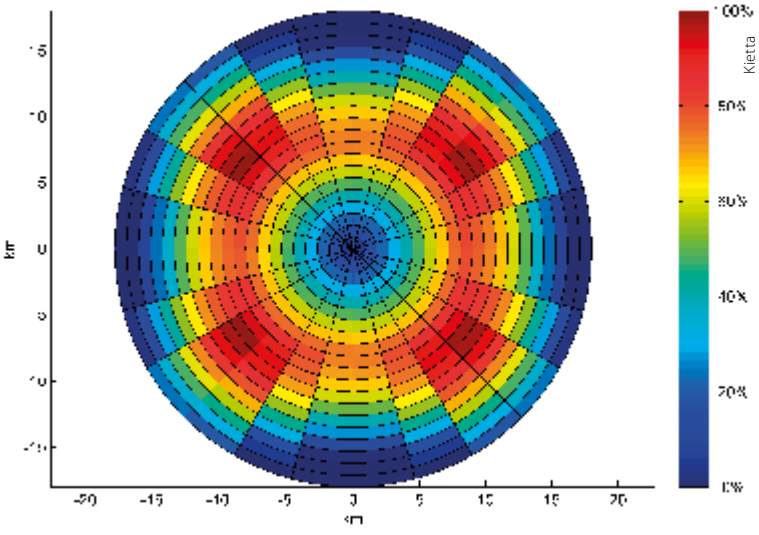
Successful Tests

In 2014 Kietta had the opportunity to test their new system in a deepwater area in the Mediterranean, where it proved very successful. Using only a small source – a 150 in^3 mini air-gun array – and in water depths of 2,400m, up to seven seconds of data was recorded. Being able to obtain such results with low energy sources at water depths of over 50m is crucial for operations close to marine mammals and fishery conservation areas.

The raw seismic data was of good quality on all four components and the ghost removal predicted through the use of the hydrophone and geophone records was achieved. The system was tested with respect to its ability to control the position of the array and for repeatability, both with satisfactory results.

So, with high productivity and efficiency in a wide range of water depths and sea conditions, a light environmental footprint, full azimuth data, a flexible geometry and a range of applications – is this the future for seismic acquisition? ■

Full azimuth and full offset: one of the main advantages FreeCable has over traditional acquisition systems.



The Oil Within

"A passion for what you are doing makes the difference," says Susan Morrice, co-founder and chairperson of Belize Natural Energy – which she believes explains why, after 50 companies had unsuccessfully spent many years looking for oil in Belize, she struck lucky with her first well.

JANE WHALEY

"The background to this story is that 50 oil companies, over 50 years, spending $450 million, had all searched for oil in Belize – and failed."

Geologist Susan Morrice fell in love with the Central American country and its people on her first visit and decided that if she could discover and develop oil in the right way she could make a positive difference in the country.

The Entrepreneurial Spirit

Susan was born and brought up in Northern Ireland and fondly remembers family outings and picnics when she was little, jumping around on rocks in famous geological sites like the Mountains of Mourne and the Giants Causeway. "I always loved rocks," she says, "but it was some time before I realized that you could study and learn about them and that could be a real job! I remember thinking 'Wow, that's amazing – I'm going to do that!'" She studied Natural Sciences at Trinity College Dublin, graduating in 1976, at a time when, as she points out, "geology was really changing as the concepts of plate tectonics took hold. I love the fact that geology is an evolving science, not all tied up, and you can still keep asking questions. Even in exams at university, you can be asked to give your ideas rather than provide a right or wrong answer."

Soon after graduating, Susan moved to America to work for American-Canadian Stratigraphic, who sent her around the world, learning how the industry works as she went. She then joined Denver-based Knight Royalty as a frontier specialist. "A great job! I love mapping and working out the geology of new areas and I went around with the 'landmen' talking to the famers and landowners. It was both fascinating and empowering," Susan says.

"When I came to the US I had the assumption that all Americans were entrepreneurs, so I determined that I would set up my own company as soon as possible. Knight Royalty were very accommodating and I worked part time for them while I started out, but I soon had plenty of work and began employing other consultants. We had projects all over the world, from Ireland, the UK and mainland Europe to Africa, Asia, Latin America and the USA. It was wonderful to brainstorm with these specialists, not all from traditional oil industry backgrounds, including mining consultants and engineers. I believe that it is important to break down subject barriers in order to let the mind soar."

International Pavilion

Susan continues: "In the early 90s the low oil price meant the industry was in a decline, but I realized that while fellow geologists in Denver were out of work, there were still plenty of exploration opportunities around the globe – but how to get them together? Robbie Gries (see *GEO ExPro* Vol. 4, No.2), later the first female president of the American Association of Petroleum Geologists (AAPG), asked Roger Slatt and me to head up the international part of the AAPG convention in Denver in 1994. We invited every country in the world to exhibit their oil and gas potential; 52 countries attended in the first year alone and thus the International Pavilion was born. We raised half

BNE

a million dollars from oil companies who thought it would be great to be able to access world deals and potential in one place; I became a bit like a matchmaker! It was organized and run by volunteers and it was good to see them get enthused by the idea; it ended up a huge and important event."

For this, Susan was awarded the AAPG's Distinguished Service Award.

Susan handed over the reins of the International Pavilion after that first event so she could concentrate on her newly adopted daughter, but it proved to be a key turning point in her life when, a couple of years later, she was asked to talk to students at a business school about how she had made a success of the International Pavilion project. She realized she could not really explain it, and wondered why not everyone has the 'get up and go' to be an entrepreneur or to set and achieve high goals.

Educo Leads to Belize

"It was an eye-opener," she explains. "I realized I knew how the earth works – but not how my own mind did. I set out on a search for a system that would enlighten me and that could also be replicated, so that other people could be open to the entrepreneurial spirit or to develop their dreams. There seemed to be a lot of talk out there about activating human potential, but not much action.

"I finally found what I was searching for in Educo, started by Dr Tony Quinn, which had the proven academic background and track record I was looking for. I attended the Educo Seminar in 2002 and, feeling fulfilled and focused, decided to follow my long-held geological gut feeling and look seriously for oil in Belize."

Susan had first visited Belize in 1983. "Like others before me, I looked at the 50 dry holes, but I also saw potential," she explains. "I had also fallen in love with the country and the people. With renewed self-belief, I went back and together with a Belizean partner, Mike Usher, who shared the same passion and had also attended the same Educo seminar, we started Belize Natural Energy (BNE). We threw out all the preconceived ideas – including the ones about there being no oil in Belize and that the only possible reservoirs would be carbonates – and started looking at the country with fresh eyes, an open mind and a clear structure.

"Against all odds, with 500,000 acres (over 2,000 km^2) in which to choose a single location and finances for just one shot, the impossible happened – a discovery in one. (Statistically it takes 10–15 wildcats before a discovery.) Sadly, however, Mike Usher had died the year before, but amazingly enough, on the exact anniversary of his death one year later, on June 24th, 2005, the first oil in Belize was discovered by BNE – in a sandstone reservoir." There are now ten producing wells named in honor of Mike in the Spanish Lookout field in Western Belize.

Holistic Approach

"In 2007 we discovered a second field, Never Delay, about 20 km east of Spanish Lookout, which, although a more complicated fractured reservoir, we believe is commercial," Susan continues. "We have now produced 11 MMbo in just

Susan and BNE colleagues, Breandon Raymond, Emogene Habet and Mateus Furtado.

eleven years, having also had to develop from scratch the infrastructure required to produce, develop and transport the oil to the coast, from where it is exported worldwide.

"We take a holistic approach to developing this resource so it will benefit all the people of Belize," she explains. "Oil is one of the main revenue generators in the country, but about 20% of the oil produced is used within Belize for electricity generation and in local industries. We are producing a range of products like propane and butane to encourage diversification, and through the development of the export terminal we see Belize becoming a major hub for the Caribbean and Central America.

"The important thing is to make a difference. BNE, which has 170 employees, is 99% Belizean and everything we do is for and about the country. BNE was founded on the deep-rooted belief that the country has the energy resources – both hydrocarbons and human – to transform the future. Our model is all about the people and their inclusion in the business; for example, crude oil haulage is outsourced to local truck operators, although they must conform to our very high safety standards.

"I strongly believe that we all have the energy and force to realize our dreams," Susan continues. "The Educo seminar enabled me to focus on my goals, dispel my doubts and see a clearer vision for the future. I found it so inspiring that all BNE employees also attend the seminars to help them understand their own minds and the vision for the company and country."

Global Partnerships

That vision is to be the total energy solution throughout the Caribbean and Central America. "At the beginning of this century Belize, like most countries in the area, was sliding into financial difficulties. Oil has turned that around and the country is at the forefront of this new holistic approach," Susan explains. "Belizeans have great respect for their environment so we needed to find new ways of working to include that. I believe we have survived the current downturn because the Educo training of BNE personnel has led to innovation and diversification in the company and the development of everyone's full potential. Our aim is for BNE to be the most holistically balanced energy company in the world, crossing boundaries and industries; for example, we produce electricity from our gas flare for use by local communities.

"We have become a beacon for holistic development and we want to share the secret of our success with everyone. We welcome visiting dignitaries from all over the world to tour BNE to learn about the new business model. Visitors notice the energy and creativity in the BNE personnel and their pride in their work and their country.

"We are really excited that in October, 2015 Belize and the United Arab Emirates signed a bilateral trade agreement, which will bring investment into Belize from the UAE. The two countries share a vision – that oil is just the start of the economic success story, and diversification is key, as the UAE has proved since oil was first discovered there 50 years ago."

All in the Mind

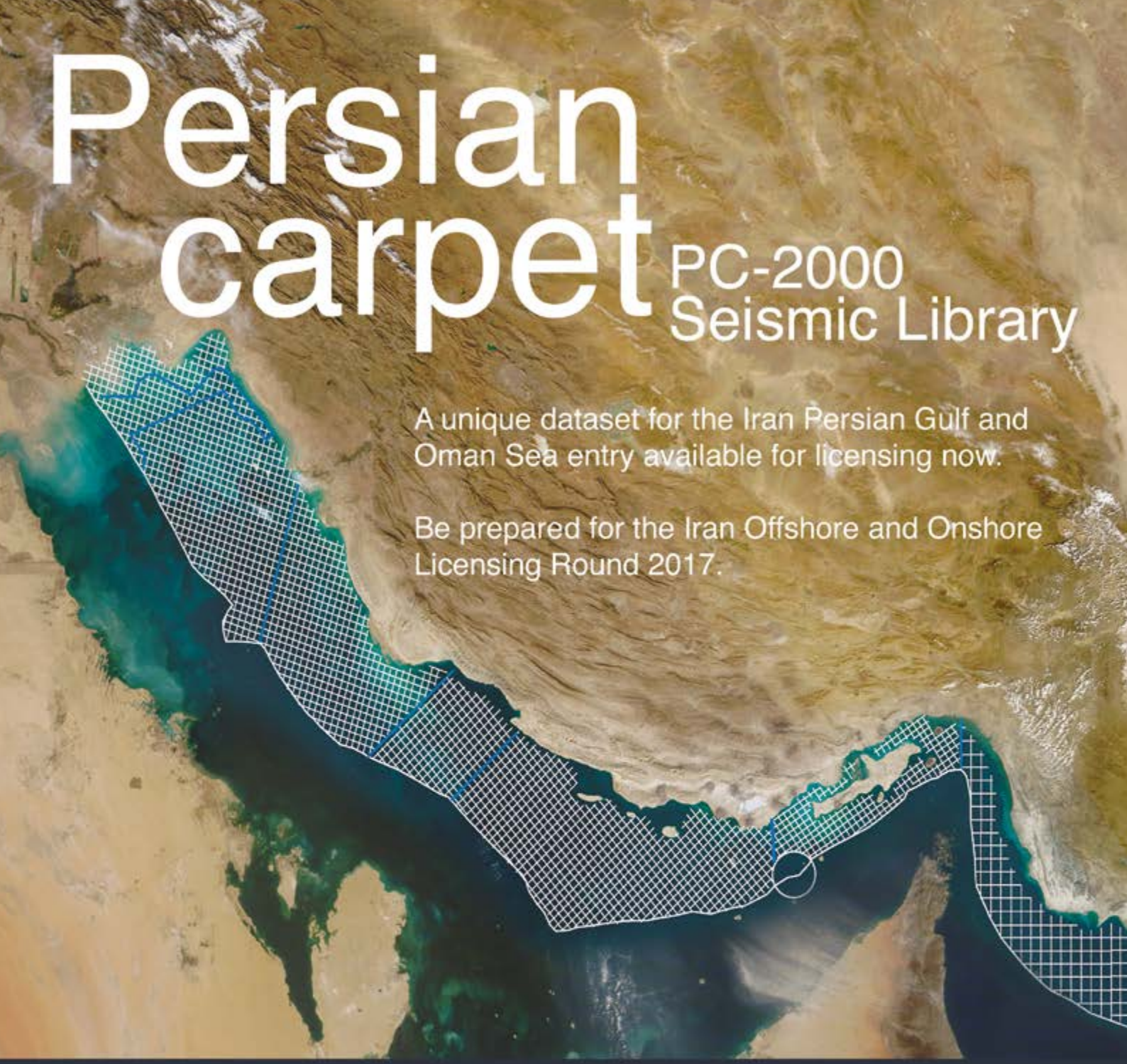
"As exploration geologists, we pull together lots of data and information, but we can't know everything – that final decision to drill is always a leap of faith," Susan points out. "I found that understanding my mind helped me make that leap and in the process changed a country. When we discover how our mind works and we live our full potential, we are not only more useful to ourselves but also to humanity. My passion when I started out on my career was for geology, but now it is for people. Geologists can make a difference!

"Wallace Pratt's oft-quoted words "Oil is first found… in the minds of men", summarizes it well. At BNE we call it 'the oil within'!" ■

Susan at the BNE headquarters.

Persian carpet

PC-2000 Seismic Library



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Beneath Belize

A new online national data repository for Belize provides access to a digital catalog of all seismic data acquired across the country since the late 1960s – hitherto tucked away in dusty corners of the Geology and Petroleum Department in the country's capital, Belmopan.

GARETH WILLIAMS
Lynx Information Systems

The Yucatan Peninsula is a distinctive landmark – a predominantly limestone-based platform that separates the Gulf of Mexico from the Caribbean Sea, and is perhaps best known for its holiday resorts, Mayan history, and of course the Chicxulub impact crater. Situated mostly inside Mexico's territorial borders, it is bounded to the west by the prolific Sureste Basin and the oil and gas deposits of the Reforma-Akal and Macuspana provinces, fields that contain combined proven reserves of over 12.5 Bbo.

Farther south, the peninsula extends into English-speaking Belize, which is nestled in the crook of the eastern Caribbean coast between Mexico and Guatemala. What of its hydrocarbon prospects? Considerable attention has been focused on Mexico's energy sector over the past two years since the launching of a series of new bid rounds that, for the first time since the 1930s, have opened the path to foreign investment. Could the recent enthusiasm for exploration in the region rub off onto other parts of Central America?

Oil Revitalized Economy

Formerly British Honduras, Belize achieved independence as a parliamentary democracy from the United Kingdom in 1981, although the country, like other former English colonies of the Caribbean, retains Queen Elizabeth II as its titular head of state and it is a member of the British Commonwealth of Nations.

Measuring 22,810 km^2 (slightly bigger than New Jersey or Wales), Belize has a population count of around 368,000, a number made up of seven recognized discrete ethnicities; these are the Maya, Mestizo, Creole, Garifuna (African-Amerindians), East Indians, Sino-Asian/Chinese, and German-Mennonites.

Belmopan has been the capital of the country since 1970. It is the smallest national capital in the continental Americas with a population of around 16,500, and was built inland as a planned community following the near-destruction of Belize City, its former capital situated on the coast, by Hurricane Hattie in 1961. Belmopan is the seat of the government and it is here that the Geology and Petroleum Department (GPD), the body that looks after all aspects of exploration and production activities in Belize, is located.

Prior to 2006, Belize's economy was primarily dependent on traditional exports such as sugar, citrus, bananas, timber and fish products, together with the inflow of money that comes with foreign real estate investment and tourism. The latter are a result of the attraction of the country's Caribbean coastline and

123rf/ lanabyko

The ancient Mayan site of Xunantunich, looking westwards across dense jungle covering of the Corozal Basin in the background.

several island resorts ('Cayes') that lie in waters sheltered by the Mesoamerican Barrier Reef system, the second longest in the world.

Then in 2005, after nearly 50 years of failed exploration, commercial quantities of oil were finally discovered by the Mike Usher-1 well, drilled around 25 km due west of Belmopan in the small Mennonite community called Spanish Lookout (after which the field was eventually named). Production from here would soon catapult oil into the category of primary revenue generator for Belize, and trigger renewed optimism for its exploration prospects.

A photo taken from the GPD offices in the center of Belmopan, overlooking the main market square.

Geology and Exploration History

Located just north of the broadly east-west trending Montagua-Polochic fault system that forms the boundary between the North American and Caribbean plates, the overall geological setting of Belize can be sub-divided into three entities: the Corozal Basin in the north, and the Belize Basin in the south, separated by the Maya Mountains. These mountains rise up in places to over 900m and are comprised of Permo-Carboniferous metasediments and volcanics with Upper Silurian and Triassic igneous intrusives, and represent a faulted block of Mayan crust that tilts westward towards Guatemala. This fault trend continues into Guatemala, where it is expressed as the La Libertad Arch, partitioning the intracratonic Peten Basin into north and south sub-basins. The Belize Basin, which borders the Maya block to the south and extends offshore, is essentially a continuation of the South Peten Basin, whilst the Corozal Basin represents the eastern extension of the North Peten Basin.

First hydrocarbon exploration efforts began with Shell in 1938, who conducted geological studies through fieldwork and aerial photos, although it wasn't until 1955 that the first well, Yalbac-1, was spudded by Gulf Oil in the Corozal Basin. Further companies tried their luck in the following decades, including majors such as Esso, Phillips, Chevron and Oxy, leading to over 75 dry wells being recorded, most of them in the Corozal Basin. However, it should be noted that non-commercial oil shows have been reported from more than 50 of these wells.

Several factors have been put forward to explain why these drilling results may not tell the complete story. Many of the wells drilled were based on poor or non-existent seismic data and were not optimally located due to accessibility issues; some wells never reached target depths or were off-structure; and for many of the wells that revealed oil shows, production casing was not lowered to enable conventional testing to be carried out.

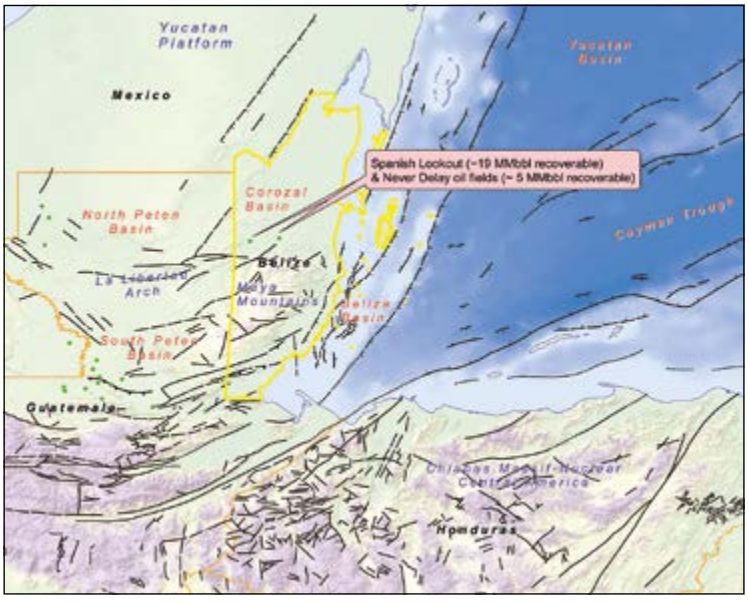
Belize eventually struck oil in 2005 when a small band of geologists, led by Susan Morrice (see page 34) and Jean Cornec, made the groundbreaking discovery at Spanish Lookout, in the Corazol Basin, where light oil was recovered from a number of intervals in the Lower Cretaceous Hillbank Formation, a 75–100m section of dolomite punctuated with evaporate and sandstone units. This was followed by another discovery in 2007, from the overlying stacked dolomite/anhydrite sequences of the Yalbac Formation at the Never Delay area just outside of Belmopan. These fields are now under the ownership of the private company Belize Natural Energy (BNE).

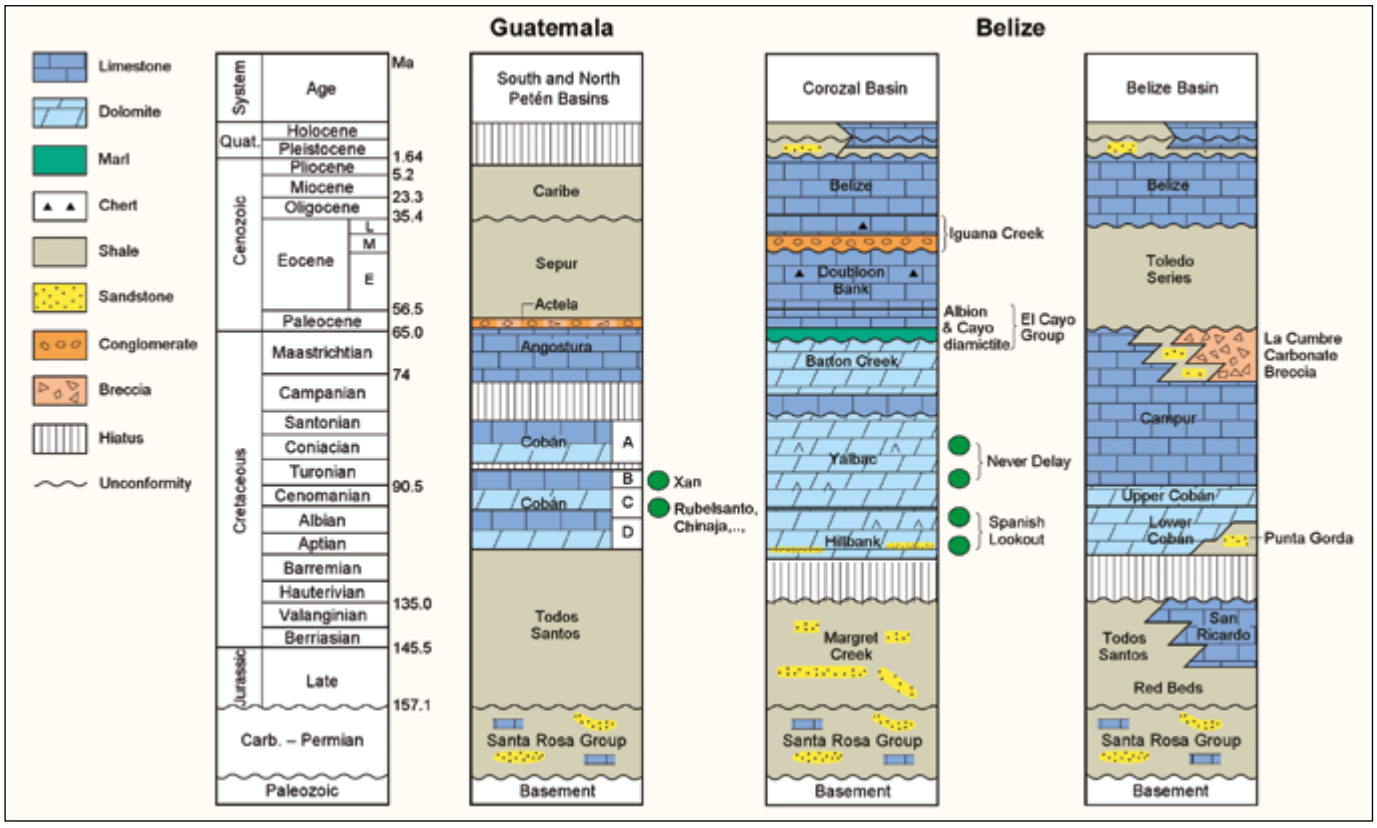
Belize's stratigraphy is considered to be poorly or incompletely defined, partly due to a deficit of good outcrop exposures and fossil control as a result of extensive dolomitization of its carbonate sections, which is especially true of northern Belize. In general, the Corozal Basin can be described as carbonate-dominated, whilst the Belize Basin sees more clastic input in large parts of the section.

Seismic Data Repository

According to the GPD archives, seismic reflection surveying first began in Belize during 1965-66, when Shell started to acquire low fold data in the offshore area between the coastal towns of Belize City and Dangriga, and around the Turneffe

Map showing the location of Belize in context with the major structural elements of the region. Adapted from USGS Open File Report 97-470-K.





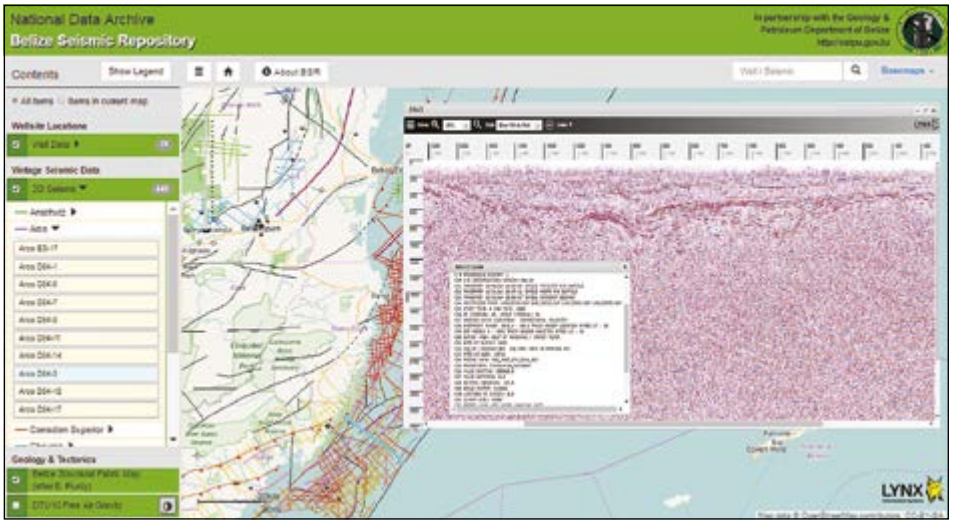
Generalized stratigraphic columns of Belize and Guatemala, marked to show those horizons where oil has been discovered and produced in both countries. (Adapted from an academic paper published in the Journal of Petroleum Geology, by Petersen, H.I. et al., 2012.)

Atol. Thereafter, acquisition programs were carried out almost every year by the permit holders of blocks in both basins up until the early 1980s, with a few surveys then completed in 1991/92 that mark the end of what the GPD refer to as 'vintage' data. The total length of vintage 2D data acquired over this time is reckoned to be just short of 10,000 km, but the remaining records of these data are almost entirely in the form of traditional post-stack sections printed onto paper or film.

Transforming these legacy sections into something potentially useful requires the application of seismic vectorizing, a process which involves carefully scanning the original sections and reconstructing the rasterized peak/trough wiggle traces into vector waveforms. The science and art of doing this has been perfected for over two decades by Lynx, who also bring considerable experience to bear to the practice of setting up and running national data repositories, having successfully implemented and managed the UK Onshore Geophysical Library (UKOGL) for many years. And so it was almost natural that, following an informal meeting between representatives from both parties in 2014, an agreement was inked that would enable the process of building a seismic repository for Belize to begin. A year later, 90% of the vintage data was completed to the extent that it now exists in an industry standard digital format (SEG-Y) that can be loaded into a workstation by geoscientists and interpreted.

A website and interactive online GIS map was launched in 2016 to help draw attention to the availability of the seismic archive, and this has since been coupled with an online SEG-Y viewer so that visitors can preview example lines from all of the vintage surveys. Recently, the scope of Lynx's remit has been extended so that modern seismic data acquired in Belize (surveys that are now publicly available following expiry of a five-year confidentiality period) will now be added to the repository, which currently includes two 3D surveys and original field (unstacked) data for most of the 2D. ■

A screenshot from the online interactive map, showing an example of one of the vintage seismic lines.



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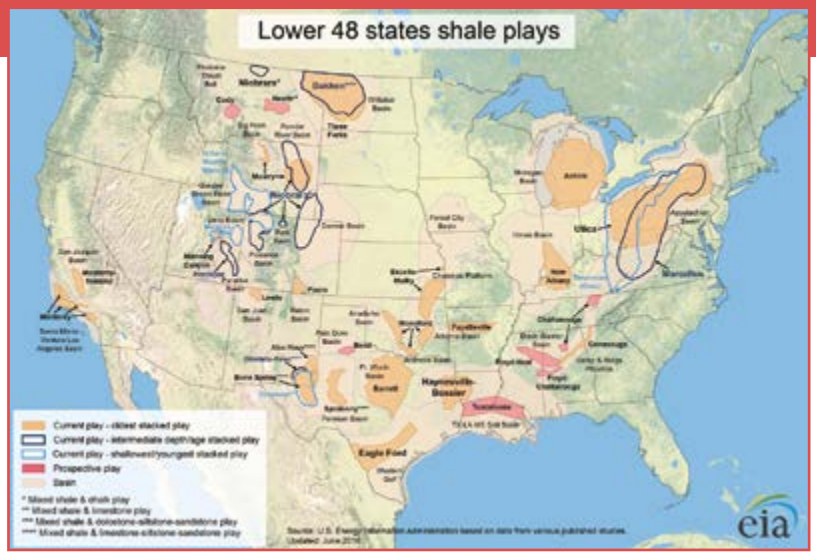

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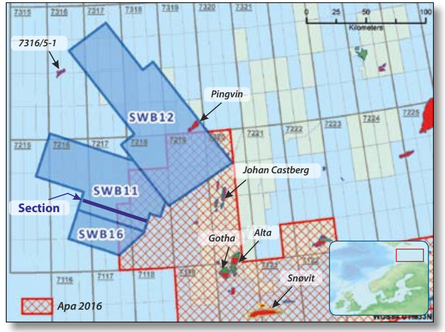
The South-West Barents Sea

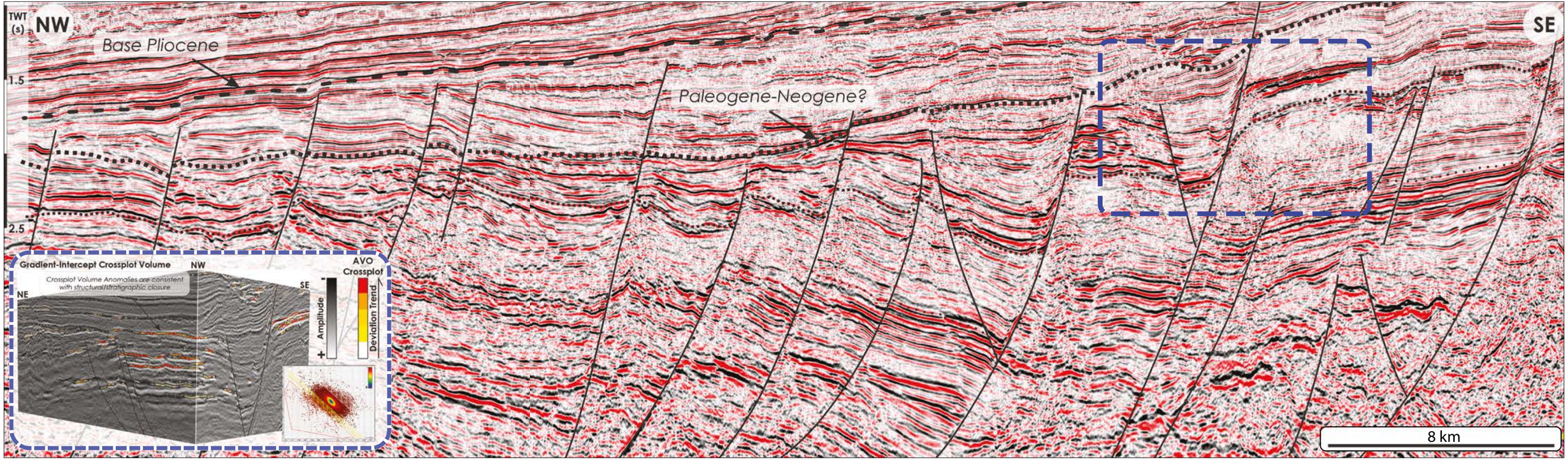
New Opportunities from the Atlantic Margin

Spectrum's modern 3D multi-client seismic has highlighted additional hydrocarbon prospectivity in Cretaceous-Paleogene plays. The 3D seismic campaigns undertaken in 2011–2012 and 2016 have resulted in a comprehensive dataset, which will generate new hydrocarbon prospects and raise the commercial profile of the most developed area in the Norwegian Barents Sea.

Section extracted from seismic volume SWB11.



Spectrum's 3D multi-client seismic library in the Western Barents Sea, showing the locations of seismic volumes SWB11, SWB12 and SWB16.



The Western Barents Sea from an Atlantic Margin Prospective

Cretaceous and Paleocene reservoirs have been proven in clastic turbidites in the Western Barents Sea. Oil- and gas-prone source rocks are expected to be widespread in the Cretaceous, as observed in other sectors of the Atlantic Margin in Norway and UK.

PAOLO ESESTIME, Spectrum Geo

The Western Barents Sea has seen the highest rate of exploration success in all the Norwegian Barents Sea; it also includes active production facilities (Snøvit field) and future plans for development (Johan Castberg field).

Successful hydrocarbon exploration in the Barents Sea relies on several hydrocarbons plays, laterally stacked in different basins (Figure 1), and vertically distributed in a variety of reservoirs. Triassic-Jurassic sands are historical targets for oil and gas; however, the recent discoveries of Gotha and Neiden have proved good reservoir properties even in Permian-Carboniferous carbonates.

The westernmost margin is currently considered a new venture area, where gas sands have been already found from the Cretaceous to the Paleogene.

Between Arctic and Atlantic Plays

The Barents Sea is a well-established hydrocarbon province in the circum-Arctic region. Its prospectivity relies on the structural and paleogeographic evolution of the region from the Paleozoic through to the Triassic-Jurassic, which created the shallow continental platform of the Norwegian Barents Sea. Source rock deposition was widespread from the Paleozoic to the Jurassic, starting maturation and expulsion during the Triassic and the Jurassic. Tectonics remained relatively quiescent, with the formation of few structures, mostly related to halokinesis in Permian-Carboniferous evaporites, as seen in the Nordkapp and Maud Basins. Cretaceous subsidence did not make a significant contribution within the main continental platform, being followed by erosion and uplift during the Paleogene and Neogene, with neo-formation of regional tectonic structures and consequent re-migration of the hydrocarbons already in place.

The opening of the North Atlantic margin enhanced the hydrocarbon habitat in the Western Barents Sea, rejuvenating the tectonic subsidence and allowing Triassic-Jurassic source rocks to generate oil and gas. The extensional tectonics reactivated previous faults from the Paleozoic in the Loppa High and Hammerfest, creating several basins. Some discoveries, including Gotha and Neiden, are preserved in Permian-Triassic structures, while the majority of the fields and discoveries are sited on tilted fault blocks from the Jurassic and Cretaceous.

The tensile tectonics of the Atlantic rift migrated westward and northward from the Upper Cretaceous-Paleogene, and also combined with volcanism and oceanic spreading during the Neogene.

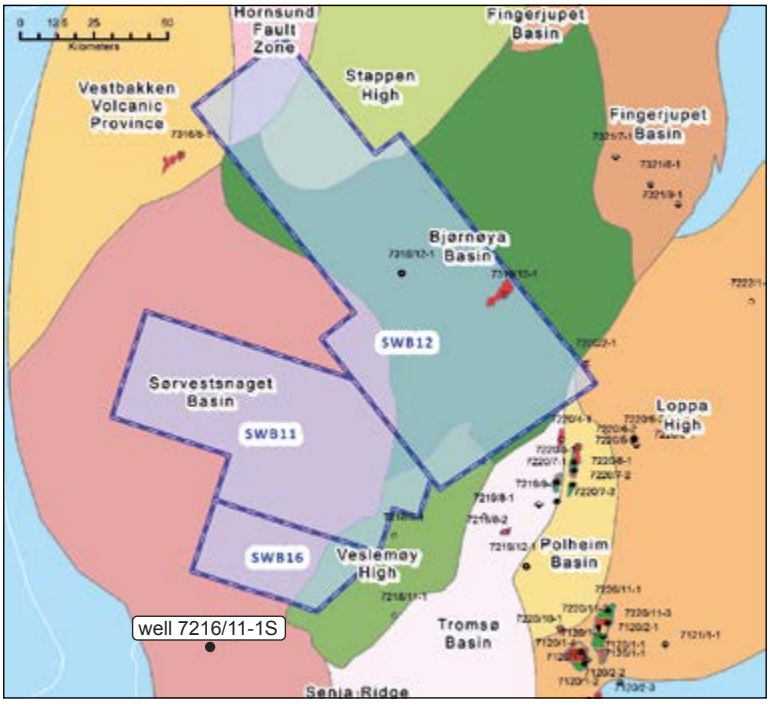
The Tromsø, Bjornøya and Sørvestsnaget Basins have developed since the Lower Cretaceous, separated by structural highs which were subsequently reactivated. Tectonic extension remained active during the Upper Cretaceous to Paleocene, leading to the subsidence of the Sørvestsnaget Basin and its southern sector and creating accommodation space for the deposition of 3,000-4,000m of clastic sequences and thick sand turbidites.

Risk Reduction in Cretaceous-Paleogene Plays

The revaluation of the regional prospectivity will reduce the exploration risk in Cretaceous-Paleogene targets, for both oil and gas in the western Barents Sea.

Source rocks: Understanding fault chronology

Figure 1: Schematic geological map of the Western Barents Sea, including Spectrum`s 3D multi-client seismic library.



is an excellent approach to reduce the risk related to the distribution of Lower Cretaceous source rocks. Good sources have been recognized in other sectors of the Norwegian Atlantic Margin, and in the Vøring Basin. Atlantic rifting resulted in a connected system of basins that extends north to the Lofoten Basin, so Lower Cretaceous source rocks are likely to be present up to the Tromsø and Sørvestsnaget Basins. In addition, future exploration may prove potential source rocks in Upper Cretaceous shales.

Thermal maturity: Jurassic source rocks can be considered oil and gas prone along the western margin of the Loppa High and the Bjornøya Basin. To the south, these units have been deeply buried since the Upper Cretaceous, generating almost exclusively gas. Lower Cretaceous source rocks show lower values of TOC than the Jurassic sources, and are around 3,000m thick, much larger than the tens of meters that characterize the Jurassic (Figure 2). The additional 2,000–3,000m of Upper Cretaceous-Paleogene may have even triggered the generation of oil and gas in Cretaceous source rocks. The Neogene section is almost entirely represented by glacial deposits of the Upper Pliocene sequence, which pushed the oil and gas windows up to the Paleogene sequence.

Reservoir: Reservoir properties are proven in clastic sediments deposited since the main syn-rift period in the Lower and Upper Cretaceous. Paleocene-Eocene sands turbidites were encountered in well 7216/11-1S (Figures 1 and 2).

Fault chronology may have strongly influenced the provenance and distribution of the Upper Cretaceous and Paleogene turbidite systems. Coarser clastic deposits are more likely to be present within the syn-sedimentary growth of the faults. Regional tectonic subsidence has shifted most of the turbiditic input southward, flowing into the Sørvestsnaget Basin, even parallel to fault trends (Figure 3).

Turbidite sands are marked by strong amplitude events and are frequently associated with AVO anomalies. Quantitative amplitude studies can be a useful tool to isolate the event or interval of interest. Interpretation of AVO responses will require accurate assumptions to model the anomalies; petrophysical information is currently limited to regional stratigraphy and the few drilling results potentially available.

Trapping mechanism: Cretaceous-Paleogene tectonism has created numerous structural 4-way dip closures, several kilometers wide (See 3D image on foldout on page 42). Large prospects may combine structural relief and sediment patterns along regional dips. The risk of trap integrity exists for shallow prospects close to or above the Paleogene-Neogene unconformity, which may have been exposed during the Pliocene.

Additional Prospectivity for Oil and Gas

Spectrum's modern 3D multi-client seismic coverage over the Western Barents Sea allows detailed analysis of the petroleum system elements resulting from Atlantic margin processes. This highlights significant additional hydrocarbon prospectivity in relatively unexplored Cretaceous-Paleogene plays proven in other sectors of the Atlantic Margin in Norway and UK.

References available online.

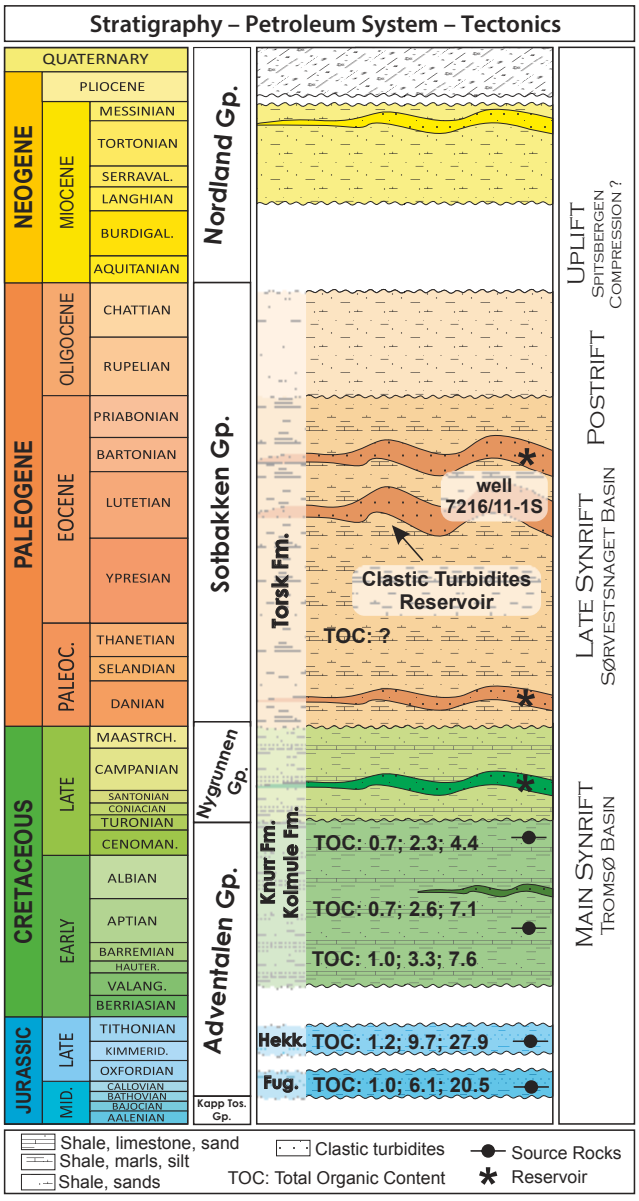
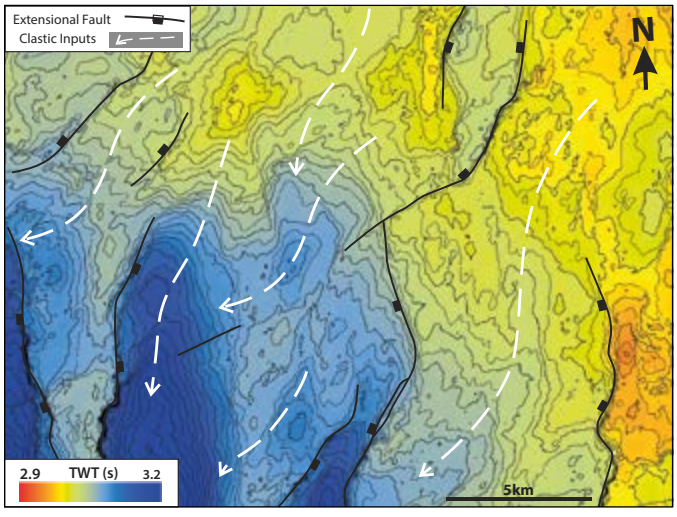


Figure 2: Tectono-stratigraphic sketch showing the main elements of the petroleum system in the Atlantic Shelf (West Barents). Inspired by Ohm et al. (2009) and Henriksen et al. (2012).

Figure 3: Time horizon map within the Paleogene section in the seismic volume SWB11.



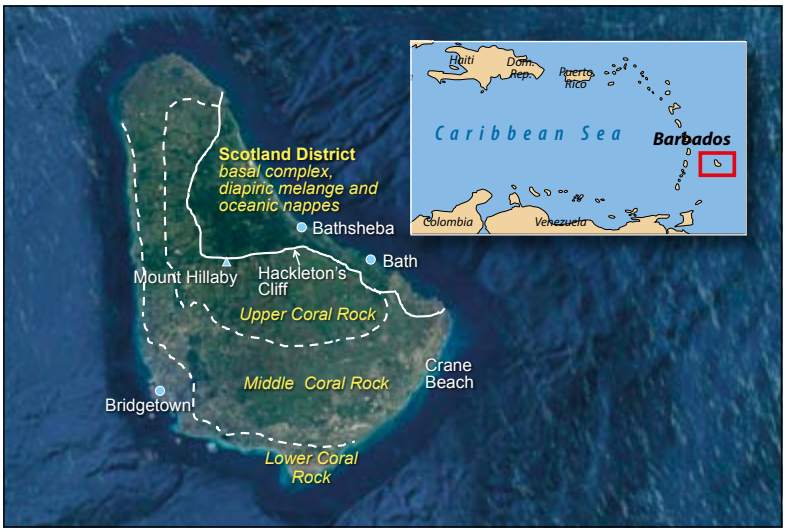
Barbados Beckons

This alluring Caribbean beach paradise is one of the few places on the planet where you can stand on an active accretionary wedge as well as visit a giant's staircase of uplifted reefs that have played a pivotal role in reconstructing ancient sea levels.

TERRI COOK and LON ABBOTT

The island of Barbados is one of only a few places on Earth where an active accretionary wedge is exposed above sea level. The island emerged about 700,000 years ago, riding on the back of a giant mud diapir, and it continues to rise at an average rate of 30 cm per 1,000 years. Its fringing coral reefs that formed during sea level highstands have been raised along with the island, producing a 'giant's staircase' of coral terraces that constitute one of the world's most important records of late Pleistocene sea level change.

On a scenic half-day drive along the island's H3 highway, you can examine diapiric mélange in the Scotland District on the island's undeveloped east coast, ascend the coral terrace staircase, and enjoy sweeping views across the island from 340m-high Mount Hillaby, the island's highest point.



An Active Accretionary Wedge on Land

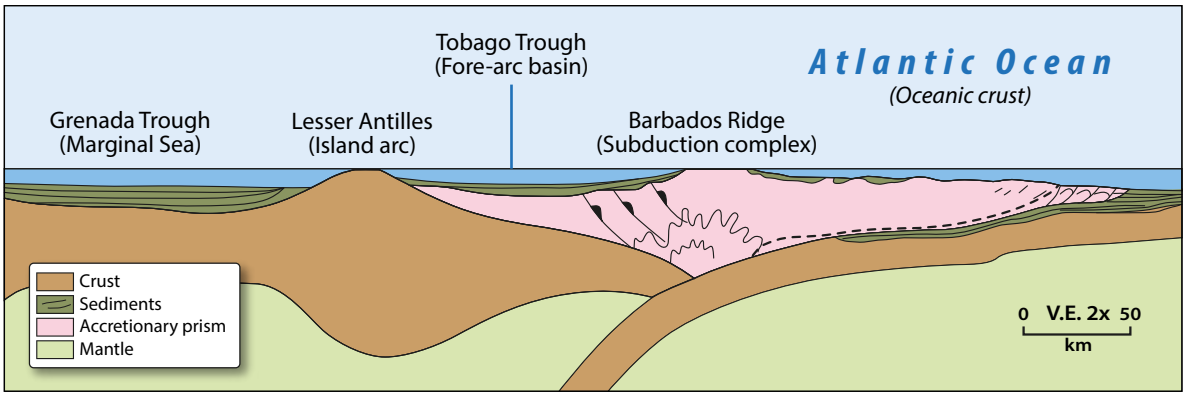
The island of Barbados constitutes the crest of the Barbados Ridge, an especially large accretionary wedge associated with the Lesser Antilles Subduction Zone. Here the abundant, sandy turbidites that Venezuela's Orinoco River is delivering to the abyssal plain are being scraped off the downgoing South American Plate and incorporated into the accretionary complex.

The Orinoco turbidite system has been studied as a model for the facies architecture of a non-fan turbidite system developing in a convergent margin setting. Researchers have compared the architecture of that modern system to the facies present in Barbados's Eocene-aged basement rocks, which are exposed at Chalky Mount in the Scotland District on the island's windswept, central east coast. Some of the turbidites at Chalky Mount display good reservoir characteristics, with amalgamated flows producing several-meter-thick sand bodies

A view of Bathsheba on the east coast of Barbados.

Terri Cook and Lon Abbott

Invertebrates feeding on algae in the intertidal zone formed a series of mushroom-shaped limestone boulders near Bathsheba.



Schematic cross-section west to east across the Barbados subduction zone.

(Modified from Kearney and Vine, 1996, and Speed et al., 2012.)

with porosities up to 40%. A petroleum seep exists near Bath, and patches of tar are common on central east coast rocks. The island even has a small oil field near the international airport, which produces about 1,000 bopd, enough to meet 11% of the island's energy needs.

At the famous east coast surfing beach of Bathsheba, outcrops of diapiric mélange contain blocks of widely ranging sizes embedded in a sheared, muddy matrix. The beach is also noteworthy for its row of large, mushroom-shaped limestone boulders that balance on narrow 'stems' rising out of the intertidal zone. The stems are formed by the feeding action of invertebrates scraping algae from the rock.

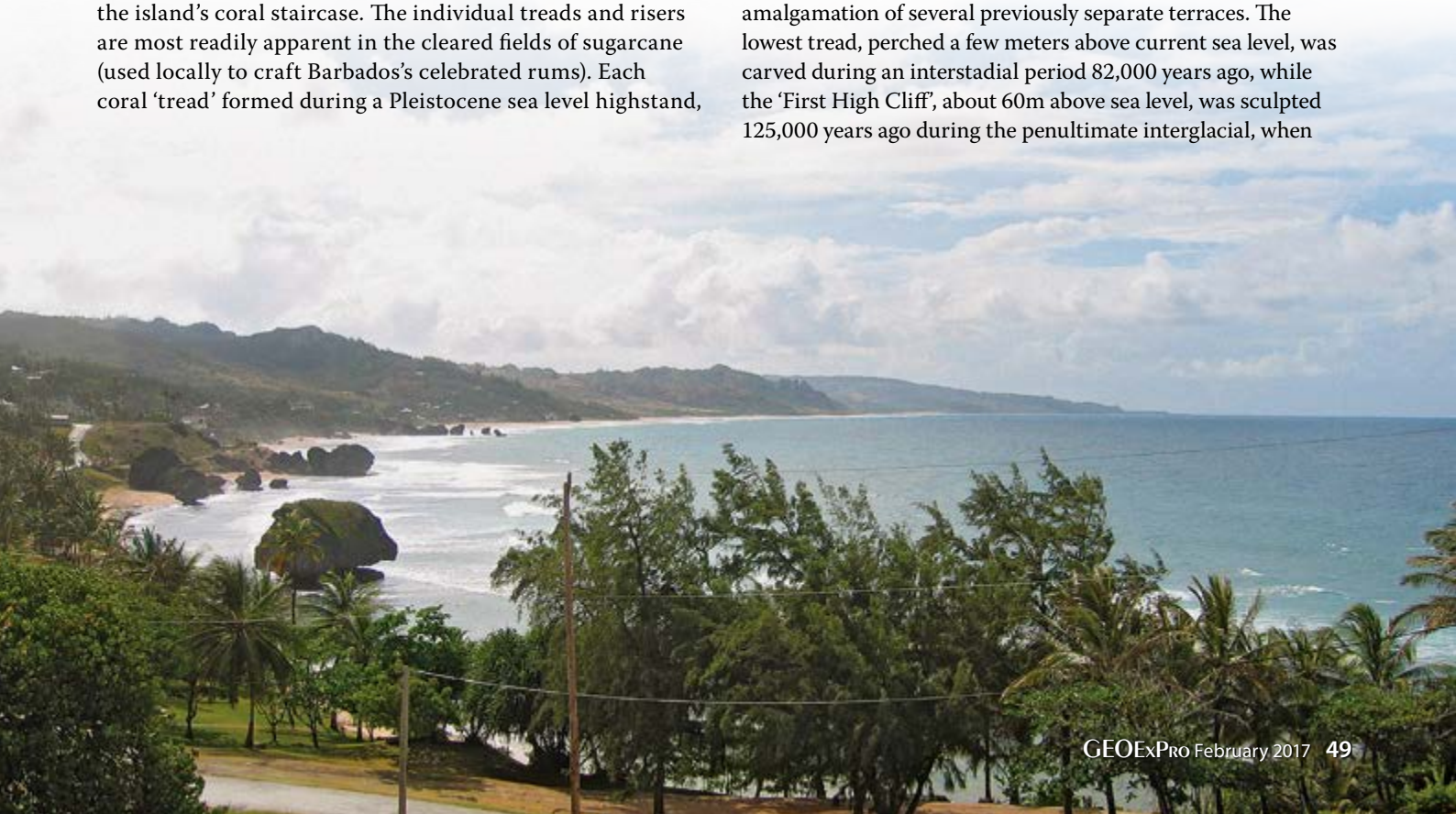
Also near Bathsheba, a series of north-east trending thrust faults has contorted Eocene turbidites into a series of dramatic folds. These basement rocks are, in places, overlain by remnants of an oceanic allochthon consisting of forearc basin sediments that were thrust eastward over the Barbados accretionary prism along a roof thrust.

Dramatically folded turbidites exposed along Barbados's windswept east coast offer rare views into the depths of an active accretionary wedge.

Sea Level Staircase

The drive inland from Bathsheba along the highway ascends the island's coral staircase. The individual treads and risers are most readily apparent in the cleared fields of sugarcane (used locally to craft Barbados's celebrated rums). Each coral 'tread' formed during a Pleistocene sea level highstand, either during an interglacial or an interstadial period.

All told, the highway crosses six coral terraces en route to Hackleton's Cliff, a striking escarpment formed by the erosional amalgamation of several previously separate terraces. The lowest tread, perched a few meters above current sea level, was carved during an interstadial period 82,000 years ago, while the 'First High Cliff', about 60m above sea level, was sculpted 125,000 years ago during the penultimate interglacial, when



sea level stood six meters higher than it does today.

The view from the top of Hackleton's Cliff is one of the best in Barbados, taking in the rural expanse of the Scotland District down to the windswept east coast more than 300m below. From this vista point, it is just a few kilometers farther inland – and several coral steps higher – to the summit of Mount Hillaby, the top of the island's highest terrace, which records a sea level highstand that occurred 640,000 years ago. The ages of the island's terraces match the times of Milankovitch-driven interglacial and interstadial episodes recorded in the deep-sea climate record derived from sediment cores.

Unbeknown to most tourists, the Crane Hotel above beautiful Crane Beach rests atop an 82,000-year-old limestone terrace carved during an interstadial period.

Since the pioneering coral dating work of Fairbanks and Matthews in the late 1970s, Barbados's staircase has unlocked one of the world's best records of Quaternary sea level fluctuations. Their subsequent work, along with that of many other researchers, has progressively refined the ages of the corals using both the ^{14}C and U/Th radiometric techniques. By subtracting the amount of elevation gain caused by the island's uplift since each reef formed, the researchers were able to calculate relative sea level height. The most precise results came from samples collected from the island's relatively dry south coast, where diagenesis has been minimal and good specimens of the coral *Acropora palmate*, whose habitat is confined to the ocean's upper five meters, have been preserved.

Radiometric dating of coral specimens in Barbados's uplifted terraces has helped unlock one of the globe's best records of Quaternary sea level fluctuations.

World Standard Sea Level Curves

Although the terraces record the timing and elevations of sea level highstands, reefs also formed during lowstands. Cores drilled through the terrace flights have recovered material from these lowstand reefs, allowing workers to constrain the timing and elevation of each nadir. The result of these combined efforts is a relative sea level curve for the last 640,000 years that has become the world standard.

Relative sea level curves of similar quality have been derived from just a handful of other locations around the globe, including Australia's Bonaparte Gulf and Papua New Guinea's Huon Peninsula. Workers have meticulously cross-correlated these various records to both refine our knowledge of Quaternary eustatic sea level fluctuations and compute the global ice volumes necessary to produce them.

Early attempts to relate the Barbados sea level curve to the global ice volume during the last glacial maximum employed a 1D viscoelastic plate model. A recent paper advanced this approach by recognizing that mantle viscosity varies in three dimensions near Barbados because of the presence of the subducting Lesser Antilles slab. These recalculations mark yet another refinement in our understanding of eustatic sea level variations.

The Barbados relative sea level record has also helped to constrain the measurement of mantle viscocity, a key geodynamic property across multiple disciplines and for which an accurate measurement is needed to properly compute the amount and rate of isostatic rebound that will result from removal of the calculated ice load.

A recent paper cross-correlating the Barbados and Bonaparte Gulf records determined that the upper mantle viscosity is likely to be between 1–3 x 10^{20} pascal seconds (Pa·s), whereas the lower mantle viscosity ranges from 5–10 x 10^{22} Pa·s.

Rainforest, Reefs, and Caves

After summiting Mount Hillaby, it's also worthwhile visiting three nearby geotourism attractions: Hunte's Gardens, Welchman Hall Gully, and Harrison's Cave. The last is a stalactite-adorned grotto that can be toured via electric tram or on foot. The gully, which formed in an adjacent cave where the roof later collapsed, preserves a scrap of verdant tropical rainforest, as do the tranquil Hunte's Gardens.

Terri Cook and Lon Abbott

Barbadian rum shops are a colorful part of island social life, and the rum, which is made from local sugarcane, is one of the country's most important exports.

Barbados is best known for its modern reef, which you can view via an Atlantis Submarines tour or, if you prefer to get wet, by snorkeling or using one of the island's many dive operators. For simply lazing on the sand, it is hard to beat gorgeous Crane Beach, rated one of the ten best beaches in the world by *Lifestyles of the Rich and Famous*. Above its sparkling, white sand, the Crane Beach Hotel is dramatically situated atop a cliff of 82,000-year-old limestone, the lowest staircase tread.

While many visitors never leave the swanky beach resorts, those who do venture farther afield, even for half a day, will be captivated by its world-class geology.

References available online ■

New Opportunities in the Central North Sea

New insights from a regional and reservoir level interpretation in the mature Central North Sea

WILLIAM REID and STEFANO PATRUNO, PGS

With the upcoming 30th UK Offshore license round centered on mature areas of the UK Continental Shelf, the challenge for hydrocarbon explorers is to find and develop new prospects in areas that have already been extensively explored.

In this article we revisit some working reservoir units in the portion of the Central North Sea that spans the Witch Ground Graben, Fisher Bank Basin, Forties-Montrose High, Central Graben, Ula/Gyda Terrace and Auk Ridge areas. Most of this vast region in the Central North Sea is covered by 23,650 km^2 of conventional PGS multiclient 3D seismic and its pre-stack derivatives, MegaSurveyPlus, which is a regional, fully migrated 3D dataset, imaged using a modern processing sequence, with the ability to obtain an improved and consistent regional geological perspective. Several recent 3D broadband dual-sensor towed streamer surveys (GeoStreamer®) are included in the study area and have been integrated into this analysis.

This region of the Central North Sea is characterized by a high well density (54 exploration wells per km^2), yielding a total of 17.4 Bboe total recoverable reserves (IHS Edin, 2016). Nevertheless, the Central North Sea is still expected to contain around 4.5 Bboe of yet-to-find hydrocarbon resources (DECC, 2015), mostly locked in near-field pools that have been challenging to characterize and are potentially located in deeper reservoirs.

New Exploration Insights

The MegaSurveyPlus dataset has been used to directly highlight sediment distribution of all Paleogene reservoir units including potential leads. To undertake this analysis, extracted stratal slices were chronostratigraphically calibrated by integrating well and field data and then a maximum amplitude extraction was performed through chronostratigraphic windows, highlighting possible sandstone- versus mudstone-prone areas (Figures 1A-C). Closures have been observed within the sandstone-prone areas, identifying further untested leads and, where possible, pre-stack derivatives (relative Vp/Vs and relative acoustic impedance) were utilized to characterize the elastic reservoir behavior of some of these leads (Figure 1D). It was found that all likely sandstone-prone areas of each chronostratigraphic interval mirror the sediment distribution maps of the Millennium Atlas (2003), further ground-truthing this seismically driven methodology (Figure 1B-C).

Furthermore, MegaSurveyPlus

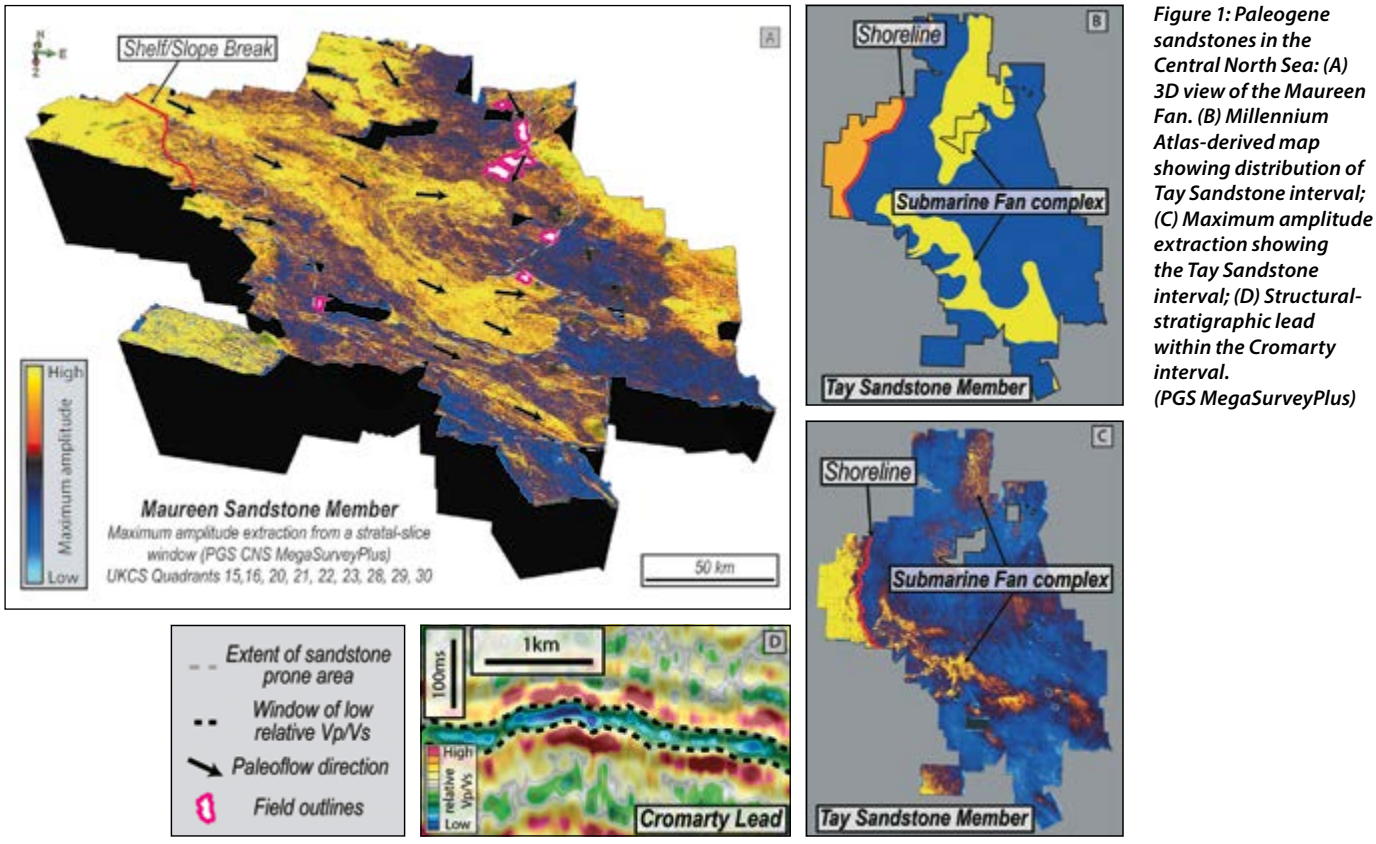


Figure 1: Paleogene sandstones in the Central North Sea: (A) 3D view of the Maureen Fan. (B) Millennium Atlas-derived map showing distribution of Tay Sandstone interval; (C) Maximum amplitude extraction showing the Tay Sandstone interval; (D) Structural-stratigraphic lead within the Cromarty interval. (PGS MegaSurveyPlus)

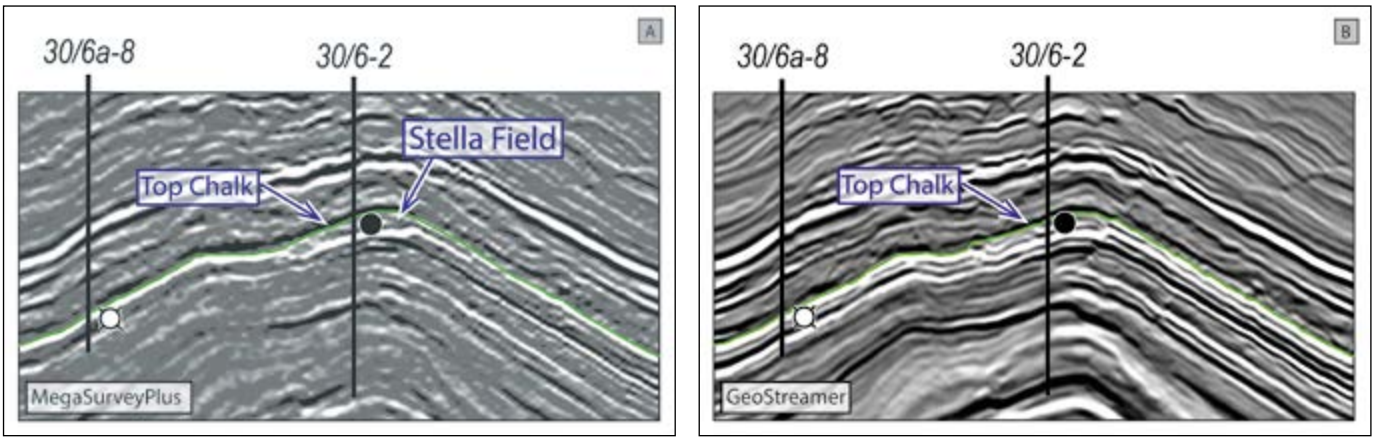


Figure 2: (A) Full stack MegaSurveyPlus, Top Chalk horizon clearly visible. (B) Full-stack GeoStreamer, Top Chalk horizon is also clearly visible, but the greater bandwidth shows significant uplift, increasing intra-chalk reflectivity.

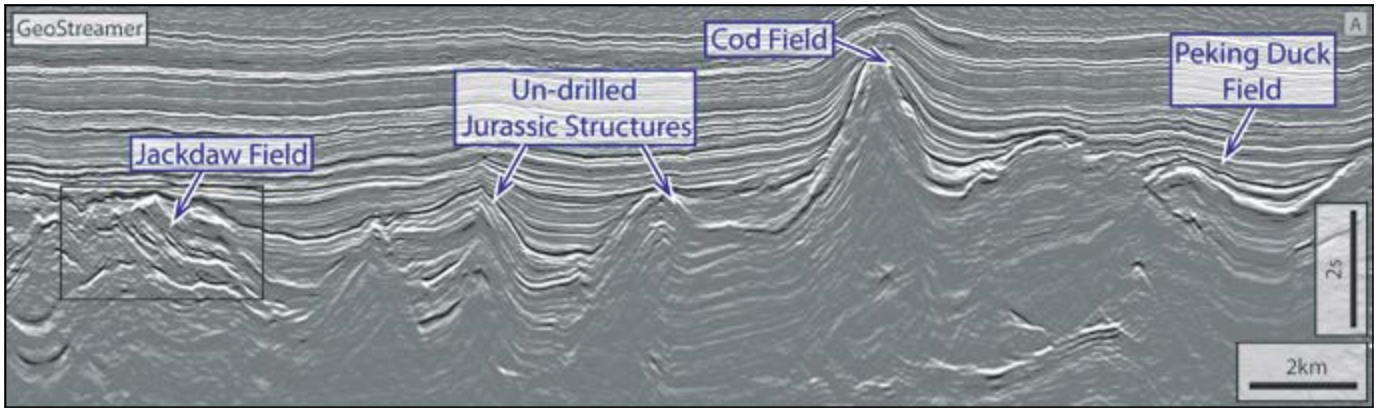
has been utilized as a consistent regional screening tool to locate areas where Mesozoic and Paleozoic plays are visible, and to compare them to existing deep discoveries. Subsequently, a pre-stack seismic simultaneous inversion of the 3D dual-sensor data has been performed over some fields and identified leads in order to better understand the reservoir-scale elastic properties distribution thanks to the pre-stack broadband AVO-compliant dataset (Figures 2 and 3).

Reliable Scanning Tool

This work has shown that new exploration insights at both reservoir and regional scale relating to leads, prospects, plays and migration pathways can be realized even in a highly mature exploration setting such as the Central North Sea.

Such new insights have been enabled by utilizing a fully migrated 3D regional dataset (MegaSurveyPlus) as a consistent and reliable regional scanning tool (particularly in the Paleogene section) and combining it with the AVO-compliant pre-stack attributes of dual-sensor broadband GeoStreamer 3D datasets. This has led to a significant improvement in subsurface understanding for both near-field exploration and field development, for both the Paleogene and deeper reservoirs. ■

All images by PGS.



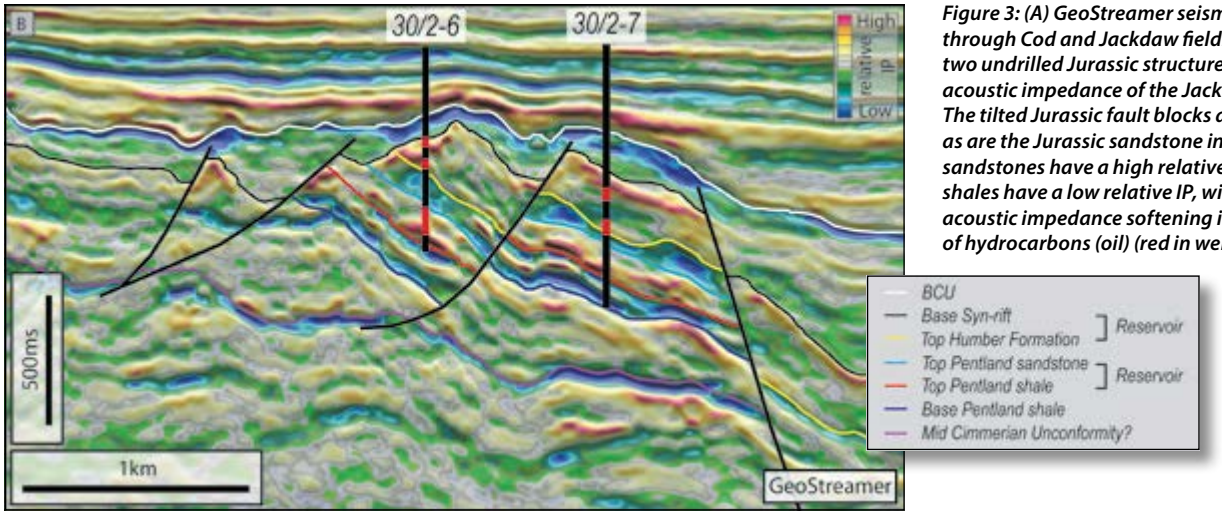


Figure 3: (A) GeoStreamer seismic section through Cod and Jackdaw fields, showing two undrilled Jurassic structures; (B) Relative acoustic impedance of the Jackdaw structure. The tilted Jurassic fault blocks are well imaged as are the Jurassic sandstone intervals. The sandstones have a high relative IP, while the shales have a low relative IP, with the sand acoustic impedance softening in the presence of hydrocarbons (oil) (red in well stick).

Communicating Geoscience: What Is Geology?

Geoscientists do not seem to be able to inspire other people with enthusiasm for their subject. What can be done about this?

JANE WHALEY

Penny: *What's wrong with geology?*

Sheldon: *Let me put this in a way you'll understand, Penny. You remember you explained to me that the Kardashians aren't real celebrities? Well, geology is the Kardashians of science.*

The Big Bang Theory

How much do most people know about geology and what do they actually think about the subject?

Finding for themselves the answers to these questions is one of the first things that MGeol students on an innovative course in communicating geoscience at Plymouth University in the UK are asked to do. They go onto the campus and ask fellow students from a wide variety of disciplines what geology means to them. "It's all about stones" and "Rocks – boring!" were fairly typical answers – but they were also met with blank looks and "What's geology?"

How did they respond? With difficulty; they realized that despite several years studying the subject, they still did not really know how to explain the importance and relevance of their science to someone without a technical background. Addressing this issue is what the course is largely about.

Different Communication Skills Required

"The MGeol course allows geology students to spend an extra year refining their skills, exploring specialist topics and learning critical thinking with respect to their subject. An important part of that is communicating geoscience, which is why it is a compulsory module in this final year," explains Professor Iain Stewart, Chair in Geoscience Communication at the university's Centre for Research in Earth Sciences.

"In their undergraduate studies we teach young geologists facts and the importance of facts, and we show them how to write for a technical audience. Then we send them out into the real world and that they discover that lots of this doesn't matter, and they also need to explain more than just the bald facts. Wherever they end up working – be it industry, research or teaching – good communication abilities, both written and verbal, will prove to be one of the most important aspects of their work. We have discovered that communication skills are as important as technical prowess in increasing your chance of promotion. Even getting through that first interview is about communication. And teamwork is an integral part of any job, and for that good communication is needed at all levels.

"We also need different types of communication skills for different parts of every job," he continues. "It is important that geologists are able to write succinct scientific reports – but they must also be able to produce the more flowery, descriptive stuff. There are no rules for this type of thing, except understanding your audience. And don't be afraid to entertain! In my opinion even giving a lecture should be a performance."

Iain believes that as geoscientists we are taught to think in a different way to most people. "For a start, we must visualize in 3D," he points out. "Thinking about the subsurface at great depth and talking casually about the vastness of geological time are what we do all the time, but for most people these

are difficult concepts. And many geoscientists seem to regard risks and hazards from a different perception to the rest of the world, who are usually less enthusiastic about looking into a bubbling volcano or climbing a cliff face than we are! So we need to 're-engineer' our brains so we can approach the subject from a different viewpoint.

"With this in mind, we ensure that our students have lectures from a range of disciplines, from both within the university and the wider community beyond."

Interdisciplinary Approach

Professor Stewart is no stranger to the interdisciplinary approach, as he studied both geography and geology in his undergraduate degree, before undertaking a PhD researching earthquakes in the Mediterranean, which brought in aspects of archaeology, climatology and history, as well as geology. After twelve years as a university lecturer, he stepped out of academia to make films and documentaries about earth sciences. As he says: "I am interested in a wide range of subjects. That's not ideal for the academic life, but perfect for telly! I spent some time talking to film-makers about why, unlike sciences such as archaeology and cosmology, we didn't see much about geology on TV, particularly considering it is so perfect for the medium: a long history, amazing scenery and epic events like continents breaking up."

Iain has spent the past 15 years trying to bridge that gap and bring geology to the masses. He has made a number of high profile BBC documentaries on earth science, with topics ranging from how geology has shaped the world to analyses of the impact of shale gas and the story of oil (see *GEO ExPro* Vol. 13, No. 1). He is also the Director of the Sustainable Earth Institute at Plymouth University, which aims to promote a new way of thinking about the future by bringing together researchers, businesses, community groups and individuals to develop cutting-edge research and innovative approaches to global challenges. An indication of this is Plymouth's new MSc course in Sustainable Geoscience, which addresses the increasingly contested societal interface between geology and sustainable development.

It's all about encouraging young geoscientists to think outside of the box. "We want to give our students the ability to engage with a range of different audiences, and to help them do this we bring in lecturers from a variety of disciplines, including neuroscience, business, chemistry and astrophysics," Iain explains.

Breaking Down Barriers

I was able to spend some time with the students, to find out what they thought about the course and what it was teaching them, and it was obvious that they enjoyed the interdisciplinary approach.

"The neuroscience lectures were fascinating," one of the students tells me. "We learnt how the brain works differently in scientific and communication mode and how we must address but not judge our audience. Effective communication is a two-way street, where we need to be

Students in the final year of the MGeol course are relishing the interdisciplinary approach used in the Communicating Geoscience module. From left: Robert Hendry, Tessa Young, Catherine Woolford, Prof. Stewart, Luke Silezin, Martha Ezeribe and Jack Palmer.

able to meet half way and to build up a baseline of trust, otherwise people won't listen to us. We also learnt about the 'dos and don'ts' of outreach and engagement and how to adapt our message and way of delivering it to different audiences, since to talk to families or children requires a very different approach to that used when addressing a specialist group. Not everyone needs to know *all* the facts, but they need to know the ones of importance to *them*."

About 60% of the lecturers on the Communicating Geoscience module are not geoscientists, but the students find they are often better at putting geological ideas across, simply because they are not experts in the subject. "We are shown how to look at communicating to non-geoscientists as a performance; a bit like a play in three acts," another student explains. "First we hook the audience with wonderful ideas; then we take them on an exciting journey with twists and turns, to spike their curiosity, to a false resolution at the end of the 'second act', before getting to the real ending and a genuine resolution – preferably with plenty of humour."

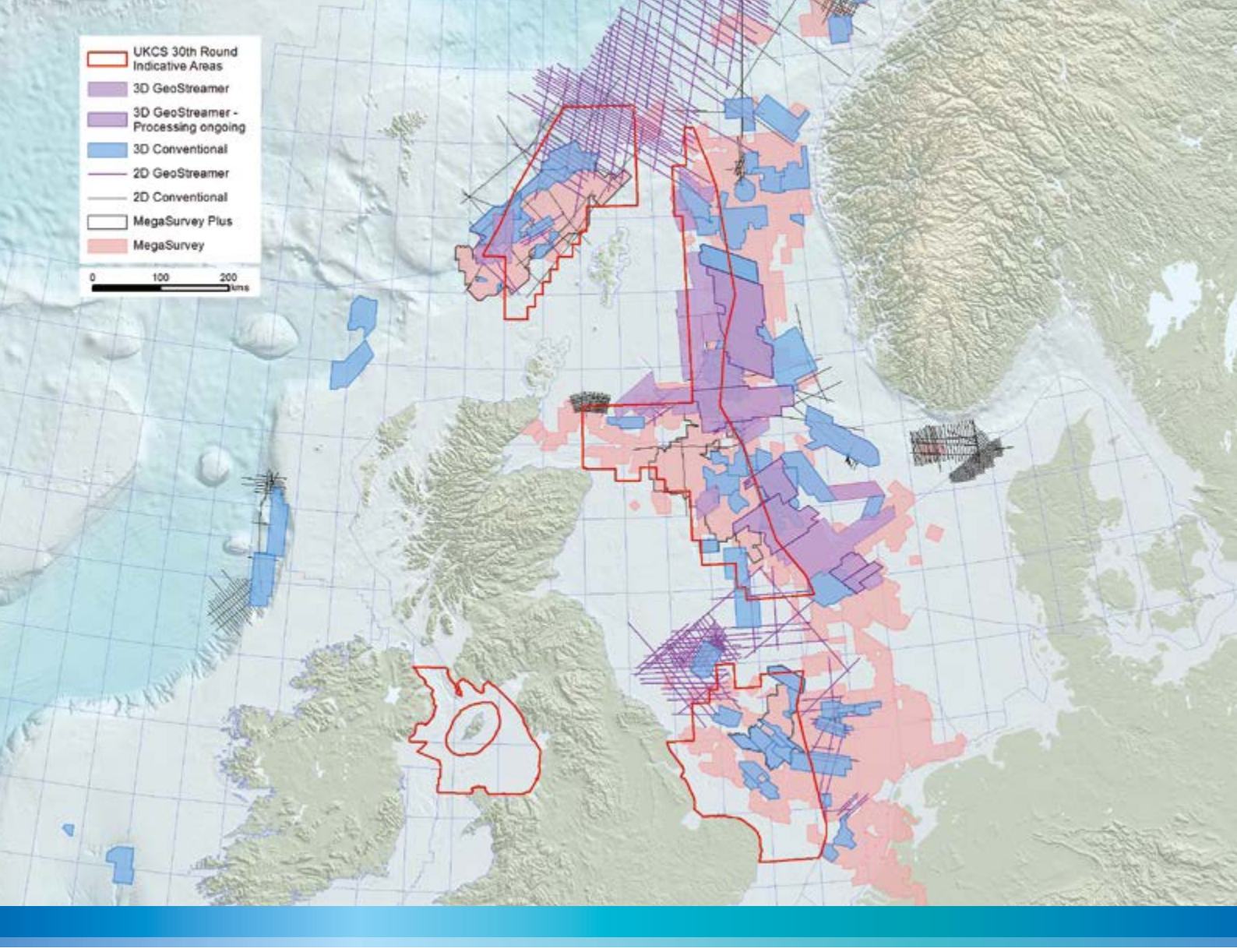
Communication comes in many forms and students spend time discussing the most appropriate medium for different messages and audiences, taking in blogs and social media, podcasts, videos, documentaries and art, all in an attempt to break down the tangible barrier between scientific facts and public viewpoints.

Disseminate Your Knowledge

The students on this course have very different plans for where they want geology and their careers to take them, but they all agree that learning to communicate the excitement and fascination of geoscience has been a very important and useful journey for them.

As one of their interdisciplinary lecturers – this time from a chemistry background – pointed out to them: "Disseminate knowledge as much as you can and whenever you can. It's not their fault if people don't understand your subject – it's yours!" ■

Prof. Iain Stewart lecturing at the University of Plymouth. He believes that every talk, whether to final year geologists or a public meeting, should be a performance with communicating your message in an effective and entertaining way at its core.



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Hydrocarbon Potential in the North Barents Basin

Discovering a potential new oil and gas province in the north-western sector of the Russian Arctic.

Dr. GENNADY KAZANIN, SERGEY PAVLOV PhD, SERGEY SHKARUBO PhD, VALENTINA SHLYKOVA PhD; JSC MAGE

The complete regional geological assessment of the northern part of the Barents Sea is nearing completion, with the density of seismic observations reaching over 0.2 line-km/km^2 (Figure 1). This density has been largely achieved through surveys by Marine Arctic Geological Expedition (MAGE), a joint-stock company commissioned by the Federal Subsoil Resources Management Agency under the Ministry of Natural Resources of the Russian Federation in 2006–2012. Completed geophysical investigations, including 2D CMP reflection seismic acquisition, shipboard gravity and differential marine magnetometer measurements, have now totaled over 30,000 line-km. The resulting seismic data along with maps of anomalous potential fields deduced from the magnetic and gravity surveys now make it possible to evaluate the oil and gas potential of this underexplored region.

MAGE seismic vessel RV Geolog Dmitriy Nalivkin working in the Arctic.

MAGE

A primary geological objective of these surveys was to establish a subsurface structural and tectonic framework that would include the main reflectors identified in the sedimentary cover and thickness maps, as well as a tectonic classification based on anomalous potential field data. MAGE also examined the formation of geological petroleum plays and their seismic facies classification in order to investigate the probable location and hydrocarbon content of potential reservoirs. An additional aim was to quantify the region's potential and undertake a cost estimation of its total subsoil resources.

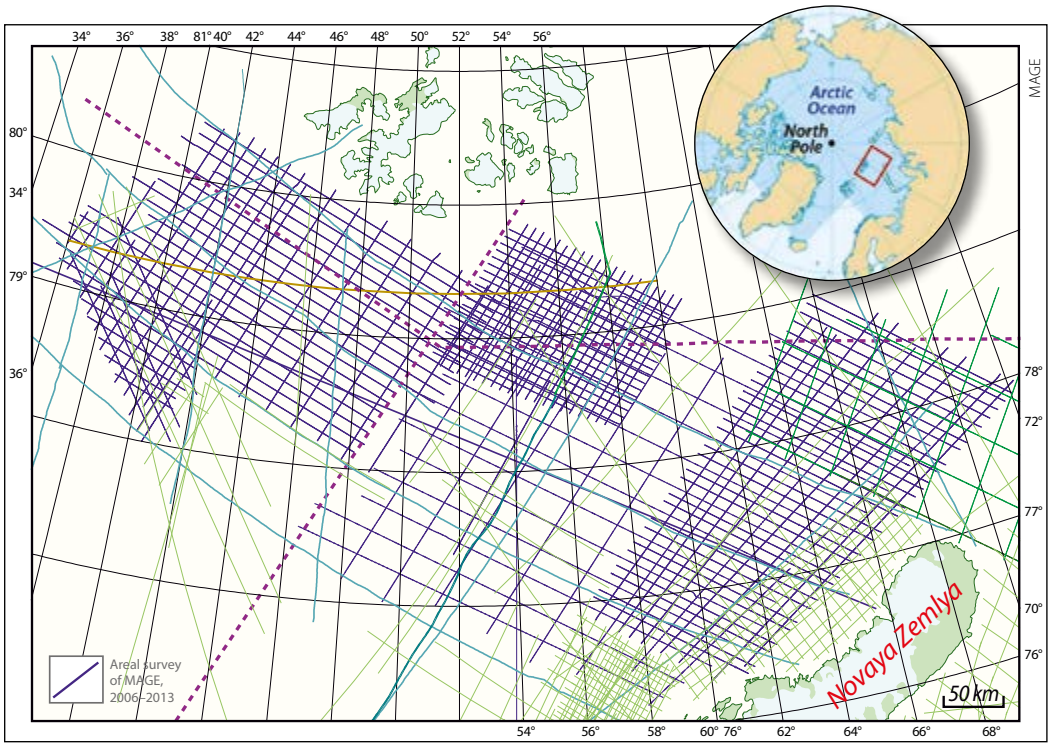

Figure 1: Available seismic information in the northern part of the Barents Sea.

It should be noted that the hydrocarbon potential identified to date in the North Barents Basin is not commensurate with the large scale of the sedimentary basin. In addition, only the gas and condensate content has been included in estimates published so far.

Unique Sedimentary Basin

Due to its thickness and structural evolution, the East Siberian megatrough, and in particular its northern part, is considered a unique sedimentary basin. The trough reaches a thickness of up to 20 km of Paleozoic and Mesozoic sedimentary fill, with almost no Cenozoic interval. Its geological evolution clearly features three phases of tectonic stabilization followed by a persistent subsidence of the basin within its present boundaries. However, the cause of this subsidence remains unclear, since there are no signs of the rifting that is commonly associated with accumulations of post mid-Devonian sedimentary strata.

Major tectonic elements identified beneath the sedimentary cover from west to east are the Aleksandrovskaya high zone, the North Barents syneclise, and the Prednovozemelskaya structural area (Figure 2).

In the North Barents syneclise the basement is not traceable on the 2D CMP seismic sections. However, according to the refraction and integrated modeling data derived from anomalous gravitational and magnetic fields, the depth to basement is estimated to be 16 km.

Geoseismic Sequences

The base of the sedimentary cover is marked by the **early mid-Paleozoic** geoseismic sequence (GS), which rests with angular unconformity on the surface of the heterogeneous base and is limited by a mid-Devonian erosional surface. The top of this sequence lies between 4,500 and 16,000m and is between 1,000 and 6,000m thick. It is most prominent in trough-shaped depressions in the marginal parts of the sedimentary basin and is less certain in the depocenter.

The Upper Devonian to mid-Permian GS rests with angular unconformity on the sediments of the early mid-Paleozoic GS and is traceable throughout the basin. In the northern part of the Barents Sea, this GS varies in thickness between 7,000 and 500m from east to west. In the Prednovozemelskaya structural area, the Admiralteiskaya-1 well, drilled on the crest of the Admiralteisky megaswell, penetrated 60m of late Carboniferous carbonates overlapped against the erosional truncation by Permian terrigenous deposits. This GS is sub-divided into the Upper Devonian to Lower Carboniferous and the mid-Carboniferous to mid-Permian geoseismic sub-sequences, which form the lower parts of large alluvial cones filling the Sedov and Western Fobos troughs (see Figure 3). The maximum thickness of sediment found in an alluvial cone of the Fobos trough is 6,000m, while the alluvial cones of the Sedov trough are marked by lesser thicknesses of about 5,000m. The clinoform structure of the Upper Devonian to mid-Permian GS suggests it has promising potential for oil and gas prospects.

The overlying **mid to Upper Permian GS**, limited at the top by an unconformity surface with toplap features, is divided into two large geoseismic sub-sequences. The GS varies in thickness between 250 and 4,500m, with the lower sub-sequence in the western margin of the Aleksandrovskaya high zone wedging out. On the whole, the mid to Upper Permian GS demonstrates a time of quieter sedimentation, in contrast to

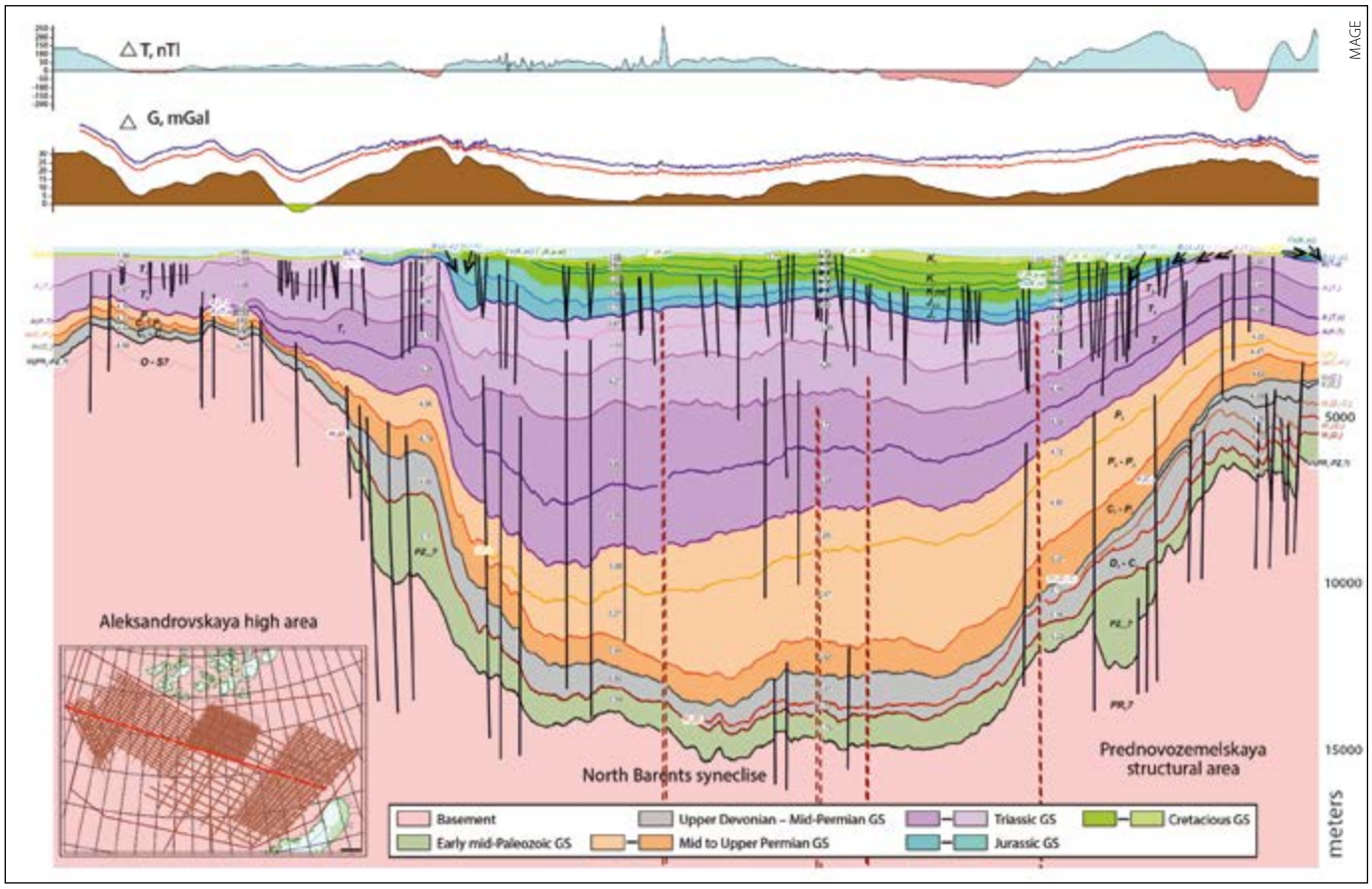

Figure 2: Cross-s ection through the East Siberian megatrough with gravity and magnetic anomaly profiles.

the 'avalanche' sedimentation of the Upper Devonian to mid-Permian GS.

The **Triassic GS** is limited at the top by a strongly pronounced erosional surface which is most prominent in the Prednovozemelskaya structural area. A stratigraphic gap has been observed on well data between the Triassic and Jurassic deposits, marking a pause in sedimentation within the northern part of the East Barents megatrough. As a result about 1,000m of Triassic sediments were exposed and denuded on the margins of the basin. The mid-Triassic formations in the eastern periphery of the sedimentary basin have a distinct clinoform structure which is not typical of the rest of the GS.

The **Jurassic GS** is limited at the top by a reflector which is associated with Upper Jurassic black clays and is a regional datum in the Mesozoic. The sequence is 2,000m thick in the North Barents syneclise. Within the Aleksandrovskaya high and the Prednovozemelskaya structural area, the Jurassic deposits wedge out against the erosional truncation extending beneath the seabed.

Jurassic deposits are related to the largest gas condensate fields of the Barents Sea, including the Shtokman, Ludlovskoye and Ledovoye fields.

In the **Cretaceous GS** deposits on the margins of the North Barents syneclise have been eroded but are found at the seafloor in the center of the trough. There has been a long sedimentation gap recorded in the post-Neocomian age. The depth of the Early Cretaceous erosion, which affected the Jurassic and Upper Triassic deposits in the Prednovozemelskaya structural area, is estimated in terms of kilometers. The Cretaceous GS is 1,000m thick.

The Neocomian clinoforms show an apparent dip towards the center of the North Barents syneclise both south-eastward and southward from the rise of Franz Josef Land.

Potential Trapping Mechanisms

From this analysis it could be argued that most sediments in the northern part of the East Barents megatrough accumulated in the Upper Devonian to Permian and Triassic ages, while the surface that divides these strata shows no indication of any significant tectonic patterns such as rifting. Heavy sedimentation occurred in the Mesozoic age, particularly in the Cretaceous period. The Paleozoic and Mesozoic sedimentary cover captures three sedimentation gaps, including the major mid-Devonian, early Jurassic, and post-Neocomian unconformities, which are most prominent in the marginal parts of the sedimentary basin, particularly within the Aleksandrovskaya high in the west and the Prednovozemelskaya structural area in the east.

Notably, during tectonic stabilization the sedimentary cover was more substantially denuded in structures adjacent to the area of the present North Barents syneclise. A similar stability in subsidence occurs in other superdeep depressions, such as the North-Chukchi, Peri-Caspian, and South Caspian troughs, where

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Lacovara enjoys sharing the wonders of science and his dinosaur discovery with audiences around the world. He has appeared in numerous television documentaries on American TV networks, as well as on the BBC, and was voted as one of the best TED speakers in 2016

Why study the ancient past? Because it gives us perspective and humility. It's the past that gives our world context. And it's the past that gives us foresight.

Dinosaurs were tiny, and huge. They were skittish and ferocious. Fast and slow. Runners, walkers, climbers, flyers, and sometimes swimmers. They were solitary and gregarious. Nocturnal and diurnal. Meat-eaters and plant-eaters. Hunters, scavengers, grazers, and browsers. They were drab, colorful, scaled and feathered. But, most of all, they were astoundingly adaptable. Dinosaurs dominated every continent and were thriving the day before their demise. Snuffed out by an asteroid, along with 75% of species on the planet, their sudden extinction emphasizes the contingent nature of Earth history. Over geological time, improbable, nearly impossible events do occur. By studying the ancient past, we begin to see ourselves as part of nature, connected across deep time to all other living things.

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the thicknesses of accumulated sediments are hard to explain by heavy tension (rifting). For instance, an estimation of the total displacement of the basement in the North Barents trough indicates that the relative stretching of the crust is less than 10%, which would have only resulted in the deposition of sediments in the order of 2 km. The joint analysis of seismic and gravity data therefore suggests that the subsidence is attributable to rock compaction in the lower crust in the transition of gabbro to a denser eclogite.

In addition to the fact that the sedimentary cover mechanism remains ambiguous, the geology of the northern part of the Barents Sea is distinguished by a lack of large anticlinal structures. However, a vast number of zones have been identified in the sedimentary cover which can be related to non-structural traps, arising from the frequent tectonic rearrangement, as described above.

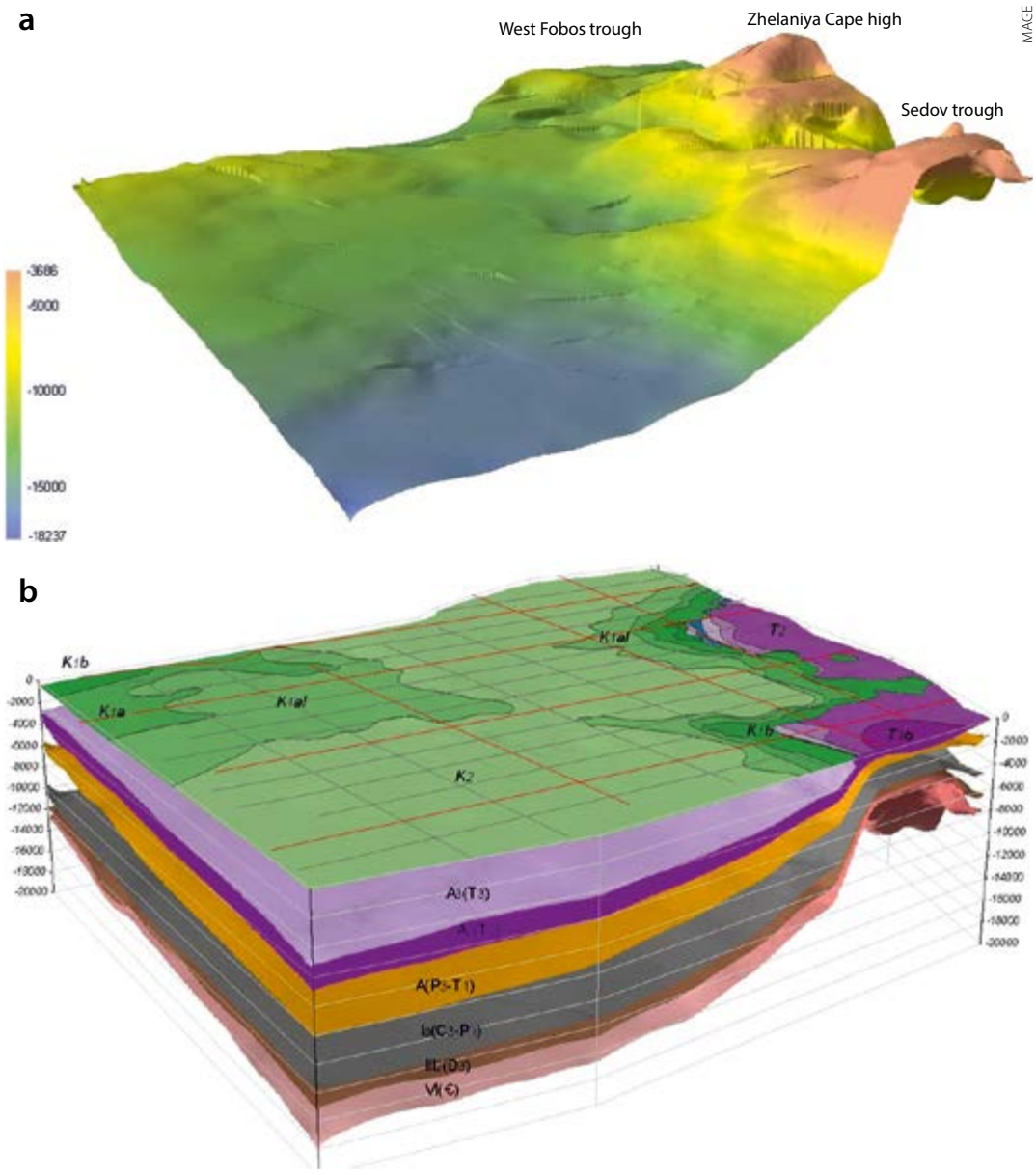

Figure 3: Prednovozemelskaya structural area: (a) basement; (b) sedimentary cover.

Inferred Hydrocarbon Resources

Until this major regional assessment, the hydrocarbon potential of the northern part of the Barents Sea was estimated according to ultimate potential resources (UPR), which meant that no quantitative estimate had been made, while the structural potential was limited to the Orlovskaya anticline structure, which only covers about 1,000 km^2. However, as a result of this targeted regional exploration program, 79 local anticline structures have been identified in the northern part of the Barents Sea over a total area exceeding 42,000 km^2. Furthermore, extensive areas of potential non-structural traps have been recognized, covering a total area in the order of 3,080 km^2.

The resulting estimate of inferred hydrocarbon resources shows that the value of subsoil resources of the region has increased by multiple orders of magnitude, becoming more attractive to potential explorers. At present, the entire northern part of the Barents Sea is divided into license blocks which have either been acquired or are pending license approval.

Based on the completed surveys, inferred resources (D2) of the sedimentary cover of the North Barents shelf exceed 23,000 MMtoe up to a depth of 7,000m. The share of recoverable resources accounts for more than 18,000 MMtoe. At a price of $250 per ton of oil equivalent in 2015, the cost of subsoil resources, including inferred (D2), recoverable (D2), and localized (D2loc), is estimated at $1.19 bn.

Thus, it appears that this region can now be considered to be an independent potential oil and gas province. These remain unproven oil and gas reserves simply as a result of insufficient exploration and a lack of drilling. ■

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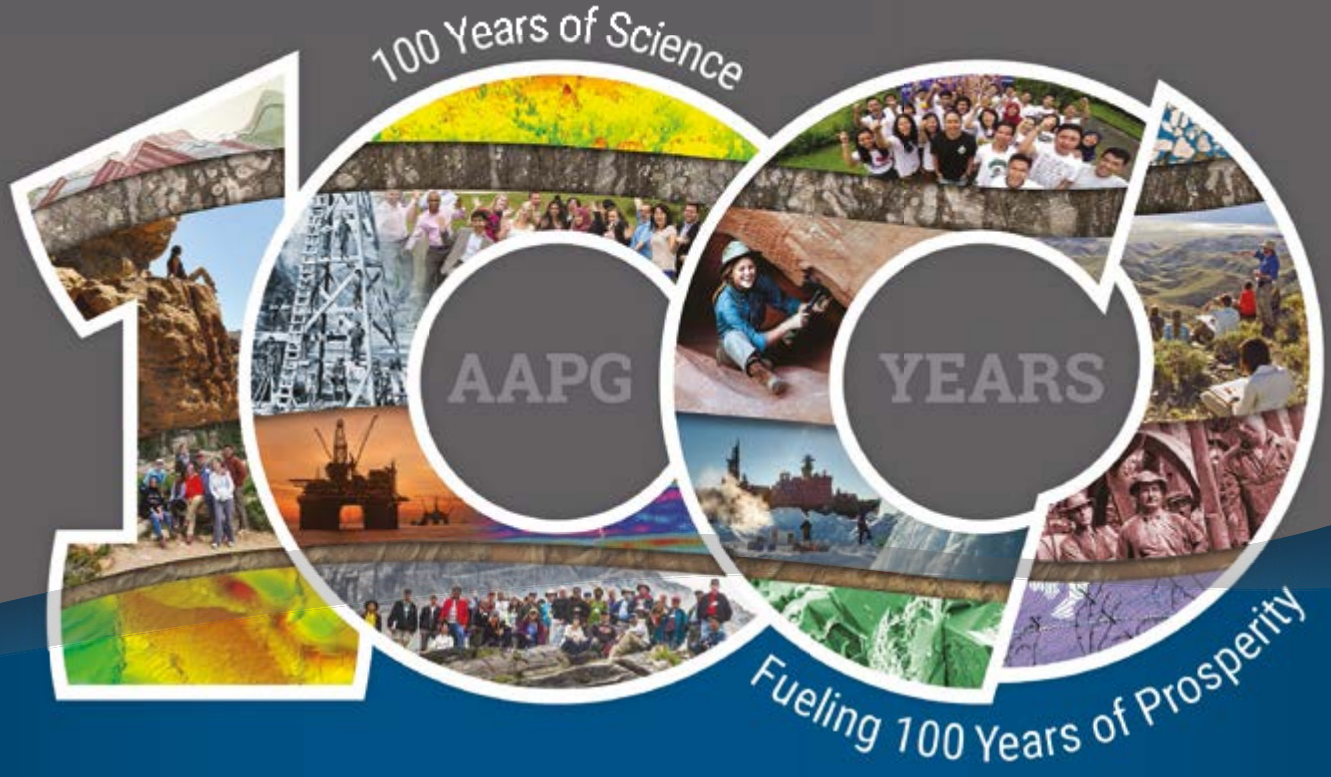

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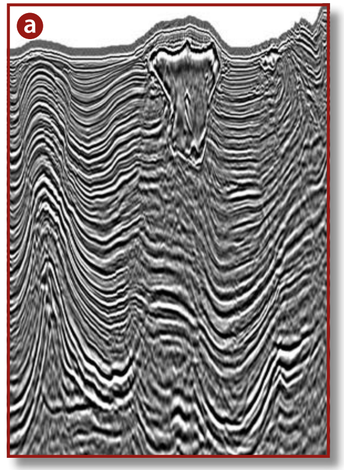
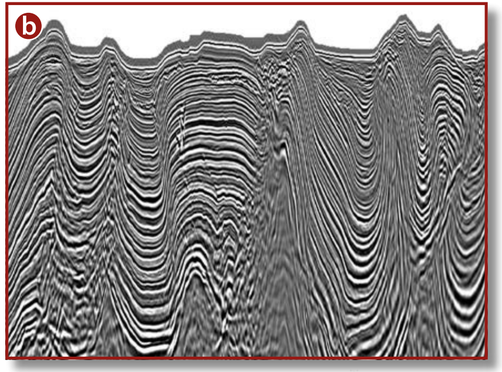
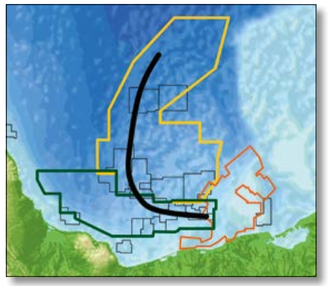
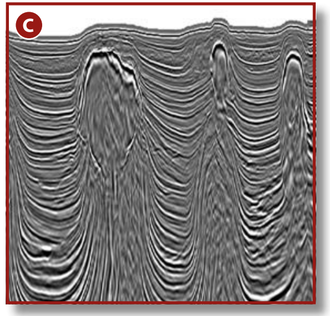
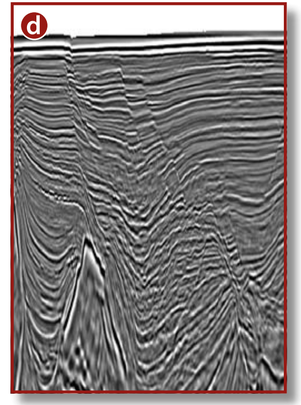


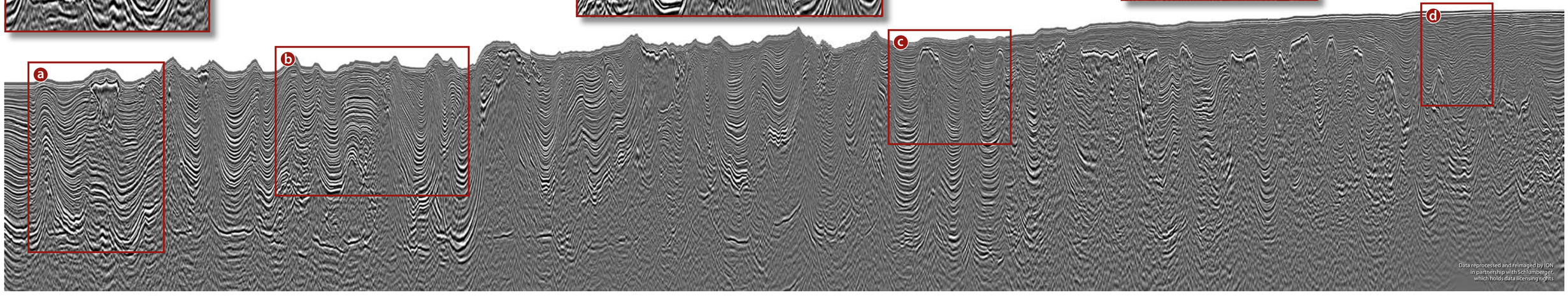








Composite line across Campeche reimaging North and South programs from the Enhanced Fast Track volume, highlighting improved imaging across the entire survey.



Data reprocessed and reimaged by ION in partnership with Schlumberger, which holds data licensing rights

Regional Framework for GoM

BRIAN W. HORN, ANDREW HARTWIG, JEFF FAW, IKA NOVIANTI, ANTARA GOSWAMI and ADRIAN McGRAIL, ION

The Gulf of Mexico has undergone several renewed phases of exploration activity in the last 70 years. During the past decade, considerable focus has been on the deepwater trends of the Lower Tertiary reservoirs, where several billion barrels of reserves have been discovered. When Mexico passed its energy reform, the volume of new and legacy seismic data made available provided the framework for yet another exploration phase which may ultimately yield billions of additional barrels of reserves. As in any basin, the development and understanding of exploration play types, petroleum systems, and future potential is often guided by the quality and availability of data.

Prior to Mexico opening its E&P sector, data was limited to proprietary surveys owned by Pemex and legacy academic studies with limited geographic extent and quality. To provide initial insight for E&P companies considering participating in Mexico, ION, in conjunction with the University of Texas (UT), reprocessed over 17,000 km of UT data, creating the first gulf-wide seismic dataset, YucatanSPAN™. This was the first time US subsurface evaluation and interpretation were extended across the entire offshore basin to Mexico. Once new acquisition offshore Mexico was permitted, ION acquired MexicoSPAN™. This program was developed with the tectonic and stratigraphic understanding from YucatanSPAN and was designed to answer regional geologic questions, creating an integrated 2D regional seismic program (see Figure 1).

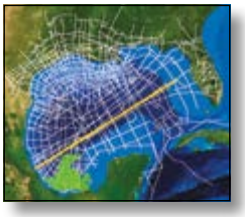
The 2D program ties the entire basin framework together and calibrates the seismic interpretation with over 20,000 subsurface wells, making it possible to map salient time-stratigraphic horizons and understand depositional changes, stratigraphic variation and location of exploration plays across the basin. The regional framework tying the US and Mexico offshore provides a perspective that is unparalleled in any hydrocarbon basin worldwide and highlights multiple exploration play types, providing E&P companies with the opportunity to evaluate and explore the basin in its entirety (Figure 2).

Regional frameworks are essential to any basin exploration program to help identify and reduce technical uncertainty and provide context and calibration for creating play-based exploration strategies. It helps geoscientists understand types of additional data that may be required to develop exploration targets that can be risked and ranked based on strategic objectives. Once data requirements are understood, acquiring or purchasing 3D data is typically next.

Reprocessed 3D Data

Recent license rounds offshore Mexico (Rounds 1.4 and 2.1) focused on the Campeche Basin, where many 3D programs were acquired for Pemex over the past 15 years. Mexico's National Hydrocarbons Commission and Secretary of Energy made these legacy data available to help inform evaluation and bidding. Although these data may appear to have limited utility, reprocessing them with the latest techniques has proven to be extremely cost-effective for E&P companies to analyze bid round acreage and detailed play and prospect evaluations.

With regional geologic understanding provided by MexicoSPAN, the next exploration step was a 3D seismic program in the Campeche Basin. The Campeche reimaging program is a state-of-the-art reprocessing and reimaging effort of ~82,000 km^2 of data across 20 existing 3D surveys. The program is being processed in three phases (North, South and



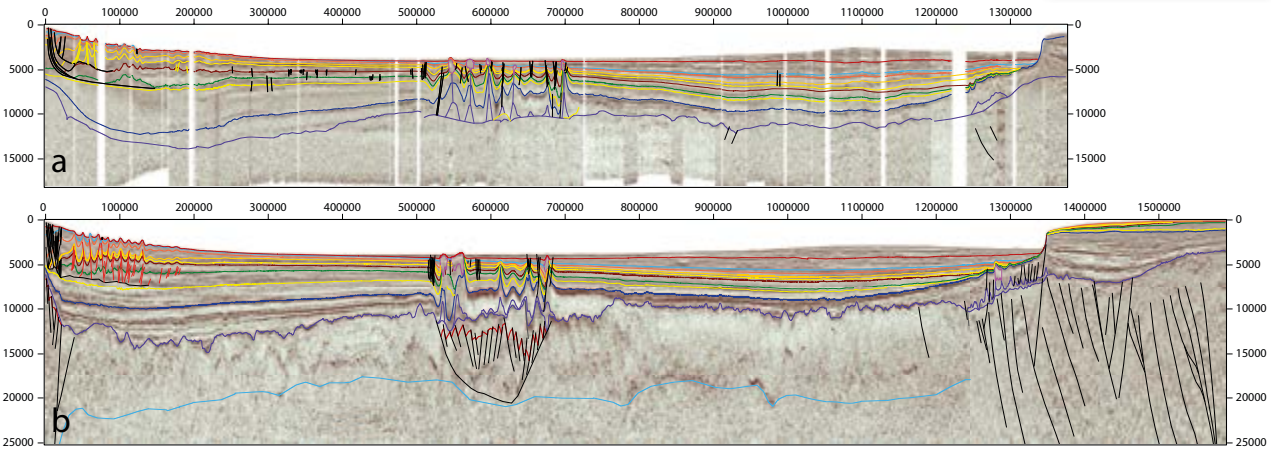


Figure 1: a) Reprocessed YucatanSPAN data was key to imaging Mexico's deep water prior to country access and for correlating exploration plays into Mexico, b) similar profile to (a) from MexicoSPAN data acquired in 2015. Longer offsets and acquisition / processing techniques provide a much better image of the Mesozoic section and regional basin framework (vertical and horizontal scales in meters).

Shallow Water) using an optimal combination of technologies and techniques to maximize data quality and geologic insights for block evaluation. The geologic complexity and variability require consistent, cutting-edge workflows to maximize bandwidth, producing data with strong low frequency content for subsalt areas and high resolution data for non-salt areas.

After just the initial Fast Track phases, the reimaging program is demonstrating significant imaging uplift. Broadband preprocessing coupled with high resolution steep dip RTM and Kirchhoff imaging algorithms is producing superior data ideal for prospect identification. In three to five months, the processing and interpretation team delivered a complete volume with updated seismic velocities and allochthonous salt interpretation for velocity model building, a step-change in turnaround time to deliver key insights before the license round. Iterative sediment and salt flood RTMs are also provided to deliver the detail and quality required for a more thorough evaluation.

The challenge to reprocess and reimage 82,000 km^2 of data from 20 separate surveys and deliver in a timeframe useful for the licensing round cannot be underestimated. The project's scale and completion timeline would not be possible without the pre-existing regional framework understanding and close integration between processing, interpretation and imaging personnel. Multiple iterations and continual calibration occurs in 'ad hoc' team discussions. In an unprecedented achievement, the first 20,000 km^2 (VTI, velocity model) were delivered in six weeks. The most recent Enhanced Fast Track (42,000 km^2) was delivered in three to five months starting from field tapes, complete with velocity models (top and base of salt interpretation) and 30Hz RTM.

Figure 3a shows legacy data from the Yoka survey in the Campeche North salt basin. The legacy beam migration helps to identify allochthonous salt and the strata in adjacent mini basins, however, base salt, steep dipping thrusted fold geometries, and autochthonous salt are not well imaged, making the interpretation and understanding of the kinematic evolution of salt difficult. Figure 3b is the same line from the Enhanced Fast Track volume. Note the base salt for both allochthonous and autochthonous is well imaged, the stratigraphy of the subsalt areas has higher frequency and better resolution, and the steep flanks of folds, mini-basins and salt canopies are clearly imaged.

The foldout on the previous pages is a composite Fast Track line across Campeche reimaging North and South. The Campeche reimaging program provides a higher resolution image and provides geoscientists with a commercial tool of choice, allowing companies to evaluate, risk and rank a portfolio of opportunities for current and future license rounds. In some instances, it provides enough information to drill exploration wells. In areas where salt geometries are more complex, it can be used as a screening tool to evaluate the need for data with greater azimuthal aperture.

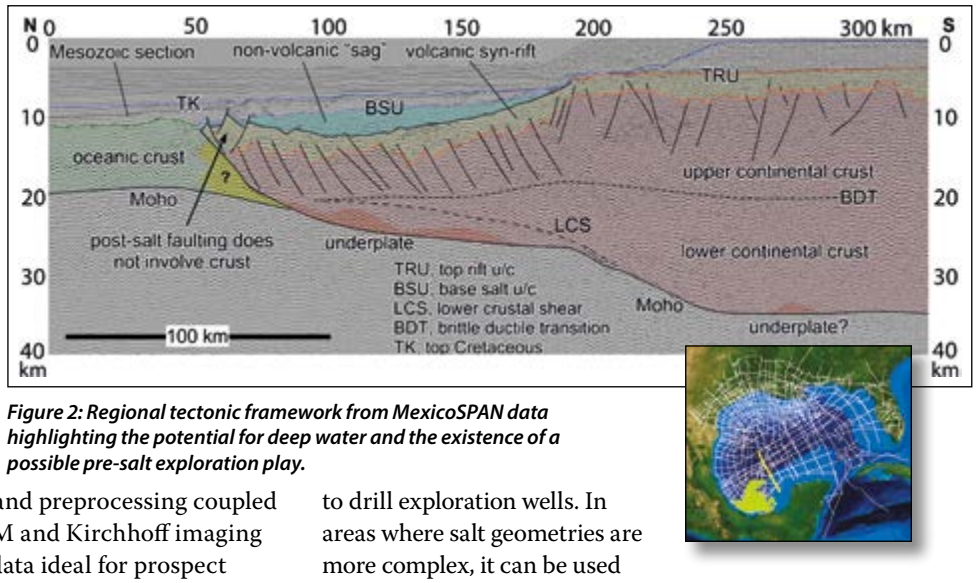
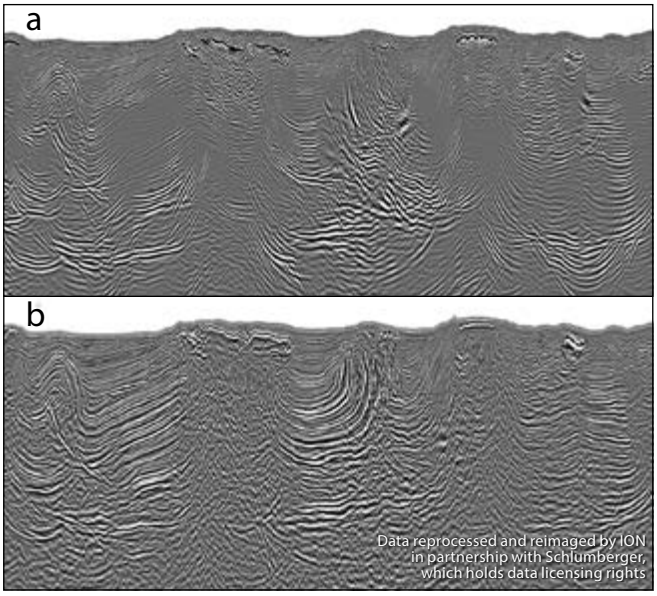


Figure 2: Regional tectonic framework from MexicoSPAN data highlighting the potential for deep water and the existence of a possible pre-salt exploration play.

Cost-Effective Methods

While exploration strategies and approaches vary by company, a consistent requirement is to understand the basin framework to position the company in areas that match strategic objectives. Companies should focus on the most cost-effective methods to evaluate and access acreage with the greatest potential. Using the basin scale approach, ION has pursued understanding hydrocarbon basins globally by utilizing the latest data processing technologies and workflows to integrate new and existing data that focus exploration programs from the regional context to a prospect. Collaborative partnerships with the University of Texas on YucatanSPAN and Schlumberger on the Campeche reimaging program are excellent examples of providing programs in a timely and cost-effective manner. ■

Figure 3: a) Legacy 3D data from the Yoka survey, b) reprocessed Enhanced Fast Track (30Hz RTM, TTI) for the same line. Note the image improvement for top and base salt, adjacent mini basins, stratigraphy and steeply dipping flanks of folds.



UAS: Innovative Technical Solution in a Dynamically Changing Industry

Unmanned Aerial Systems have the potential to transform operational efficiency and technical solutions across the energy sector, and are providing an additional tool for training geoscientists.

Dr. KAREN DALTON, RPS Energy

Unmanned Aerial Systems (UAS), more commonly known as drones, have now developed to the point where they can provide affordable and easily controllable platforms for all manner of aerial work that previously would have involved expensive manned vehicles such as helicopters or aeroplanes. Applications of this relatively new technology range from real-time inspection of inaccessible and remote infrastructure; remote sensing surveys for unexploded ordnance (UXO); topographic surveys for operational planning and environmental baselines, to providing 3D digital outcrop imagery for training purposes. The benefits in cost-effectiveness, understanding, safety and security are significant to an industry which has undergone radical change during the latest down-cycle.

UAS in Training

The use of UAS has enabled RPS Nautilus to develop new methods of interactive training to improve understanding of the geological environment both in the field and in the classroom. The 3D digital outcrop models (DOM) derived from drone imagery and real-time video sequences allow students to interact with entire outcrops, thus complementing existing training materials and facilitating the learning experience when time, resources and cost are at a premium.

Aspects such as the understanding of scale, new viewpoints and perspectives on the relationships of rock units and access to otherwise inaccessible outcrops all serve to clarify, consolidate and enhance what can be learnt from the study of rocks at outcrop. The ability to manipulate scale from macro geology down to fine detail can deepen the learning experience for geoscientists and engineers in the field.

Classroom learning has been enhanced by the combination of 3D models from UAS photogrammetry, HD video fly-throughs, high resolution photographs and hand samples as well as the traditional paper maps and well logs, to provide a more interactive, multi-faceted and effective experience. In play fairway analysis training, for example, these innovative materials engaged participants by providing a hands-on approach to the understanding of petroleum systems and reservoir heterogeneity as applied to the creation of play fairway maps and risking.

Modern approaches to training such as this are proving to be very effective means of learning and can be improved further by the use of additional innovations including 3D visualization software, virtual reality (VR) and augmented reality (AR) techniques both in the field and the classroom.

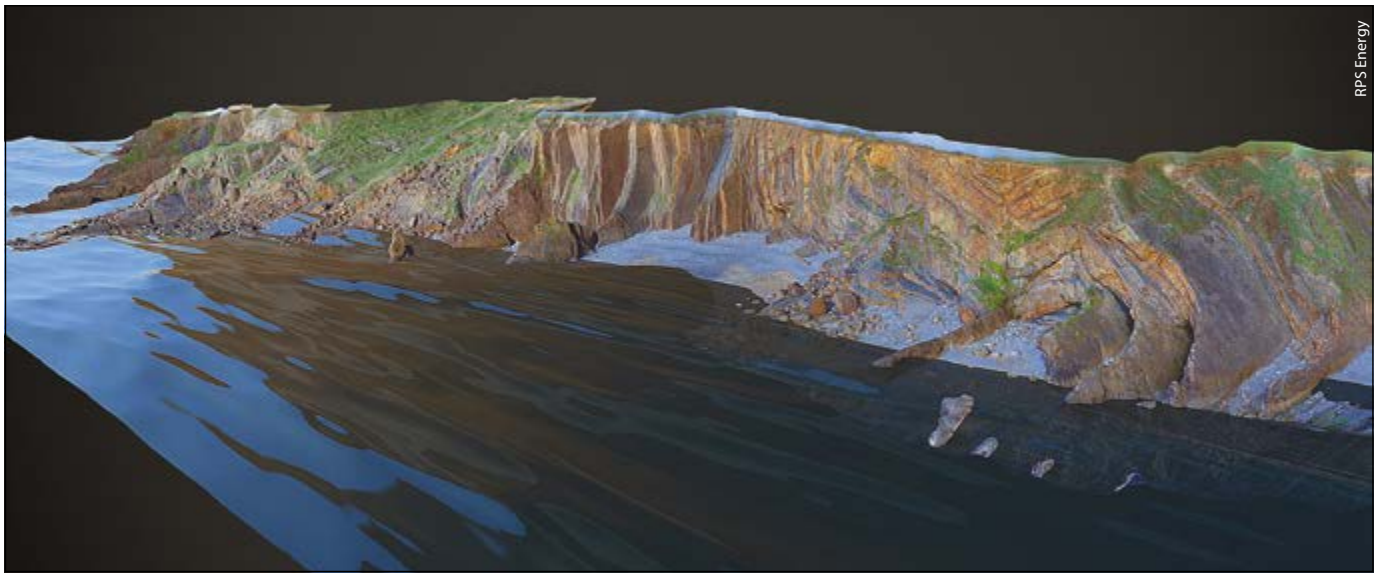
Wide Area Operations

The nature of these operations requires cost-effective and efficient solutions, which can range from initial screening through to camp and personnel security. UAS systems provide a quick overview of an area or site to allow more detailed planning of ground survey and to aid in the planning of operations from line layouts to siting infrastructure.

During operations drones can be effectively used to monitor progress and site security. Research is ongoing into the use of drones for harvesting data as well as using these platforms for

Drone in the process of capturing outcrop imagery.

RPS Energy



Digital outcrop model (DOM) from the Culm Measures of south-west England. This aerial view provides a broad overview of the fold trains and overall structural style of the outcrop – a perspective not available from the ground. Zoom functions enable individual folds and their internal structure to be examined closely and 'nested' models can provide resolution to centimeter or even millimeter scale. Tides often constrain access to certain parts of the outcrop. Length of outcrop is approximately 1 km.

deployment and recovery of equipment. In these types of operations it is likely that a number of platform types would be utilized, ranging from short duration quadcopters to long endurance fixed wing assets.

The use of drones for exploration using gravity and magnetics is at an early stage, in part driven by the requirement to miniaturize the sensors so they can be mounted on the platforms, as well as the cost-effectiveness of UAS versus current technology. Drones may simply be just part of the solution.

From Unexploded Ordnance to Archaeology

A game-changing use of UAS has been in the detection of unexploded ordnance, traditionally both personnel-intensive and risky. The use of unmanned and roboticized platforms alongside other solutions such as ground buggies has the potential to significantly reduce those risks and costs.

Currently, associated technology is developing rapidly, allowing more equipment and sensors to be carried on a drone. However, the need for stable and accurate flight and positioning requires significant detailed engineering, integration and testing.

Further applications for this technology are wide-ranging across all parts of the industry, from land fall survey for cable and pipeline shore landings to archaeological investigations during developments. Survey and inspection techniques can be enhanced by the use of UAS carrying a range of sensors from visual and infra-red cameras to LiDAR and laser scanning. The ease of use and cost-effectiveness means that these systems are increasingly being used during infrastructure inspections, from platforms to wind turbine blades.

Challenges

As well as the ability to miniaturize the sensors and the drone components, battery chemistry is still a major limiting factor, but fuel cell technology, amongst other ideas, is rapidly advancing. Integration of sensors and accurate positioning still remain key factors around the use of UAS in the energy sector but these challenges will be overcome as drones are finding their place as part of collaborative project solutions. ■

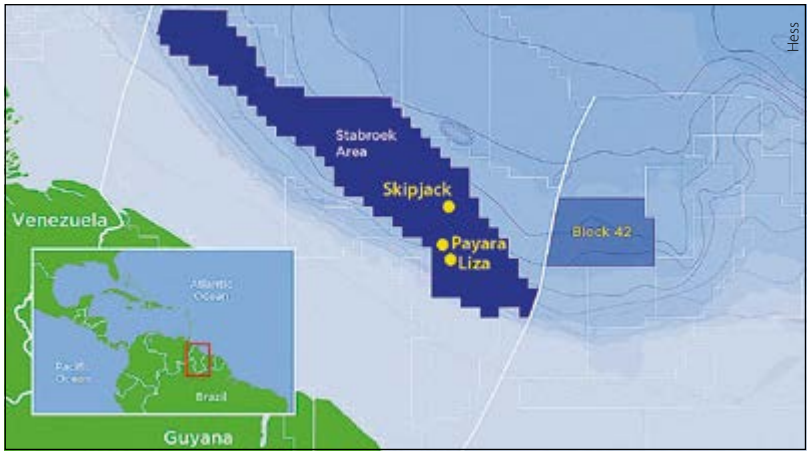
Extract from the DOM of the Bencliff Grit outcrop at Osmington Mills, Dorset. Large concretions or 'Doggers' are found at the base of the unit, while yellow-brown staining in the upper parts of the sandstones mark oil seeps and illustrates variations in permeability and the presence of barriers to flow. Sedimentary structures and architecture are clearly visible in three dimensions in the model. Access to this outcrop is restricted due to a high and periodically unstable rock face above. The Dogger in the foreground is about 1m in diameter.

Guyana: New Discovery Near Liza

One of the most exciting discoveries of 2015 was **Liza**, in **Guyana's** offshore **Stabroek Block**, which opened up a new South Atlantic play and was the first commercial field found in the country. This has now been followed by another promising discovery on the same block, about 16 km north-west of Liza. Well **Payara 1** was drilled in 2,030m of water at the end of 2016 and reached a TD of 5,512m. **ExxonMobil** said the well targeted similar-aged reservoirs to those proven successful in Liza, and found over 29m of high-quality, oil-bearing sandstone reservoirs. Two sidetracks have been drilled to evaluate the discovery and testing is underway to better determine the full resource potential, which is thought to be in the region of 250 MMboe.

The 26,800 km^2 Stabroek Block, located approximately 200 km offshore Guyana, contains multiple prospects and play types. The Liza field is believed to hold recoverable reserves of between 800 MMboe and 1.4 Bboe in Upper Cretaceous reservoirs, while recent appraisal drilling identified an additional high quality, deeper reservoir, estimated to contain 100–150 MMboe, directly below the field.

Esso Exploration and Production Guyana Ltd. is operator with 45% interest in the Stabroek Block, while Hess Guyana Exploration Ltd. holds 30% and CNOOC Nexen Petroleum Guyana Limited has 25%. ■

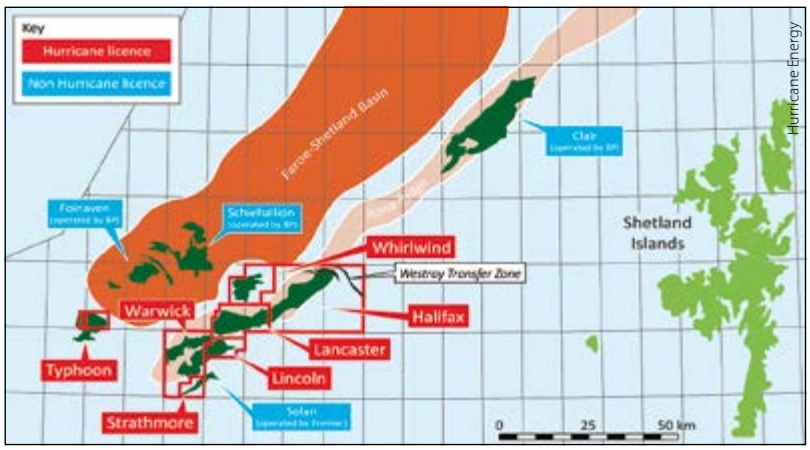


UK: Basement Discovery for Hurricane

Basement specialist **Hurricane Energy** announced in December that it had made a significant fractured basement discovery with well **205/26b-A** on its **Lincoln** prospect, about 160 km north of Scotland. Hydrocarbons were encountered about 520m TVD below structural closure, and gas chromatography and logging-while-drilling data indicate a very significant hydrocarbon column of at least 660m TVD. Hurricane believes that the size of the oil column indicates that its pre-drill resource assessment of approximately 250 MMb recoverable oil for the Lincoln prospect may be conservative. Additional analysis of wireline and sidewall core data will be undertaken to examine this further.

Lincoln is a few kilometers south-west of and on trend with Hurricane's 2010 Lancaster basement discovery, which found light (38° API) oil flowing to surface from fractured basement and has 2C contingent resources of 207 MMboe.

To learn more about the search for oil in fractured basement reservoirs, see *GEO ExPro* Vol. 13, No. 6. ■



PNG: 2 Tcfg Discovery

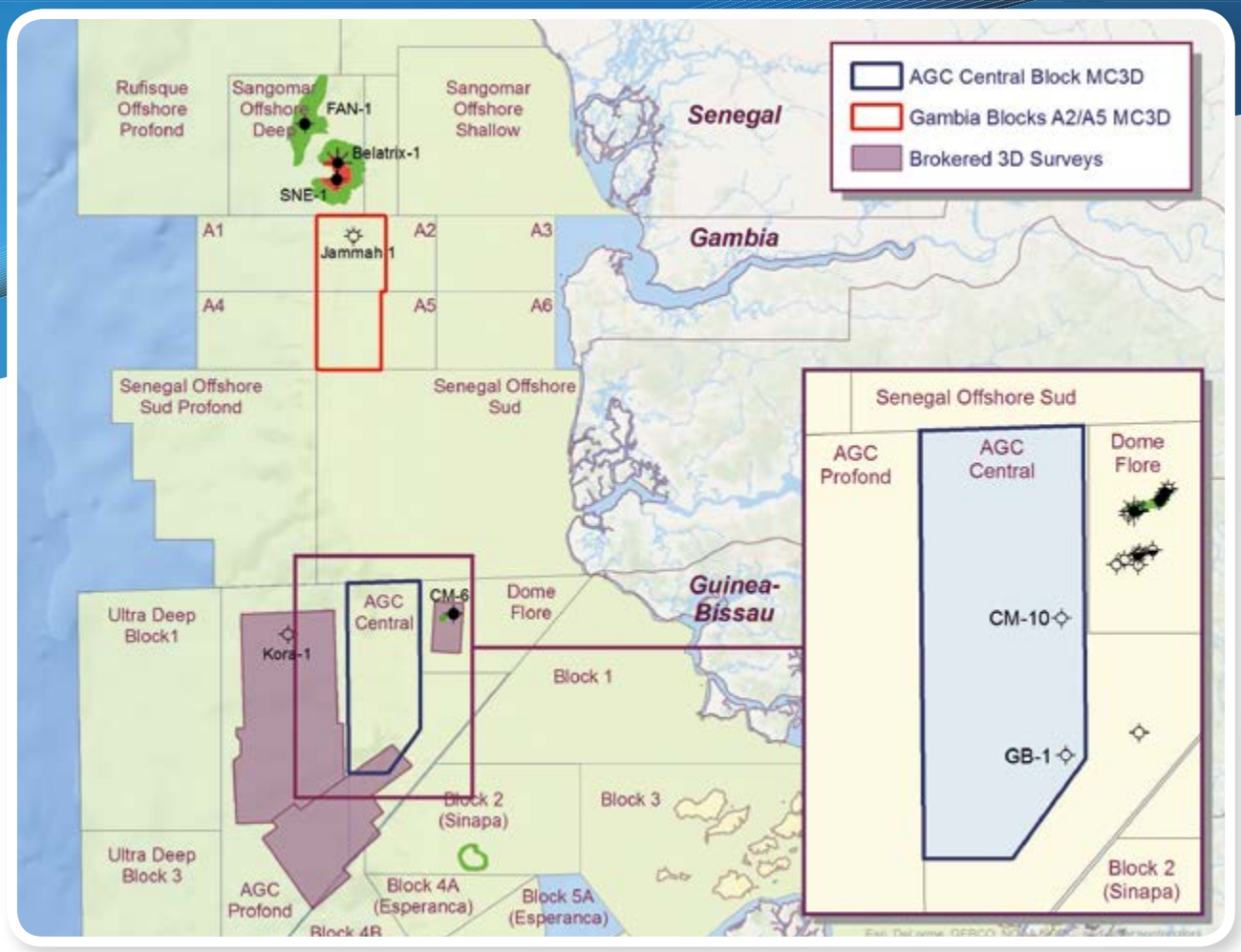
A new discovery in the New Guinea North Highlands of **Papua New Guinea** (PNG) has the potential to extend the recently opened PNG LNG plant in Port Moresby with a fifth production train. In December 2016, Oil Search Limited, operator of block **PPL 402** in the Papuan Fold Belt, announced that its **Muruk 1** well had encountered high quality sandstone reservoirs in its primary objective, the Toro Formation. The sandstones are very similar to those in the Hides gas field, about 20 km to the south-east, which has an estimated 5.3 Tcfg 2C reserves and is the largest field in the country. Muruk 1 was spudded on November 2, 2016 and reached TD of 3,130m at the end of December. Evaluation is underway to determine the size of the discovery, but initial reports put it in the region of 2 Tcfg.

The Muruk discovery is close to PNG LNG infrastructure and it would be easy to hook into the infrastructure and pipeline which takes gas from the highland fields to the LNG plant in Port Moresby about 650 km to the south-east. Oil Search have a 37.5% interest in the 510 km^2 block, with ExxonMobil holding 42.5% and Santos, 20%. ■

GeoPartners

AGC Central Block

New Broadband Multi-Client 3D Survey



In cooperation with the Agence de Gestion et de Coopération entre le Sénégal et la Guinée Bissau (AGC), GeoPartners are pleased to announce the acquisition of a new Broadband Multi-Client 3D survey on the Atlantic Margin of North West Africa. The survey covers 1921 km² of the AGC Central Block and was completed in January 2017 utilising the vessel BGP Prospector. The survey has been acquired in partnership with BGP Marine and DownUnder GeoSolutions.

The survey compliments the ongoing activities to provide the highest quality new 2D and 3D Multi-Client seismic in the MSGBC Basin, an area of heightened exploration interest following the world-class discoveries announced by Cairn Energy and Kosmos Energy in nearby Senegal.

The survey is currently being processed through a comprehensive Broadband sequence to produce both PreSTM and PreSDM final volumes. A Fast Track cube will be available for licensing early in April 2017.

Jim Gulland: jim.gulland@geopartnersltd.com • +44 (0)20 3178 5334

Unesco Global Geoparks

UNESCO Global Geoparks encompass 119 designated areas, varying in size from 57 to 12,884 km², in 33 countries. Prof. Patrick McKeever, Secretary of the UNESCO International Geoscience and Geoparks Program, explains this important initiative.

• ***What are UNESCO Global Geoparks?***

The official definition is: *UNESCO Global Geoparks are single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education and sustainable development… UNESCO Global Geoparks use geological heritage, in connection with all other aspects of that area's natural and cultural heritage, to enhance awareness and understanding of key issues facing society in the context of the dynamic planet we all live on.* Essentially, they are special places around the world that not only tell part of the history of the planet but also celebrate how our geological heritage is linked to all other types of heritage. This forms the basis for community empowerment and the promotion of the area's sustainable economic development.

• ***Why are they important?***

At the most basic, they bring international recognition to areas of internationally significant geology. But because they are a bottom-up initiative that will only develop where there is local community support and involvement, they also help bring the wonders of geology to a whole new audience, explaining the importance of the geological sciences to the wider sector. But it is more than that. UNESCO Global Geoparks engage with local people to ensure that the Geoparks are active territories where promoting geological heritage assists the area's sustainable economic development through, for example, the development of sustainable tourism. It allows local people to place greater value on their geological heritage, to take local ownership of it.

Prof. McKeever in Warrambungle National Park in New South Wales, Australia, which with the surrounding area is working to become a UNESCO Global Geopark.

• ***Is a UNESCO Geopark only about geology?***

Indeed, no! We think of the 'geo' part of Geopark as everything Earth has given us and how it has shaped us. Only when you delve into these topics will you begin to see how geodiversity, biodiversity, cultural diversity and even the diversity of our intangible heritage are so intimately linked. Many local communities associate their geological heritage with their myths and legends (think of the Giant's Causeway in Ireland, or how the indigenous people of the Andes explain their volcanoes). Geoparks help explore these links.

• ***What advantages does ratification bring?***

Geoparks first developed in Europe. In 2004, in UNESCO HQ, they came together with eight new Chinese Geoparks to create the Global Geoparks Network. The relationship with UNESCO developed until, in 2015, the member states of UNESCO voted to accept all existing Global Geoparks as new UNESCO Global Geoparks – the first new site designation of this type since the ratification of the World Heritage Convention in 1972. As a result, Geoparks can officially use the name UNESCO Global Geopark and a new logo with the official UNESCO brand, which means sites must have official national government approval, something that often wasn't there before. It marks a step change in how sites can promote themselves. In the future this should mean increased income to the local communities of our UNESCO Global Geoparks.

• ***What's the difference between Geoparks and World Heritage Sites and can an area be both?***

An area can be both but they should not overlap 100% as they have different requirements, sometimes mutually exclusive. World Heritage Sites are solely about conservation, without involving local people or sustainable development; within their core zones there can be little development. There are no such restrictions on UNESCO Global Geoparks; indeed, they are obliged to promote the economic development of the area. We have examples of individual World Heritage Sites being just one of many individual sites within a much larger UNESCO Global Geopark and there is excellent cooperation between the two labels.

• ***Tell us about the bottom-up approach.***

An unpopulated area cannot become a UNESCO Global Geopark, which must have not just the support of the local population, but their inclusion in its day-to-day running. Local people are trained to be Geopark Rangers or Ambassadors; they act as tour guides, sell local produce and crafts, provide visitor services and accommodation and act as focal points for explaining the risks of local geohazards like earthquakes. So important is this bottom-up approach to local community involvement that it is one of the reasons UNESCO only gives an area the Global Geopark designation for four years. After that there is a thorough revalidation exercise and if the local communities are no longer supportive or benefiting, the area risks losing the designation.

• ***What ambitions do you have for the network?***

Looking ahead, I would really like the title 'UNESCO Global Geopark' to be fully recognized as a global label of quality, transforming the lives of local people for the better in a fully sustainable way. I would like to see UNESCO Global Geoparks established across Africa, Latin America and Asia, as in these areas the economic development potential of Geoparks could be maximized. Finally, I hope that more people will know about and cherish the wonderful history of our planet, which can be read in the rocks all around us. ■

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DATA ACQUISITION DATA PROCESSING DATA LICENSING

The Quest for Oil

Once again the message is that, despite a phenomenal increase in renewable energy, oil is here to stay.

BP is finally giving in. In the recently published *BP Energy Outlook 2017 Edition* the key message is that an energy transition is underway that is "likely to continue to take place over the next 20 years", meaning that "the story is one of a continuing shift in the fuel mix towards lower carbon fuels".

This is all in response to the exponential growth in renewable energy like solar and wind that we have experienced in the last 10 years. So how does such a transition affect oil and gas production, in terms of volume? Do we need to continue to explore in order to find more oil and gas, or have we already found enough to meet a declining demand?

In the BP base case, the world's economy almost doubles in size over the 20-year period, but the extent of this growth is substantially offset by rapid gains in energy efficiency. The energy demand is thus predicted to increase by only around 30%. "Renewable energy is the fastest growing energy source and will be quadrupling over this period of time" (7.1% per year, with its share in primary energy increasing to 10% by 2035), says Spencer Dale, group chief economist of BP. That does not, however, mean it is doomsday for the oil exploration industry, because fossil fuels will provide about half of the total increase in primary energy over the next 20 years.

Consequently, in terms of carbon emissions, the projected growth during the next 20 years will be far slower than in the past (about a third). This is in contrast to the current trend of no or minimal increase in CO_2 emissions. As stated by CarbonBrief, "the topline from the Global Carbon Project is that the amount of CO_2 we put into the atmosphere from burning fossil fuels, gas flaring and cement production has held steady for three years in a row, neither increasing nor decreasing significantly".

According to BP, oil demand will keep growing by 0.7% per year in response to transport demand, in particular in the fast-growing Asian economies. But the pace of growth will slow over time because of increased fuel efficiency. In fact, BP believe that *fuel efficiency* will reduce demand by about 16 MMbopd through the next 20 years, while *electric cars* will reduce it by only 1 MMbopd. So even if the number of electric vehicles grows from about 1 million today to 100 million by 2035, according to BP's 'best guess', "the implication for oil demand is not a game-changer".

In conclusion, the world will consume 98.2 MMbopd in 2035. Keep exploring! ■

Halfdan Carstens

Electric cars – not a game-changer, according to BP. In the 2017 edition of the* Energy Outlook, *it is suggested that demand for oil will continue in spite of a rapid increase in the use of renewable energy and fuel efficiency in the transport sector.

Julian Herzog/Wikipedia

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

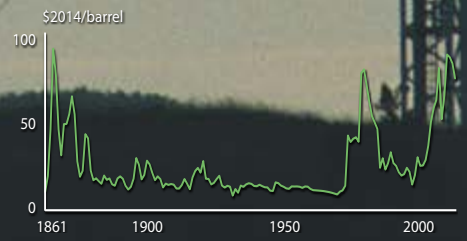
Giant field

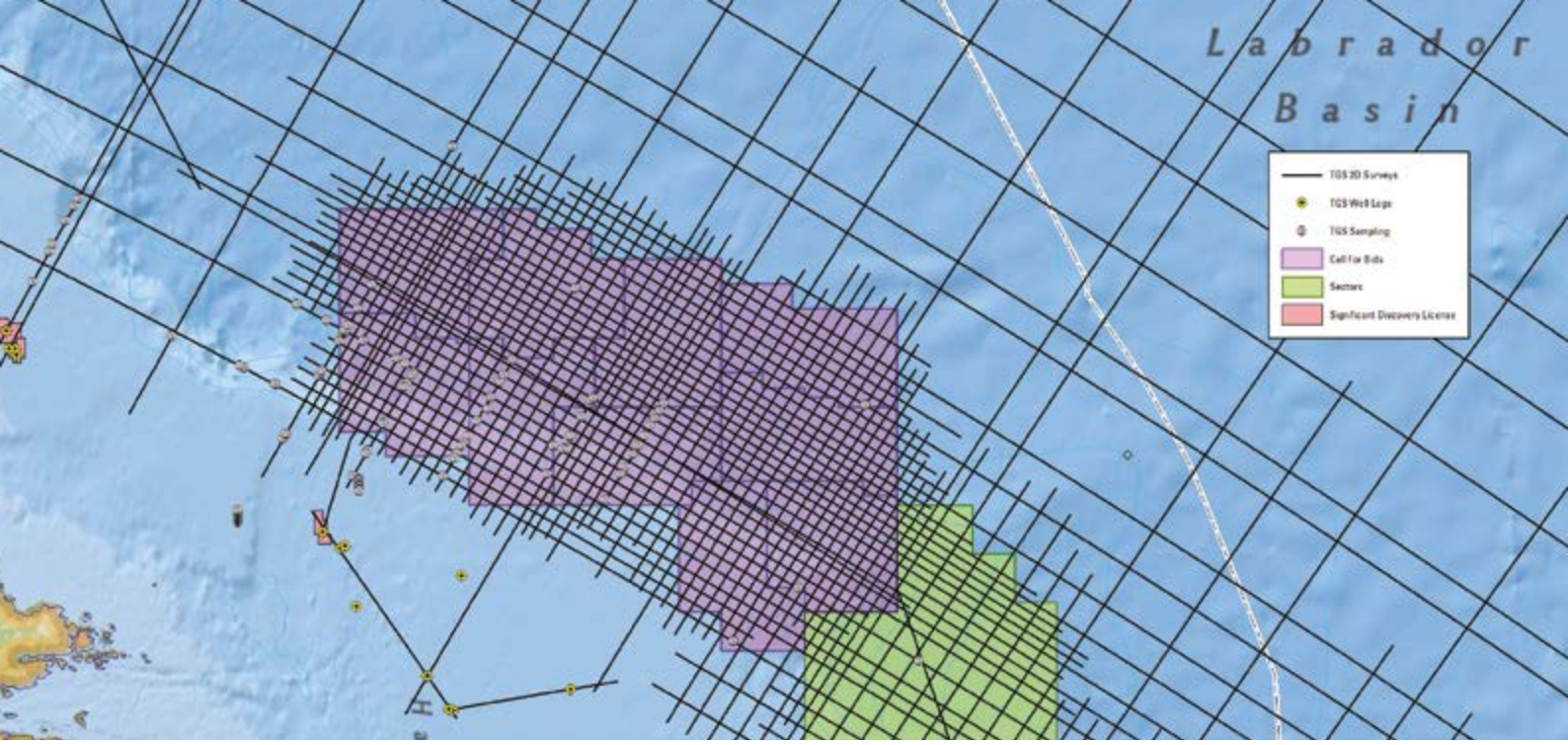
Recoverable reserves > 500 million barrels (80 million Sm^3) of oil equivalents

Major field

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

Historic oil price





Set your sights. Labrador Sea

When you have unlimited insight into Labrador Sea you have unbeatable advantages.

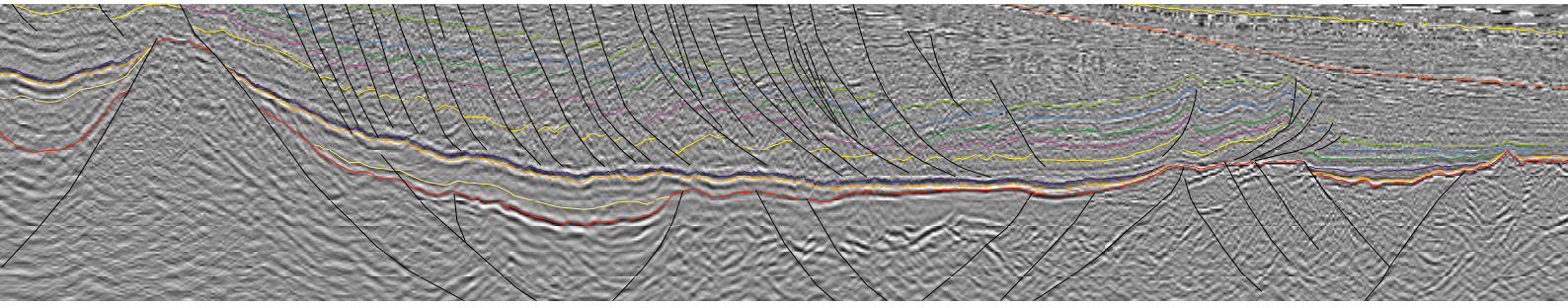
TGS is pleased to offer a comprehensive data package including over 20,191 km of seismic, gravity, interpretation and well data covering the NL01-LS Sector area in preparation for the upcoming East Coast Canada bid round. This dataset of newly acquired and older vintage data is currently undergoing pre-stack time and depth reprocessing, incorporating unsurpassed flow with enhanced multiple suppression, prestack time and depth migrations with AVO compliance through the entire flow.

This complete data package provides exceptional, value-added digital well data including, where available, interpretation ready LAS+, reports, directional surveys, check-shot surveys and digital mud logs for 32 wells selected from our overall East Canada database of almost 800 wells. These data may be purchased individually as well packages, or as a bundle with seismic or other TGS products.

TGS has also completed a series of interpretation studies integrating TGS' extensive data library of offshore East Canada, including a regional Sequence Stratigraphic and Play Fairway Analysis study, Post Well Analysis Study, and a Seismic Interpretation study focused on NL01-LS area.

This June, expect improved signal, reduced noise, AVO compliant, updated velocities, and consistent processing flow across the entire area.

See it here.



Labrador Sea 2D Reprocessed

See the energy at **TGS.com**

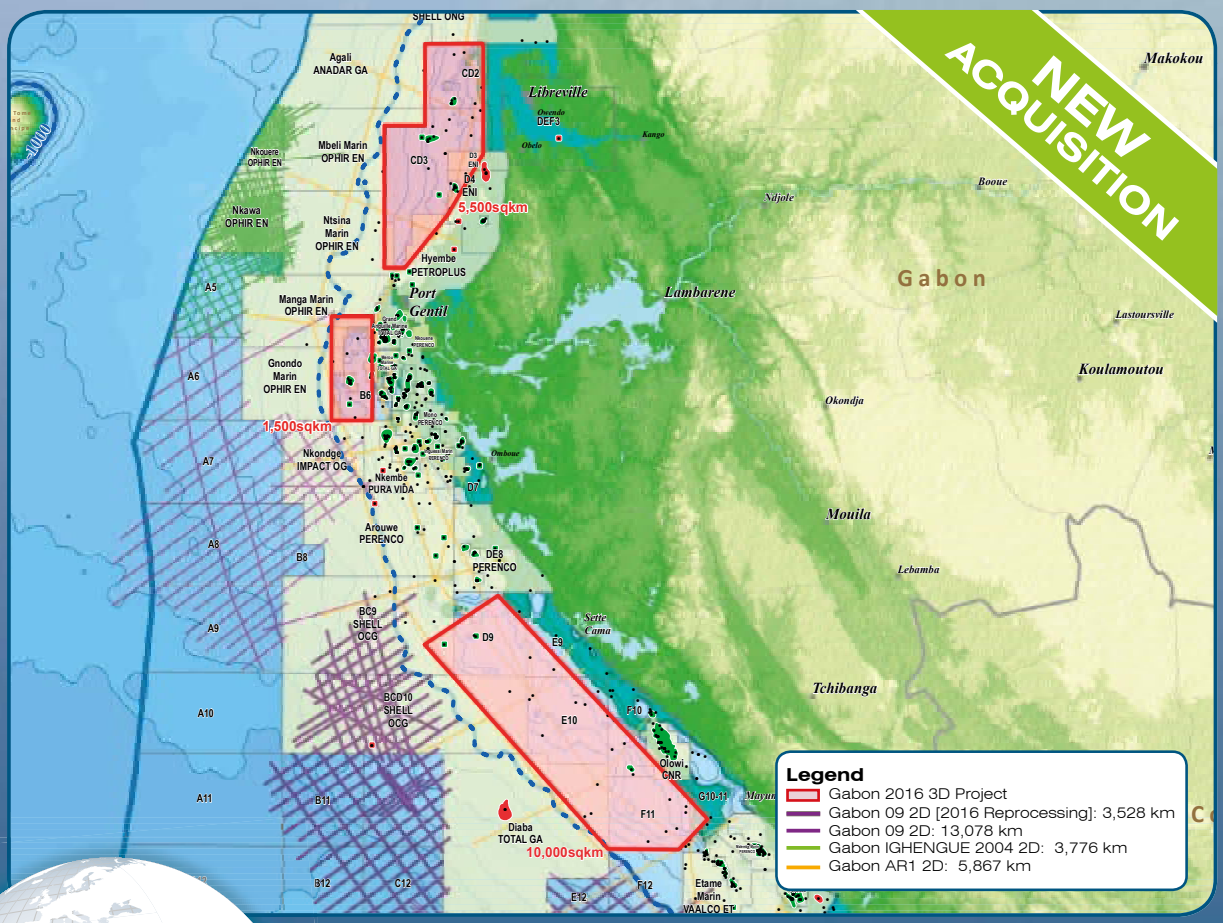
SOME PROJECTS IN COOPERATION WITH PGS TGS

multi-client seismic

GABON

Offshore Gabon 3D

New Multi-Client 3D Seismic in Open Acreage + Regional 2D



Spectrum, in collaboration with the Direction Générale des Hydrocarbures (DGH), is undertaking a series of 3D Multi-Client seismic acquisition programmes offshore Gabon. These programmes, located in under-explored shallow water open blocks, have already secured significant industry support and will offer the most up-to-date 3D imaging in the area. To accelerate exploration data will be made available for future License Round evaluation, facilitating immediate activity when the blocks are awarded.

The 10,000 km² Gryphon 3D survey in southern Gabon is currently underway. In addition, acquisition of a 5,500 km² 3D survey over open acreage in Northern Gabon is due to begin Q1 2017.

Data is expected to start becoming available toward the end of 2017 ahead of anticipated future Licensing Rounds.

spectrumgeo.com
mc-uk@spectrumgeo.com
+44 1483 730201

in association with DIRECTION GENERALE DES HYDROCARBURES

Spectrum