VOL. 13, NO. 4 – 2016

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

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Neuquén Foothills: Geology, Dinosaurs and Asado

EXPLORATION

Global Analogs

GEO PHYSICS
Marine Seismic: Faster, Better, Cheaper?

INDUSTRY ISSUES
Social Seismic: Petroleum and the Public

GEO PROFILE
Gladys Gonzalez: Making a Difference

Mexico's hidden potential

A watchful eye

- **Digital Geology Atlases**
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GEOExPro
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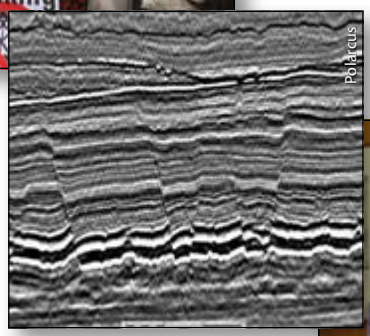

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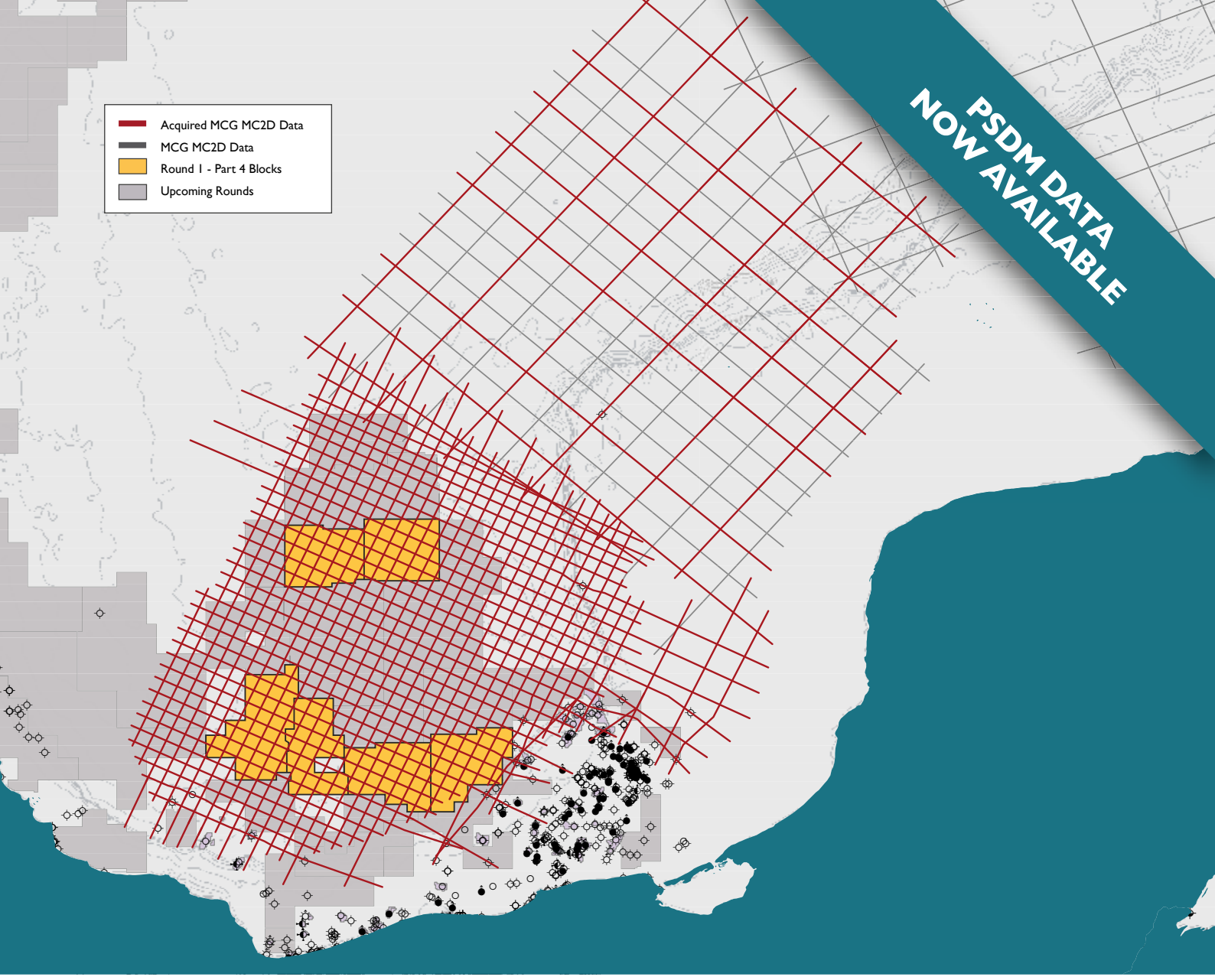
This edition of *GEO ExPro* magazine focuses on South America and the South Atlantic, and Geophysics.



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Innovate and Grow

Autonomously steered seabed nodes.

As the oil price continues bouncing around the $45 mark, and it feels as though it is impossible to tighten belts any further, one word has come to represent the way ahead: innovation.

At the forefront of technology, a number of companies have been investigating underwater drones and other autonomous marine vehicles. Fleets of seismic nodes, programmed to find their individual location, will soon become a standard tool throughout the E&P cycle. Swimming and gliding through the water, or crawling on the seabed, their uses are many, from shooting seismic in novel layouts in order to illuminate subsurface structures, to monitoring life-of-field production and investigating environmental changes. Recent huge strides in battery development are enabling these autonomous vehicles to continue working for long periods of time.

New acquisition techniques are being complemented by innovative ways of making more of seismic through processing, not just data newly acquired though the most modern broadband multi-azimuth techniques, but also to look at vintage seismic with new eyes and understanding. Seismic analysis, combined through advanced modeling with electromagnetic and other geophysical methods, is attempting to achieve the near impossible: to find more with less. Exploration is not the only focus; with global recovery rates stuck at about 35%, novel ways of increasing productivity without increasing costs are needed.

Innovation is being encouraged in many different ways. Scottish universities, for example, are offering a new research MSc specifically for oil and gas innovation, 75% of which is based on working on a project which will advance the industry. Awards are being given at major conferences for the best innovation or technology, again judged on how they benefit the business. The UK O&G Authority ran an exploration license 'competition' to encourage geoscientists and engineers to develop innovative interpretations and products which will stimulate offshore oil and gas exploration activity.

In a traditionally risk-averse industry there is a natural reluctance to change but, looking ahead, this emphasis on innovation, with the implication that any new technologies and methodologies must also be very cost-effective, should reap high rewards. We will ultimately have not just a leaner and more productive industry, it will also be more forward-thinking. There's a positive side to low prices: it's not all bad news. ■

Jane Whaley
Editor in Chief

GLOBAL ANALOGS

The image shows isostatic residual gravity anomaly for the South America area extracted from Getech's global gravity database – one of the many innovative tools which can be used in exploration to develop analog geophysical signatures of 'typical' margin types.

Inset: The Neuquén region is the most important hydrocarbon-producing province in South America. As well as having volcanoes and textbook geological exposures, it is stunningly beautiful and has outstanding food and good wines – and extraordinary inhabitants.

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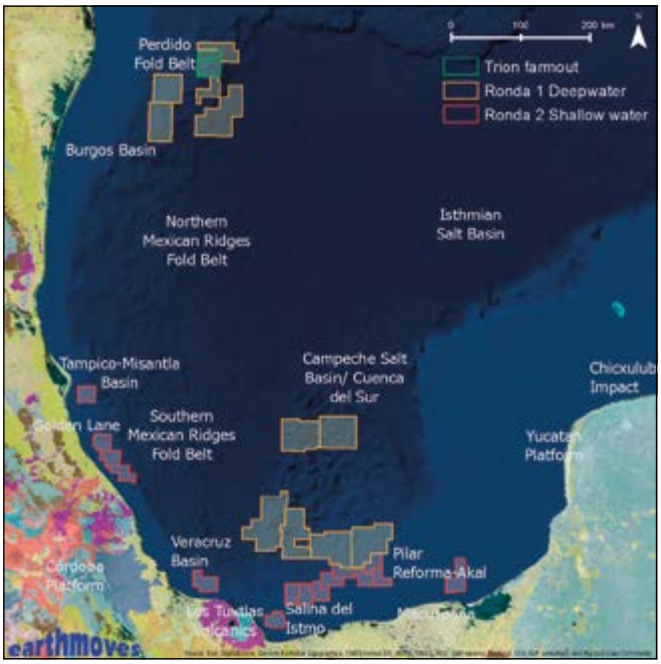
Mexico:
Second Round Launched

There was considerable excitement in the hydrocarbon industry when, in August 2014, the Mexican Comisión Nacional de Hidrocarburos (CNH) announced its first ever licensing round for foreign investors. For 75 years state-owned Pemex had held a monopoly on oil exploration and production in the country, and the company had been allocated over 80% of Mexico's proven and probable reserves before the licensing rounds opened. However, Pemex is now allowed to take on private partners, and is actively seeking investors for the deepwater Trion field near the US border.

The first phase of Round 1 turned out to be not quite as hotly fought over as expected, with initially only two of the 14 blocks on offer being awarded. However, the Mexican government appear to have learnt a lot from feedback from this process and have eased the bidding terms and conditions, resulting in the successful award of a large number of blocks in the later phases of the round.

Round 2, Phase 1, which was launched in July this year, concentrates on the shallow offshore. In this phase, 15 shallow water blocks are on offer, covering an area of 8,908 km^2 off the coast of Veracruz, Tabasco and Campeche and thought to potentially hold over 500 MMboe. The government is offering 30-year production-sharing contracts which could be extended for up to an additional 10 years if the fields are producing, with an initial exploration period of four to six years. The second phase of Round 2 will concentrate on conventional onshore oilfields and both phases close in March next year. ■



UK: Over 1,200 Blocks Available

In an effort to maximize economic recovery from its waters, the UK is offering 1,261 blocks in the 29th Offshore Licensing Round, which opened at the end of July and closes on October 26, 2016. All waters surrounding the UK are included, with over 800 blocks lying in the relatively frontier areas in the Rockall Trough and West of Scotland. Other blocks are in underexplored parts of the Mid-North Sea High, which was recently covered by a £20 million government-funded seismic acquisition program, the data from which is freely available. The 29th Round also marks the launch of a new 'Innovate License' which will allow licensees to work with the UK Oil and Gas Authority to design an optimal work program covering phasing of activity, rental fees and competency tests, with a stage-gate process for better monitoring of progress. ■

ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids
barrel = bbl = 159 litre

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

Gas

MMscfg:	million ft^3 gas
MMscmg:	million m^3 gas
Tcfg:	trillion cubic feet of gas
Ma:	Million years ago

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

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

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

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

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

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

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* GME and geo-chemical surveys;
* Geophysical equipment manufacturing;
* Multi-client services.

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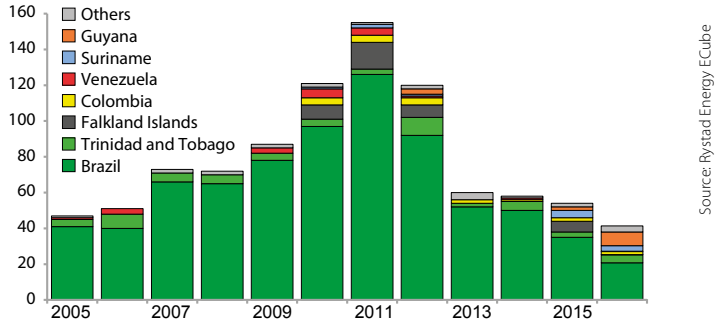
Brazil Declines

…as exploration activity is becoming more diversified in South America

Historically, offshore exploration activity in South America had been dominated by Brazil. Over the last two years, this picture has changed, as drilling activity in Brazil declined and activity grew in other parts of the region.

At the beginning of this decade, Brazilian exploration activity peaked at more than 120 exploration wells drilled per year. Petrobras and OGX led the charge by exploring the Campos and Santos Basins. Since then, exploration activity has declined in Brazil: only 35 exploration wells were drilled in 2015, and the number will fall to about 20 wells this year.

While activity in Brazil has declined, exploration in the rest of South America has been growing. In fact, 2016 will be the first year in history where the number of spudded wells outside Brazil exceeds those in Brazil. The growth is driven by a number of countries, including Suriname, Guyana, and the Falklands.



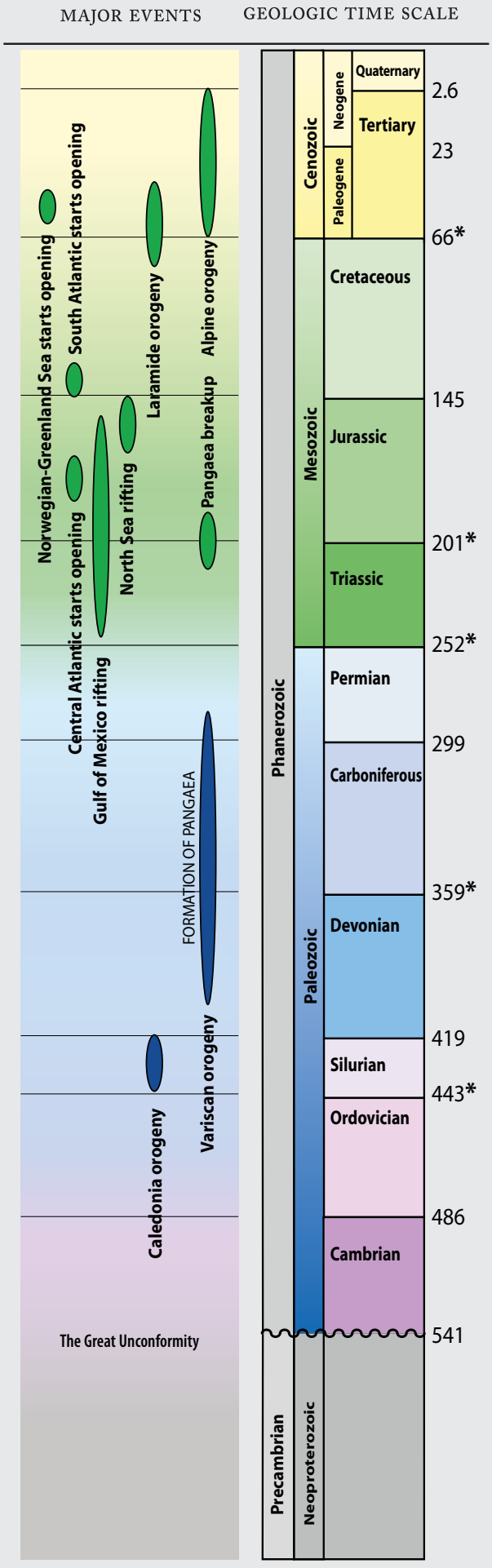
Number of spudded offshore exploration wells in South America by country.

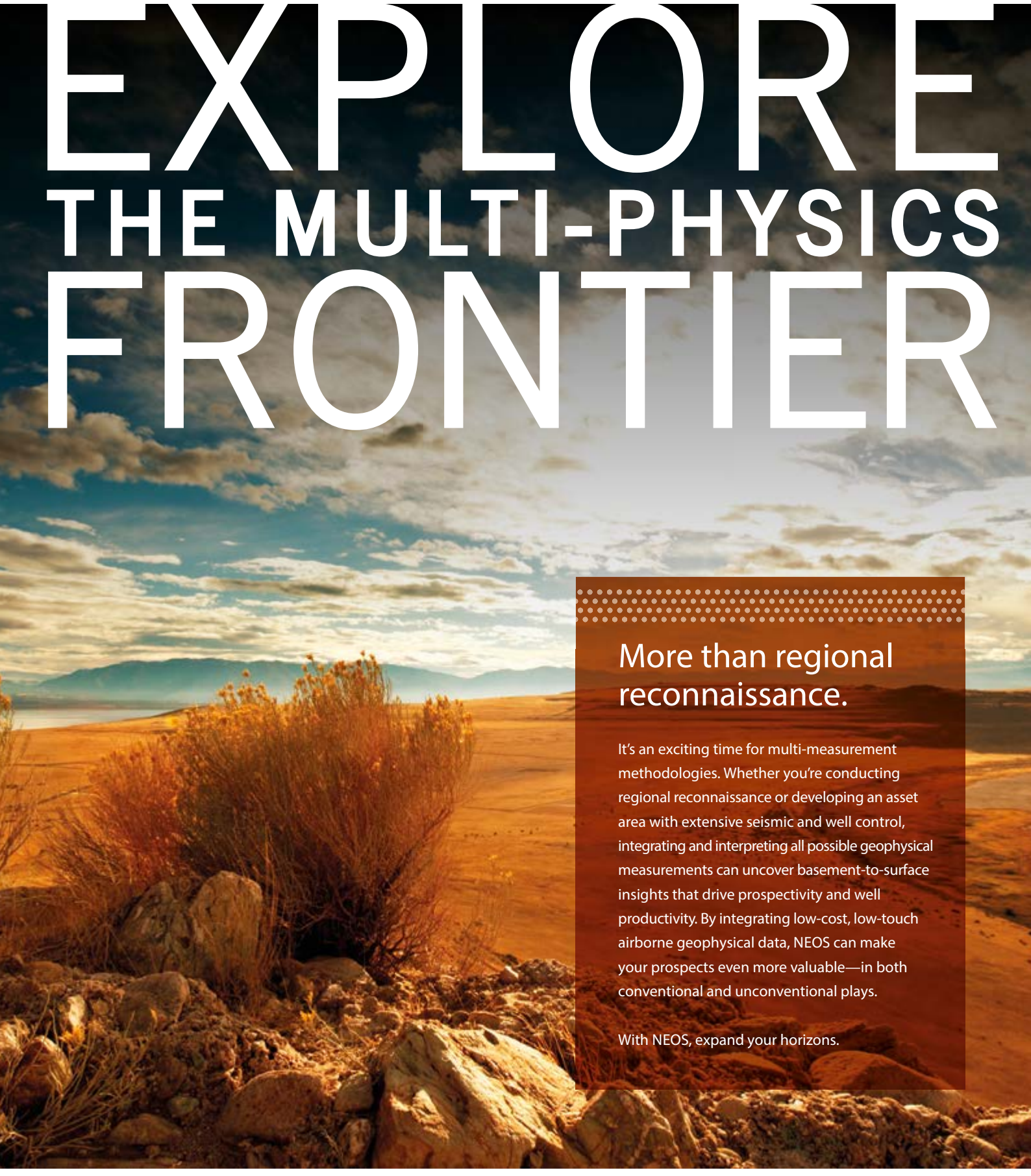
In Suriname, the national oil company drilled two wells in 2015, while Apache and Inpex drilled one each, although none of these resulted in a major discovery. In 2016, Petronas and DEA plan to drill a well on the Roselle prospect, offshore Suriname (see page 34).

In Guyana, ExxonMobil found the giant Liza field last year, the largest oil discovery globally in 2015, which is estimated to be able to produce 1 Bboe. Exxon plans to appraise the discovery in 2016 and will target other prospects in the same block, bringing the total number of exploration wells for the year to around five.

Two other high impact exploration wells drilled this year were Total's Raya (Uruguay) and BHP's LeClerc (Trinidad & Tobago). At 3,412m below sea level Raya is the world's deepest water hydrocarbon well ever drilled. This well could open up one of the greatest exploration opportunities this century, as predicted by studies carried out on Spectrum seismic on both sides of the Atlantic margin. LeClerc is notable as it is the first deepwater well off Trinidad and Tobago. As exploration activity started to fall in 2012, so did exploration results. In the period 2008–2012 the average annual discovered offshore volumes for South America were around 9 Bboe; in 2015, this number had dropped to about 1.1 Bboe. In total, the average discovery cost per barrel has increased from ~1.3 to ~7.0 US$/boe over this period. This shows that South America, along with the rest of the offshore world, is struggling to deliver the necessary exploration results. The opportunity to diversify the exploration effort around the continent might be one way of reversing this development. ■

Espen Erlingsen, VP Analysis, Rystad Energy





More than regional reconnaissance.

It's an exciting time for multi-measurement methodologies. Whether you're conducting regional reconnaissance or developing an asset area with extensive seismic and well control, integrating and interpreting all possible geophysical measurements can uncover basement-to-surface insights that drive prospectivity and well productivity. By integrating low-cost, low-touch airborne geophysical data, NEOS can make your prospects even more valuable—in both conventional and unconventional plays.

With NEOS, expand your horizons.

Inside Africa's O&G Game

Despite the industry slowdown, Africa is still hot! But for those who really want to get the inside story, and meet all the right people, the place to be is not the scene of the most recent discoveries off Mauritania and Senegal, but Cape Town in early November, at the 23rd Annual Africa Oil Week/Africa Upstream 2016 Conference. Hosted by Global Pacific & Partners with ITE Group, this event will again showcase the African governments, national oil companies, licensing agencies and corporate players who are shaping the continent's future. It provides a unique continental platform portraying deep insight, rich content, strategies, acreage opportunities, farm-ins and deal flow, with extensive high-level senior executive networking to help secure new venture possibilities and financial and investment opportunities. Conference topics cover the expanding Africa-wide gas-LNG and energy game and emerging unconventional ventures in shale and diverse hydrocarbons, as well as conventional exploration and production. 180 exhibitor companies and more than 1,000 senior executive delegates are expected at this year's event, which will be held from October 31 through November 4, 2016 at the Cape Town International Convention Center, South Africa. Go to www.africa-oilweek.com to register.

You're only inside Africa's oil and gas game if you're at Africa Upstream 2016! ■

New Magnitude Formula: Events Overestimated

A Nanometrics broadband seismic monitoring station.

Research recently submitted for publication in the Bulletin of the Seismological Society of America provides a **local magnitude formula** (ML) specific to the **Western Canadian Sedimentary Basin**. The study shows that the standard ML formula currently used to drive induced seismicity traffic-light protocols in western Canada overestimates earthquake magnitudes. Obtaining accurate ML is critically important for the effectiveness of these protocols, given the high costs of operational shut downs. The new magnitude equation, developed by the science department of **Nanometrics Seismic Monitoring Solutions**, takes into account the seismic-wave attenuation behaviors specific to the region, resulting in reliable event size estimates.

Key to the development of this new equation was access to over 125,000 high-quality ground motions recorded by Nanometrics broadband instruments deployed in monitoring networks belonging to seismological agencies and regulators as well as those it operates on behalf of oil and gas companies. The next phase of the research involves deriving predictive models for ground motions produced by induced events in western Canada. Such models are used for estimation of seismic hazard, evaluation of structural integrity of critical facilities, emergency response plans and enhancement of traffic-light protocols for more effective induced seismic monitoring. ■

New GOM Revolution

TGS and Schlumberger recently commenced shooting new Dual Coil Shooting* multivessel, full-azimuth acquisition, multiclient surveys in the US Gulf of Mexico. Known as Revolution XII and XIII, these surveys will cover approximately 7,150 km^2 over 306 blocks in the Green Canyon, Atwater Valley and Ewing Bank areas of the Central Gulf of Mexico. The Revolution series of Dual Coil Shooting surveys in the Gulf started in 2010.

Revolution XII and XIII will be acquired and processed by Schlumberger WesternGeco utilizing proprietary technology such as Q-Marine* point-receiver marine seismic system combined with the multivessel Dual Coil Shooting acquisition technique, which will provide broadband, long-offset, full-azimuth data, recording offsets of more than 16 km. Autonomous marine vehicles (AMV) will also be used, which will simultaneously acquire ultra-long offsets of more than 20 km, which benefit full waveform inversion in the accurate velocity model-building. This combination of leading-edge technologies and techniques will result in improved illumination, particularly in imaging the subsalt and other complex geologic features in this highly prolific region.

Acquisition is expected to complete in late Q1 2017. Final processed data will be available in early 2018. ■

*Mark of Schlumberger

Time for a re-think?

*Results from Dan Field Ocean Bottom Node (OBN) Survey – A Shallow Water Case Study. Zaske *et al.*, EAGE Conference (2014)

Seabed Delivers a Paradigm Shift

Innovations in ocean bottom seismic acquisition mean that a 4C full azimuth seismic survey can be as cost effective as high-end streamer solutions. Seabed seismic offers state-of-the-art, efficient and safe acquisition as well as 4D repeatability in all marine environments.

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Capturing More Data

One of the reasons for the recent growth in broadband acquisition and processing is the simple truth that more data leads to better resolution. By capturing as much of the frequency response as possible, more information about the subsurface geology is available for analysis. Broadband enables better discrimination of facies, and it allows for the removal of the ghost notch in processing. The end result is tighter resolution. Taking all of the frequency data into account can produce sharper images of both the shallower and deeper areas of interest, as well as improving the differentiation of acoustic impedance contrasts.

Deployed P-Cable seismic acquisition system, with 18 streamers (100m) at 12.5m spacing.

Another important feature to consider is data acquisition density. Smaller bin sizes allow for tighter horizontal resolution, capturing actual reflection data without interpolation. The **P-Cable** marine acquisition system, from **NCS SubSea** and **P-Cable A/S**, utilizes bin sizes as small as 3m to capture extremely high density data. The P-Cable system captures broadband spectrum as well, with useful frequency response up to 300 Hz and beyond. The net result is high resolution data, both in the vertical and horizontal domains.

This system is currently in use in several exploration and assessment projects, some of which will be publishing data in the next year. ■

Brazil Subsalt Hits Record

Not just Olympic records are being broken in Brazil this year! In May, **Petrobras** announced that oil production from its facilities in the **Brazilian subsalt** broke a new record, by producing more than **1 million bopd** – just two years after the 500,000 bopd mark was reached, and less than ten years since the first discovery in the play: and then in July it surpassed this level, reaching 1.11 MMbopd. By way of comparison, the company only reached a total output of 1 million bpd in 1998, 45 years after it was established, which required more than 8,000 production wells; the subsalt production utilizes only 52.

The Itaguai City FPSO operating in the Santos Basin subsalt.

About 25,000 bopd is produced per well in the subsalt layer of Santos Basin, and this high rate is attributed by Petrobras to enhanced knowledge of geology and the dynamic behavior of accumulations, progressive improvements in the efficiency of projects, and the introduction of state-of-the-art technologies. Petrobras reports that this combination of new technologies and a rapidly-ascending technical learning curve, focused on costs and productivity, makes subsalt projects highly profitable, so they are now the main focus of investment for the company. ■

Free MSc Study Places

Two Scottish universities, the **University of Aberdeen** and **Robert Gordon University**, are offering up to seven free places to study for a new MSc in **Oil and Gas Innovation**. These fully funded places are accessible to Scottish and EU students as part of an initiative by the Scottish Funding Council to fund 30 places across the five Scottish universities that deliver the program. Co-ordinated by the University of Aberdeen, the Masters is a collaboration between the Oil & Gas Innovation Centre and the universities in order to develop new technologies in exploration, production and decommissioning. The degree is aimed at graduates and individuals with industry experience or companies with innovative ideas that they wish to develop and while primarily research-led, the program will include modules on business innovation and technical modules related to the specific areas of research being pursued by candidates. The idea is to equip graduates with the expertise required to develop innovative solutions to challenges faced in the oil and gas sector. ■

Atrium of the main Sir Duncan Rice Library at King's College campus, Aberdeen University

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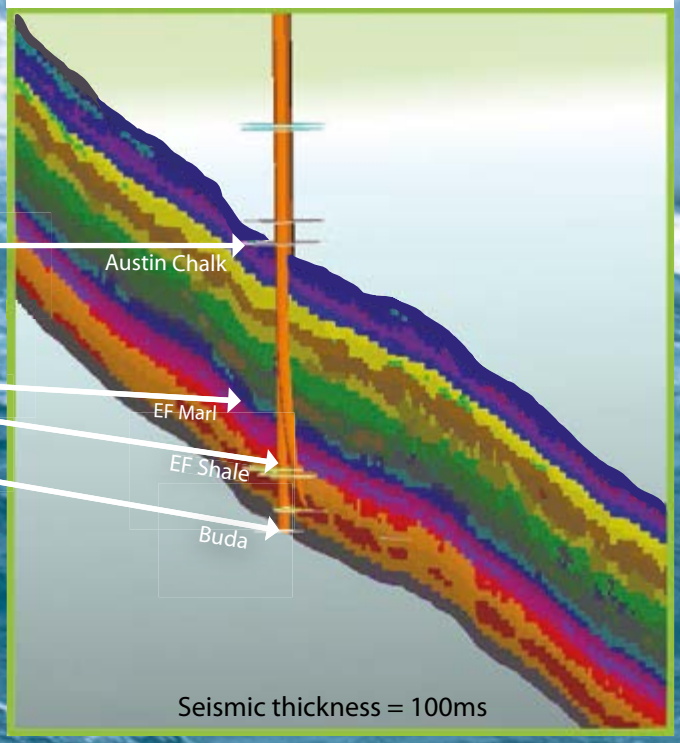

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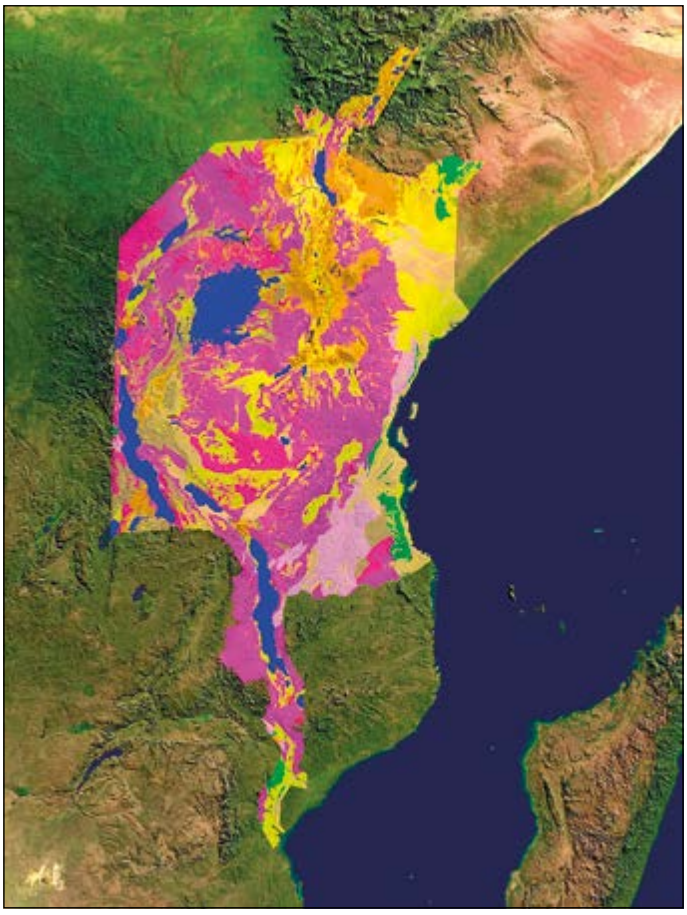
Interpret Below Seismic Resolution

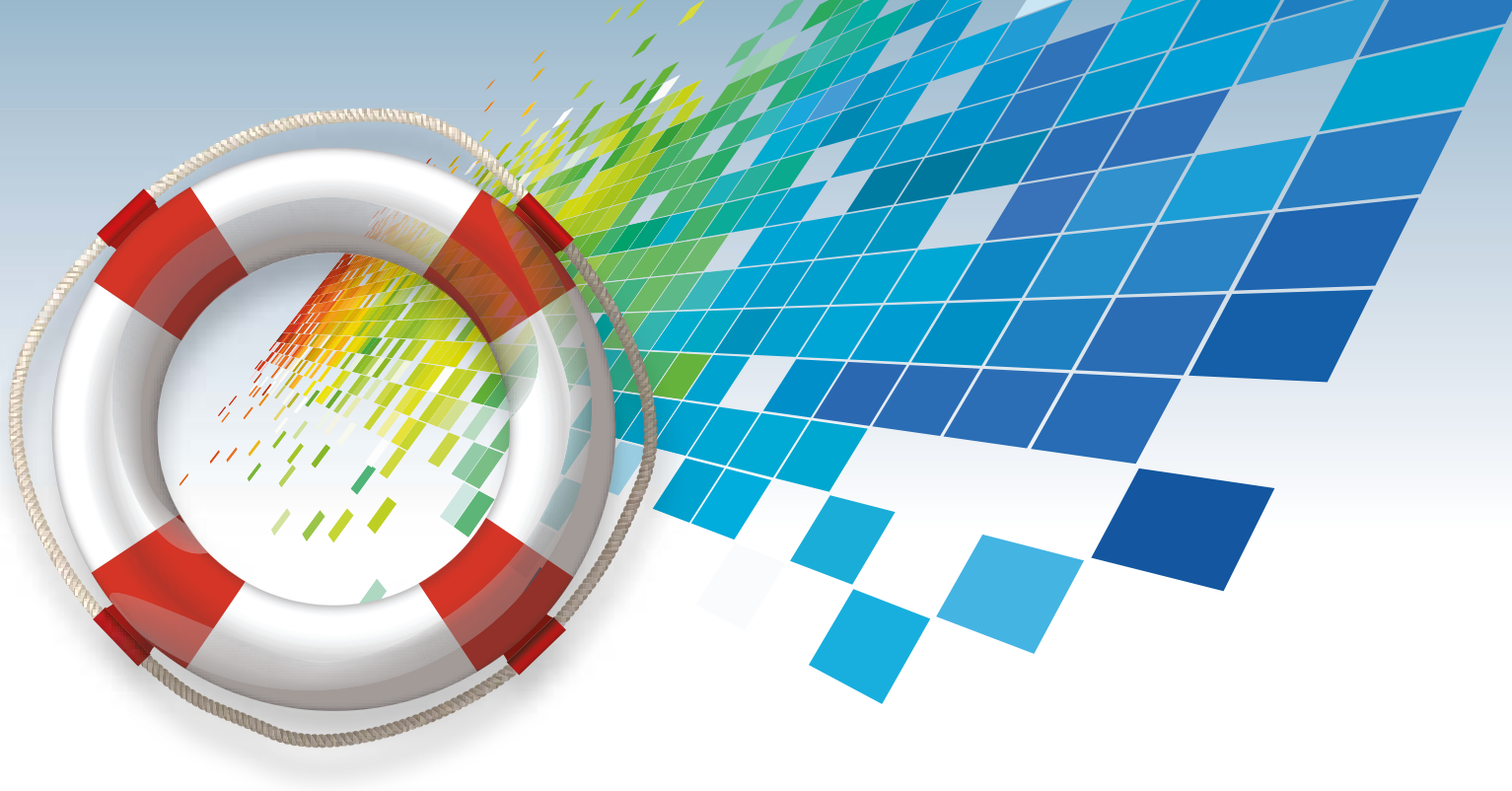
Seismic data owned and provided courtesy of Seitel, Inc.

Interactive East Africa Map

To help de-risk exploration in Africa, a new queryable geological map and database of the **East African Rift System** (EARS) has been launched by **CGG GeoConsulting's NPA Satellite Mapping** group. The 1:200,000 scale map integrates structural history, drainage analysis and sediment provenance so that exploration teams can rapidly gage and understand the structural dynamics of ongoing rifting and predict the location of favorable sediment sequences with high reservoir potential. Across the under- and unexplored rift basins, where exploration data quality and quantity are limited, the map will be particularly useful for analyzing the timing and history of regional fault movement, uplift and erosion, which control sedimentation and accommodation space within the basins and are therefore crucial to a better understanding of the remaining hydrocarbon potential of the region. The combined elevation data and map data provide valuable insight on geological evolution, source-to sink depositional systems and reservoir quality.

Compiled by expert interpretation of the latest satellite optical imagery and topographic data, the EARS BasinMap and database extends across approximately 2.5 million sq km of East Africa, taking in Kenya, Uganda, Tanzania, Rwanda, Burundi, Malawi and parts of Ethiopia, Mozambique, Zambia and the Democratic Republic of Congo. It is available for licensing for either the entire East Africa region or cropped large sub-regions. ■





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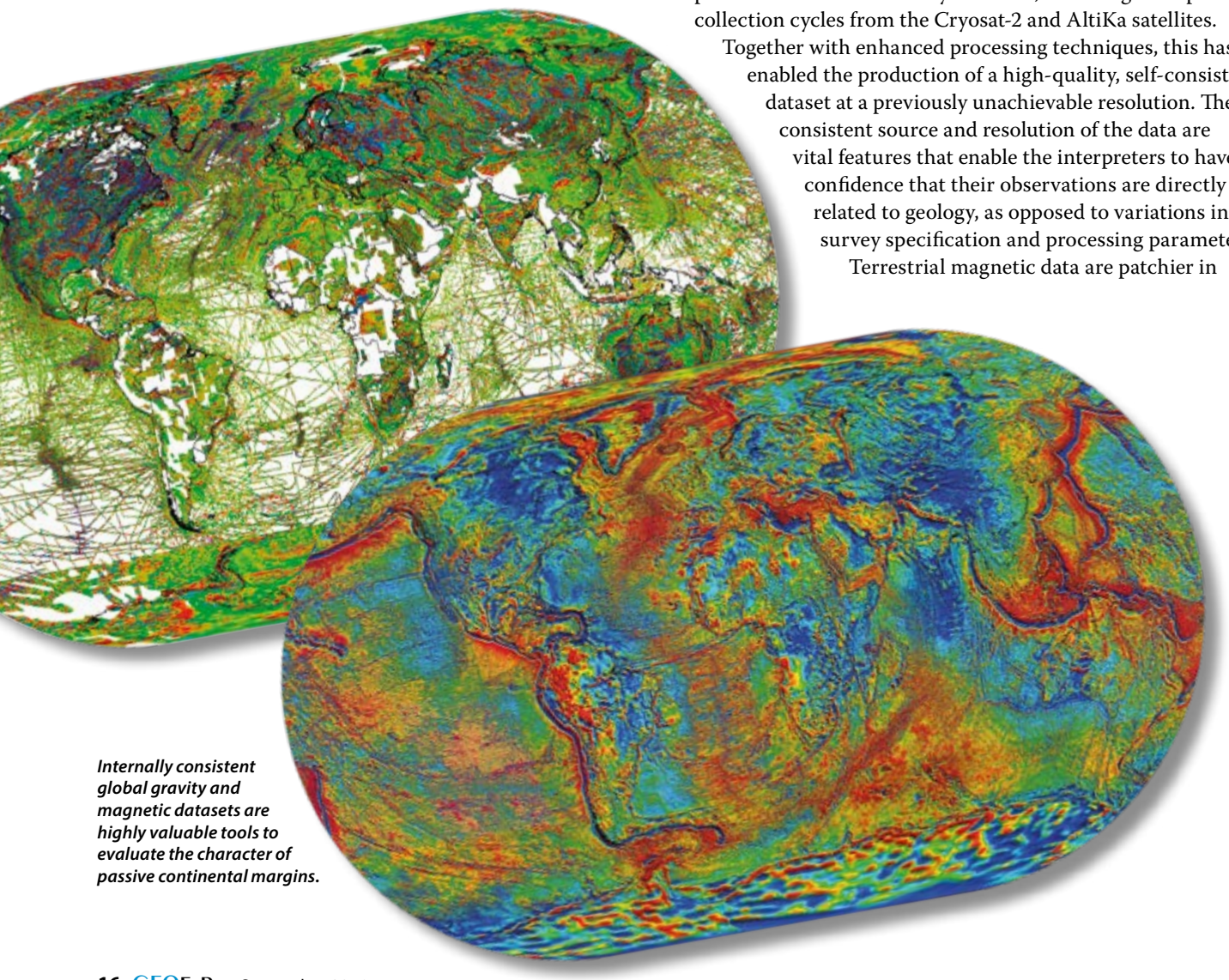
Haven't I Seen That Somewhere Before?

David Sagi, Simon Campbell and **Peter Webb** from Getech consider the value of global analogs when characterizing passive continental margins.



Internally consistent global gravity and magnetic datasets are highly valuable tools to evaluate the character of passive continental margins.

Understanding the nature of continent-ocean transition zones along continental margins and classifying them is key to building robust plate models. Together these can lead to a better understanding of the evolution of sedimentary basins and depositional systems along continental margins.

One tool to help illustrate margin structure is to look at analog geophysical signatures of 'typical' margin types. In this article we investigate the character of the continent-ocean transition zone in potential field data at a number of Atlantic passive margins. We also consider whether common elements are observed in equivalent environments. Margin types are classified in general terms as magma-rich or magma-poor; in reality, a spectrum of variations exists between these end-members. Nevertheless, with appropriate independent support, analog examples can significantly support this classification.

Self-Consistent Datasets

To look at continental margin classification on a broad scale and to allow a sufficient pool of comparison material requires excellent, internally consistent data coverage. The gravity and magnetic datasets developed at Getech enable the problem to be addressed in a truly global perspective. The company's continental margins' gravity data are derived from the latest, post-2010 satellite altimetry missions, including multiple data collection cycles from the Cryosat-2 and AltiKa satellites.

Together with enhanced processing techniques, this has enabled the production of a high-quality, self-consistent dataset at a previously unachievable resolution. The consistent source and resolution of the data are vital features that enable the interpreters to have confidence that their observations are directly related to geology, as opposed to variations in survey specification and processing parameters. Terrestrial magnetic data are patchier in

coverage, but the reduction to common processing parameters and nominal reference elevation increases their usability in this context.

Margin Classification Examples

From the continent to the ocean, Getech classifies the crust at passive continental margins into four domains: continental, attenuated, transitional and oceanic. The transitional domain is generally classified into the end-member type it best resembles: magma-poor or magma-rich. The magma-poor transitional domain includes crust that has undergone ductile thinning, hyperextension, igneous underplating, or exhumation and serpentinization of the mantle. The magma-rich transitional domain includes crust with widespread crustal intrusions and voluminous surface volcanism, which is imaged in seismic sections as seaward-dipping reflectors.

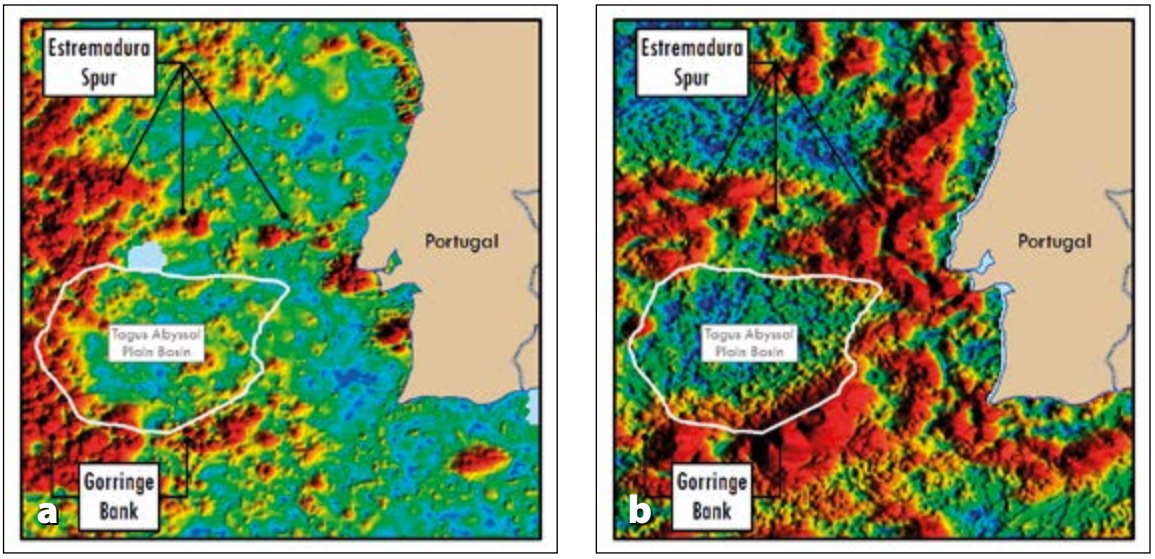


Figure 1: The Iberian continental margin. a) Analytic signal of total magnetic intensity. b) Analytic signal of free-air gravity. Note the subdued character of the gravity and magnetic data in the areas highlighted. Higher-amplitude zones adjacent to these are not directly related to the composition of the transitional crust.

Iberian Continental Margin

The first example is from the Iberian Atlantic margin, which we consider to be a magma-poor margin. Figure 1 shows examples from the vicinity of the Tagus Abyssal Plain, offshore Portugal. To highlight the textural character, the analytic signal (also known as total derivative) of the gridded gravity and magnetic data is presented. Figure 1a shows that the magnetic data are relatively subdued (low amplitude) over the transitional domain. The gravity data (Figure 1b) are also relatively subdued, with the exception of two areas that show high-amplitude responses that are associated with the presence of the Gorringe Bank (an uplifted and tilted block of exhumed mantle at the boundary between the Eurasian and African Plates) and the Estremadura Spur (which contains pre-rift volcanics). In the vicinity of the Tagus Abyssal Plain, the character and amplitudes in potential field data are also subdued. We modeled the crustal structure (Figure 2) of the margin with several 2D gravity and magnetic models (supported by seismic observations where possible), and consistently observed the characteristically subdued magnetic and gravity response (Figure 3). It is suggested that this character supports the interpretation of a magma-poor transitional margin, with the hypothesis of exhumed mantle flooring the basin being reinforced by the low-amplitude magnetic and gravity responses.

Figure 2: Getech crustal classification for this part of the Iberian margin.

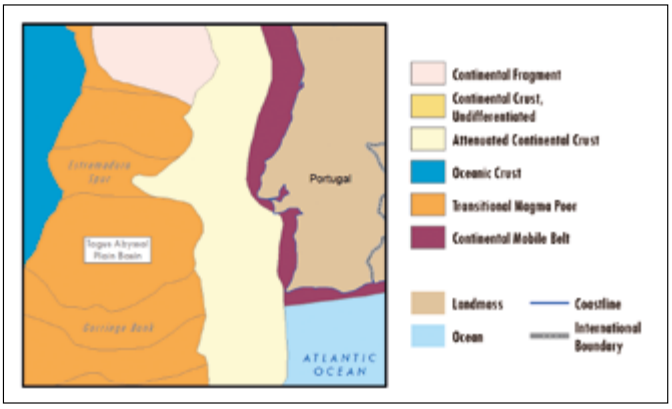
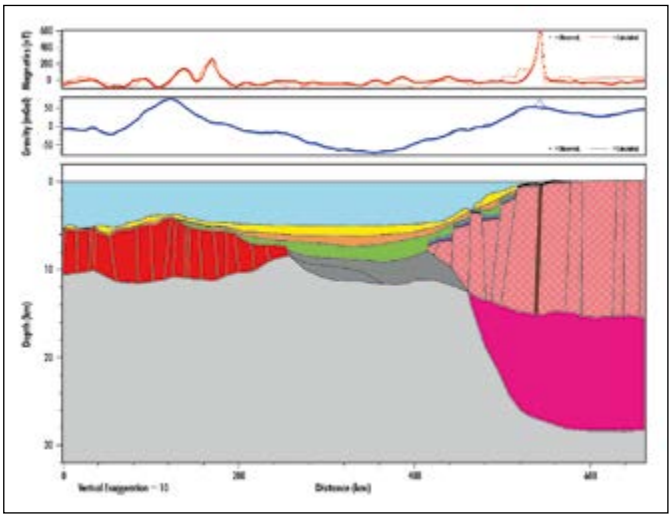


Figure 3: A 2D gravity and magnetic model of the western Iberia continental margin that highlights the subdued nature of the magnetic and gravity response over the magma-poor transitional crust at ~180–450 km.



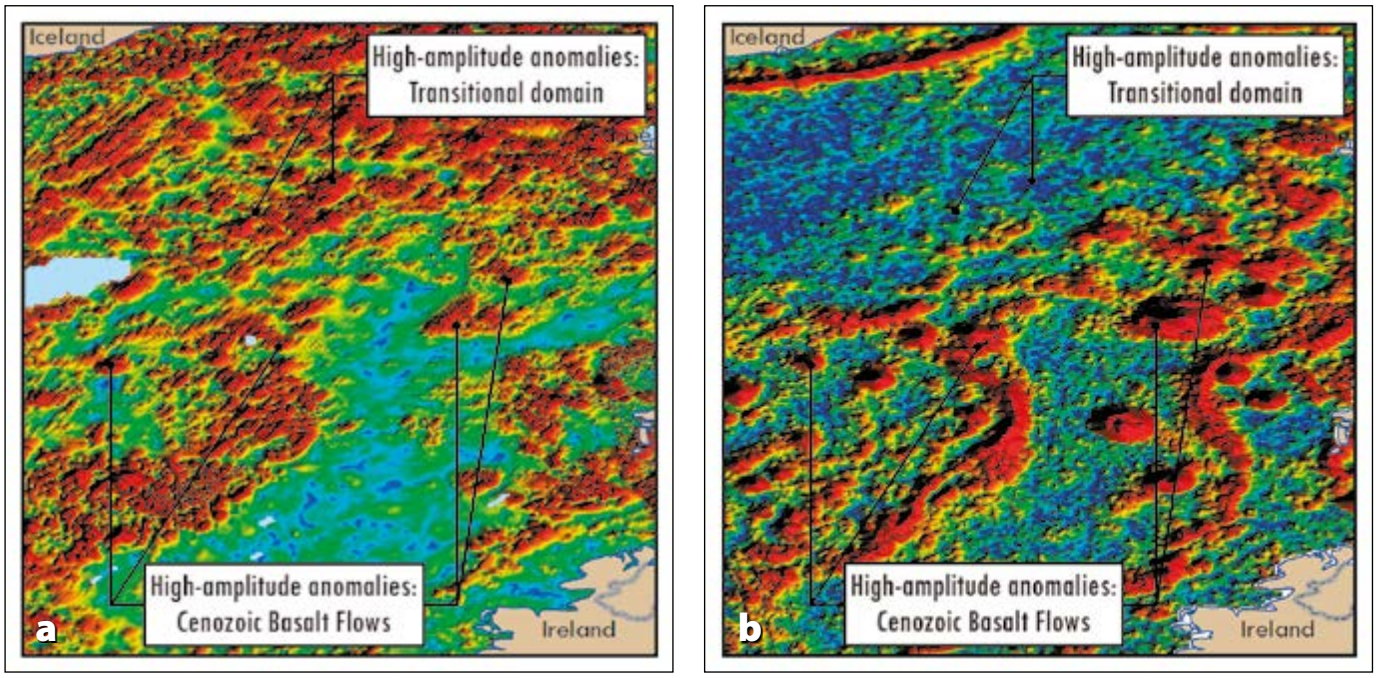


Figure 4: a) Analytic signal of total magnetic intensity. b) Analytic signal of free-air gravity. Note the high-amplitude character of the magnetic and gravity data in the areas highlighted. These areas are partially associated with the magma-rich transitional crust or Cenozoic basalt flows.

West Ireland/UK Continental Margin

The second example is from the West of Ireland/UK Atlantic margin. We interpret this as a magma-rich continental margin, as evidenced by both the dense crust that was formed by the intrusion and addition of igneous material, and the seismic interpretation of the seaward-dipping reflector sequences indicative of tilted volcaniclastic flows. To highlight the margin's textural character, the analytic signal of the gravity and magnetic maps is again shown. Figure 4a indicates that the magnetic data of the western Rockall margin display significantly higher amplitude in the transitional domain than the magnetic data observed in the Tagus Abyssal Plain; the gravity data (Figure 4b) are of similar nature. It is important to be aware that the characteristic signature is not solely due to the magma-rich crust associated with break-up as pervasive Cenozoic basalt flows also contribute to the observed signal. A representative 2D model from the margin highlights the high-amplitude, high-frequency character that we consider diagnostic of this type of margin (Figure 6).

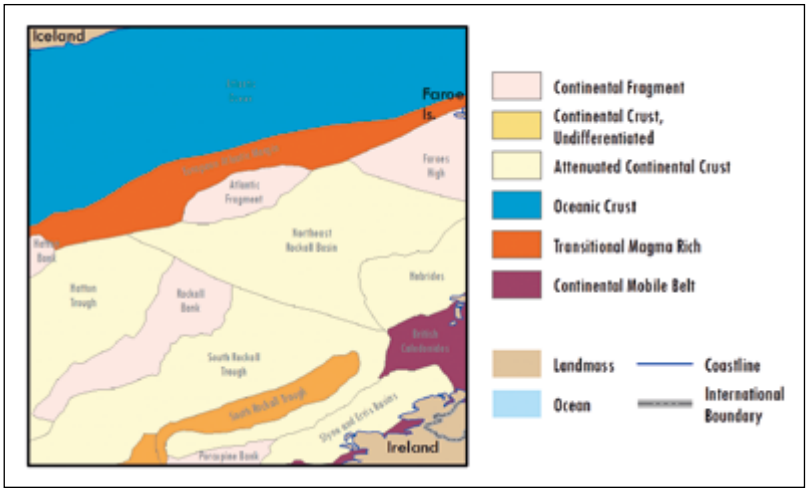


Figure 5: Our crustal classification for this part of the Rockall margin.

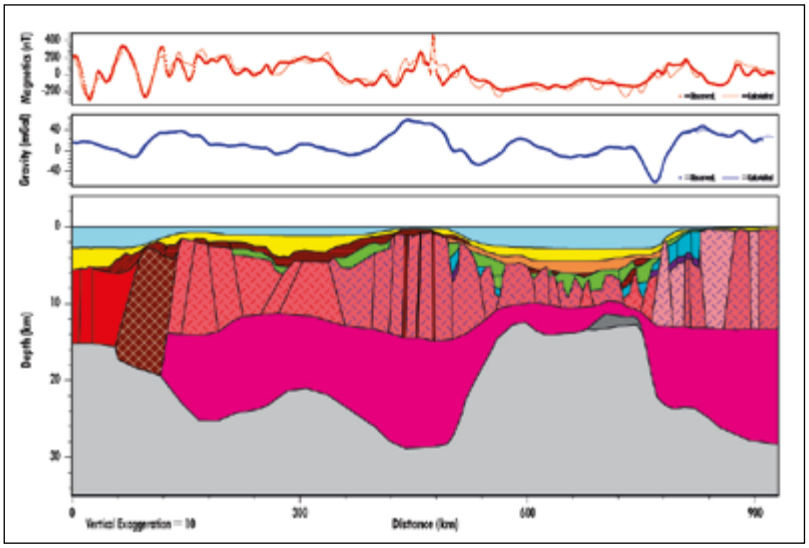
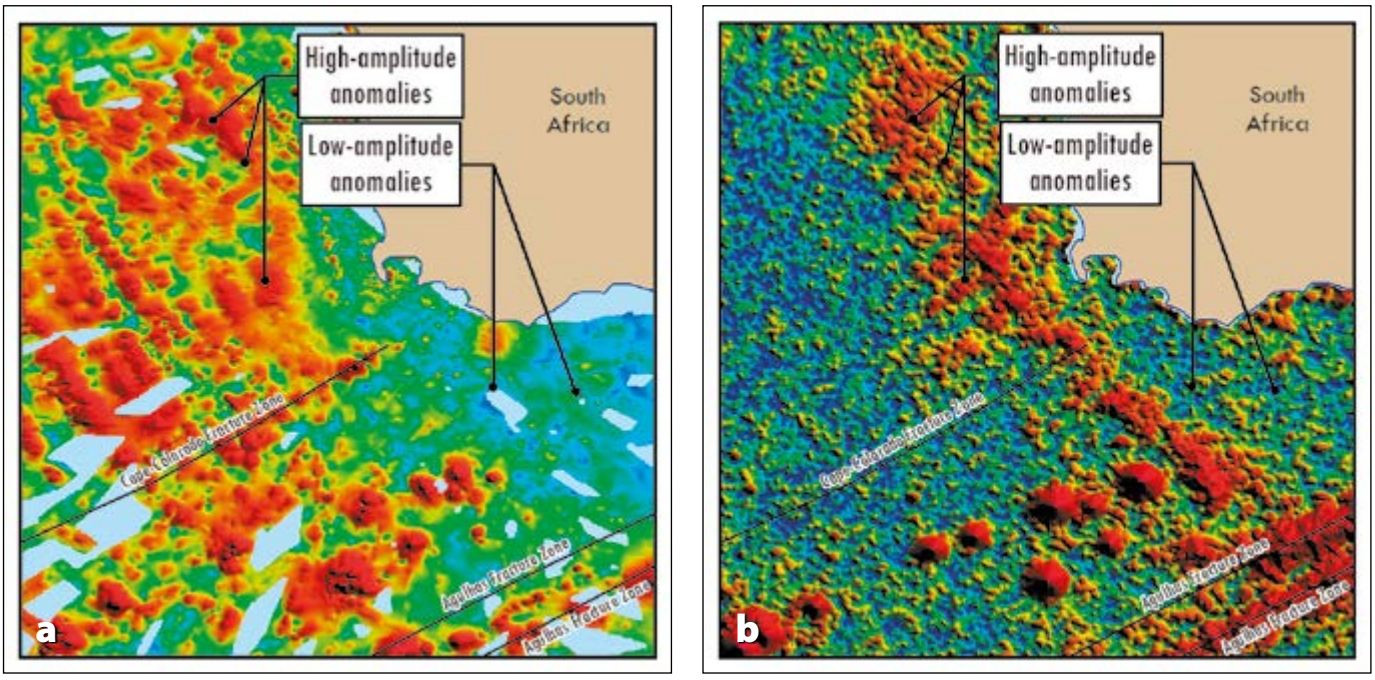
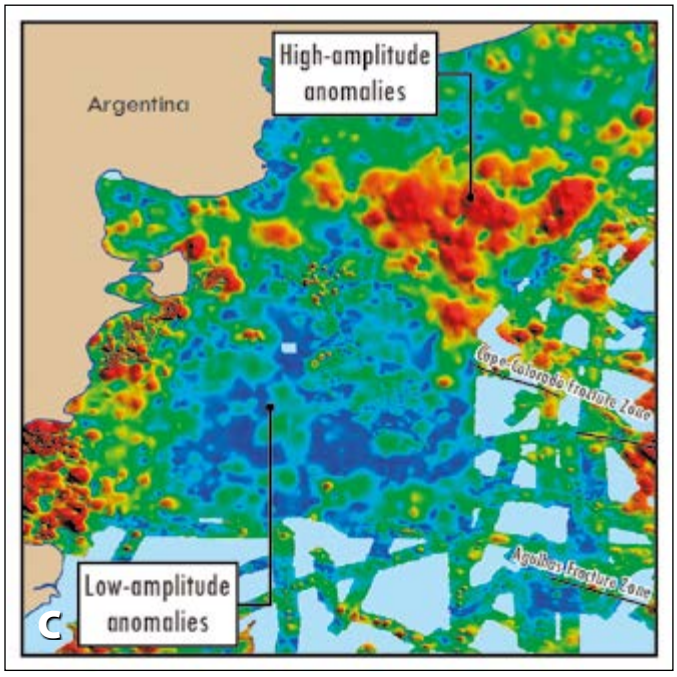


Figure 6: A 2D gravity and magnetic model of the western Rockall continental margin that highlights the high-amplitude nature of the magnetic response over the magma-rich transitional crust at ~30–200 km.





South Atlantic

Figure 7 shows the same derivatives of potential field data applied to both the southern West African continental margin in the vicinity of the Orange Basin and a corresponding example from its conjugate margin in offshore Argentina. In these examples, we see high-amplitude responses to the north of the Cape-Colorado Fracture Zone, with generally smoother, lower-amplitude responses to the south, between the Cape-Colorado and Agulhas Fracture Zones. Extending the analog approach based on the observations from Iberia and Rockall leads us to an initial interpretation of a volcanic, magma-rich margin being present to the north of the Cape-Colorado Fracture Zone. The margin then sharply transitions to a magma-poor setting to the south of this fracture zone. This interpretation requires further testing with 2D modeling and ground truthing against independent data.

Figure 7: a) Analytic signal of total magnetic intensity for the Orange Basin area. b) Analytic signal of free-air gravity for the Orange Basin area. c) Analytic signal of total magnetic intensity for the conjugate offshore Argentina area. Note the high- and low-amplitude characters in the areas highlighted, particularly in the magnetic data. This reinforces the hypothesis that the margin is largely magma-rich in nature to the north of the Cape-Colorado Fracture Zone, transitioning to a magma-poor setting to the south of this fracture zone.

Consistent Data and Good Coverage

Defining crustal types based solely on the character of potential field data is ambitious, and an overarching typical character is unlikely to be consistently observed globally; however, when ground truthed against independent observations, these data allow the users to extend their initial interpretations along the margins to develop crustal architecture models. Key to this process is the use of self-consistent gravity and magnetic datasets with good regional coverage. Some elements that are consistent with magma-rich and magma-poor transitional domains are clearly observed, particularly in the more direct crustal response of the magnetic data. Additionally, the gravity data can also be used for these interpretations owing to both the bulk density contrast between intruded and unintruded crustal blocks and the long-wavelength response generated by an elevated Moho at hyperextended margins. Initial observations and geological models should be further tested by detailed 2D gravity and magnetic modeling; ideally, this modeling should be constrained by seismic data and 'pegged' at both ends in the margin-bounding oceanic and undeformed continental crust domains. ■

Neuquén Foothills: Geology, Dinosaurs and… *Asado*

An ideal place for geologists features most aspects of geology, from sedimentology, tectonics, and volcanism to hydrocarbons; has a warm climate; perfect outcrops; breathtaking landscapes; outstanding food and good wines; and extraordinary inhabitants. This heavenly place has a name: Neuquén.

OLIVIER GALLAND, University of Oslo and **CAROLINE SASSIER**

Continuing Olivier and Caroline's epic cycle journey through South America

We felt good in the temperate green of southern Chile's Ring of Fire (see *GEO ExPro,* Vol. 12, No. 5), but our journey was calling us. We left Pucón, nestled at the foot of Villarrica Volcano, for a new crossing of the Andes through the Mamuil Malal pass, 1,253m above sea level. The horribly steep dirt road zigzagged through an araucaria forest and climbed the dissected topography of the Chilean side of the Andes. After a hard day's cycling, we eventually reached the summit of the pass, and we looked forward to riding down the Argentinian flank of the Andes.

This delightful downhill ride never happened! We realized that the Argentinian Andean foothills consist of a wide plateau at around 1,000m. Here, there is no green forest, but yellow dry grass; no steep topography, but an endless elevated Patagonian pampa; and no nice climate, but a heavy burning sun. We had entered the domain of Neuquén.

Overview of Neuquén Geology

The Neuquén region is known among geoscientists mostly through the Neuquén Basin, which lies at the eastern foothills of the Andes, between 32°S and 40°S. The basin comprises Late Triassic to Early Cenozoic sequences covering an area of more than 120,000 km^2, with up to 6,000m of well-preserved marine and continental deposits. An initial Triassic rifting

Olivier Galland – Géoroute

Horse-riding gauchos at the foot of Tromen Volcano, on the shore of Laguna del Tromen lake.

was followed by a Jurassic to Lower Cretaceous thermal subsidence phase, marked by the deposition of several high quality marine organic-rich shale formations, including the famous Lower Cretaceous Vaca Muerta Formation. From the Upper Cretaceous until the present day, the western margin of the basin was affected by east-west shortening as a result of the Andean orogeny, resulting in the deposition of thick continental deposits in a foreland setting. Since the Cretaceous, the Neuquén Basin has experienced successive igneous episodes, leading to the emplacement of voluminous intrusive complexes and large back-arc volcanic fields. The present configuration of the basin includes two main sections: the Neuquén Andes, which corresponds to the deformed western edge of the basin, and the Neuquén Embayment, which is made up of the eastern, non-deformed, flat part of the basin.

The textbook geological marvels of the Neuquén Basin can be discovered through a fabulous ~1,000 km-long road trip, starting from Neuquén city and travelling westwards to Zapala, before following the famous National Road 40 (RN40) towards the north along the Andean foothills. The road crosses vast, breathtaking landscapes, including the hostile desert of the southernmost Mendoza Province, and bends around the imposing Payunia volcanic field, following the Río Grande river. Finally, the itinerary leaves RN40 at Bardas Blancas to cross the Andes back to Chile, reaching the wild springs of Río Grande at the Vergara pass, at the foot of the Planchón-Peteroa volcano.

The Dinosaur Valley

Argentina hosts a tremendous paleontological inheritance. Abundant evidence of this treasure is found in the Neuquén Basin, which is sometimes known as the 'Valley of the Dinosaurs'. Most dinosaur fossils are concentrated in the Upper Cretaceous continental deposits of the Neuquén Embayment. The most amazing pieces are exhibited in the least expected place on Earth: the charmless oil town of Plaza Huincul, isolated in the middle of the flat Neuquén Embayment.

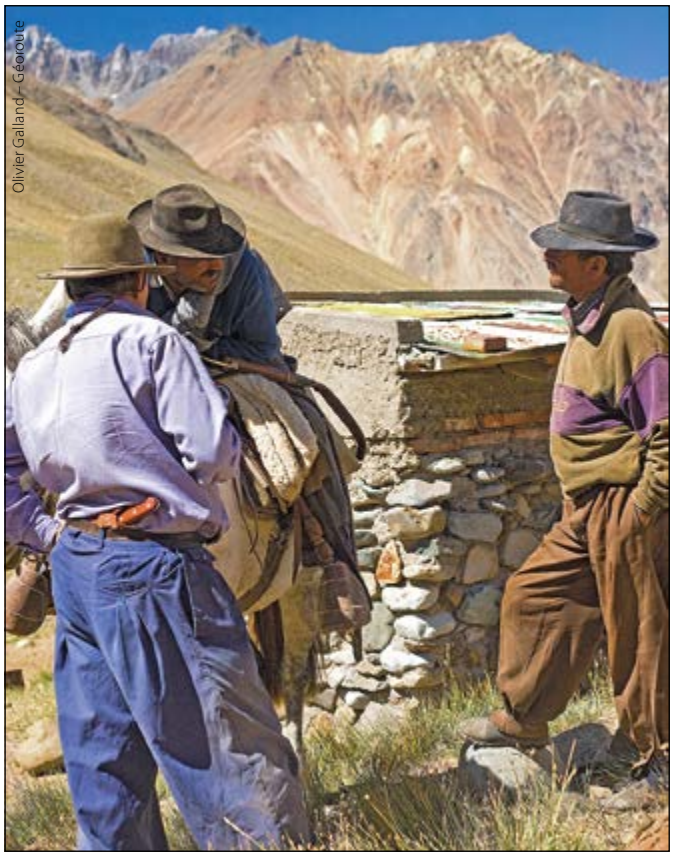
When passing through Plaza Huincul, visitors should make sure they don't miss the Carmen Funes Museum where, for less than €2, they can access a vast hall with incredible reconstructions of dinosaur skeletons. In particular, one can appreciate the impressive dimensions of the *Argentinosaurus huinculensis*, a herbivore of the sauropod family, considered one of the largest, if not the largest, dinosaurs discovered. Other stunning pieces exhibited at the museum are reconstructions of the *Giganotosaurus carolinii*, one of the largest carnivores ever found, and the most complete ichthyosaur fossil in South America. In addition, the museum features the only known embryos of sauropods, found in an extraordinary nesting site near Auca Mahuida, 150 km north-west of Neuquén City. The preservation of these embryos is such that they contain patches of delicate fossilized skin.

True and Fake Volcanoes

The road north of Zapala approaches imposing volcanoes which protrude out of the vast, low-lying Neuquén Basin. The most prominent is the Plio-Pleistocene Tromen volcano, the second highest peak in Patagonia, situated at the gates of the town of Chos Malal. This 4,114m-high sentinel, located 100 km east of the main Andean range, is visible from most of the Neuquén Embayment up to several hundred kilometers distance. RN40 offers various stunning viewpoints over the slopes of this very picturesque volcano. In addition, the visitor should not miss its north-western flank, which offers a unique scenery of shallow lakes (Laguna del Tromen), flamingos, high Patagonian plateaus and gauchos, dominated by a 2 km-high volcano that recently erupted voluminous lava flows.

Satellite image of the Neuquén Basin with our itinerary.

The gigantic Argentinosaurus huinculensis, considered to be the largest dinosaur ever discovered, at the Carmen Funes Museum, Plaza Huincul, Neuquén Province.



Argentinian gauchos in the vicinity of Planchón-Peteroa, after sharing their meal with us.

In addition to its beauty, Tromen can offer something of particular geological interest: it crowns the hanging-wall of a large-scale thrust fault that is well exposed around the eastern foot of the mountain. In fact, what looks like an enormous 3,000m-thick accumulation of volcanic products is a tectonic structure consisting of Mesozoic sediments uplifted 3,000m above sea level and covered by thin volcanic products. In addition, Tromen built up during tectonic compression, providing one of the first proofs that volcanism does not need tectonic extension to occur.

Further north, RN40 traverses the Miocene-Pleistocene Payunia volcanic field. It is one of the largest volcanic fields on the planet (5,000 km^2), dominated by the flat Payún Matrú (3,680m) and pointed Payún (3,715m) volcanoes, and containing about 800 individual volcanic cones. Recently, it was discovered that Payún Matrú emitted the longest known individual Quaternary lava flow on earth – 181 km (Pasquarè et al., 2008). Crossing the Payunia volcanic field is an unforgettable, almost mystical experience. It offers a true feeling of isolation in the middle of the elevated Patagonian pampas and invites the visitor to meditate on the beauty of such pristine nature. Because of its uniqueness, the Payunia volcanic field is strictly protected and is a candidate to be a UNESCO world heritage site.

North of Tromen stands the 'Roof of Patagonia', a massive, rounded snow-capped mountain 4,709m high and visible from much of the Neuquén Basin. All maps of the region mark this landmark as Domuyo Volcano; the problem is, Domuyo is not a volcano! Despite its prominent, sub-conical shape, it is a tectonic structure brought to high altitude by the Andean orogeny. The confusion probably results from the presence of hot geothermal fields at the western foot of the mountain. Whatever its nature, the shining white summit of Domuyo is attractive to every mountain lover.

Textbook Geology

The Neuquén Basin is a significant economic player in Argentina, as it is the most important hydrocarbon-producing province in South America. Most of the fields are found in the Neuquén Embayment, where the petroleum systems are buried, but in the western margin of the basin the main formations of these systems are brought to the surface in a well-developed and well-exposed fold-and-thrust belt. The resulting outstanding outcrops have been the targets of voluminous academic research, and have global significance having been instrumental in defining new concepts in paleontology, sequence stratigraphy, reservoir geology and structural geology.

The numerous road-cuts along the RN40 spectacularly expose several organic-rich shale formations, the most famous of which is the Lower Cretaceous Vaca Muerta Formation. This world-class source rock potentially hosts gigantic reserves of shale oil and shale gas, and the outcrops along the RN40 are thus of primary importance for those studying it. Beautiful views of reservoir sandstone and Upper Jurassic gypsum are also found along the route. The fantastic, wide outcrops allow the visitor to understand large-scale textbook tectonic structures such as anticlines, synclines and thrust faults.

Sunrise on Mount Domuyo, the roof of Patagonia.

Outcrop of the organic-rich Vaca Muerta Formation between Bardas Blancas and Planchón-Peteroa.

The Gauchos' Spirit

Definitive geology and stunning scenery make the Neuquén Basin an incredible place for geologists to visit, but the experience would be incomplete without coming into contact with what makes the spirit and soul of the land. Everywhere along the route and in the desert there are stone or wooden huts standing in small green oases: the abodes of gauchos, or Argentinian shepherds. Despite living in remote areas and in harsh climatic conditions, gauchos are incredibly welcoming, curious and generous people. How many times during our journey have we spent hours chatting with them, sharing homemade bread and 'mate', a typical local tea? We will never forget our fabulous encounters with, among others, Faustino, a gaucho in the Río Grande Valley and the leader of a folkloric music band with his family; or a group of gauchos travelling down from the Vergara pass for the autumn transhumance, who spontaneously shared with us an amazing meal of grilled meat (*asado*) in the heart of the mountain. Discussions with gauchos seem to slow time down, and bring the visitor into a state of harmony with the extraordinary geological environment of the Neuquén Andean mountains.

Acknowledgments:

The Andean Geotrail project was endorsed by the International Year of Planet Earth. The authors acknowledge financial support from SPB-Guilde Européenne du Raid, the Conseil Régional Rhônes-Alpes, the Conseil Municipal de Bourg-en-Bresse, the French Ministère de la Jeunesse et des Sports, and material support from Decathlon. ■

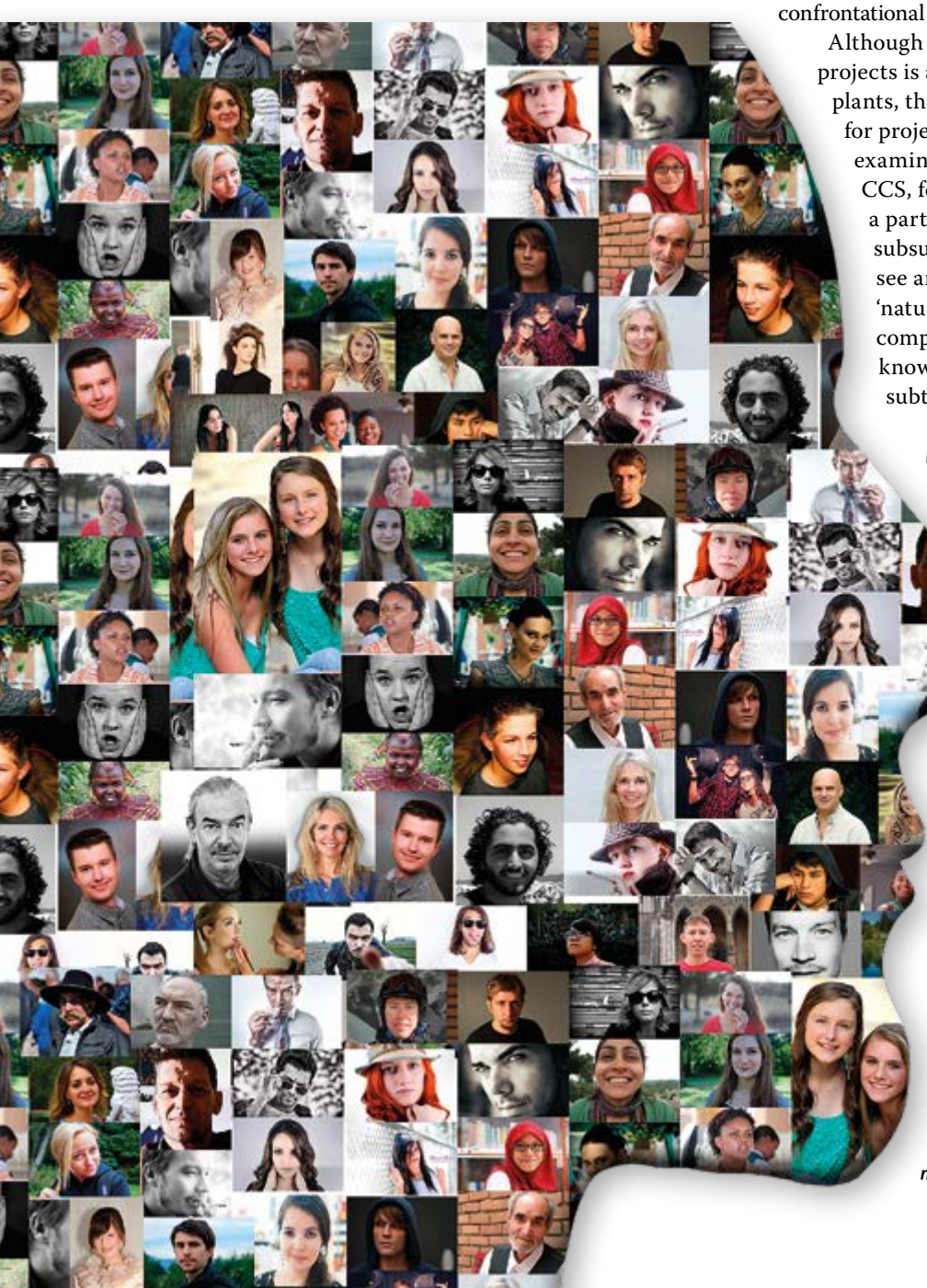
Social Seismic

Petroleum and the public: how do we win the battle for community hearts and minds?

PROF. IAIN STEWART and HAZEL GIBSON, University of Plymouth

"We underestimated the level of community concern and unrest… Inadequate engagement led to decisions that, in hindsight, were too legalistic in approach… What we ended up doing to rebuild relations and trust was what we should have done in the first place – that was having local community people engaged as liaisons, working at the very start of the project to understand what the concerns were, rather than be driven by a project schedule, which is what essentially happened… We didn't have what we might have called social license".

(Murtagh, P., 2015)



These comments from Michael Crothers, at the time Shell's managing director for exploration and production in Ireland, concern the local conflicts and chronic delays that accrued a €2.4 billion cost overrun on Corrib Gas, Ireland's most expensive energy infrastructure project. The difficulties of securing public acceptance – the social license to operate – for major infrastructure or energy projects is not confined to Ireland. For a number of years public anxiety over shale gas, coal bed methane, underground coal gasification and carbon capture and storage (CCS) projects has embroiled energy companies in lengthy and confrontational planning disputes.

Although gaining community participation in energy projects is also a problem for wind and solar energy plants, there seems to be particular popular unease for projects that delve into the subsurface. In an examination of what drives public protest about CCS, for example, Wallquist et al. (2012) note a particular objection to 'tampering with the subsurface'. This notion of people wishing to see an apparently pristine subsurface remain 'naturally untouched' implies a deep-seated comprehension gap between the technical knowledge of geoscientists and the vaguer subterranean conceptualizations of the public.

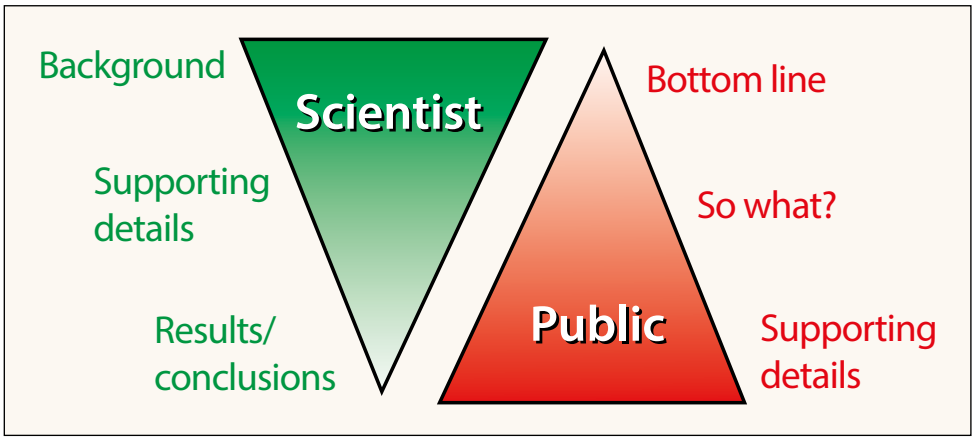
Mental Models

The realization that ordinary people lack a clear grasp of the geological subsurface has been examined in a collaborative research project between geologists and cognitive psychologists at Plymouth University (Gibson et al., 2016), which looked at how geologists and non-geologists perceive the geology beneath south-west England, an area where deep geothermal projects are proposed. Heat was a recurring feature in interviews with local residents, but the depth at which this was encountered was a source of confusion. One interviewee suggested it was "… down towards the very, very bottom of the Earth. That's because it's

"It is a fact often overlooked by scientists that most (other) people are mostly interested in other people, and they are mostly not interested in anything else. The fact that scientists are more interested than average in things and ideas… marks them out as mentally very unusual." (Stewart & Nield, 2012)

where it's all broken down even more and I presume that's where the heat of the Earth is." While an anthropologic subsurface of shafts, tunnels and even buildings were readily imagined, the surrounding rock was labelled simply as 'dark' or 'hot'.

These results support the view that there is a cognitive dissonance with what lies beneath. As trained geologists, we see the subterranean world very differently from 'normal' people (Stewart & Nield, 2003). In exchanges between geoscientists, this is not a problem, but in dialogs with the public it becomes more problematic.



"…without resorting to simplification it is nearly impossible to communicate the implications of the scientific results to a broad audience." (Schneider, 2008)

Multiple Publics

By and large, when geoscientists confront the public we do so recognizing that there are very different stakeholders. Technical experts, industry professionals, regulators, elected civic officials, activists, concerned citizens, the media and everyone else represent multiple publics which require targeting with different communication messages. More problematic is the recognition that each of these stakeholder groups are themselves multiple publics, which not only display very different levels of scientific knowledge, but also show a diverse grasp of what science is and how it should be used. People's attitudes to scientific or technological issues and their underpinning values and beliefs explain why conflicting, and at times contradictory, views emerge from within the same stakeholder community.

"This business of meddling with nature, I don't like it at all."
Respondent quoted in Oltra et al., 2010

There is long, extensive academic literature about public attitudes to science and technology, but arguably one of the most succinct and pointed summaries lies in a recent CSIRO report (Cormick, 2014). This Australian survey follows previous studies in recognizing different science publics, each requiring different messaging strategies. For 40% of the sample population, science was a turn-off; not only was science largely unknown to them, but they were largely unknown to science. This disengaged camp lie beyond the reach of conventional science communication strategies; indeed, when asked who, if not scientists, they relied on to tell them about a scientific issue, this group cited friends, relatives and media commentators, without expecting these people to have any additional technical expertise; they simply trusted them.

The CSIRO survey also examined people's underlying values and beliefs as a gage of how they positioned themselves with respect to science. Four groups emerged: Group A, the 'science fans' (23%), expressed highest agreement that science is important to solving society's problems and least concern that it did more harm than good or advanced too fast; Group B, the 'cautiously keen' (28%), had a high interest in science but reservations on some aspects of it; the 'risk averse' group C, (23%) were conservative in their outlook, less inclined towards science and more concerned with its risks; and finally, Group D, 'concerned and disengaged' (20%) – the least enthusiastic about the benefits of science and technology and most suspicious of its motives.

Interviewee 2: Yeah. Well, fracture means break, doesn't it.
Interviewee 1: Absolutely.
Interviewee 2: You're breaking something.
Interviewees, Williams, 2013

The key point that emerges is that responses from the pro-science 'fans' were significantly different from the community responses from any other segment; i.e. those who see scientific knowledge and technology as the answer to societal challenges are a marginalized sector of the general population.

This is an uncomfortable recognition that underpins the key communication challenges highlighted in the study, which are:

- When information is complex, people make decisions based on their values and beliefs;
- People seek affirmation of their attitudes or beliefs and will reject any information or evidence that are counter to these;
- People most trust those whose values mirror their own;
- Attitudes not formed by logic or facts are not influenced by logical or factual arguments.

The Community Play

Public industry communication strategies are built around conveying clear, simple explanations of the technical detail surrounding a particular issue, because that is what they have been trained to do, and because technical know-how satisfies their own perspective on the problem. Relevant facts and figures, simple graphics and language uncluttered by jargon are brought together to address the wider public worries. It appears, however, that such an approach does little to influence the majority of the concerned public, who have made up their mind about the issue not on the basis of the facts but on the basis of their gut instinct, reinforced by consulting with those around them.

A 'community' is a heterogeneous group of competing stakeholder groups, of varying coherence, power and networks, amid a background of disparate political, economic, social and cultural interests. Critically, every community has a history – a 'social memory' accrued through past disturbances, interventions and opportunities that condition how the current community reacts.

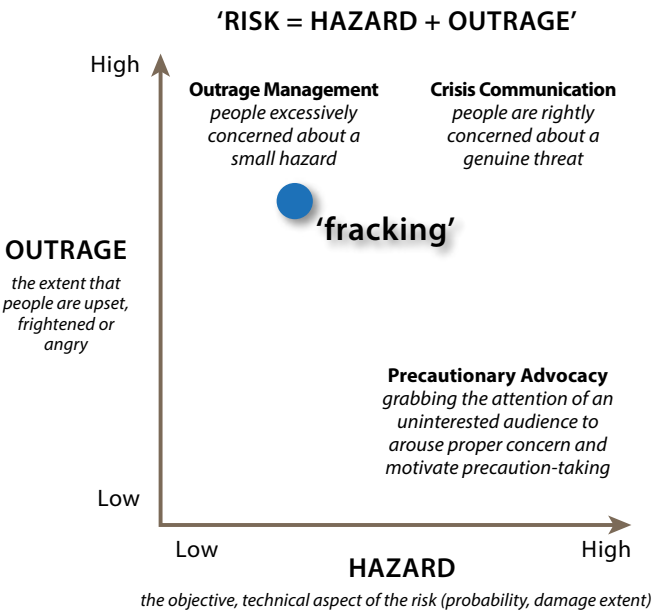
Environmental risks can be deconvolved into two competing public frames (Sandman, 1993). The first is technical, involving a scientific analysis of the hazards that are perceived to threaten a community. The second is social, focusing on the processes by which a community's concerns about hazard threats build into anxiety, then anger, and finally outrage. Sandman contended that when the experts and the public disagree about the technical side, the experts are more likely to be right. At the same time, the public's perceived risk is dismissed by technical experts as irrational, unfounded or manipulated. However, as evident from community protests, the resulting outrage is as real and measurable as the underlying hazard.

The public often misrepresent the hazard. The experts often misperceive the outrage. But the overarching problem is that the public cares too little about the hazard, and the experts care too little about the outrage. If people are outraged because they overestimate the hazard, the solution is to explain the hazard better.

In this context, risk is a product of hazard and outrage. Generally, the anxious public cares too little about resolving the hazard component and anxious experts care too little about resolving the outrage component. Sandman argues that technical experts – fixated by the hazard – tend to overestimate the risk when the hazard is high and the outrage is low, and underestimate the risk when the hazard is low and the outrage is high. The public are a mirror image, fixating on outrage and ignoring the technical hazard, overestimating the risk when the outrage is high and the hazard is low, and underestimating it when the other way round.

Effective Communication

For technical experts to engage more effectively with communities they are going to have to improve two fundamental skillsets. First, they must learn how to more simply convey the technical basis of their work, particularly the hazard, but this is only half of the community risk equation. The second, arguably much more tricky task, is to listen better – to hear first-hand the views of non-experts about their informal comprehension of the hazard in order to better appreciate the roots of community concern.



> *It's where they're drilling and it like vibrates the Earth and it caused earthquakes and somebody was saying "Yes it does, it's okay, it's manageable". That was recently. My instinct went, "Oh, what are you doing? You know, it's not right. It doesn't feel right."*
>
> **Interviewee, Williams, 2013**

The message that professional geoscientists ought to be responsive to the lay concerns of non-experts may irritate many, but confronting these concerns and gaging their significance as barriers to gaining the social license to operate allows us to design more effective strategies to convey aspects of the science that community members do consider most worrisome. In addition, more equitable dialogs with concerned citizens, acknowledging the legitimacy of their worries, brokers trust, builds goodwill and bonds shared values and beliefs. In other words, the very act of engagement with a community itself reduces outrage.

For those who prefer the long-standing view that the battle for community hearts and minds will be won by filling the knowledge gap in people's technical understanding, a key conclusion of the recent Australian study of public attitudes to science and technology is pertinent (Cormick, 2014):

"Public concerns about contentious science or technologies are almost never about the science… and scientific information therefore does little to influence those concerns."

A longer version of this article with references is available online: www.geoexpro.com/articles/2016/06/social-seismic-petroleum-and-the-public ■

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Clari-Fi™ Broadband Processed 2D Seismic in Portugal and the Mid-North Sea High

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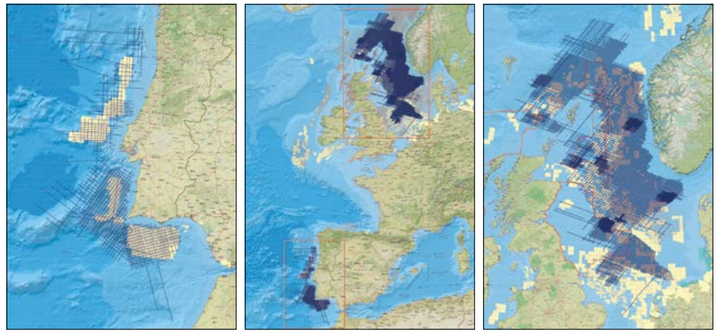
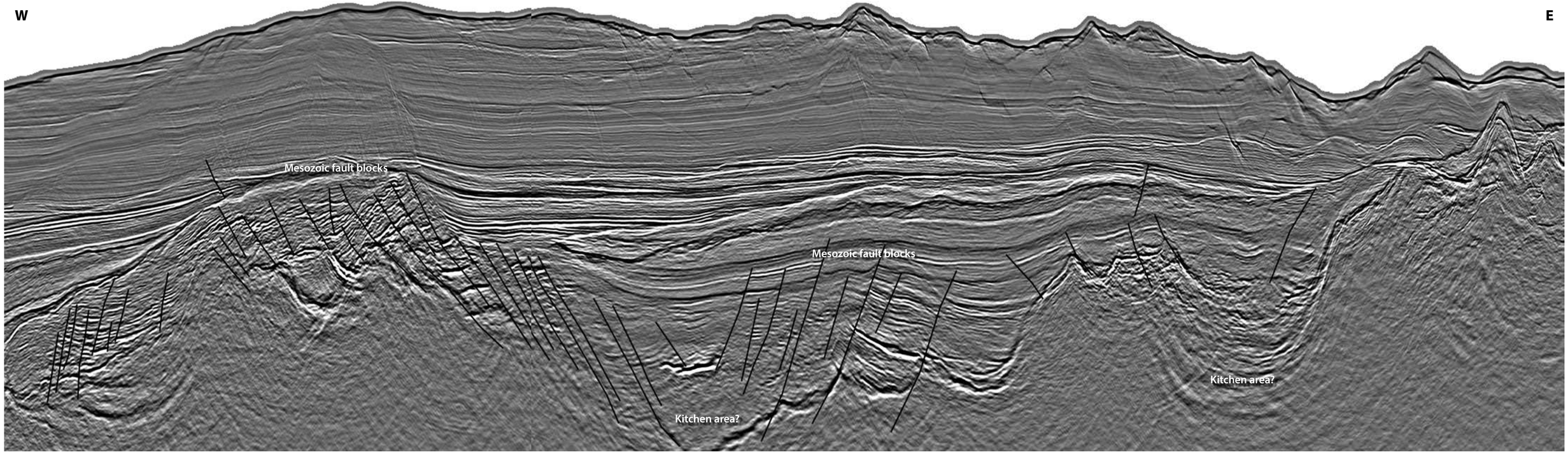
Recently, TGS delivered more than 120,000 km regional broadband data offshore Portugal and in the North Sea.



Clari-Fi broadband reprocessed east-west seismic section through expected bidding areas west of the Porto Basin offshore Portugal. Clari-Fi reprocessing reveals rotated Mesozoic fault blocks creating huge closures with sharp imaging of faults.



Clari-Fi™ Reveals Portuguese and North Sea Secrets

SINDRE JANSEN,
WILL BRADBURY and
BENT ERLEND KJØLHAMAR, TGS

North Sea Renaissance: Exploring the Mid-North Sea High

Offshore exploration in the North Sea dates back to 1964 when the UK Continental Shelf Act came into force. Several gas discoveries were made, but exploration interest quickly declined towards 1968 due to low gas prices and therefore little commercial value. In 1969, Phillips Petroleum discovered Ekofisk with 6.4 Bbo in place. This triggered a surge of discoveries which up until now has made the North Sea one of the most prolific oil provinces in the world.

Clari-Fi Broadband Reprocessing

During the exploration history of the North Sea, a huge variety of seismic surveys has been acquired. However, by early 2000 few datasets existed which had been shot using long-offset streamers for deeper imaging, and no regionally consistent dataset had been acquired. In 2003 TGS therefore decided to start acquiring a multi-year super-regional south-west to north-east/north-west to south-east grid using long-offset streamers. The project was named North Sea Renaissance (NSR). By end of 2013, this huge NSR multi-year project had resulted in a super-regional grid with ~100,000 km of long-offset 2D seismic covering the entire North Sea.

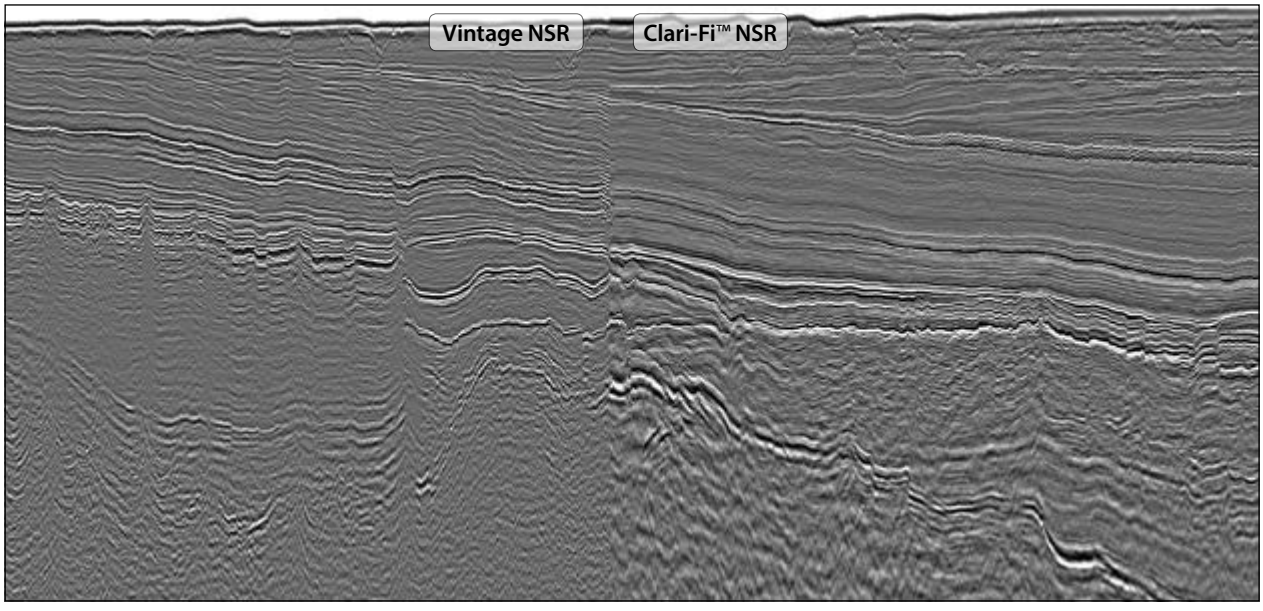
One of the main objectives while acquiring the NSR grid was to ensure a regionally consistent long-offset 2D dataset. This was partially ensured by maintaining consistency in the acquisition parameters for the different vintages. However, some variations between them occurred due to each vintage being separately processed as they were acquired, as well as variations in processing sequences as TGS processing technology advanced.

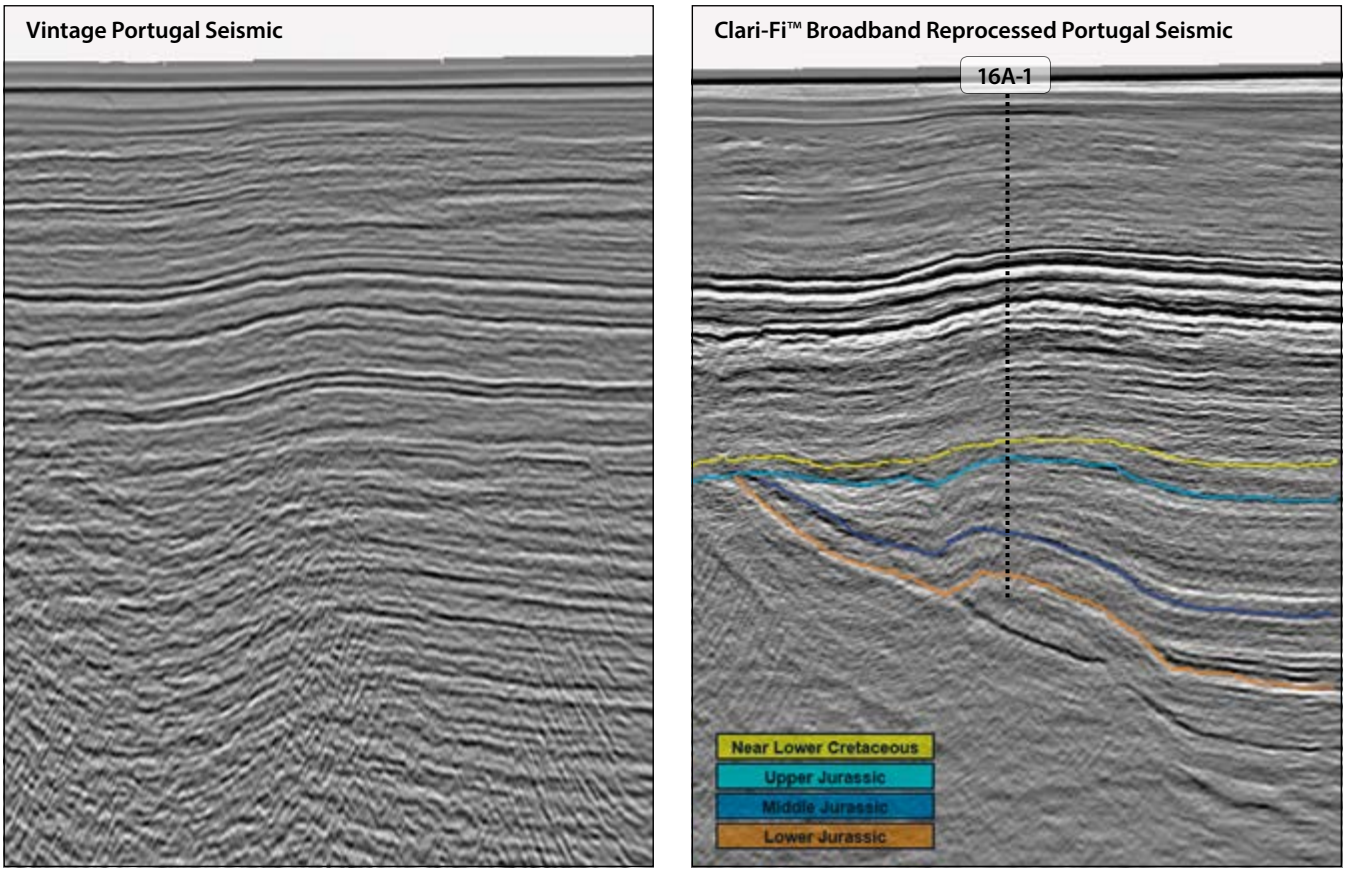
In 2014, TGS therefore decided to fully reprocess the entire long-offset NSR grid into one seamless matched and merged Clari-Fi broadband dataset, using the latest TGS processing technologies.

Preparing for the Next UK Licensing Rounds

Exploration through the last decade in the expected 29th round area has focussed on pre-Zechstein targets. Leads and prospects have suffered significant uncertainties due to the poor imaging of the vintage data available. The Clari-Fi broadband dataset allows better definition both regionally and at prospect level, significantly reducing key uncertainties within a wider regional structural and stratigraphic framework. Utilization of gravity and magnetic data during processing highlighted the areas in the 29th Round that required more focussed processing effort in order to provide better imaging of deeper basins and sub-basins. Further integration of seismic, gravity and magnetics will allow both previously identified and new leads in the older sections to be more confidently evaluated. ■

The figure shows an east-west Clari-Fi broadband reprocessed seismic section (right) versus NSR vintage (left) through the Mid-North Sea High. This area is included in the UK 29th licensing round.





An east-west Clari-Fi reprocessed seismic section (right) through well 16A-1 in the Lusitanian Basin highlights great differences in imaging compared to the vintage data (left). While the vintage data is ringing with multiples and few seismic horizons can be interpreted with confidence, the Clari-Fi reprocessed seismic clearly outlines the drilled 4-way dip closure, and enables detailed seismic interpretation of the structural and stratigraphic framework.

Portugal: New Clari-Fi Broadband Reprocessed Data Available

Initial offshore exploration in Portugal was restricted to shallow waters close to shore. In total 27 offshore wells were drilled from the mid-seventies up to up the early nineties with water depths ranging from <200m up to 540m. Most of the well locations were based on old vintage 2D data compromised by shallow high velocity carbonates causing strong multiples. Despite the uncertainties regarding the structural interpretation, six of the wells in the Lusitanian and Porto Basin yielded hydrocarbon shows, with two recovering oil on DST.

The northernmost well in the Porto Basin, Lula-1, is positioned at the break from a shallow carbonate platform into the deep waters in the west. Based on considerations that the oil shows in Lula-1 did not have the same footprint as the known source in the Porto Basin, indicating that this oil probably migrated from the west, TGS acquired a small seismic program into deep waters early in 2000. The results were encouraging and confirmed the presence of basins with thick sedimentary sequences and interesting structural features. In 2000–2002 TGS therefore acquired in total over 22,000 km of multiclient conventional 2D seismic offshore Portugal.

Conjugate Margin

Continental plate reconstruction at the Early Mesozoic era indicates that the north-western margin of Portugal was situated as a conjugate to the Jean D'Arc and Grand Banks Basins offshore Eastern Canada. These basins have experienced great success in recent years with several high impact oil discoveries. Most of these discoveries occur in huge rotated Triassic and Jurassic fault blocks associated with the opening of the Atlantic Ocean from the Late Triassic to the Early Cretaceous. As expected, great similarities can be observed on seismic lines along the north-west margin of Portugal, and similar play types are expected within the same interval.

Unlocking the Subsurface Potential

Huge variations in water depth (150–4,300m), extremely rough seabed, shallow carbonates, salt, and highly complex structures in the subsurface offered great challenges with respect to processing the TGS Portugal vintage data in 2000–2002. Recent TGS processing technology advances now significantly reduce the uncertainties in the structural and stratigraphic interpretation. Steeply dipping events have been preserved in the data through pre-stack time migration and very little post-stack scaling. This is especially important in order to get the necessary structural control of the prospective pre/syn rift Mesozoic basins with huge rotated fault blocks as shown in the foldout seismic line.

Observations on the new Clari-Fi reprocessed dataset show that this dataset will be key in the process of tying-in existing well information with seismic interpretation to unlock the great future hydrocarbon potential offshore Portugal. ■

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Suriname
New Technology Unlocks Hydrocarbon Potential

An improved knowledge of fault systems is important in understanding Suriname's onshore oil fields – and the application of FTG data can be a vital tool in unlocking this knowledge.

CLYDE GRIFFITH, RALPH KARIODIMEDJO and MOHAMED CHANDOE, Staatsolie
CHRISTIAN RICHARDS, PAUL VERSNEL and BEN SPURGEON, AustinBridgeporth

Suriname is part of the Guiana Shield, which stretches between the Orinoco and the Amazon rivers and includes eastern Venezuela, Guyana, Suriname, French Guiana, and northern Brazil. Geologically, the onshore Surinamese territory is divided into exposed crystalline basement, principally igneous and metamorphic rocks (80%) and the coastal plain (20%), where the crystalline basement is covered by Upper Cretaceous to Holocene sediments, although only Pliocene to Holocene sediments can be found at the surface (Figure 1). The coastal plain is part of the larger Suriname-Guyana Sedimentary Basin, which encompasses the coastal area of French Guiana, Suriname and Guyana. Most of the basin lies offshore, where the sediment section becomes thicker as the basin deepens.

Three oilfields are present in the onshore area of Suriname, namely Tambaredjo, Calcutta and Tambaredjo Northwest. They produce from Paleocene, Eocene and Miocene reservoirs, which were deposited in a continental to shallow marine setting. The Tambaredjo oilfield has been in production since 1982. Close to 115 MMbo have been produced from these three oilfields with a remaining reserve of more than 87 MMbo. The current production from them is about 17,000 bopd.

Onshore Stratigraphy

The sediments of the Suriname part of the Suriname-Guyana Basin are part of the Corantijn Group. Based on age data collected to date, the onshore sedimentary column comprises mainly clastic sediments from probably the Upper Cretaceous to the Holocene.

The regional dip and thickness of the total onshore sedimentary column is governed by the topography of the Precambrian basement. The Calcutta Uplift, located more or less in the center of the Suriname part of the basin, has had an effect on the sedimentary thickness and stratigraphy. The sediment package thickens east to west away from the Calcutta Uplift (see Figure 3), with the thinnest sedimentary column on the Uplift itself. In a north-south direction the sedimentary column thickens northwards (see Figure 2).

The Cretaceous section consists of continental deposits with evidence of several cycles of exposure to erosion. The Tertiary section, by comparison, comprises coastal to shallow marine deposits, while Quaternary sediments are mainly composed of sand and shales with minor shell sand. The presence of hydrocarbons in the onshore are from Saramacca (Paleocene) to Coesewijne (Miocene) sands. The sedimentary

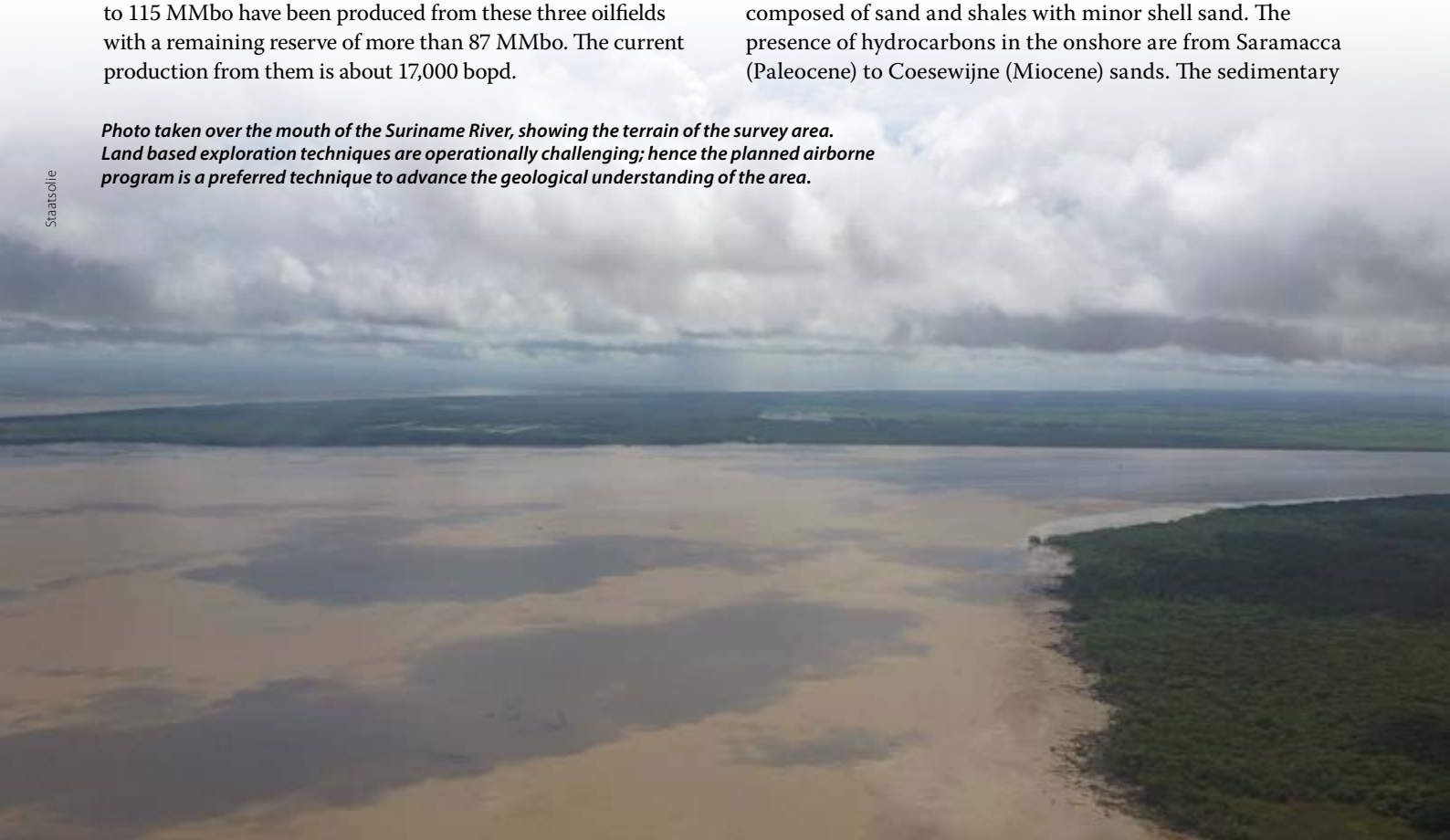


Photo taken over the mouth of the Suriname River, showing the terrain of the survey area. Land based exploration techniques are operationally challenging; hence the planned airborne program is a preferred technique to advance the geological understanding of the area.

Staatsolie

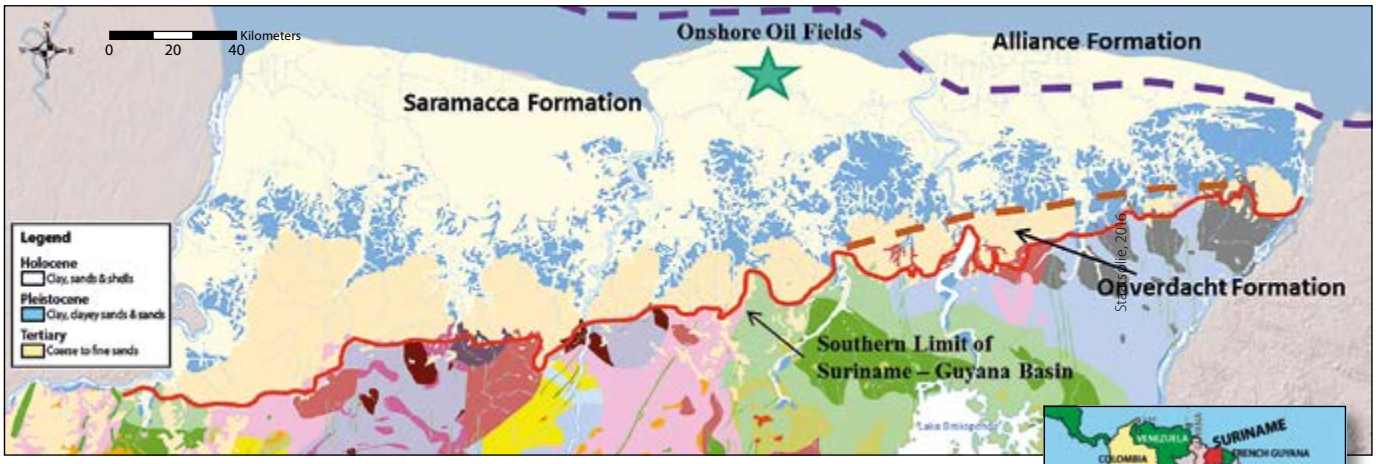


Figure 1: The coastal plain of Suriname.

facies of the Paleocene section changes laterally and is divided into the Saramacca, Alliance and Onverdacht Formation.

Structure and Plays

The total onshore sedimentary section was deposited during the Passive Margin Phase in the Late Cretaceous to Recent. The structure in the onshore area is dominated by basement-rooted faults, as can be observed on seismic data. Only minor tectonic activities occurred in this period along the margins of the Guiana Shield, including eastward movement of the Caribbean Plate in the Tertiary and the Miocene Andes Orogeny. Most of the faults in the onshore area terminate in the Eocene Upper Saramacca Formation, with some in the Miocene Coesewijne Formation. 2D seismic data has been acquired in all onshore blocks and the Tambaredjo Block is also covered with 3D seismic data.

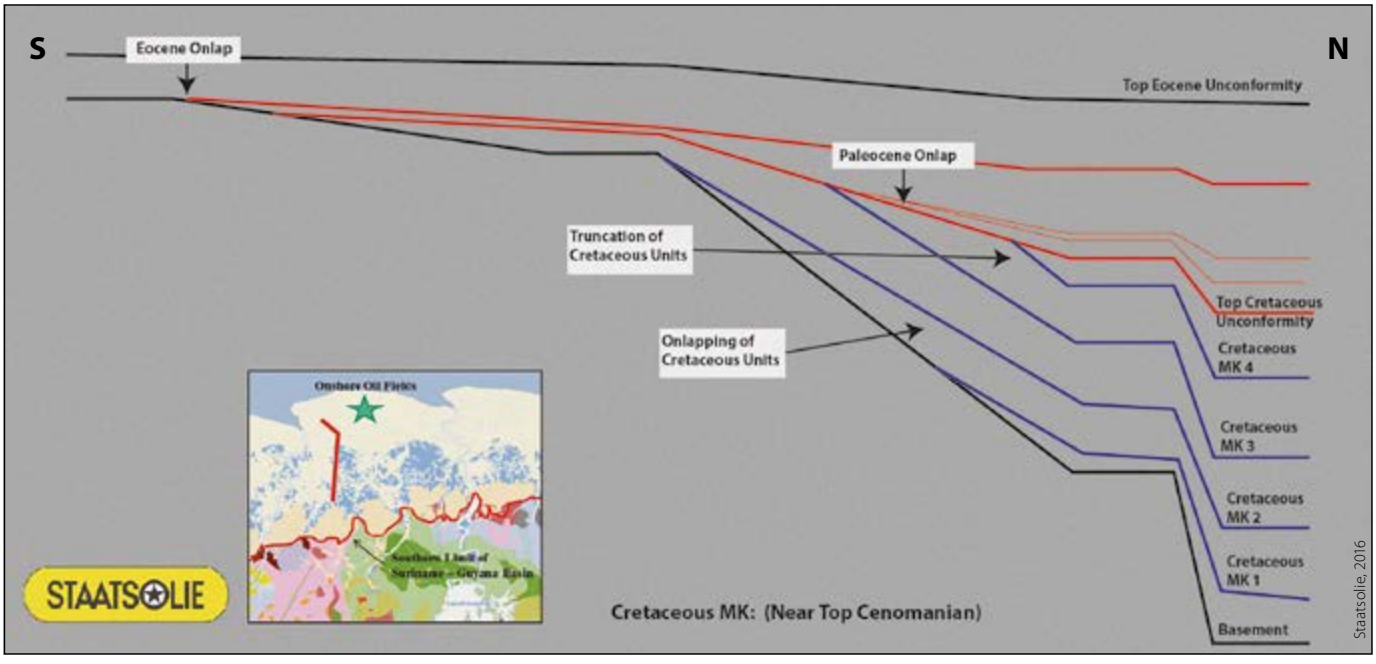
Based on interpretation of the 3D seismic data over the Tambaredjo oilfield, two major fault systems can be seen impacting the hydrocarbon entrapment, namely the east–west Tambaredjo Fault and the north-east to south-west Broederschap Fault. A major north-east to south-west fault system in the Weg naar Zee Block in the central coastal area also created traps for hydrocarbon accumulations. The majority of the faults mapped in the onshore to date follow these orientations, and most can be categorized as strike-slip type.

Structuration has had a high impact on oil migration and entrapment, and an improved understanding of the architecture of faults may give explorers a better understanding of the exploration risks in certain areas – which is where FTG data comes in.

What is FTG Technology?

Onshore Suriname is a very high cost environment in which to acquire seismic. Integration of the sparse 2D seismic with potential field (magnetic and gravity) data defines some

Figure 2: South–north stratigraphic cross-section.



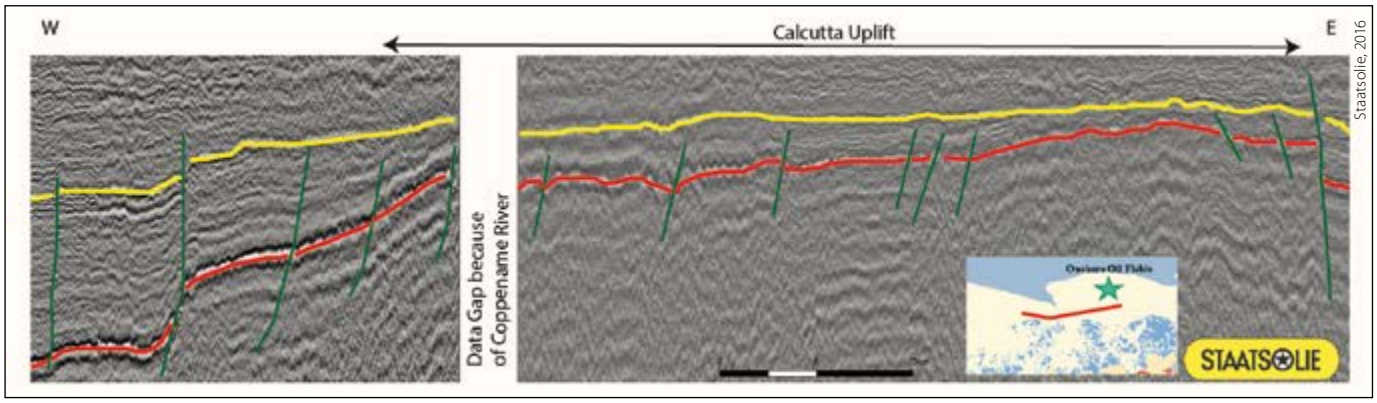


Figure 3: West–east 2D seismic cross-section with the fault-bounded Calcutta Uplift.

structural elements. The magnetic lineaments (Figure 5) correspond to faults in many cases and thus contribute to the understanding of the geological model of the area. Potential field data offers the opportunity to extrapolate and interpolate the fault system between sparse seismic data.

It is believed that the remaining potential of the onshore area is linked to fault-bounded plays. Even with the available 2D regional seismic data, together with aeromagnetic data, all faults could not be mapped with high accuracy. In order to improve accuracy and confidence of fault mapping and further de-risk prospects and/or leads, Full Tensor Gravity Gradiometry (FTG) data will be acquired and integrated with the existing 2D seismic and aeromagnetic data.

The Lockheed Martin FTG system was originally conceived as a US Navy sensing instrument, but the technology was declassified in the mid-90s and made available for commercial exploration use. The FTG instrument design differs somewhat from conventional (i.e. scalar) gravimeters, which measure the bulk downward pull of the Earth's gravity, whereas FTG instruments measure the gravity gradients between multiple sensors in all three orthogonal directions, thereby fully describing the gravity field at the measurement point. This allows the user to measure how the gravity field varies in all directions at a much higher resolution, all from a moving platform. In practice, multi-directional gravity gradients are useful to an interpreter as they can yield extra information on the orientation of structural grain and faulting.

Airborne data can be acquired rapidly over large areas that are difficult to access from the ground and provide a data-rich map that can de-risk future exploration. Historically, FTG data have been used in a variety of geological settings to aid with mapping basin architecture, basement depth, faults, and intra-sedimentary structure. Where young sediments are juxtaposed against crystalline basement, the often large density contrast associated with such a configuration suggests that the gravity technique is the appropriate geophysical

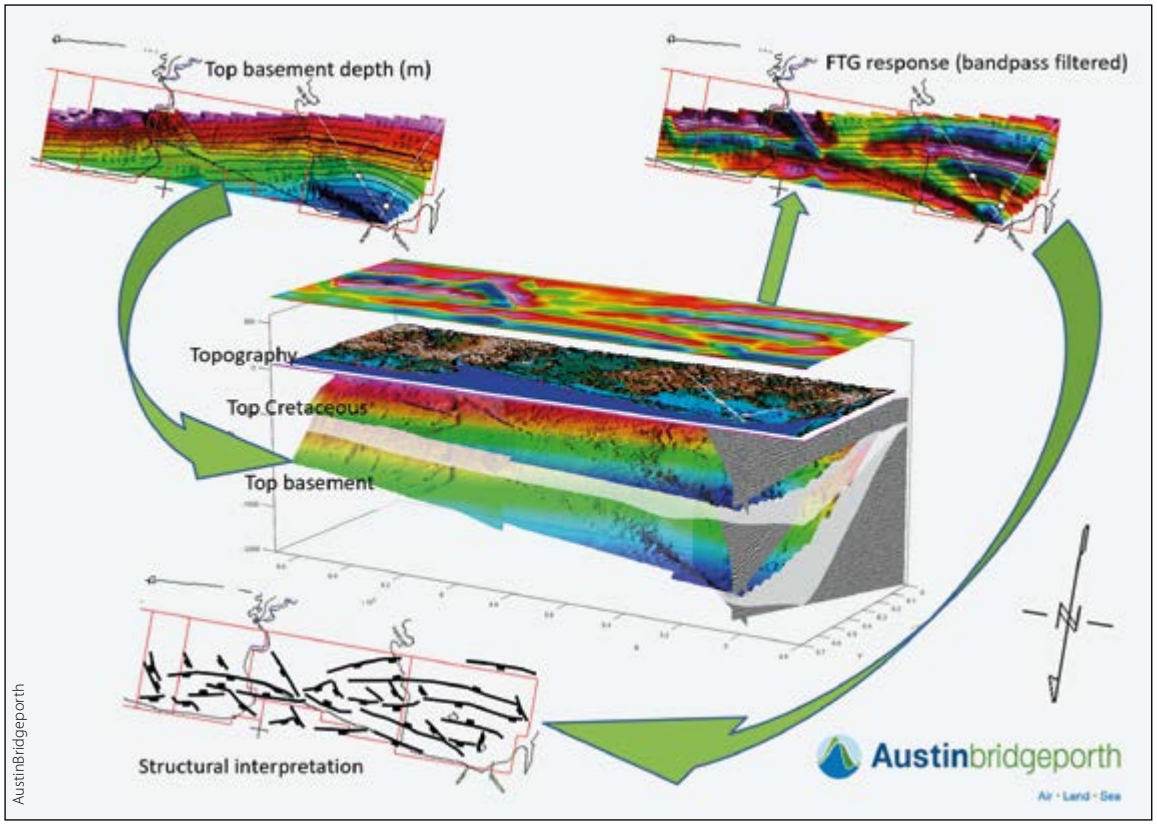


Figure 4: The center image shows the stacked horizons used to build a representative 3D geological model. The filtered FTG response is also shown (top-right image) which is then interpreted to produce a structure and faults map (bottom-left image).

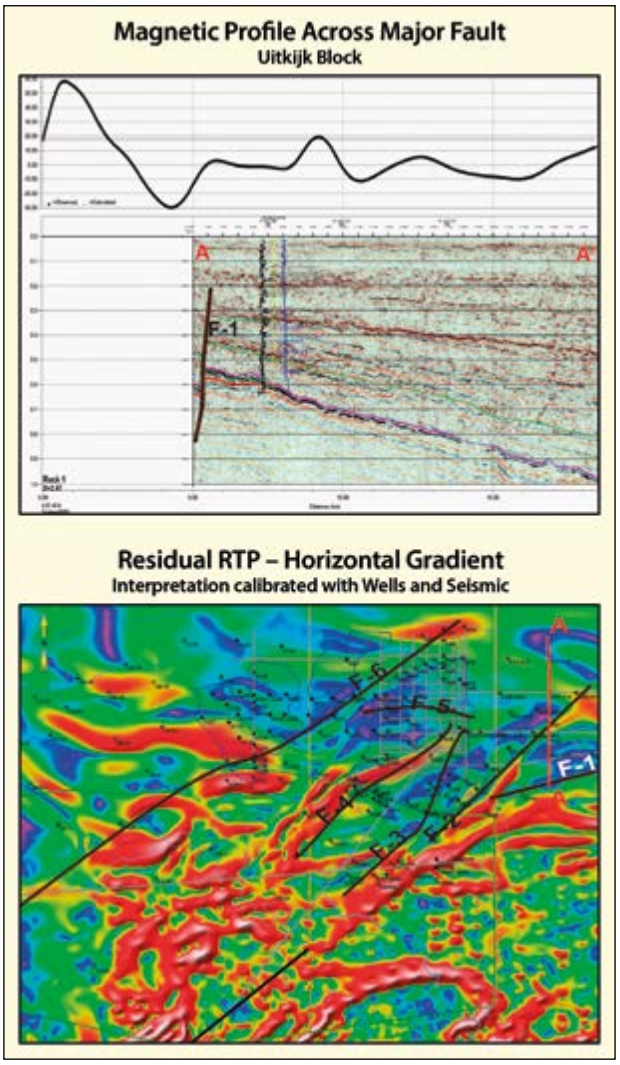


Figure 5: Incorporation of residual RTP – horizontal gradient vs. seismic section. Fault F1 has an offset of 80–90m as can be seen on the seismic section. The map on the bottom shows this fault to have a west-south-west to east-north-east orientation. Other faults can also be depicted on the residual RTP – horizontal gradient.

technology to use. The successful and much publicized application of FTG in the rift valley system in East Africa is a good example of this. Onshore Suriname presents a similar geophysical model in the sense that younger sediments overly old crystalline (and thus denser) basement. Therefore, in areas such as onshore Suriname where 2D seismic data are sparse, FTG data can be integrated to link structure and map faults between the seismic lines.

FTG Feasibility Modeling

In order to demonstrate the applicability of FTG data to onshore Suriname, AustinBridgeporth conducted a feasibility study over part of the coastal region to test the expected FTG response to a geological model. The initial stage in the workflow was the construction of a representative 3D geological model with densities assigned to the key lithological units. The expected FTG response was forward calculated and typical instrumentation noise was added to the calculated FTG response to simulate realistic survey conditions before the final filtered grids were analyzed.

Figure 4 shows the top basement, top Cretaceous and topography horizons used to build the 3D model and compute the associated FTG response, which was then bandpass filtered. The FTG color-scale depicts cooler colors as gravity lows and warmer colors as gravity highs. Wavelength filters can be applied to the broadband FTG data to focus on deeper or shallower geological structures. In this case, longer wavelength signal is analyzed to yield information on the deeper broad trend of sediment thinning from north to south. Shorter wavelength signal is analyzed to reveal intra-sedimentary structure and faults both at basement level and within the overlying sediments. Interpretation of the FTG response then illustrates how a structure and fault map can be derived.

Based on the representative model, the feasibility study demonstrates the technical applicability of airborne FTG to map sediment thickness and faulting in the study area. An improved knowledge of the fault systems will deliver insight into the potential prospectivity of onshore Suriname and help drive further focused exploration.

For further information on the geology and potential of Suriname, see GEO ExPro Vol. 10, No. 4. ■

Codes and Ciphers

Decoding Nature's Disorder PART I

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Column Editors:
LASSE AMUNDSEN and MARTIN LANDRØ

Information is the resolution of uncertainty.

Claude Shannon

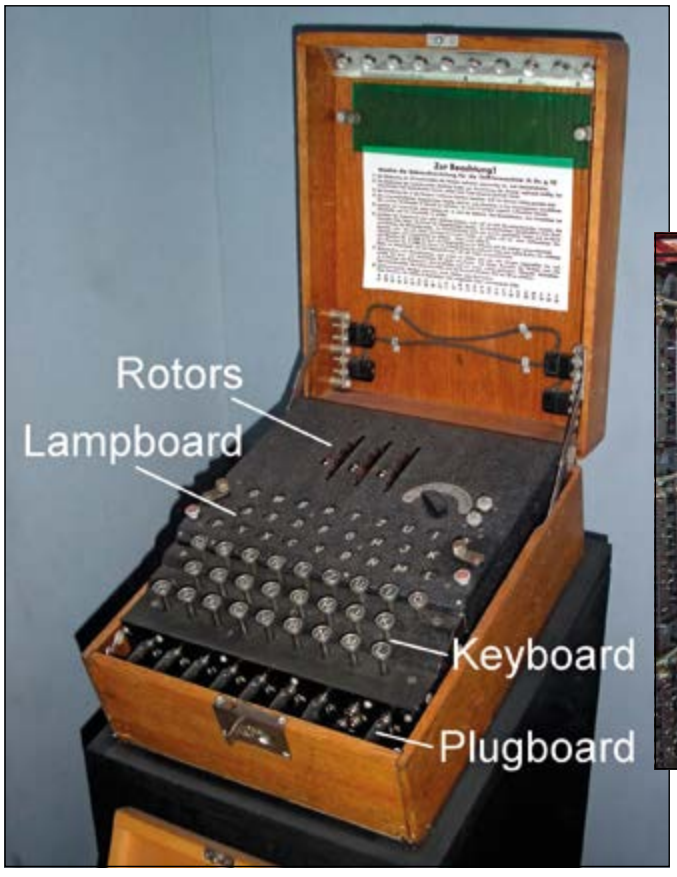
Talk clearly and not so far-fetched as a cipher.

Medieval – origin unknown

In many languages the word 'cipher' means 'number'. However, the current meaning of 'cipher' in English – an 'algorithm for performing encryption or decryption' – can be traced back to the time when it meant 'zero' and the concept of 'zero' was new and confusing.

In the military barracks of Bletchley Park in Buckinghamshire, UK, one of the world's first computers (the so-called 'Bombe') was constructed for the single purpose of cracking military codes generated by the German Enigma encryption machine. Combining three rotors from a set of five, each rotor setting having 26 positions, and a plug board with ten pairs of letters connected, the Enigma machine had 158,962,555,217,826,360,000 (nearly 159 quintillion) different settings. Even a very fast modern computer could not systematically go through all those settings. The British had access to an Enigma machine but did not know the settings, which varied daily. A team of highly talented people working with the brilliant mathematician Alan Turing managed to crack the German codes in an ingenious way that involved realizing that the Germans would always start their encrypted radio transmissions with a weather report. This observation combined with groundbreaking advances in statistics allowed Turing and his team to limit the possibilities and guide the 'Bombe'. The story of Alan Turing is as fascinating as it is tragic; only recently has the true nature of his genius and his impact on the 20th century been recognized. Breaking the Enigma code is believed to have shortened WWII by two to four years and saved millions of lives.

The goals for encrypting or encoding messages and signals have been and always will be as varied as they are interesting: from communicating securely with the front-line in war time, to increasing the communication capacity in cellular phone networks. A 'bit' of information represents the resolution of



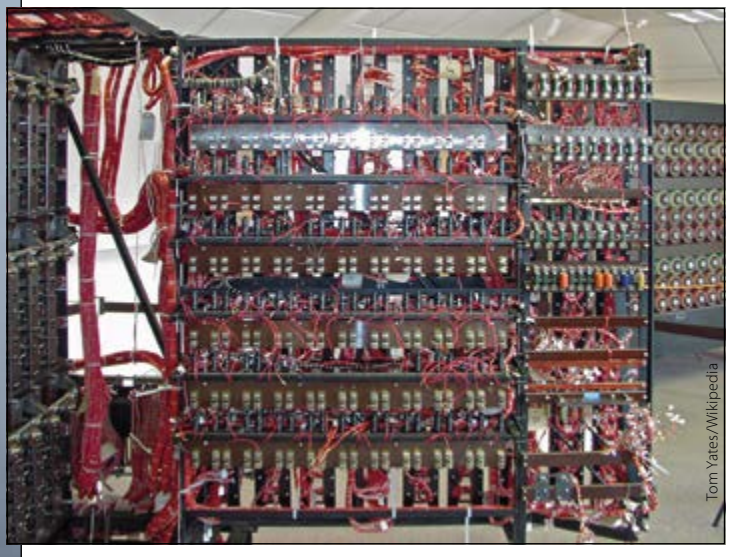


Figure 1: Military Enigma Machine. The three (of five) rotors with 26 positions each are clearly indicated. (Inset) Replica of the 'Bombe' decoding machine built by Turing at Bletchley Park during WWII.

uncertainty between two distinct states/symbols. N bits of information resolve or distinguish between 2^N different states or symbols.

In 1948, Claude Shannon calculated that the maximum amount of information that can be reliably communicated between a single source and receiver is given by the formula:

$$I = \log_2\left(1 + \frac{S}{N}\right) \text{ bits s}^{-1}\text{Hz}^{-1}$$

where S is the received signal power, N is the noise power, and information is measured in bits per second per Hertz of bandwidth available for transmission (Shannon, 1948; Simon, 2001). Note that Shannon's equation is a statement about the *channel* through/over which the information is communicated. It does not say anything about the source that is producing the signals or messages. The average information produced by a source is called the *entropy* of the source and is also measured in bits. For a source producing n discrete symbols with probability p_n, the entropy is computed as:

$$H = -\sum_{i=1}^{n} p_n log_2(p_n)$$

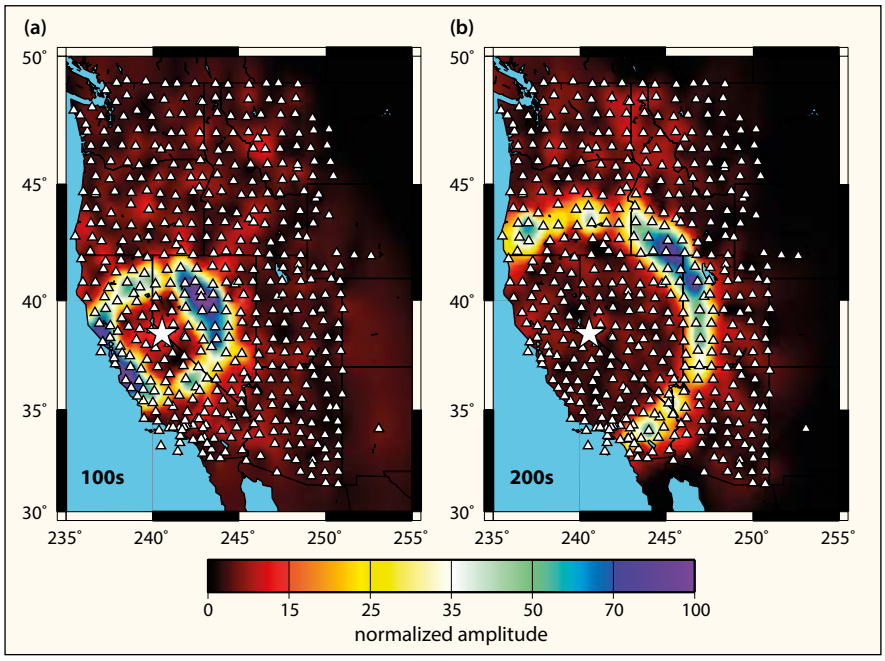


Figure 2: Snapshots of the normalized amplitude of the ambient noise cross-correlation wavefield with TA station R06C (star) in common at the centre. Each of the 15–30s band-passed cross-correlations is first normalized by the rms of the trailing noise and fitted with an envelope function in the time domain. The resulting normalized envelope function amplitudes are then interpolated spatially. Two instants in time are shown, illustrating clear move-out and the unequal azimuthal distribution of amplitude. (Reproduced from Lin et al., 2009, with permission from Profs. Lin and Snieder.)

The concept of a measure of the average information content produced by a source is extremely important and parallels concepts such as *structure* or *sparseness*, which we will briefly get back to in the next instalment. We will now look at what limited hopes we have when encoding signals if we ignore or do not know the statistics of the signals produced by the source.

Encoding, Decoding and the Welch Bound

Often one does not have access to the source signals per se (i.e., one cannot encode them), but it is the structure in the source signals, together with a multiplicity of measurements, that enables the decoding or separation. In many other cases, however, one does have access to the source signals and the question arises as to whether one can do better when encoding the source signals and if one can do away with the requirement of multiple measurements. One strategy could be to encode the source signals with a unique time-series, each of which has both low autocorrelation (apart from the central peak) as well as mutual cross-correlation properties. The individual source wavefields can then be obtained from the encoded simultaneous-source signal simply by cross-correlating the recorded data with the respective encoding sequence. In 1974, L. R. Welch derived a lower bound on the maximum cross-correlation of signals. This bound shows that, as one might expect, the maximum cross-correlation and off-peak autocorrelation values of a set of sequences cannot be arbitrarily low.

Consider a set of M general, complex-valued sequences $\{a_n\}, \{b_n\}... \{m_n\}$ of length N, the discrete aperiodic/nonperiodic correlation function between a pair of sequences is defined as:

$$C_{a,b}(\tau) = \begin{cases} \sum_{n=0}^{N-1-\tau} \hat{a}_n \left[\hat{b}_{n+\tau}\right]^*, & 0 \le \tau \le N-1 \\ \sum_{n=0}^{N-1-\tau} \hat{a}_{n-\tau} \hat{b}_n^*, & 1-N \le \tau < 0 \\ 0 & |\tau| \ge N \end{cases}$$

When a=b, this equation also defines the discrete aperiodic autocorrelation function. Let C_{am} denote the maximum out-of-phase (i.e. off-peak) autocorrelation value and C_{cm} denote the maximum cross-correlation value. Then the Welch bound is derived as follows (Welch, 1974):

$$\frac{C_{max}^2}{N} = \frac{max\{C_{cm}^2, C_{am}^2\}}{N} \ge \frac{N(M-1)}{2NM - M - 1}$$

The Welch bound is a very useful result since it tells us, given the number of sequences in the set (M) and the length of the sequences (N), how low the maximum cross-correlation and off-peak autocorrelation values can be. Sequence sets which achieve the Welch lower bound exactly are known as Welch bound equality sets, the best-known of which is the Kasami sequence set.

Nature's Way of Encoding

It turns out that random noise can be an extremely effective natural encoder. While earthquakes are recorded only intermittently, a seismic background noise wavefield is present and being continuously recorded. Usually, the exact origins of this wavefield are unknown. One source can be attributed to atmospheric pressure variations, which induce water waves that convert into low-frequency microseisms (faint earth tremors caused by natural phenomena) when crashing onto the shore. Despite the relatively low amplitude level, the

continuous and random nature of such a background wavefield makes it possible to correlate it between receiver stations.

Although the existence of these noise bands have been known for more than half a century, it was only in the early 2000s that seismologists realized that, by cross-correlating such noise wavefields at different receiver stations, a wealth of information about the structure in between the correlated receivers can be extracted in the form of the inter-receiver Green's function. This process of cross-correlating (noise) data recorded at different receivers is now known as interferometry and can also be thought of as turning one of the receivers into a virtual source (Figure 2). As noise data from any pair of receivers can be cross-correlated, the number of virtual sources and receivers that can be created using this method is proportional to the square of the number of receivers. It turns out that such inter-receiver Green's functions constitute ideal datasets for high-resolution surface wave tomography in regions where there is ample background noise and many receivers but few earthquakes. Thus, nature had conveniently encoded the information for us, but it took us some time to understand how to decode it! A similar strategy for interferometric modeling of Green's functions between a large number of points in the interior of a model has been proposed by van Manen et al. (2005). In that case, however, when the data does not come for free the Welch bound predicts that the quality of the data after separation of the simultaneous simulation is proportional to the square root of the simulation time (Figure 3).

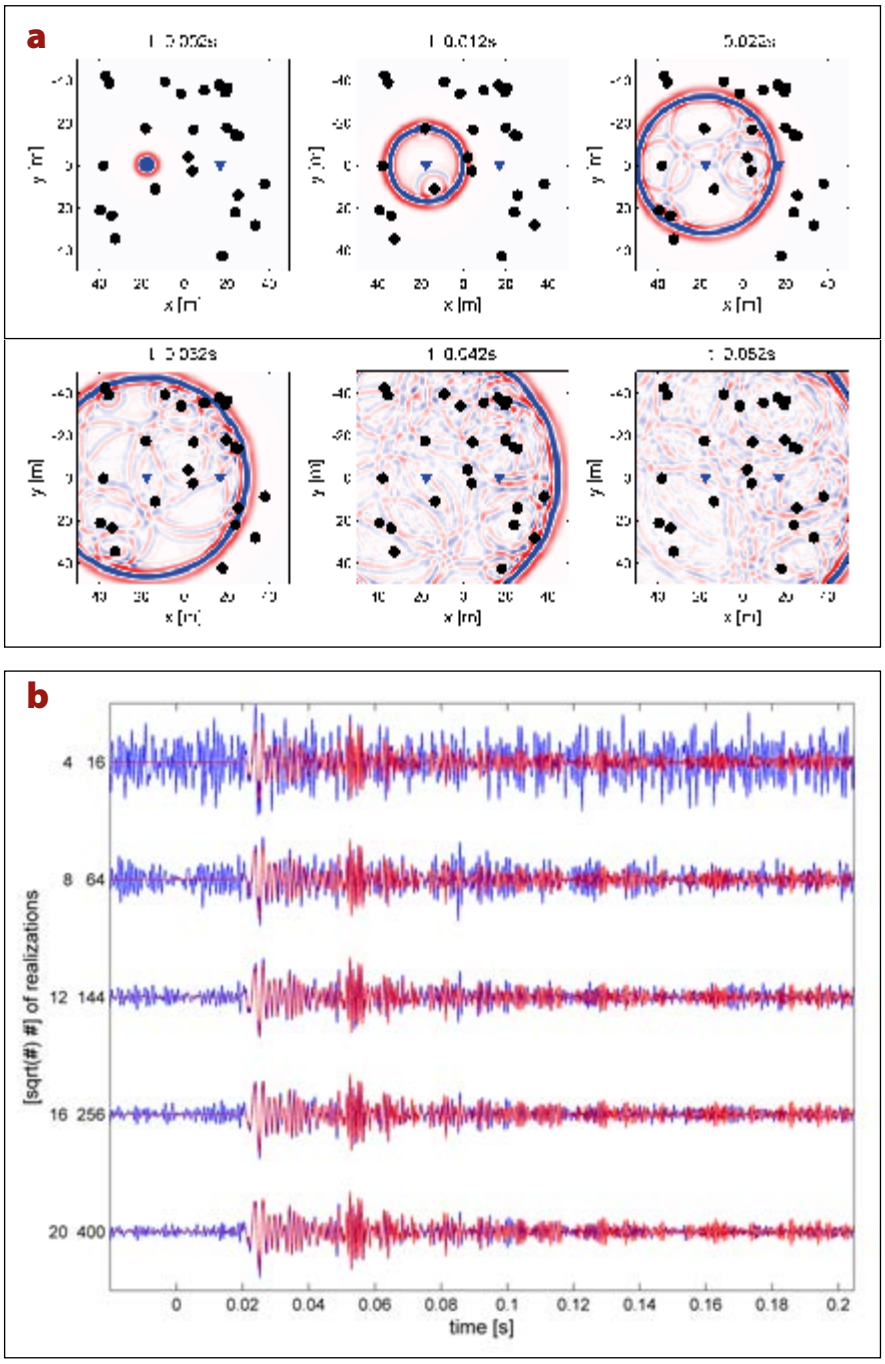


Figure 3: (a) Snapshots of the multiply-scattered reference wavefield when placing a source in one of the receiver positions (blue triangles). (b) Retrieved Green's function (blue) obtained by cross-correlating and stacking an increasing number of 65,536 sample segments of noise-encoded wavefields recorded at the receiver locations versus the reference waveform (red). As expected from Welch's bound, the quality of the decoding improves as the square-root of the number of segments stacked (or the total length of the simulation).

Multiple Scattering: Friend or Foe?

Multiple scattering adds significant complexity to the Green's functions (impulse responses). Therefore, if one considers every impulse response to be a realization from one or more stochastic information sources, one could say that the multiple scattering significantly increases the entropy of the information sources. Another way to say this is that the number of degrees of freedom in the source signals increases dramatically if we know that the signals do not only consist of, e.g., primary reflections. Fortunately, in the interferometric applications, we do not have to worry about this additional complexity when reconstructing the virtual source responses in ambient noise surface wave interferometry or when encoding Green's functions between points in the interior, since interferometry intrinsically reconstructs the full Green's function.

It is also interesting to consider the role of multiple scattering when it is present in the medium through which one wants to communicate, i.e. when the multiple scattering is part of the communication channel and not the source signals. Until the late 1990s, the reigning paradigm was that multiple scattering hinders communication and lowers the maximum rate of communication, rather as the noise term in Shannon's equation lowers the information capacity. It

turns out that the opposite is true. A first clue came in the classic paper by Derode and co-workers from 1995, who demonstrated that it is possible to time-reverse a high-order multiply-scattered wavefield through the actual scattering medium, to achieve super-resolution focusing at the original source location. The multiple scattering effectively enlarged the aperture of the linear array of transducers such that focusing well below the free-space diffraction limit was achieved. Around the same time, a researcher at Bell Labs named Gerry Foschini realized that the multitude of paths in a scattering medium actually help to increase the rate at which information can be transferred. Conceptually this can be thought of as sending different messages over the different multiple scattering paths (Figure 4) (Simon et al., 2001). What is more, the encoding and decoding algorithm that Foschini proposed, which realizes the higher rates of communication, does not require knowledge of the details of the scattering environment. When keeping the total transmitted power constant, but using MT transmitters and MR receivers, it turns out the channel capacity can be roughly MT as large.

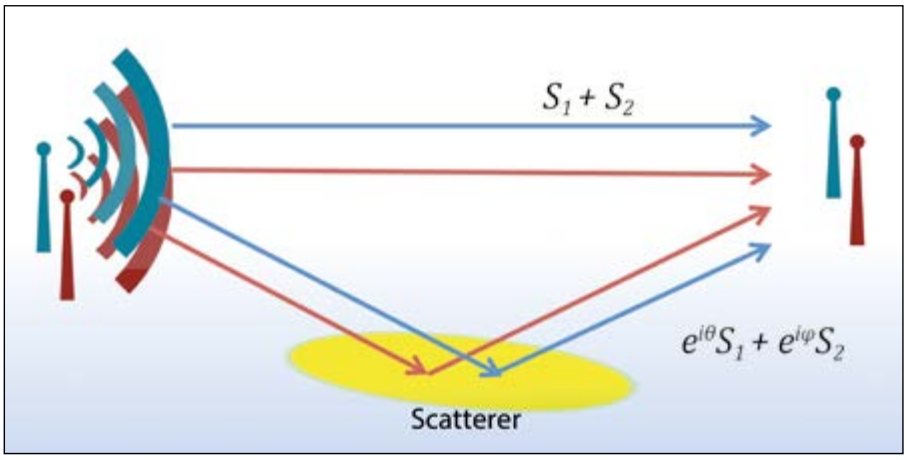


Figure 4: Scattering can enhance communication. In the absence of the scatterer, a single linear combination of the blue and the red signals is measured. The scatterer causes a second, different linear combination of the blue and the red signals to be measured. With the antennas displaced slightly, it becomes possible to separate the signals using an inverting linear transformation and increase the transmission rate. Modified from Simon et al. (2001).

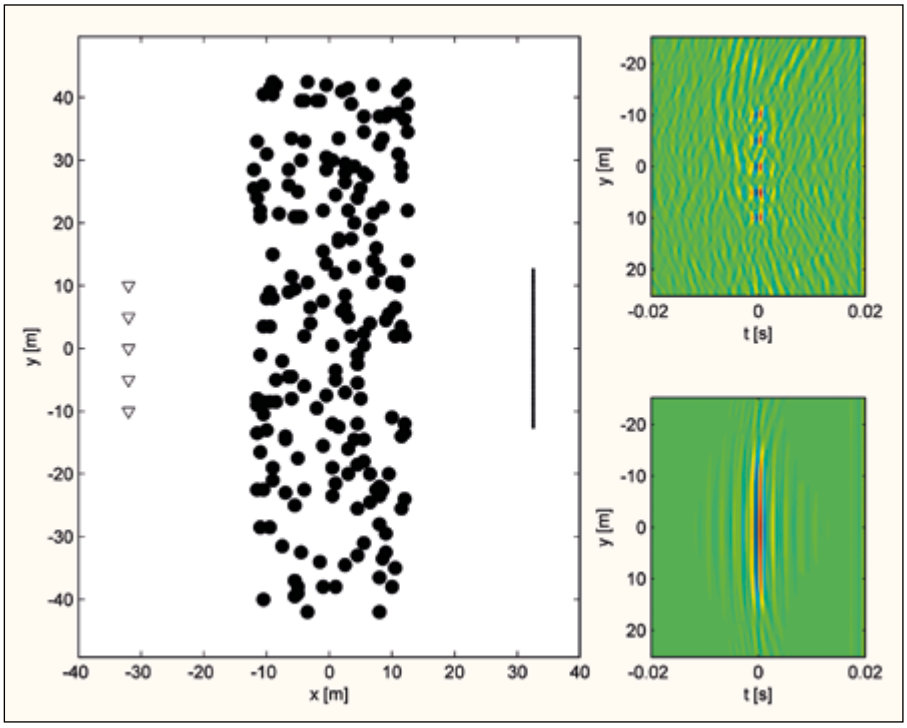
These developments come full-circle in a more recent contribution by Derode et al. (2003), which shows how to exploit multiple scattering when communicating with time-reversal antennas. Taking advantage of the super-resolution enabled by acoustic time-reversal, they can transmit random bit series to receivers that are only a few wavelengths apart. In contrast, in a homogeneous medium, the communication breaks down completely as individual bit series are no longer resolved (Figure 5). The transfer rate is directly proportional to the number of eigenvalues of the time-reversal operator at a given frequency and increases with increasing multiple scattering.

Thus, to answer the question posed above: if you are trying to recover the multiply-scattered wavefield between two arbitrary receivers, and you are measuring in the presence of a strong and somewhat uniform ambient noise field, chances are that nature has already encoded the desired wavefield for you and all you will have to do is measure the ambient noise field for long enough at the receivers, and decode it using interferometry (cross-correlation), implicitly making use of Welch's bound. Similarly, if you want to communicate through a high order multiple scattering medium, the multiple scattering can actually help you achieve higher transfer rates. Thus, in both these cases, multiple scattering is more a friend than a foe.

In the second part of this article, we will consider the case where we are not interested in an interferometric construction of seismic data but rather want to decode the original sources, including their multiply-scattered waves, directly as we consider the marine simultaneous source separation problem. As we will see, geophysicists have a few more tricks they can bring to bear on the seismic encoding and decoding problem.

References available online. ■

Figure 5: (Left): Experimental time-reversal setup (plan view) consisting of a forest of steel rods. Initially, a source is placed at the location of each receiver (at x=-30m) and the impulse response recorded on a 23-element array of transducers (at x=30m). (Right): The scattered signals are time-reversed and used to encode a bit stream. Through a multiple-scattering medium (top) five short pulses very well focused on each receiver can be observed. Through water (bottom), the pulses overlap, indicating a strong cross talk between the receivers. After Derode et al. (2003).



Marine Seismic Data: Faster, Better, Cheaper?

New ideas in acquisition and processing have finally realized the full potential of broadband data.

ED HAGER, Polarcus

Traditional towed streamer marine seismic acquisition has been stuck with the same old geometries for many years: two sources at the head of multiple streamers. The only real improvements have been the adoption of broadband to increase resolution and a steady rise in the number of streamers to improve operational efficiency. By utilizing developments in processing we can not only build on the efficiencies that multiple streamers give us, but also finally realize the full potential of broadband data.

Innovation Through Necessity

When Polarcus undertook the Capreolus multiclient project on the North West Shelf of Western Australia, the area was sufficiently big to potentially require two conflicting survey designs to accommodate the different play types – one high-fold for the shallow water area and the other conventional fold with a long time record for the deepwater area. A real bonus in both cases would be to have imaging to the basement. Traditionally, the choice has been rather stark: compromise both from the desired outcome, or place a boundary somewhere between survey types with little geological input as this is a frontier basin.

The solution proposed was to acquire data with overlapping shots, a concept that has been brewing within the industry for many years and was proved to work by the principal pre-funder of the Capreolus survey, Quadrant Energy (formerly Apache Energy), over a series of surveys acquired by them since 2011. Encouraged by this company, Polarcus decided to actively investigate this option with DownUnder GeoSolutions (DUG).

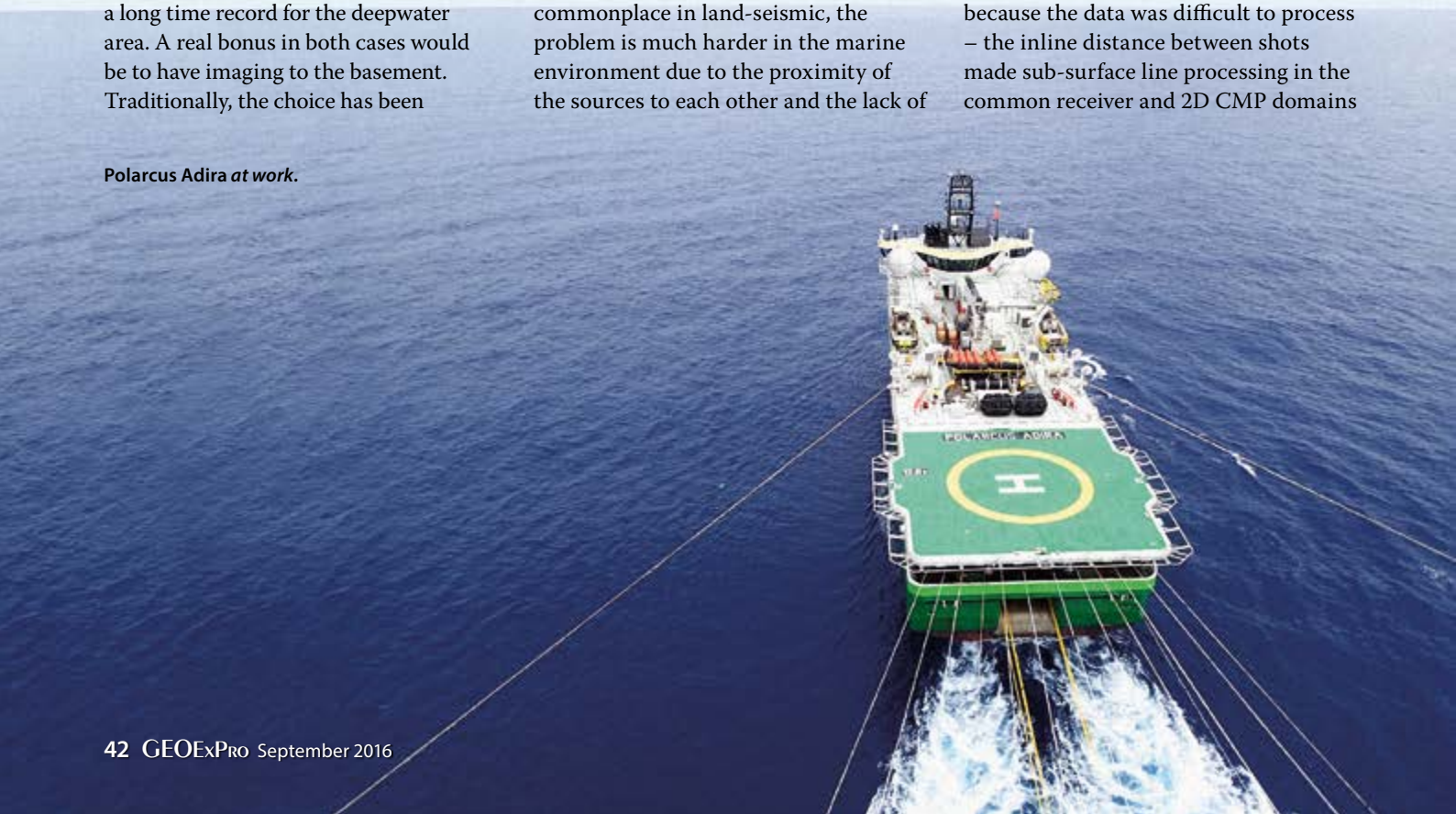
Overlapping shots occur when sources are sending acoustic pulses more often, such that the energy from one source is visible on the recorded data from another – i.e. they overlap. This overlap noise needs to be removed or 'de-blended', and whilst this is commonplace in land-seismic, the problem is much harder in the marine environment due to the proximity of the sources to each other and the lack of azimuth/offset variation. The advantage of this method is to increase the fold, and as data is recorded continuously, we dissociate the record length from the shot-point interval. By using overlapping sources, we thus solve the high-fold and long record length that was desired for Capreolus.

To convince ourselves and other pre-funding clients, besides Quadrant, that overlapping shots were the solution, test data was acquired just prior to the survey start. With an extremely short timeframe, DUG was challenged to run tests and produce an acceptable early result that showed the viability of de-blending in the area. 23,000 km^2 later, with a honed de-blending workflow, the survey was deemed a success.

Pick Any Two… or All Three?

Triple source was an old idea born in the nineties but was not very successful because the data was difficult to process – the inline distance between shots made sub-surface line processing in the common receiver and 2D CMP domains

Polarcus

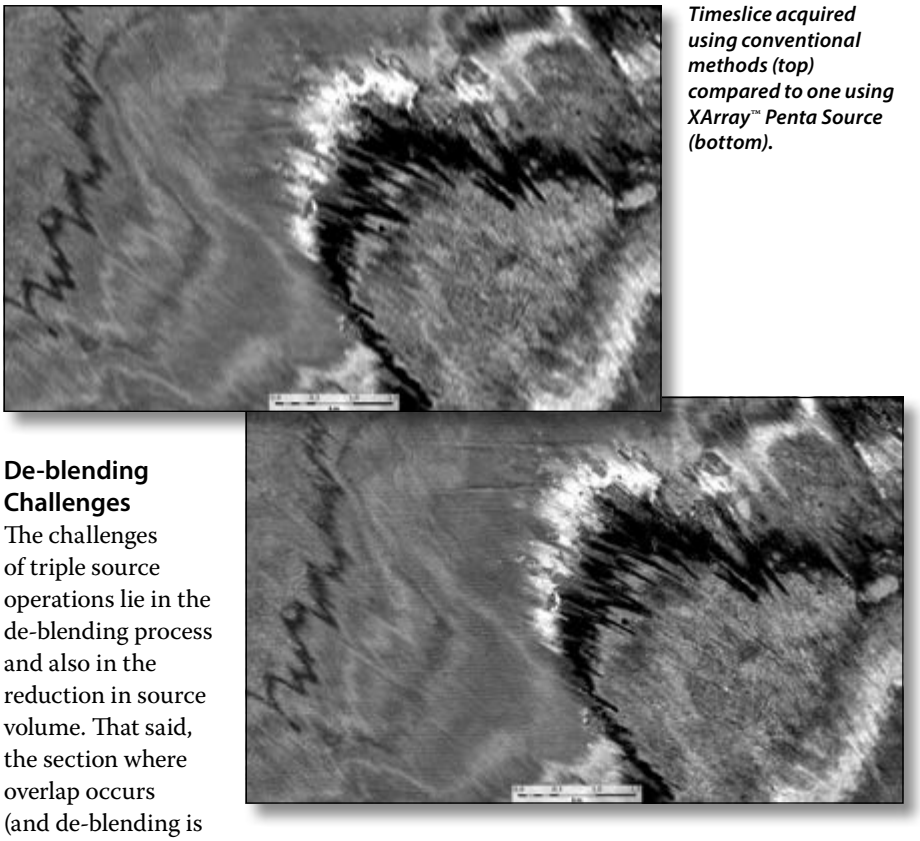


Polarcus Adira ***at work.***

difficult, with large trace spacing and low-fold respectively. Our Capreolus experience confirmed that the problem of maintaining adequate fold and long time records could be solved by source de-blending. If we marry this solution with triple sources, we can overcome or mitigate the inherent weaknesses of using multiple sources. We can then look at extending the range of source/receiver geometries and resemble land-seismic in being able to optimize a survey's source/receiver ratios and geometry in order to meet given 3D sampling criteria. Those criteria are a balance of quality and cost, but also external non-geophysical considerations like fair-weather windows or whale migrations. A key advantage of Polarcus' XArray™ Triple Source is the substantial reduction in HSE risk, given that less towed equipment is required to achieve the same cross-line sampling of conventional dual source acquisition. This also makes an XArray™ survey more efficient and cost effective.

The efficiencies that result from the use of XArray™ arise due to the ability to widen the streamer separations to acquire the same cross-line bin size that one would obtain from a conventional dual source design. As a result, the volume of data acquired increases by 50% per pass, which represents a great improvement in efficiency. Of course, we should also consider the reduced HSE exposure when acquiring data in such a time-efficient manner: there is simply less in-sea equipment that the crew have to handle. As a result, the small boat operations needed to maintain streamers – the most hazardous aspect of marine seismic – are reduced significantly.

However, when using three sources, an alternative to efficiency gains is the option to keep the streamer spread the same as for the conventional set-up and create a technical gain via the smaller cross-line bin size, thereby providing improved cross-line resolution. In the past, a smaller bin size meant narrower streamer separations, perhaps shorter streamers to address the risk of tangles, but certainly more sail-lines to acquire which also added more cost. If we add a third source, we reduce the bin size whilst maintaining conventional acquisition efficiency.

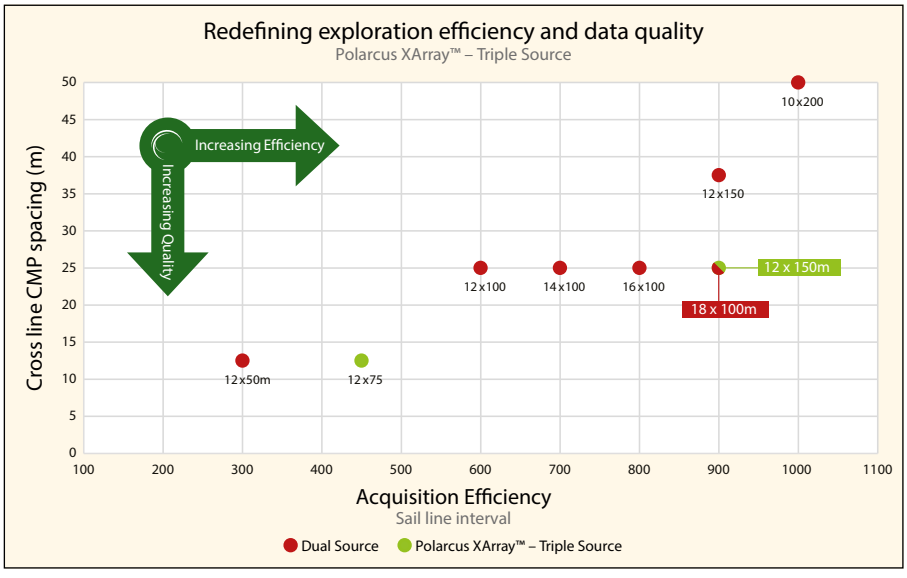


Timeslice acquired using conventional methods (top) compared to one using XArray™ Penta Source (bottom).

De-blending Challenges

The challenges of triple source operations lie in the de-blending process and also in the reduction in source volume. That said, the section where overlap occurs (and de-blending is essential) is relative to the water bottom time, plus the time between shots. So, for a typical shot-point interval of 12.5m, we would have 5 seconds of clean data below the water bottom, which will cover the majority of target times, and pre-stack analysis like AVO or inversion can take place in the usual manner. De-blending enables the record length to be extended to whatever length is desired, allowing the deeper section to be interpreted as well. As triple sources are limited to two sub-arrays per source and here, we can consider that the inline fold is actually increased by a third as the shot-point interval between the same source drops from 50m to 37.5m, the concern of smaller sources is thus mitigated. Apart from the shot density during final imaging, the smaller shot-point interval means that sub-surface line processing quality is improved with better de-noise and de-multiple.

Have we really found a way to achieve a faster, better and cheaper, not to mention safer process? Yes, would be the answer. By expanding the normal streamer spread slightly and inserting

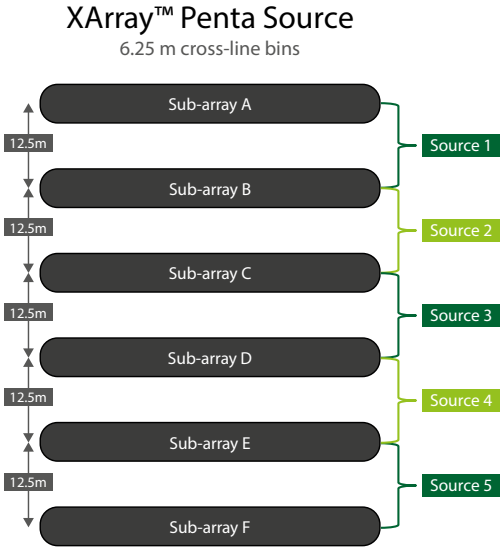


the third source, we end up with smaller bin sizes and a wider acquisition footprint than a traditional survey with the same number of streamers.

Better Through Design

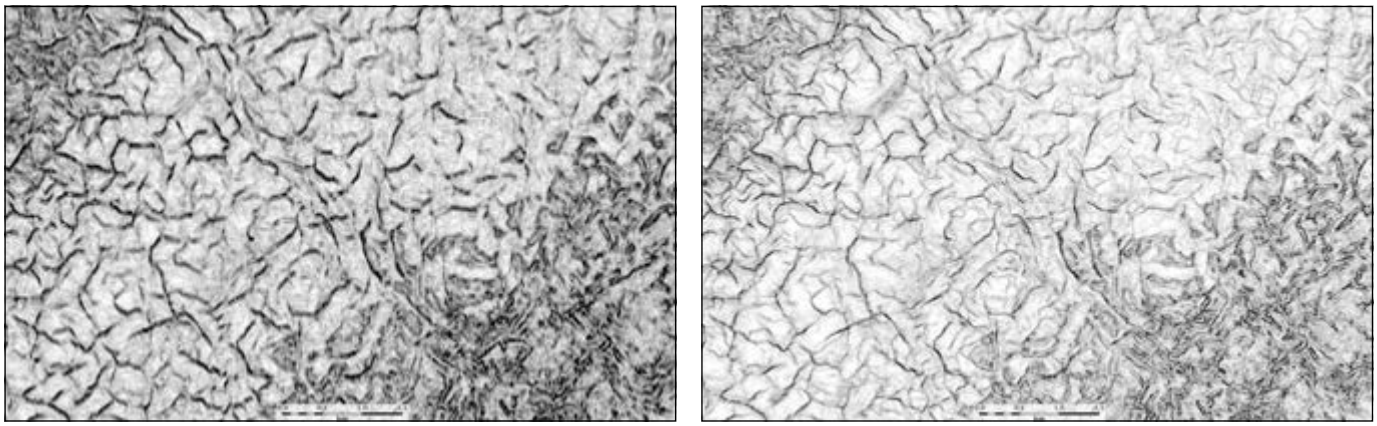
So far, we've considered triple sources, and we've seen that we can reduce the cross-line bin size to improve resolution. But what if we add more sources? If we consider five sources, then we can reduce the cross-line bin size so that virtually all data is imaged un-aliased, finally realizing the full potential of broadband seismic – temporal and spatial.

XArray™ Penta Source, which utilizes five sources, is not straightforward, as marine seismic vessels typically have six sub-arrays, which would allow for a five-source design, but with very small source volumes. The solution to the problem is to simply reuse sub-arrays in more than one source definition; for example, we use sub-arrays A and B for source one, and sub-arrays B and C for source two, and so on. This novel design allows for reasonably big source volumes, and for five sources to be defined with six sub-arrays. To maintain a reasonable inline fold for processing, the shot-point interval needs to be lower than even 12.5m, and 9.37m is the next logical interval – a multiple of the 'base unit of seismic' of 3.125m – and with this we actually increase the inline fold over conventional! The time between shots is about 4 seconds, so the first 4 seconds below the water-bottom time will be without interference. With these sorts of shot-point intervals, we get over 200 shots/km^2, compared to 80 shots/km^2 for conventional, which will easily compensate for smaller source sizes during imaging.

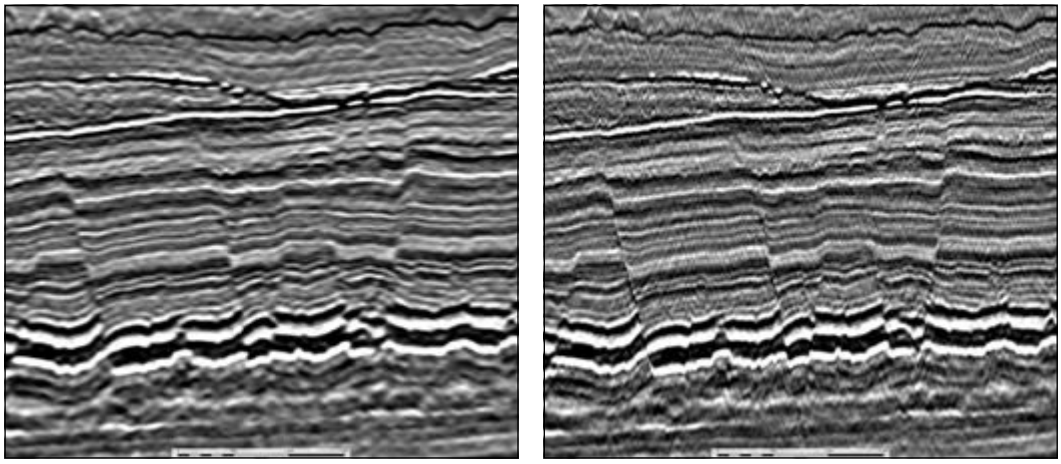


The design and initial test survey were intriguing for Quadrant Energy, who found themselves with a suitable area in which to deploy XArray™ Penta Source commercially. Additionally, a conventional reference survey was acquired over the center to better understand the uplift obtained and both were processed through an identical flow so direct comparisons could be made, as seen below.

Through innovation, the Polarcus team, together with DUG's processing expertise, are defining an exciting path for the future of the seismic industry driven by forward-thinking companies such as Quadrant Energy. ■



Shown above are coherency slices at 3,100ms covering 50 km^2 through an area of polygonal faulting. On the left we have the conventional dual source data migrated at 6.25 x 25m and on the right, the XArray™ Penta Source migrated at 6.25 x 6.25m. The Penta Source coherency slice clearly shows sharper fault details.



Crosslines after PSTM migration, with conventional on the left and 25m trace spacing and XArray™ Penta Source on the right with 6.25m spacing. Section covers approximately 0.5 second and 2 km in width. Fault resolution is far sharper with direct fault plane imaging because of the superior spatial sampling of Penta Source.

Making a Difference

Gladys Gonzalez, 2013–2014 President of the European Association of Geoscientists and Engineers, is an enthusiastic geoscientist, committed to increasing diversity in the oil and gas industry.

JANE WHALEY

"I am always very committed in everything I do," says Gladys Gonzalez, the first female President of the European Association of Geoscientists and Engineers (EAGE). "As soon as I started working in the oil industry I knew that that was where I wanted to be and became passionate about it." This enthusiasm and commitment has characterized a career which has covered major oil companies, service organizations and consultancy and in which Gladys has proved to be a trail-blazer in leadership and diversity.

Interested in Innovation

At heart a natural scientist, Gladys, who was born and brought up in Argentina, toyed with a few degree subject options, including astronomy and archaeology, before settling for geology. She firmly believes that a good grounding in a range of sciences as well as in mathematics is a pre-requisite for the subject. "Geology is driven by physical, chemical and mechanical processes such as tectonism and deposition, so to be a good geologist you need a firm scientific background. This is particularly important nowadays in the hydrocarbon industry with our emphasis on the integration of geosciences and engineering in the whole E&P process," she explains.

Initially planning to stay in academia after graduation, where she intended specializing in geophysics and structural geology, Gladys found the lack of financial support for research in Argentina very frustrating, and eventually she moved to the private sector. Western Geophysical opened an office in Buenos Aires, and she joined them as a geophysicist and sought to increase her experience at every opportunity. "In those days Western didn't have a formal training system; it was more an immersion process, as you moved around different departments and got to know them all in a very hands-on manner," Gladys says. "While it is good to have theoretical training as well, this method helps fix concepts in your head in a practical way rather than just getting an overview. I think it is very important that all geoscientists have a very good grounding in the concepts behind the science and don't just rely on software.

"I'm always interested in innovation," she adds. "I was working in seismic data processing when the first 3D surveys came to our office in 1992, so I offered to process them. I also asked to go out in the field and got several opportunities to visit some of the more remote locations we were working in, which was fascinating. I spent a number of years with Western and also with Geco-Prakla-Schlumberger and CGG and it was great experience, as I had the opportunity to work with and implement all the latest technology; it was all very exciting."

Managing – or Leading?

Schlumberger soon recognized Gladys as a high potential employee and ensured she underwent training in management as well as technical subjects to prepare her as a future leader. Soon she was supervising several teams of geoscientists working on complex land and offshore processing projects in her first managerial post – a role she is clearly very good at, and about which she has some interesting insights.

As she explains: "There are two ways in which you can supervise people: you can just manage, or you can

Gladys addressing the EAGE Conference in Amsterdam during her presidential year.

be a leader. A leader looks out for the team and wants it to be successful; if it is, then so is its leader. Sometimes things are difficult, and it is challenging or stressful to deliver results and if you are in a top position you have to realize this. Not everyone is willing to be exposed to these challenges, and I think this seems to particularly apply to women, something which I have tried to address."

In 2000 Gladys joined Paradigm Geophysical and two years later she and her family moved to Houston, because she was keen to be exposed to a different environment and culture. She became senior geoscience technical advisor for depth imaging, time depth conversion, mapping, seismic inversion and velocity modeling for Paradigm's North American office. In 2007 her enthusiasm for innovation led her to the role of emerging technology leader at Paradigm, focused on wide-azimuth anisotropic depth-imaging applications for deepwater exploration. This was followed two years later by a move from the service sector to E&P company Repsol. "As Geophysics Research and Innovation Manager and later as Senior Geophysical Advisor for Exploration I was responsible for providing seismic and unconventional technologies to solve complex subsurface structure issues. I think it is really important to work for a number of different companies in order to enrich your experience," she adds. "You need to be put in a place where you are challenged and out of your comfort zone, to help you grow and learn and demonstrate that you are capable of solving problems. In this way, you can develop new skills and this all helps innovation."

Diversity in Geoscience

In 2011 Gladys Gonzalez was elected as the EAGE President, the first – and, to date, only – woman to fill the role in the organization's 66-year history. She dedicated her presidential period (2013–2014) to improving diversity in the industry and, in particular, to increasing the participation of women in the geosciences, a topic which she feels very passionately about.

"In general, women still need to outperform men in order to progress; I have found that in my own career," Gladys explains. "To change this we need leaders to recognize achievement – but at the same time, women need to ask for recognition more; surveys have found that it is often hard for women to realize that and to look for rewards for their work. Some women still do not feel confident enough to express what they want, often worried it will be misrepresented, so companies need to ensure that the workplace is an environment which encourage all employees to look for change and to advance their careers. I firmly believe we need women in positions of power in companies to make this happen; we must stop writing about it and start putting diversity into employment practice.

"But while we need companies to provide the opportunities, it is up to us women to take risks and be ready to be exposed to challenges," she continues. "For that to happen we need support, both from each other and from our families. A united family can meet challenges, and partners must support and help each other in their career moves; that is important for everyone, not just women. We each have to find the right balance for our own family and circumstances."

Gladys during her year as EAGE President.

Gladys during a trip to the Grand Canyon in March 2006.

During her year as president, Gladys worked on strengthening the organization to have it ready for a new chapter of sustainable growth, focused on regional diversity and office organization according to new needs and growth. She set up the 'Women in Geoscience and Engineering Special Interest Community' to facilitate communication between women and to promote their active participation in professional society activities through the exchange of knowledge and experience and to offer mutual support. "We have special sessions during the annual meeting, where female speakers are invited to share their experiences of a career in the O&G industry, with its pitfalls and pleasures, as well as round table discussions on subjects like career development, mentoring and increasing retention of women. We need to help ourselves to be strong."

She also addressed the EAGE's plan to help younger people into the industry by creating the 'Young Professional Special Interest Community' to encourage the earlier involvement of young professionals by addressing their needs and empowering their skills.

An Independent Role

Early in 2016 Gladys took on another major career challenge when she left the multinational oil company Repsol and joined V&G Exploration Consultants, a small group of independent consultants in Houston. "I had really enjoyed my time in Repsol, where I had been in charge of a team which I had started from scratch, working on new geophysical techniques. It was very exciting, as we were developing workflows and technologies which could deliver new geophysical packages customized to our needs – in fact, Repsol was the first oil company to claim that it had in commercial use a proprietary reverse time migration system providing improved imaging in subsalt areas.

"But after several years in the company I was ready for a new challenge and a widening of my experience," she explains. "I was also keen to work more in exploration and closer to the point where the decision on where to drill is made, and also to have a greater variety in my workload. At V&G I work advising clients on exploration and development projects and am fully immersed in qualitative and quantitative aspects of validating plays, leads and prospects.

"I love the change! In big companies like Repsol the management overhead makes it difficult in a senior position to have much focus on exploration and development. In large technology companies like Schlumberger and Paradigm, by contrast, you are dealing with clients in order to deliver tools that satisfy their requirements. I enjoyed that work as I learnt a lot about process management, as well as human resources and how to help my staff progress. In this new departure I have much more influence over the projects I am working on with my clients and I am learning so much. We are based in Houston, because it is the heart of the oil industry, but our clients are working all over the world and this is giving me experience in many different basins and regions."

Narrowing the Gap

Gladys has been active in professional societies for all her career. In 2011 she was elected to the EAGE board and she serves on the Awards Committee of that organization. She is also a member of the SEG's Advanced Modeling Corporation (SEAM) Board of Directors and until recently was chair of SEAM Phase II Management Committee, the industrial consortia project focused on land seismic challenges.

"I firmly believe professional associations have an important role in narrowing gaps towards equal opportunities – like, for example, balancing knowledge levels and recognizing outstanding professionals across regions," Gladys says. "We, the members, all want to see the results of these visions and we are all responsible for making them happen. Through volunteering and active involvement there are a number of channels available through which everyone can contribute; we can do more than just be spectators waiting for results."

For her year as President of the EAGE, Gladys chose the theme of 'making a difference at a global scale – narrowing the gap'. "I am very focused on increasing diversity in the E&P workplace. I don't just mean I want to narrow the gap caused by gender imbalance, but also want to ensure we employ people covering a range of ages, geographical or regional backgrounds and race and ethnicity," she explains. "Embracing diversity also includes integrating a range of scientific and technical disciplines in decision-making teams, and encouraging more collaboration between academia and industry. Only then can we start to narrow the gaps and begin to make a significant difference." ■

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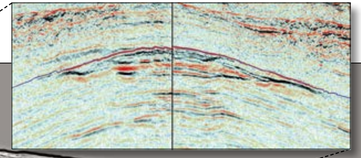
World Class Exploration Opportunities in Deepwater Mexico

New long-offset seismic data provides a closer look at the structure and petroleum potential of the Campeche Basin offshore Mexico.

The Campeche Basin holds tremendous hydrocarbon potential with several proven commercial oil and gas fields. The first bid round in the Campeche deepwater salt basin is underway.

MULTICLIENT GEOPHYSICAL

Figure 1: Kunah-1 well gas discovery.



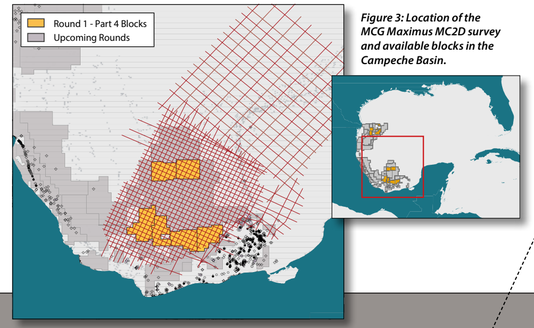
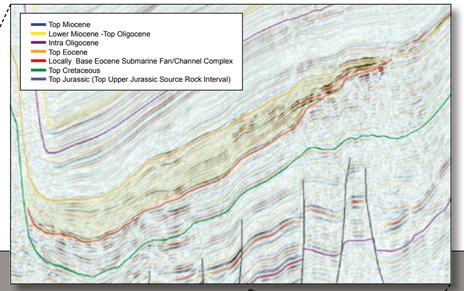


Figure 3: Location of the MCG Maximus MC2D survey and available blocks in the Campeche Basin.

Figure 2: Possible Eocene target in open blocks.



New Dataset Reveals Plays

PETER ABRAHAMSON and KENNETH MOHN, MultiClient Geophysical ASA (MCG)

Mexico has a long and colorful history of oil and gas exploration that started at the end of the 19th century. Between 1868 and 1938 there was active exploration by foreign oil companies. In 1938, a decree was made that the oil and gas resource in Mexico belonged to the state and soon thereafter Pemex was formed as the National Oil Company. However, in 2013 Mexico opened up for outside exploration investment after decades of monopoly on producing, refining and selling oil and gas in the country. Pemex has now been privatized and foreign exploration companies are invited to explore for oil and gas both offshore and onshore Mexico. A new Petroleum Agency, the CNH (Comisión Nacional de Hidrocarburos), has been formed to regulate these new activities. In 2015 the CNH developed a five-year plan for bid rounds, which is considered an excellent opportunity in the exploration community, despite the current low oil price. Several international oil companies see these Mexican bid rounds as some of the best investment opportunities in the world.

In anticipation of the bid round plan, MultiClient Geophysical (MCG) acquired a long-offset grid of high resolution 2D seismic together with gravity and magnetic data, called the Maximus Survey, over the Campeche Basin and the Yucatan Platform. The Maximus MC2D dataset has recently been completed (see Figure 3). The survey was acquired using very long offsets and deep records in an attempt to provide exploration companies with a complete profile of the sedimentary section. Processing is using a broadband solution. Both pre-stack time migrations and pre-stack depth migrations are being produced using a detailed velocity grid. The Maximus survey is an excellent dataset to use when carrying out regional play fairway analysis and to high-grade prospective exploration areas. The survey has clear imaging and broad coverage of the regional structure and stratigraphy of all play elements (source rocks, reservoirs and seals) in the region, which are shown in Figure 4.

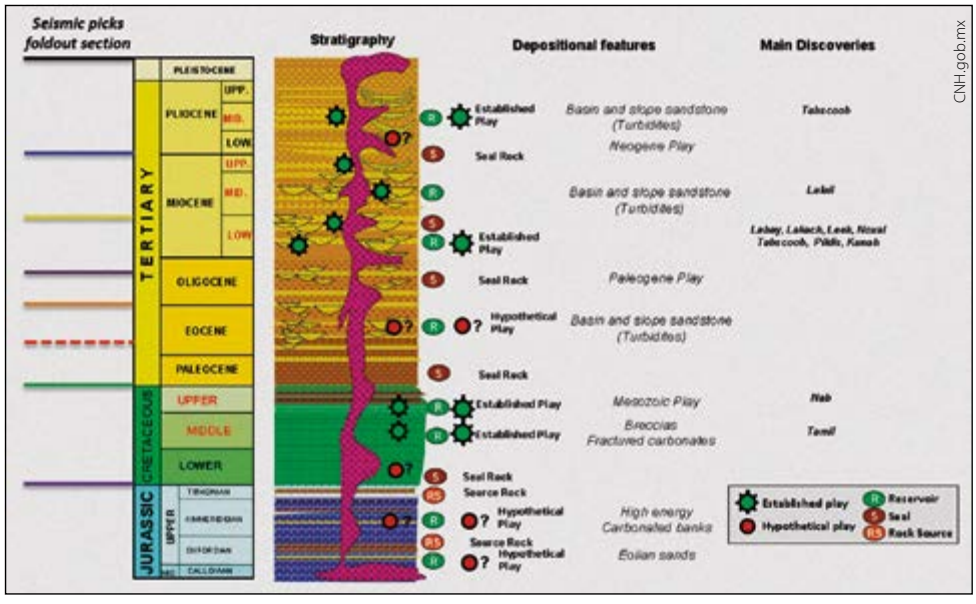
Salt-Related Structures

The seismic line shown in the foldout is located close to the western edge of the deepwater salt basin. The dominant trapping configurations are salt-related anticlinal and flank structures to the salt domes and walls. The top of the Upper Jurassic source rocks is easy to map throughout the whole survey area where thick allochthonous salt is not present. Key surfaces representing reservoir and seal bearing intervals within the Cretaceous to Tertiary levels are also consistent and present within large parts of the survey area. The complex salt-cored foldbelt in the middle of the basin presents some imaging challenges in the time domain. However, these challenges are being addressed through the pre-stack depth migration processing. This survey is an excellent dataset for reducing risks of prospects as illustrated in distinct imaging of Direct Hydrocarbon Indicators (DHIs, flatspots and amplitude anomalies).

Two interesting examples of prospective trends are shown on the foldout. The drilled gas discovery Kunah-1 (Figure 1) shows two pronounced flatspots, where the shallower one proved to be gas/water contact while the deeper was a remnant from an earlier hydrocarbon contact. This is also consistent with EM anomalies presented by Pemex at the EM conference in Oslo, May 2013. The Eocene turbidites in Figure 2 show clear imaging of stratigraphic trapping possibilities and the strong, up-dip amplitudes that may indicate hydrocarbon presence within a Lower Tertiary submarine fan in open bidding blocks.

The relationship between the interpreted seismic horizons and the stratigraphy and play elements are shown in detail in Figure 4. Four proven and three possible plays are shown in the stratigraphic column.

Figure 4: Deepwater stratigraphy and play elements.



In the deepwater salt basin, it is understood that only two wells deeper than 1,500m have been drilled. This region is highly folded and very complex, with many large structures and deep basins, as shown in Figures 5, 6 and 7. These structures are large and some are active at the present time. Many of the structures are cored by allochthonous Callovian-age salt. In the north of the Yucatan Peninsula, the salt is more autochthonous and thinner than in the core part of the basin west and north-west of the Peninsula. An example of this is shown in Figure 7.

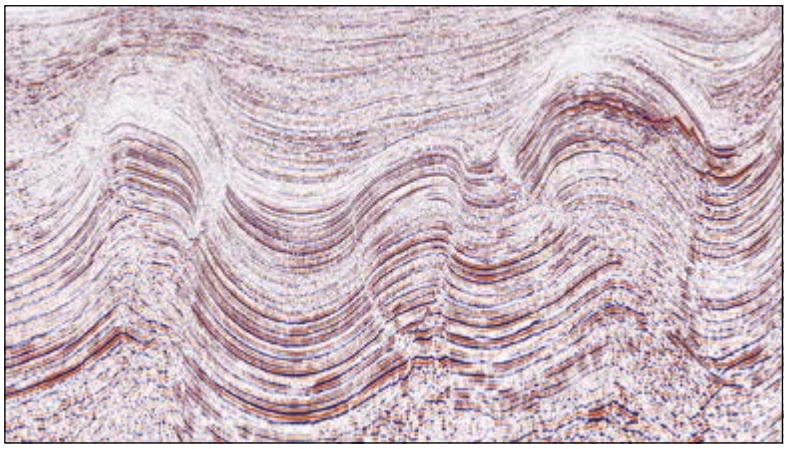


Figure 5: Highly faulted folds without salt.

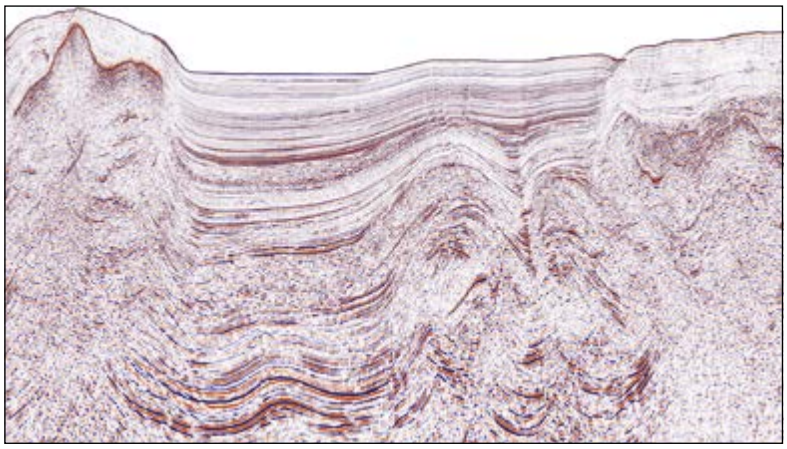


Figure 6: Folds with allocthonous salt.

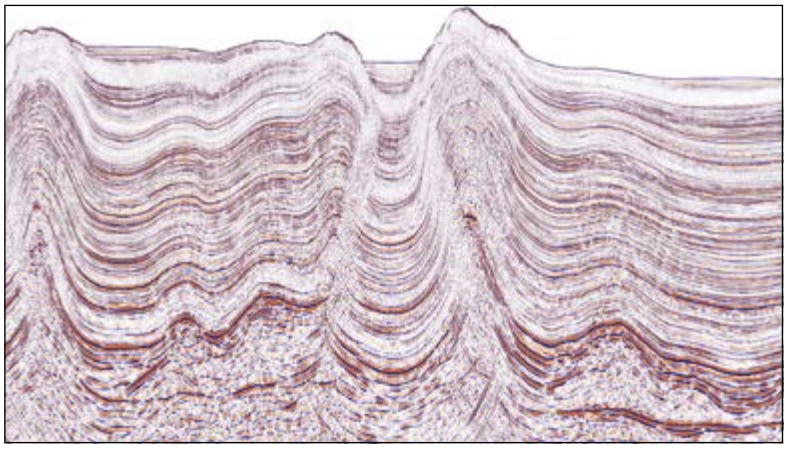


Figure 7: Structures in the north end of the deepwater salt basin.

Cantarell-Type Plays

Potential play fairways on and near the Yucatan Peninsula shelf edge, near the Cantarell field, have the same rationale as the proven commercial play in the Cantarell reservoir rock, which was formed by the impact of the Chicxulub meteorite on the Yucatan Platform. The reservoir rock for the Cantarell field is a brecciated carbonate that was part of the debris created by this meteorite 66 million years ago. One target for exploration companies is to understand the distribution and depositional conditions that make this breccia a commercial reservoir rock. Figure 8 shows the connection of the Yucatan Peninsula and the equivalent deepwater section located roughly the same distance from the impact site as the Cantarell field.

There is much information available from the CNH on the bid round blocks, as well as data packages and Pemex 3D seismic data available for purchase. Pemex was an active company in this basin for some time with good success, including the giant Cantarell field and associated plays. Exploration companies will be able to generate more exploration success in the upcoming bid rounds by using new data to develop new, fresh ideas for the region. New regional long-offset seismic datasets will play a key role in this effort. The Maximus seismic survey was developed for this purpose. ■

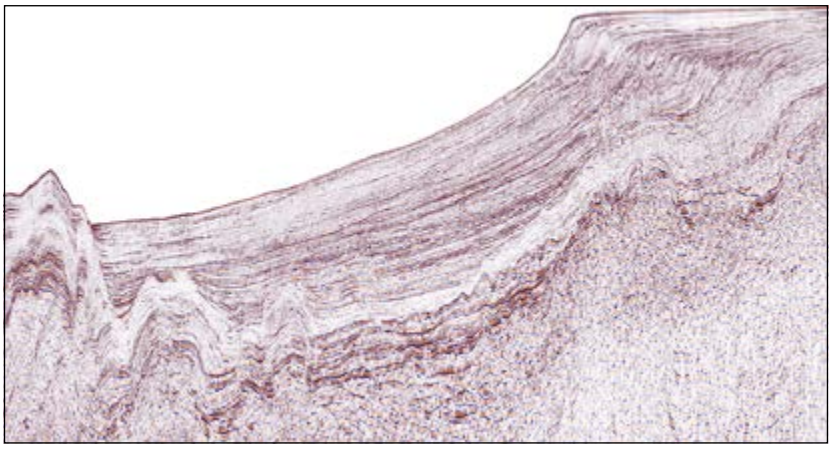


Figure 8: Data at the Yucatan Platform; the deepwater structures are roughly the same distance as the Cantarell field is from the Chicxulub Meteorite impact site.

Argentina

The Final Atlantic Margin Frontier

An enterprising company will be required to find oil, and to boldly drill where no drillship has drilled before!

IAN DAVISON and IAN STEEL, Earthmoves Ltd.

Argentina has the least explored continental margin along the Atlantic Ocean. Its coastline extends for some 1,700 km in a north-east to south-west direction from the Uruguay border to the South Scotian Foldbelt; and yet there are no wells drilled in more than 200m water depth. Government policies of oil pricing and export restrictions are partly responsible for this lack of activity. However, with the recent change of government, the state company Enarsa has handed back all its offshore blocks to the government. Argentina may now be looking to attract foreign explorers; and here we offer some new perspectives on the exploration potential of the Atlantic margin.

The Argentine margin is transected by a series of isolated rifts within the continental shelf which are filled with non-marine sediments. They initiated in mid-Jurassic times, and rifting continued into the Early Cretaceous. The rifts are generally highly oblique to the Atlantic shelf edge indicating an approximately north-south extension at this time. The north to south trending Rawson-Valdes Rift is an exception, but this may have developed as a pull-apart basin along a north-west to south-east trending shear zone. These rifts have been the main focus of oil exploration to date, and all of them have at least one exploration well.

During the Early Cretaceous South Atlantic rifting event the extension direction switched to approximately east-west and a narrow zone of small north-south trending rifts developed along the present continental shelf edge shortly before ocean spreading initiated. The exact timing of the onset of ocean spreading is difficult to determine because of the lack of magnetic reversals at this time. Also, the first magnetic anomalies are located on seaward dipping reflector (SDR) volcanics, and not typical oceanic crust. Suggested spreading onset ages range from 140 to 130 Ma.

Several Underexplored Rift Basins

Salado Basin: This northernmost basin has been tested by only six onshore and four offshore wells. All the onshore ones were dry, with two reported to have minor oil shows.. The offshore Samar-1X well encountered some residual oil in Cretaceous and Paleocene sandstones, while Dorado-1X was drilled on a basement high and did not test the rift sequence. Paleozoic sediments were encountered in the adjacent Punta del Este graben in Uruguay, and similar shales and sandstones and extrusive volcanics can be expected in the Salado. The non-marine syn-rift and early

Shutterstock

Aptian-Albian drift sequences consist of red sandstones and shales. There is no known source in this basin.

Colorado Basin: The Colorado Basin is the largest and deepest of the Jurassic rifts with up to 13 km of pre-rift Paleozoic strata and Jurassic-Early Cretaceous syn-rift fill (Figure 2). Twelve wells have been drilled in the basin. The Cruz del Sur-1 well recovered a small amount of good quality (39° API) moveable oil from an Early Cretaceous syn-rift sandstone reservoir. The oil is believed to be sourced from a Permian shale, and Paleozoic strata are imaged on the seismic data as a parallel bedded pre-rift sequence in the offshore Colorado and Salado Basins. Permian strata also crop out in the Claromeco Basin.

A Neocomian source rock with some hydrocarbon potential was also encountered in the Cruz del Sur-1 well, but was immature at the well location. A 25m-thick source interval was reported to have an average TOC value of 2.4%. Neocomian source rocks are more deeply buried in the center of the Colorado Rift, and could source hydrocarbons which migrated into rotated fault terrace plays, which are present along the basin margins. The Colorado Basin is separated from the Atlantic margin by an outer high. This high could also access a syn-rift source rock kitchen. Subtle closures have been imaged above the syn-rift faults at Early Cretaceous level over this high and later small reactivations caused faulting extending up to the Cretaceous level to allow migration into potential shallow water reservoirs. Bright, structurally conformable amplitude anomalies have been identified by YPF over at least one of these large Cretaceous level closures in their previously-operated Colorado blocks. The prospects lie in shallow water, and have good access to Neocomian source rocks sitting in the oil window (Figure 2).

Rawson-Valdes Basin: This is a complex north-south trending system of rifts with a similar history to Salado and Colorado. Two dry holes have been drilled in the basin. The Tayra-1 well was a good test of a rotated fault block play and was adjacent to a 5 km-thick graben sequence. The onshore part of the basin is floored by large volumes of Mid-Jurassic volcanics. There are no proven

Figure 1: Map of the Argentine Basins.

source rocks in the Rawson-Valdes rift, but the southern Rawson rift has not been drilled yet.

San Jorge Basin: San Jorge is the only basin with proven commercial volumes of hydrocarbons, with more than 4 MMbo recoverable reserves (Fitzgerald et al., 1990). The basin opened in a north-south direction during Late Jurassic to Early Cretaceous rifting (rift trend is east-west). The western half of the basin was affected by Late Cretaceous to Miocene Andean compression, which produced a north-south trending foldbelt in the Andean foreland. This combination of orthogonal extensional rifting and compression has produced numerous structural traps in this basin.

The main source rocks are syn-rift lacustrine Late Jurassic to Early Cretaceous Aguada Bandera Formation and Barremian to Aptian age Pozo D-129 Formation, which were deposited during rifting. The current oil production is all onshore. The basin extends offshore, but the rift fill is generally less than 2.5 km, and any potential source will probably be immature. Approximately 25 dry holes have been drilled in the offshore basin.

Reservoirs are mainly discontinuous fluvial and deltaic sandstones of Tertiary and Cretaceous age. Oil recovery is difficult from such reservoirs, and over 30,000 wells have been drilled in this basin. Unconventional shale oil and gas reserves are also present (Kuuskraa et al., 2013).

San Julian Basin: San Julian is the smallest and southernmost Jurassic rift, with some indication of an earlier Permian phase of rifting. Early Jurassic volcanism marked the initiation of the Jurassic rift phase. An Early Cretaceous transpression caused inversion of the

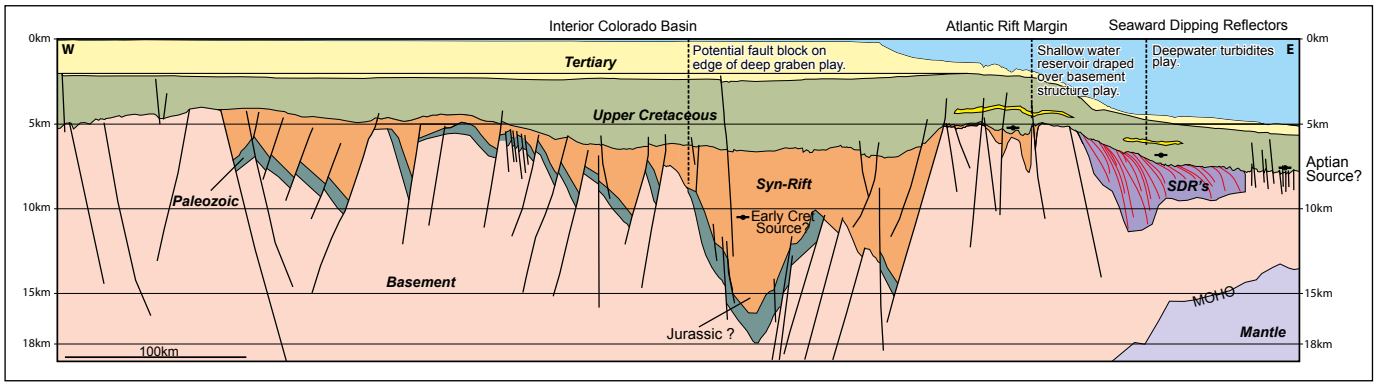


Figure 2: Cross-section through the Colorado Basin, partly based on interpretation of seismic line in Horn, 2015 (for line of section see Figure 1).

basin, and a late Miocene Andean compressive reactivation also occurred.

The syn-rift Jurassic strata mainly consist of continental sandstones and interbedded lavas and pyroclastics, with some intercalated calcarenites in the late Jurassic (Figueiredo et al., 1996). The lavas have been dated in the onshore Deseado Basin at 168–170 Ma. Total sediment thickness reaches up to 6 km. San Julian-1 was drilled on a transpressional fold adjacent to deeper graben fill. Petrobras considered this to be the best location to drill within the basin, but it was dry. Some thin source rocks (1.5–5.4% TOC) were encountered in the well in the Neocomian-aged Bajo Grande Formation, but this is generally immature throughout the basin due to lack of burial (Soares et al., 2000). The north-eastern segment of the rift has an older untested section with potential for a deeper source in the Permian sourcing Triassic reservoirs. The adjacent Deseado onshore basin has good surface oil seeps in Cretaceous strata at Los Navarros and Santa Catalina, but the source of the biodegraded oil is not known.

Atlantic Margin Post-Rift Potential

The break-up of the South Atlantic Ocean initiated between Africa and Argentina in the Early Cretaceous (ca. 130–135 Ma) with the development of a relatively narrow zone of rifting (50 km) and small grabens 5–10 km wide and 1–2 km deep, which are aligned along the present continental shelf edge. This style of extension is in stark contrast to the Brazilian margin farther north where the rifted margins extend for several hundred km width, and the large fault blocks reach up to 50 km wide and 5 km-deep rifts developed.

The reason for this is probably the presence of a linear zone of hot upwelling mantle which extended southward from the Parana plume head in southern Brazil. This upwelling and sub-aerial volcanism occurred at 135–130 Ma. Crustal extension was achieved by dyking with rapid magma injection to fill the accommodation space. The narrow Atlantic rift zone and wide seaward dipping reflector sequences are therefore unlikely to have any significant syn-rift hydrocarbon potential as no source rocks or reservoirs are predicted.

However, the overlying Cretaceous to Recent deepwater sediment pile reaches up to 6 km in places and has significant exploration potential, but is untested. Good source rocks of Barremian to Aptian age have recently been discovered in wells on the conjugate Namibian margin in the deepwater (Mello, 2012); and similar source rocks may be present in Argentina, although there is no well data to support their presence so far. There is also good evidence of large channels with bright reflectivity cutting through the continental slope onto the oceanic abyssal plain at many localities. Carbonate build-up reservoirs may also be present on top of the SDRs when the first marine incursion occurred into the basin.

Bold Explorers Required

The Argentine margin is the least explored segment of the Atlantic Ocean. Initial exploration efforts have focused on the shallow water internal rifts, which indicate the Colorado has the best potential. This is the deepest basin and has some fair source rock potential within the rift. No viable source rocks have been proven in the other Jurassic rifts to date. However, the deeper half grabens of the Jurassic rifts have never been drilled. The true Atlantic margin has very little potential in the syn-rift, but the post-rift sequence (Barremian to Recent) may contain a Barremian to Aptian source rock. The Early Cretaceous post-rift interval is buried to 4 km along the Atlantic hinge so the source may be mature (see Figure 1 for sediment thick locations). Reservoir channels have been mapped in the deepwater on 2D seismic (our own work). A bold well is required to test this play.

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Quantifying Reservoir Performance for Deepwater Slope Channel Deposits

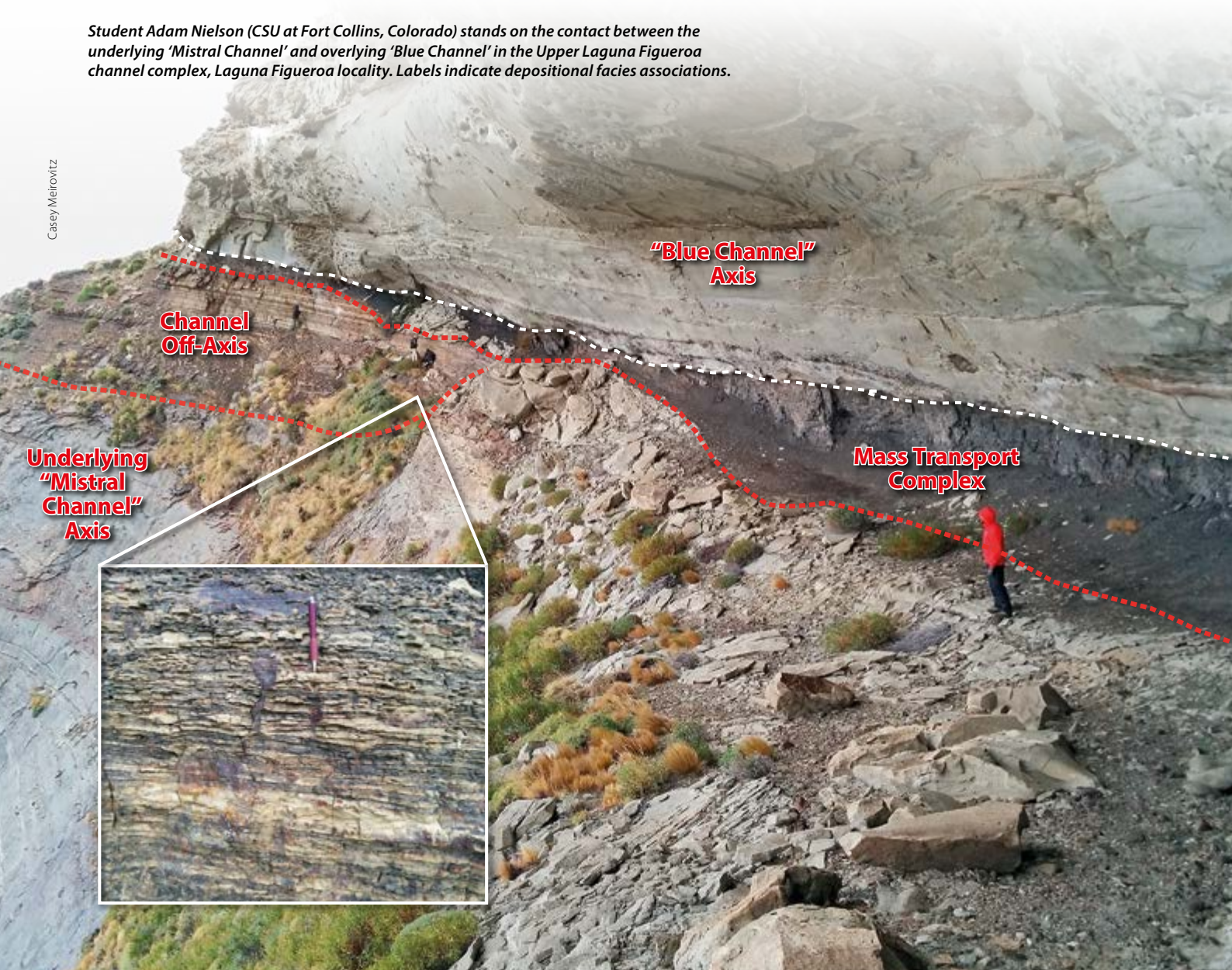
Turbidite slope channel deposits pose numerous challenges to risk management during exploration and development planning. Spectacular basin-scale outcrop exposures of slope deposits in southern Chile are providing useful insight in predicting channel sandstone distribution and connectivity in these complex reservoirs.

THOMAS SMITH

From the Gulf of Mexico, south to the Campos Basin off the coast of Brazil and across the South Atlantic to the petroleum basins of offshore Angola, deepwater slope channel petroleum reservoirs are important targets in today's exploration environment. Exploitation of these deposits are high reward, but also high risk, with little room for errors. Reservoir performance is impacted by the different reservoir facies, varied channel stacking patterns, and the effect of low flow barriers within these reservoirs. Our ability to capture that impact through reservoir modeling is critical to efficient well designs and development plans.

Ongoing outcrop-based study of middle to lower slope strata of the Tres Pasos Formation in the Magallanes Basin of Chilean Patagonia is providing critical insights into the evolution of

Student Adam Nielson (CSU at Fort Collins, Colorado) stands on the contact between the underlying 'Mistral Channel' and overlying 'Blue Channel' in the Upper Laguna Figueroa channel complex, Laguna Figueroa locality. Labels indicate depositional facies associations.



Casey Meirovitz

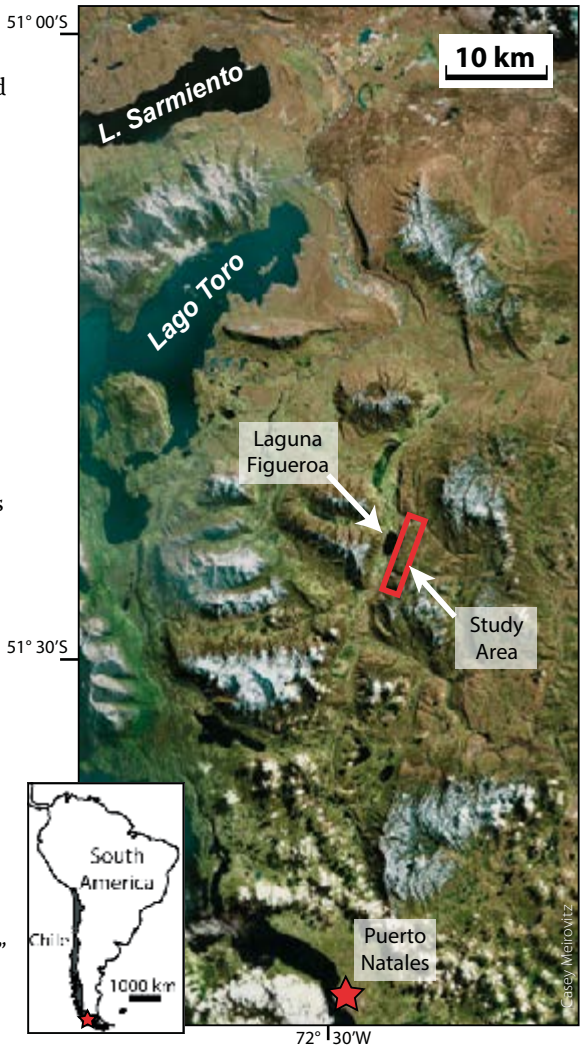
channelized deepwater slope systems and analog data for subsurface characterization of complex reservoir architectures. As part of this effort, bed-scale geocellular models are being produced to look at the influence of sub-seismic scale reservoir architecture on reservoir performance and prediction. These models evaluate the impact of geologic parameters such as facies distributions, channel-stacking patterns, and variations in internal channel architecture, as well as the effects of reservoir model cell sizes or upscaling. Their findings will help refine future reservoir modeling and development strategies.

Gaining a Better Understanding

"Geologic heterogeneity, though complex, is not random," says Casey Meirovitz (Department of Geology and Geophysics, University of Utah in Salt Lake City, Utah), a doctoral student working with Dr. Lisa Stright of Colorado State University (CSU, Fort Collins, Colorado) and the Chile Slope Systems Joint Industry Project. "Geologic architecture that we observe at outcrop contains a record of multiple depositional processes. By understanding the depositional processes which create the observed variability in architecture, and the preservation of sediments, we become more predictive in creating geologic models of the subsurface where data is more limited.

"Sub-seismic scale heterogeneity in channelized deepwater reservoirs can lead to significant uncertainty in reservoir connectivity and predicted performance," Casey continues. "Oil companies actively working in deepwater channelized reservoir systems have struggled to accurately predict reservoir volumes and therefore wrestle with optimal well placement. With these wells costing in excess of $200 million, a better understanding of these depositional systems is urgently needed."

The Chile Slope Systems Joint Industry Project (JIP) was formed to study a unique set of deepwater outcrops located in the Magallanes Basin of Chilean Patagonia. This project is a collaboration between the University of Calgary, Colorado State University, Virginia Tech, University of Utah, and their industrial partners. Continued orogenesis of the Andean fold thrust belt exposes the fill of the Magallanes Basin, revealing nearly continuous down-deposition-dip panels for about 100 km. According to Dr. Stright, "The high quality of outcrops placed in the context of position along the slope profile and slope evolution makes the Ultima Esperanza District worthy of the attention of the oil and gas industry, which is exploring channelized systems in the deeper waters off of continental margins around the world."



The study area is located in southern Chile in the Ultima Esperanza District near the Chile-Argentina border.

Predicting Reservoir Performance

"Within the oil industry, reservoir model cell sizes and resolution of available data do not typically allow for the direct representation of internal channel architecture," says Casey. "In this study, I have tried to find out if the internal architecture really mattered in reservoir modeling. If it does, when is it important and what is the amount of error that could be introduced by not representing it?"

Casey set up a case that closely mimics the bed-scale architecture, which we will call a realistic condition, using a high-resolution outcrop-based geocellular model; a random condition that preserves the facies proportions of the realistic condition but distributes them randomly throughout the channel body; and finally a homogenous condition using a uniform flow-averaged permeability. The homogeneous case was an attempt to create the type of data that would be available in an exploratory field study. Reservoir simulations are performed using a single injector-producer pair completed in an off-axis position at the opposing margins of the channel. Simulations were run for each of the fill scenarios.

"We initially ran simulations on the simplest case, a single channel element," says Casey. "We found that both the random and homogenous cases over-predict total oil production by ~10% with a delayed water breakthrough when compared to the 'actual' condition. This was primarily due to both the random and homogenous cases over-predicting the sweep of the marginal facies."

Adding Complexity

"To test the influence of stacking patterns on reservoir performance," says Casey, 'we took two channel segments with identical internal architectures defined by the realistic conditions. We held one channel stationary and a second channel was rotated around it at different angles and offset distances. We used a single injector-producer pair as was used in the single channel simulations. The injector and producer have been placed

diagonally in opposing margins of the two channel segments, forcing flow to travel between the two segments."

What they found is that recovery efficiency is highest for laterally offset channel segments and decreases to its lowest when channel segments were stacked vertically on top of each other. In the vertically stacked channels, a fast flow path is created along the axis (a thief zone created by sand on top of sand), leaving oil in the marginal, siltier facies. When water is forced to travel through the marginal facies of laterally offset channels, recovery increases, albeit the time to recover the same amount of oil is prolonged.

"We expected, and confirmed in the simulations, that while recovery efficiency is higher from the laterally stacked channels, the rate of oil production is much lower than that of the vertically stacked channels," says Casey. "While out of the scope of this investigation, this does ask the economic question 'is it better to get more oil at slower rates than to get less oil overall but sooner in the project?'"

Scaling

"We have been dealing with a very fine-scaled, high resolution representation of internal channel architecture in our simulation runs," says Casey. "These fine scales used thus far are not feasible to produce large field-scale simulations. We upscaled from the original geologic detail to quantify the error introduced by different cell sizes used in the models and to identify an optimal cell size. Cell grids ranged from 2m x 2m x 0.25m up to 50m x 50m x 2m."

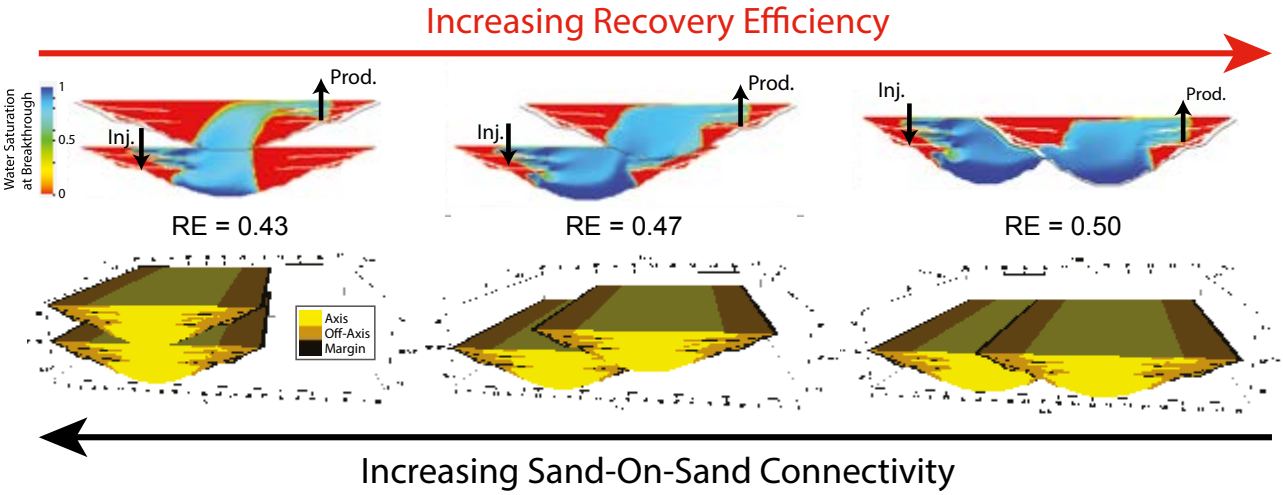
Once again, they used a single, realistic case type channel and ran production simulations at different scales. They repeated the simulations with two channel stacking patterns, ranging from lateral to vertical, using 12 different offset models. The margin of error in oil recovery over the fine-grid 'actual' condition induced from upscaling was greater in laterally offset channels than in the vertically stacked channels. Upscaling was not able to capture the fine-scaled heterogeneity of the marginal facies and thus overestimates oil recovery. They found that cell sizes up to 25m x 25m x 1m captured fairly accurate oil recovery estimates when compared to fine-grid realistic cases. It should be pointed out that these cell sizes are still well below what is used for a full-field simulation. Additional studies are needed to build coarse-scale models that can mimic bed-scale controls on flow.

Expanding the Study

The Tres Pasos outcrop belt within the Magallanes Basin spans approximately 100 km and covers over 1,200m of vertical stratigraphic thickness. Individual outcrops are many kilometers long and 100s of meters thick, representing seismic scale outcrops. "What makes them most useful is that we are able to characterize sub-seismic scale internal architecture and trends within the context of the larger seismic-scale slope-channel architecture," says Casey. "These outcrops capture channelized deepwater deposition for the basin floor up the middle and lower slope all the way to the genetically linked deltas on a

Laguna Figueroa Outcrop Belt

Two channel complexes, each over 100m thick, have been delineated in the Upper Cretaceous Tres Pasos Formation in the Laguna Figueroa area. The Tres Pasos Formation consists of a turbidite-dominated slope system that records the terminal phase of deepwater deposition in the Magallanes foreland basin, southern Chile. This channel complex, pictured here, is comparable in scale to systems that have been explored in the subsurface in petroleum basins off numerous continental margins around the world.



Casey Meirovitz

Oil recovery increases across lateral channels as more oil is recovered from the marginal facies than over vertically stacked channels. Each channel element is 14m thick and 200 to 300m wide and a reservoir is comprised of stacks of these channel elements into composite sets.

scale comparable to similar subsurface features off Brazil, west Africa, the Gulf of Mexico, and other important petroleum basins of the world.

"This study was focused on a set of channels on the slope. However, architectures vary along the slope and from clinoform to clinoform and continued studies of the unique area will help us predict reservoir performance as a function of location along the slope."

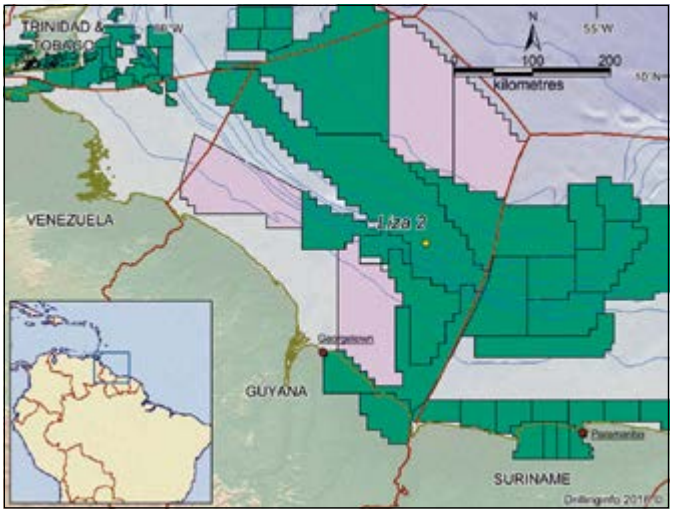
Casey goes on to say that, "All of our simulations, including upscaled models, reveal the critical role of the marginal facies on the movement both within and from channel to channel. In doing this work, we hope to quantify the influence of inter- and intra-channel heterogeneity on reservoir performance, and ultimately produce results which will aid industry professionals in producing predictive models and optimized production strategies for channelized deepwater reservoirs."

Acknowledgments: *Special thanks to Casey Meirovitz and Dr. Lisa Stright for the information and edits. More information on the program can be found at http://Chileslopesystems.com*

Guyana: World-Class Discovery

On June 30, 2016 **ExxonMobil** reported that it had encountered a recoverable resource of between 800 to 1,400 MMboe at the **Liza 2** well, in the offshore **Stabroek Block**, **Guyana**, 193 km from the coast in 1,692m of water. Describing it as a 'world-class discovery', the company said Liza 2 encountered 59m of oil-bearing sandstone in the Upper Cretaceous. The well, which was drilled to a TD of 5,475m, is a follow-up to the 2015 Liza 1 discovery, located about 3 km to the west, which found more than 90m of high-quality oil-bearing sandstones, and has an estimated resource of about 700 MMboe. A production test on Liza 2 indicated that the oil was contained in the same reservoir.

The Guyana Basin is a largely unexplored petroleum province which has seen little exploration activity since the late 1980s. The USGS have estimated the potential offshore Guyana to be at least 15 Bbo and 41 Tcfg. Seismic company Spectrum recently undertook a detailed prospectivity evaluation and have identified multiple play types including large early Cretaceous structures, amplitude-supported structures with large areas of closure, stratigraphic on-laps, ponded turbidites, basin floor fans and Tertiary mass transport complexes. The source rock is expected to be the Cenomanian-Turonian Canje Formation, which in the



Stabroek area is overlain by a thick Cretaceous section deposited within a major submarine canyon.

ExxonMobil plans to drill more exploration wells in the area, to investigate the Liza and additional prospects. Operated by ExxonMobil (45%), Hess holds 30% and CNOOC subsidiary Nexen Petroleum holds 25% interest in the block. ■

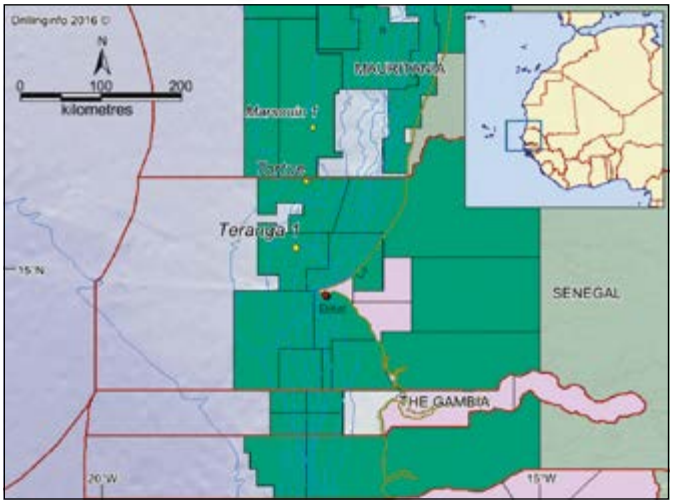
Egypt: Shallow Water Messinian Gas

During July 2016, it was reported that the gas-in-place figure for the recent Egyptian offshore **Baltim South West 1X** gas discovery stands at approximately 700 Bcfg. The discovery was announced in June 2016, after the well was drilled to a TD of 3,750m in shallow waters of 25m. It encountered a 120m gross (62m net) pay in what is understood to be the Messinian Abu Madi sandstones. The well, drilled on the Baltim South development lease of the Baltim concession in the Nile Delta Basin, is situated approximately 12 km offshore and lies on trend with the Nooros and Baltim East fields. The operating **Medgas** consortium will now look at fast-tracking the discovery, which lies within the newly defined 'Great Nooros Area', estimated by Eni to contain over 2 Tcf gas-in-place. Medgas operates the Baltim concession, with equity split between Eni (25%), BP (25%) and EGPC (50%, carried). ■

Senegal: Another Significant Discovery

Kosmos has made another significant north-west African gas discovery with the **Teranga 1** new field wildcat, located on the offshore **Cayar Profond Block**, **Senegal**, about 100 km north-west of the capital, Dakar. The well, which was drilled to 4,485m TD in 1,800m of water, encountered 31m net gas pay in good quality reservoir channel sands in the Lower Cenomanian objective. These results confirm that a prolific inboard gas fairway extends southwards around 200km from the Marsouin 1 well on Block C-8 in Mauritania through the Greater Tortue area on the maritime boundary to this new well in Senegal. Initial estimates suggest Teranga could contain 5 Tcfg Pmean resources (gross) and Kosmos now estimates it has discovered 25 Tcf gas resources across the area, with the fairway containing some 50 Tcf of resource potential.

Kosmos Energy farmed into the Cayar Profond and St Louis Profond blocks in 2014, acquiring 60% equity and operatorship from Petro-Tim, and has now met its



commitments for the current exploration period. Equity is split Kosmos Petro-Tim (30%) and Petrosen (10%, carried). ■

6 Books To Refresh Your Geology

RASOUL SORKHABI

There is something fascinating about being a college student (even if we may not have fully appreciated it at the time): the energy, an urge for learning our favorite subjects, and hopes for building a great future. Those of us working in the geological sciences and industries have experienced this ourselves in our college years. But, over time, we tend to become more engaged in our specialized fields and projects, and thus have less and less time to refresh our knowledge of general geology. Reading about the progress made, problems still remaining, and prospects of new findings in our science can also be fun. And if we find an informative and engaging book, it would be nice to give it to friends as a birthday and Christmas present. Here I introduce six popular geology books that may be of interest to the readers of *GEO ExPro*.

Reading the Rocks: The Autobiography of the Earth by **Marcia Bjornerud** (2006) is a good start. Written by an experienced geology professor (Bjornerud won the Association of Women Geoscientists 2011 Outstanding Educator Award), this book sums up the vast expanse of geology in a succinct style, and is thus a great review of the subject. The author's choice of titles for the chapters and sections as well as the opening epigrams and quotes give a flavor of poetry to the book; for example, the chapter "The Tao of Earth" begins with this phrase from the Roman writer Plutarch: "For water continually dropping will wear hard rocks hollow" (similar to a phrase in *The Tao Te Ching*). The book is full of information and insight.

Why Geology Matters: Decoding the Past, Anticipating the Future by **Doug Macdugall** (2011) is another well-written book on important topics in geoscience including the geologic time scale, the earth's interior, meteorite impacts, plate tectonics, earthquakes, mountain building processes, ice ages, climate warming, large volcanic eruptions, and so forth. Macdugall, an emeritus professor at Scripps Institution of Oceanography, University of California in San Diego, has published three other geology books - *Nature's Clocks*, *Frozen Earth*, and *A Short History of Planet Earth*.

Richard Fortey's *Earth* (2004) and ***Life*** (1997) are a must not only for the educated public but also for professional geologists. Highly detailed, with historical anecdotes, and written in a masterly prose, these two books take the reader on a tour of 20 geologically interesting places around the world (*Earth*) and through the four billion-year history of life on Earth (*Life*). Fortey, a renowned trilobite paleontologist at the Natural History Museum in London and 2007 president of the Geological Society of London, has won several awards and honorary doctorates for his writings on geology (see *GEO ExPro* Vol. 4, No. 3).

Here on Earth: A Natural History of the Planet by **Tim Flannery** (2010) is a lucid narrative of planet Earth and earth science. It contains 23 chapters on various topics, and builds a solid bridge between geology and the history of humans including their role in the environmental issues of our time. Flannery, an Australian paleontologist, has published a number of books on the ecological history of mammals and present-day climate change.

The Story of Earth: The First 4.5 Billion Years, From Stardust to Living Planet by **Robert M. Hazen** (2012) is a systematic discussion of Earth's history from its birth in the bosom of the solar system to the near-future scenarios of our ever-changing planet. Based on recent research, in even chapters it examines the Precambrian history of Earth like no other popular geology books have covered; chapter 10 ('Green Earth') is the history of Earth from the Cambrian to the Recent. Coming from the pen of a master science writer, this is another must-read book. Hazen is a professor at George Mason University and a researcher in mineralogy at Carnegie Institution's Geophysical Laboratory. Closely related to this book are his recordings (48 lectures, each 30 minutes), *The Origin and Evolution of the Earth: From the Big Bang to the Future of Human Existence* (The Great Courses, 2013).

There are, of course, a number of other fascinating geology books on the market; this list comes from my personal experience and my interest in reading science books.

For many of us, geoscience is a profession (whether in a teaching, research, laboratory, field, industrial, consulting or publishing environment) and probably a passion as well. Reading about geology can be enjoyable and entertaining – so what better gift than a good science book to give to friends and help promote the scientific literacy and public education that our society badly needs. ■

GEOExPro

PESGB

Charity Photo Competition

aberdeen cyrenians

3 Categories
Landscape, Industry, Community

The Cyrenians are a charity based in Aberdeen, working to support all sections of the community, including many who have been devastated by the downturn in the oil industry.

GEOExPro and **PESGB** are delighted to announce their partnership with the **Aberdeen Cyrenians** in 2016. Our first initiative is a photo competition. A selection of the best photos will feature on an A1 2017 Calendar Poster available to buy from the GEO ExPro stand at PETEX in November. **All proceeds go to the Aberdeen Cyrenians.** PETEX delegates will have the opportunity to vote for their favourite photo and the most popular shots will feature as the covers of both the PESGB magazine and GEO ExPro magazine in 2017.

How to Enter:

Send your photograph and caption to **rosy@pesgb.org.uk**
Image must be high resolution, at least 300dpi
Multiple entries welcome but maximum 10 entries per category
Enter one or more categories
Entrants agree use of accredited images in future PESGB and GeoPublishing publications
Deadline September 30th 2016

Independent Geophysical Research

Norwegian Foundation NORSAR is at the forefront of geophysical research. Senior Vice President Arve E. Mjelva tells us about their work.

Can you tell us a little bit about NORSAR?
NORSAR is an independent, not-for-profit, research foundation established in 1968 within the field of applied geoscience. Our core competences are the wider use of seismology, geophysics and related software development within four main focus areas: oil and gas, sustainable energy, safe society and weather and climate.

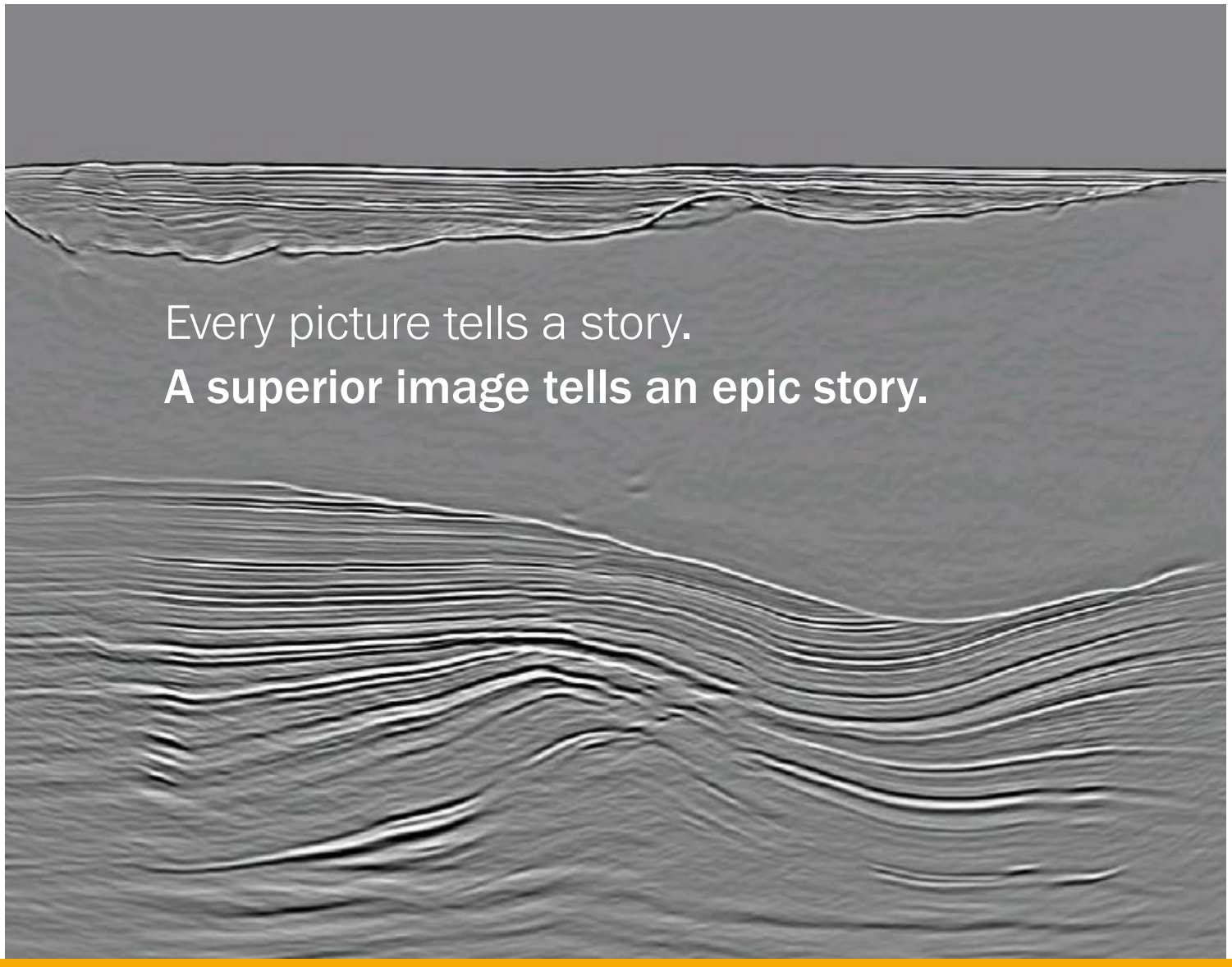
We are at the forefront internationally regarding research and development of software products and services in the field of seismic oil and gas prospecting. The second core activity is microseismic monitoring of both natural and induced seismicity applied to oil and gas production, CO_2 storage, fracking and effective geothermal energy. Thirdly, NORSAR is responsible for operating one of the world's largest seismological installations for monitoring earthquakes, explosions and underground nuclear tests, being the Norwegian National Data Center in the global network verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). In addition, our extensive network of infrasound and seismic stations provides novel observations of weather- and climate-related phenomena in the atmosphere and the cryosphere.

What is its role in the O&G industry?
NORSAR is today a world-leading provider of seismic modeling software and consultancy services to enhance the value of seismic acquisition, processing and interpretation allowing better subsurface imaging. We also provide feasibility studies for microseismic monitoring of petroleum reservoir production and CO_2 storage. Our software products, sold under the brand names NORSAR-2D, NORSAR-3D and SeisRoX, are used for seismic survey evaluation and planning, seismic reservoir characterization studies and a wide range of feasibility studies related to seismic modeling, such as illumination and resolution modeling, PSDM simulation processing, amplitude analysis and synthetics generation. We recently launched a new application called MDesign for microseismic network design.

How important is it that you are independent and not-for-profit?
The not-for-profit policy enables NORSAR to focus solely on R&D and re-invest all surplus into R&D projects. We conduct research on and develop software solutions independent of the O&G contractors and provide objective recommendations and second opinion studies based on state-of-the-art technology. This gives valuable input to ensure that O&G exploration and production can be de-risked and optimized. It also supports an important goal for NORSAR: to be a leader in our fields, able to contribute to society by applying advanced technology into useful products and providing expert services for non-expert users. This applies both to internationally recognized researchers, and also to an institutional competence which ensures that NORSAR's expertise is both reliable and continually increasing.

What subjects are at the forefront of geophysical research?
Today's research within petroleum-related seismic modeling goes far beyond the traditional goal of generating synthetic data. The focus in today's market is on cost saving technologies especially in the marine seismic industry. New technologies like ocean bottom seismic require modeling tools to find a cost effective and optimal design, especially for 4D seismic reservoir monitoring. More computing power gives rise to new possibilities for computer intensive simulations like Kirchhoff migration and the development of new efficient seismic modeling tools which are almost interactive. In addition, we see more integrated software solutions, helping bridge the gap between geoscientists and geologists. Deepwater basins, marginal fields and IOR require better tools for re-processing and interpretation to produce more realistic subsurface imaging, which can be done by modeling the wave propagation in complex anisotropic media. In addition, new fields in vulnerable environments require real-time passive seismic monitoring to de-risk the production.

How did NORSAR develop a specialism in seismic modeling?
NORSAR started out as a seismological observatory focusing on seismic array research for developing methods for the verification of compliance with a future nuclear-test-ban treaty. From this strong competence in interpreting seismological processes by monitoring wave propagation in the earth, NORSAR broadened its research activities to apply the knowledge into new subjects like earthquake hazard and risk assessment and seismic modeling for the petroleum industry. The latter started in 1978 with the aim of developing seismic modeling tools for the emerging petroleum industry to improve and support better subsurface imaging. Later, we expanded into the field of microseismic, which has been very successful. These activities are now part of our core undertakings and have led to our solid, recognized position as a supplier of new innovative software solutions for the O&G industry. ■



Our story begins with a challenge—imaging a reservoir in 2,000 meters of water beneath 6,000 meters of salt. Plot twists include a capable field crew, a flexible commercial model, the acquisition of repeatable, wide-azimuth data, and advanced processing techniques, culminating in a superior image that only nodal technology can provide. And a story that only we can tell. **Read more at fairfieldnodal.com/julia.**

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DATA ACQUISITION DATA PROCESSING DATA LICENSING

27 Years of Misery

Is it time to learn from the past?

Statistics teach some basic history. In the time that Norway has been an oil producer, the oil price was lowest in 1971 (the first year of production) and in 1998, at $13 and $18 (US) per barrel respectively.

In 2015, the price averaged **$52 per barrel**, a catastrophic low both for Norway and for the world oil industry that had grown accustomed to high costs and extensive exploration budgets. But $52 is certainly not exceptionally low if we look at historical figures.

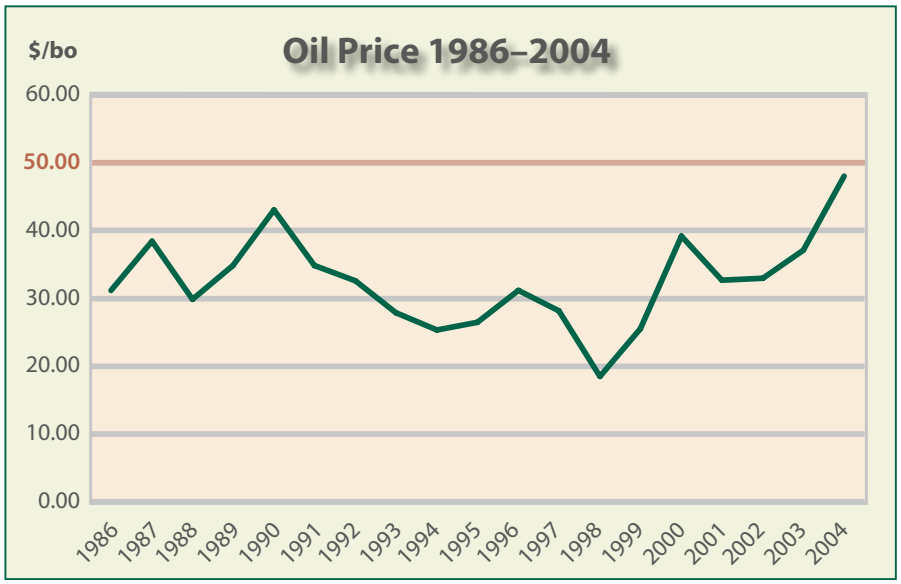
Over the 45 years that Norway has been producing oil, prices have been **lower than $52** a barrel (in 2015 dollars) for as many as **27 years**. It was also consistently lower than the 2015 level from 1986 to 2004 – 19 years – at a time when Norway grew powerful as an oil nation; the average price over that period was $32.5 per barrel.

The 'unfortunate' thing is actually that it was *over* $52 in all years from 2005, and that it bounced well over $100 per barrel in 2008 and from 2011 to 2013. Those are the years when everything went wrong. The knowledge of historical prices suddenly disappeared. History had nothing to do with the future. That is why 2015 became a 'Black Monday'. Politicians, executives, geoscientists all said the same: "High prices are here to stay". Those of you who did not, please raise your hand.

One example of the sad consequences of this neglect of attention to historical statistics is the Goliat field in the Barents Sea, which was put on stream half a year ago. With 180 million barrels of recoverable oil, it probably needs $100 per barrel to break even.

Most people I talk to in the oil industry say that the price will return to 'old highs,' implying a high level is a normal level. But then someone must define what is normal. The average price between 1971 and 2015 was $71 per barrel. Maybe we should be OK with such a price? ■

Halfdan Carstens



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.

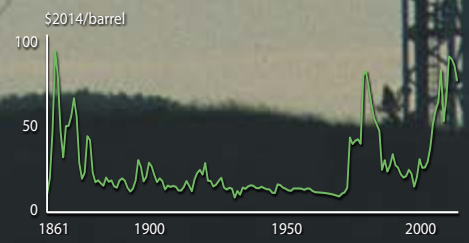
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

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



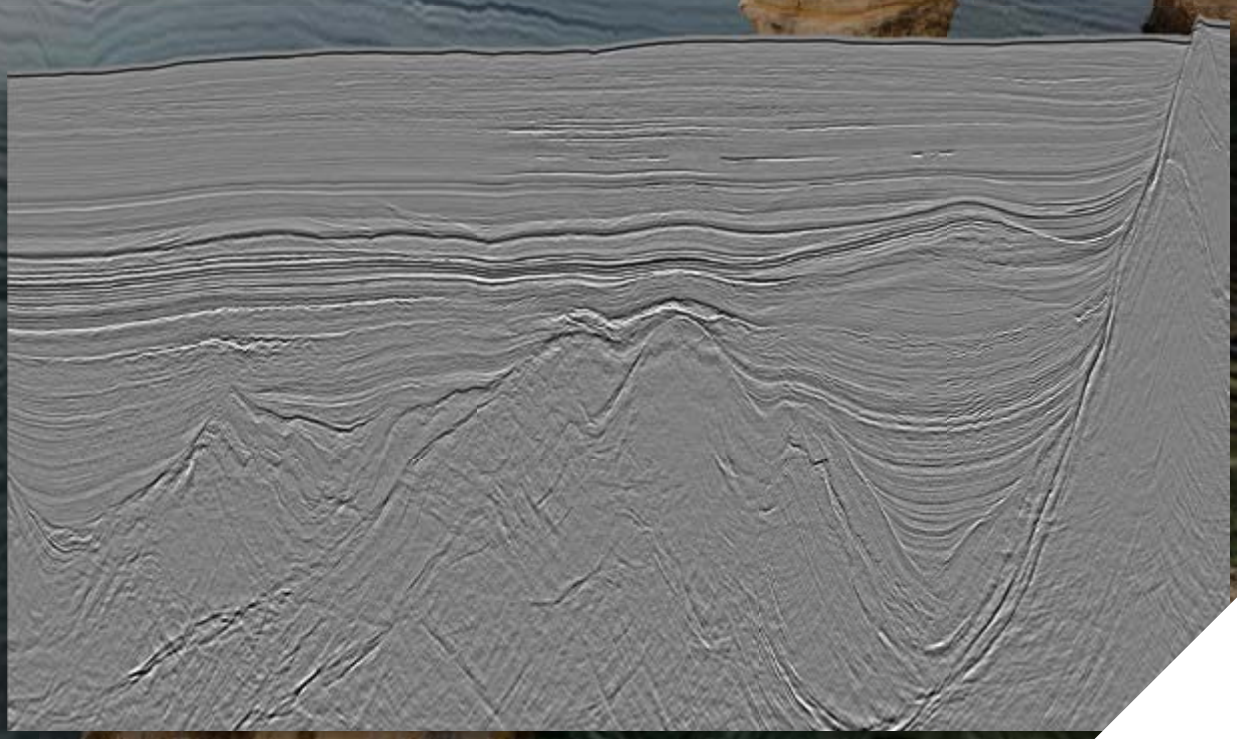
Set your sights.
Portugal 2016

22, 800 km Clari-FI™ Broadband Reprocessed 2D Data Available

The next place to explore is Portugal, and the super-regional TGS Clari-Fi™ reprocessed dataset is what you need to succeed. In recent years East Coast Canada has experienced great exploration success, with several high impact oil discoveries in the Jean D'Arc and Flemish Pass basins. Northwest Portugal is situated as a conjugate margin to East Coast Canada, and great structural similarities can be observed with our high-quality 2D dataset.

To further facilitate your exploration efforts and gain a better understanding of this region, TGS is able to offer high quality, value added digital well data for all released wells in Portugal, in conjunction with the deep-water boreholes drilled under the DSDP, ODP and IODP programs across both sides of the Atlantic.

Let's explore.



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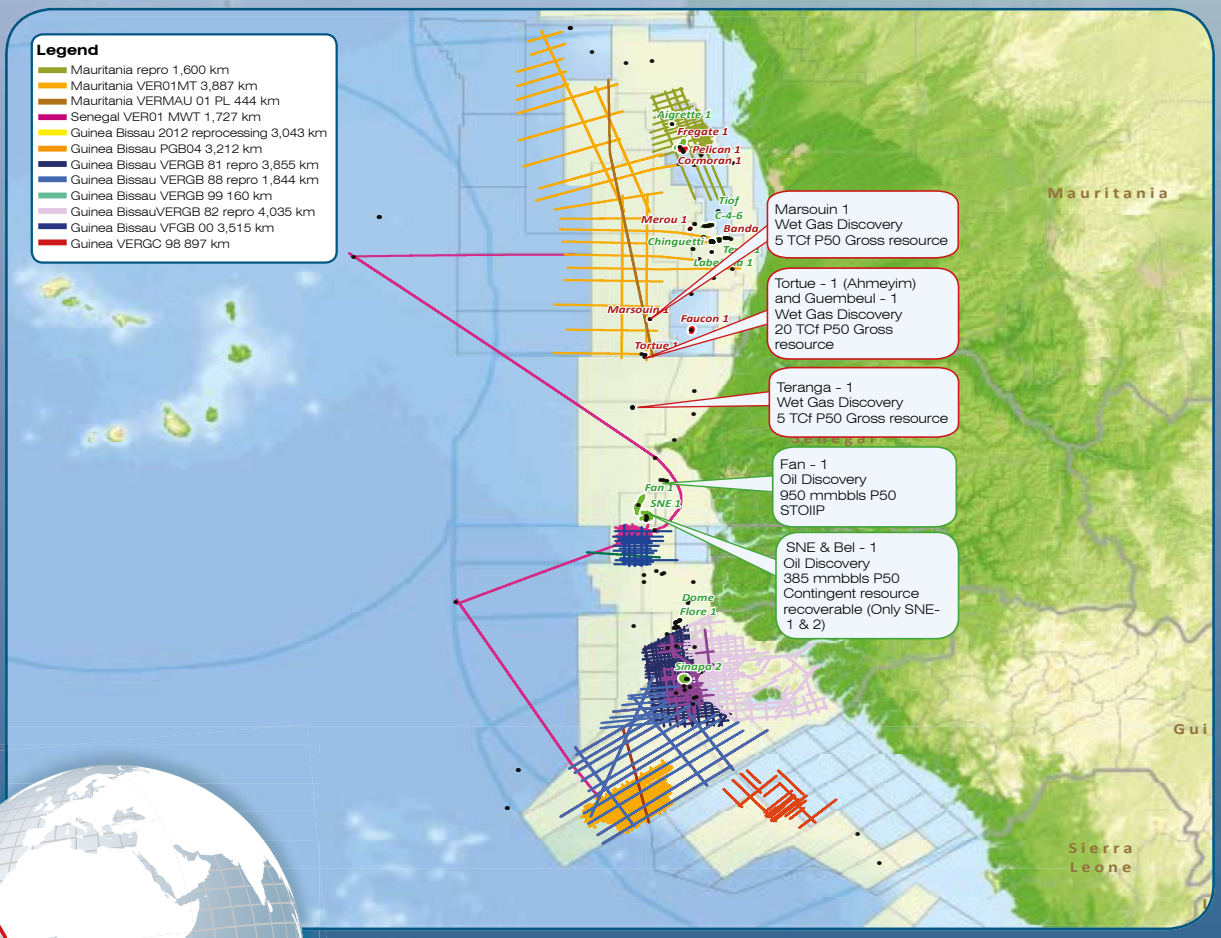

Recent hydrocarbon discoveries in the deep water offshore Mauritania and Senegal have significantly de-risked Cretaceous clastic plays along the North West African margin and opened up the outboard petroleum system. Spectrum's highly competitive seismic data packages in the region provide an excellent regional view for future exploration.

Spectrum 2D seismic data reveals substantial continuation of prospectivity offshore North West Africa, including a diverse range of plays, extensive fairways and numerous deep water fans and shelf leads. There remains great potential for further gas and oil discovery across this margin.

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