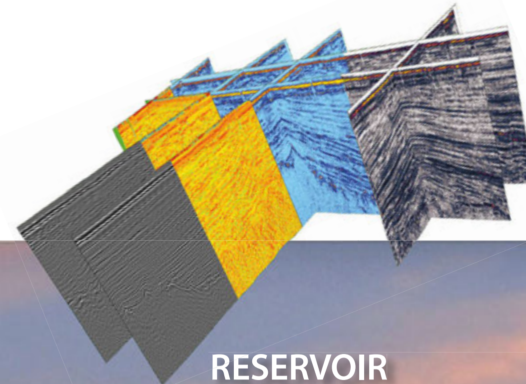
VOL. 17, NO. 3 – 2020

# GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED



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RESERVOIR MANAGEMENT
Journey to the Centre of the Earth

ALTERNATIVE ENERGY

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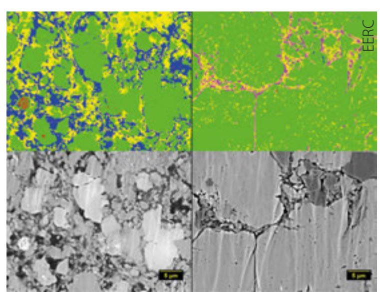


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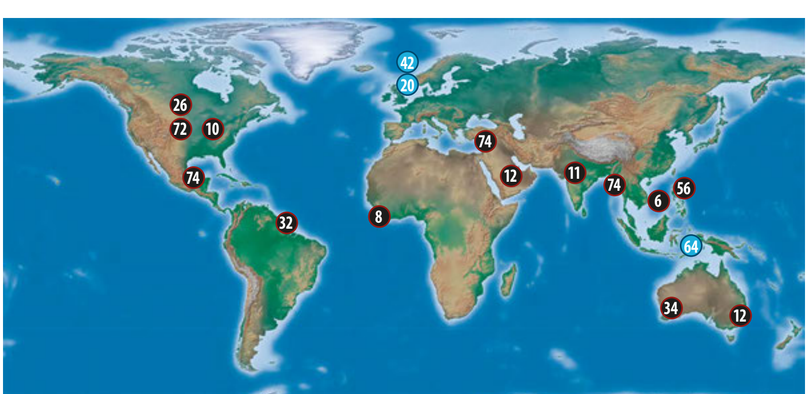


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This issue of *GEO ExPro* Magazine focuses on Europe and South East Asia; Unconventional Exploration; Visualisation and Imaging; and Alternative Energy

# Energy Reimagined


Erich Westendarp/Pixabay

According to the International Energy Agency (IEA), global energy demand declined by nearly 4% in the first quarter of 2020. Oil demand reduced by nearly 5% in the same time period, driven primarily by massive reductions in flights and road transport as lockdowns were enforced in many countries throughout the world, while gas demand was down by 2%. Recovery is expected to be gradual, with demand unlikely to reach pre-Covid levels before the end of the year, and oil prices are still volatile and will probably remain at low levels for some time.

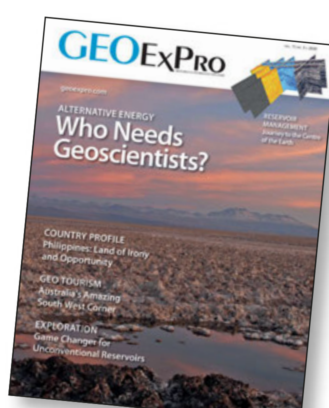
The oil industry has been hit by a ‘double whammy’ of lower demand and lower prices; Rystad Energy predict that global E&P revenues could fall by as much as a trillion dollars in 2020. However, the crisis has stimulated further moves in the E&P industry to increase productivity and cut costs, as well as increase the use of digitalisation, AI and remote operational tools. Some organisations will not survive these difficult measures, but many feel that they can now be profitable in a $35-a-barrel world.

Meanwhile, the only energy source that recorded an increase in demand, according to the IEA, was the renewable sector, increasing in the first quarter of 2020 by about 1.5% in comparison to 2019. Despite reduced demand, renewable electricity generation increased by almost 3% in the first quarter as new wind and solar projects came on stream. The use of renewables is expected to rise by nearly 5% in 2020. Crucially, with that $35 oil price, renewables can compete with many oil and gas projects.

Should we be worried by these developments? One thing that has become abundantly clear from this crisis is that energy security is vital for the whole global population. In particular, we all need a reliable supply of electricity. Without that, our hospitals could not have functioned and the economic activity that has been maintained through home-working and virtual networking would not have happened. Renewable energy has supply issues just as oil and gas does but as we move to a lower emissions world, choice and variety in our energy supply is vital, and we need to work together to ensure that supply is available to all.

As the CEO of BP, Bernard Looney, recently said: it is time to start reimagining energy. ■

***Jane Whaley***
*Editor in Chief*




WHO NEEDS GEOSCIENTISTS?

The salt flats of the Salar de Atacama are the world’s largest and purest source of lithium, currently supplying over 35% of the world’s lithium carbonate supply. A new generation of geoscientists is needed to work in the energy industry of the future.

Inset: Innovative visualisation and imaging techniques help to bring the subsurface world to life.



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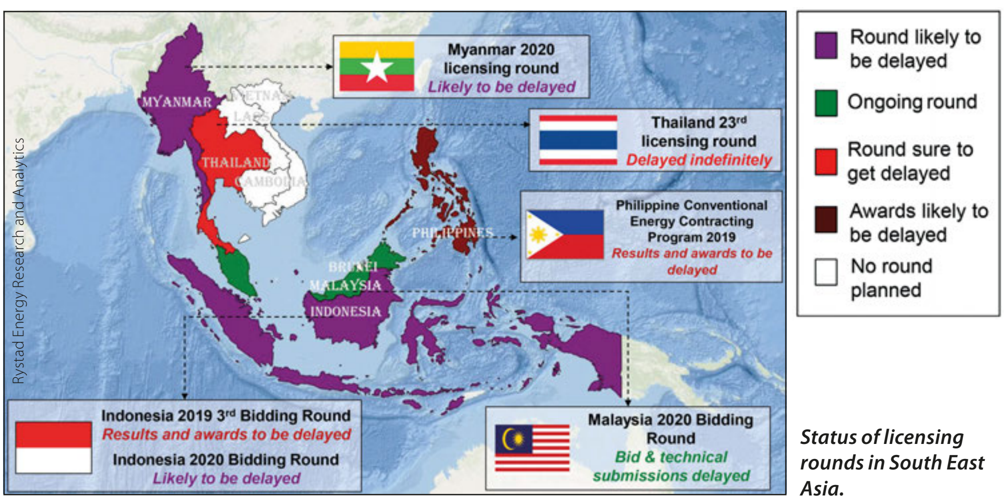
# Challenges in South East Asia

The South East Asian upstream sector initially entered 2020 with ample optimism, with a long list of projects lined up ready to help the industry recover from the downturn. However, the situation took a fast turn with the Covid-19 pandemic, leading to a sharp decline in fuel demand and the resultant oil price crash.

South East Asian explorers started 2020 with new licensing rounds and extensive exploration drilling and seismic programmes planned but the current economically challenging conditions and the uncertainty created by Covid-19 is likely to extend, delay or temporarily suspend these activities. In **Indonesia**, SKK Migas has reported a reduction of 56% in exploration drilling, 84% in its 3D seismic studies and 49% in 2D seismic planned for 2020. A delay in the announcement of both the 2019 3rd Bidding Round awards and the 2020 Bidding Round is expected. In **Malaysia** certain exploration programmes by PTTEP and Petronas are likely to continue but at a slower pace and deadlines for submissions for the ongoing 2020 Bidding Round have been deferred. **Thailand's** long-awaited 23rd licensing round has been delayed indefinitely; however, drilling activity is likely to continue in this low-price environment. **Myanmar** started 2020 with the Mahar discovery and has a 10-well plan for 2020 by Eni, Posco and PTTEP which is likely to continue as most of the rigs are already contracted, but the 2020 licensing round will probably be delayed to 2021. The evaluation/award stage of the recently closed **Philippines** licensing round will be slowed down, while in **Vietnam**, Eni's plans for Block 114 are likely to be delayed.




*Status of licensing rounds in South East Asia.*

## Reduced Sanctioning

South East Asia expects reduced sanctioning activity during 2020, with merely 100–150 MMboe of reserves reaching final investment decision during 2020, down from an average of over 800 MMboe since 2015. Across the region revised investment budgets, lockdowns and uncertainty around prices mean major projects will be delayed. The Limbayong gas development in Malaysia had FPSO awards due in 2019 but now longer delays are expected as operator Petronas is unlikely to go alone on this geologically complicated deepwater development. In Indonesia, the 2020–2021 production schedules for Merakes, Tangguh phase 3 and Jambaran-Tiung Biru will almost certainly be delayed. SKK Migas has revised down its annual production targets accounting for delay in the start-up of top projects and lower production enhancement activities. Although south-east production may not be impacted significantly in 2020, the region faces the risk of much higher production decline in the future due to the cascading effect from postponed projects. With over 70% of production coming from the mature assets and around 4.5% year-on-year decline, delayed sanctioning and start-up of new projects mean the region might witness an increased decline rate of over 7% by 2024. That said, planned activities on major NOC-operated projects in Indonesia, Thailand and Malaysia will have a crucial role in minimising the impact on production.

Overall, we expect the South East Asia upstream sector to face a challenging year as operators and oil companies try to balance prioritising projects, managing cashflows for survival and maintaining future growth. ■

**Eugene Chiam, Rystad Energy**

## ABBREVIATIONS

**Numbers**
**(US and scientific community)**

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

**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.

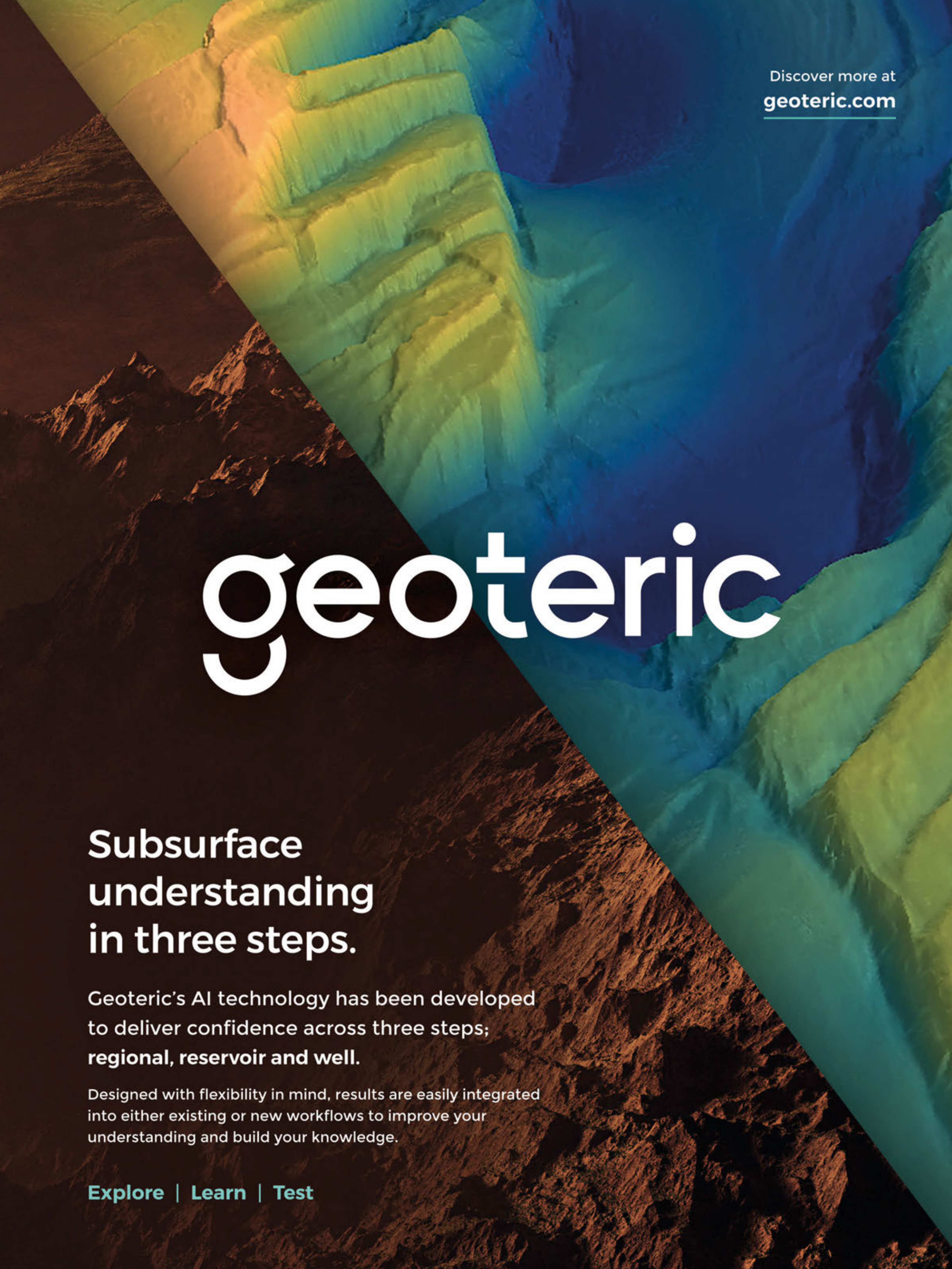
**Reserves and resources**

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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Licensing Update

# Liberia: Undrilled Harper Basin

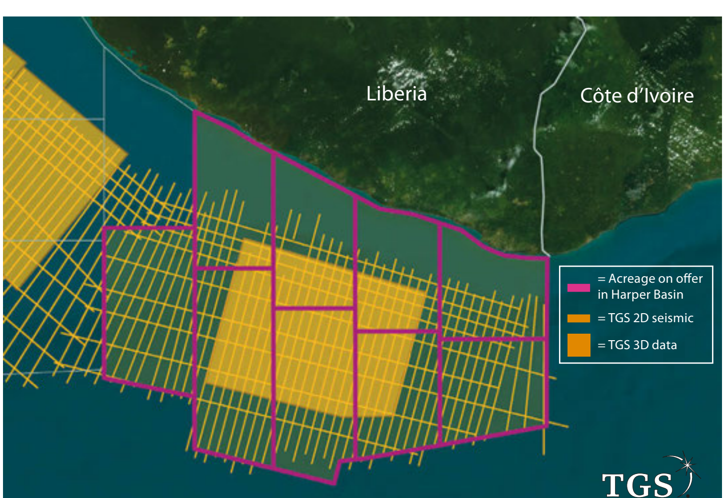
Unlike many countries, Liberia has decided to continue with its planned 2020 Licensing Round, which was launched in April – fully embracing the current situation by using a webinar as the launch vehicle and conducting a number of online interviews and participating in further webinars and virtual meetings.

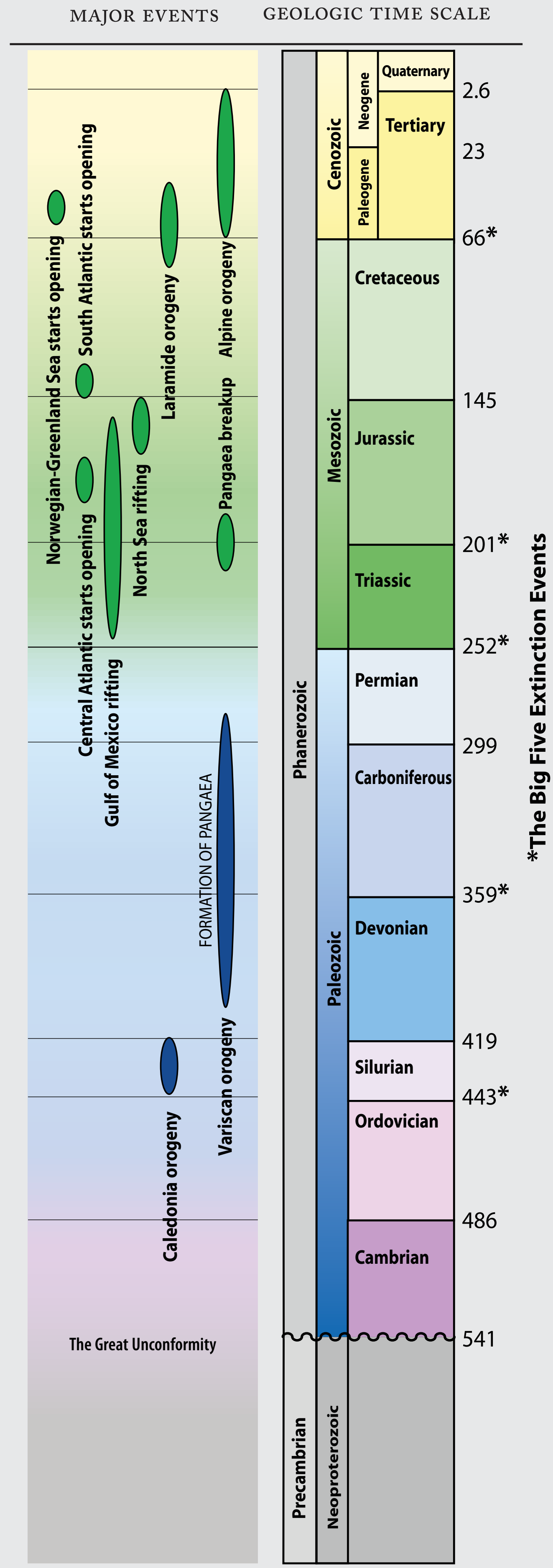
The round offers nine blocks, each up to 3,500m², covering all of the offshore Harper Basin, which is situated in the south-eastern part of the country and is one of the only remaining undrilled and essentially unexplored areas of the West African Transform Margin. Water depths range from less than 200m to over 3,500m. Over 17 wells have been drilled offshore Liberia, all in the Liberia Basin to the north-west of the Harper Basin, and although no commercial discoveries were made, several sub-commercial discoveries prove that there are working petroleum systems offshore Liberia.

Nearly 6,000 line-km of 2D and 6,167 km² of 3D seismic data cover the blocks on offer, together with marine gravity and magnetic data. TGS, which is working with the Liberian authorities on the licensing round, believes that this data reveals significant subsurface prospectivity that suggests that the Harper Basin has a petroleum system analogous to those of surrounding basins associated with the recent discoveries in Ghana, Côte d'Ivoire and also the conjugate Guyana. The company has identified many leads and prospects across the entire basin.

The geological history of the region is closely related to the opening of the Atlantic Ocean. Sources are thought to include Albian lacustrine and Cenomanian marine shales and, in common with other basins on the West African Transform Margin, the main reservoir targets are Albian and Upper Cretaceous sandstones. Anticipated plays include tilted fault blocks; syn-rift basin floor fans; pinch-outs against growth faults; and channel systems such as turbidites and contourites.

The licensing round has been timed to coincide with positive amendments to Liberia's Petroleum Law, including a provision for a mandatory 5% interest in all petroleum agreements to be awarded to Liberian-owned companies and the extension of the exploration period. The bid submission period starts on 1 November 2020 and the license round closes at the end of February 2021. This bid round is specifically for the Harper Basin, but there is a provision in the Law to allow for direct negotiation for blocks in the Liberian Basin. ■



# What's on for Geos at AOW 2020?


In a volatile oil price environment, **Africa Oil Week (AOW)** understands that enabling deal-making is now more important than ever. So, the refined AOW 2020 programme will bring fresh opportunities for the event's geophysical and geological communities, which have supported AOW throughout its 27-year history.

**Geo Showcase:** With an audience of VPs and SVPs of Exploration, New Ventures and Africa, the Geo Showcase aims to facilitate the development of new opportunities across Africa. The concept is simple: G&G companies present proprietary information on their 2D or 3D seismic, in a strict 30-minute time limit.

**National Showcases:** When the world emerges from the current pandemic, the onus will be firmly on African governments to promote their country as a destination for investment. AOW's 2020 National Showcase Programme will offer 21 countries the opportunity to host a bidding round or demonstrate information on exploration history, seismic updates, future drilling campaigns and commercial terms.

**Exploration Technology Forum:** New for 2020, this Forum expands AOW's focus from traditional E&P to exploring the technology unlocking wider geological insights and hydrocarbon potential of the most compelling frontier markets. Presenters will showcase their latest research and innovations to an audience of operators and NOCs. ■

# PGS Targets East Shetlands


*The seismic vessel Ramform Tethys.*

One of the most popular areas for bids in the UKCS 31st Offshore Licensing round in 2019 was the frontier area of the **East Shetland Platform**, abutting the mature graben axes of the **North Sea** rift system. Historically, this region had been dismissed as a broad flat high, with shallow basement and few visible structures, but results from **GeoStreamer** surveys undertaken by **PGS** between 2011 and 2016 have revealed significant unexplored potential (see *GEO ExPro* Vol. 14, No. 6). The company now believes that the East Shetland Platform comprises an alternation of persistent basement highs and intra-platform Permo-Triassic depocentres containing a nearly continuous Palaeozoic-Mesozoic succession, with Middle Devonian source rocks and fault- and tilting-related migration pathways.

In order to discover more about this promising area, PGS recently undertook a 3D broadband seismic multiclient survey covering both frontier and mature parts of the East Shetland Basin to enable the interpretation of the internal reflectors of the main Brent Group reservoir level. The new dataset will help de-risk the less tested Upper Jurassic Intra-Draupne sandstone analogue of the Home and Magnus sandstones and improve understanding of the trapping mechanism and the petroleum system.

The PGS seismic vessel Ramform Tethys has completed work on the survey and the first data is expected Q3 of 2020. ■

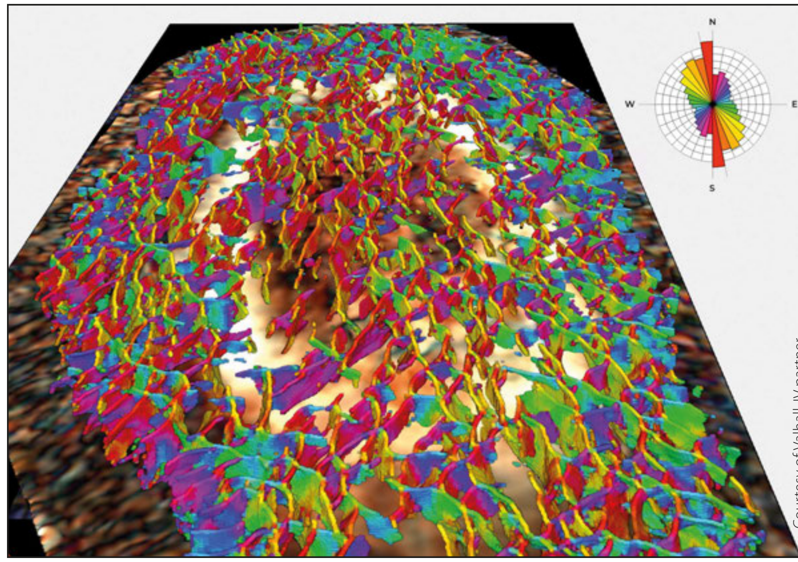
# A Virtual Platform

**The Oil & Gas Leadership and Success Virtual Summit**, which will be held from **July 6–10, 2020**, is being organised in response to the challenges the industry and world is facing. This online only event will bring together the top oil and gas business experts, industry thought leaders, key stakeholders, strategic thinkers and operational leaders.

You will be able to access five day's-worth of content live or on demand addressing the challenges arising from the current oil industry crisis. Panel discussions and presentations from C-Suite and senior executive speakers will cover a broad range of topics with the objective of helping you to navigate the current problems being faced within the industry. This is indeed a virtual platform for thought leadership, ideas and solutions!

Showcase your brand and gain targeted exposure to the O&G industry leaders, influencers and potential clients by sponsoring or being part of the Exhibition Gallery. ■

# Enhancing Operational Efficiency with AI



Courtesy of Valhall JV partner

The **Valhall** field is located in the Norwegian sector of the North Sea, at 70m water depth. Producing oil from the Upper Cretaceous chalk for over 35 years, the densely faulted field is heavily compartmentalised. As the reservoir is depleted through production it compacts, resulting in significant subsidence extending up to the seabed.

To see if any further structural knowledge could be gathered from their data, earlier this year **AkerBP** undertook an **AI Fault Interpretation** project with **Geoteric**. Their data-driven AI technology was able to delineate with a high degree of accuracy the faults that are present in the reservoir interval and in the overburden.

The AkerBP Lead Geophysicist stated: "AI fault interpretations are proving to be very useful inputs for well planning. They are full field from the shallow overburden to the reservoir, our most comprehensive fault interpretations to date", adding: "This has improved the rigour of our work so that our decisions are based on a better understanding of where faults may introduce drilling risks, and so that we can better understand lateral changes in our reservoir". ■

# India's $CO_2$ Emissions Fall


Photo by Yogendra Singh from Pexels

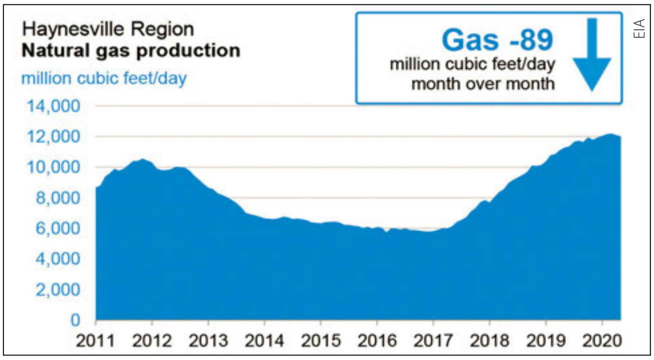
According to the environmental website CarbonBrief, **India's $CO_2$ emissions** have fallen year-on-year for the first time in 40 years, showing a drop of about 1% in the fiscal year ending in March 2020. Obviously, the economic slowdown resulting from Covid-19 is a significant factor in this – Indian $CO_2$ emissions fell 15% in March, and probably about 30% in April – but statistics show that the country has been reducing emissions even without coronavirus.

The main reason for the deceleration of the increase in $CO_2$ before the pandemic was a slowdown in the expansion of coal-fired electricity generation. Since 2005 India's $CO_2$ emissions have doubled, primarily due to the use of coal, but also as the result of a strong increase in electricity demand in the country, partly driven by a drive to bring electricity to every village. In recent years, however, there has been increased competition from renewables which has reduced the reliance on coal: in the first six months of 2019, for example, wind, solar, and hydro generation met a record 70% of the increase in electricity demand, according to CarbonBrief (www.carbonbrief.org). The percentage of the supply of energy from renewables has remained the same throughout the pandemic.

While the power sector has been the largest contributor to India's greenhouse gas emissions, its industry and oil consumption have also been seeing significant growth in $CO_2$ output as the country's economy expands. However, growth in oil consumption has been slowing since early 2019, down 5% on average over the past 10 years.

The trend in India's $CO_2$ emissions is of global importance because since 2013, the country has accounted for more than half of the increase in global $CO_2$ output. With a population of 1.4 billion it is one of the world's fastest-growing major economies, and while the country has impressive and ambitious targets for the energy transition, ensuring that its citizens have access to electricity and clean cooking must remain a major energy priority, along with efficiency, sustainability and security. ■

# LNG Decline in Haynesville




The **Haynesville Basin**, one of the most important basins for **liquefied natural gas** exports in the US due to its proximity to existing and planned terminals, is expected to see output decline by as much as 20% by 2023 if Henry Hub prices remain at an average of their current value of \$1.80–\$1.90 per million British thermal unit (MMBtu), a **Rystad Energy** analysis recently revealed. This suggests that an average of only 20 horizontal wells a month will be put into production, meaning that Haynesville gross gas output will fall from 12.5 to 10 Bcfd throughout 2020–2022 before stabilising in 2023. If prices averaged \$2.20–\$2.40, there would be about 30 new wells a month, allowing production to remain roughly at its current level. Rystad Energy's own base case scenario has Henry Hub prices steadily recovering to nearly \$3 per MMBtu in 2022.

According to Rystad Energy, no meaningful slowdown in Haynesville production has been identified so far, but the total number of horizontal wells spudded has already declined from approximately 110 to 120 wells per quarter in 4Q17–3Q19 to 85 wells in the first quarter of this year. With the current rig count, the basin will likely be down to 75 horizontal spuds per quarter by the end of 2020. Similarly, about 94 wells were put onto production in the basin in the first quarter of 2020 but the recent decline in fracking will likely result in about a 15% contraction in the nuimber of wells put on production in the second quarter of the year. ■

# Australian Energy from Hydrogen


**Australia** took an important step towards developing a hydrogen industry in May 2020 when key legislation passed through Parliament. It is thought that the brown coal resources in the Latrobe Valley in the **Gippsland Basin** in south-east Australia – 25% of the world's known brown coal reserves – are the ideal feedstock for hydrogen generation, creating energy that can both be used in the state of Victoria and potentially exported.

In fact, a pilot project to look at ways of safely and efficiently producing and transporting clean hydrogen from the Latrobe Valley to Japan was set up in 2018. Called the **Hydrogen Energy Supply Chain**, this is the first such pilot project in the world. The project envisages a seven-stage hydrogen supply chain, which first requires the gasification of brown coal to produce synthetic gases, including hydrogen. The refined hydrogen gas would then be sent by truck from the Latrobe Valley to the Port of Hastings in Victoria, where it would be converted to hydrogen liquid, stored, and ultimately transported to Japan using an advanced technology, purpose-built ship. If the pilot is successful, commercial production should commence this decade. The project would require carbon capture and storage to ensure low emissions.

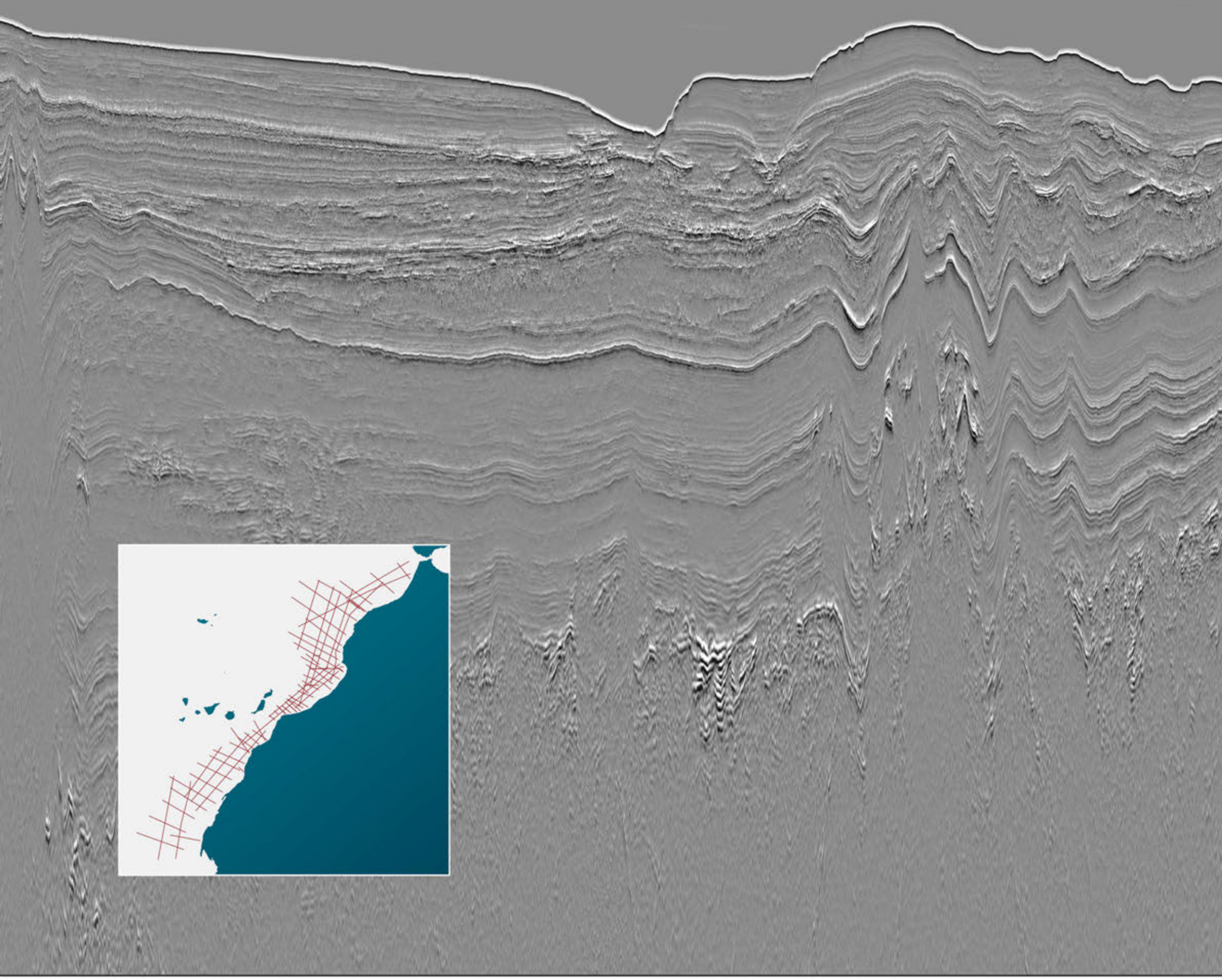
The photo above shows the the Suiso Frontier, the world's first liquefied hydrogen carrier, launched in December 2019 in Japan; the large central hydrogen tank is not yet installed. ■

# Sercel, Sinopec and Saudi Arabia

With over 50 systems deployed worldwide, the **Sercel 508$^{XT}$** is considered the industry's most field-proven acquisition system for all types of **challenging land surveys**. The company have recently announced the successful large-scale deployment of this leading seismic data acquisition technology for a mega-crew survey currently being conducted by **Sinopec Geophysical Co. (SGC).**


***Nomad 65 Neo all-terrain vibrator trucks.***

The survey, covering large areas of **Saudi Arabia**, began in late 2019. An extensive range of Sercel equipment is being used to meet the requirements of this project, including over 60,000 channels of Sercel's 508$^{XT}$ land-based seismic acquisition system and a fleet of more than 45 Nomad 65 *Neo* all-terrain vibrator trucks that are providing the source. By simplifying field operations and offering full monitoring capabilities, Sercel's revolutionary cross-technology architecture optimises productivity. When combined with Nomad 65 Neo vibrators and vibrator electronics' Smart LF function, accurate high-resolution data can be generated and recorded at low frequencies (down to 1 Hz). This allows for a more detailed broadband seismic image and attributes without the noise issues that would otherwise arise. SGC reported that it had reached target VP figures within the first few days of commencing activities. ■



# Who Needs Geoscientists?

## The evolving role of geoscience through the energy transition.

MIKE SIMMONS, ANDY DAVIES, ANDY W. HILL and MIKE STEPHENSON

At the time of writing, the world is enduring the effects of the Covid-19 pandemic, and the global economy is struggling. Nonetheless, we should look ahead to a brighter future and consider the role of geoscience once society returns to something resembling normality.

The start of the 21st century has seen unprecedented cultural and behavioural change as the energy transition accelerates. Geoscientists, who are fully committed to overcoming some of the societal and environmental challenges this raises, will see, in turn, a diversification of career opportunities as society and industry evolves. In addition to their domain expertise, geoscientists are typically skilled in problem solving, deductive thinking, data integration, and holistic approaches to assessing risk and uncertainty, as well as data visualisation in 3D and 4D. Consequently, they are well placed to help solve the energy and resource challenges of the future.

Prior to the pandemic dominating the news, environmental issues were being extensively reported, seldom placing geology-related extractive industries in a positive light. Consequently, there has been a dramatic decline in uptake of undergraduate geoscience courses. Many British universities are declaring a climate emergency, and encouraging geoscience departments to disassociate from relationships with extractive industries – particularly oil and gas.

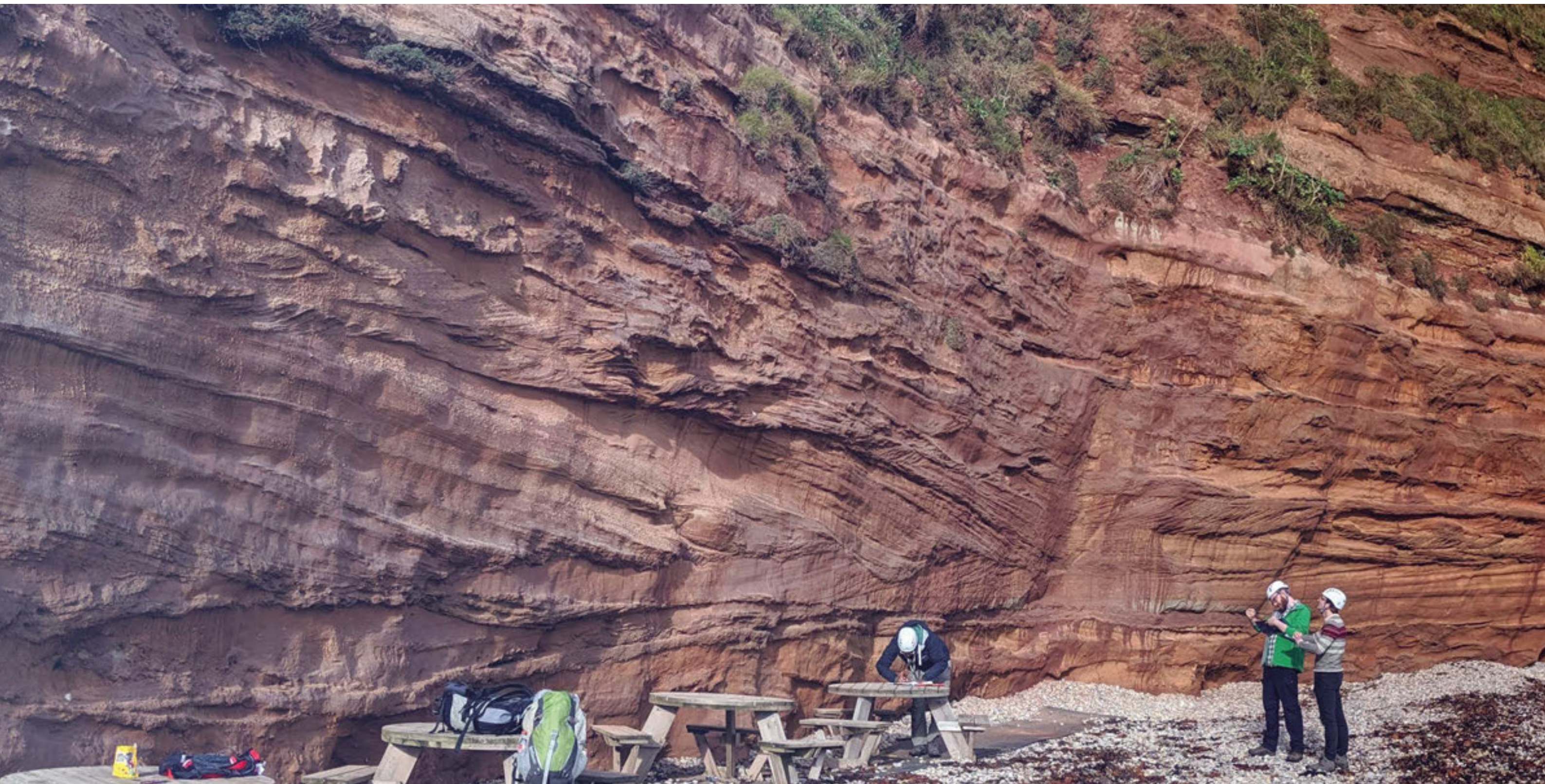
This article examines the importance of geoscience to our changing society, and how the subject is evolving to meet the challenges created by economic and population growth, while society demands changes in our sources and use of energy and resources. We contend that the evolving role played by geoscientists will be vital to maintaining prosperity and sustainability.

### The Energy Transition

Access to affordable energy is essential for economic growth and social development, yet energy production and consumption generates about two-thirds of global greenhouse gas emissions. Without a paradigm shift in the efficiency of energy usage, a growing global population will inevitably consume more energy, as every nation seeks economic growth to ensure the prosperity and well-being of their citizens.

There is a clear link between energy consumption and life expectancy (Figure 1). Globally, one billion people do not have access to electricity and three billion do not have clean fuels for cooking. This delivers a negative imbalance in both health and economic opportunity, especially for the female population in developing countries. Population and economic growth will likely drive global energy demand growth in the developing world by around 50% by 2050, according to the Energy Information Administration (EIA).

The fundamental question is: how will the rising demand for energy be sourced while minimising, and preferably reducing, related impacts to climate change? Renewable energy sources will form an increasing proportion of the energy mix, especially as the price of their supply falls. The EIA forecasts that by 2050 renewables will be the single most important source of energy globally – but in pre-pandemic supply predictions almost all energy



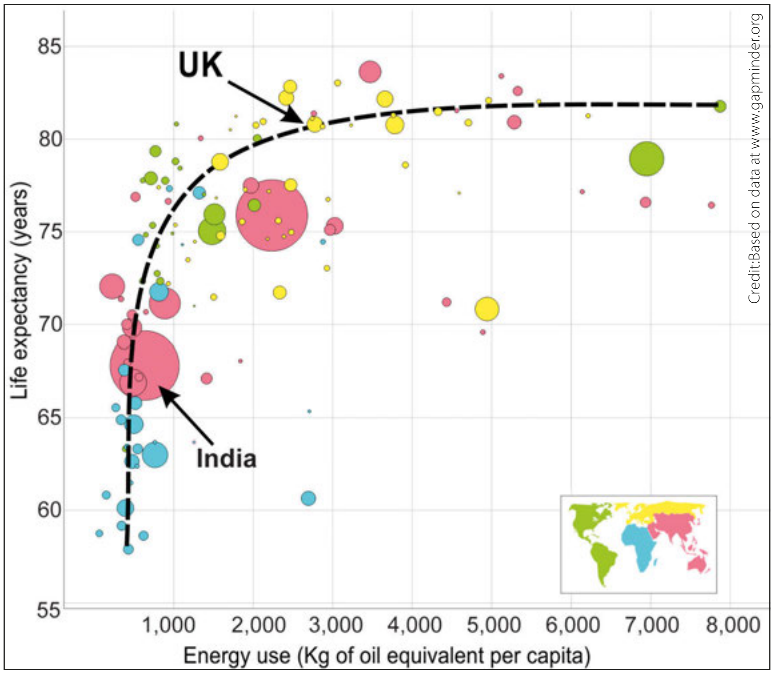



*Figure 1: Life expectancy vs. energy consumption (data for 2014). Each coloured bubble represents a country, size proportionate to population. A clear trend indicates that greater energy consumption relates to greater life expectancy.*

sources see rises in supply (Figure 3) so by 2050 global energy will be supplied in almost equal proportions of oil, gas, nuclear and renewables, with only coal reducing. This effect is seen even in scenarios that model a rapid transition to renewable sources. Hydrocarbon demand for petrochemicals — to make the materials to allow electric cars to be lighter and run further, for fertilisers, medicines, medical supplies and clothing feedstocks — shows no indication of being displaced.

Why will the energy mix continue to be diverse over coming decades? Key issues relate to energy density (e.g. to power an aircraft engine, or industrial machinery), geopolitics and the capital intensity of the energy system. Our infrastructure is dominated by machines and buildings that are relatively long-lived. New cars tend to be run for at least ten years before being changed, let alone scrapped, while power stations can operate for 30 years or more. This acts as a brake on the pace at which new sources of energy can displace the old.

## Evolving Hydrocarbon Industry

Geoscientists working in the energy resource industries, especially oil and gas, face a challenge to be as responsible as possible in obtaining these resources. Across the industry, moves are underway to reduce the production carbon footprint and the methane intensity of operations. Oil and gas exploration strategies are shifting from quantity to quality, with companies aiming to locate resources with the lowest carbon footprint and with minimum impurities (e.g. no $H_2S$ or low $CO_2$ cuts) and selectively develop only the best.

Economic considerations and environmental factors are not incompatible. Wealth generated from the extraction of oil in a developing nation can help it achieve many of the UNESCO sustainable

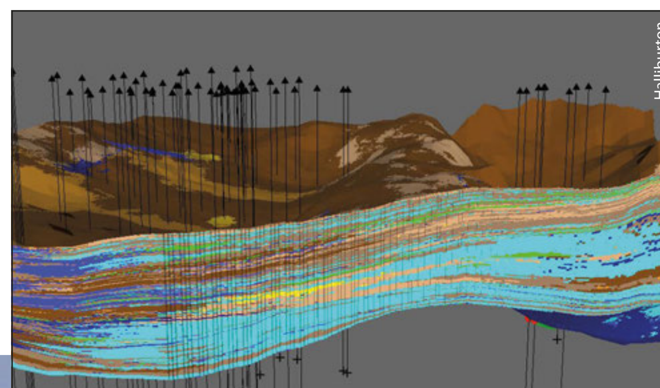




*Figure 2: Outcrops, such as these Triassic fluvial sediments in North Devon, can be used to build better digital models of reservoirs (insert). Better understanding of reservoir-scale geology is needed to drive efficient, low-environmental impact, oil and gas production and to model $CO_2$ repositories.*

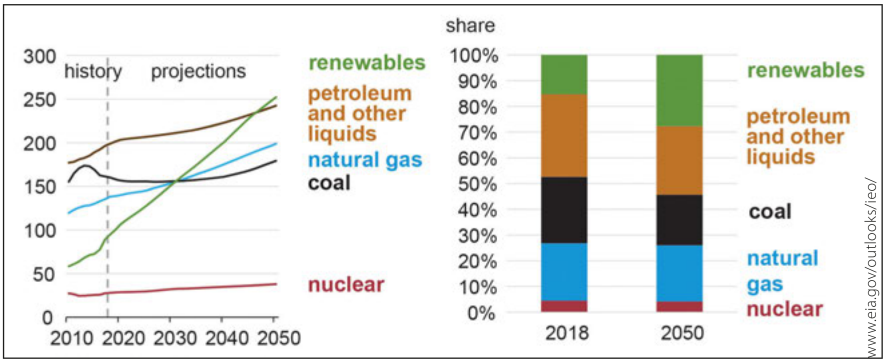



*Figure 3: Projections of global energy consumption (quadrillion BTU). By 2050 renewables will have become the most important energy source, but other remain significant.*

development goals. A far smaller carbon footprint can be seen in recent major discoveries off Guyana, for example, compared with large US onshore shale oil plays. The Guyanese Liza development will initially produce 120,000 bopd from only eight subsea production wells with a development capex of $3.2 billion, compared with the same production being achieved by over 1,000 wells with a development capex of $10.5 billion in the US Permian Basin.

A fundamental understanding of reservoirs and the overburden will only grow in importance in order to reduce well numbers by optimising placements and trajectories, and to ensure long-term production integrity (Figure 2).

The same geoscience skill-set will also contribute to carbon neutrality targets. Carbon capture and underground storage will only grow in importance. Secure storage will require geoscientists who can locate and model suitable subsurface repositories for $CO_2$, and model the behaviour of $CO_2$ injected into those repositories, and who can undertake ongoing monitoring of the subsurface. The hydrocarbon industry has long injected $CO_2$ into the subsurface to enhance oil recovery and has a good understanding of the processes involved.

As oil and gas operators transition into energy companies, many are increasing their investment in wind power. Determining the appropriate location for wind farms requires an analysis of numerous factors, but understanding soil variability and implications to foundation design is a key concern. In the North Sea, for example, the considerable variability of shallow sediments resulting from Quaternary glaciations faces key technical challenges associated with a buried landscape of glacial and fluvial channels and thrusted moraine complexes.

Geothermal energy is another potential geoscience growth area. Once suitable locations have been identified, such as areas of elevated heat flow and coal mine-related geothermal sites, the behaviour of water injected into permeable layers requires a sound understanding of the subsurface.

### An Insatiable Appetite for Resources?

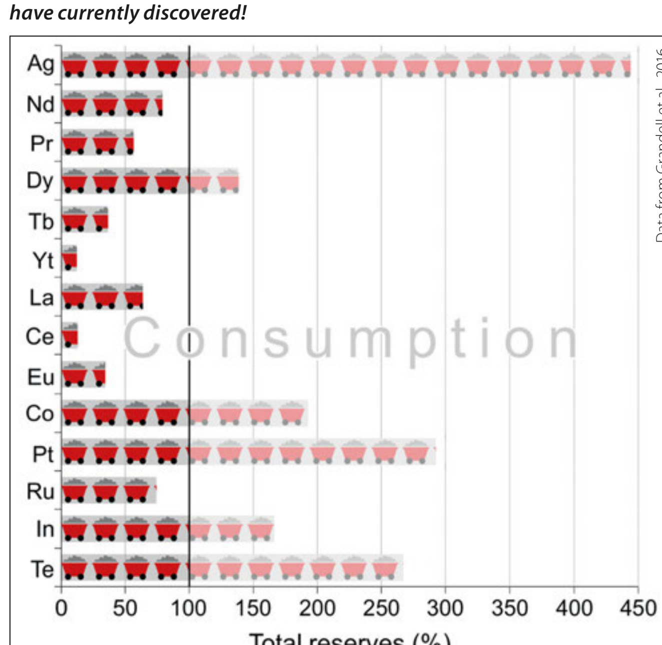
What about geoscientists working in extractive industries outside of the energy sector? Global society's relentless appetite for technology places a heavy demand on minerals, especially metal ores. Moreover, the energy transition and renewable energy technology places a heavy demand on silver, cobalt, lithium carbonate, copper and various rare earth metals such as neodymium. A leading group of academics within SoS MinErals, an interdisciplinary programme of research, estimated that over 200,000 tonnes of cobalt will be needed to make all UK cars and vans (not including goods vehicles) electric by 2050, and powered purely by battery by 2035. This is twice the current annual global production (Figure 4). Similarly, 2.5 million tonnes of copper will be required, half the annual global production. If these figures are scaled-up globally, the metal resource demand to support renewable energy is, at the risk of understatement, spectacular!

Notwithstanding enhanced recycling and efficiencies in end usage, mining geologists are going to be busy locating these resources. This may involve deep-sea mining of cobalt crusts on seamounts, manganese nodules from the deep ocean floor, or sulphides from around hydrothermal vents. There are major environmental concerns and trade-offs to be reconciled before such approaches can proceed. As noted by Grandell et al., (2016): "…solar energy future projections presented in the IPCC Fifth Assessment Report do not seem to be realizable with the currently known technologies and metals resource."

### Geoscience Also Evolves

The impact of the digital data revolution on geosciences is highly significant. Computing power has accelerated in line with Moore's Law, while data science is accelerating the pace at which routine tasks are executed (Figure 5). The combination of ever-increasing computing power and data science is providing new scientific insights, thereby

*Figure 4: Predicted demand until 2050 for selected metals needed for renewable energy in relation to current global mineral reserves. 100% is all reserves known to date, so we need four times more silver than we have currently discovered!*



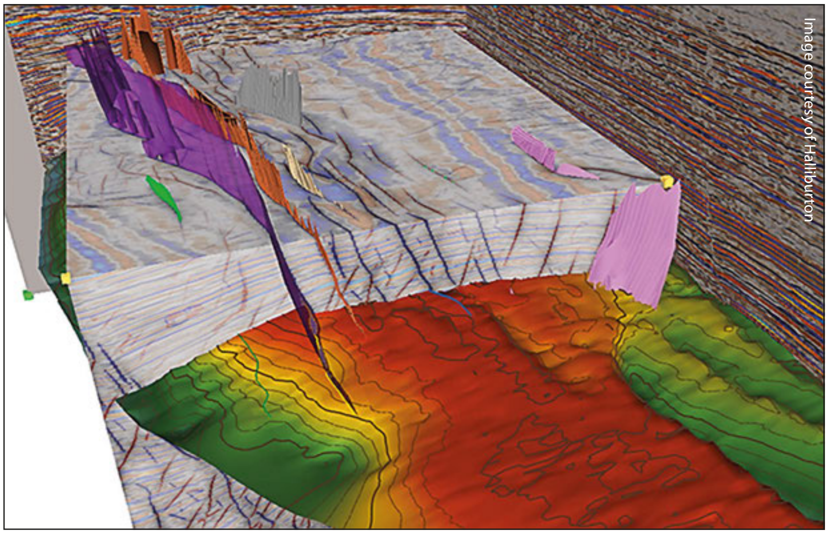



*Figure 5: A seismic volume in which faults have been detected using machine learning. Labelled (i.e. previously interpreted) data are used to train algorithms to recognise features (in this case faults) in data. Such interpretations take seconds instead of days.*

transforming all resource industries, contributing to improved efficiency and associated environmental benefits, such as reduced emissions and reduced footprint. The future geoscientist needs to be technology and data science literate, but with a sound foundation of fundamental geoscience knowledge.

At this key time in our planet's development there is still much to learn about processes operating in and on our Earth today compared to past activity and their implications to the evolution of life through geological time. A key area for research is Earth Systems Science, which takes a holistic approach to integrate tectonics, sedimentary systems, palaeoclimate and eustasy (Figure 6). Such approaches offer potential for modelling the effects of climate change, with current and future change being informed by comparison with identified changes in our geologic past. Geoscience research not only provides us with the potential to understand past natural atmospheric behaviour, but to use that understanding, such as can be gleaned from the Eocene warming, to calibrate our future climate models. At the same time, this provides an understanding of present natural geological contributions to the atmosphere, including $CO_2$ from volcanism and $CH_4$ from natural seepage, or the identification and value of natural net carbon sinks like wetlands, and the need to protect or restore them.

The fundamental understanding of the risks from natural hazards such as volcanism, earthquakes and tsunamis, is significant to the global population and economy. Similarly, geological study supports the selection of environmentally neutral, yet safe, holistic designs for flood protection or coastal erosion, which may be crucial to the protection of communities faced by increasing weather-related impacts of climate change.

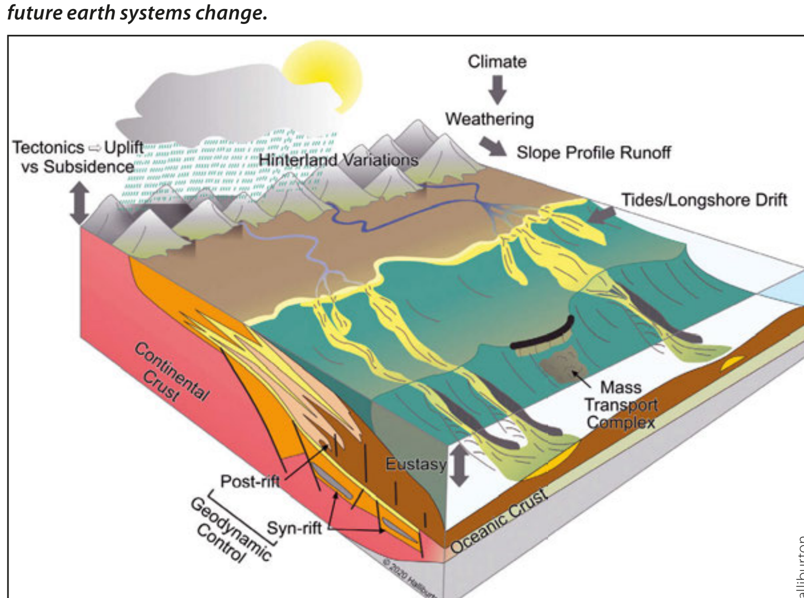
Indeed, the role of geoscience in supporting safe urban growth and nourishment of the world's growing population cannot be understated. The current global population of 7.8 billion is projected to rise to 11 billion by 2100. As the global population expands, water supply is likely to be one of the major challenges societies face. Hydrogeologists are needed to locate and manage aquifers as climate evolves, and to protect them from pollutants. The monitoring of subsidence from water abstraction and associated increased flooding risk similarly highlights the critical input of hydrology.

It has, therefore, never been *more* relevant to study geoscience. Not only to understand the way the Earth has developed to its current state, but also to understand its future. Geoscientists have an immediate role to play in public understanding and education: society has never needed them more than now to maintain a healthy and prosperous world that meets UNESCO sustainable development goals. Consider, for example, how readily available and reliable energy has facilitated communication during the current Covid-19 crisis or how access to energy industry high performance computing centres is facilitating research into vaccines and medication.

There is an urgent need to publicise the benefits that geoscience brings to society, and to encourage a new generation to study it, in preparation for a diversity of emerging, related career opportunities. We need to send a clear message to society that we are a vital part of the solution to achieving a prosperous, yet sustainable, future for our planet.

*References available online.* ■

*Figure 6: Schematic representation of a holistic Earth Systems Science approach, including source-to-sink concepts. The whole geological tectono-sedimentary system is considered from sediment source to its ultimate destination in a basin, with a variety of earth systems factors controlling this. Such an approach can inform understanding of past, present and future earth systems change.*



# GeoStreamer X in the Viking Graben Illuminates Complex Targets

To meet the industry demand for improved subsurface insight at a reduced cost and with faster turnaround time than ocean bottom surveys, PGS deployed a pioneering acquisition configuration in the Viking Graben in the autumn of 2019. Three months after the last shot on the GeoStreamer X survey in the Viking Graben, the early-out multi-azimuth (MAZ) PSDM seismic stack was delivered to pre-funders. From an interpreter's point of view the results are stunning, and what started as a novel concept now provides new insight to geoscience teams in near-field exploration, appraisal and development.

There are many targets in the area, ranging from Eocene sand injectites to fractured basement, and an approach integrating survey design, imaging solutions and quantitative interpretation has enabled a significant improvement in the resolution of these reservoirs. The main imaging challenges are the large shallow channels and massive sand mounds in the Miocene as these introduce shadow zones beneath them. Eocene cemented sand injectites, called V-brights, have anomalously high velocities which historically have been very difficult to estimate. Deeper, a thin, rugose Cretaceous chalk layer causes multiples and dispersion of the seismic energy.

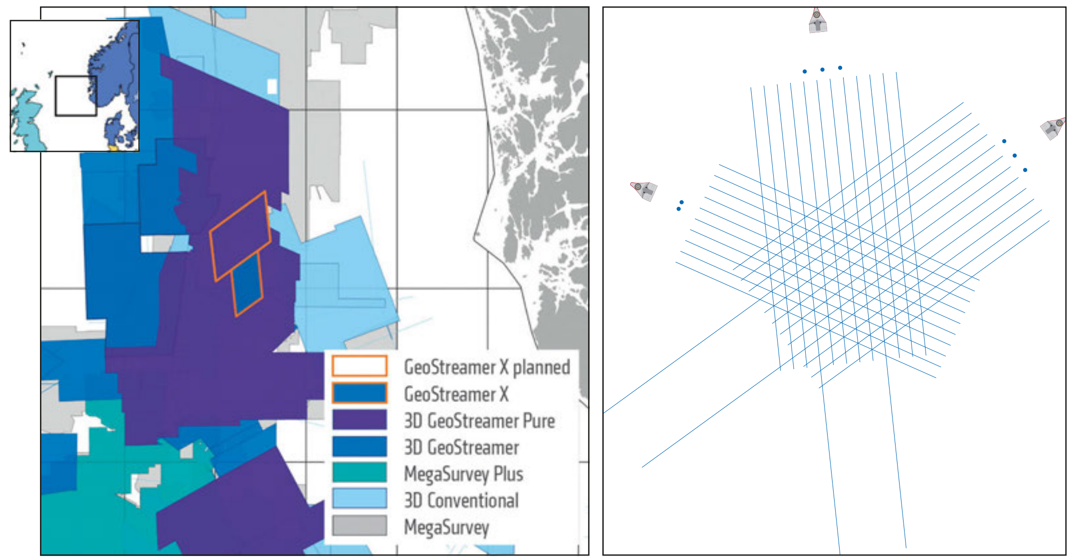



*Figure 2: The GeoStreamer X Viking Graben location (left) and acquisition configurations (right). Two new azimuths were acquired in 2019 in addition to the 2011 survey; the new azimuths are indicated by the two extended streamer tails.*

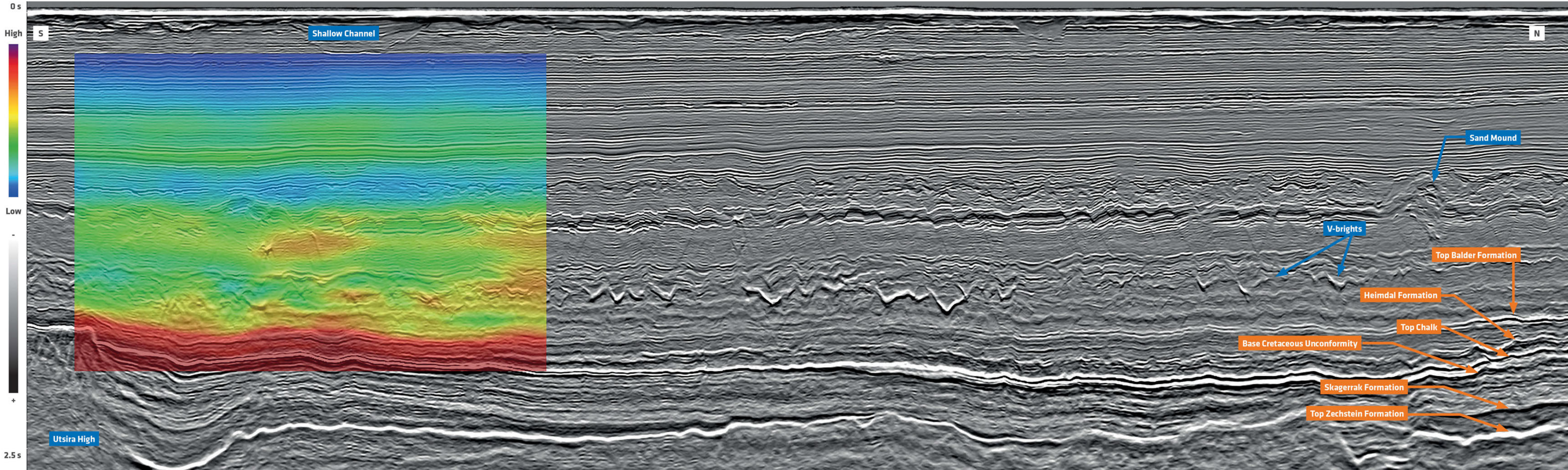



*Figure 1: An early-out PSDM full stack seismic section with a partial velocity overlay starting on the Utsira High in the south (left) and stretching north (right) to the Gudrun Terrace. Faults in the Tertiary section are sharper and reflection continuity is radically improved in the Paleocene and Jurassic section, refining seismic interpretation and de-risking the location of the source kitchen, reservoir targets, trap size and competency.*

# GeoStreamer X: A Fast and Efficient Solution

**A faster, smarter solution tailored to the geological and geophysical challenges and with a significantly reduced environmental footprint.**

**KAI FLØISTAD AND JULIEN OUKILI, PGS**

The pioneering new acquisition configuration used by PGS for this survey combines wide-towed sources close to the multisensor streamers with longer offsets and multi-azimuths. The result is a high-resolution, multi-azimuth illumination seismic dataset with an accurate velocity model and robust and reliable AVO attributes. It is suitable for near-field exploration, appraisal and development. Being acquired with 12 streamers on a ten-streamer pre-plot also makes the dataset suitable as a 4D baseline.

As shown in Figure 2, the 2019 acquisition added two new azimuths and used a 12 × 6 km × 85m high-density multisensor streamer spread, including two 10-km long streamer tails, and a wide-towed triple source with 225m separation between outer source arrays. These additional azimuths are complementary to the existing GeoStreamer multi-client data coverage from 2011. All three datasets form the basis of an efficient azimuth- and offset-rich acquisition and imaging solution designed to resolve the main geological and geophysical challenges in the area.

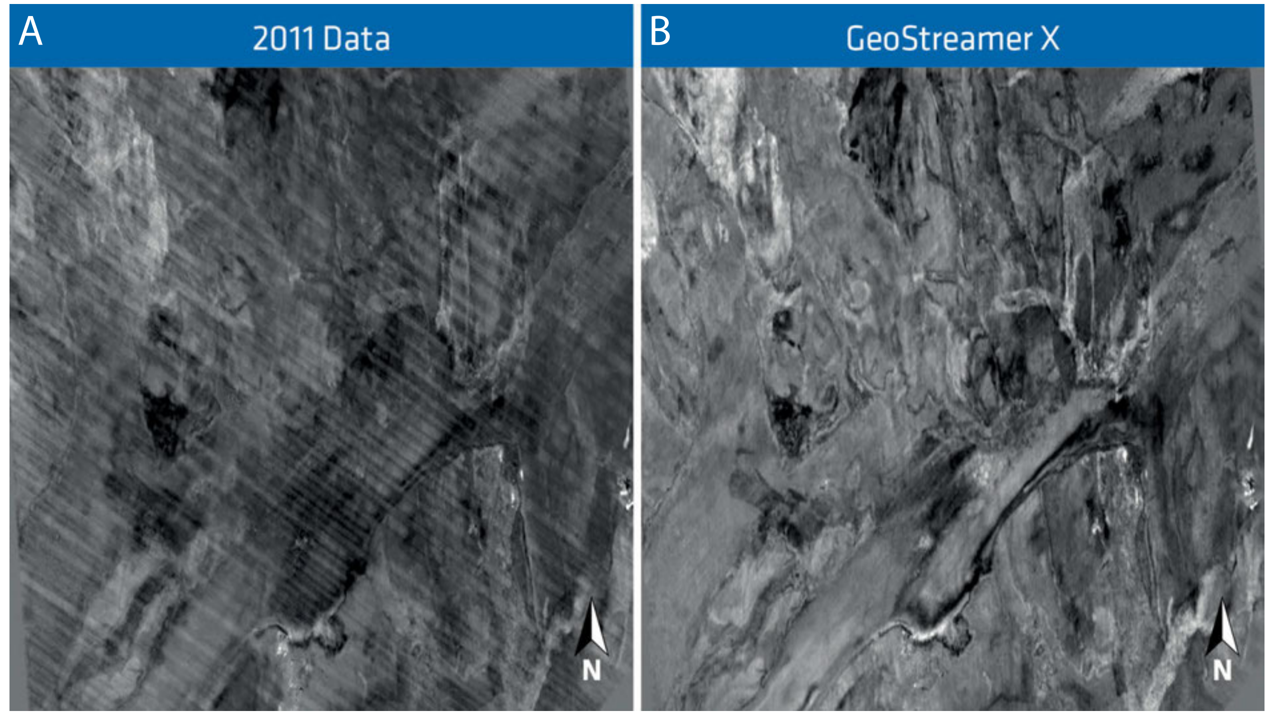
### Wide-Towed Sources: Multiple Benefits

The GeoStreamer X Viking Graben survey demonstrates full coverage of reliable near offsets in the 50–125m range. The improved near-offset coverage is achieved by distributing multiple sources widely along the front end of the streamer spread, thereby increasing confidence in the AVO attributes. Reducing the distance from the outer streamer to the nearest source enables towing of wider streamer spreads, which increases lateral data coverage and provides efficiency gains in acquisition. The extension of two streamers to 10 km for the two new directions, combined with the wide triple source set-up, generates appropriate sampling for a velocity survey using full waveform inversion (FWI).

### Resolving the Shallow to Reveal the Deep

The MAZ time slice (Figure 3B) reveals a number of large channels within the first 50 – 350 ms below the seabed. With a conventional acquisition set-up (one azimuth), imaging of these channels has been an issue due to the lack of near-offset data. The original survey configuration shows clear acquisition footprint (Figure 3A) which can have a detrimental effect on amplitude analysis and interpretation. While the sail-line related amplitude footprint may be mitigated in processing, the lack of detail in the image has serious consequences for shallow amplitude analysis, be it for drilling hazard identification or shallow prospectivity analysis (for example in the Barents Sea). Properly resolving and characterising these channels provides a clear improvement in the seismic section underneath.

*Figure 3: Shallow seismic time slices (224 ms TWT) of the 2011 data after reprocessing (A) and 2020 early-out GeoStreamer X MAZ stack (B). The acquisition footprint on the MAZ stack is barely visible, adding confidence to the channel interpretation.*



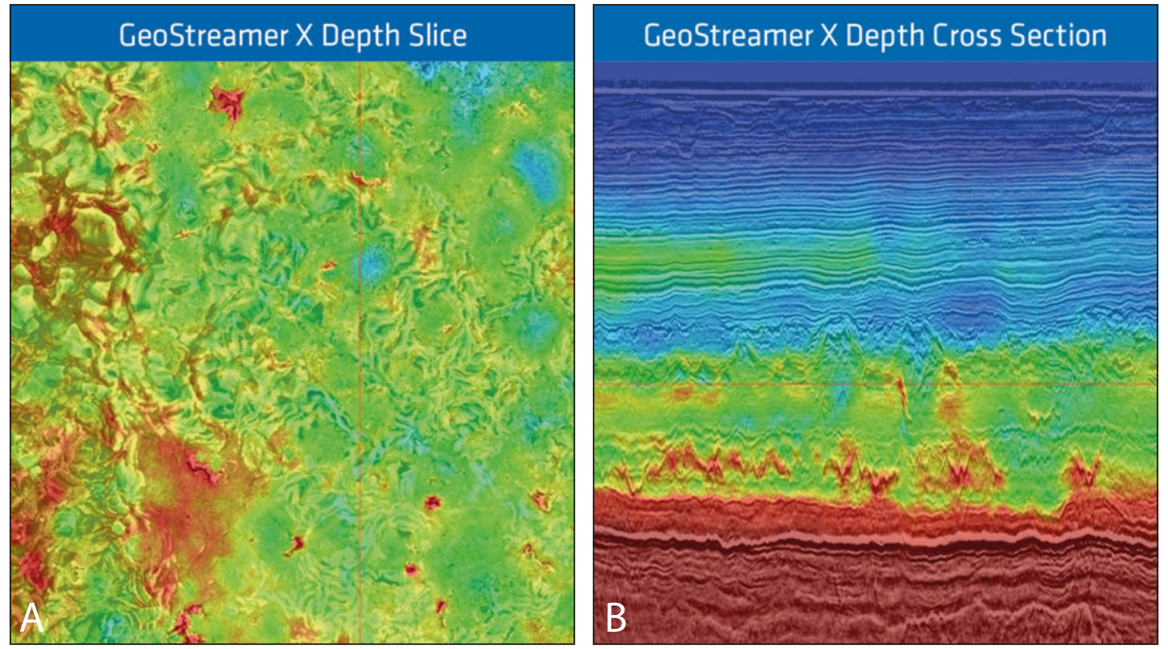




*Figure 4: Depth slice at 1,280 ms (A) and depth cross-section (B) of the early-out GeoStreamer X full stack product with the current velocity model. The new FWI results using all azimuths show clear improvements; note especially how precise the velocity contrast of the sand mounds (blue circular features on depth slice) and V-brights (red features) are defined. Key targets are located immediately below these velocity anomalies, so resolving the velocities properly is key to revealing their exploration potential.*

The early-out GeoStreamer X products have delivered on expectations, in terms of both timing and quality, as seen on the seismic examples in Figure 3. There is a significant increase in signal-to-noise ratio and clear indications of illumination improvements. The full benefits will be revealed when utilising all of the azimuthal data simultaneously in the velocity model building work and the final imaging stages. The full integrity processing is ongoing and includes a complete rework of the 2011 velocity model to take full advantage of the rich offset and azimuth distribution from the new acquisition. At present, the bulk of the low wavenumber updates using refraction data for FWI are complete. This focuses the early inversions using the 10 km long-offset datafrom the two new survey directions and provides a stable and accurate background velocity model. Anisotropy was incorporated and will be reviewed with the more detailed velocity updates based on reflection data (the latter is a mix of FWI and ray-based tomography).

As illustrated in Figure 4, the velocity model is already updated at all depths, down to the acoustic basement. The first rounds of inversions were performed using frequencies from 2 Hz to 9 Hz and were effectively able to pick up both low and high velocity anomalies. It is worth noting that some of the velocity contrasts are rather weak but nonetheless important, and validating the velocity model correlation with the seismic requires that we observed both small and large contrasts. In the examples shown in Figure 4 the intermediate depths are highlighted as they show complex sand systems and mounds. The resolution of this particular interval was considerably improved due to the increased fold and additional azimuths provided by the long offset data between 6 and 10 km. The long streamer tails have contributed to both increased penetration depth and increased overburden accuracy in FWI.

The ongoing work with the higher resolution velocity updates will resolve thinner layering, in the order of tens of metres, and sharpen velocity contrasts as well as give a higher dynamic range in the velocities. Ultimately, with the improved illumination at the imaging stage, all the final pre-stack depth data will benefit from minimal angular and azimuthal misfits and can be optimally combined. This not only reduces noise in the image, but also improves resolution, depth accuracy and interpretability.

### Define Challenge – Apply Technology

GeoStreamer X is a flexible acquisition and imaging integrated solution tailored to the geological and geophysical challenges, be it illumination and resolution of injectites in the Viking Graben, shallow targets in shallow water such as in the Barents Sea or better illumination around salt structures in Brazil. The ambitious goal of GeoStreamer X is to deliver an effective solution for improved reservoir insight. Using a single Ramform vessel, geoscience teams were provided with the early-out MAZ PSDM seismic data three months after the last shot, delivering superior data quality efficiently with a turnaround comparably to a conventional NAZ survey. GeoStreamer X has proved to be a faster and smarter solution than nodes with a significantly reduced environmental footprint as an added bonus. ■

# Game Changer for Unconventional Reservoirs

**No, we are not talking about a new drilling or fracking technology, but a way to accurately model and calculate true moveable fluid phase saturation in organic-rich shale reservoirs.**

THOMAS SMITH

New and greatly improved technologies in drilling, hydraulic fracturing and imaging have been the game changers that helped lead the oil industry into the shale revolution. The advances in these technologies have brought costs down and production up, yet efficient development and finding the 'sweet spots' in these vast fields still remain elusive. A new way to calculate and model saturations in organic-rich shales described in this article could have profound effects on infill volumes, future field development and global oil supply projections.

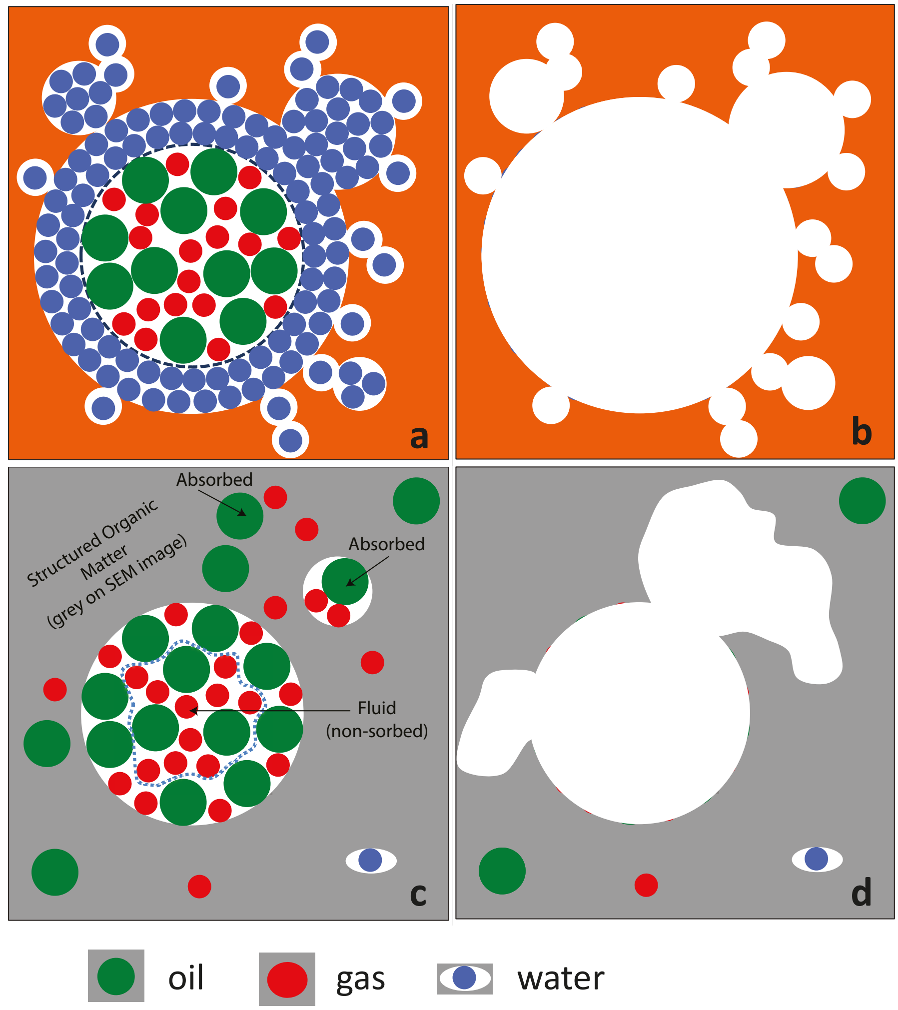
Developing any conventional oil field is a daunting process. Multiple development options often exist and selecting the best one can make huge differences in ultimate recovery and overall profitability. Conventional fields have known extents concentrated in discrete accumulations or pools. Saturations of oil, gas and water are well understood, as is the relative movement of these elements through the reservoir when being produced. Now, imagine developing the resources from a widespread, very low permeability and porosity oil-charged horizon composed primarily of shale. Over the vast areas that some of these reservoirs occupy, finding the 'sweet spots' and developing them efficiently at current oil prices is essential if a company and this play is to remain profitable.

To date, saturations in organic-rich shale reservoirs have been calculated using methods ported from conventional reservoir and shale dry gas reservoirs. These methods did not account for oil molecules sorbed in/on organic matter in an immobile, solid state. A new and independent method for calculating saturation patterns in

organic-rich shale reservoirs subtracts the immobile sorbed oil component, making it possible to calculate the true fluid phase saturations in these reservoirs. Having the ability to calculate accurate recovery factors has an impact on reservoir drainage efficiency and well spacing. Companies can now optimise landing zones based on these new saturation patterns.

### Pore Systems

"While developing our method for calculating water saturations, we looked at both mineral matrix and organic matrix pore systems," says Andrew Pepper, Managing Director of This is Petroleum Systems LLC. "The big difference between the two is the presence of organic sorption in the latter system. We took pore sizes about 4 nm, or about the resolution of an SEM [scanning electron microscope] image. Current core analysis methods employ Dean-Stark clean and extraction to recover all the water and extractable oil from the samples. The pore system cartoons (shown here as a, b, c, and d) clearly illustrate the differences where the organic matrix pore system has a considerable amount of oil and gas molecules locked or sorbed into/onto the matrix and thus not moveable. The cartoons also clearly illustrate how the Dean-Stark method for recovering the water and oil from cores can give misleading saturations in this type of rock. The problems illustrated in cartoons b, and particularly d, persist in current standard mudrock core analysis."



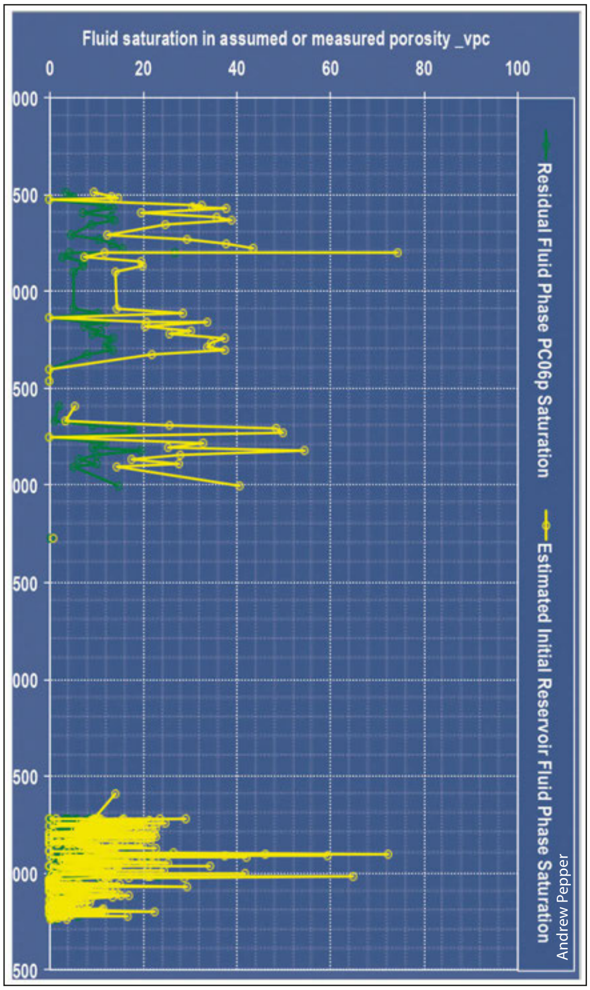

*(a) shows the total pore system, although only the large circle is actually visible; the 3–5 nm resolution limit of SEM imaging means the smaller and parasitic pores are actually invisible; (b) shows the quantities of Dean-Stark water and organic extract (reported as oil), assuming that the Dean-Stark process is able to access the water molecules in the tiniest pores; (c) presents the same size pore space in an organic-rich shale, showing both the pore and the matrix system. Note the sorbed molecules of oil and gas are both in and attached to the matrix, outside the dotted blue line. Only the molecules inside that dashed line are in the fluid state. (d) shows the quantities of organic extract and solid organic matter removed by overly aggressive solvent extraction during cleaning. The white space will be reported as pore volume even though it includes sorbed molecules that were part of the solid state.*

### Quantifying Sorption

"Sorption is a bucket term that includes adsorption (of molecules onto pore surfaces) and absorption (of molecules dissolved in the solid organic matter)," says Andrew. "Sorption is an important process in both the conventional and unconventional parts of the petroleum system, since it controls and delays the transfer of molecules generated from kerogen into the true pore space of the rock. Generated petroleum molecules must be expelled from organic matter before they can form a phase able to accumulate in the mineral matrix or organic matrix pore system as an unconventional reservoir fluid; or migrate through the mineral matrix or organic matrix pore system to a conventional reservoir."

Being able to accurately subtract the sorbed oil fraction from the total fluids and predict moveable oil became a priority for Andrew and his team. They needed a way to predict a sorption coefficient from the shale geochemical data. Sorption models were developed in the 1980s and use an estimate that carbon can sorb 10% by weight. These estimates were based on the pyrolysis volatile hydrocarbon yield, usually called S1 in Rock-Eval parlance. When it came to organic-rich shales, Andrew recognised the need to further quantify sorption coefficients and has since built a database that has been validated by data from the Delaware Basin and elsewhere.

"We noted that the higher amount of sorbent (kerogen carbon) and the higher the sorption coefficient, then the more petroleum will need to be generated to overcome sorption capacity before expulsion from the organic matter can occur," says Andrew. "This factor becomes very important when comparing sorbed petroleum quantities in organic-rich shales like the Wolfcamp in the Permian Basin of Texas to organic-lean reservoirs similar to the Middle Bakken Member in North Dakota.




*Calculated fluid saturations from the Sb interval in the Permian Basin Wolfcamp well. Sorbed and reservoir fluid quantities were derived from core and sidewall core samples by pyrolysis measurements. The yellow line represents live reservoir fluid saturations.*

Sorption coefficients defined using solvent extract (i.e. toluene used in Dean-Stark core cleaning) are also typically higher by a factor of two in organic-rich shales when compared to pyrolysis yields. This is because solvents extract significant amounts of non-hydrocarbon (resin/NSO and asphaltene) compounds in addition to hydrocarbon (saturate and aromatic) compounds from the organic matter in shale. For this reason, we rely on pyrolysis hydrocarbon yields which are similar in composition to the oils produced from shale reservoirs."

The data show that the sorption decreases with thermal stress, which probably reflects decreasing molecular weight and the effect of higher temperature decreasing sorption. In shale sweet spots, which tend to be at high thermal stress, sorption coefficients can be as low as one third the value at the low thermal stresses encountered at the edge of the source kitchen. Obviously, it is important not to subtract too much sorbed oil from the oil budget, otherwise the true fluid saturation will be underestimated.

## Quantifying Fluid Saturations

"After being quantified by subtracting the sorbed oil right from the total pyrolysis volatile weight, the non-sorbed petroleum weight of each sample is transformed to a bulk volume of dead oil in the rock; and then to a live reservoir fluid bulk volume using an appropriate formation volume factor. If porosity data are available, saturations are then calculated," Andrew adds. The calculated fluid saturations presented in the figure on the left are typical of a productive shale sweet spot where there is a significant amount of non-sorbed oil throughout the rock. Fluid saturations are locally high in streaks of high quality reservoir, though overall low.

## Petroleum to Water Mobility

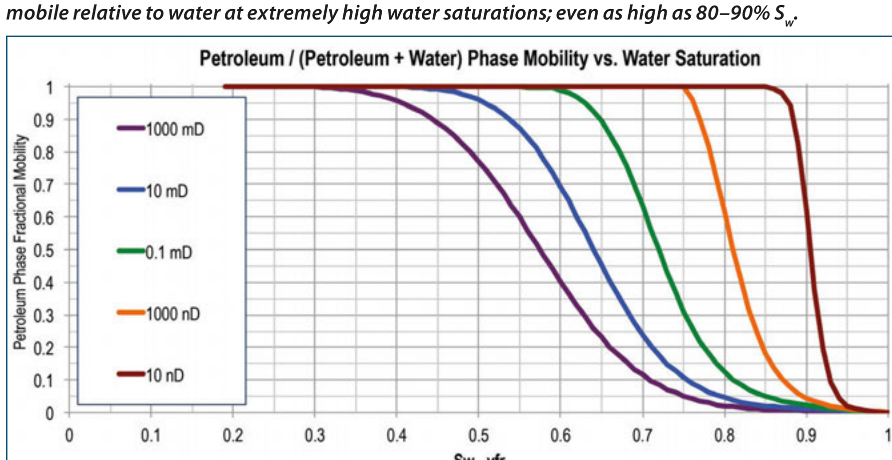
"Modelling by Okui and others using relative permeability curves found an interesting correlation between relative permeability and irreducible water," says Andrew. "By studying conventional reservoirs with differing absolute permeability, they found increasing irreducible water with decreasing permeability. 'Conventional' water-wet reservoir relative permeability curves require low water saturation, typically less than 50%, in order for petroleum to flow preferentially to water. However, with decreasing absolute permeability and increasing irreducible water, they projected that petroleum should be able to flow preferentially to water at higher and higher water saturations."

"Using the results presented in these graphs at the bottom of the page, and given the shale permeability and saturation, water cuts may be estimated in advance of the completion of a lateral well," says Andrew. "The results confirm that with lower permeability, more and more of the water occupies tiny pores that are disadvantaged in the flow process: it is the location of the water – not just its volumetric saturation – that determines the relative flow of petroleum and water from a reservoir."

## Implications

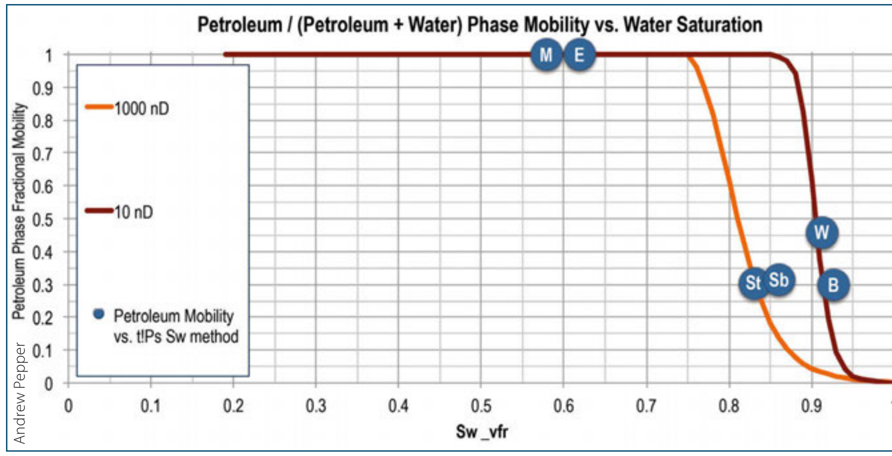
For companies exploiting and exploring organic-rich shale reservoirs, being able to predict water saturations before drilling will certainly be a game changer. For

*This graph demonstrates that conventional reservoirs with up to a Darcy of permeability will need low water saturations (less than 50%) to produce oil. However, for unconventional reservoirs in the 10 to 1,000 nD permeability range typical of many mudrocks, petroleum remains preferentially mobile relative to water at extremely high water saturations; even as high as 80–90% $S_w$.*



some of the Delaware Basin wells that encountered hard-to-explain water production and for some oil-bearing rocks that failed to produce fluid, the concepts presented here help explain certain trends for shale production. Early pore fluid analyses did not capture the whole picture nor did it recover all the water. Correcting the pore fluid calculations and separating sorbed from fluid phase is key to understanding how fluids move in very low permeability reservoirs.

How does this apply to the unconventional field? We now can conclude that since presumed saturations have been incorrect typically by a factor of two or more, recovery factors are much higher than originally assumed. Using only the potentially mobile fluid phase petroleum translates to lower oil-in-place and higher than expected recovery factors. Therefore, frac jobs are accessing a larger fraction of the net mobile fluid which has a huge impact on reservoir drainage efficiency and well spacing. "Enhanced profitability can come from drilling




*This graph compares actual unconventional reservoirs in the 10 to 1,000 nD range. Points M (Marcellus gas-condensate play in West Virginia) and E (Eagle Ford high GOR play in Texas) are from mudrock reservoirs that return frac-water, with no significant formation water production. The model predicts, correctly, that they should produce water-free petroleum at ~60% $S_w$. Note that with 'conventional' reservoir relative permeability (from the previous graphs) this level of saturation would result in a about a 50:50 petroleum:water mix at downhole conditions! Points Sb, St, W, and B are from Wolfcamp targets in the high GOR play in the Delaware Sub-basin of the Permian Basin in West Texas. Note the low oil saturations in this very prospective play.*

fewer wells to get the same EUR," speculates Andrew. "There is evidence from reservoir simulation that current infill (daughter) wells may be delivering production rate without recovering significantly more than the parent wells would do, over time."

Using the new saturation calculations and thus the higher recovery factors from shale production, operators can further optimise landing zones and adjust infill programs, all of which could have implications for US and global oil supplies. ■

# A Geoenergy Collage

JULIEN MOULI-CASTILLO, PhD

## Can synergies between technologies be used to fill the energy storage gap?

With renewable energy sources becoming cheaper, and a societal and political push to decarbonise our societies, the contribution from renewable sources to the total energy mix is increasing (CCC, 2019; COP, 2015). This transition from a reliable fossil fuel supply to more variable and intermittent renewable energy sources threatens the reliability and stability of our energy systems. Part of the solution is to increase the amount of energy storage in the energy system, in order to provide sufficient balancing capacity to ensure that supply and demand can be matched (Dodds and Garvey, 2016; Elliott, 2016).

This storage needs to happen over timescales ranging from seconds to years, and at power input and output spanning from Watts to hundreds of Megawatts. Currently, the inter-seasonal storage of energy is achieved primarily through hydrocarbons in the forms of stockpiles of coal and known oil and gas reserves. However, this method of achieving large-scale energy storage will have to be decarbonised in the future, particularly when the amount of variable generation from renewables exceeds approximately 80% of the power generation capacity (Cebulla et al., 2017; Elliott, 2016).

Yet at the moment the most common energy storage technologies, such as batteries and pumped storage hydroelectricity, are not scalable to achieve grid-scale inter-seasonal energy storage (Mouli-Castillo et al., 2019). If unaddressed, this situation could lead to an unreliable energy system, or one reliant on hydrocarbons by default, thus jeopardising ongoing efforts to decarbonise.

### An Electric and Heated Challenge!

To make things worse, we also need to consider that the storage challenge is applicable not only to our societal electricity needs, but also to our heating (and cooling) needs. This might not be obvious today in the UK at least, as natural gas is used to both generate electricity and to heat homes. However, in a future where a significant portion of heating becomes electrified it will be necessary to be able to produce electricity rapidly and at large scale from stored energy.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Currently, many consider hydrogen as a way forward that could provide storage on a large scale to meet both electrical and heating needs. There are, however, technological limitations; an approximately 70% energy loss incurred by the conversion of electricity to hydrogen, and back to electricity, makes this option economically unattractive at present (Salameh, 2014; Samsatli and Samsatli, 2019; Shiva Kumar and Himabindu, 2019).

Compressed Air Energy Storage (CAES) provides a scalable alternative for large-scale inter-seasonal storage of electricity. In this technology, electricity is used to compress air in either underground caverns or underground porous rock reservoirs, before releasing the compressed air through a turbine to generate electricity on demand.

A suggestion is therefore to use both technologies in conjunction: hydrogen at grid scale to balance the seasonal heating needs; and CAES to balance the electricity needs.

## Geology: A Key Piece of the Puzzle

The subsurface has huge potential to meet society's needs for energy, even in a decarbonised society – in particular, by achieving reliable large-scale energy storage with a limited surface footprint. A recent study identified that CAES in porous rocks in the UK Continental Shelf could provide between 77 and 96 TWh of electricity to the grid during 60 winter days (Mouli-Castillo et al., 2019), with between 15 and 25 TWh of that energy co-located with existing and planned offshore windfarms. This juxtaposition could help in providing storage for large amounts of renewable offshore wind energy, which would otherwise have to be wasted at times of low demand. Onshore salt basins have also been studied, but in contrast to porous rocks, salt has been identified as having only between 5 and 8 TWh of storage capacity per cycle (Evans et al., 2016; Garvey, 2019).

This highlights the importance in unlocking the potential from the wider storage volumes within porous rocks. This is an expanding area of research, with hydrogen storage in porous formations currently being considered by the HyStorPor project at the University of Edinburgh (https://blogs.ed.ac.uk/hystorpor/). Hydrogen's potential for seasonal storage has been highlighted by many other researchers (Amid et al., 2016; Sainz-Garcia et al., 2017).

## Technology Collage to Maximise Value

It is important to consider other subsurface technologies, such as the ongoing hydrocarbon production and storage as well as carbon sequestration and geothermal storage. These types of technologies are, however, often seen as competing for a given geological reservoir asset. These concerns are, in some respects, valid, in that although the subsurface is vast, the portion of it which is understood sufficiently enough for the deployment of such technologies is limited.

It can be hypothesised, however, that much more value could be had if a given subsurface reservoir is considered as a valuable asset, rather than just simply looking at the technology deployed to it. Considering the synergies between different technologies could add value, since a given geological asset could be allowed to generate value from multiple technologies (Quattrocchi et al., 2013). In that sense, synergies between technologies at a single site should be considered over time. In this hypothesis, the given is the geological asset, and preserving and understanding it will allow enduring and evolving value to be generated from its use with multiple technologies.

To illustrate this point we can consider a few examples:

- **$CO_2$ Enhanced Oil Recovery:** This technology has been used for decades as a way to extend the production life of a subsurface asset whilst storing carbon dioxide ($CO_2$). Although the primary focus has been the recovery of oil, rather than the storage of carbon dioxide, it still illustrates the benefits of combining technological concepts in a geological asset.
- **$CO_2$ – CAES in porous reservoirs:** Oldenburg and Pan (2013) proposed that $CO_2$ could be used as a cushion gas for a site operating CAES. This stems from the need for a large portion of the gas being injected into the storage site to remain in place, whilst only a smaller portion, the working gas, is cycled in and out of the 'store'. In addition to the apparent advantage in terms of decarbonisation, this approach also aims to capitalise on the density changes in the $CO_2$ phase to increase the CAES efficiency.
- **Nitrogen – Hydrogen:** A similar approach has been considered for geological hydrogen storage, where nitrogen would be used as the cushion gas (Pfeiffet et al., 2016). The aim here is to reduce the cost of developing the site, as hydrogen is expensive to produce. Air has also been considered and could provide synergies with a CAES site.
- **$CO_2$ storage – geothermal:** Combining $CO_2$ storage with geothermal energy has also been recently proposed. Although this system appears more complex than others, as it requires two reservoirs with one being shallower than the other, it still provides interesting synergistic opportunities and possibly an opportunity to combine electrical and thermal storage (Buscheck et al., 2016; Fleming et al., 2018).

Aside from $CO_2$ Enhanced Oil Recovery, these opportunities tend to be modelled and considered from site development through to operation only. Value could be added by considering the whole life-cycle of a geological asset, in particularly by learning from the implementation of technologies early on, to de-risk future usages. For example, a site used for $CO_2$ storage could experiment (whilst still maintaining operations) with cyclic variations in injection rate to provide valuable information on the asset's behaviour for future use as a CAES site.

## Research Needed

Now is the time to embark on the research and development needed to undertake site demonstrations of these technologies and their interactions. In this way, it should be possible to lay the foundations, ready for a time when large-scale inter-seasonal storage of energy is required to maintain a reliable supply of energy to society.

*References available online.* ■

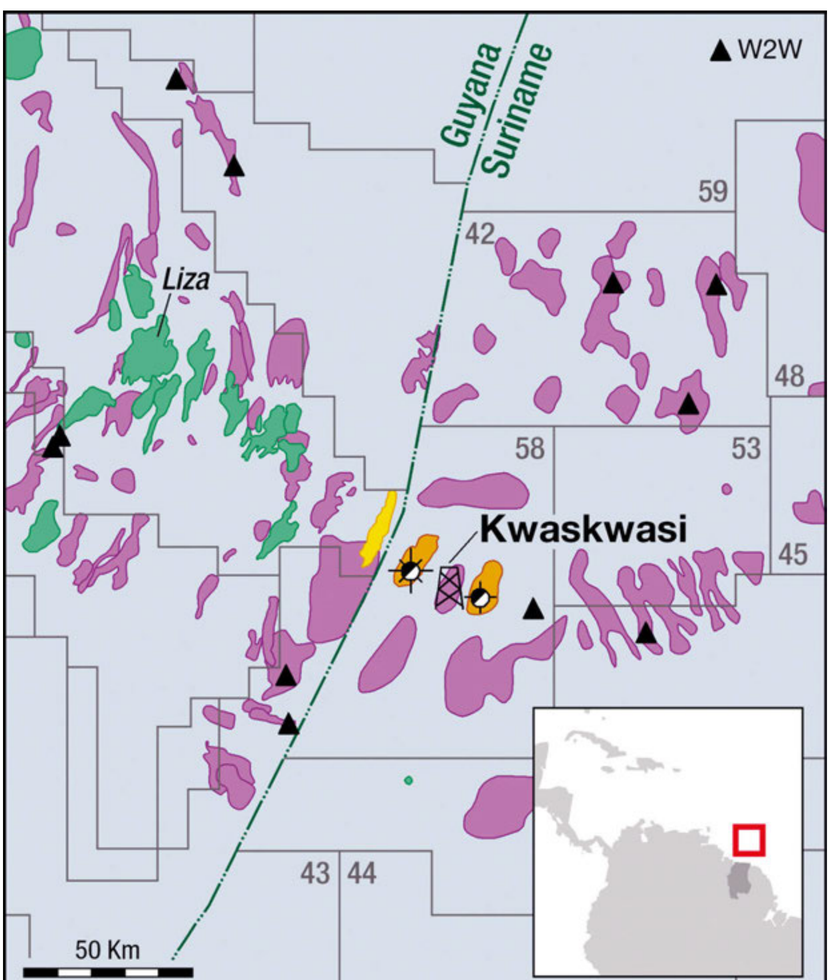
# The Guyana–Suriname Connection

PETER ELLIOTT and ROG HARDY, NVentures

**Following the trend and showing that the Canje source does not stop at borders.**

Operator Apache and partner Total are two-for-two on Block 58 Suriname with the Sapakara West discovery, and have now spudded their third consecutive well on trend, Kwaskwasi-1. This follows on the country – and company – maker Maka Central discovery and extends the prolific 'Liza' trend south-east from Guyana into deepwater Suriname, where Upper Cretaceous clastics are stacked and nestled up against the greater Demerara High. Likely winners on the back of this could be nearby interest-holders Petronas, Cepsa, Kosmos, Chevron and Hess, as the Upper Cretaceous trend, along with the Canje source kitchen, appears to sweep along the eastern edge of Blocks 53 and 48 against the high. The southern extension will also be of great importance as the national oil company, Staatsolie, plan a bid round in this open acreage later in 2020.

*The proposed Kwaskwasi well lies between the Maka Central discovery to the north-west and Sapakara to the south-east.*




## Long Road to Success

Exploration began onshore Suriname in the early 1940s. In 1965 the Geological and Mining Service discovered shallow heavy oil at the Calcutta and Tambaredjo fields, where some 109 MMbo has been produced onshore from Palaeocene and Eocene reservoirs over the last 40 years. Approximately 40 wildcats have been drilled onshore and offshore Suriname since then, almost half with shows (see *GEO ExPro* Vol. 10, No. 4, 2013), but only now has this resulted in a major discovery offshore.

The Sapakara West discovery reached TD at 6,300m in 1,400m water depth, encountering 79m oil and gas condensate pay in the Campanian – 13m of gas condensate, with 30m of API 35–40° oil pay – and a 36m oil leg (API 40-45°) in the Santonian. The initial discovery made in January to the north-west, Maka Central-1, encountered 50m light oil and gas condensate in Campanian sands and 73m oil in the Upper Cretaceous Santonian clastics. Both wells so far have found these good oil legs in the Santonian with lighter oil and gas condensate in the Campanian. The Turonian, a potential target at Maka Central but with TDs at over 6 km clearly beyond the limits of the drilling engineers in this block, is not mentioned at Sapakara West.

Neither is the source interval alluded to, but Staatsolie and various authors place an oil mature TOC-rich marine source rick of the Canje Formation, variably described as Cenomanian Turonian and Albian to Santonian, in the heart of the Block 58 area. Other source rock intervals are thought to exist; Palaeocene heavy oils are found onshore, for example, and the Jurassic may host lacustrine, lagoonal or algal source facies.

Some regional maps show a north-west to south-east Jurassic graben running through the area. Apache report the Sapakara fan system target is separate from the reservoir fan at Maka Central, suggesting a cluster of larger discoveries is possible.

## Follow-on Potential

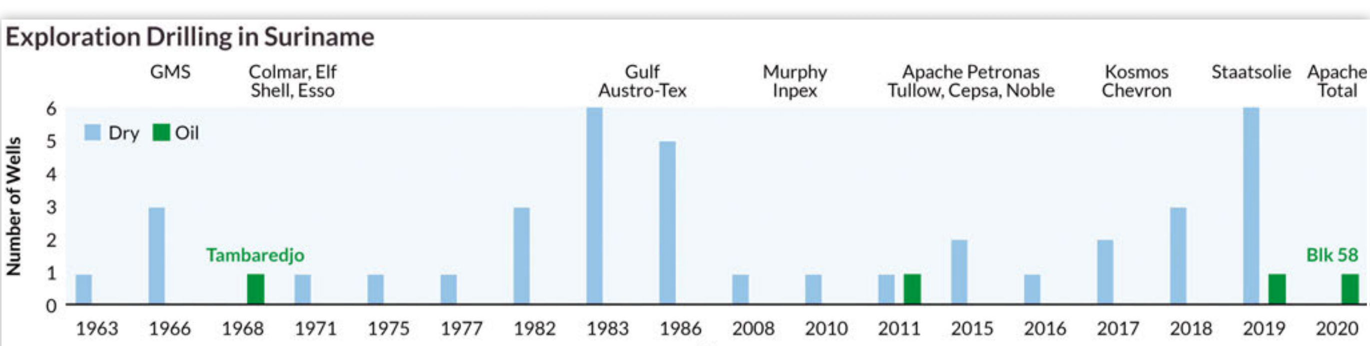
Apache and Total now plan to make strides with two further wells, proposing to drill Kwaskwasi between Maka Central and Sapakara West, to be followed by a fourth well, Keskesi, about 20 km south-east of Sapakara West to test the limits of this kitchen.

Other significant wells to look out for: Kosmos, with Chevron and Hess, have Aurora and Walker planned in Block 42, while Tullow, with Ratio and Pluspetrol, are targeting Goliathberg in Block 47 and Tullow may also test Block 54. Petronas intend drilling the Sloanea-1 well in the third quarter of 2020 in Block 52, probably the closest to this play: ExxonMobil recently farmed-in to this block for 50% WI. Apache may or may not be drawing up plans for drilling in the adjacent Block 53 with partners Petronas and Cepsa, having drilled Kolibrie and Popokai there between 2015 and 2017, which only resulted in shows.

### Don't Stop at Discovering

Whilst this is an expensive deepwater wildcat campaign for Apache in these straitened times, the US firm does benefit greatly from the advantageous terms secured from Total when the French giant took a 50% piece of the action as Maka Central was approaching the top of the reservoir. The French major paid $100 million to get a seat at the table, with promises of imminent help with development costs as well, clearly hoping to repeat the astonishing success of ExxonMobil, Hess and CNOOC, which together managed to mobilise the first of four 2 MMbo FPSOs within just two years of discovering light oil on Starbroek in neighbouring Guyana. Apache will operate the first three wells on Block 58 before transferring operatorship to Total. Total will also pay all development-related expenses up to the first $5 billion and 25% of Apache's expenses afterwards, up to the first $7.5 billion total development capex on the block; both companies will then fund 50% of the exploration and development costs. No acreage relinquishments are required until mid-2026.

A game changer for Suriname, these high volume, high productivity deepwater developments can provide great returns to all stakeholders at relatively low oil prices. ■



# Australia's Amazing South West Corner

Dr DIANNE TOMPKINS, Leisure Solutions

**The iconic drive along the Great South West Edge is the trip of a lifetime with plenty to interest both the geo-tourist and the nature lover.**

The Great South West Edge National Landscape is a collaboration between tourism, community and conservation that aims to attract both Australian and international tourists to the beautiful south-west of Western Australia. Its focus is the iconic drive along the Great South West Edge (GSWE) of Australia's largest state by area – a journey of between 700 and 750 kms, depending on the actual route taken, linking destinations from Bunbury to Esperance (or vice versa). It includes numerous untouched coastal vistas, ancient geology and swathes of natural bushland. This scenic drive can be completed in several days, a couple of weeks or even take months.

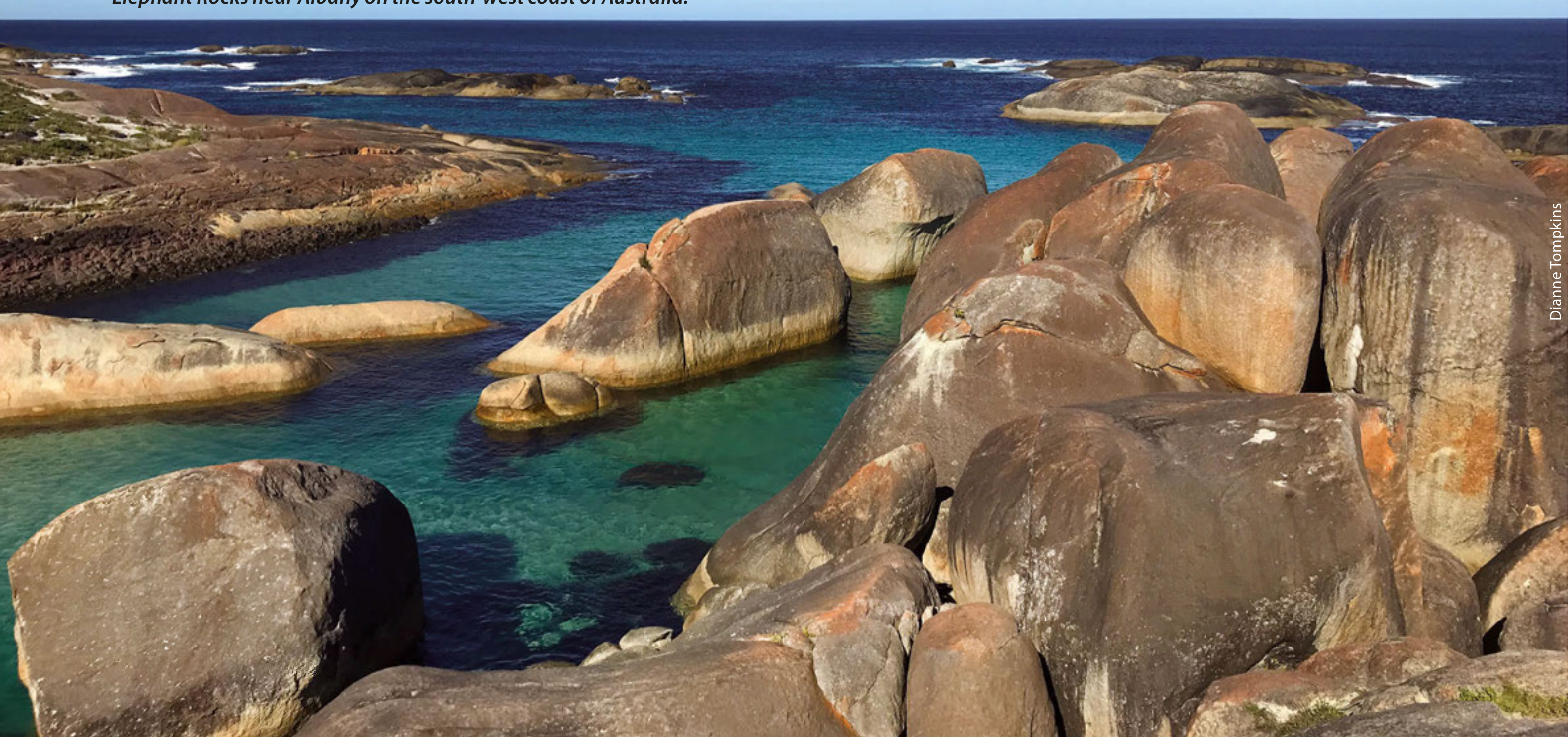
The area's geology is dominated by the giant Yilgarn Craton which dating suggests was formed some 2.94 and 2.63 billion years ago by the accretion of existing blocks of continental crust, most of which are thought to have been formed between 3.2 and 2.8 billion years ago. The regional geology is typified by the widespread granite and granodiorite intrusions that make up over 70% of the craton. In addition there is evidence of extensive basalt and komatiite volcanism as well as regional metamorphism and deformation. The Yilgarn Craton also has extensive gold mineralisation which has led to the area being designated the Goldfields-Esperance region.

### Surfing Beaches and Vineyards

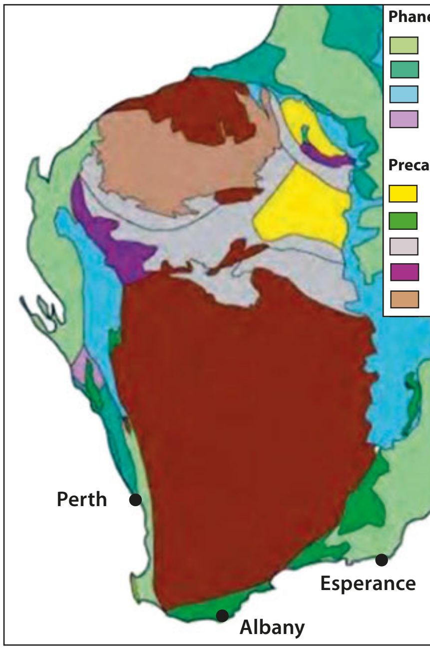
An amazing place to begin the GSWE drive is in the lovely city of Perth and there is no better place in the city to begin than in Kings Park. This is a magnificent park and botanical garden, 400 hectares in area, overlooking Perth Water and the Swan River and with magnificent views of the Darling Range in the distance. The park contains many examples of native and imported flora and fauna as well as the state war memorial dedicated to those who gave their lives in World Wars I and II. It is easy to spend an entire day here enjoying the peaceful surroundings and having a taste of some of the experiences awaiting on your upcoming adventure.

Around 175 km south of Perth and a suggested first stop on the GSWE drive is the city of Bunbury, located on the Leschenault Estuary. The original inhabitants were the indigenous Noongar people who named the town Goomburrup, prior to the colonists' arrival around 1830. It is known locally as the 'city of three waters', with excellent surfing on the Indian Ocean to enjoy as well as the calmer environments of Koombana Bay and the estuary itself. As you can imagine, water sports dominate leisure time here, but also worth a visit are the Leschenault mangroves. These 25,000-year-old trees can be seen on trails and from the viewing platform at the Big Swamp Reserve. A nearby site of geological interest is the basalt along Bunbury's Back Beach at Wyalup Rocky Point. Wyalup means 'a place of

*Elephant Rocks near Albany on the south-west coast of Australia.*



Dianne Tompkins




mourning' and was an ancient Noongar burial site. The basalt is around 130 million years old and is part of the Kerguelen igneous province that formed some 130 to 95 million years ago as Australia, India and Antarctica split apart.

The second stop on the GSWE drive, around 220 km south of Perth, might be the lovely old town of Busselton, famous for its pier, thought to be the longest timber-piled jetty in the southern hemisphere. Located on the Indian Ocean, Busselton has beautiful white sand beaches where once again water sports are the main leisure and vacation pursuits. Busselton is also known as the gateway to the Margaret River wine region. This is a very popular tourist area and is famous not only for its wine, but also for its surf breaks including Main Break and The Box. Sugarloaf Rock, a large natural granite island in the Indian Ocean, as well as Cape Naturaliste where it is located, are both worth a visit.

The Margaret River area has many excellent wineries, and it is possible to spend several days in this area and not visit them all by any means. The Mediterranean climate of hot dry summers and warm wet winters create ideal grape-growing conditions. The soils are a deep, well-drained red gravelly loam that, together with the ideal climate, allow for some exceptional wines to be produced.

## Forests and Dunes

Pemberton is located 335 km south of Perth and is another suggested stop on the GSWE drive. The region was originally occupied by the Bibbulum indigenous peoples, who also gave their name to one of South Western Australia's best-known tourist attractions – the Bibbulum Track. This is one of the world's most famous long-distance walking trails, and in its entirety stretches around 1,000 km, from Kalamunda in the Perth Hills to Albany on the south coast. The track is for walkers only and passes though karri and tingle forests, coastal heathlands and several national parks. This is an adventure in its own right as the entire walk takes between six and eight weeks to complete, although many people will only walk some shorter parts of the track at any given time to enjoy its abundant wildlife and scenery.

In addition to walking part of the Bibbulum Track, there are many other things to see and do in this area, not least of which is a visit to the Gloucester National Park and the Gloucester Tree. This giant karri tree is 58m high and is reputed to be the world's second tallest fire-lookout tree, the tallest being the nearby Dave Evans Bicentennial Tree. Visitors can climb up to a viewing platform in its upper branches from where they will have superb views of the surrounding karri forest. Karri trees are eucalypt trees native to this area and have the Latin name *Eucalyptus diversicolor.*

If you have the time, then another interesting place to visit is the Yeagarup Sand Dunes, located in the D'Entrecasteaux National Park just 28 km south of Pemberton. Here the Warren Dune chronosequence comprises three dune systems with the youngest up to 7,000 years old and the oldest up to 2 million years old. A four-wheel drive vehicle can be hired to drive on the dunes or simply enjoy the beach. This is an experience that is not quite unique to Western Australia, but is certainly well worth the effort for a fun day trip out of Pemberton.

## The Rainbow Coast

Just over 400 km south of Perth is the town of Walpole, located on the

*Path in a karri tree forest in western Australia*

dreamstime_m_126822178.jpg


*The dramatic granite coastline near Albany.*

Walpole River. The town is part of what is known as the Rainbow Coast, which includes Albany, Denmark and Walpole, several national parks and reserves, many pristine white sand beaches, ancient forests with giant trees and includes parts of the Bibbulum Walking Track. Whales and whale-watching are popular with both tourists and locals as they enjoy this scenic and beautiful area.

*The pink Lake Hillier: the colouration is due to algae and salinity.*


Leaving Walpole and about a 30-minute drive from the town is the world's longest and highest tree-top walk at 600m in length and 40m high. From here you can see the forest canopy including giant tingle and karri trees. Nearby Mandalay Bay is just one of many white sand beaches where it is possible to relax and also enjoy the view of Chatham Island in the distance.

About 15 km west of the town of Denmark, in the William Bay National Park, are Elephant Rocks and Elephant Cove, so named because, from several angles included from the air, these giant granite boulders look like a herd of elephants paddling in the shallow water. Close to Elephant Rocks is Green's Pool, a popular swimming and snorkelling location where fish and coral can be seen on the inner side of the rock breaks.

Albany, also on the Rainbow Coast, is around 420 km south-east of Perth and is the oldest colonial settlement in Western Australia, predating both Perth and Fremantle by over two years. It was founded on 26 December 1826 and was originally called Frederick Town. It is also known as the gateway to the Goldfields owing to its deepwater port and proximity to the Eastern gold-mining towns. The rugged coastline, settler and convict history and the National


*A panoramic view of the coast and typical white sand beach close to Denmark.*

Anzac Centre all make this a wonderful place to stay and explore for a few days. Albany was the last port of call for troopships leaving for the First World War, and this and much more is well documented in the National Anzac Centre located in town.

The penultimate stop on the GSWE drive might be Hopetoun, located around 590 km from Perth. This town and its port once thrived when it supported the nearby Ravensthorpe nickel mine in addition to several other nearby mining operations. The Ravensthorpe Mine was originally owned and operated by BHP Billiton but is now placed in 'care and maintenance' by the current owners, First Quantum Minerals. The nickel is contained in Cretaceous to Middle Tertiary lateritic clay minerals such as goethite, limonite and serpentine. The bedrock source is serpentine-talc-magnesite rocks, serpentinised dunite and serpentinised peridotite.

## Trip of a Lifetime

The final destination on the GSWE drive is Esperance, which is around 700 km east-south-east of Perth. Esperance has many white sand beaches, but perhaps the most famous is Lucky Bay with its archipelago of some 110 islands and resident kangaroo population. In the middle of this archipelago is Lake Hillier, one of Western Australia's famous pink lakes. The pink colour is due to the combination of high salinity and the presence of the algae *Dunaliella salina* which thrives in this type of environment. Sadly, the lake is now less pink than it was previously owing to changes in salinity largely brought about by human interference in this unique natural environment.

Completing the GSWE drive is truly an experience of a lifetime and will create lasting memories of this amazingly beautiful landscape, as well as good times enjoying some fabulous Margaret River wines in some of Australia's most memorable settings.

*References available online.* ■

*Part of the Great South West Edge drive near Esperance.*

# Sir Mark Moody-Stuart and Sustainable Leadership

JANE WHALEY

**An exciting childhood running wild in Antigua and an adventurous life as a geologist around the world led Sir Mark Moody-Stuart to very senior roles in the oil and gas industry and a strong interest in sustainable development.**

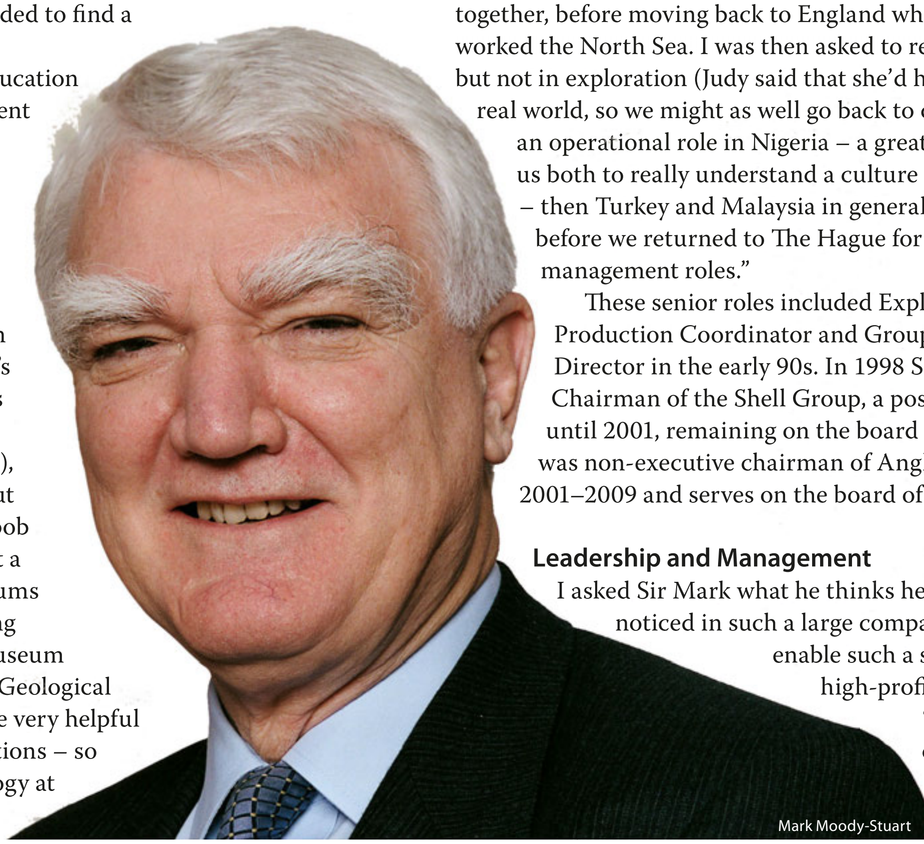
"There is no point in working unless you think what you are doing is worthwhile," explains Sir Mark Moody-Stuart. "I've always thought that developing reliable, economical energy is a noble cause; the source may need to be different, but the fundamental underlying need remains."

### Inspired by Museums

Sir Mark has spent his career in large organisations but has a very independent mind when it comes to the best way that a business should be run, built on his wide experience throughout the world. The youngest of six, he was born in Antigua and has fond memories of the island, which he still visits regularly.

"After WWI my father was sent to run the family sugar estates in Antigua, where he met my mother, whose family had been there for decades," he explains. "However, when I suggested I followed the family footsteps as an agri-industrialist in the Caribbean, my father declared there was no future in it; he realised the time of empire and colonisation would soon end and thought it only right that the industry should be turned over to the people who had been brought there as slaves. So I needed to find a different line of work."

After starting his education in Antigua, Sir Mark went to boarding school in Shropshire, where he began to develop an interest in the rocks of that well-known geological area. He spent school holidays in London with his father's three unmarried sisters ("typical of that First World War generation"), who would "shoo me out of the house with two bob in my pocket, so I spent a lot of time in the museums in Kensington, including the Natural History Museum and what was then the Geological Museum. The staff were very helpful and answered my questions – so I decided to study geology at Cambridge University."


Mark Moody-Stuart

As an undergraduate, he went on an expedition to Spitsbergen, returning there to study its Devonian fluviatile sediments for his Shell-funded doctorate. "Then I had three choices: the National Coal Board, mining in southern Africa, or the oil industry? I didn't fancy coal mines and the politics of southern African mining didn't appeal to me – but Shell had some very good sedimentologists, publishing interesting papers, so I joined them."

### The Travelling Geologist

Thus Sir Mark and his chemist wife Judy, who he had married while he was doing his PhD, began the life of the travelling exploration geologist. "I did field work in Spain in Franco's time, while Judy was back in Cambridge with our son," he tells me. "I then went to Oman, again on bachelor status but a very worthwhile experience. I was working with Ken Glennie, mapping the Al Hajar mountains for PDO [Petroleum Development Oman]; my speciality was the thrust elements – all very complicated – but it meant another year of separation, communicating by very slow letters.

"After that, however, we were in Brunei and in Australia together, before moving back to England when I briefly worked the North Sea. I was then asked to return to Brunei but not in exploration (Judy said that she'd had six years in the real world, so we might as well go back to camp life!), before an operational role in Nigeria – a great opportunity for us both to really understand a culture from the inside – then Turkey and Malaysia in general management, before we returned to The Hague for my senior management roles."

These senior roles included Exploration and Production Coordinator and Group Managing Director in the early 90s. In 1998 Sir Mark became Chairman of the Shell Group, a position he held until 2001, remaining on the board until 2005. He was non-executive chairman of Anglo American from 2001–2009 and serves on the board of Saudi Aramco.

### Leadership and Management

I asked Sir Mark what he thinks helped get him noticed in such a large company and thus enable such a successful and high-profile career.

"When I originally joined Shell I did wonder how

I would fit into this massive, highly efficient organisation – not being very well organised myself!" Sir Mark explains. "But from the time I started I always found things that 'needed fixing'; that probably got me noticed. Also, we were flexible. I believe that if your boss says, 'I think you should do this', then your reaction should be to say yes; you're being asked because the job needs doing and if somebody thinks you're the best person to do it, why question it? I think my willingness to say yes and show commitment to the organisation was important in my progress through the company.

"I enjoy making things work, and that's basically what management is," he explains. "For example, in the late 70s I was asked to go to Brunei in the new post of Services Manager, overseeing the departments of logistics, procurement, services and maintenance to encourage them to work together more efficiently. The heads of these departments were all much older and more experienced than me and all very good. We all knew I could not do their jobs. Until then, as an exploration team leader I had a full understanding of the jobs of the people I was working with, increasing my knowledge through them. In this case I had to work with these managers to find out what was making their lives difficult and what they felt needed changing, working with them and others to find and deliver solutions. My function was to remove blockages in the system. This is true of most management positions; you're basically a facilitator of the operational environment, ensuring that your team can do their jobs.

"That's what I call stage 2 management; stage 1 is the football captain, who can do all the jobs to a certain extent. Stage 3 is when you are at the top of the organisation. You can see the broad direction in which you want to go but you don't have the capacity for all the creativity needed, so instead you set up an environment with enough free rein for others to be creative, but within a controlled environment. Building strong trust is important. When I was a child in Antigua, we used to ride these rather wild ex-race horses, which would explode down a field at top speed whenever they could. All I could do was steer the horse – the organisation – to make sure it didn't get into trouble. Similarly, you need to know when to give the organisation its head, but also safeguard the investment. Of course, it doesn't always work!"

*Sir Mark with Wen Jiabao, former Premier of China; "a real geologist, and a nice man".*

Sir Mark adds: "People talk about medicine, teaching and art as vocations; no one talks about business as one, but it is. Supplying honest, reliable goods and services gives enormous satisfaction, but it has to be done right."

## Sustainability and Social Responsibility

Sir Mark Moody-Stuart is Chairman of the Foundation for the United Nations Global Compact and was, until recently, the Vice Chair of the Global Compact Board, a non-binding pact to encourage businesses worldwide to adopt sustainable and socially responsible policies.

He was an early advocate of sustainable energy policies. "It's linked to development really," he explains. "Working and living around the world in different economies and seeing the contributions, both good and bad, that oil has made to countries gets you interested in development. The evolution of energy has usually been through technology and convenience – cars replacing horses, for example, or oil replacing coal for domestic heating. I always assumed that something would eventually come along to replace oil, but it was only in the 90s that we began to realise the potential effect of hydrocarbons on the climate."

In 1995, as Group Managing Director, Sir Mark and Shell were faced with the twin challenges of the decommissioning of Brent Spar and associated public outcry, and the execution of Nigerian journalist and environmental activist, Ken Saro-Wiwa, whose death it was claimed Shell could have tried to prevent. "In response, we developed groups throughout the world," he says. "Half of each group came from within Shell, sliced down through the company, and half were outsiders – journalists, politicians etc. We asked them to outline the responsibilities of a global company in the late 20th – early 21st century. We had always clearly stated that we don't give bribes and we don't get involved in politics, but it was felt that this was not sufficient any more. As a result of the groups' findings we modified Shell's principles to include, firstly, a commitment to human rights, and secondly, a realisation that we have a responsibility within political relationships to engage in politics and to express our views.


*Sir Mark and his wife Judy in the UN General Assembly Hall.*

"The third commitment, which I think was the easiest to say but the least understood, was to sustainable development," he continues. "We included an acknowledgement of the challenge of climate change in our 1996 annual report, the first major oil company formally to do so. At the time, people understood sustainable development to mean renewable energy, but of course it also includes hydrogen and carbon taxing and pricing as well as all the social aspects."

## Public Perception

Sir Mark believes the industry did not try hard enough to engage with civil society when it needed to. "In about 2002 the CBI [Confederation of British Industry] set up a working group covering industries from producers to users of oil to look at what we now call the energy transition. They came up with a set of excellent proposals, including carbon pricing, but rather than try to involve civil society in the creation of this report, they instead just presented it and asked for comments. As a result, its publication didn't get much coverage; the feeling was that it had come from business so it must be biased.

"Compare that to action taken by the mining industry, which has also been hugely criticised," he continues. "In the early 2000s they set up a group called 'mining, minerals and sustainable development' and involved civil society. Effectively, the industry said: 'you need what we do but you don't like how we do it, so let's get together and find a different approach.' Out of this came the International Council for Mining and Metals and a very open conversation with civil society, including charities. If the oil industry had similarly got people together earlier, we would have all realised we were working in the same direction, although with different ideas about how to do it. We would then have been able to talk to government together, to help them take positive steps. We should have had an alliance of oil industry leaders standing shoulder to shoulder with environmental groups."

## Looking to the Future

Sir Mark is on the advisory board of Envision Energy: "a highly creative Chinese company that is now the second largest wind turbine manufacturer in China, he explains. "When I talk to the founder, a very visionary man called Zhang Lei, I feel optimistic for the future. "The development of alternative energies is moving at a great pace. Oil companies have the cash flow that could be used to develop other energy sources; it's the same mission, just a different source.

"We will need some of the majors to be involved in the energy transition to help develop an integrated system, which they can do while they have capacity and good cash flow. Hydrogen is important; in areas where wind and solar can produce more energy than needed, the over-capacity can be used to make hydrogen, which can in turn be used to decarbonise hard-to-reach sectors, like heavy transportation and shipping. Creating hydrogen by electrolysis is a better option for excess electricity than using batteries, because if we're not careful we'll soon find ourselves with another resource and disposal crisis over them.

"Sometimes I feel less optimistic and think that this is all going to take too long. Many predict that oil will still be in use for decades to come – but we need to remember the speed at which change can happen; take the spread of bioethanol from maize, for example, or the exponential rate at which fracking spread.

"Rapid change can happen – but it needs commerce to make it come about," Sir Mark concludes. ■

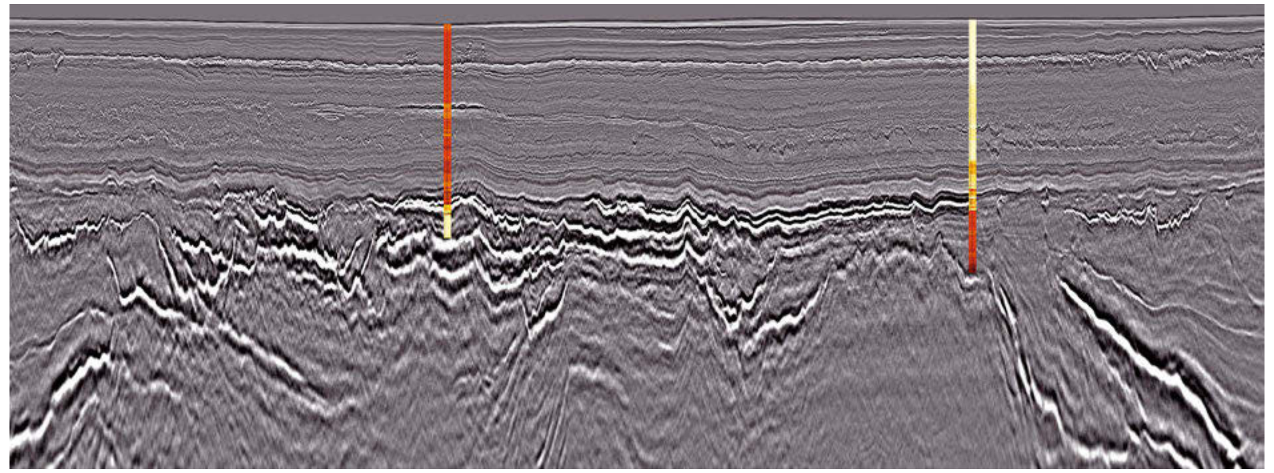
*Sir Mark and young students in Iran.*

# Geology-Driven Imaging in the Faroe-Shetland Basin

*The foldout image shows a 3D view of Cretaceous and Paleogene intervals within the Erlend Basin. Climbing sill intrusions can be seen within the Cretaceous (A). Remobilised Eocene delta sands injected in the younger succession are a potential lead to be evaluated (B) and inter-basalt slow velocity layers point to potential reservoirs between flow basalts (C).*

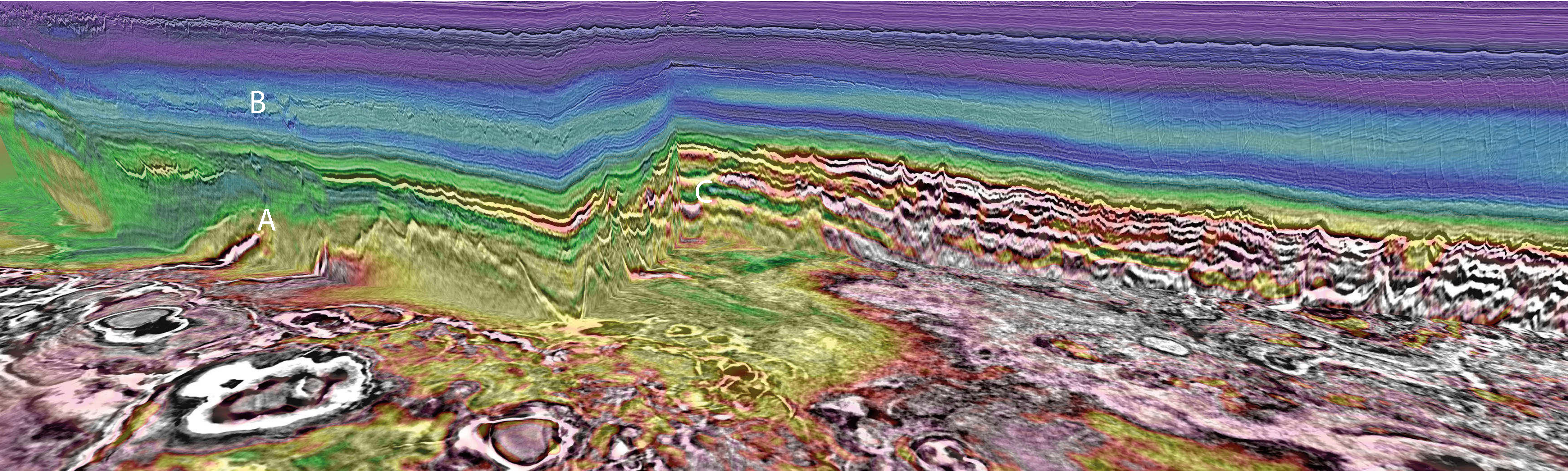
It is something of a surprise to realise that in 2020 we can look back on nearly 60 years of exploration activity in the Faroe-Shetland Basin, which has resulted in the great oil fields such as Clair, Schiehallion and Lancaster. However, in the northern areas, including the Erlend and Brendan basins, only a few exploration wells have been drilled so far, in stark contrast to the well-explored southern part. New interest and efforts are now being made to uncover more hydrocarbons in this area. Several gas discoveries have been proven and new data will certainly help to unlock the full potential.

Much of this potential sits between and under volcanic rocks that require new seismic processing technology to be imaged effectively. Over the past decade, TGS has covered the northern Faroe-Shetland Basin with large 3D seismic surveys. The latest of these is the Erlend Wild West 3D, acquired in 2018 (EWW18), which was then merged with the Erlend West 3D survey, acquired in 2012, in a pre-stack depth, merged project. The highlight of this processing work is the use of Reflection Full Waveform Imaging (FWI) and interpreted geomodels of the different volcanic facies, linked to analogues in nearby wells to improve the migration velocities.



TGS

*Seismic image from the Erlend Wild West survey showing two well paths: Tobermory gas discovery (left) and the Bunnehaven gas discovery (right) the latter penetrating Cretaceous sub-lava.*



# Improved Imaging Reveals Potential

**Better tools based on geological models and full waveform inversion reveal further potential in the Faroe-Shetland Basin.**

**REIDUN MYKLEBUST, BENT KJØLHAMAR and AURÉLIEN VAN WELDEN, TGS**

Based on new 3D seismic on the North Atlantic margin, it has been possible to map a wider range of volcanic facies in the Faroe-Shetland Basin (FSB) and surrounding area. Large variations in basalt thickness have been mapped and interpreted on the Norwegian side of the margin and linked up to the Erlend Basin in the UK. In particular, the base basalt transition and underlying sedimentary sequences have been a focus, with testing of various processing parameters, including extensive velocity analysis, which has resulted in improved definition of top and base basalt with their related geomorphological features. Furthermore, it has been possible to identify layering and velocity contrasts within the volcanic sequence which affects large parts of the basin area.

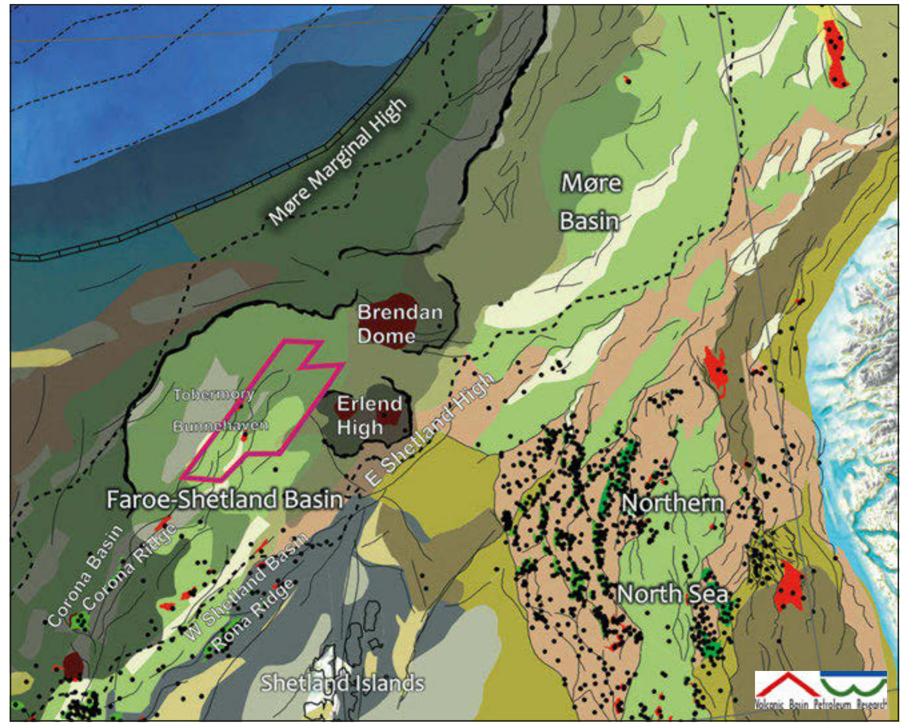
Locally, the basalt can be very thin or absent, as we can see in places in the Erlend and Brendan Basins, where sub-aerial lava flows, shallow marine flows and debris flows have all been interpreted. Well-defined interfingering of basalt flows and inter-lava sandstone are present in the Rosebank hydrocarbon discovery (Duncan et al., 2009) and new seismic data in the Erlend area reveals several similarities with the Rosebank type of play. Based on a combination of field and seismic examples from mid-Norway and the UK, including borehole data from the Rosebank field in the Faroe-Shetland Basin, it has been possible to identify several volcanic facies that developed in a wet sediment environment. Lava flowing across typically wet, unconsolidated sediments begins to nose beneath the surface (Millett et al., 2019), and examples of this can be interpreted from the new Erlend West 3D survey.

## Reservoir Trends Observed

A large channel system within the Flett Formation is sand-rich, sourced from the Lewisian gneisses in the Shetland Platform. Sand injectites have increasingly become of interest as exploration targets because of their potential high quality reservoirs. In the FSB study area, sand injectites are penetrated at the Tobermory (214/4-1) and Bunnehaven wells (214/9-1), and the Tobermory gas discovery occurs in a sandstone interval within the Eocene Strachan fan. Sand injectites can be observed directly above this fan coming in from the west, suggesting that many of these injectites are interconnected and might be sourced from the fan. Sand injectites above the Strachan Fan have stronger amplitude responses than those below the fan and are generally distinct singular reflections. They are similar to igneous sills but occur shallower in the geological succession and with a much smaller diameter.

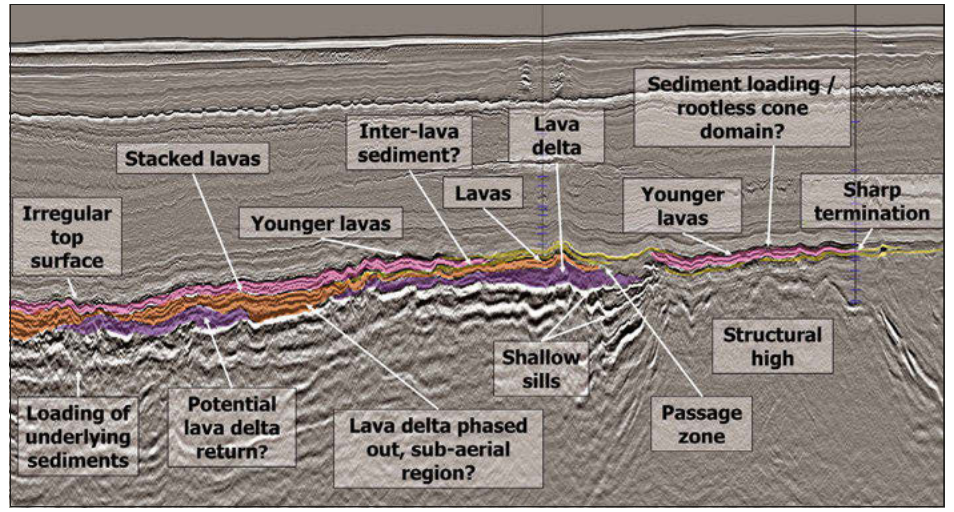
Fluid migration associated with hydrothermal vents is typical for the area not covered by lava but where sill intrusions are dominant. Inter-basalt low velocity layers and bright soft reflections suggest the possibility of interfingering sands and Rosebank analogues. The new imaging of the EWW_Merge survey gives better definition of sub-basalt strata that now can be evaluated with reference of traps and leads.

*West of Shetlands area, northern North Sea. The EWW18 survey area is shown outlined in red.*



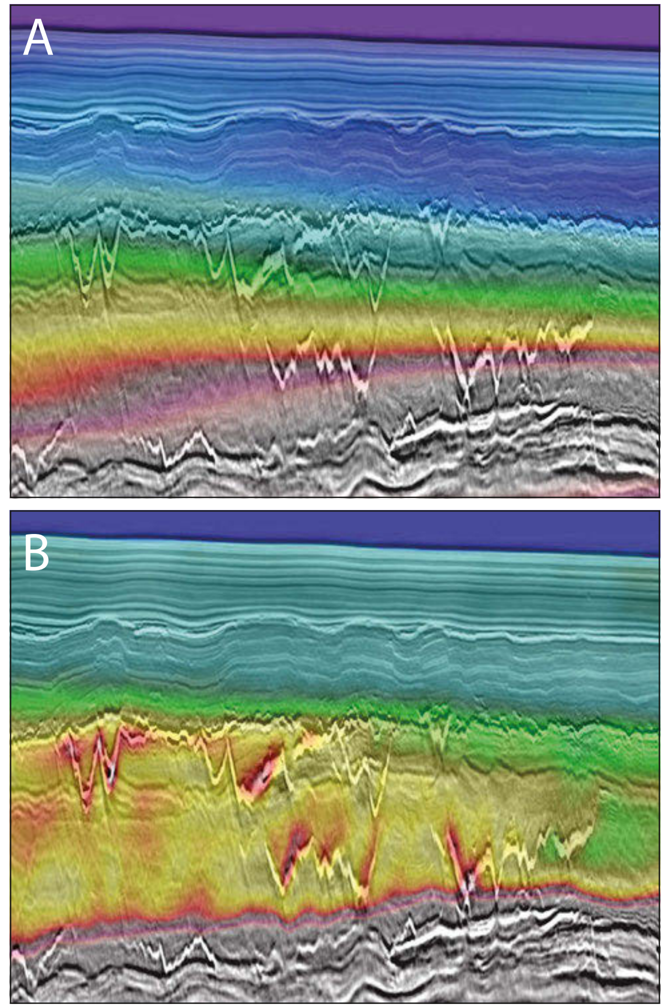



The presence of volcanic sills in typically flat mud-dominated basins is a great benefit for the hydrocarbon system. In many places worldwide, it has been demonstrated that the heat from sill emplacement in a low organic shale can produce large quantities of hydrocarbons – typically gas, but also oil. The cooled sill intrusion has cracks and porosity along the surface and in many cases the secondary porosity along the sills is the most porous part of a mud-dominated sequence. Hydrothermal vents create vertical migration paths and can lead the hydrocarbons from deeper source rocks up into shallow and drillable traps. Within this area, Tobermory, along with the Balderbrå and other discoveries in the Norwegian Sea, are good examples of this process. The sill intrusions 'armour' the basin, altering the basin stiffness locally and thereby facilitating asymmetrical subsidence that, in turn, creates anticlinal structures that can trap hydrocarbons. In general, sill intrusions in a mud-dominated post-rift basin are mostly positive. The only challenge we have – which is now being addressed – is imaging in between and below the volcanic rocks.




*An example of the interpreted volcanic facies (by VBPR) based on well-derived field analogues, with velocities to guide the final 3D velocities.*

*Before (A) and after (B) FWI-corrected velocity field. The sand injectite level in the middle shows slightly higher velocity and details that help the imaging below.*




## The Imaging Technology

With such a complex geology and possibly stacked pay, re-imaging with depth migration was the obvious next step for the area. A TTI (Tilted Transverse Isotropy) KiPSDM route was chosen, with the focus on a very detailed pre-processing sequence and advanced velocity model building.

The EWW18 survey was acquired using a triple source set-up. While enabling effective acquisition and reducing environmental footprint but still retaining excellent spatial sampling, multiple source acquisition requires careful de-blending. Therefore, an important step in the pre-processing was to remove the overlapping shots using a sparse inversion method (after Masoomzadeh et al., 2019) and recover the primary energy. In order to eliminate the sidelobes and obtain a broadband frequency content, an inversion approach was used to deghost on the receiver side. Optimal preservation of the low frequencies was instrumental to imaging within and below the sills.

In order to correctly image the geology in deep water and with limited offset on older vintages, image-guided tomography and Reflection Full Waveform Inversion were used. Detecting the subtle velocity changes in the shallow section led to an improved imaging of the Balder and Flett Formations and enabled better focus of the deeper units. The interpretation of deep-seated fault blocks can now be made with more confidence. Slow velocity layers between the high velocity lava layers gives hope for interbedded reservoirs, such as in the Rosebank field.

Future work will target the sill complex using reverse time migration, which has been successfully applied by TGS in similar settings on the Norwegian continental shelf. ■

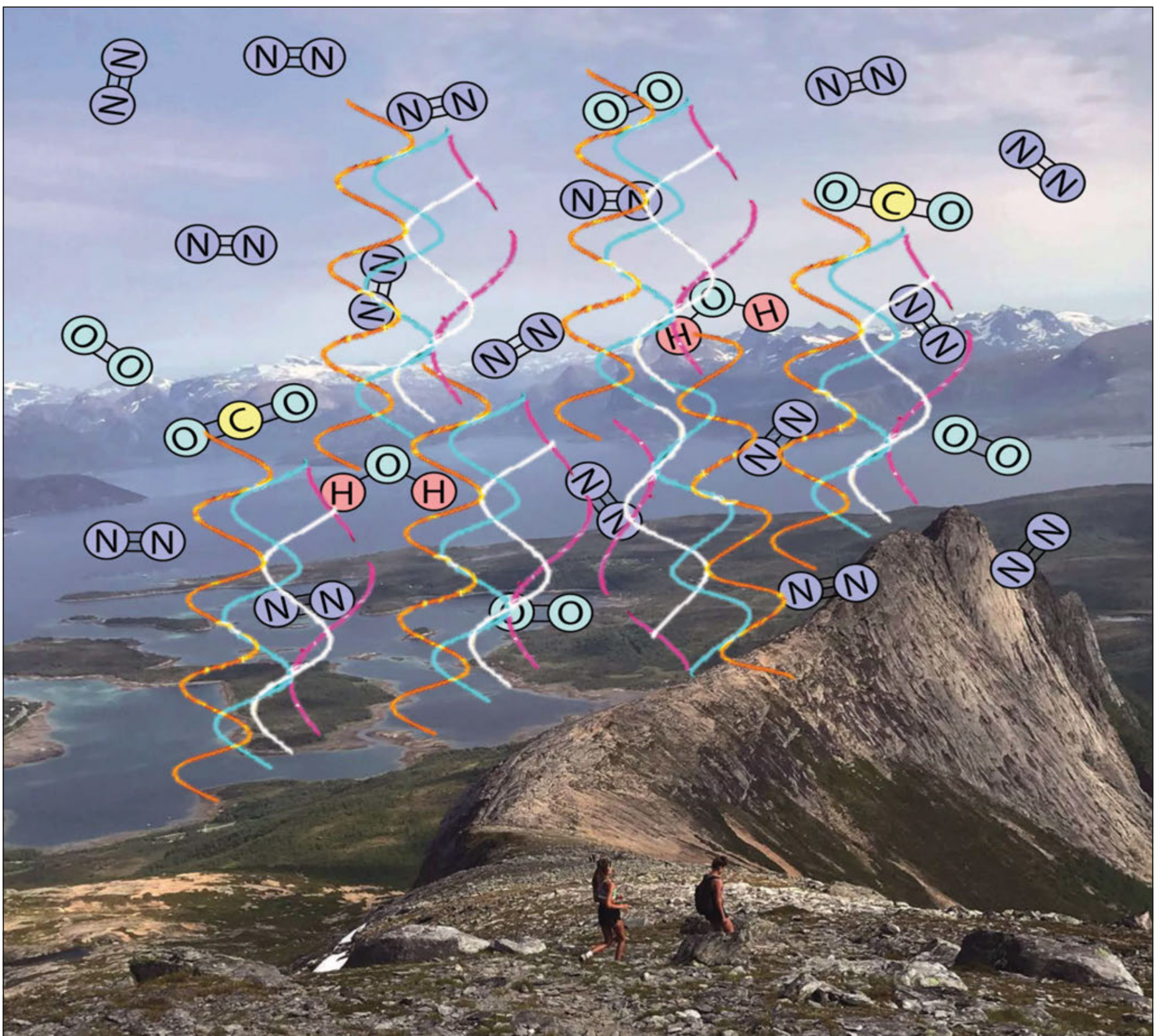
# From Arrhenius to $CO_2$ Storage

## Part VIII: How $CO_2$ Absorbs Earth's IR Radiation

**Skydive with us into the quantum world! Find out how $CO_2$ molecules absorb thermal IR radiation.**

> *"I call this Spirit, unknown hitherto, by the new name of Gas, which can neither be constrained by Vessels, nor reduced into a visible body, unless the feed being first extinguished."*
>
> *Jan Baptist van Helmont (1580–1644), Flemish philosopher and chemist who recognised the existence of discrete gases and identified carbon dioxide*

**LASSE AMUNDSEN* and MARTIN LANDRØ, Bivrost Geo/NTNU**



***The atmospheric gases ($N_2$, $O_2$, $H_2O$, Ar, $CO_2$, He etc.) are constantly bombarded by IR radiation, or photons, emitted from Earth's surface in myriads, but only the greenhouse gases ($H_2O$, $CO_2$, $CH_4$, $N_2O$, $O_3$, CFCs, HFCs) can absorb the IR photon energy. When a photon hits a greenhouse gas molecule, the photon's energy is absorbed, causing it to vibrate. A molecule, however, cannot absorb any old photon; the photon must have certain wavelengths, or energies. Those with energies not within the narrow wavelengths correct for the molecule will just pass by and look for friendlier greenhouse gas molecules that are able to absorb their energies. If they do not meet any friendly molecule, then they disappear into space. $CO_2$ is an important player in the global climate system and is under scrutiny in this part of our series. (View from Bjønnkjeften/Bear Mouth Mountain, Hamarøy, Norway. Photo: Eli Reisæter.)***

| Dominant Transition | Band | Wavelengths | Wavenumbers | Energies |
|---|---|---|---|---|
| Rotational | Far IR, microwave | >20 μm | <500 cm$^{-1}$ | $10^{-5}$–$10^{-3}$ eV |
| Vibrational | Near IR, thermal IR | 1–20 μm | 500–$10^4$ cm$^{-1}$ | 0.05–1.25 eV |
| Electronic | Visible, UV | <0.4 μm | >2.5–$10^4$ cm$^{-1}$ | 1.75–10 eV |

***A gas molecule absorbs radiation of a given wavelength only if the energy can be used to increase the internal energy level of the molecule. This internal energy level is quantised in a series of electronic, vibrational and rotational states. Electronic transitions, where the orbital states of the electrons change in the individual atom, generally require UV radiation (<0.4 μm). Vibrational transitions, where the individual atoms vibrate with respect to the combined molecular centre of mass, require near-IR radiation (0.7–20 μm), corresponding to the wavelength range of peak terrestrial radiation. Rotational transitions, where the molecule rotates around the centre of mass, require far-IR radiation (>20 μm). Little absorption takes place in the range of visible radiation (0.4–0.7 μm) which falls in the gap between electronic and vibrational transitions.***

This outgoing radiation is absorbed by various gases in the atmosphere. $CO_2$ absorbs IR radiation in two narrow bands around wavelengths 4.26 and 15 μm (wavenumbers 2,349 and 667 cm$^{-1}$) and in narrow bands around 2.7 and 2 μm.

Photons act as individual quanta. A photon can interact with individual electrons, atoms, molecules and so on, depending on the energy the photon carries. From equation 1 it follows that the energies in the Earth's thermal IR radiation are 0.0248–0.31 eV. When we compare those photon energies with the eV-energies required for allowed molecular transitions in the table left, it reveals that the photons of Earth's IR radiation can mainly affect the vibrational energies of molecules in the atmosphere.

## Infrared (IR) Emission Spectrum of the Earth

In Part I of this series of articles on carbon dioxide (*GEO ExPro* Vol. 16, No. 2) we introduced you to electromagnetic radiation which can be described in terms of a stream of photons, being mass-less particles travelling in a wave-like pattern at the speed of light. The different types of radiation are defined by the amount of energy found in the photons. The energy $E$ of a single photon is related to the frequency $f$ and wavelength $\lambda$ of the radiation by:

$$E = hf = hc/\lambda \qquad [1]$$

where $c$ is the speed of light and $h$ is Planck's constant. For the IR region, the wavenumber $\nu = 1/\lambda$ is commonly used to measure energy. Since many wavelengths are stated in micrometres it is useful to know that $hc$ = 1.24 eV · μm. The eV unit of energy means electron volt. Photon energy is larger at high frequencies or shorter wavelengths and lower at low frequencies or longer wavelengths.

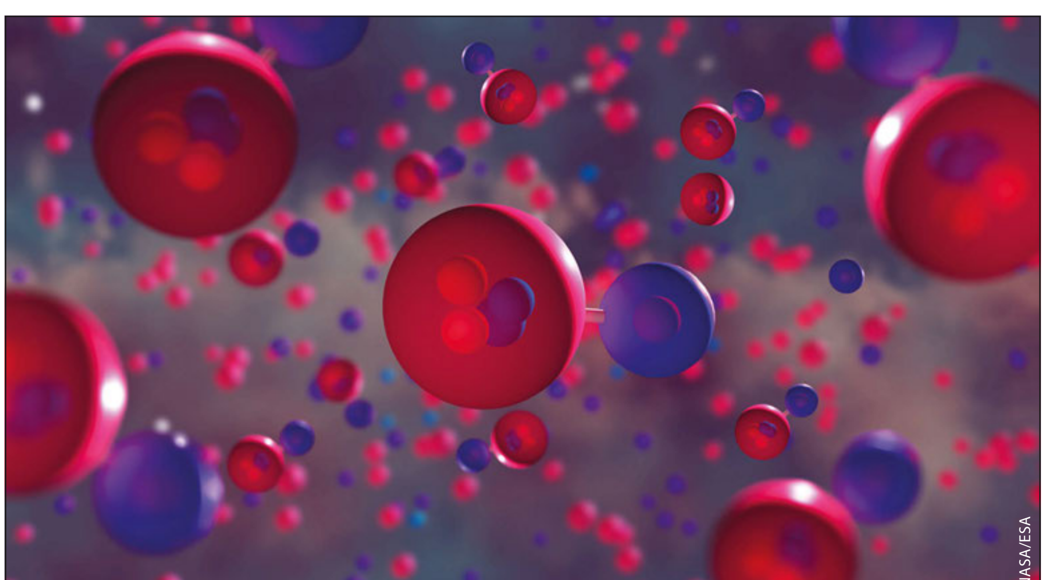
Earth emits long-wave radiation with wavelengths 4–100 μm. Contributions with wavelengths larger than 40 μm are few, therefore often only wavelengths up to 50 μm are considered. The wavelength range 4–50 μm reads wavenumber range 2,500–200 cm$^{-1}$.

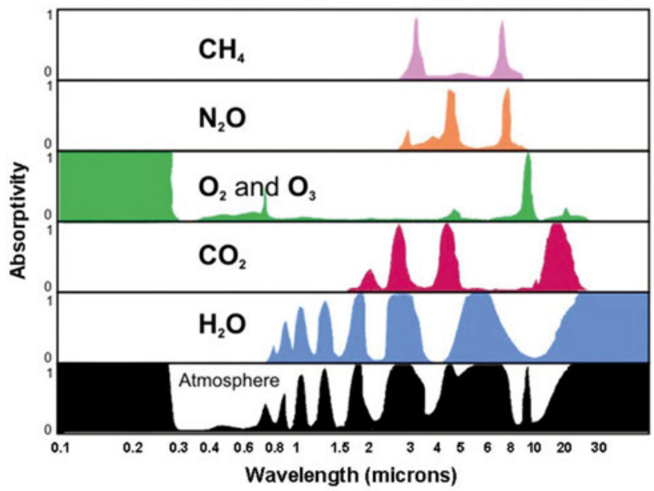
## Infrared Spectroscopy of Gas Molecules

In the IR range there are plenty of photons. IR spectroscopy is the study of how molecules – groups of atoms that share electrons (chemical bonds) – absorb IR radiation and ultimately convert it to heat. Spectral lines are the result of interaction between a quantum system (in our case, molecules) and a single photon.

Most polyatomic molecules have vibrational transitions in an energy range corresponding to IR radiation in the

***The helium hydride ion or helonium was first produced in the laboratory in 1925. Its occurrence in the interstellar medium has been conjectured since the 1970s and it was finally detected in April 2019 using the airborne SOFIA telescope. Helium hydride is believed to be the first molecule to have formed after the Big Bang, in which the only chemical elements created were hydrogen, helium and lithium, the three lightest atoms in the periodic table. Made of a combination of hydrogen and helium, astronomers think the molecule appeared more than 13 billion years ago and was the beginning step in the evolution of the universe. Carbon and oxygen resulted from the nuclear fusions taking place in the early massive, short-lived stars; when these died, they spread the elements of life, carbon and oxygen, throughout space. Carbon dioxide was recognised as a gas different from others early in the 17th century by van Helmont when he observed that the mass of charcoal declined in the process of burning. From that he concluded that the rest of the charcoal must have turned into an invisible substance that he called Gas (from the Greek word chaos) or 'Spiritus Sylvestre' (wild spirit)***



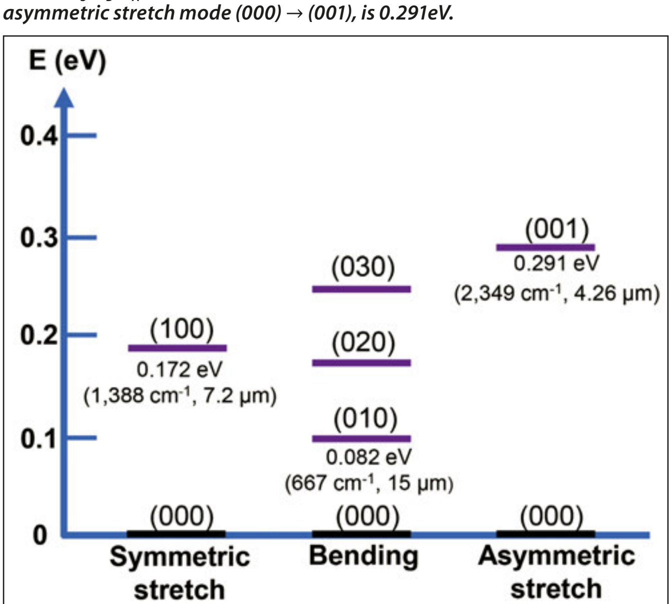


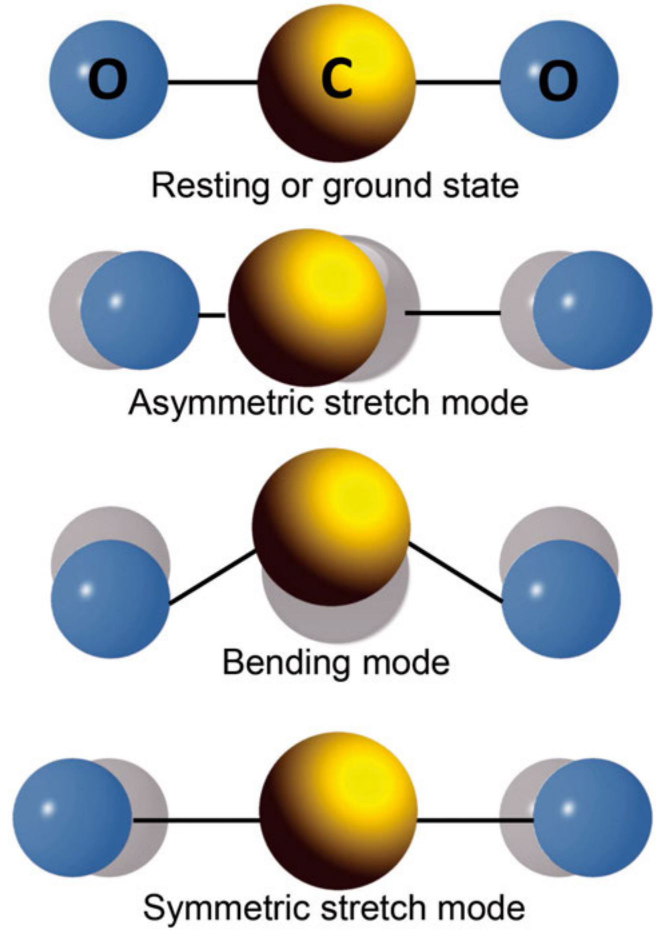



***Absorption spectra of various gases in the atmosphere and of the atmosphere as a whole. 98% of the radiative power from the Sun is emitted in the 0.25–4 µm range; 98% of the radiative power from Earth is emitted in the 5–80 µm range. Greenhouse warming is related to the fraction 'x' of radiation emitted by Earth's surface that is prevented from escaping to space by the greenhouse gases. $H_2O$ is the main greenhouse gas responsible for blocking Earth's IR radiation. $CO_2$ is also seen to contribute with additional blocking around the 15 µm spectral range; it alone blocks around 20–21% of Earth's radiation. The 'blocked' radiation must ultimately return to the surface. Observe that the absorption bands of $H_2O$ and $CO_2$ overlap in part.***

wavelength region between 2.5–25 µm. At lower-atmospheric temperatures, the vibrational excitation is most often from the ground state to the first excited level. When 'broad-band' IR radiation passes through the atmospheric gas containing an infrared-active molecule, then the energy of wavelengths corresponding to the transitions will be absorbed and lost

***Simplified vibrational energy levels for the electronic ground state of the $CO_2$ molecule. A manifold of finely spaced rotational energy levels (not shown) is associated with each vibrational level. The excitation of the $CO_2$ molecule is commonly characterised by a triplet of vibrational quantum numbers ($v_S$, $v_B$, $v_A$) for symmetric stretching, bending and asymmetric stretching. The vibrational excitation energy for the bending mode, ($v_S$, $v_B$, $v_A$)=(000) → (010), is 0.082eV, and correspondingly, for the asymmetric stretch mode (000) → (001), is 0.291eV.***




***The villain: $CO_2$ has three vibrational modes, but the molecule can absorb radiation to access only two of them. Vibrations occur only where the dipole moment can change. This is a general selection rule from quantum mechanics: a change in molecular dipole moment must occur in the vibration for the transition to the vibrational level to be allowed. $CO_2$ does not have a molecular dipole moment in its ground state. The symmetric stretch mode has no dipole moment and does not couple to IR radiation. Note that the bending mode of $CO_2$ is doubly degenerate.***

from the path of radiation. Thus, when the photon has the right amount of energy to allow a change in the energy state of the molecule, the photon is absorbed. Gases that absorb in the wavelength range 4–50 µm, where most terrestrial radiation is emitted, are called greenhouse gases.

A selection rule from quantum mechanics is that vibrational transitions are allowed only if the change in vibrational state changes the dipole moment $p$ of the molecule. Vibrational states represent different degrees of stretching or flexing of the molecule, and a photon incident on a molecule can modify this flexing or stretching only if the electric field has different effects on different ends of the molecule, that is if $p \neq 0$. Most of the gases in the atmosphere, including the major gases $N_2$ and $O_2$ are homonuclear, symmetric molecules, and can therefore not absorb (or emit) IR radiation at all. All diatomic heteronuclear molecules (with just one vibration) are active in IR. Likewise, most polyatomic molecules in some of their vibrations are IR active.

In the following discussion we focus on $CO_2$ as this gas plays a dominant role in global-warming research.

### The $CO_2$ Molecule's Absorption Lines

In this section we describe how $CO_2$ has absorption lines in the near-IR. The $CO_2$ molecule has three atoms. It is a linear molecule with four vibrational modes, where the vibrations consist of coordinated motions of atoms in such a way as to keep the centre of mass stationary and non-rotating. These modes are called normal modes, where each can be described by a wavelength or wavenumber. The vibrational state is defined by a combination of the normal mode and by a quantised energy level within each mode. The modes are shown in the figures on page 50.

In the 'symmetric stretch' mode vibrations represent stretching of the chemical bonds in a symmetric fashion, in which both C=O bonds lengthen and contract together, in-phase. Since the distribution of charges is perfectly symmetric this mode has no dipole moment; transition to a higher energy level of that mode is forbidden. The symmetric stretch is not infrared active, and so this vibration is not observed in the IR spectrum of $CO_2$. In the 'asymmetric stretch' mode the stretching of the chemical bonds differs, as one bond shortens while the other lengthens. The asymmetric stretch is infrared active because there is a change in the molecular dipole moment during this vibration. IR radiation at 2,349 $cm^{-1}$ (4.26 μm) excites this particular vibration. The two bending mode vibrations in $CO_2$ are degenerate (have equal energy); one mode is in the plane of the paper, and one is out of the plane (not shown). IR radiation at 667 $cm^{-1}$ (15 μm) excites these vibrations.

### $CO_2$ Absorbtion in the Atmosphere

The figure on the right shows Earth's blackbody spectrum for outgoing radiation flux and number of emitted photons as function of wavenumber for surface temperature 288K (15°C). The $CO_2$ 667 $cm^{-1}$ centred absorption band (bluish, 540–800 $cm^{-1}$) is positioned near the peak radiation wavelength for Earth's temperature and is therefore very important for terrestrial radiative transfer in the atmosphere. It renders the atmosphere fully opaque around the centre wavenumbers while partly absorbing towards either side of these wavenumbers. The $CO_2$ 2,349 $cm^{-1}$ centred absorption band (red, 2,100–2,400 $cm^{-1}$) is located out on the edge of the thermal radiation band. The area under the top curve is proportional to the total outgoing flux. The effect of $CO_2$ absorption is to take a bite out of Earth's blackbody spectrum, thereby decreasing the outgoing energy flux to space.

The number of emitted photons from Earth per second per square metre is computed by using Watt equals Joule per second, where $1J = 6.24 \cdot 10^{18}$ eV. The number of photons per wavenumber is the flux energy divided by the photon energy (given by equation 1). In the lower figure the red area is around 0.5% of the bluish area; therefore, the 2,349 $cm^{-1}$ centred band is only of moderate importance for $CO_2$ photon absorption.

### Can $CO_2$ Molecules Ever Relax?

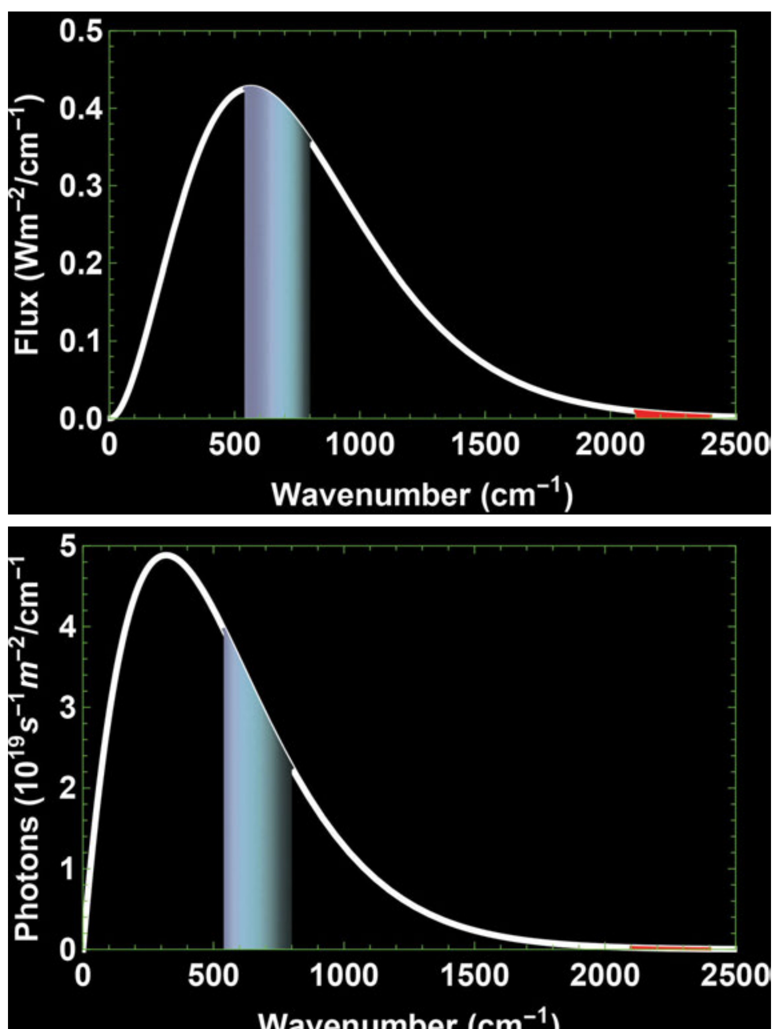
For $CO_2$ we have seen that the bending mode vibration at 667 $cm^{-1}$ dominantly absorbs Earth's IR radiation as this band is positioned near the peak radiation wavelength for Earth's temperature. Further, we have seen that IR radiation interacts with an IR-active molecule by a photon transferring its energy to the molecule. The photon is removed from the radiation field while the photon energy raises the molecule to a higher vibrational state. But excited states are energetically unfavourable; the molecule wants to return to the ground state by giving up energy. Keep reading *GEO ExPro* to learn about the life events that disrupt the usual activities of $CO_2$ molecules, causing substantial changes and readjustments in their lives.

***Acknowledgement***

The authors have enjoyed many helpful discussions with Tore Karlsson.

*Lasse Amundsen is a full-time employee of Equinor. ■

*Earth's blackbody spectrum (white curve) for outgoing radiation flux (top) and number of emitted photons (bottom) as function of wavenumber for surface temperature 288K (15°C).*



# Mapping in Microns

## An image-based approach for identifying pores and particles.

SHANE BUTLER, BLAISE MIBECK, BETHANY KURZ and ALEXANDER AZENKENG; EERC

The capture of carbon dioxide ($CO_2$) from industrial sources and subsequent injection of the captured gas into geological formations for permanent storage has been identified as a potential means of mitigating climate change. Improvements in directional drilling technology and hydraulic fracturing of organic-rich shales and other tight rock formations have opened new opportunities for $CO_2$-based enhanced oil recovery and associated $CO_2$ storage. As a result, shales previously viewed mostly as $CO_2$ storage seals for conventional geological formations are now considered as an emerging potential $CO_2$ storage resource. The $CO_2$ storage potential of shales, especially those that are rich in organics and clay minerals, can be quite high given the $CO_2$ sorptive capacity of organic matter (OM) and clay minerals. In addition, pore space and induced and naturally-occurring fracture networks create opportunities for free phase $CO_2$ storage.

### Image Analysis-Based Approach

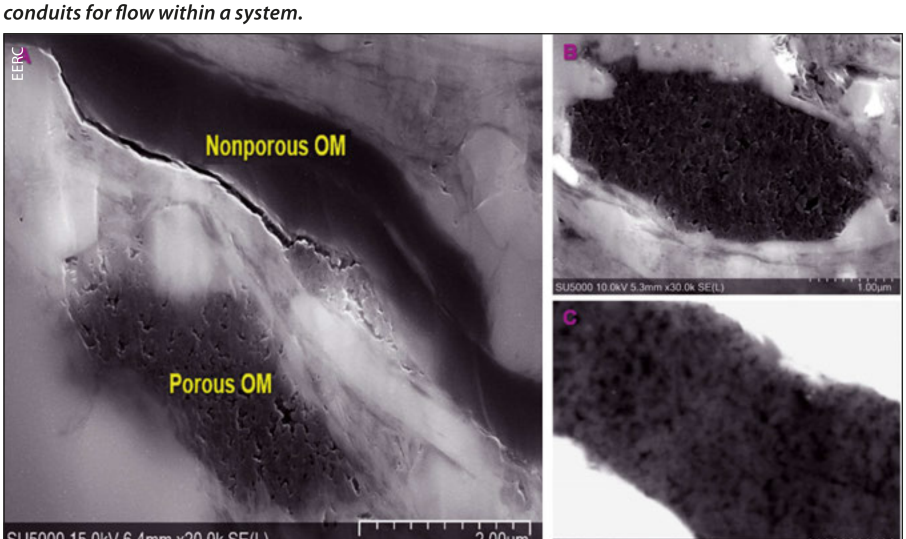
Characterisation of key features of interest such as pores, fractures, OM and clays in unconventional reservoirs can be challenging because of the scale. Traditional lab techniques are often unable to detect or quantify these nano-size features of interest; however, comprehending their occurrence and their relationship to each other is important to understanding fluid flow, potential sorption sites and void space volumes. Standard laboratory methods of investigation continue to be important tools in the characterisation of these unique rocks, providing the data used in making assessments related to all facets of operations. The key is to enhance and complement these methods with new tools in order to extrapolate data with greater efficiency and at different scales. In this case, the existence of nanopores and nanofractures in tight rock matrices offers a chance to study mechanisms to better understand potential $CO_2$ transport, enhanced oil recovery (EOR) potential and storage mechanisms in organic-rich shales and other unconventional reservoirs. Understanding the detailed mineralogy offers insights into the propensity of rock to fracture during well stimulation operations, or for clays to swell during drilling or fluid injection. From a $CO_2$ EOR and storage perspective, clay type and occurrence can affect the $CO_2$ migration pathways and adsorption potential of the reservoir.

Field emission scanning electron microscopy (FESEM) coupled with energy-dispersive spectroscopy (EDS) offers enhanced capabilities for unconventional reservoir characterisation. The challenge with using FESEM to better understand the matrix of unconventional reservoirs is the high resolution needed to adequately detect and image nano- or microscale features of interest in areas of the reservoir as small as 100 µm$^2$. To extract statistically relevant information about features of interest requires analysis of multiple locations on a single sample and analysis of multiple samples. As a result, automated solutions and machine learning become much-needed tools in the development of an image analysis-based approach.

### Developing the Approach

Work to develop such an image analysis-based approach for the identification of pores, fractures, OM and clays in organic-rich shales and other unconventional reservoir rocks, was conducted at the Energy & Environmental Research Center (EERC) in Grand Forks, North Dakota, using samples from the Bakken petroleum system. The organic-rich shale source rocks of the Bakken, coupled with interbedded carbonate-rich, tight siltstone reservoir lithofacies that serve as targets for horizontal drilling, provide an ideal opportunity to apply advanced image analysis-based workflows to different types of unconventional reservoir rocks. The coupled FESEM image analysis, machine learning workflow developed by the EERC allows for automated and efficient characterisation of minerals, OM, pore spaces and fractures in unconventional reservoirs to evaluate

*Examples of porous (A, B, C) and non-porous (A) organic material in the shale source rock of the Bakken. There is also an example of fractures adjacent to pore space (A). These void spaces provide conduits for flow within a system.*

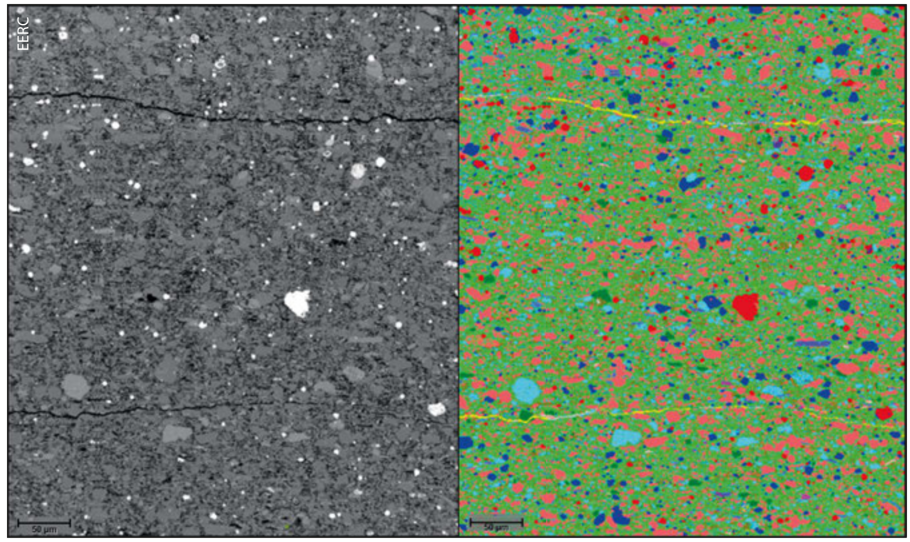


their potential for $CO_2$ EOR and storage applications. The key software packages used for the advanced image analysis method included the Advanced Mineral Identification and Characterisation System (AMICS), ImageJ and ilastik.

### Tools of the Trade

AMICS is software for automated mineral analysis, specifically developed for the identification and characterisation of minerals in ores and other types of materials (Bruker, 2019). In this study it was employed to process FESEM images to classify and quantify the mineralogy on a particle-by-particle and grain-by-grain basis in the form of mineral maps. To enhance any features of interest at the nano- and microscale, the samples were polished using a broad ion beam milling system, in which the top layer of a material is removed to reveal a fresh sample surface for high-resolution imaging. This increases the chances of imaging the different features of the rock matrix that represent the sampled interval. The output included quantitative estimates of key sample characteristics such as porosity, OM content, clay mineral types and content, and the whole suite of major, minor and trace/accessory mineral components.

ImageJ (Rasband et al., 2016) was employed to segment FESEM images into phases. Binary images of each phase were extracted, and operations were performed on those images to extract information and facilitate classifications of size, shape, area, and border contacts. Ilastik (Sommer et al., 2011) efficiently segments image features based on several attributes, including texture, shape and grey scale. Together, these programs were used to perform machine learning processes to interpret grain (or pore) size and shape, grain counts, and fractal analysis at a pixel-level detail. The power of these two programs is that they are able to classify features of interest based on things like texture, shape or spatial relationships. Thus, image classification is more advanced than that of traditional image analysis techniques which rely solely on grey scale for image segmentation.

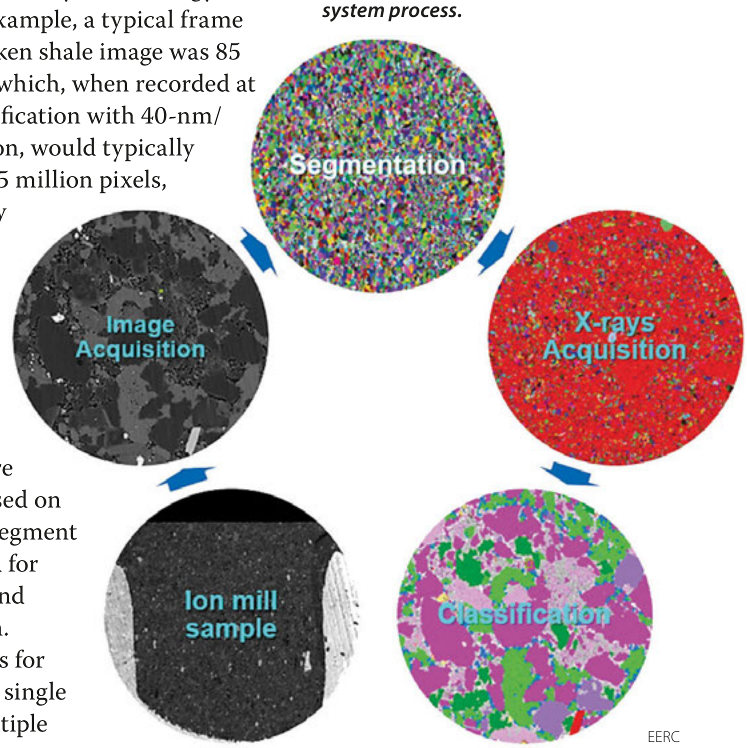



***FESEM image with associated AMICS map demonstrating texture and mineral, OM, and pore content in detailed colour.***

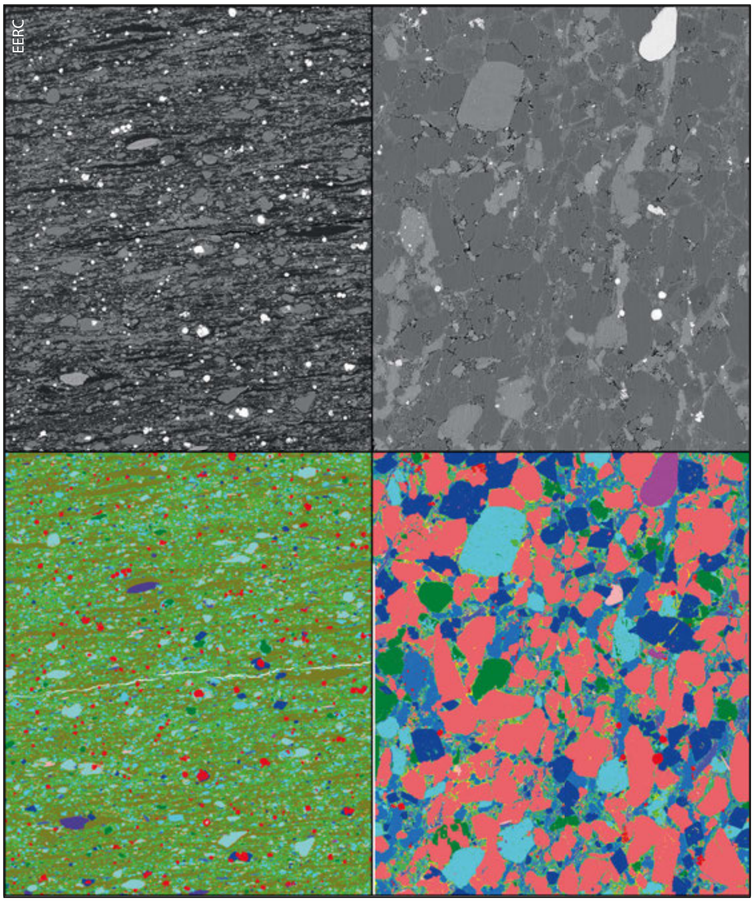
### Workflow to Data Flow

The beauty of the AMICS software interfacing with the FESEM is that images acquired (and subsequent x-rays) are automatically passed to the software for further processing. Each image frame is then divided into several thousand segments based on differences of back-scattered electron (BSE) values and x-rays are acquired for the segments. The smallest segment for which x-rays were acquired was determined based on the smallest feature of interest in the sample. This is generally dictated by the lithology of the sample. For example, a typical frame size for a Bakken shale image was 85 µm × 85 µm, which, when recorded at 1,500× magnification with 40-nm/pixel resolution, would typically yield about 4.5 million pixels, approximately 66,000 segments and 47,000 x-ray points in an analysis. The image size and x-ray count are adjustable based on the smallest segment that is needed for observation and interpretation. AMICS allows for acquisition of single as well as multiple frames. The versatility of the program enables preliminary observation to occur in isolated areas with multiple x-ray count tests in order to establish a final determination of the ideal observable area and point density. This maximises data recovery efforts while eliminating wasted time on unfruitful testing areas.

The AMICS approach generated mineral maps that could illustrate




***Visual demonstration of the acquisition and analysis workflow during the AMICS advanced mineral identification and characterisation system process.***




*BSE images (top) of shale source rock (left) and reservoir (right). The AMICS maps (bottom) clearly demonstrate the textural difference between the two horizons.*

spatial mineral/pore/OM relationships within the samples for a succinct comparison of different samples or different lithofacies, illustrating the vivid differences between the Upper, Middle and Lower Bakken samples. These maps allow for qualitative assessment because of the observed spatial relationships of potential $CO_2$ flow pathways and sorption sites through the visualisation of pores, fractures, clay and OM occurrence.

## Data Flow to Understand Fluid Flow

The high-resolution images with distinct contrasts in features allowed for further processing of the data. An advanced image analysis (AIA) approach that combined open source software with in-house code was used to manipulate, adjust, filter, analyse and segment LowMag (3,000×) and HighMag (20,000×) image sets. The workflow was separate from but complementary to the AMICS data and relied on the images acquired by the FESEM.

The AIA workflow also allowed for quantification of the spatial relationships between key features of interest, such as the distribution of non-sorptive minerals, clays or OM surrounding pore spaces or fracture networks. This is important, because when trying to determine what OM or minerals $CO_2$ might contact when flowing through the pore spaces or fracture networks of a rock, it could be misleading to just use the bulk mineralogy or total organic carbon content of the sample. For example, many of the pore spaces in the Middle Bakken samples are lined with clay minerals, whereas within the shales, almost all of the porosity occurs within OM. Thus, the $CO_2$ sorption potential will vary significantly between the Bakken shales versus the reservoir rock because $CO_2$ has a much higher sorption affinity for OM than clays.

The sets of FESEM LowMag and HighMag images with distinct feature contrast were critical to the spatial resolution of different scales of pores and features in the tight rock matrix and within the OM particles for AIA. The LowMag images were used to segment and quantify the total pore space, OM, clay and medium-density mineral content. The latter includes quartz, calcite, dolomite, K-feldspar, etc. while the high-density mineral content consisted of pyrite, zircon or monazite. The HighMag images were used primarily to segment and quantify the porosity associated with OM, focused specifically on OM particles found within the sample matrix. Both image sets were acquired in BSE and secondary electron (SE) modes to distinguish different surface topological and textural attributes of clays, OM, and pores and fractures within both the matrix and within OM particles.

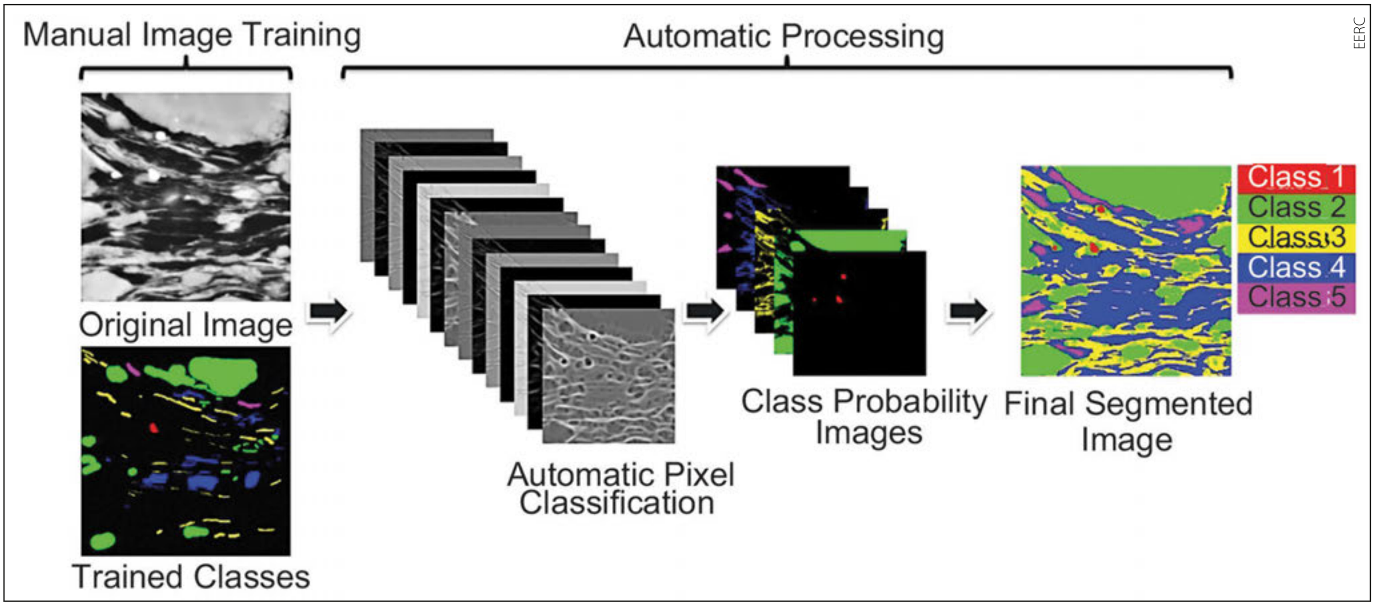
## Illustrated Results

The AIA approach provided striking images of the relationships between the classes identified for machine learning, selected to represent features of interest to better understand the Bakken $CO_2$ storage potential. Any number of class combinations could be designated based on which parameters the user wants to quantify, such as pores associated with OM versus matrix-only pores versus the void space within fractures. The distribution of pores between the different void types can provide useful insight into potential fluid and/or $CO_2$ migration pathways. The ability to distinguish and quantify porosity within pores versus fractures is a significant step in better understanding the primary mechanisms of fluid and $CO_2$ flow and storage within tight reservoirs.

## Growth and Promise

As can be seen, the analysis of FESEM imagery using the machine learning-based capabilities of AMICS, ImageJ and ilastik provided a new way to interpret and quantify key unconventional rock features at the micron and nanoscale. AMICS mineral maps create powerful visuals of the various mineral grains and their associations in the rock matrix with effectively characterised and quantified mineralogy, clay content, fractures, porosity, and OM content at the resolution needed for unconventional reservoir characterisation. The maps also facilitate quick, at-a-glance comparisons of different samples and highlight mineral phases that may be reactive to $CO_2$. Resulting 2D imagery analysis with AIA methods highlighted the important features needed to identify and better understand potential flow paths and to quantify void space within pores versus that associated with fractures.

There is potential for future development and application of these methods to better understand the

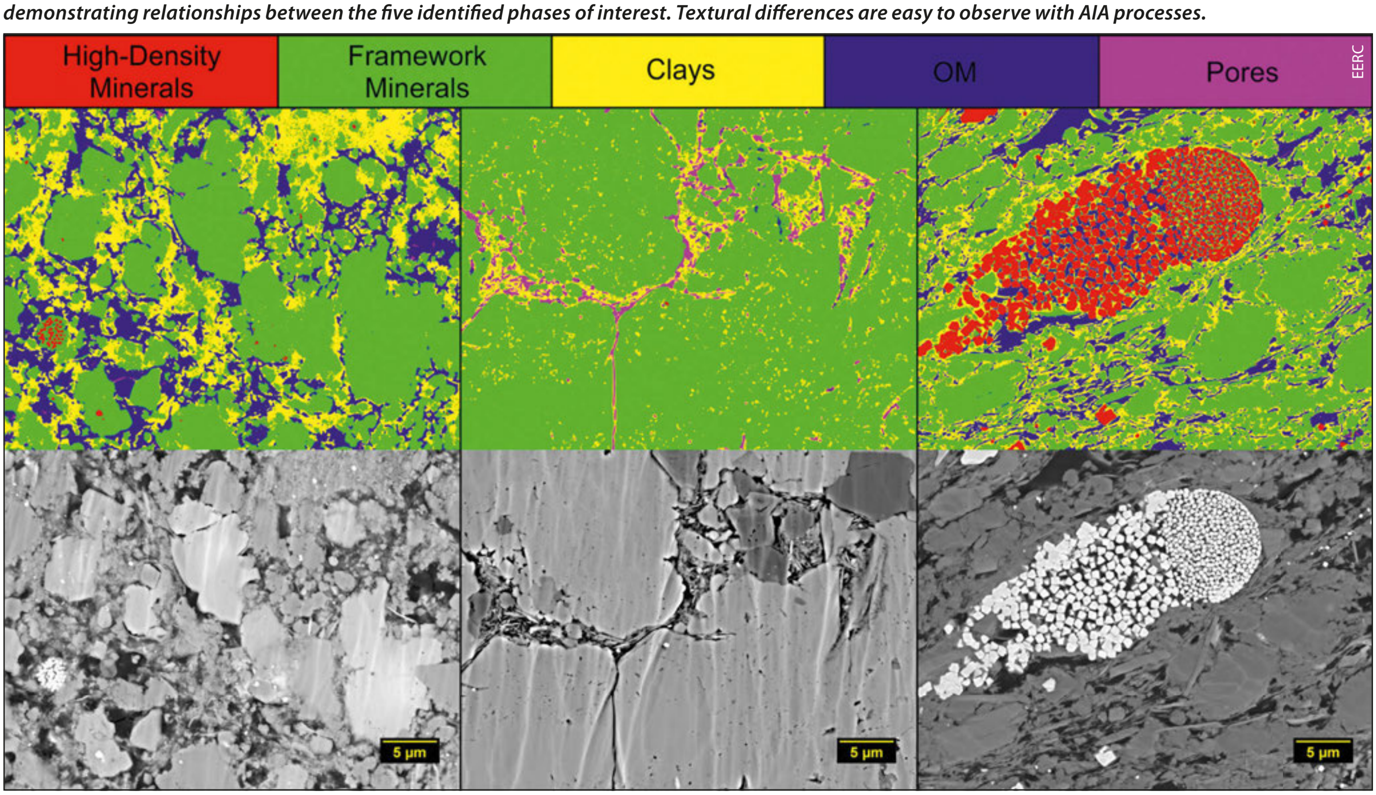



***AIA workflow to segment images to understand spatial relationships of key identified phases of interest.***

primary mechanisms of fluid and $CO_2$ flow and storage within unconventional reservoirs. One example is investigations to better understand the number of images needed to use stereological approaches to estimate the volume of sample components using 2D and 3D imagery. Also, while AIA techniques successfully identified and quantified the void space in organic matter, making a differentiation between void space in pores versus fractures, additional work could determine connected and non-connected porosity. This would facilitate the ability to take sample characterisation data acquired at the nano- and microscale and upscale it to core, well and eventually to reservoir scale by incorporating log data, petrophysical analysis and advanced mathematical techniques. Integrated results could facilitate and improve reservoir modelling and simulations for $CO_2$ EOR and storage potential. This workflow, while developed using rocks from the Bakken, can easily be applied to other shales and unconventional reservoirs to characterise key features of interest and to better estimate $CO_2$ storage and EOR potential.

*References available online.* ■

***FESEM images (bottom row) from left to right of the Upper, Middle and Lower Bakken, with associated ilastik and ImageJ segmented images (top row), demonstrating relationships between the five identified phases of interest. Textural differences are easy to observe with AIA processes.***



# The Philippines: A Land of Irony and Opportunity

**Dubbed as 'Pearl of the Orient', the Philippines is no stranger to rich natural resources. However, history has not been kind as to the use of such resources, and the time to correct it is now.**

JOHN MARK BAUTISTA, Philippines Department of Energy

The Philippines is an archipelagic country located in South East Asia, lying between Taiwan to the north and Borneo to the south. Sited at the crossroads of the eastern and western business worlds, it is a critical entry point to over 500 million people in the Association of Southeast Asian Nations market and a gateway for international shipping and air lanes servicing European and American businesses. Comprised of 7,107 islands covering a land area of around 300,000 km$^2$, the Philippines is generally categorised into three main geographical divisions, namely: Luzon in the north, Visayas in the centre and west, and Mindanao in the south-east.

The Philippines is known for its rich natural resources and an even richer history, both in terms of geology and civilisation. The coral reefs are no stranger to the Philippines, as the country houses rich marine biodiversity habitats. Many of these may date back to the formation of the islands, as shown by the reef build-ups that commonly serve as either source or reservoir rocks in the country's petroleum systems. Other limestone structures that have captured the attention of both local and foreign tourists can be seen in the Puerto Princesa Subterranean River National Park in the Saint Paul Mountain Range in the north-western part of the island of Palawan, including the Puerto Princesa Subterranean River, an 8.2-km-long underground section of the Cabayugan River. Another attraction is the Masungi Limestone Reserve, a National Geologic Monument about 20 km east of the capital, Manila, on the large northern island of Luzon, which features rugged limestone karst landscape with steep slopes, and caves.

However, limestone is not everything as far as the Philippine's geological history is concerned. The 'mainland' of the Philippines is a product of volcanism and accretion, and "can be used as an analogue to better understand inactive and accreted island arcs" (Morrison, 2014). Since most of the volcanic rocks

Jer Rey/Pixabay

*Limestone formations on the island of Palawan. The majority of hydrocarbon exploration in the Philippines to date has been off the west coast of this island.*

in the country are of andesitic to mafic composition, they are very much susceptible to weathering. This, together with violent volcanic episodes that have produced layers of tuff, gave rise to thick sedimentary deposits, both onshore and offshore.

### Patchy Exploration History

In terms of petroleum exploration, the Philippines is still very much underexplored. Roughly only 10% of the country's territory has viable data in relation to petroleum exploration, with the data heavily concentrated in the offshore western side of Palawan and onshore Cebu.

Petroleum exploration in the Philippines dates back to 1896 when the Toledo-1 well was drilled in Cebu Island by Smith and Bell, obtaining small but uncommercial production. There was also some drilling pre-1938 on the Bondoc Peninsula on Luzon, with some evidence of oil and gas, but again not considered to be in commercial quantities. There were also some early investigations near seeps on the island of Mindanao.

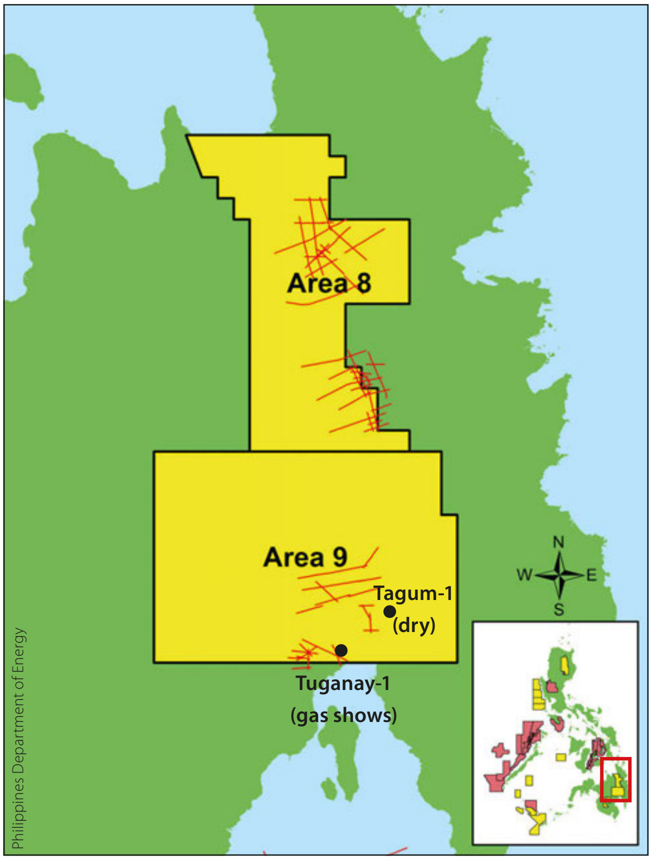
Widespread exploration activities were carried out from the 1950s to 1970s, by which time exploration was governed by the Petroleum Act of 1949, which introduced the concession system. This was replaced by a revised contract system in 1973, which was particularly favourable to offshore exploration, so activities shifted to marine areas like the Northwest Palawan Shelf, where the first field, Nido, was discovered in 1977. Having started production in 1979, by the time it ceased in 2019 it had produced over 18 MMbo.

Exploration moved into deeper waters off western Palawan in the 1980s, with several relatively large fields being discovered, including the West Linapacan Field in 1990. Also in 1990, Shell discovered the Malampaya field, 80 km offshore north-west Palawan in 820m of water, which became, by far, the largest gas discovery in the country.

At the start of 2020, there were only three active petroleum-producing fields in the Philippines, namely: Malampaya (gas and condensate) and Galoc (oil) offshore north-west Palawan


*The Malampaya project offshore Palawan provides 20% of the Philippines' total electricity requirements.*

*Map of the Philippines showing active Petroleum Service Contract areas in red.*




*An example of an underexplored onshore area: open blocks 8 and 9 in the northern Agusan-Davao Basin in Mindanao cover an area of 12,360 km$^2$, but as can be seen from the map, the seismic coverage (red lines) is very limited and to date only two wells have been drilled, one of which had gas shows.*

and Alegria (oil) onshore Cebu. Two oil fields were decommissioned in 2019. These were Nido, as mentioned previously, and Matinloc, also on the Northwest Palawan Shelf.

## Frontier Under our Feet

The Province of Palawan experiences rotational power outages despite being near to active petroleum-producing fields such as Malampaya. This is due to the fact that there are no power plants in the island province that can use natural gas as fuel, so the gas from Malampaya is sent over 500 km to the power plants in Batangas, south of Manila, and is used for power generation in mainland Luzon. Other oil-producing fields in the Palawan Basin also contain gas but this is usually flared since there are no eligible customers in Palawan. However, there are Petroleum Service Contracts (PSCs) still in operation near Palawan with pending or ongoing exploration activities which might be able to find and produce natural gas. Is this all a sad irony – or a missed opportunity?

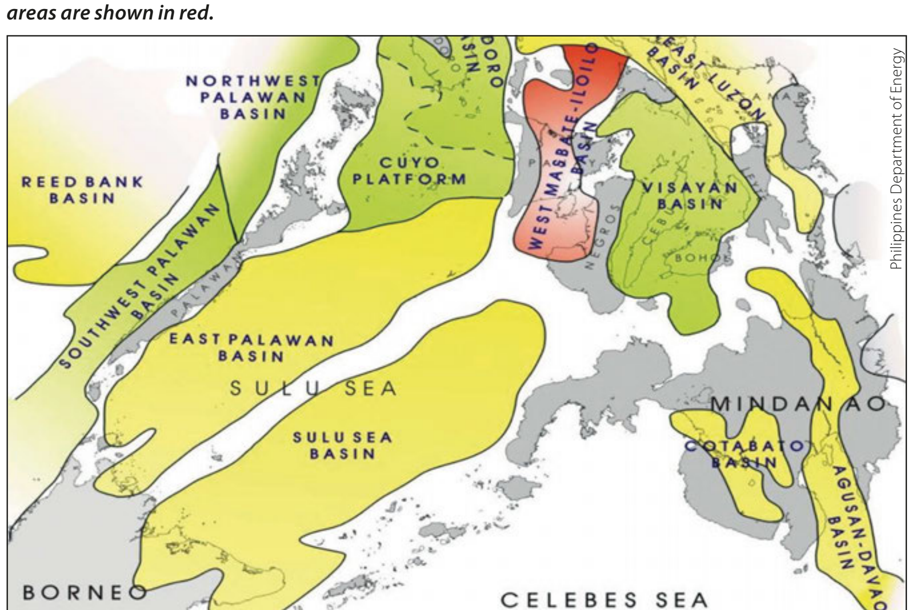
Onshore petroleum exploration has not been gaining the same traction as that of its offshore counterpart, which is mainly due to the unique geology of the Philippines, featuring both large-scale and small-scale faults. Oil production in the island of Cebu, part of the Visayas group of islands in the centre of the Philippines, has faced difficulty because of this. The San Antonio gas field in northern Luzon, discovered in 1994, until recently supplied gas to a small local area and there are areas in Luzon that are still underexplored.

Similarly, the island of Mindanao could be considered underexplored although petroleum accumulations have been found in some parts of these islands. For example, very little is known about the underexplored Agusan-Davao Basin in eastern Mindanao, where a dry well but with gas shows was drilled in the area (Tuganay-1), supporting the idea that there is still an accumulation of petroleum in the area. In addition, in the south-western part of the main island of Mindanao is the Cotabato Basin, a gas-rich area which has not been thoroughly explored for geopolitical reasons.

## Huge Offshore Potential

Though various PSCs are already operating in the north-west Palawan area, it is thought that there still remain vast accumulations of petroleum in the region, including, for example, the Camago-Malampaya Oil Leg (CMOL) and the Cadlao discovery. CMOL was discovered in 1991 during the drilling of Malampaya-1 but was relinquished by the Malampaya consortium since it was considered to be sub-commercial. Although a contract to develop the area was awarded in 2006, it was cancelled in 2011, mainly due to non-compliance by the operator to the provisions of the work commitments. The Philippines Department of Energy (DoE) is currently trying to find new options for exploring the oil-rich structure, which

*The geological basins of the southern Philippines. The most prospective basins are shown in green, those considered prospective but underexplored – such as the Sulu Sea – are in yellow, while frontier areas are shown in red.*



is believed to contain an estimated reserve of around 27 MMbo.

The Cadlao discovery, on the other hand, started producing in 1981 as the first-ever subsea well and FPSO development project and produced about 10 MMbo. However, it is still thought viable for redevelopment given the advancements in technology the world has seen since it came on production.

Further offshore north-west Palawan is Recto Bank, also known as Reed Bank, a gas-rich area with hypothetical (mapped) resources of at least 600 Bcf of gas. It is thought there are more resources in this area and three new applications for PSCs have been received by the DoE as of March 2020, in addition to the already existing Service Contract in the area, SC72, which lies about 200 km west of Palawan.


*Lake Seloton, in South Cotabato on the island of Mindanao, is dotted with fish pens and lotus flowers which only blossom early in the morning.*

However, the main focus of upcoming exploration in the country is expected to be the large sea area lying between Palawan, Mindanao and Western Visayas. This region consists of two sedimentary basins, the East Palawan Basin and the Sulu Sea Basin. Only two PSCs are currently operating in the area, SC56 and SC76, operated by Total E&P and Ratio Petroleum Ltd respectively.

The East Palawan Basin is thought to be a fore-arc basin, formed when Palawan and its surrounding basins rifted and separated from southern China during the opening of the South China Sea in the Oligocene and Early Miocene. Only five wells have been drilled in the basin, one of which had shows, but it is thought that it should have similar plays to those found in the producing basin west of Palawan, including anticlinal and stratigraphic structures and carbonate reef build-ups.

The Sulu Sea Basin, by contrast, is a delta superimposed on a back-arc basin where expected play types are carbonate reef build-ups, anticlines and fault blocks. The basin extends to the north-east portion of Sabah in Borneo where there have been gas discoveries, another indication of prospectivity. A resource estimation for the Philippine's Sulu Sea area undertaken by DoE in 2002 suggests that for the Sulu Sea Basin, the hypothetical (mapped) resources are estimated at 109 MMboe, while for the East Palawan basin, the figure is 166 MMboe.

### Energy Hungry Economy

The demand for energy in the Philippines is ever-increasing with the thrust of many business sectors to automation and paperless transactions. The continuing emergence of business process outsourcing companies and electronic portals for learning and government processes, for example, require a constant source of electricity. The current administration's policy, dubbed, "Build, Build, Build" will also require energy in various forms to implement, from fuel to electricity. Unfortunately, the Philippines remains vulnerable to changes in world market prices of petroleum products, as roughly half of its energy needs come from imported fuels. A downturn in exploration activities does not help the cause, as the Philippines only averaged three wells drilled per year for the period of 2013–2018.

The policy of the Department of Energy is to "Explore, Explore, Explore", trying to make the Petroleum Service Contracts system easier while still heavily penalising operators that fail to deliver their work commitments without valid and uncontrollable impediments. To this end, new laws and regulations have been put in place to expedite petroleum exploration (and other business transactions, as may be applicable), such as the Philippine Conventional Energy Contracting Program, the creation of the Energy Investment Coordinating Council and the Ease of Doing Business Act of 2018 (RA 11032).

The first round of applications for petroleum exploration blocks closed in August 2019, but the Philippines, through the DoE, still accepts applications through nomination of specific areas of interest at any time of the year. Submissions under this application mode shall be subject to a 60-day challenge period and are treated independently of other applications. For more information, please visit the Philippine Conventional Energy Contracting Program microsite: https://www.doe.gov.ph/pcecp.

*References available online.* ■

# A Journey to the Centre of the Earth

**A buried world is brought back to life through visualisation and imaging.**

SVEN PHILIT, SEBASTIEN LACAZE, BENJAMIN DUROT, Eliis; JAKE MARSON, Eliis Inc.

The realm of seismic interpretation has now undergone several decades of technological advancements and improvements. The days of interpreting on long hard copy seismic lines and the art of hand contouring are memories, having given way to the numerical revolution and the arrival of large 3D seismic volumes and their representations managed in dedicated interpretation software.

The underlying goal of these improvements has been to help interpreters efficiently process increasingly larger quantities of data, supported by optimised tools that can help interpreters make more accurate maps. In particular, a significant amount of effort has been placed on how a software displays data, driven not by pure aesthetics. In fact, this effort stems from the realisation that the interpreter must truly understand the data in order to gain a natural and comprehensive understanding of the information available within it. Although, strictly speaking, the seismic realm does not relate to the centre of the Earth, it is still the reflection of a buried world, and the objective of any interpretation software should be, through its imaging techniques, to help unlock the secrets of this world and display them in vivid reality.

In the modern world, we must acknowledge that most seismic interpreters are still bound to the 2D dimension of their screens. With this in mind, in this article we present a few concrete techniques that are known to greatly enhance the experience of seismic interpreters.

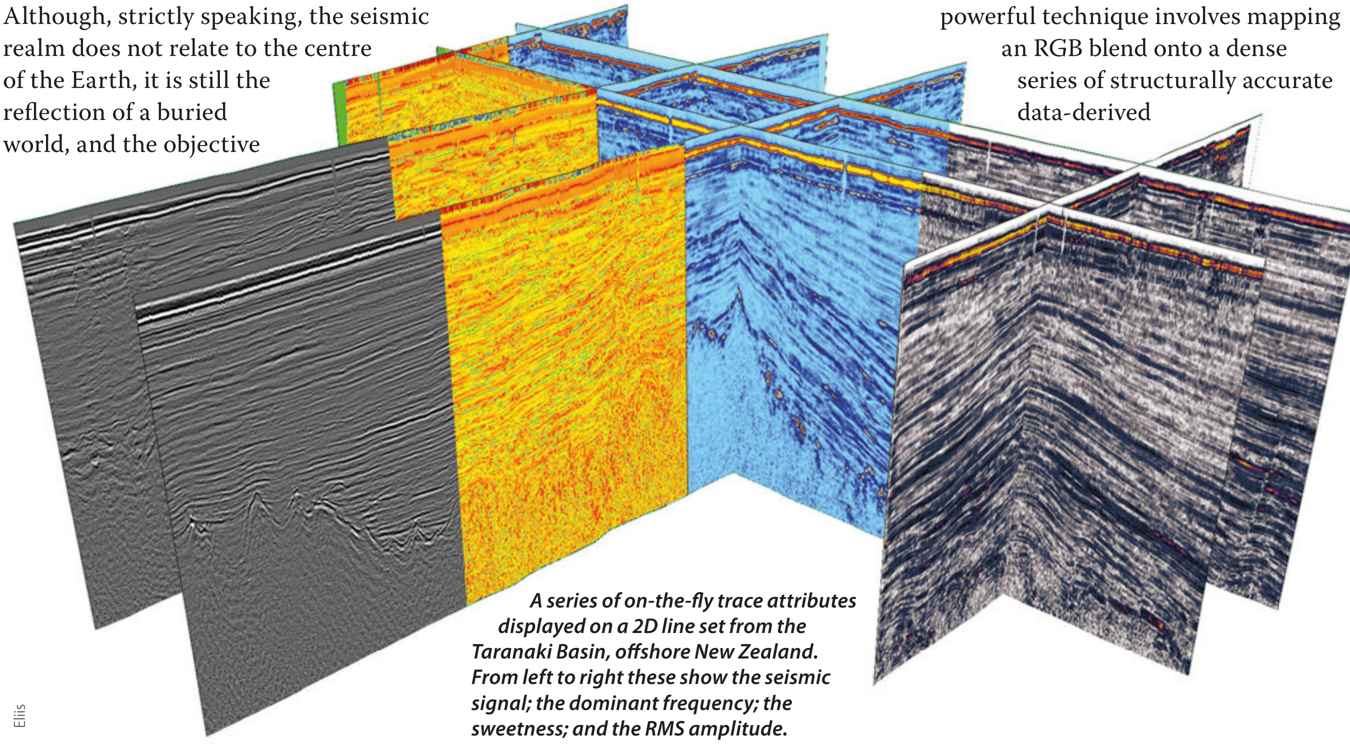
## Instantaneous Perspective

It is useful to view a variety of seismic attributes to better understand the geophysical signature of the data prior to starting an interpretation project. For example, an interpreter may want to enhance the detection of structural discontinuities with structural attributes, or to gain insight into the geological organisation of the deposits with stratigraphic attributes. The latter attribute type mostly corresponds to trace attributes and since the computation of trace attributes is simple, it would be wise to take advantage of that fact to display them 'on-the-fly', thus allowing the interpreter to instantly put the data into perspective. These attributes should be easily accessible, no further than a pull-down menu, and its availability immediate.

While on-the-fly attributes are useful prior to interpretation, they are also a powerful tool while prospecting when coupled with co-rendering and cross-plotting techniques. As co-rendering involves blending several attributes, an on-the-fly display quickly offers a look at a series of trace attribute combinations without having to physically compute the corresponding volumes.

## A Bright and Comprehensive Picture

At an advanced stage of interpretation, when a target is being refined, an integrated and detailed analysis of the seismic data is beneficial. One especially powerful technique involves mapping an RGB blend onto a dense series of structurally accurate data-derived



*A series of on-the-fly trace attributes displayed on a 2D line set from the Taranaki Basin, offshore New Zealand. From left to right these show the seismic signal; the dominant frequency; the sweetness; and the RMS amplitude.*

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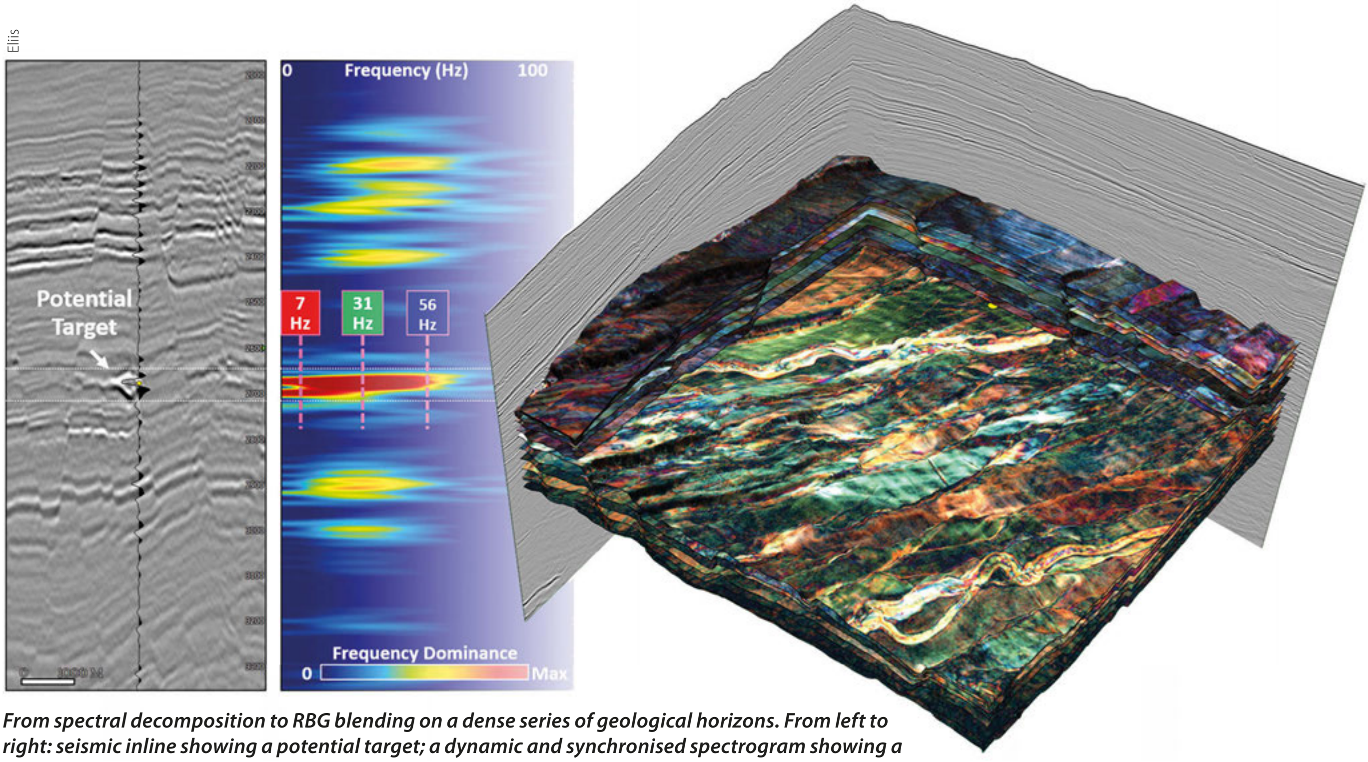
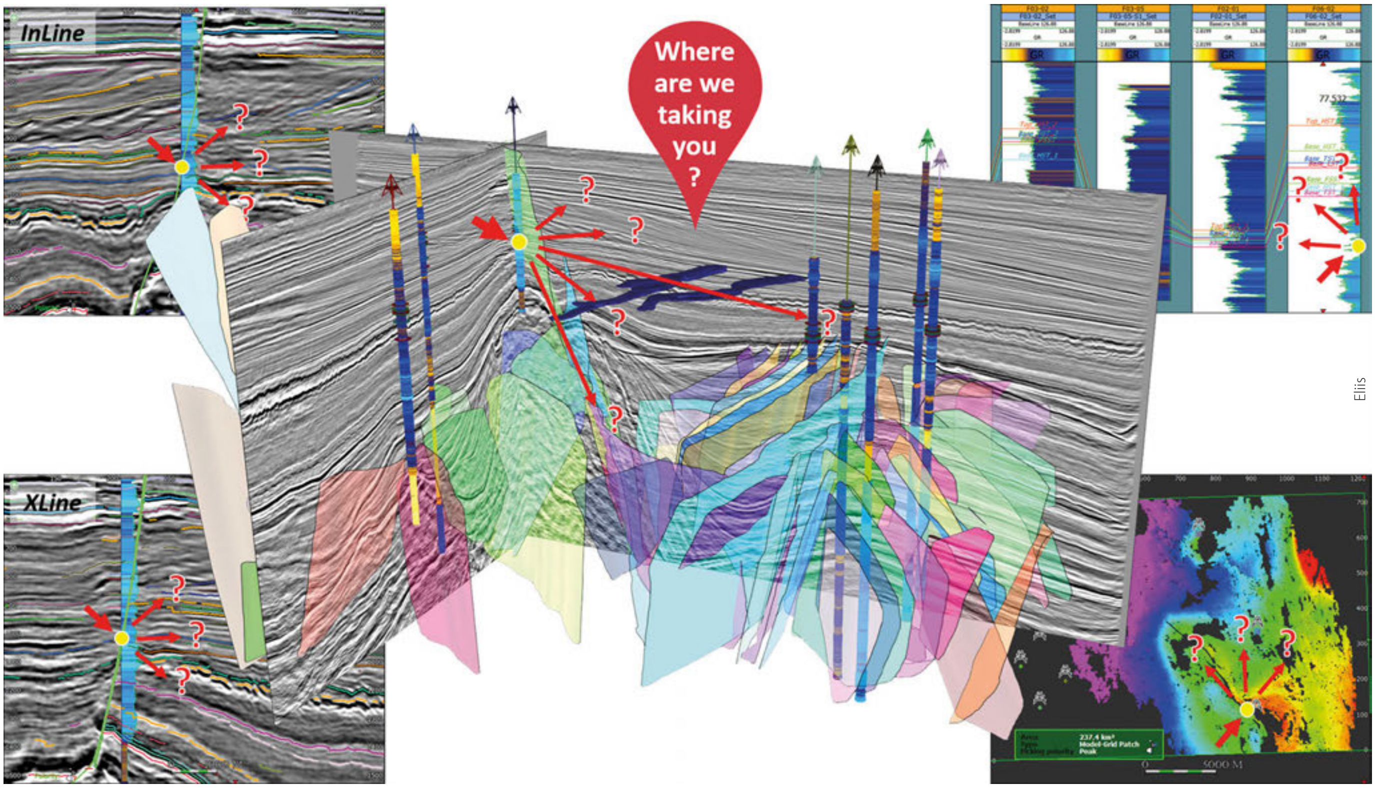



*From spectral decomposition to RBG blending on a dense series of geological horizons. From left to right: seismic inline showing a potential target; a dynamic and synchronised spectrogram showing a spectral decomposition in Short Time Fourier Transform and three target-representative frequencies; the RGB blending of the three frequencies mapped on a dense series of horizon slices in the Exmouth sub-basin (North West Australia margin).*

horizons, i.e., a horizon stack. The RGB blend, derived from selected frequencies (or frequency ranges), helps to reveal singular geological structures or the extent of depositional environments. This rich blending of colour helps to highlight the complex arrangement of specific lithofacies. To avoid the creation of erratic blending, the software design must include a convenient representation of the spectral decomposition or amplitude spectrum to allow the interpreter to easily select relevant frequencies or frequency ranges, respectively. Hence, an RGB blend mapped onto a dense horizon stack represents




*A synchronised interface: all dimensions and data are spatially connected to allow for intuitive and rapid navigation through all stages of the workflow.*

a compelling tool to scan an interval of interest and to identify previously ignored targets.

### Flying Through the Data

From the start of a project to the final deliverables, it is essential for an interpretation software to offer an interactive, user-friendly interface. In this world of XL monitors and the desire to have all available data types, including seismic, attributes, horizons, faults, well logs and markers, displayed in multiple viewers, software designers should put a specific effort into facilitating the interpreter's cognition. This can be achieved by managing spatial visualisation with the synchronised navigation between the viewers and dimensions. For example, a user interpreting a seismic line should be able to place a tracker at a given location and immediately be able to see the same position in a 3D viewer, where well trajectories and markers would be displayed. Furthermore, for the sake of cognition, he or she should also be able to drag the tracker along the line(s) and continuously follow its position on all viewers when navigating through the data.

The advantage of this synchronisation, which is maintained during navigation and applied to all objects, is enhanced further by a smart interface with options like a synchronised scaling display and the ability to quickly synchronise colour bars, thus allowing for consistent analysis. Intuitive interaction between the database and the viewers is likewise enhanced via the use of a drag and drop option. In the end, this interaction should draw the interpreter intuitively and swiftly nearer the position of a geologist in the field, with the added benefit of using the whole potential of the available database.

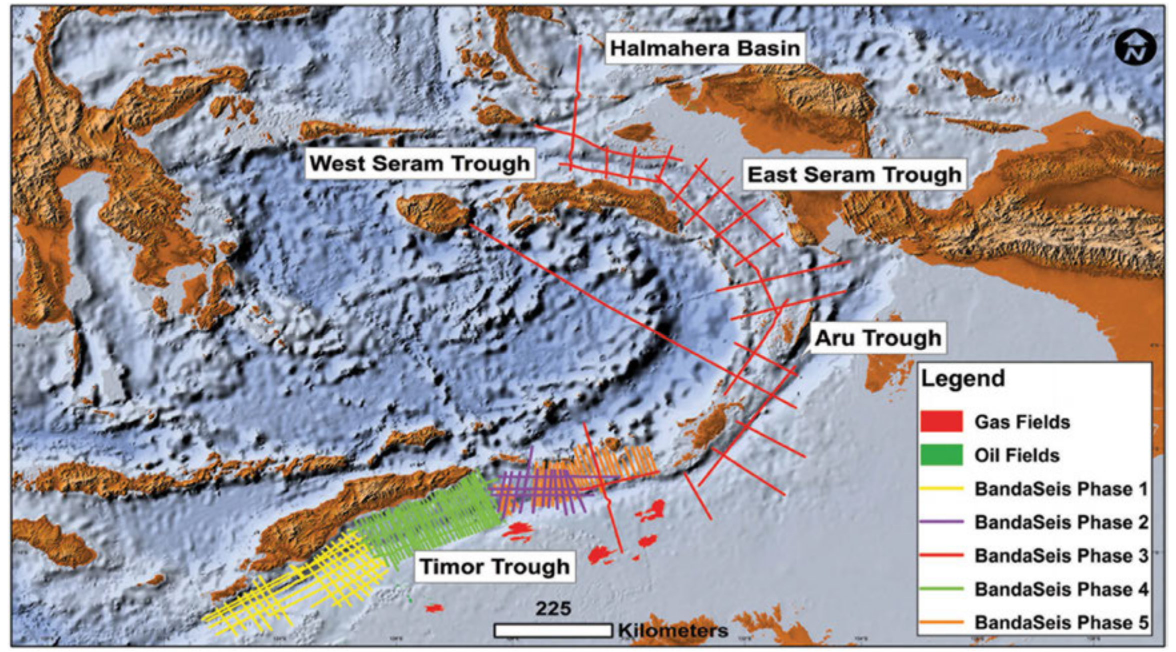
### What's Next?

We have seen that, if used properly, these visualisation and imaging techniques increase efficiency and have a positive effect on a user's experience throughout the seismic interpretation workflow, thus helping to unravel the potential of what lies underground. As we believe these techniques will become the standard or norm for modern seismic interpretation software, the question becomes: what's next? Should we seek for the massive development of augmented reality and immersive technologies, allowing users to set foot upon a virtual paleo-scene as a geologist would tromp through a gigantic outcrop – but without the gear? Should we strive to use restoration to interactively see time roll back before our eyes, unearthing the buried world with its diversity of depositional environments? This, I guess, only the future can tell.

***Acknowledgements***

*The title of this article is inspired from the novel of the same name by Jules Verne, first published in 1864. The examples presented were obtained using PaleoScan™, software developed by Eliis. The author would like to thank New Zealand Petroleum & Minerals and the Government of New Zealand for their permission to publish the 2D data from the Taranaki Basin; Geoscience Australia and the Government of Australia for block HCA2000A (Exmouth); and TNO and the Dutch government for the authorisation to publish their data on the block F03.* ■

CGG



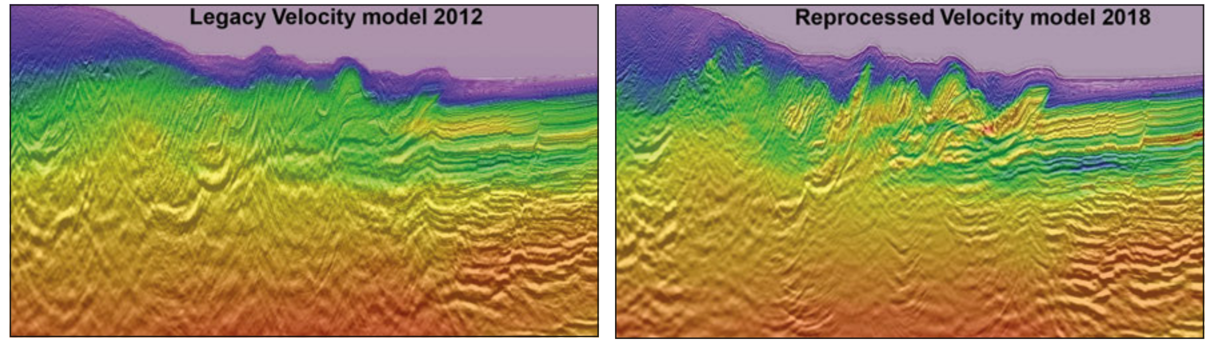

*BandaSeis 2D seismic line locations by phase, and corresponding offshore areas.*

# Banda Arc: Broadband 2D Seismic Unlocks Frontier Area

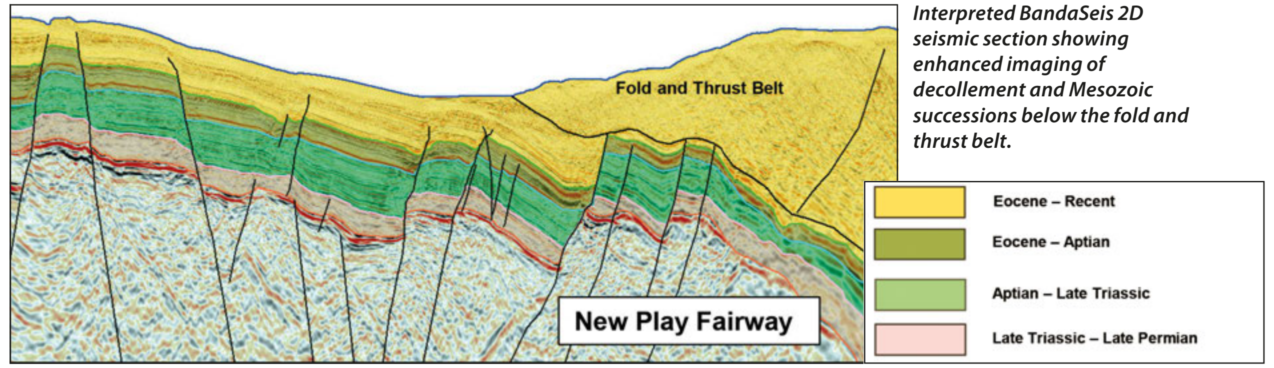
CGG's high quality BandaSeis 2D seismic data set, acquired and recently reprocessed with the latest imaging technology, and accompanying comprehensive Jumpstart™ geological study enhance the exploration potential of the Banda Arc region.

The BandaSeis multi-client programme is located within Eastern Indonesia's Banda Arc region which, although a proven hydrocarbon province, is largely underexplored with large undrilled areas and poorly understood petroleum system elements.

The surveys were acquired and processed using CGG's BroadSeis broadband imaging solution to clearly define new play levels in the area, including Mesozoic sub-thrust plays.




*Enhanced velocity model resolution. Original 2012 vs 2018 reprocessing.*




*Interpreted BandaSeis 2D seismic section showing enhanced imaging of decollement and Mesozoic successions below the fold and thrust belt.*

N

*BandaSeis 2D line intersecting the Timor Trough. Enhanced imaging enables interpretation of Late Palaeozoic and Mesozoic successions, pushed down into the hydrocarbon generation window beneath the fold and thrust belt.*

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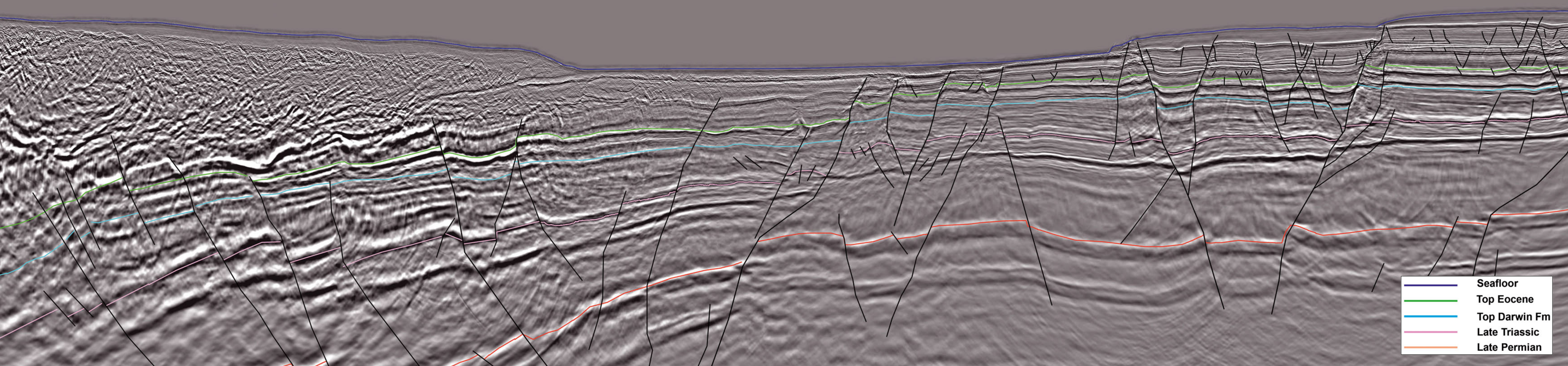


# New Broadband Imaging Reveals Prospectivity Insights

JARRAD GRAHAME and PEDRO MARTINEZ DURAN, CGG

**New high quality seismic datasets and a regional prospectivity study bring greater understanding of the distribution and extent of resource plays throughout the Banda Arc.**

CGG acquired its BandaSeis broadband multi-client 2D dataset around the entire Banda Arc region of Eastern Indonesia using its advanced BroadSeis™ acquisition and imaging solution.

The key objectives of the programme were to provide enhanced imaging of sub-thrust successions and structuring and to better constrain the Palaeozoic and Mesozoic petroleum system elements, which are widely regarded as equivalent to the northern Bonaparte and Browse Basins of the North West Shelf of Australia. The five phases of the BandaSeis programme represent 16,409 line-km of 2D broadband seismic data, with coverage from the island of Timor in the south to Seram in the north, including a single regional line across the Weber Deep and the entire Banda Sea.

The data was processed to PSDM using CGG's advanced techniques to significantly enhance image quality, with further reprocessing undertaken in 2018 on three of the five phases of the dataset. The resulting PSDM products provided unrivalled image quality, particularly below the fold and thrust belts of the arc system.

CGG has also conducted a comprehensive regional Jumpstart™ prospectivity study leveraging new information derived from the enhanced data.

## Geological Overview

The Banda Arc is located within a complex convergence zone between the Eurasian, Australian and Pacific tectonic plates, resulting in intense deformation, subduction and orogeny (Hall, 2012). This highly complicated and hence poorly understood geological region represents one of the most tectonically active areas in the world.

The Banda Arc exhibits a characteristic curvilinear geometry and can be divided into four main tectonic regions: an outer arc comprising a continental lithosphere and the larger islands, the major ones being Timor and Seram; an inner volcanic arc; the Weber Deep between the Inner and Outer arcs at the area of greatest curvature; and the fold-and-thrust belts that formed outboard of the Outer Arc (Baillie et al., 2014).

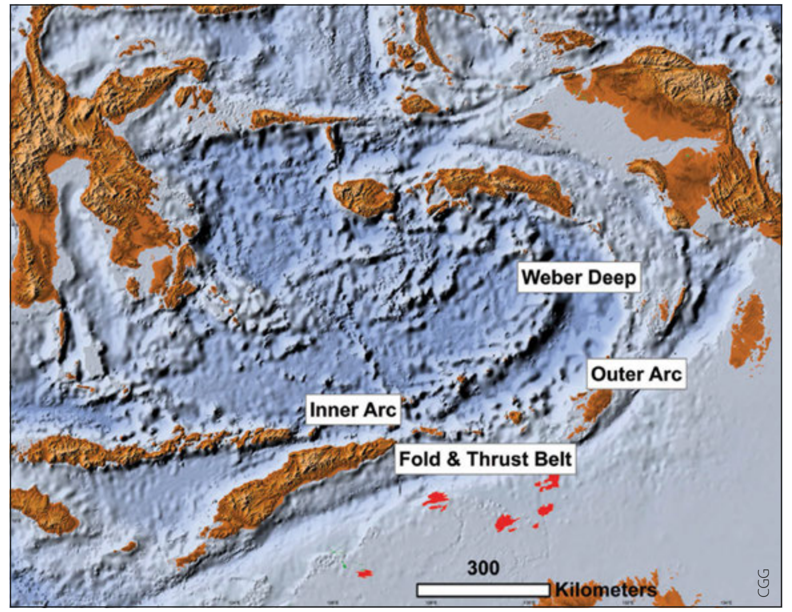
Eight key petroleum systems within the southern Banda Arc region can be summarised, analogously based on geological and geochemical information derived from the Bonaparte Basin (Barrett et al., 2004). They range from late Palaeozoic to late Mesozoic, including three Jurassic systems, one Triassic, three Permian, and one Permo-Carboniferous system.

Within the central Banda Arc/Tanimbar region the hydrocarbon-generative sequences are considered to be an extension of those within the Timor area, and therefore also North West Shelf equivalents. For the Tanimbar area, these petroleum systems include two Jurassic and three Palaeozoic sourced systems, equivalent to the Jurassic Echuca Shoals and Plover Formations of the Browse Basin, and the Permo-Carboniferous Milligans-Kuriyippi systems of the Bonaparte Basin.

The northern Banda Arc region, including Seram and its offshore area, hosts Lower Jurassic source rocks with potential contribution from Cretaceous, Triassic and Permian intervals.

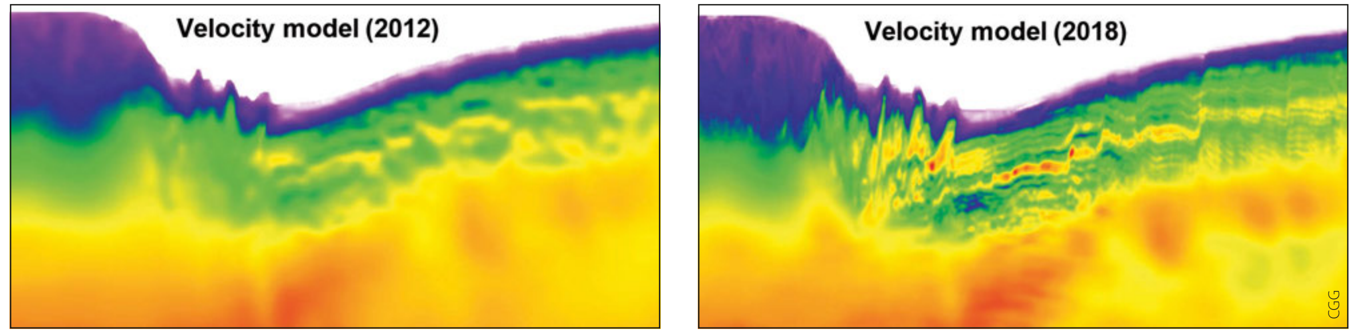
Abundant onshore and offshore seeps attest to the widespread presence of active source rocks throughout the Banda Arc, making the area of particular interest for hydrocarbon exploration. Factors influencing the limited exploration to date include remoteness and water depths. However, seismic imaging challenges, particularly beneath the fold and thrust belts, represent the key contributor to exploration uncertainty. CGG has sought to ameliorate this by providing high quality images beneath zones of significant deformation and by undertaking complementary, integrated geological interpretation and analyses to mitigate exploration risk.

*Banda Arc regional tectonic elements.*








*Legacy vs reprocessing velocity model showing the high level of geologically consistent detail provided by HF-FWI.*

## BandaSeis 2D - Key Technologies

The BandaSeis 2D seismic programme was acquired in five successive phases over a period of three years, from 2012 to 2015. It used CGG's proprietary BroadSeis broadband acquisition and imaging solution with 10 km maximum offset streamers. It utilises a unique variable-depth streamer profile and CGG's proprietary broadband processing technology, including ghost wavefield elimination, to produce superior imaging results compared to conventional datasets.

The first three phases of the data set were reprocessed by CGG utilising an updated broadband processing sequence and advanced full-waveform inversion (FWI) velocity model building to enhance visualisation of potential targets underlying highly-deformed fold and thrust belts, and to improve the low-frequency content of the data (Ping et al., 2019). High-frequency FWI (HF-FWI) was applied to the data to produce a higher-resolution velocity model with greatly improved correlation with the geology, as seen in the velocity model comparison above. The FWI technology overcomes the limitations of conventional reflection tomography in complex settings where the curvature picking and inversion are less reliable and stable.

Another key technology employed was joint source designature and deghosting, which produces a more stable wavelet phase, particularly in the low-frequency range. Application of these key technologies enhanced data quality and the ability to constrain geological features below the complex deformation zone.

## Prospectivity Insights from Regional Interpretation

Given significant knowledge gaps in the geology of the region, and a number of supporting indicators of active petroleum systems, CGG initiated a major regional study, deriving key insights from the data. The Banda Arc Jumpstart study involved an integrated methodology, leveraging the company's extensive multidisciplinary geoscience resources. This work included new interpretation of the dataset, correlation of satellite slicks and seismic data, onshore field studies, including source rock and live oil seep sampling for geochemical analyses, integration of seismic, well and potential fields data, basin modelling, and palaeogeographic reconstructions. The new seismic interpretation, covering the entire BandaSeis dataset, was undertaken in two phases: firstly, within a regional structural and stratigraphic context; and secondly, with a detailed prospect-level interpretation. CGG also correlated the seismic interpretation with structural and potential field data analyses undertaken in parallel in a regional context.

Some key highlights from the interpretation and analyses included identification of a new Jurassic sub-basin; mapping of a Mesozoic palaeo-high that changes the understanding of deposition and thermal history; new structural insights into the whole Banda Arc tectonic evolution; and identification and evaluation of 42 new leads throughout the Banda Arc offshore areas. These key highlights, which underlie the discovery of new prospectivity insights, can be directly attributed to the ability to image beneath the fold and thrust belt, since, for the first time, geological structures can be clearly seen below more than 5,000m of orogenic wedge sediments. Most importantly, the new level of imaging quality enables a greater understanding of the distribution and extent of resource plays.

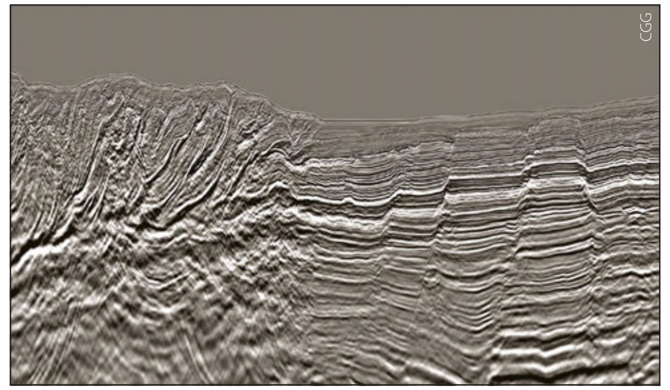
A comprehensive regional study produced to complement the dataset will enhance understanding of the palaeogeography and petroleum systems of the Banda Arc. This integrated approach to understand the total depositional systems in a geodynamic context allows for progressive de-risking of emerging plays and will underpin future exploration success in the region.

## Acknowledgements

The authors wish to thank CGG Multi-Client for permission to publish this work and CGG Geoscience for their significant contribution to these results.

*References available online.* ■

*Detailed imaging: decollement beneath fold and thrust belt revealed by the reprocessing of Phase 1 using the latest broadband processing and HF-FWI.*

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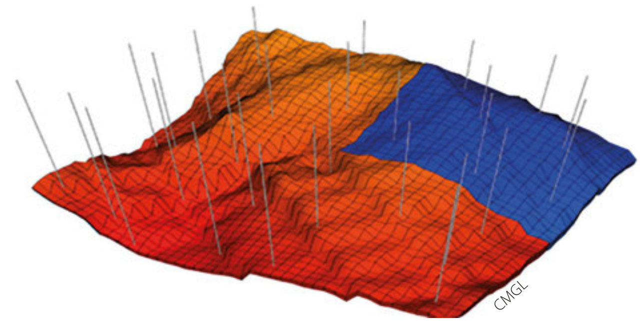
# Seeing the World in Three Dimensions

**A geologist turned reservoir engineer makes a plea to fellow reservoir engineers to use all the tools at their disposal, including studying 3D visualisations.**




*Geological reality or engineering?*

**SUSAN FELLOWS, Computer Modelling Group Ltd**

People see the world in different ways. Some people have red/green colour-blindness; some people have acute myopia; nearly all people have some form of astigmatism; some people have synaesthesia; some people cannot see at all; some people choose not to see at all.

I am a geologist by training. A childhood obsession with dinosaurs did not, in fact, lead to a lifetime fascination with ancient life, due to the necessity of dissecting rats during biology classes, which had no appeal whatsoever. At 14 years old, geography and ancient landscapes beckoned instead. Raised in the Weald in south-east England, with the undulating chalk curves of the North and South Downs encompassing the horizons, and the valleys in the middle alternating their sticky clay and crumbling sandstones, geomorphology and thus palaeo-landscapes and geology became my fascination. To this day, on daily walks in the Wiltshire countryside where I live – another chalk manifestation, smeared with clay by Ice Age scouring – I amuse myself by 'undressing' the landscape, and reconstructing the aeons. I see the world in three dimensions. To me, it is natural. I do not believe I can look at the world in any other way; whether surface or subsurface, it is a three-dimensional environment.

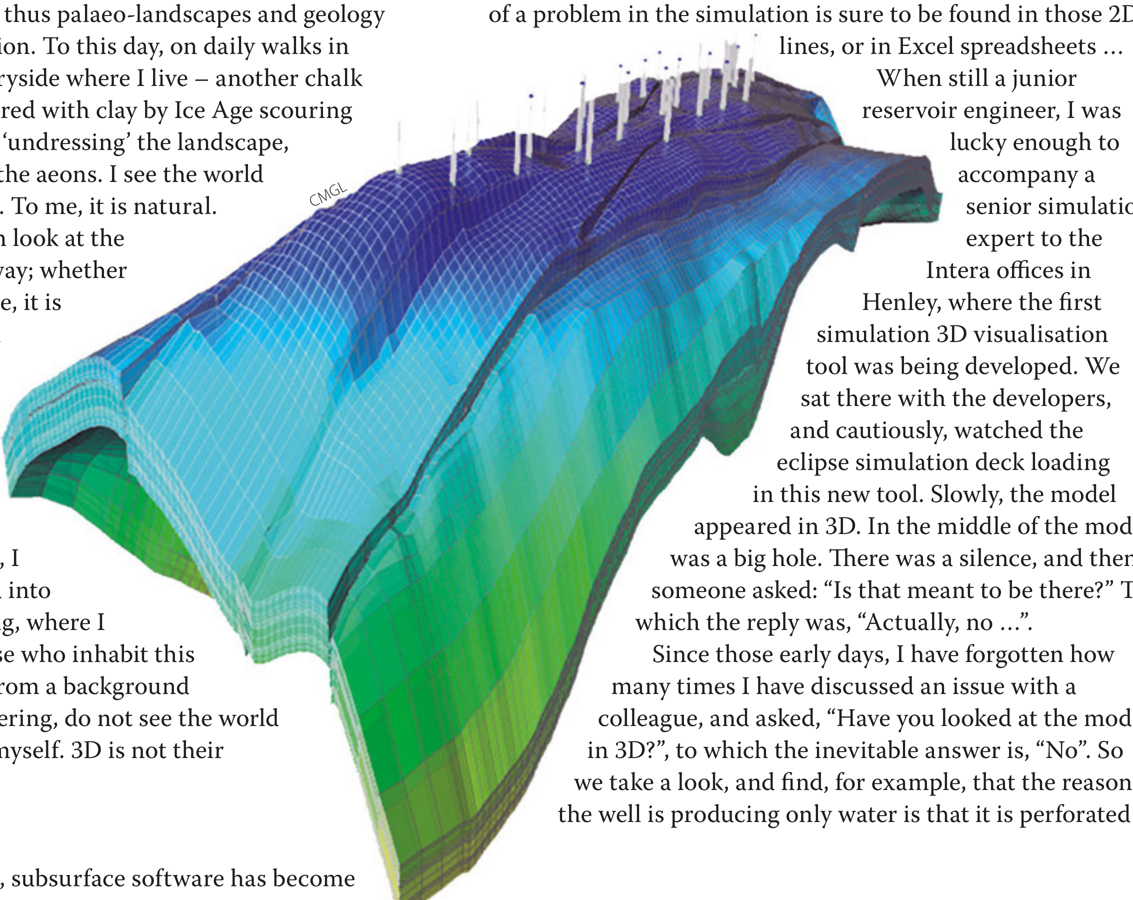
I have not, however, spent my career working as a geologist. In the way that life twists and turns, I subsequently moved into reservoir engineering, where I recognised that those who inhabit this discipline, coming from a background in physics or engineering, do not see the world in the same way as myself. 3D is not their viewpoint.

## Use the 3D Model

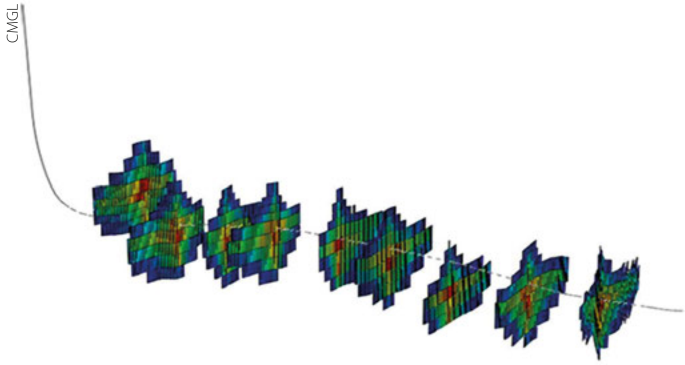
Since the mid 1990s, subsurface software has become increasingly abundantly provided with 3D modelling capabilities. The subsurface workflow is an intricate pattern of surfaces, planes, logs and cross-sections, all dissected and re-compiled, with the almost single-minded objective of building a 3D model of the hydrocarbon reservoir – the static model – which is then passed to the reservoir engineer for dynamic modelling, and fluid flow analysis. At which point, although I appreciate why the geological understanding is inclined to evaporate, so, unfortunately, does any desire to look at the dynamic model in 3D, despite the fact that the entire previous workflow has been focused on creating just that. Yes, endless 2D plots of production profiles, bottomhole pressure, cumulative production etc. are produced, but to actually 'look' at the reservoir to understand the behaviour, is most often the last course of action, if it is taken at all. Rather, the cause of a problem in the simulation is sure to be found in those 2D lines, or in Excel spreadsheets …

When still a junior reservoir engineer, I was lucky enough to accompany a senior simulation expert to the Intera offices in Henley, where the first simulation 3D visualisation tool was being developed. We sat there with the developers, and cautiously, watched the eclipse simulation deck loading in this new tool. Slowly, the model appeared in 3D. In the middle of the model was a big hole. There was a silence, and then someone asked: "Is that meant to be there?" To which the reply was, "Actually, no …".

Since those early days, I have forgotten how many times I have discussed an issue with a colleague, and asked, "Have you looked at the model in 3D?", to which the inevitable answer is, "No". So we take a look, and find, for example, that the reason the well is producing only water is that it is perforated




*Seeing the subsurface in 3D can be very revealing.*




*Hydraulic fractures along the wellbore.*

in the water leg; that the reason for early water breakthrough is that there is a high permeability streak in the model, due to an incorrect multiplier; that the reason for the convergence problems in the box model was that it was divided into four quarters (for which the reservoir engineer had no real explanation), and one of the quarters had four times the porosity of the other three quarters, which the engineer could not explain. All these things require meticulous checking in the simulation input deck, but are quickly identified in the 3D visualisation.

## A Tool for Simulation Engineers

I generalise of course, but with a strong undercurrent of truth. In the reservoir engineering world, 2D comes first, with 3D most often used as a way of demonstrating what is happening to management, rather than as a tool for the simulation engineers themselves. We cannot change the way people think, or how the individual brain maps its surrounding world, but we can 'choose to see' when the option is there in front of us, on our desks. ■

*Susan Fellows is the Regional Manager for Europe for Computer Modelling Group. Her initial degree was in geology, but she then gained MScs in Petroleum Exploration and Petroleum Engineering and has spent her career working as a reservoir engineer in business development with both E&P companies and service organisations.*

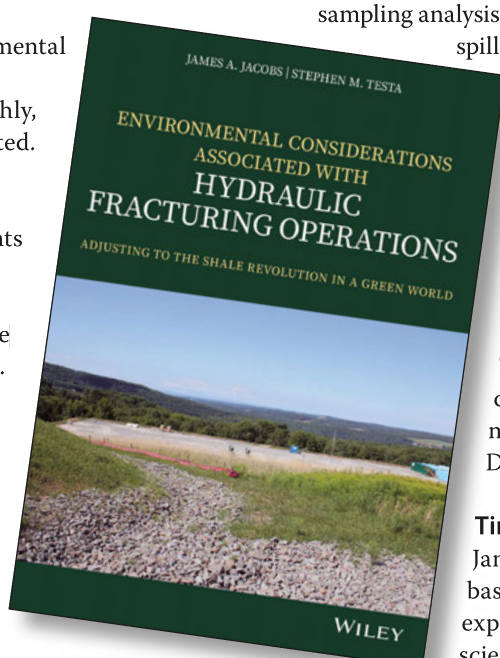
# Hydraulic Fracturing and Environmental Issues

RASOUL SORKHABI

*Environmental Considerations Associated with Hydraulic Fracturing Operations: Adjusting to the Shale Revolution in a Green World*, by James A. Jacobs and Stephen M. Testa
Wiley, New York, 2019.

The shale revolution in the USA over the past decade has been phenomenal, but it has not been without its environmental issues and debates. Environmental activists have pushed for banning hydraulic fracturing altogether; the oil and gas industry has been all for it, no matter what. A third position – that of independent scientists and engineers – is obviously required in this debate.

In this third perspective environmental issues associated with hydraulic fracturing are scientifically, thoroughly, and honestly investigated and reported. Most of the literature and reporting on the shale revolution has focused either on environmentalist viewpoints or on the reservoir engineering and geomechanics of shale plays and fracking. This new book is a welcome addition to the literature and debate. With a large format – 576 pages, 15 chapters, 12 appendices, 222 figures and 163 tables – it is a monumental work on the subject. At the end of each chapter there are also references and suggestions for further reading.




## A Systematic Approach

After an introductory chapter, the book opens with an informative history of hydraulic fracturing. Leaving aside 'shooting wells' with nitroglycerine in the 1860s, the first fracking was done in 1946 by Riley Farris and Bob Fast (of Standard Oil in Tulsa) in the Hugoton limestone gas field in Kansas. Interestingly, Riley 'Floyd' Farris applied for a fracking permit in 1998 – the same year Mitchell Energy in Texas achieved gas production from the Barnett Shale using slickwater fracking. Chapter 3 reviews the geology of the US shale plays, followed in Chapter 4 by an overview of prospect evaluation, drilling, and fracking (stimulation) techniques for tight (shale) oil and gas formations. The remaining chapters constitute the meat of the book.

A systematic approach has been adopted here. The entire shale petroleum development process is divided into eight phases: prospect generation, planning, drilling, completion and stimulation, fluid recovery and waste management, oil and gas production, and well decommissioning and site restoration. Chapter 5 gives an overview of the environmental impacts in each of these phases; Chapter 6 is on the risks posed to surface and groundwater; and Chapter 7 is on induced seismicity. These two slim but critical chapters will require more work and elaborations should the book go to a new edition. Air-quality issues (flares, fugitive methane, etc.) and their mitigation measures are examined in the next chapter, followed by a discussion on land use and socioeconomic issues such as noise pollution and road traffic. Chapter 10 deals with drilling footprints, oil spills and other impacts on ecosystems and Chapter 11 with US federal regulations and how they pertain to fracking. This is followed by a chapter on water and soil sampling analysis methods, exposure pathways (e.g. surface spillage, abandoned wells, faults, non-structural migration paths, injected fluids) and operation site characterisation. Chapter 13 discusses the financial aspects of shale petroleum development as related to real estate and property value, road traffic, water supplies, land remediation, and so forth, while the following chapter briefly reviews legal considerations and case studies of environmental activism against fracking. The final – and longest – chapter reviews case studies of oil spills and forensic chemical methods from Pennsylvania, Texas, North Dakota, California and Colorado.

## Timely and Comprehensive Book

James Jacobs and Stephen Testa, the California-based authors of the book, are both highly experienced petroleum and environmental scientists and they have done an amazing job of distilling so much technical information into a single volume. They also collaborated on a previous book, *Oil Spills and Gas Leaks* (McGraw-Hill, 2014). Both books will be extremely useful to geoscientists, engineers, managers and consultants in the petroleum and environmental industries. The new book could also serve as a textbook for training and academic courses in this field; each chapter ends with ten questions for examination, which could easily be expanded to include more exercises and calculations.

The authors conclude that shale petroleum, if managed well, provides economic development, but "managed poorly without effective mitigation measures, large-scale industrial processes have also been known to degrade the environment, lower availability and quality of water resources, negatively impact air quality, generate noise, odors, and dust, induce seismicity, and lower the overall quality of life for those living or working nearby." In short, this timely and comprehensive book is a pioneering work in the environmental science of shale petroleum. ■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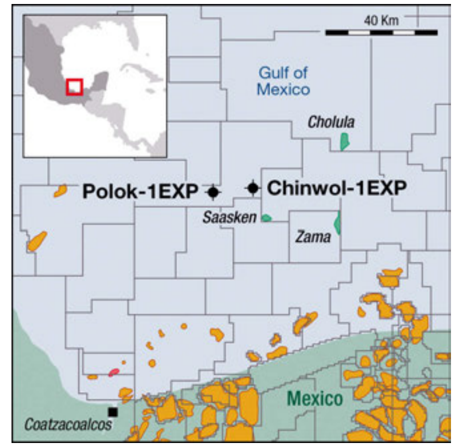
NVENTURES

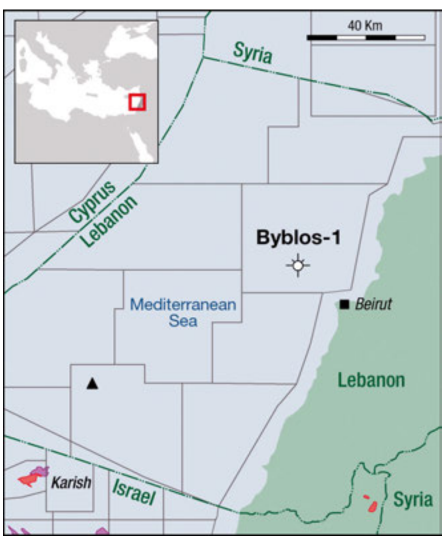
# The Spanish Return to Mexico!




Spanish IOC **Repsol's** foray into **Mexican** waters has paid good dividends, nailing impressive discoveries on their first two tries, drilled back-to-back 12 km apart in 600m of water on Sureste Basin Block 29. **Polok-1EXP** TD'd at 2,620m in April 2020 and logged over 200m net oil pay from two high permeability Lower Miocene sand zones, followed by **Chinwol-1EXP**, which TD'd at 1,850m in early May, finding more than 150m net oil pay from three excellent Lower Pliocene sand zones. Both wells sit in a region of high quality post-salt Neogene clastic objectives on salt-induced structures with strong AVO support.

Until Mexico opened up in 2015, Pemex was the sole player in this prolific region, establishing an impressive track record. In the second and third bid rounds Repsol won three deepwater and three shelf blocks in three basins as operator and is justifiably proud, as these discoveries are the first from deepwater Round 2.4, held just 29 months ago. Despite stellar geology, success is not a certainty in this basin; savvy operators Eni and Cairn have recently drilled dry holes, and Shell released a vessel on a deepwater well with no announcement. Reservoir presence and seal are the primary risk, followed by charge, as discussed in *GEO ExPro* Vol. 17, No. 2.

Repsol will next drill **Juum-1EXP** in the rank frontier deepwater Cordilleras basin Block 10 off central Mexico. Going three-for-consecutive-three just over two years after a new-country entry would be truly an impressive achievement. ■

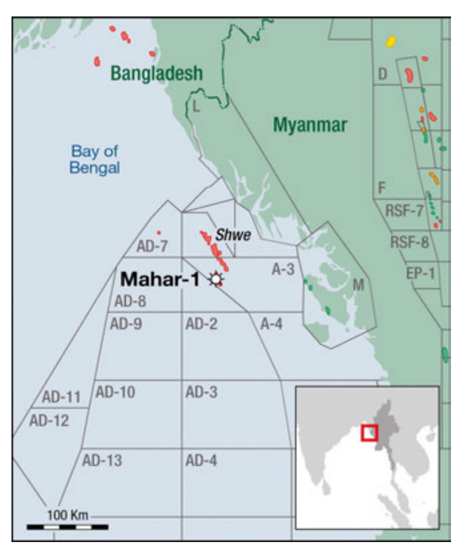



# The First Offshore Lebanon Well

**Byblos-1**, the first well offshore **Lebanon**, is a failure despite earlier rumours of a gas find. Gas shows were encountered in the Oligo-Miocene but the main objective Tamar sandstone, the reservoir for the Israeli fields to the south, was absent. This sand is believed to have been derived from the proto-Nile delta to the south, so may not have been transported this far north.

**Total**, with partners **Eni** and **Novatek**, spudded Byblos-1 in Block 4 on 27 February 2020. It targeted the highly successful Levantine Basin Tertiary gas play being developed to the south in Israel and to the west in Cyprus. This play consists of locally continuous turbidite fans forming high quality Lower Miocene reservoirs (>25% porosity, even at depths of 5 km). Traps are structural, commonly large, faulted 3-way dip closures. Interbedded flooding surface shales seal gross columns over 100m high vertically and across the faults. Whether the proposed second well, on Block 9, will go ahead as planned in 3Q 2020, or be delayed due to this result compounded by Covid-19 crewing problems, remains to be seen. ■

# Rakhine Basin Gas Discovery




**Korean** company **Posco International** has discovered a new gas field in **Myanmar** with exploration well **Mahar-1**, located in offshore Block A3 in the **Rakhine Basin**. The well was targeting anticlines in Late Miocene/Pliocene turbidite sands which are currently producing gas in Posco's nearby Shwe and Mya fields. Mahar is understood to be a downslope extension of the Shwe/Mya complex in Blocks A1 and A3 which is thought to hold around 4 Tcfg. The combined production rate from the nine wells in these two fields is approximately 500 MMcfd.

The Mahar-1 well reached a TD of 2,598m in water depths of around 1,200m in February. A gas column of around 18m was encountered and a DST indicated that the reservoir could yield about 38 MMcfd. An early internal assessment puts the estimated contingent resources at around 660 Bcfg. One or two appraisal wells will be drilled in 2021. This was the second of a three-well drilling programme in the block. The results of the first well, Kissapanadi, close to the Mya field, are being assessed. The next well, Yan Aung Myin, 24 km south-east of Mahar-1, is expected to be drilled in May. ■

# No Pain, No Gain

## Is the E&P industry prepared for a post Covid-19 world?

At the time of writing there are more cars on the road than for many a week and most of them still run on petrol. Lockdown, it seems, is finally being eased in different parts of the world and for the moment at least the oil price has responded positively. From a low of $20 a barrel – not to mention the negative territory of paying for storage – the Brent oil price has risen back up to over $30 and big oil can at least break even.

So where do we go from here? One bright spot is that in contrast to governments around the world who failed to stockpile enough PPE for dealing with the virus, oil companies are for the most part more streamlined, downturn-prepared beasts than they were just a few years back. Even in the North Sea, for example, the slump before this one in 2014 brought the bare break-even price for a project down from over $30 a barrel to just $15. We are not talking about Saudi Arabia here, but most oil companies have just about been able to hold their own.

One problem though, as we enter another round of slimming and trimming, is the nature of oil and its associated infrastructure as a physical asset. Not only is it a physical challenge to shut down and re-open a well but there is also the question of which wells should close in the bad times and what is the cost of closure versus the cost of keeping a well open when the price is low. In the US, for example, low volume onshore wells, known as stripper wells, are the first candidates for shut-in. The cost of shutting down one of these wells ranges between $20,000 and $40,000 a well and even when the price of oil falls below the cash break-even price it can still be cheaper to keep the loss-making well ticking over for some time rather than close it.

Like so many of us in these lockdown days it seems that OPEC+ oil ministers got together via Zoom (what else!?) over Easter to agree their latest 10 MMbpd production cut. If Russian and others keep the faith and lockdown does indeed come to end with, who knows, a viable vaccine that much closer, we could be in for a more sustainable oil recovery. Jobs are going, dividends are being cut and all but the juiciest projects, for the moment at least, could find themselves on the back burner.

No pain, no gain, may well be the mantra, once more. ■

**Nick Cottam**

*A Marcellus shale gas drilling operation in rural northern Pennsylvania.*

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## Conversion Factors

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

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

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

### Numbers
Million = $1 \times 10^6$
Billion = $1 \times 10^9$
Trillion = $1 \times 10^{12}$

### 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