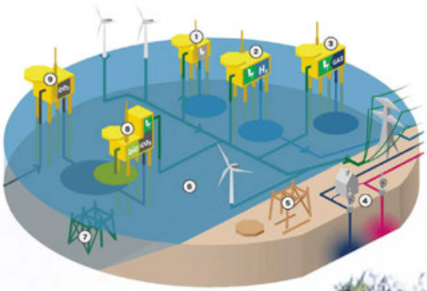
VOL. 18, NO. 1 – 2021

GEOExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED



RESERVOIR MANAGEMENT
Mature Fields: Retirement or Second Career?

GEO TOURISM

Auckland's Geoheritage

EXPLORATION
Undiscovered Potential in the Basement

GEOPHYSICS
Sustainable Geophysics

ENERGY TRANSITION
The Net Zero Transition: An Important Conversation

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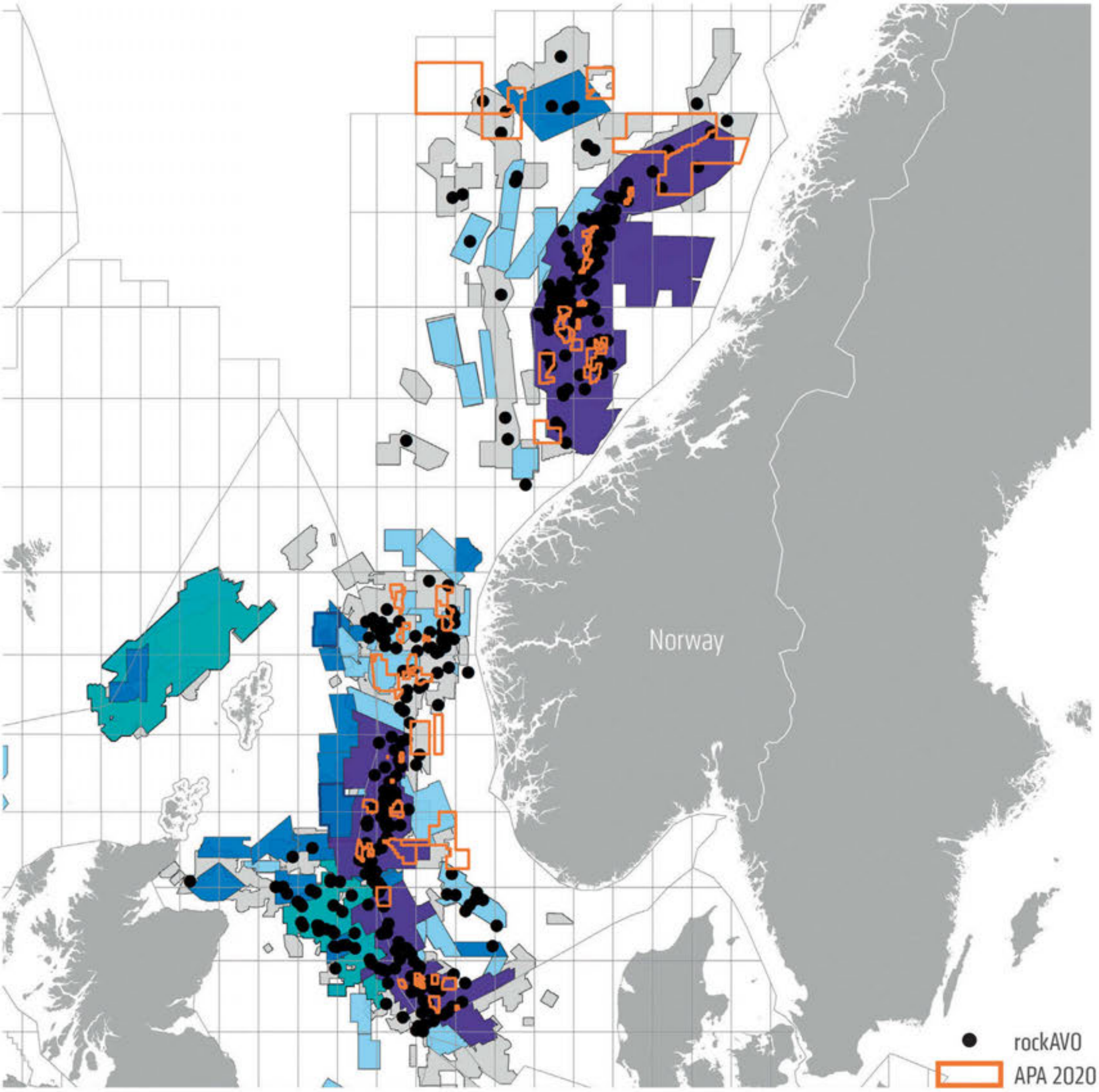

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GEOSCIENCE & TECHNOLOGY EXPLAINED

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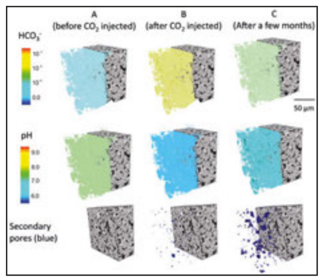

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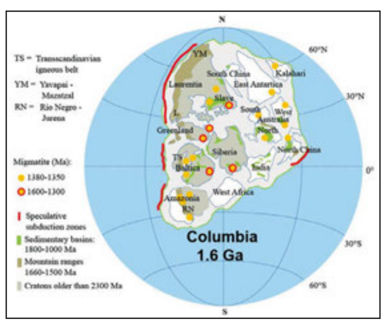

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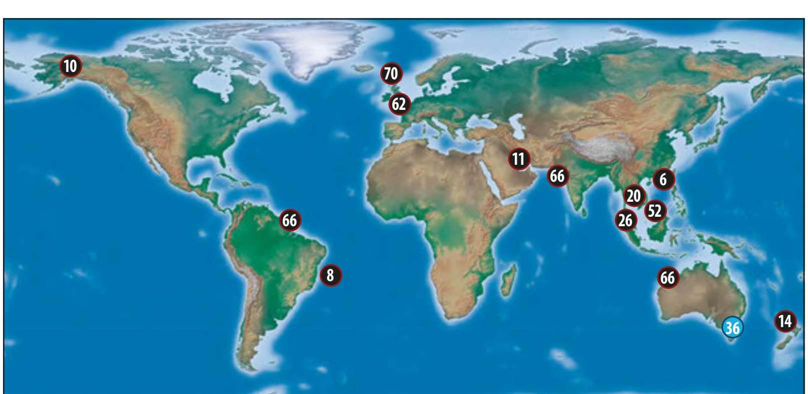

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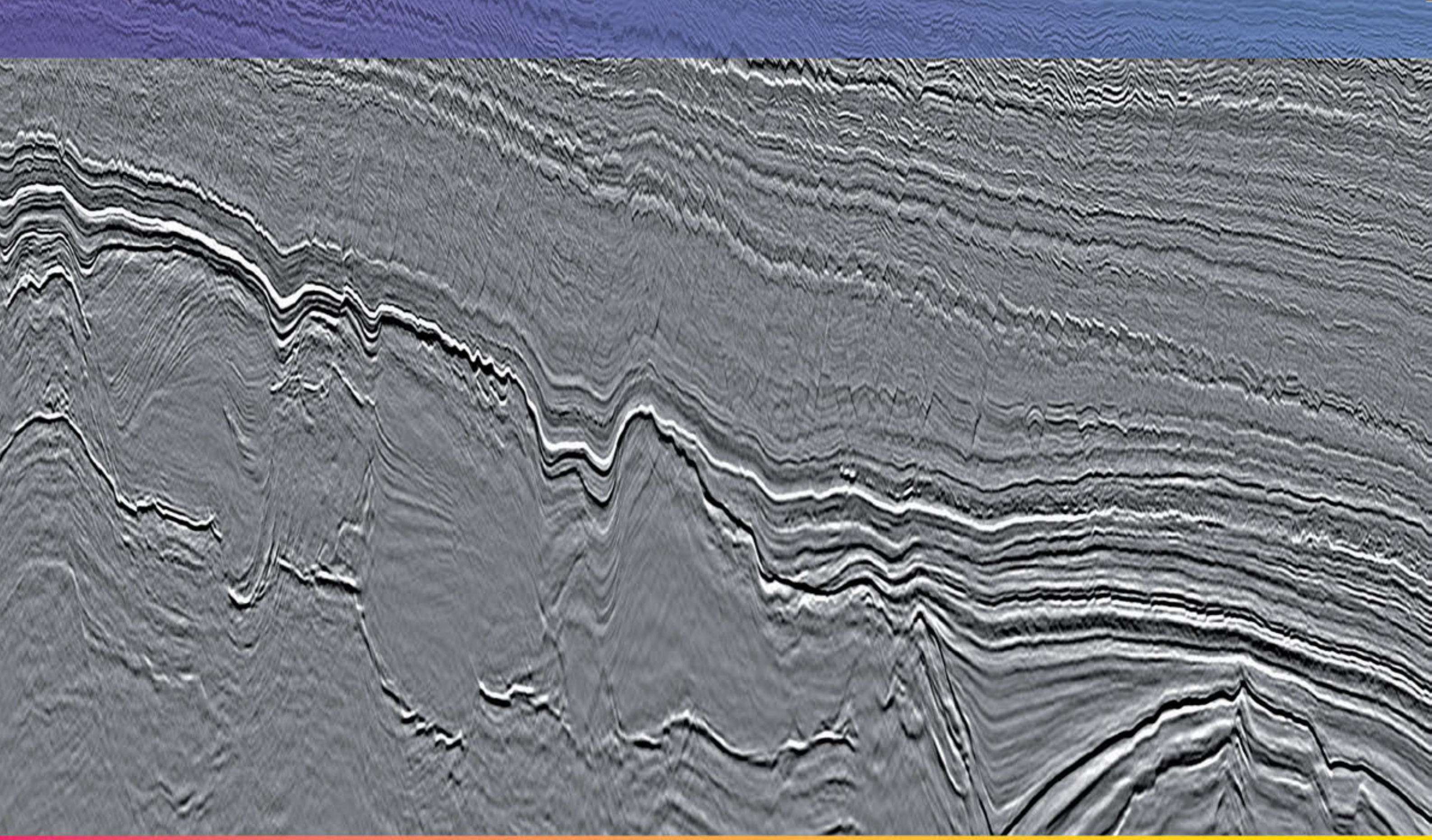

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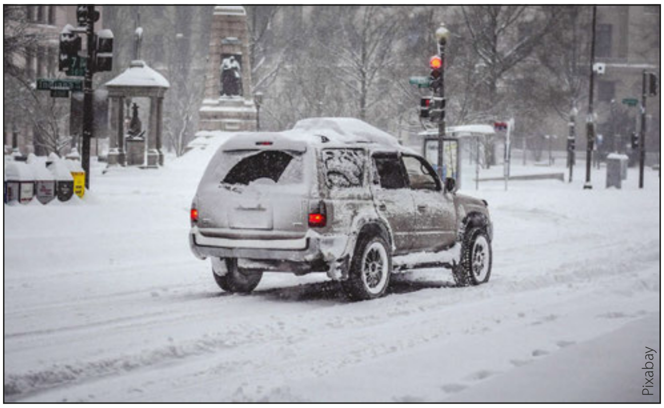
Energy Transition with Security



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In this my first editorial for *GEO ExPro*, I would like to start by thanking my colleague Jane Whaley for her outstanding contribution to the magazine's content and development over the last 10 years. During this time, *GEO ExPro* has matured into a well-respected magazine with an excellent reputation and I am honoured to be taking over the reins from her.

Having spent almost all my career in the upstream business, initially as an exploration geologist, I have been saddened by the very negative press our industry has been receiving in recent times, particularly in Europe and North America. The transition to sustainable energy is one of the fundamental challenges we face over the coming decades and it is my intention that *GEO ExPro* will continue to report fully on this, whilst championing the genuinely critical role the oil and gas business plays in ensuring security of energy supply.

Extreme winter weather in the United States in February brought arctic cold to extensive areas of the country and in Texas, a surge in electricity demand led to widespread power cuts. A sobering reminder that energy security relies on high density energy sources.

In this edition we have a GeoProfile of Katerina Garyfalou who, following a very successful career in hydrocarbon exploration, is now helping lead the way in clean fuel production derived from waste-plastic. Geoscientists have all the skills and inventiveness required to contribute to the energy transition and this is just one example of critical skills transference.

With the crew change well and truly behind us and the recent terrible loss of experienced geoscientists from our business, I do fear we will face a skills shortage in the near future. This situation is compounded by a frighteningly precipitous fall-off in students studying earth science. Post-graduate study in the Geosciences was particularly difficult in 2020 with project-based thesis work severely impacted. It is heartening to see how resilient and inventive both the academic community and the students have been in successfully navigating these challenges. Kirsty Lewis, a recent Masters graduate from Aberdeen University, describes in our Q&A article how she tackled an MSc in the pandemic and successfully landed a job with a major energy company.

To attract these geoscientists of the future, we all have a responsibility to ensure we do whatever we can to promote the science and the awareness of its current, and future importance to the global economy. Perhaps that starts with communicating a far more positive message about the important contribution petroleum geoscientists make to society. ■

Iain Brown
Editor in Chief

TASTE THE GEOHERITAGE OF AUCKLAND, NEW ZEALAND

In the cliffs above Maukatia/Maori Bay is one of New Zealand's most treasured geoheritage features, the spectacular columnar fans and pillows of a basaltic andesite flow that was erupted in deep water on the lower slopes of the Waitakere Volcano about 17 million years ago.

Inset: Oil and gas fields can have much longer lives than initially envisioned if organisational and regulatory barriers, as well as capital, technology and other factors can be resolved. Repurposing depleted hydrocarbon reservoirs and production facilities can be an attractive option in the energy transition.

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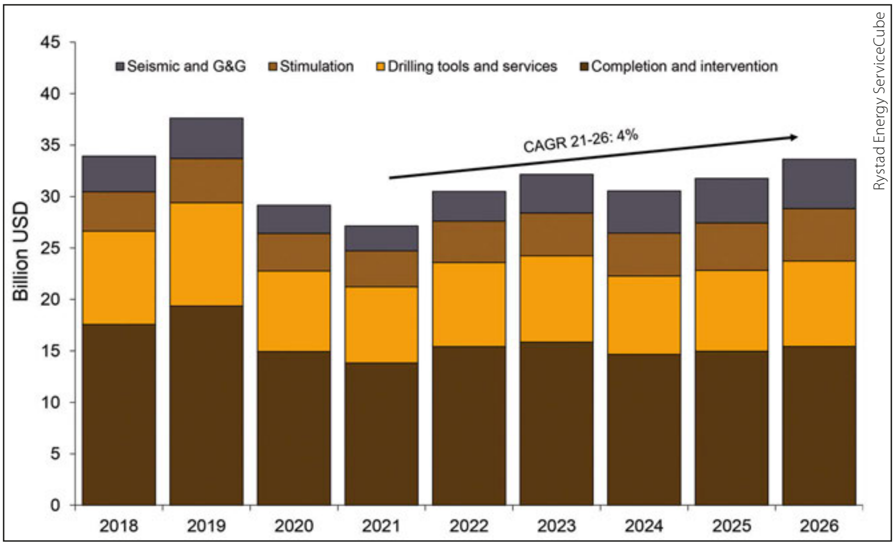
New Technologies Unlock Value

With an increased focus on remote operations, productivity, and cost efficiency by operators in the wake of Covid-19, oilfield service providers are turning to new technologies based on digitalisation and automation. With remote drilling operations having gained traction and becoming the new normal, innovation within the drilling and well services segments has also gained momentum as both major well service companies and smaller players develop new technologies and niche product lines to fill the gaps to capture market share.

The figure below shows the expenditure for each of these segments in Asia Pacific from 2018 to 2020, with the significant impact of the pandemic evident in 2020. We can see that even though these segments were hit hard in 2020, they are expected to experience a marginal average growth of 4% each year until 2026. The drilling and completion segments account for 26% of the total cost of the well on average, providing ample incentives for service providers to develop technologies and solutions.

The global pandemic has accelerated remote work, but in the context of the oilfield service industry, this presents a number of challenges. Remote working in the oilfield industry can be hindered by hardware and software resource constraints. This is amplified within reservoir engineering in particular as it requires vast computing resources to run computer intensive reservoir simulations. Some operators have sought to minimise hardware and software capex, and have rolled out Schlumberger's DELFI (cognitive E&P environment), a high-performance cloud computing system that enables complex and different systems to talk to each other and promotes more collaboration between multiple disciplines. Woodside Australia, for example, has managed to shorten the duration of running more than a thousand simulations, which would otherwise typically take six months, to only one week using the DELFI system.

Growth of drilling, completion and geoscience purchases in Asia Pacific by Billion USD.



Looking at the different focus areas within technological innovation, it is expected that digitalisation will add significant value within a field's lifecycle by way of optimised production. In November 2020, service provider Silverwell installed the Digital Intelligent Artificial Lift (DIAL) technology in dual string wells in the Baram South field in Malaysia as part of a pilot campaign of five wells across multiple mature fields. The digital valves are controlled by electric lines and the choke sizes can be manipulated from the surface unit. Greater efficiencies can be realised with a quicker response time to well issues caused by changing well conditions. These changes could include managing the repercussion of surface gas injections which require manual well interventions with slicklines, where well performance can be impacted whilst having to wait for the mobilisation of crews and slickline units onto the platforms. With the number of offshore intervention trips minimised, potential health, safety and environmental (HSE) issues associated with slickline operated conventional gas lift valves change-outs on fields are also reduced. This technology is an enabler of intervention-less, remote operating capabilities for gas lift optimisations, which further enhance production from fields. ■

Goh Lin Lin, Rystad Energy

ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids

barrel = bbl = 159 litre
boe: barrels of oil equivalent
bopd: barrels (bbls) of oil per day
bcpd: bbls of condensate per day
bwpd: bbls of water per day

Gas

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

Ma: Million years ago

LNG

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

NGL

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

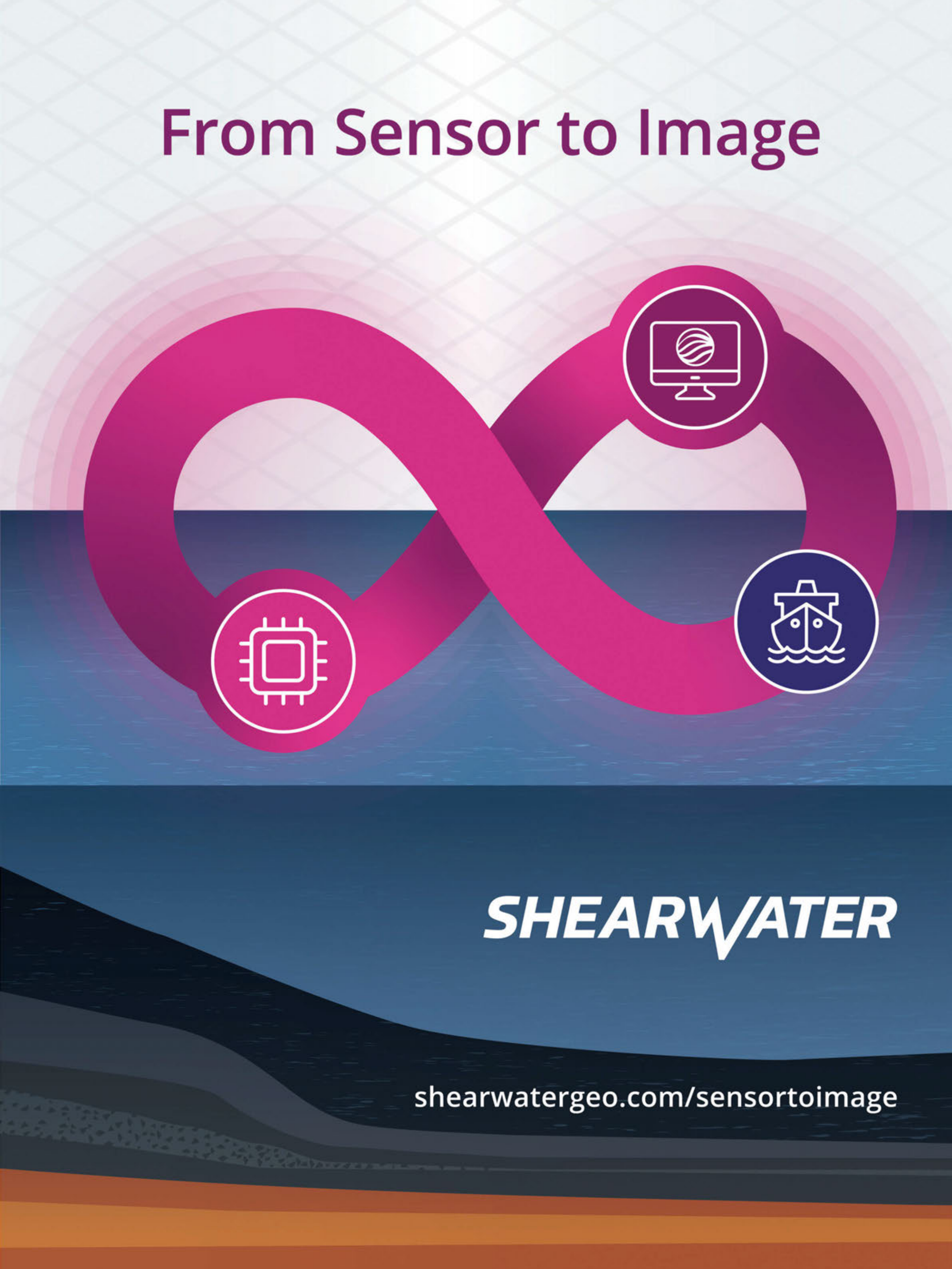
Reserves and resources

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

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

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

Oilfield glossary:
www.glossary.oilfield.slb.com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Brazil Offering Deepwater Blocks

Late in 2020 Brazil announced details of its 17th Licensing Round, delayed by the Covid pandemic, in which 92 blocks in the offshore Campos, Pelotas, Potiguar and Santos Basins, covering a total of 53,900 km^2, will be offered. The preliminary schedule announced by the ANP, the Brazilian licensing authority, included a public hearing to discuss the auction and concession contract in February and technical and environmental, legal and tax seminars at dates yet to be confirmed. The public bidding round is scheduled to be held in October and awards are expected in December. Technical data packages, including seismic lines and well data, are available for all areas.

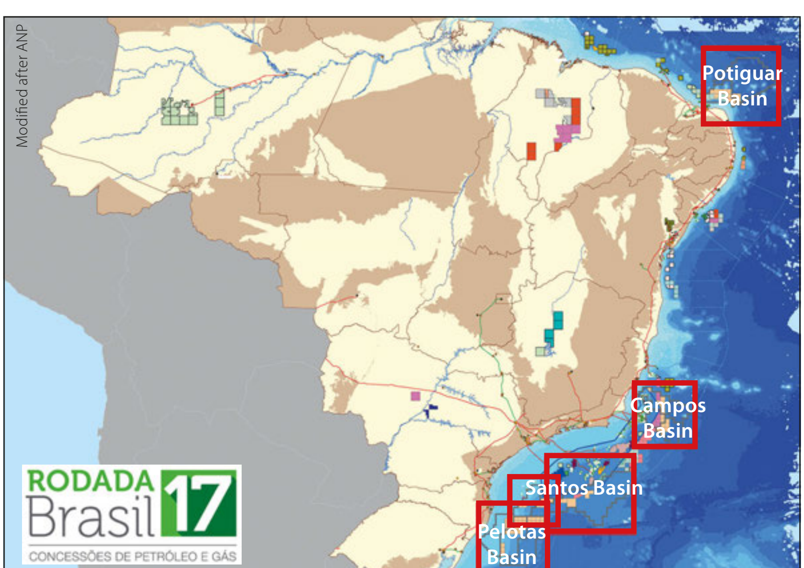
The Campos Basin, where 15 blocks are offered, has the longest history of oil and gas exploration in Brazil and is now considered mature. Extending into ultradeep waters, it is attractive because the blocks offered are on the edge of the defined pre-salt polygon and there is extensive geological data, including seismic, over the area.

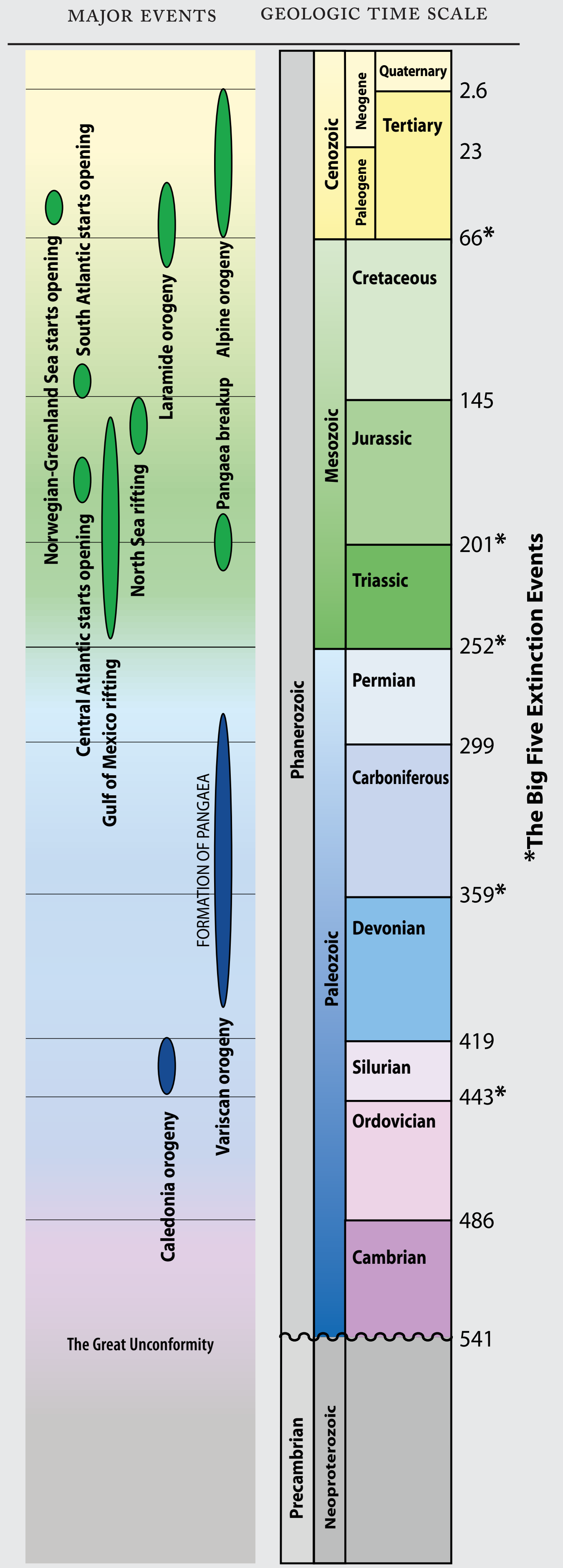
No discoveries have yet been made in the Pelotas Basin, which lies on the border with Uruguay and it is relatively underexplored, but there are indications of a working petroleum system. Eight of the blocks on offer are in water depths greater than 2,000m, 16 lie between 440 and 1,000m and the remaining 26 are smaller blocks situated in shallower waters.

The onshore Potiguar Basin in north-east Brazil has considerable onshore and shallow water production but is significantly underexplored in the deeper waters. The majority of the 14 blocks available in this round are in over 2,000m of water.

Santos, currently Brazil's top producing basin, usually attracts a high number of bidders interested in its extensive pre-salt areas. The 13 blocks available in the 17th round all lie just to the south of the delineated pre-salt polygon, mostly in over 2,000m water depth. Interestingly, three of them straddle the 200 nm line limiting the extent of Brazil's exclusive economic zone for the first time, so any discoveries beyond that limit will require the adoption of specific procedures under different legislation.

It had been anticipated that blocks in the Pará-Maranhão and Foz do Amazonas Basins along Brazil's equatorial margin in the north-west would be offered, but these have been dropped because of environmental concerns. This has disappointed several players who had hoped to see how far the successful ExxonMobil Stabroek trend extended into Brazilian waters. ■

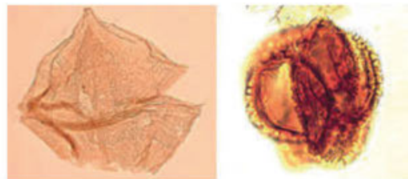


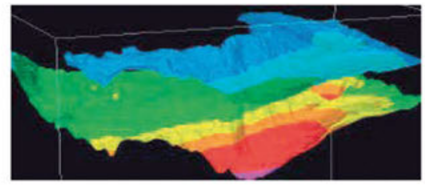


apt Applied Petroleum Technology

Our scientific staff cover a wide range of expertise gained from many parts of the globe, dealing with many and varied projects. The unique combination of in-house geological services and a staff boasting extensive offshore and oil company experience provides a competitive edge ito our services. We offer complete services within the disciplines of Petroleum Geochemistry, Biostratigraphy and Petroleum Systems Analysis, and our customers expect high standards of quality in both analysis and reporting.

High quality analyses and consulting services to the oil industry





Geochemistry services

In addition to providing a full range of geochemical analyses of unsurpassed quality analysis, APT also offers insightful and tailor-made interpretation, integrated data reporting, and basin modelling and consulting services. We pride ourselves on quality and flexibility, and perform analyses and report results to our clients' specifications.

Biostratigraphic analysis and services

APT delivers a full range of biostratigraphic services, ranging from single well reports and reviews of existing data to full-scale field or basin-wide evaluations. We take no established truths for granted, and we turn every stone in the attempt to bring the stratigraphic knowledge a few steps forward.

Petroleum systems analysis

APT has gained extensive experience in Petroleum Systems Analysis using the "PetroMod" suite of programs. Projects range from simple 1d modeling of a set of wells to complicated 3D models with maturation, kinetics, generation, expulsion, and migration and accumulation issues to be resolved or predicted.

Geochemistry services
- Analytical services
- Reporting
- Interpretation
- Exploration Solutions
- Petroleum consulting services

Biostratigraphy
- 24 hours Hot Shot analysis
- Routine biostratigraphy
- Well-site biostratigraphy

Petroleum System Analysis
- Analysis
- Interpretation
- Data Reporting
- PetroMod or other tools

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Alaska: Lease Sale Struggles


Pixabay

After decades of dispute, the rights to drill for oil on about 5% of the 78,000 km^2 **Arctic National Wildlife Refuge** (ANWR) went ahead in the last months of the Trump presidency. Opponents have criticised the rushed nature of the sale and the results have been poor. The government sold only 11 tracts of the 22 it was offering in the refuge's coastal plain, or about 550,000 acres out of around one million offered. Revenues raised through the sales were low at approximately $14.4 million and none of Alaska's three top oil producers, ConocoPhillips, ExxonMobil and Hilcorp, participated.

The push for exploration in the park has been a decades-long battle between oil companies and environmental and indigenous opponents. Supporters of the sale believe that the ANWR shares the same geology, and potential reserves of crude oil as Prudhoe Bay, which is the largest oil field in North America. The change of leadership in the White House means it is likely that efforts to explore for and extract new reserves in Alaska will be subject to further review and delay. ■

DEVEX 2021: Virtual Conference

DEVEX

Transitioning to a low carbon industry will be a key theme at **DEVEX 2021**, where attendees will look at the opportunities, skills required, and how to work together to maximise economic recovery during the energy transition.

This will be the 18th DEVEX conference and following last year's success, it will take place virtually from **7–11 June**. Abstracts are open until 5 March and this is an opportunity for companies to share lessons learned and innovative ideas that are being deployed. Just 200 words are required, and the submission process is simple.

DEVEX is the only technical conference of its size which is focused on the full E&P project cycle: from exploration, appraisal, development and production through to decommissioning. For more information on the conference and to book your place visit the DEVEX website. ■

UK to End Funding for Overseas Oil and Gas Projects

The **UK Government** has announced that it will become the first major industrialised nation to end all public finance for fossil fuel projects overseas. Prime Minister Boris Johnson announced this decision as he opened the Climate Ambition Summit in December 2020 co-hosted by the United Nations, the UK, and France. The policy will see the UK end export finance, aid funding and trade promotion for new crude oil, natural gas or thermal coal projects, with very limited exceptions.

The decision is a significant change when compared to the last four years when the government supported £21 billion ($27.6 billion) of UK oil and gas exports through trade promotion and export finance. The government said that the policy will be implemented after a short period of consultation and is intended to come into force quickly and before the UN Climate Change Conference COP26 in November 2021 in Glasgow.

The government also said it will work with the UK's oil and gas sector to support the move to low carbon energy sources through the North Sea Transition Deal, so that the UK can become a global hub for wind energy, carbon capture and other clean technologies of the future. ■

TGS Launches New Energy Solutions

In February, **TGS** announced the launch of its **New Energy Solutions (NES)** business unit. TGS's goal is to be the leading provider of data and insights directed towards industries actively contributing to the reduction of greenhouse gas (GHG) emissions, such as carbon capture and storage (CCS), deep-sea mining (DSM), geothermal energy, wind energy and solar energy. The starting point is the company's large subsurface data library, combined with core skills in geoscience, data processing, data management, data analytics and AI. This will be complemented by relevant additional data types and subject matter expertise.

Chief executive officer, Kristian Johansen, sees increasing interest from industries outside of oil and gas for TGS's data and services. The new business unit will be headed by Jan Schoolmeesters and will focus on the transition towards sustainable energy systems using carbon capture and storage, deep-sea minerals, and renewables. ■

World's Largest LNG Project

Qatar Petroleum has formally decided it will now be developing the **North Field East Project (NFE)**, the world's largest liquefied natural gas (LNG) project. In addition to LNG, the project will produce condensate, liquefied petroleum gas, ethane, sulphur and helium and will increase Qatar's LNG production capacity from 77 to 110 million tonnes per annum (MMtpa). The main scope of the engineering, procurement and construction contract is the construction of four huge LNG trains with a capacity of 8 MMtpa each, with associated facilities for gas treatment, natural gas liquids recovery, as well as helium extraction and refining within the Ras Laffan Industrial City.

The total cost of the NFE project will be almost 29 billion dollars, making it one of the energy industry's largest investments in recent years, in addition to being the world's largest LNG capacity addition to date. One of the most important environmental elements of the NFE project is its CO_2 carbon capture and storage (CCS) system, that will be integrated with the existing CCS scheme in Ras Laffan. When fully operational, this will be the largest of its kind in the LNG industry. ■

Searcher Diversifies

Searcher, a leading service provider of geoscience products for oil and gas exploration and production companies, has announced its expansion into the mining sector with the completion of an airborne exploration survey in **Queensland**, on behalf of **Longreach Mineral Exploration Pty Ltd** (Longreach).

The new airborne magnetic and radiometric geophysical survey was acquired over Longreach's exploration permit (EPM27423), located approximately 40 km north-east of Clermont, Queensland, Australia. The survey covers 387 km^2 and includes 8,770 km of data acquisition lines.

Searcher were contracted by Longreach to assist with project management. Searcher's input included project planning and survey design, sourcing and contracting MAGSPEC Airborne Surveys Pty Ltd as the principal contractor, for management and quality control of the acquisition and processing and interpretation of the final data.

This is another good example of how upstream service companies are diversifying and applying transferable skills to other business sectors. ■

Seismic 2021: Unlocking Value in the Energy Mix


Seismic 2021

This year, **Seismic 2021** will be going virtual again, with events taking place from **17–21 May**. This will open up new possibilities for communication and collaboration to a global audience.

The role of seismic in the energy mix is difficult to overstate. Seismic 2021 will cover the entire geophysical spectrum, from exploration through appraisal, development and production and through to abandonment and repurposing for carbon capture and storage (CCS). The full lifecycle of the asset.

The focus will be on how seismic supports both the UK's maximising economic recovery strategy and its Net-Zero ambitions, as well as how seismic can sustainably support the increasing development of renewables into the energy mix.

For more information on the conference and to book your place, visit the Society of Petroleum Engineers Aberdeen Section website. ■

US $11 Billion of Australian Gas Projects


Artist rendition Australian Industrial Energy

Wood Mackenzie's Australasian upstream 2021 outlook report shows at least US$11 billion of gas projects poised for Final Investment Decision (FID) in 2021. With liquefied natural gas (LNG) backfill as the focus, these projects include three upstream FIDs – **Mitsui's Waitsia, Santos's Barossa** and **Woodside's Scarborough** – and the Australian Industrial Energy (AIE) **Port Kembla** LNG import terminal which will supply the east coast market.

The first project is expected to be Waitsia, located in the Perth Basin. The project will export LNG from the North West Shelf with production starting in late 2023. Next, Santos is expected to sanction the high CO_2 content Barossa gas project late in Q2, despite its new carbon targets. Woodside is also likely to sanction the Scarborough to Pluto project. The lean Scarborough gas suits a new expansion train and Woodside can control the pace of a Pluto Train 2 development.

Wood Mackenzie also expects the Australian Institute of Energy to sanction the Port Kembla import terminal to supply the east coast market. With the formal final investment decision expected in Q1, 2021, the facility will operate on a toll basis with gas buyers reserving capacity.

Liquefied natural gas (LNG) imports will become the marginal cost of supply and domestic prices would rise as they move towards global LNG prices, including the cost of regasification. This is positive news for upstream players with uncontracted gas. ■

GeoConvention 2021

Based on the success of the 2020 virtual program which boasted nearly 600 presentations and scored a 96% overall satisfaction rating among attendees, **GeoConvention 2021** will again be hosted virtually with an even wider and more geographically diverse technical programme.

With over 60 technical sessions identified, GeoConvention 2021, scheduled for **13–15 September**, will feature a fully integrated programme representing a diverse collection of earth science disciplines, including geology, geophysics, petrophysics, minerals, water, earth, environment, and the energy world. From live panel discussions to targeted technical content, GeoConvention provides an opportunity to expand your knowledge and connect with companies and opportunities.

Virtual delivery allows for live and pre-recorded talks and posters with integrated question and answer periods, one-on-one and group networking, and exhibition floor, featuring live webinars and training, showcasing the latest industry advancements, all in a fully accessible, interactive format. More information available from the GeoConvention website. ■

Challenging Times for Seismic Operators

Two well-established service providers in the seismic acquisition market became victims of the current challenging market conditions at the beginning of this year.

Marine seismic contractor **Polarcus**, formed in 2008, saw its lenders take control of its vessels following a debt payment default notification on 26 January. The company had $415.7 million of total debt as of 30 September 2020 and earlier this year signalled its near-term outlook was uncertain due to operator budget cuts.

On 8 February 2021, Joint Provisional Liquidators (JPLs) were appointed by an order of the Court; the JPLs are specifically authorised to take all steps to develop and propose a restructuring of the company's financial indebtedness, with a view to making a compromise or arrangement with the creditors.

Although the banks were initially open to having a standstill period to allow continued operations and existing projects to be undertaken, it does look as though this is the end of the line for another vessel-owning seismic operator, after a vessel sale process was initiated. Sadly, this means all group employees will lose their jobs.

The Polarcus fleet consists of seven seismic vessels including the Vyacheslav Tikhonov, which is on bareboat charter to Russian shipping giant SCF Group and not subject to lender control. Most of the fleet was built to the ULSTEIN SX124 design, incorporating the innovative and distinctive ULSTEIN X-BOW® hull. These are amongst the most environmentally designed seismic vessels with diesel-electric propulsion.

In February, **Axxis Geo Solutions ASA** filed for court-protected reconstruction having failed to reach agreement with its creditors. Axxis, unlike Polarcus, is an exclusively ocean-bottom seismic node focused operator and this illustrates how the full spectrum of seismic companies have been negatively affected by the coronavirus pandemic and last year's oil price downturn.

The vessel-owning companies in particular have been very hard hit and an obvious question is 'will these developments help the other vessel-owning seismic companies weather the storm until better times and could it signal further consolidation within this business area'? ■

Taste the Geoheritage of Auckland, New Zealand

Boutique volcanoes, fossil forests and pillow lava fans are some of the amazing features around the country's largest city.

BRUCE W. HAYWARD

Most tourists coming to New Zealand land in Auckland and, at most, stay overnight before moving on to see the geothermal and volcanic highlights of Rotorua, in the middle of the North Island, or flying on to the glacial landscape attractions of the Southern Alps and fjords in the South Island. If you can spare a few more days, you will be rewarded by the amazing and diverse geoheritage features in and around New Zealand's largest city.

Auckland: City of Volcanoes

Auckland is one of those rare large cities that has been built over a dormant field of small, monogenetic basalt volcanoes. Fifty-three of them have each erupted just the once in the last 190,000 years. Far more of them erupted in the past 40,000 years than prior to that. As a result, their landforms are still crisp and uneroded, except that in many places the city's suburbs have spread right over the lava flow fields and a number of the scoria cones have been removed or desecrated by quarrying activities that helped build the young city. The nineteen best remaining scoria/cinder cones and eight best maar craters are now major scenic oases and recreational reserves within the city.

Before the arrival of European colonisers in 1840, the Auckland Volcanic Field was greatly prized by the country's first human settlers, the Maori. They grew crops in the rich volcanic soils, collected and caught shellfish and fish in the two major harbours and when skirmishes broke out between the various tribes, they used the cones as natural defensive positions. The summit and upper slopes of all the cones, large or small, were fortified at one time or other with the construction of defensive terraces, ditches and banks surmounted by wooden stockades. Today the

Takapuna Fossil Forest on Auckland's North Shore has one of the best examples anywhere of a forest that has been destroyed by a passing lava flow that has preserved the shape of the lower trunks of many trees as basalt moulds that formed around them as the lava passed through. Moulds of fallen trunks and branches are also common.

Bruce Hayward

earthwork remains of these forts, called paa, are highly valued archaeological and cultural heritage sites.

The youngest and by far the largest of Auckland's volcanoes is Rangitoto, which erupted in the middle of the main Waitemata Harbour channel just 650 years ago. It is still intact and largely in its natural state and can be visited by tourists by taking a twenty-minute ferry ride from downtown Auckland. Most of the island is a gently-sloping shield of overlapping basalt flows. The summit consists of three abutting scoria cones, the highest and youngest of which has a deep bowl-shaped crater. The one-hour walking track to Rangitoto's 259m-high summit passes over the rugged surface of many lava flows before the last steeper climb up the scoria cone, revealing panoramic views of the region. Ascending the track, the classic successional sequence of plants colonising the bare lava flow surfaces is clearly seen from lichens through mosses to vascular plants and kidney ferns.

For something a little different take a bus or drive over the harbour bridge to Takapuna Beach on the North Shore. The rocky reef at the north end, beside the carpark, is one of the best examples anywhere of a forest that has been fossilised as basalt moulds by a passing lava flow. Here you will see the 1m-high moulds of several hundred tree stumps in situ, where the passing molten lava has chilled and solidified around the lower trunks before mostly draining away and leaving the stump moulds standing proud. The lava flow was erupted from the field's oldest volcano, Pupuke, about 190,000 years ago, and the basalt fossil forest buried and preserved beneath many metres of volcanic ash. Only in the Holocene, with the return of high sea level, has this ash been removed by intertidal erosion to display the fossil forest crisp and fresh. In addition to the moulds on the reef, walk along the coastal path to the north and you will see many horizontal moulds of branches that were rafted along and later incinerated by lava flows, but not before their shape had been captured in the cooling basalt.

If you are worried about an eruption while you are in Auckland, sleep soundly in the knowledge that there is a network of seismometers all focused beneath the city to detect the earliest signs of moving magma at depth. There is no shallow magma chamber. Instead, the magma rises to the surface in small batches from the partly molten asthenosphere, 60–90 km down. The first seismic signals are expected when the magma enters the base of the crust at 30 km depth and will give an estimated two days to two

weeks warning of the next eruption; plenty of time for everyone to evacuate a 10 km-diameter area around the determined vent area.

Eroding Submarine Stratovolcano

Auckland volcanoes are one of four similar Pleistocene–Holocene intraplate basalt fields that have erupted 150–200 km west of the modern volcanic arc that erupts above the subducting boundary between the Pacific and Australian plates. Twenty million years ago in the Early Miocene, the plate boundary and associated volcanic arc was further west and the southernmost volcano on the western arm of the Pacific Rim of fire at that time lay just to the west of present-day Auckland. The uplifted, eroded eastern remnants of this largely submarine stratovolcano now form the Waitakere Ranges, the city's forested western skyline.

There are effectively four, no-exit roads out to the surf-battered, rocky Tasman Sea coast of the Waitakere Ranges. I recommend you try two of them. The one over the top to Piha and Karekare beaches takes you to the ancestral home of surfing in New Zealand at South Piha. One of New Zealand's best-known views is from a lookout on the side of the road as you drive down the hill to the beach. The view up the rugged coastline stretches north beyond the imposing Whakaari/Lion Rock, the eroded neck of an ancient eruption centre standing tall in the middle of Piha Beach.

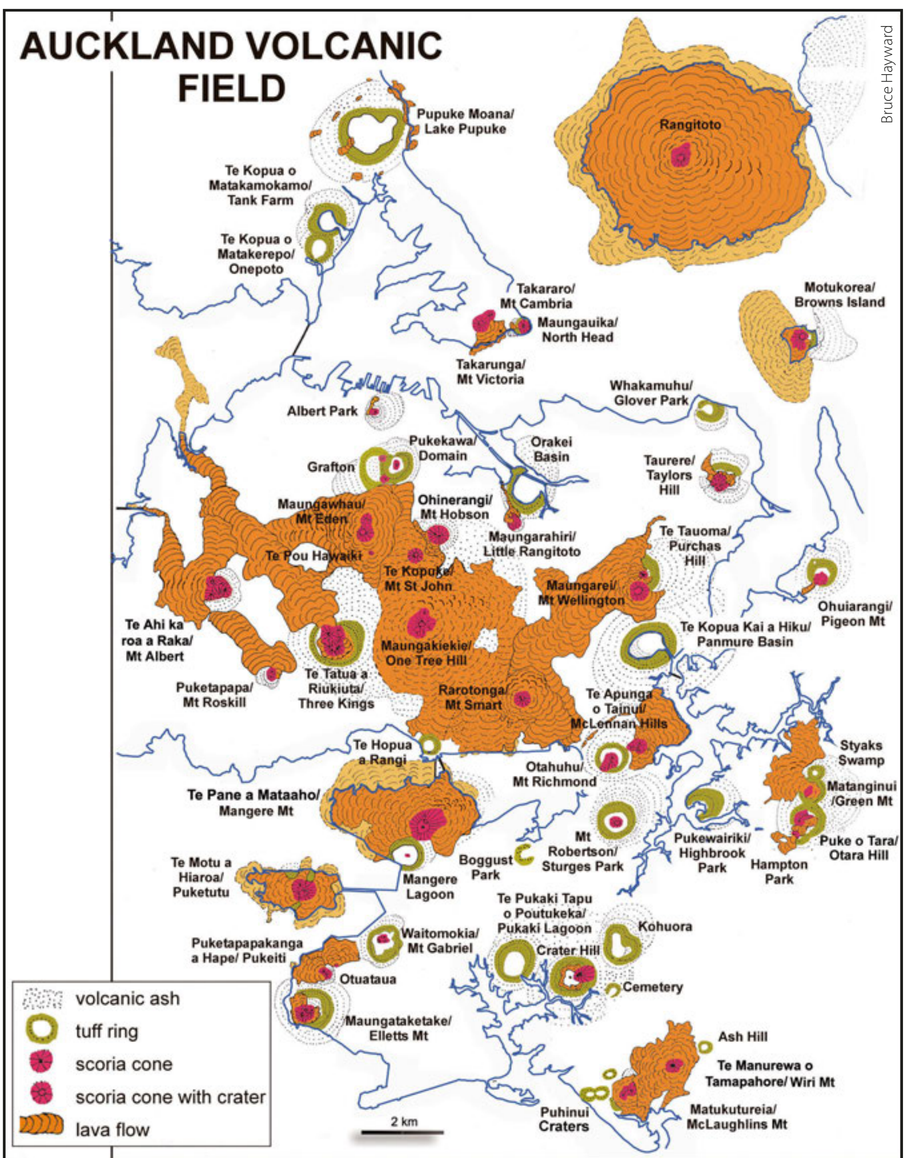
Walk around the shoreline or take the track over the cliff tops to the scenic Puaotetai Bay/The Gap, south of South Piha. It is surrounded by towering cliffs of stratified volcanic conglomerate that was left behind as lag deposits by debris flows that swept down the submarine slopes of New Zealand's largest stratovolcano nearly 20 million years ago. Today the eroded stump of this long-extinct Waitakere Volcano spans 60 by 40 km with three quarters of it submerged offshore. In picturesque Puaotetai Bay there are classic examples of sea caves, tunnels, and a blowhole, all of which have been eroded along vertical joints or andesite dikes by the crashing waves.

The black sand grains at the top of these west coast beaches are titanomagnetite. They were a minor component in the huge Quaternary ignimbritic eruptions in the centre of the North Island, and have been transported here down the Waikato River and up the coast by longshore drift. They have been left behind in high concentrations around high tide level because of their high density, with more voluminous and much lighter quartz, feldspar and pumice being swept further north along the coast. Older Pleistocene sand dune deposits of titanomagnetite, 40 km to the south, provide the major feedstock to New Zealand's only steel mill at Waiuku.

Giant Andesite Fans

Venture out to the west coast at Muriwai at the northern end of the Waitakere Ranges and you will join the throngs viewing New Zealand's most accessible mainland gannet colony. Just to the south of this, however, in the cliffs above Maukatia/Maori Bay is one of the country's most treasured geoheritage features – the spectacular columnar fans and pillows of a basaltic andesite flow that was erupted in 1,000–2,000m of water on the lower slopes of the Waitakere Volcano about 17 million years ago. Sea erosion of the cliffs has sliced a section right through a 400m-wide, 30m-thick pillow lava flow, exposing the large, solidified internal feeder pipes surrounded by more usual, 1–2m-diameter branching pillow lobes or fingers. From the beach look up and admire the flow and its huge fans of columns in the cliffs behind. On a good low tide, it is

The 53 volcanoes of Auckland's basalt field.



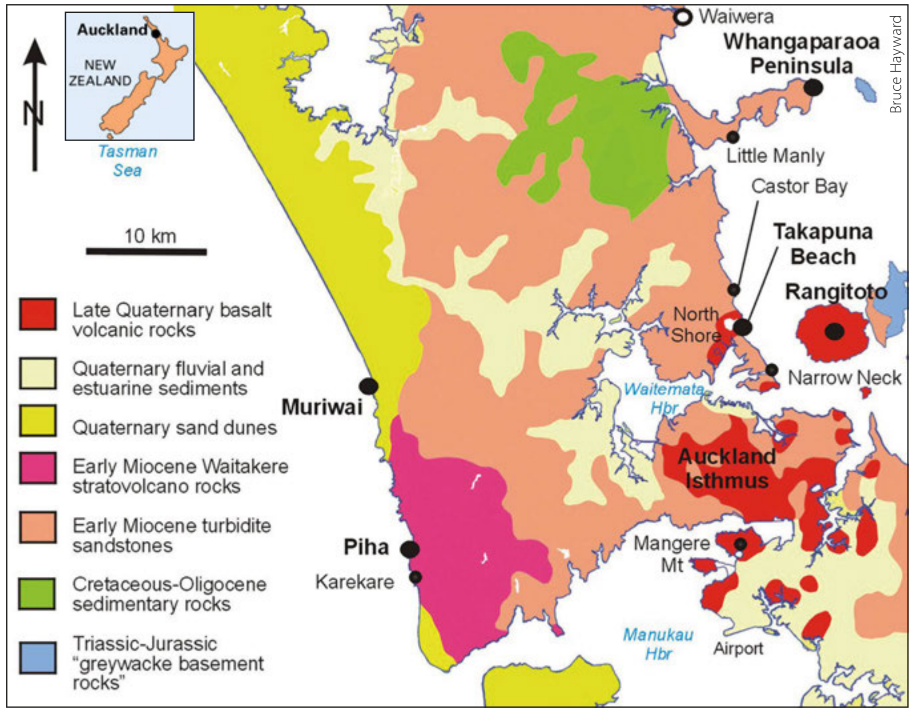
possible to walk south and see further smaller pillow lava flows up close and even dikes captured in time with an extruded pillow roll being squeezed out into the unconsolidated sediments just below the sea floor.

Highly Deformed Miocene Turbidites

The young volcanic rocks that underlie Auckland City are just a thin mantle that buries a rolling landscape of ridges and valleys eroded out of the region's most common rocks, interbedded Early Miocene sandstone and mudstone. The sandstone layers were deposited by turbidity currents flowing down submarine canyons from the north into a rapidly subsiding deep bathyal-abyssal marine basin. The thinner and less erosion-resistant mudstone layers were deposited by the settling out of the fine tails of the turbidites and by slow hemipelagic mud sedimentation in between turbidity current events. This Waitemata Basin was formed as a result of the initial propagation of the modern Australian–Pacific plate boundary, obliquely beneath northern New Zealand.

The relatively soft Waitemata Sandstone strata can be seen forming 20–100m-high sea cliffs around the coastlines of most of Auckland's two harbours, the Manukau and Waitemata. The total thickness of accumulated turbidites is about 1000m and these have been uplifted, tilted west and partly eroded down during several episodes of enhanced tectonism since sedimentation ceased, 17–18 million years ago. In many of the cliffs of the North Shore's eastern beaches and particularly around the finger-like Whangaparaoa Peninsula, the strata exhibit sections of intense faulting and folding. The larger faults are probably of young age but it is clear that most of the mix of ductile and brittle deformation occurred within the upper parts of the sediment pile as it was accumulating.

One hypothesis is that there was a major seafloor failure event on the basin's northern slopes involving as much as several hundred square kilometres of seafloor to a depth of up to 500m or more. No doubt this failure was a compound event with slabs



Simplified geological map of Auckland region showing location of places mentioned in the text.

Rangitoto's 259m, forested summit in the middle of Auckland's Waitemata Harbour is Auckland's largest and youngest volcano, erupting just 650 years ago.

Whakaari/Lion Rock is an eroded Early Miocene volcanic neck, consisting of collapsed agglomerate intruded by tongues of andesite, in the middle of Piha's surf beaches.

progressively sliding downslope and thrusting over the top of earlier slide blocks and compressing, folding and fracturing strata around and beneath their toe. Other unrelated slope failure slumps are also likely to be responsible for some of the deformed sections. The best places to examine some of this amazingly complex deformation are at low tide in the cliffs south of Narrow Neck, north of Castor Bay, at Waiwera Beach, and all-around the Whangaparaoa Peninsula. I recommend an exciting four-hour walk during low tide around the tip of Whangaparaoa Peninsula from Army Bay to Pink Beach, returning overland through the natural bird sanctuary of Shakespeare Regional Park.

A 5m-wide portion of a smaller pillow lava flow exposed in the cliffs 1 km south of Maukatia, Muriwai. Note the well-exposed finger-like lobes that form the classic pillows when viewed in cross-section.

Further reading

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A recumbent fold of Early Miocene turbiditic sandstones in 60m-high cliffs at the tip of Whangaparaoa Peninsula.

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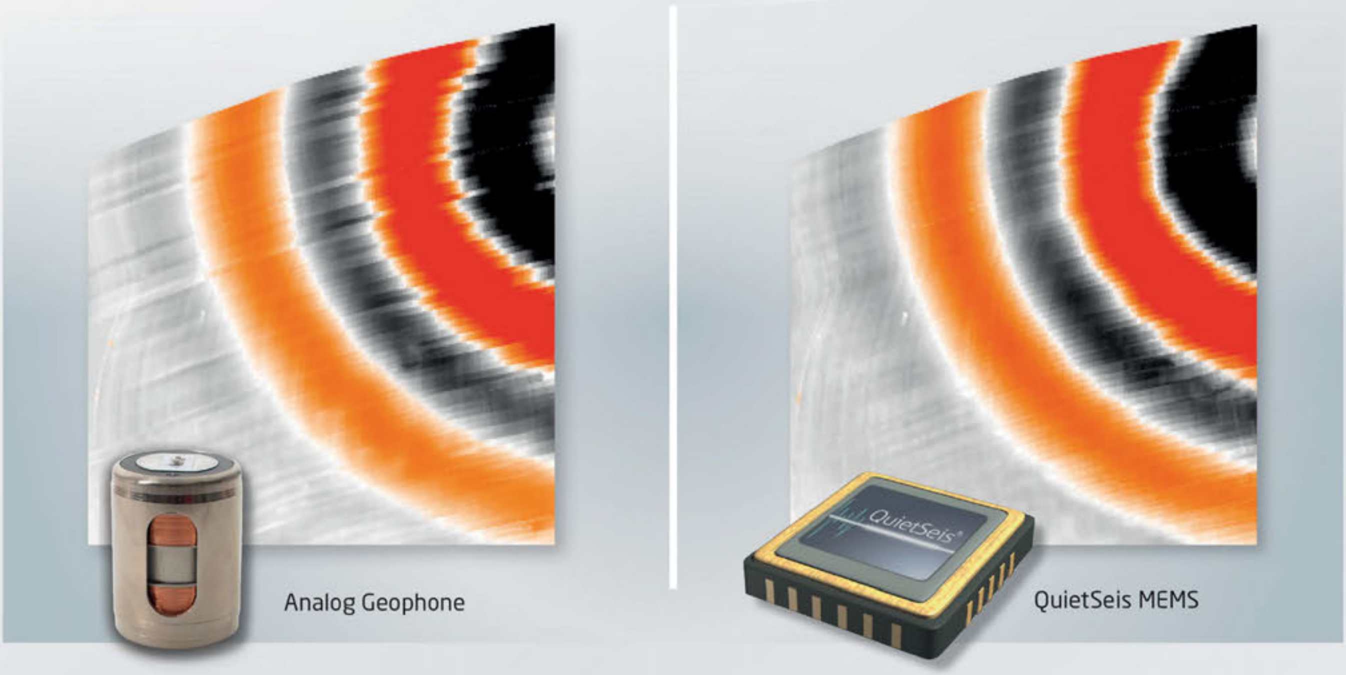

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South East Asia: Renewables Moving Centre Stage

Although still heavily dependent on hydrocarbons, renewables are beginning to provide an increasing share of South East Asia's energy.

JANE WHALEY

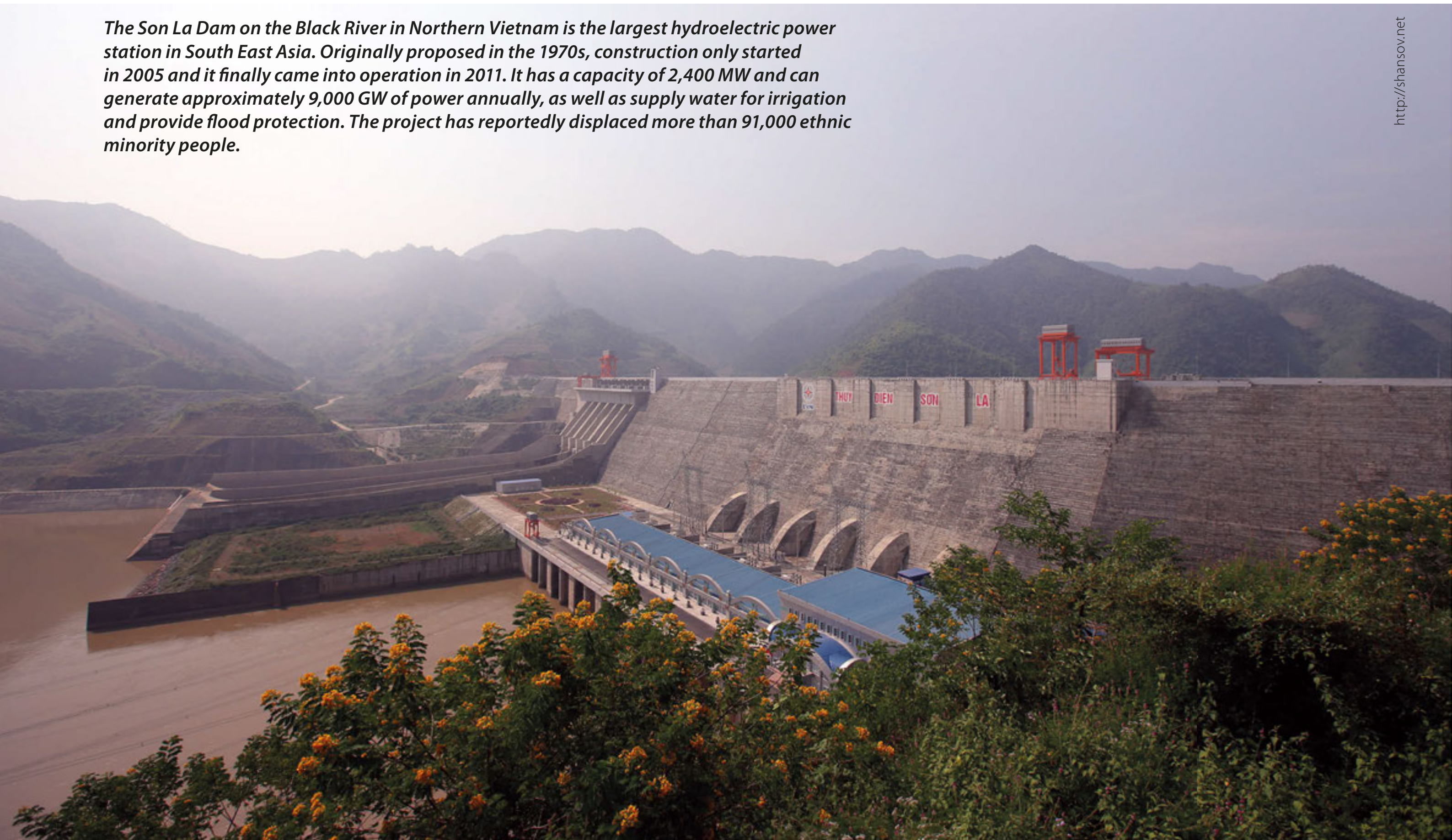
The last couple of decades has seen tremendous economic growth in the countries that make up the Association of South East Asian Nations (ASEAN) – Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam. This has brought enormous benefits and opportunities to the region, together with many challenges. Demand for energy, particularly for access to electricity, continues to rise and is projected to grow by an average of 4.7% per year until 2035 across the region. Incomes have increased substantially and fewer people are living in poverty, but with growth has come higher levels of air pollution and increases in CO_2 and other emissions.

Coal and Gas Dominate Electricity

Since 2000, overall energy demand in the region has risen by over 80% and most of it has been satisfied by fossil fuels, particularly coal. In fact, according to the International Energy Agency (IEA), South East Asia is one of a few regions in the world where the share of coal in the power mix increased through the last decade. Based on present policies, it is projected to continue rising, possibly not peaking until 2027, according to Wood Mackenzie. Part of the attraction of coal is that it is mostly supplied from within the region, thus reducing its cost.

Energy demand is driven by rapid growth in electricity consumption, particularly for cooling, which is set to continue, since less than 20% of households in the region have air conditioning at present. Coal is predominantly used in electricity generation, with new plants still being built. In 2018 it accounted for about 40% of electrification in South East Asia and some estimates suggest it may still be contributing as much as 36% in 2040. Change is in the air, however; the Philippines, for example, recently announced a moratorium on any increases in coal-fired power generation, and in the first-half of 2019 approvals for new coal-fired projects were exceeded by additions of solar capacity for the first time.

Gas accounted for 35% of electricity generation in 2018 and is projected to increase its share slightly in coming years. However, local gas production is not anticipated to be able to cover the projected increase in demand and the region may change from being self-sufficient in gas to becoming a net importer by the end of this decade, unless major new fields are discovered.



The Son La Dam on the Black River in Northern Vietnam is the largest hydroelectric power station in South East Asia. Originally proposed in the 1970s, construction only started in 2005 and it finally came into operation in 2011. It has a capacity of 2,400 MW and can generate approximately 9,000 GW of power annually, as well as supply water for irrigation and provide flood protection. The project has reportedly displaced more than 91,000 ethnic minority people.

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Scope for Renewables

South East Asia has considerable potential for renewable energy but in 2018 these only accounted for 15% of the region's total energy demand (IEA). ASEAN has set an ambitious target of securing 23% of its primary energy from renewable sources by 2025.

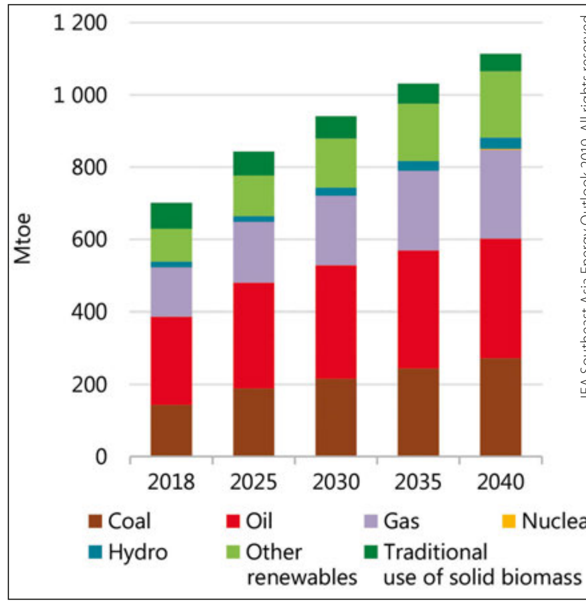
About 22% of the region's electricity comes from hydropower, output of which has quadrupled since 2000. Vietnam is the main producer, but there is also potential in other countries such as Cambodia, Indonesia and Thailand. However, the overall financial cost is similar to that of coal and there are environmental issues associated with the dams involved, such as damage to communities and soil health.

As of 2018, other renewable energy sources accounted for less than 10% of South East Asia's electricity supply, but this is set to increase rapidly, with Wood Mackenzie projecting that solar and wind power plants will contribute 35% of the region's power mix by 2040. Vietnam, for example, had a tenfold expansion in installed solar capacity in 2019, partly driven by a generous 20-year feed-in contract. The region is an important producer of components such as photovoltaic (PV) cells; Malaysia is already the world's third-largest producer of them, while Thailand is increasing PV output for both home and global markets. This will assist in energy security for the region, alleviating the increasing dependency on imported hydrocarbons.

Another source ripe for development is geothermal energy. The Philippines is the world's second-largest producer of geothermal electricity after the US, and Indonesia is also producing an increasing volume, with plenty of scope for expansion.

The use of bioenergy (excluding the traditional use of biomass for cooking) in heating and transport has also increased rapidly in recent years, accounting for about 15% of power generation at the moment. Thailand is the leader in this sector both for energy production and in the use of gasohol, a blended fuel of gasoline and bioethanol derived from crops such as molasses, cassava and sugarcane juice.

In late 2020 the ASEAN nations launched the Energy Transition Partnership, which aims to support sustainable energy transition in South East Asia in line with the Paris Agreement, with an initial focus on countries like Indonesia, Vietnam and the Philippines, which have significant coal consumption. There is plenty of scope for a variety of energy sources in ASEAN countries and the use of sustainable energy sources both domestically and industrially are increasing fast. However, to deliver on the Paris Agreement level of emissions, coal-fired power plants need to be switching to gas, while the uptake of renewables will need to grow substantially; the IEA, for example, estimates that the share of renewables in power generation will need to reach about 70% by 2040 to achieve this.



IEA Southeast Asia Energy Outlook 2019. All rights reserved.

Primary energy demand in South East Asia, as predicted by the IEA, assuming policy frameworks and ambitions remain as they were in 2019.

Regional Policies Needed

Regional power system integration could hugely help the uptake of renewables in South East Asia, allowing access to a flexible variety of energy sources to help reduce the innate variability of wind and solar energy. Such integration will need high levels of investment from both government and the private sector, as well as commitment through consistent government policies, including the phasing out of fossil fuel subsidies, increased use of carbon capture and encouraging ways to improve energy efficiency.

With the help of renewable energy sources, universal access to electricity across South East Asia is within reach, which would be a major achievement for this rapidly growing region.

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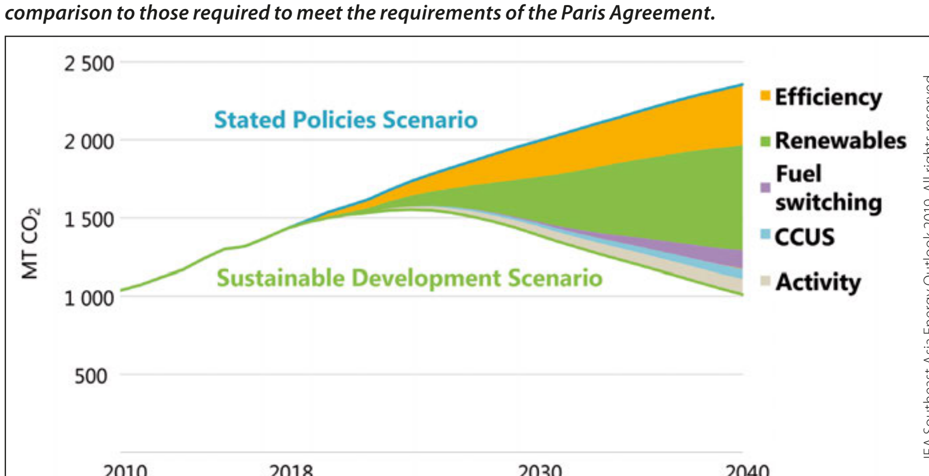
Comparison between emissions anticipated as a result of present South East Asian energy policies in comparison to those required to meet the requirements of the Paris Agreement.



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What Can Multiscale 3D Imaging Do for Energy Geoscience?

Will examining rocks at multiple scales extend the productive lives of our fields and help to repurpose these assets, our facilities and ourselves?

KEVIN G. TAYLOR and LIN MA, University of Manchester

As energy geoscientists we continually strive to understand the rocks that are the building blocks of energy systems. Whether that be in the hydrocarbon systems that have underpinned industrial development over the last two hundred years, or in those systems that are key to the energy transition as society shifts away from fossil fuels, such as geothermal, heat and energy generation and storage (e.g., hydrogen, compressed air) and also long-term storage and disposal of CO_2 and radioactive waste.

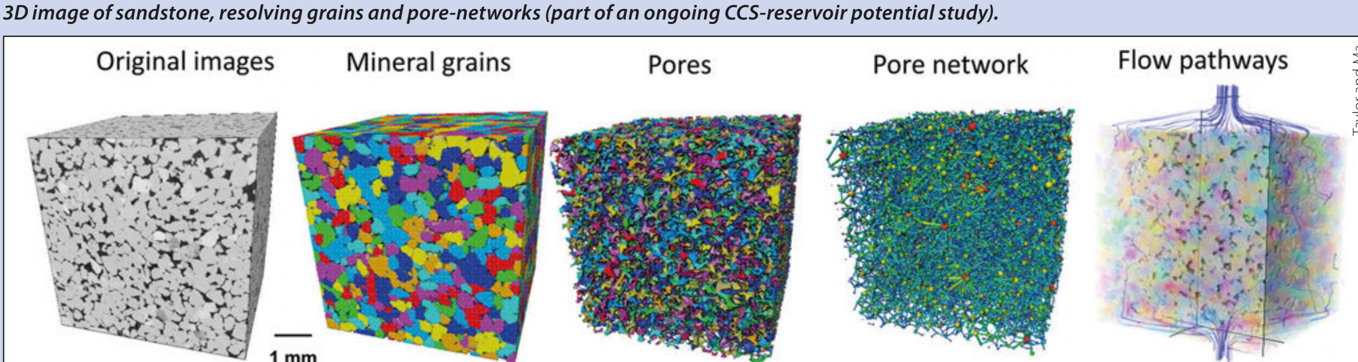
Modeling is Key

Whilst the large-scale (e.g. geophysical) and traditional petrographic techniques have continued to evolve over the last three decades or so, the last ten years has also seen enormous growth and development in the application of new X-ray and electron microscopy techniques to image, in three and four dimensions, the microstructure and nanostructure of rocks (both porous reservoirs and relatively impermeable seals) in order to better understand sealing properties, fluid/gas storage and flow in these rocks, as well as to build physical and chemical models to effectively simulate and predict subsurface behaviour. All subsurface energy technologies depend upon fluid movement and storage as well as impermeable cap rocks to retain the fluids in the subsurface. In order to do this effectively, and understand key uncertainties and manage the resultant risks, there is a critical need to understand in both 3D and 4D wherever feasible, porosity (fluid storage), porosity connectivity (permeability) together with microfracture characteristics (transmissibility and seal integrity). Whilst offering significant opportunities to understand these systems with new techniques and technologies being developed and improved all the time, there are still challenges and workflows that need to be understood in applying these techniques.

It's a Matter of Scale

There are many techniques that can be applied; these are selected based on the resolution required, and what can be achieved by each and on the features that we wish to image and quantify. As can be seen from Figure 1, the scale and resolution of interest dictates the method selected. Macro-X-ray Computed Tomography (CT), micro-X-ray CT, nano-X-ray CT, Focussed Ion Beam Scanning Electron Microscopy (FIB-SEM) and Transmission Electron Microscopy (TEM) tomography, are techniques that, respectively, offer a sequence of increasingly higher spatial resolution. In the workflows we apply, it is important to be aware that as imaging resolution improves, and smaller features can therefore be resolved (in effect the voxel size – a 3D pixel – decreases), the volume size of rock that can be imaged also gets proportionately smaller. At the extreme end, the volume of sample that can be imaged by TEM tomography is as small as tens of nanometres (nm); this offers a resolution as small as 0.1 nm. At the other end, microfocus, X-ray tomography (macro-XCT) can image very large samples such as core material, but image resolution is rarely better than a few millimetres. It follows that we must select carefully the imaging method based upon the features we are interested in studying. For sandstones and other coarser granular materials, we would primarily be looking to use microfocus X-ray tomography (micro-XCT) for pore imaging, whereas for microfractures in cores/mudstones/carbonates, macro-XCT is commonly good enough. For pores in shales, where high resolution is demanded, then the techniques of FIB-SEM and TEM tomography are needed to understand fully the nature of the rocks.

3D image of sandstone, resolving grains and pore-networks (part of an ongoing CCS-reservoir potential study).



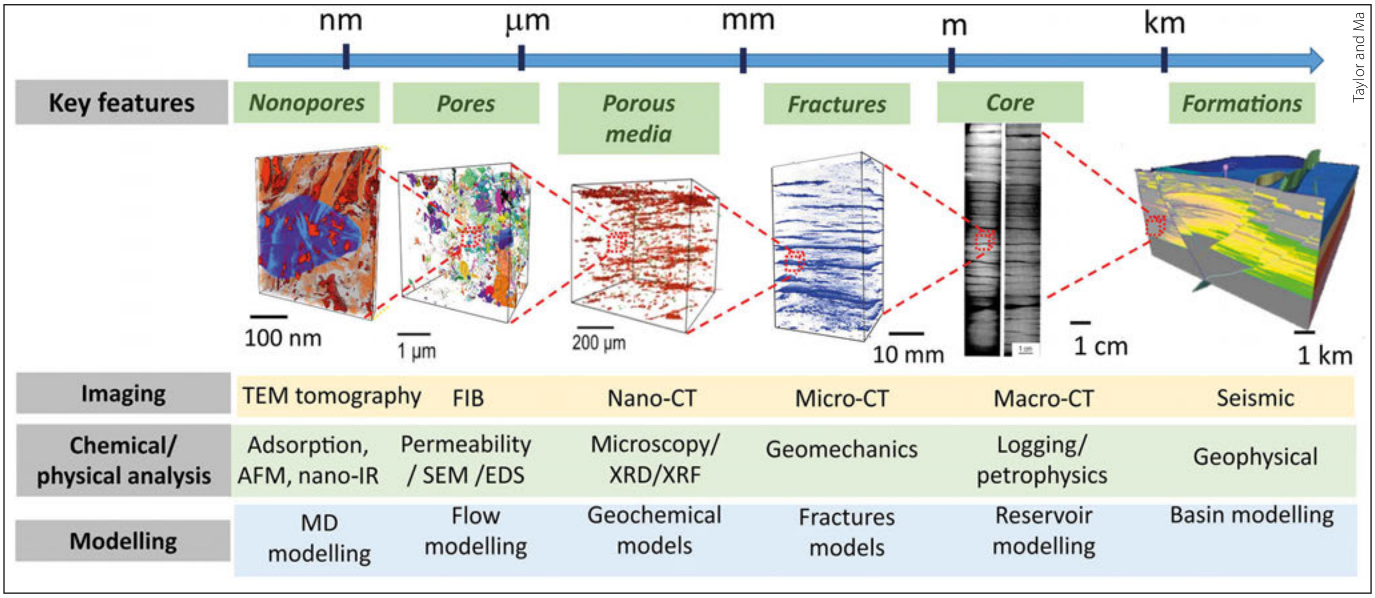
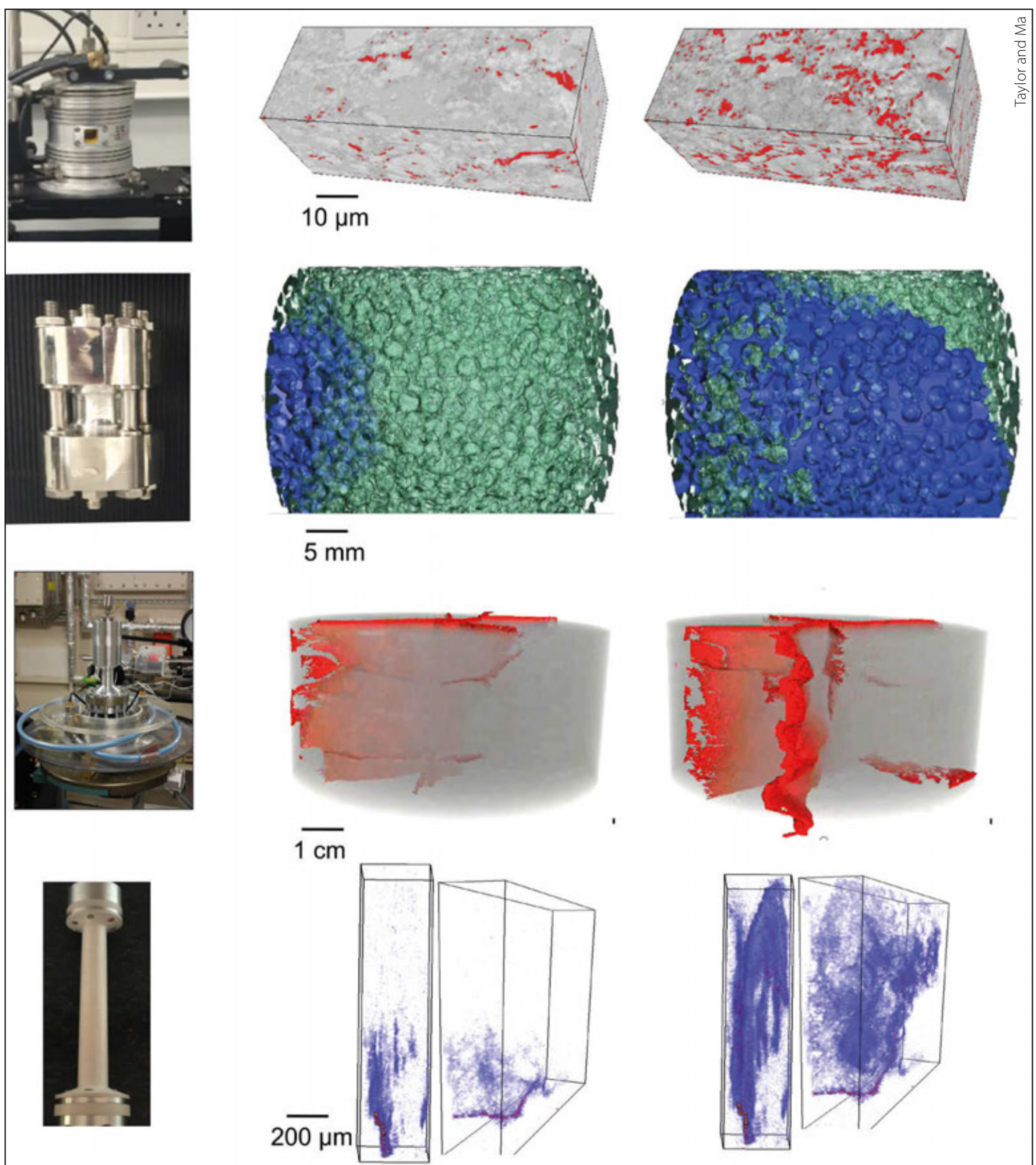


Figure 1: Multiscale methods for 3D imaging, characterisation and modelling.

Challenges and Opportunities

The obvious question arises, whether the images and features that are measured in a sample are representative of the rock as a whole and how can we upscale observations whilst retaining the integrity of the original observation or measurement? This is a difficult challenge that people have addressed in two ways. The first way is to collect multiple images at the same resolution and scale and stitch them together into a larger 3D volume – a 3D version of the widely used gigapan approach in 2D. This results in a larger volume of imaged rock, but at a high spatial resolution. Such an approach is often time-consuming and costly, as well as generating very large datasets; with the advent of machine learning this is more achievable and offers a more viable option than in the past. The other approach is to develop mathematical upscaling models that can be applied to datasets. The approaches for this have been varied and taken the form of several

Figure 2: 4D imaging examples of thermal expansion, stimulated fracturing, multi-phase flows and mineral reactions.



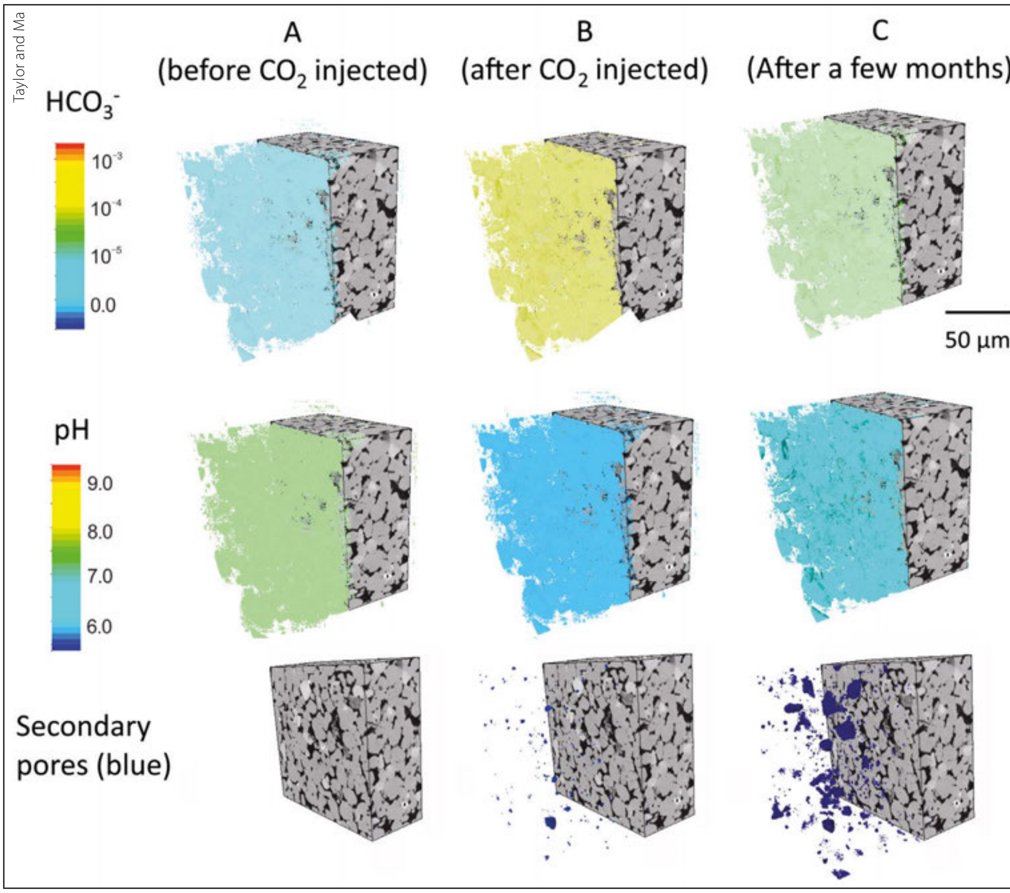


Figure 3: Image-based modelling of carbonate dissolution after CO_2 injection in the subsurface.

different mathematical solutions; here a number of robust methods have recently been developed and published that allow for increased confidence in the representativeness of the final result.

An exciting recent development has been the application of 3D imaging techniques to show the evolution of micro- and nanostructures under subsurface-realistic conditions often with the application of external factors such as heat, pressure and chemical fluids. This has come about with the development of higher flux lab-source X-ray tomography and increased flux and coherent X-rays from new generation synchrotron facilities. These advances in techniques have made taking a series of 3D images over time (i.e., 4D imaging) possible. The time resolution of 3D images depends on the CT scanners and scales. Typically, it takes a few hours to acquire a 3D tomographic image using a laboratory-source X-ray CT scanner and so reactions and changes in rock microstructure and fluids over hours or days can be captured by using this technique. For more rapid changes in samples, such as fracture propagation in response to pressure or heat stress changes, synchrotron-source X-ray CT, that can collect a full 3D image in seconds, is required to capture the evolution and impact of these processes (see Figure 2).

Fast reactions, such as multi-phase flows, mineral precipitation and dissolution, can also be imaged, quantified and modelled in synchrotron beamlines (see Figure 3).

In addition to being able to capture images in 4D, a key challenge is whether we can design rigs to safely confine samples under certain conditions in order to observe the reactions or structural and textural changes that may occur. Researchers have shown that 4D imaging under subsurface conditions, involving temperature (-100 to over 1000°C), pressure (up to 20 MPa), fluids (gas, liquid, supercritical fluids), and chemical conditions (brine, acid, etc) can indeed be achieved using specifically designed rigs (see Figure 2). These rigs allow for samples to be positioned within the X-ray beam and images collected in real time during in-situ experiments. A major limitation of this approach is that in order to obtain high pressure and/or corrosive fluids, material that would normally be used to contain these conditions such as steel, is not transparent to X-rays, and thus there are limitations to what can be analysed. The development and increasing application of neutron-scattering and neutron-imaging techniques, where steel and other metals are neutron-transparent, will likely lead to further advances in this field.

New Techniques Allow Observation of Fast Reactions

3D and 4D multiscale imaging has proven to have been a very powerful tool in the geo-energy field, both in the academic and industrial sectors. But as discussed above, there are several challenges that we need to address to be able to fully unlock the potential of these 3D imaging techniques, but through careful observational and experimental design, combined with appropriate modelling, these can be solved (see Figure 4).

The application of novel techniques will allow for enhanced observation of heterogeneous features and fast reactions which could not be observed previously. For example, the tri-beam system (laser-plasma-ions FIB) provides both higher resolution and large sample volume (nm-scale static 3D SEM images of mm^3-sized sample) to bridge mm- to nm- scales, and the new generation of synchrotron sources, can capture super-fast reactions such as fracturing (down to seconds) through tomography images at high resolution (down to 30 nm). Also, the involvement of machine learning has reduced the experimental and computing time significantly and

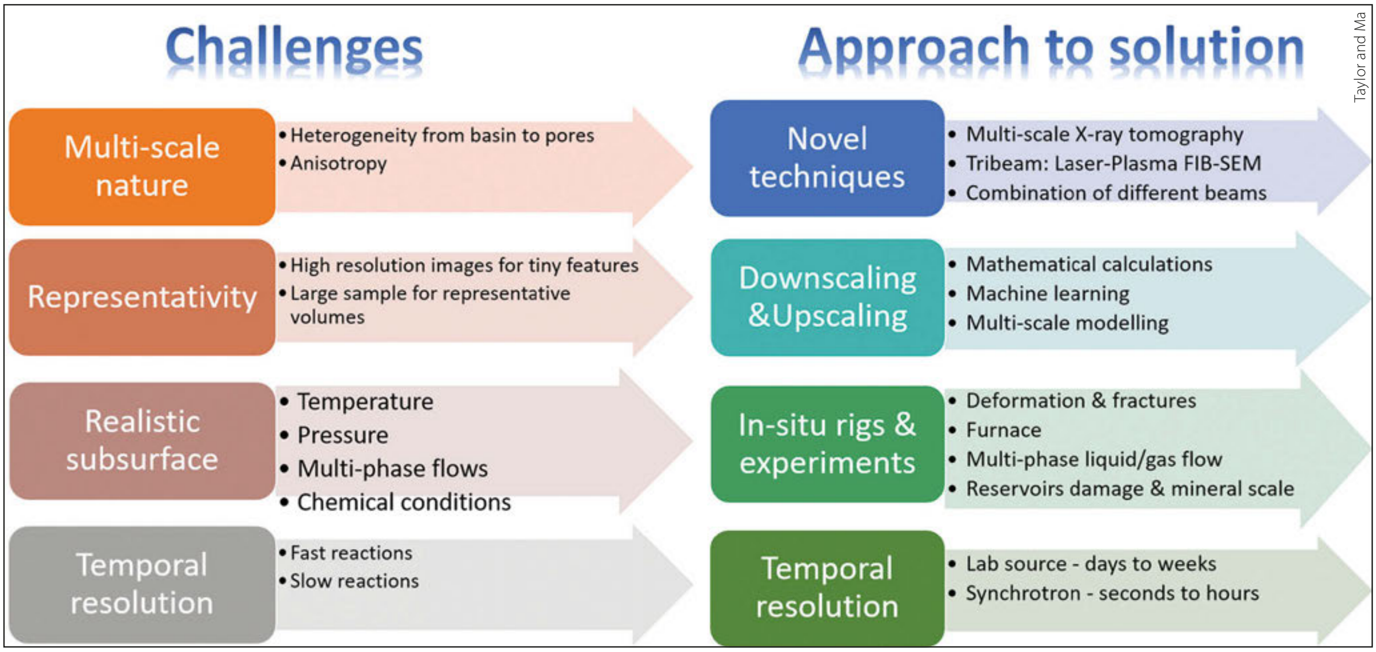
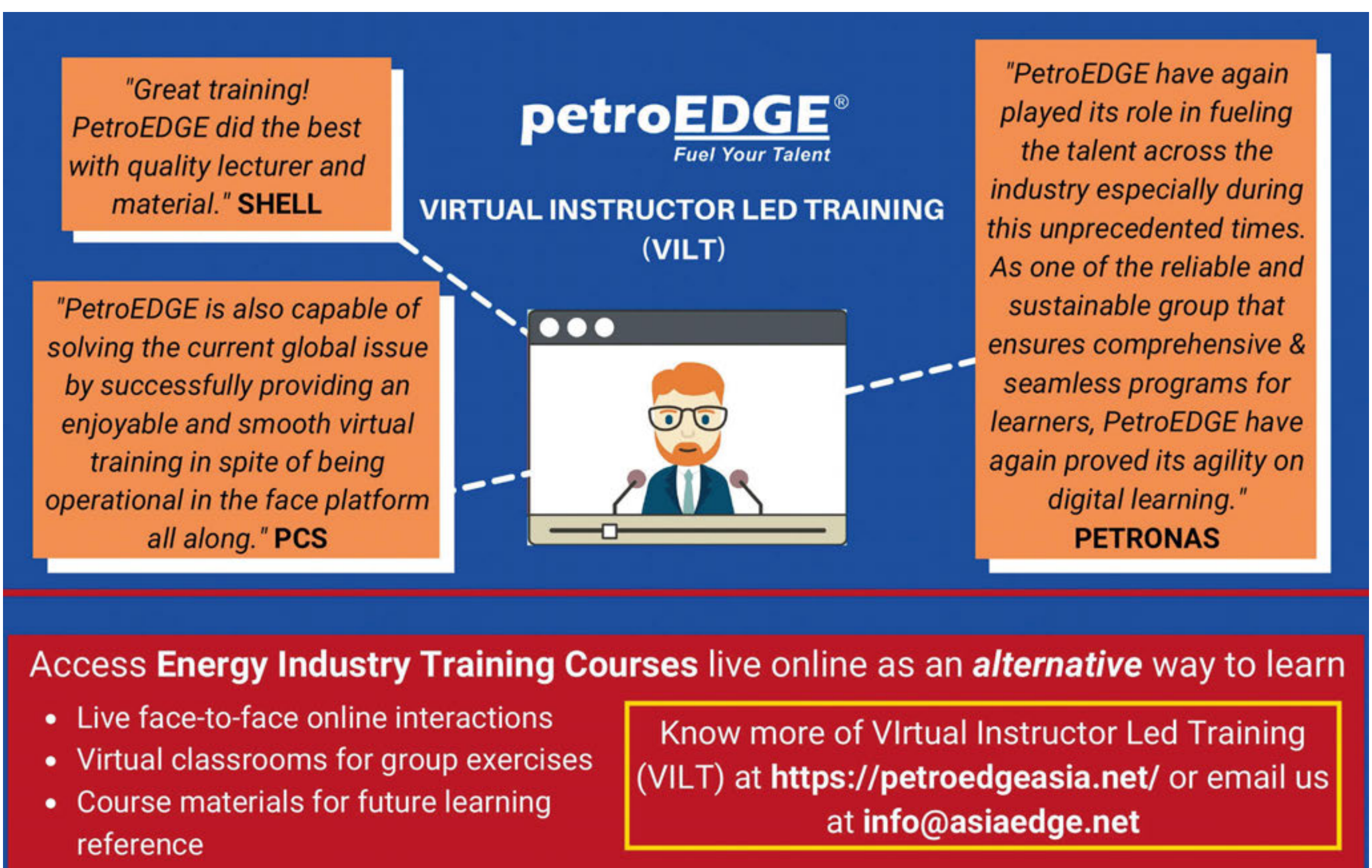


Figure 4: Challenges identified in the 3D and 4D imaging applications and the proposed approach to solutions.

also provides opportunities to reveal hidden mechanisms behind the images. All of these techniques will further increase the accuracy of modelling (e.g., flows, mechanical, chemical and combination) to improve the theoretical understanding of the rock reactions under complex subsurface conditions and provide optimising suggestions for industrial applications.

In many energy transition applications, the reactions of rock and fluids in the subsurface are poorly constrained. For example, chemical and mechanical reactions during thermal fluids injections for heat storage, hydrogen or compressed air injection for energy storage, and long-term carbon storage and sequestration. Multiscale 3D and 4D image workflows, combined with image-based modelling, will certainly help us open a new chapter for a lower carbon geo-energy future. ■



Undiscovered Potential in the Basement

Exploring in Sumatra for oil and gas in naturally fractured and weathered basement reservoirs.

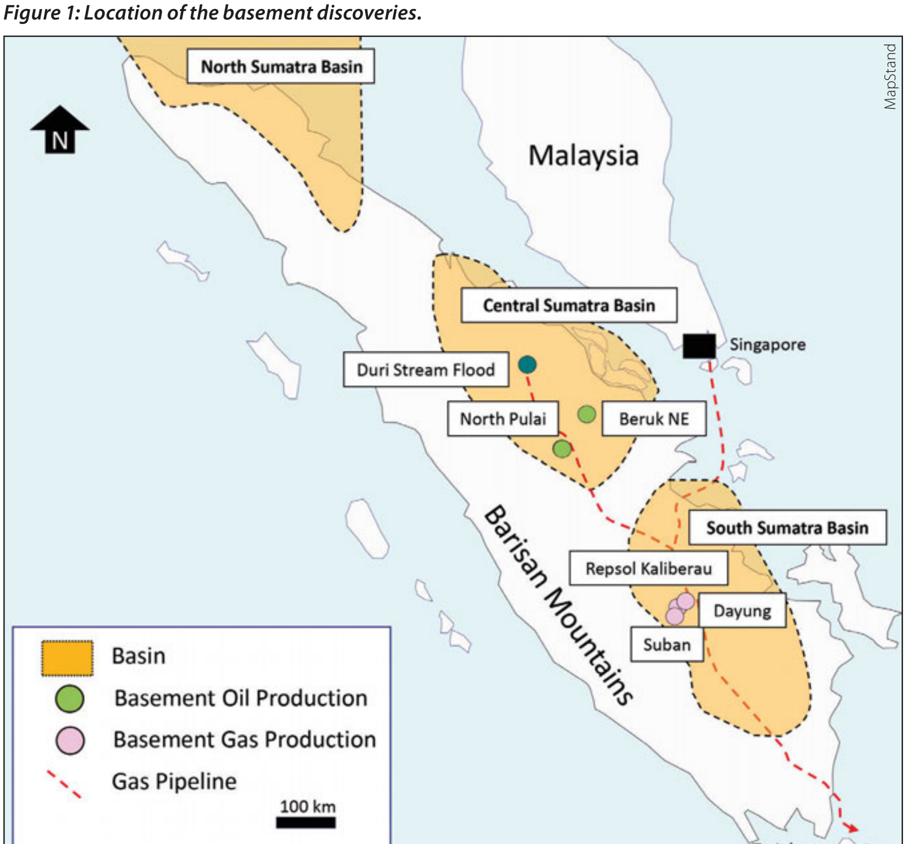
TAKO KONING, Consultant, Calgary; NICK CAMERON, GeoInsight Ltd, UK; and JOHN CLURE, Consultant, UK

Sumatra, Indonesia, is the sixth largest island in the world. Sumatra has been a major producer of oil and gas and has current total discovered resources of almost 28 billion barrels of oil equivalent (Bboe). This is broken down into the North Sumatra Basin with 6 Bboe, the Central Sumatra Basin with 15 Bboe and the South Sumatra Basin, with 6.7 Bboe. Although Sumatra is now viewed as a mature hydrocarbon province, a major gas discovery by Repsol in February 2019 in basement rocks highlights significant potential for further discoveries.

Repsol's well was the Kali Berau Dalam (KBD)-2X well and encountered at least 2 Tcfg of recoverable gas. The well targeted the basement reservoirs that are highly gas productive in the nearby Corridor Block operated by ConocoPhillips. This was the largest hydrocarbon discovery in Indonesia in 18 years. The KBD-2X well was reported to have flowed gas at 45 MMcfpd.

During the many decades of exploration in Sumatra, little attention was placed on exploring for oil or gas in basement. Globally, most discoveries of oil and gas in basement rocks were made 'by accident' rather than by deliberate exploration. Giant oil discoveries in naturally fractured and weathered basement in Venezuela in 1953, Libya in 1965 and Vietnam in 1975 encouraged more exploration in basement. However, exploration in basement in Sumatra remained minimal until 1991 when the first major basement gas discovery was made in the South Sumatra Basin.

Figure 1: Location of the basement discoveries.



South Sumatra Basin

Oil and gas in basement was first discovered in 1913 in the Kluang field. Thereafter a handful of small oil and gas fields were found in basement, but the reserves were small. This abruptly changed in 1991 when Gulf Indonesia discovered gas in fractured basement at Dayung-1. Seven more major basement gas discoveries rapidly followed, culminating in 1998 with the finding of the Suban gas field with its 5–7 Tcfg of reserves. The gas reserves of these eight discoveries were estimated at 15 Tcfg. Repsol's discovery, now renamed the Kaliberau field, represents the first large basement gas discovery in the South Sumatra Basin in over two decades.

The basement reservoirs comprise Jurassic granites and metasediments whose ages range from Carboniferous to Jurassic. The complexity of the play is illustrated by the lithologies of the Dayung Gas Field, where the host rock which includes Permian marbles is invaded by hydrothermally altered granites. As is apparent from Figure 2a, the discoveries lie at the intersection of two trends. These are firstly north-east running, rift-related highs formed during the Oligocene and secondly, late Miocene and younger, west-north-west to east-south-east aligned, compressional features (Figure 2b). Maximum fracturing is likely in such settings. The rift created highs which survived as 'buried hills' in the Miocene before being covered by sealing shales. They were subject to deep weathering and are the origin of the Talang Akar

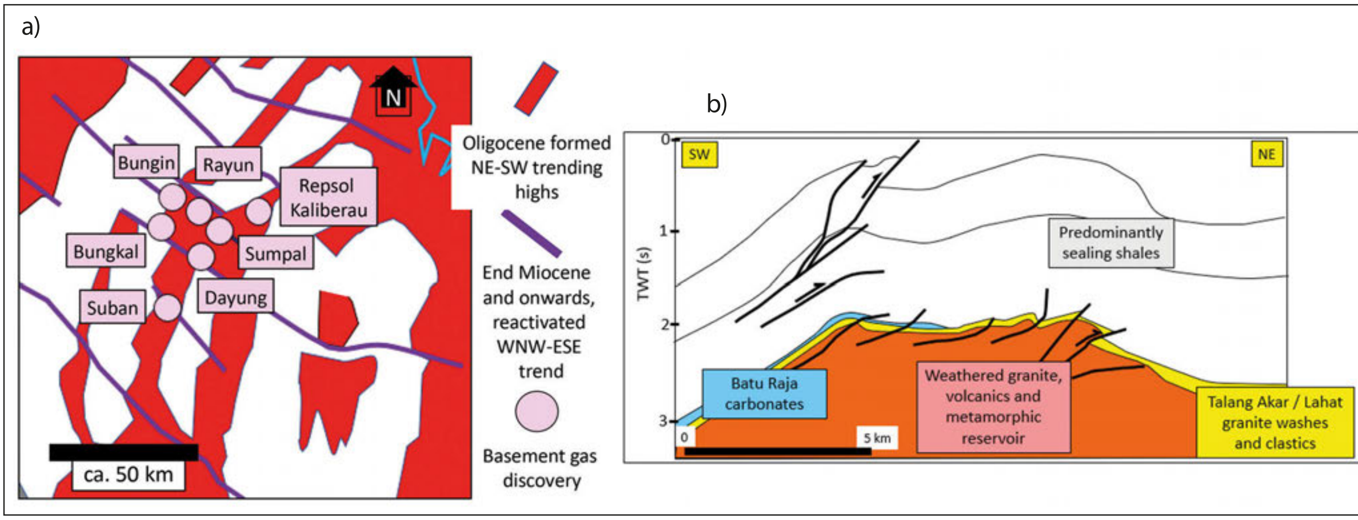


Figure 2: a) Basement gas discoveries in the South Sumatra Basin are associated with trend intersections. (Simplified from Ginger and Fielding, 2005.) b) Suban Gas Field viewed in the dip directions is an evolving compressional structure. (Simplified from Hennings et al., 2012.)

reservoirs sands and granite washes. Gas was sourced from the Talang Akar and Lahat succession.

Most of the Corridor Block fields have clearly defined gas–water contacts and the basement traps are filled to spill-point. In the Suban Field, the gas column rests on water and has a height of 1,450m. In some Suban wells, granitic basement is deeply weathered with up to 155m of weathering thereby creating a thick section of reservoir rock at the top of basement. The excellent gas deliverability of the Suban basement reservoir is illustrated by Suban-11 which had an Absolute Open Flow (AOF) rate of 1 Bcfpd and deliverability rate of 150 MMcfpd. Well trajectories are critically important, since wells must be drilled perpendicular into the dominant fracture orientations to maximise gas production. The highest flow rates are associated with active fracturing and tracking their location is a critical factor in optimising the field's development. The carbon dioxide content ranges from 32–90%. Suban is distinctive by having an exceptionally low CO_2 content of only 5.5%. This field supplies more than 70% of the gas production from the Corridor Block.

Table 1 presents an estimate of the basin's ultimate oil and gas production. It is predicted that another 5 Tcfg gas will be found in basement due to continued advances in 3D seismic technology and enhanced geological understanding of these prolific but complicated reservoirs.

A 'super basin' is defined by the American Association of Petroleum Geologists (AAPG) as a basin that has produced at least 5 Bboe and contains at least another 5 Bboe future production. Based on our analysis, the South Sumatra Basin is on the verge of becoming a super basin due to the continued impact of the basement gas play.

Table 1: South Sumatra Basin: estimated ultimate oil and gas production.

Formation	Oil (Bboe)	Gas (Tcf)
Late Miocene Muara Enim	0.2	
Middle Miocene Air Benakat	0.6	
Early Miocene – Middle Miocene Gumai	0.1	
Early Miocene Batu Raja	1.0	
Early Miocene – Late Oligocene Talang Akar	2.0	
Basement gas found including Kaliberau	2.8	(17)
Estimated yet-to-find basement gas	0.8	(5)
Total oil and gas	7.5	

Central Sumatra Basin

The Central Sumatra Basin has produced prodigious volumes of oil since the Duri oil field commenced production in 1944. This basin is classified as a super basin. Except for the small North Pulai and Beruk Northeast basement oil pools, all the production in this basin has been from Oligocene and Miocene clastics. The giant Duri heavy oil field was discovered in 1941 and has produced 2 billion barrels of oil. The giant Minas oil field, discovered in 1944, is the largest oil field in South East Asia and has produced to date approximately 5 Bbo.

The small North Pulai field was found in 1951 within a faulted anticline. The reservoir consists of pre-Tertiary quartzites which are overlain by late Oligocene Lakat sandstones. A 49m oil column occurs in basement and the overlying Lakat sandstones have a 74m oil column. Cumulative oil production up to 1990 from North Pulai was 37.5 MMbo with presumably half (19 MMbo) from basement and the other half from the Lakat.

The second discovery of oil in basement was the Beruk Northeast oil pool. BNE-1 was drilled by Caltex and tested oil at 1,600 bopd from fractured quartzite (Figure 3).

Beruk Northeast started production in 1981 and experienced rapid influx of formation water. Cumulative oil production has been only 2.6 MMbls. The disappointing results are due to poorly-defined thin oil columns in basement and the high variability of the basement lithologies. Although

Table 2: Beruk Northeast field. Basement lithologies oil production.

Beruk NE well	Lithology	Age	Oil flow rate (Bpd)
BNE-1	Quartzite	Permian	1600
BNE-2	Granite	Jurassic	Tight
BNE-3	Argillite	Cretaceous	200
BNE-4	Granite	Triassic	200
BNE-4	Argillite	Cretaceous	200
BNE-5	Quartzite	Undated	2252 (34% water cut)

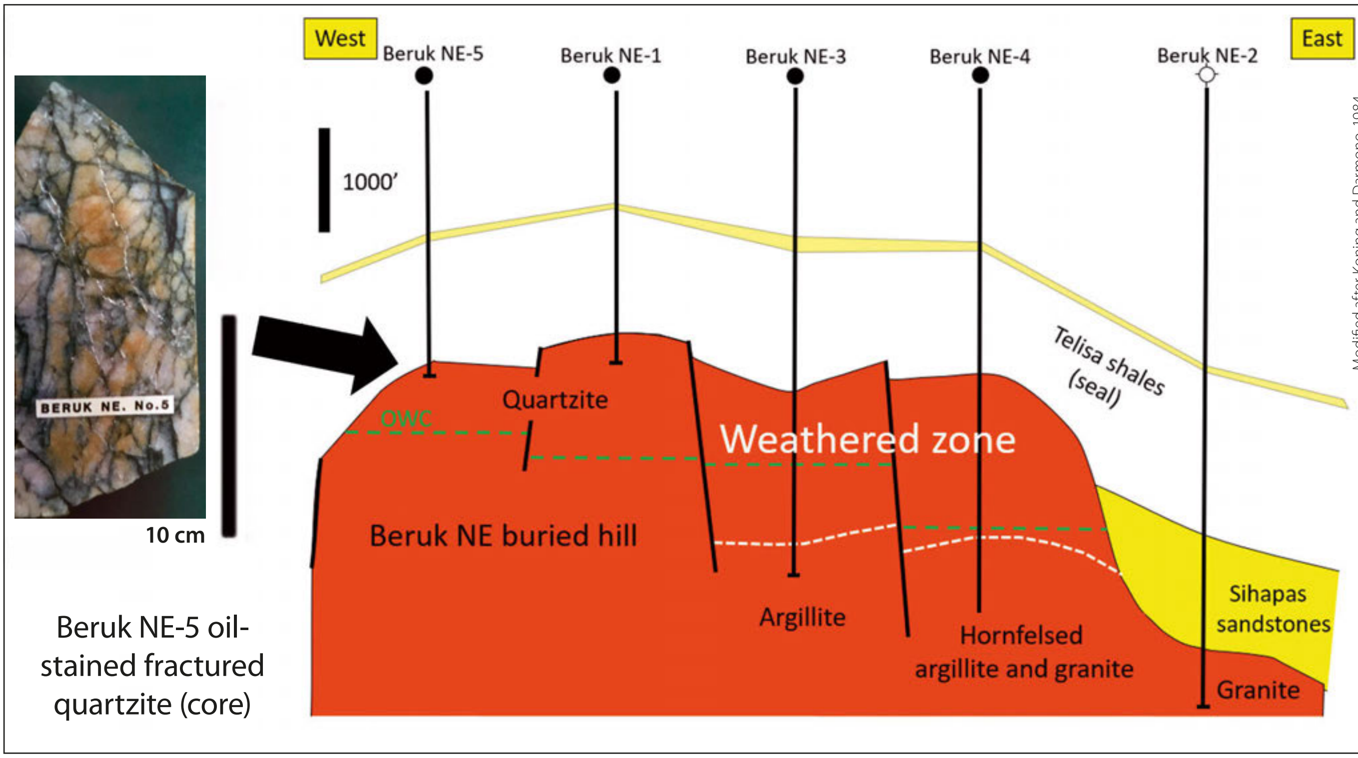


Figure 3: Beruk Northeast oil field cross-section and a drill core of oil-stained, fractured quartzite from the Beruk NE-5 well.

exploration in pre-Tertiary basement in the Central Sumatra Basin has been discouraging, the lack of success may also be because there has never been a serious and deliberate search for oil and gas in this type of reservoir. Most wells in the basin only 'tagged' into the top of basement and may have overlooked significant oil or gas fields.

North Sumatra Basin

The North Sumatra Basin is the least oil-productive of Sumatra's three basins. However, it does contain the super giant Arun gas field with reserves of 15 Tcfg. No oil or gas has been reported from definitive basement in this basin, although in the literature, hydrocarbons within the Eocene-aged Tampur carbonates are often referred to as basement occurrences. It is thought that this basin has the geological ingredients required to contain significant, true basement hosted, oil and gas deposits. Especially favourable is the deep succession below the Arun region, with its narrow horsts and deep Bampo source grabens.

Is Hydrothermal Activity the Key?

It remains unclear why only the South Sumatra Basin has yielded significant basement finds when the geology of the two other coastal, hydrocarbon-bearing basins with their rich source succession is optimal for their presence, given the island's long history of disruptive basement tectonics. One reason is lack of exploration. For the South Sumatra Basin, two other factors are in play. The first is that the cross-cutting fault sets are prominently developed at the gas discovery locations. The second and perhaps critical, is the existence of Tertiary radiometric ages from the hydrothermally altered granites at Dayung. This may highlight that rather than fractured pre-Tertiary basement, it is altered granites that are supplying the most prolific pay zones. It is these granites that may yield the bulk of the additional 5 Tcfg yet-to-find gas for this basin. Furthermore, it could be that intrusions are focused on the fault set intersects (Figure 4) resulting in the further enhancement of porosities. Given the induced, hydrothermal nature of the porosity, conventional structural traps may not be required, provided there is access to migrant gas and that a top seal exists. Smaller finds may now be economic since the infrastructure for their development already exists. Finding such small volume bodies will be limited by the ability of seismic to discriminate potential pay. A key question to be resolved is whether the bulk of the weathered and hydrothermally altered granites are of Jurassic origin or whether a novel play involving a pre-Lahat suite of volcanics and intrusives with granite-like affinities exists.

A corollary to these observations is that a consistent definition of basement for use in Sumatran exploration is required. We suggest that it should be any rock, regardless of age or origin, that lies below the oldest Tertiary-aged sediments. Thus for the South Sumatra Basin, a Tertiary-aged granite or volcanic lying below these sediments would be basement.

Economic Impact

The economic impact for Indonesia of South Sumatra's gas production is highly significant. For example in 2001, following the development of the Corridor Block's basement gas fields, Indonesia signed a 20-year, $9.0 billion agreement with Singapore to sell 2.3 Tcfg gas from South Sumatra. The agreement called for Indonesia to export 350 MMcfpd through a 500 km

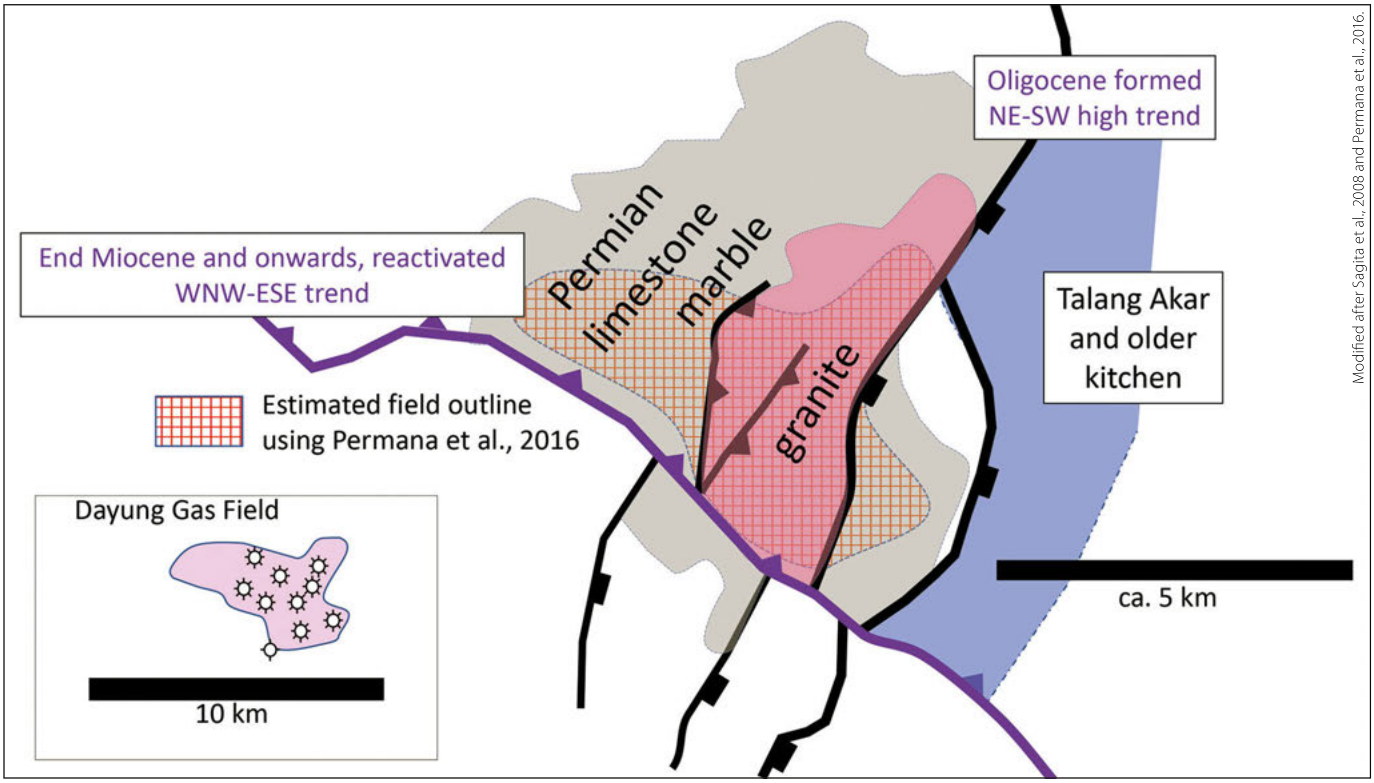


Figure 4: Dayung Gas Field top basement surface and geology. Simplified after Sagita et al., 2008 and Permana et al., 2016.

pipeline constructed between the two countries. Total gas production from South Sumatra was assessed in 2015 to be 1.9 Bcfpd, almost 70% of which was supplied by ConocoPhillips. Deliveries are to the Duri Steam Flood, Singapore and Java. Further exploration for gas in the South Sumatra Basin is strongly supported by the Indonesian government which is aiming to double the nation's gas production in the next 10 years and to become one of the top global gas exporters.

However, in the short term, Indonesia is faced with a looming natural gas deficit estimated to start in 2025 when consumption exceeds domestic supply. To partially mitigate this deficit, in 2019 Pertamina signed a long-term contract with Anadarko Petroleum to buy 1 million tonnes per year of LNG for 20 years from the yet-to-be constructed Mozambique LNG terminal. On 10 February 2020, Indonesia's Downstream Oil and Gas Regulatory Agency (BPH Migas) announced that Indonesia would stop gas exports to Singapore in 2023 to meet the ever-increasing domestic demand for gas. The announcement said that this would create added value for Indonesia's natural gas by using it to replace oil for power generation and reduce its trade deficit by reducing the consumption of imported oil. The gas is also much needed by industries in Indonesia such as petrochemicals, fertilisers, ceramics and steel. The government is strongly encouraging Repsol to fast track the development of Kaliberau so it can start producing gas by 2024–2025. Accordingly, more gas discoveries in Sumatra such as the Kaliberau basement gas discovery will be welcomed by Indonesia's government and economy.

Acknowledgements

Mike Crow provided guidance on the nature and origin of the igneous bodies in the Suban and Dayung fields.

We also wish to acknowledge MapStand for the use of their maps of Sumatra.

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The Net-Zero Transition: An Important Conversation

This article, from one of the two joint GEO ExPro student competition winners, focuses on the oil industry's role in the green energy transition.

JAMES BALL

Discussing climate change and its impact can be an especially uncomfortable subject for some in the oil and gas industry. However, it is an important conversation and one which must be had if the industry wants to not only survive but thrive in the second half of this century. Climate policy does not mean the end of the oil and gas industry, but an effective transition from our current carbon economy to a green economy will require oil and gas companies to strategise, restructure and reposition within the broader energy industry.

Geoscientists in the 21st century are living in unprecedented times for their profession. Society will become less reliant on hydrocarbons, with demand projected to decrease towards the second half of the century. As a consequence of prior emissions, the UN Intergovernmental Panel on Climate Change (IPCC) estimates that by the year 2100, 100 gigatonnes of CO_2 – double the current annual carbon output – will need to have been sequestered from the atmosphere to keep global temperature increases below 2°C. It is also doubtful whether this temperature target will be achieved. There is overwhelming consensus amongst climate scientists that anthropogenic activity is responsible for the most recent episode of climate change (Cook et al., 2016), although public sentiment remains less well defined. Climate-related natural disasters cost the global economy $650 billion between 2016 and 2018 and the social and financial cost of these as a consequence of their increasing frequency and strength will only grow as the world awaits solid climate action.

Some governments are heeding the calls of climate scientists, opting to adopt long-term emissions reduction strategies and hard emissions targets, whilst others are taking a more tentative approach towards climate change. Bans on internal combustion engine cars and a decreasing reliance on hydrocarbons for power, plastics and heating in favour of greener alternatives have already begun to contribute to a slowdown in the increase in global demand for fossil fuels. The future of climate policy and the direction that governments

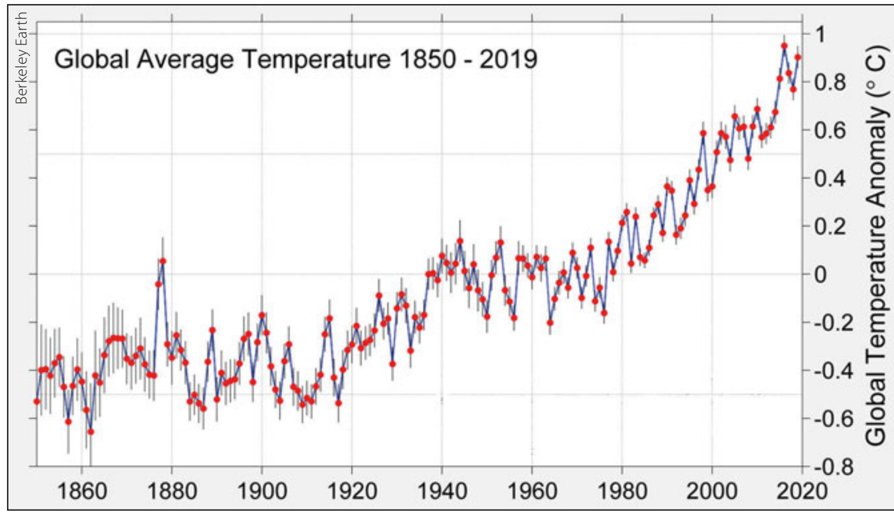
Emissions from gas flaring.

choose to take remains complex, with unpredictable policy directions still lying ahead for many, particularly in developing nations where investment may be lacking.

O&G Contributions and Solutions

Oil and gas industry operations are directly responsible for 9% of all anthropogenic greenhouse gas emissions, with a further 33% of emissions being produced from burning fuels. The industry is under increasing pressure to reduce emissions, and there is renewed focus on a broader decarbonising of society. As a result, activist investors are exerting pressure on integrated oil companies to reduce the intensity of emissions from operations in their portfolios. The act of decarbonising also presents a business case, as climate change intensifies the likelihood that the global community will reach an international consensus about reducing emissions, making the introduction of a carbon reduction tax inevitable. Large IOCs are best placed to lead this charge, and those which want to remain competitive are investing in optimising their operations for emissions reduction. In an increasingly likely scenario where a global carbon tax exists, emissions reduction will equal cost reduction, and the companies which have the lowest carbon emissions will likely have the lowest cost operations.

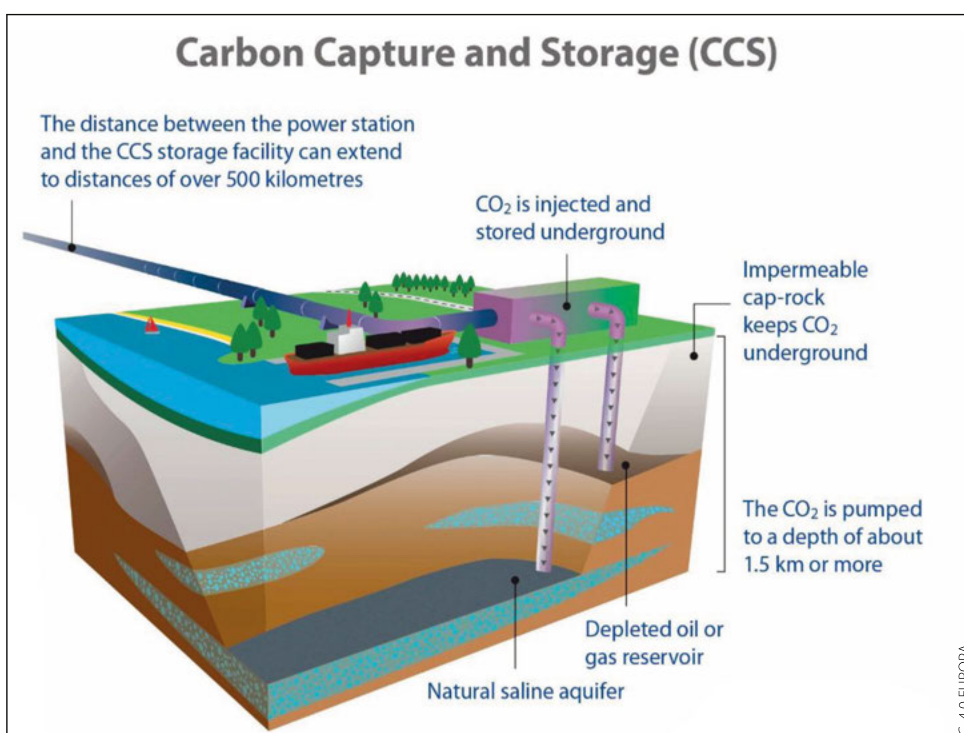
Net-zero refers to operations with total offset of carbon emissions. This can be isolated to upstream or midstream but it is often used to refer to total operation decarbonisation. The reality is that oil and gas companies will have to achieve near net-zero status if global temperature increases are to be kept below 2 degrees from baseline. There is a worry that the word net-zero is being overused or misconstrued by aggressive greenwashing marketing campaigns. Some operators have diluted down the true spirit of net-zero targets by adopting the term to refer to soft targets or carbon reduction initiatives backed by a lack of action and commitment.



Global average temperature 1859–2019. Land data prepared by Berkeley Earth, ocean data from UK Hadley Centre. Vertical lines indicate 95% confidence.

A 2020 report by McKinsey identified that if the oil and gas industry plays its part in mitigating the effects of climate change, it must reduce its emissions by 3.4 gigatonnes of CO_2 per year by 2050, a 90% reduction from current emissions. The report found that many current emissions could be feasibly reduced across operations through investment in solutions currently available such as carbon capture (CC) and vapour reduction techniques. Some companies are already embracing CC, and as of June 2020 there were 59 CC facilities worldwide with a capacity of 127 million tonnes per annum, with plans for more industrial-scale facilities in the 2020s. A recent study from Stanford has shown that eliminating flaring to levels already achieved by Norway could help reduce what is considered to be the most polluting part of oil extraction, removing 700 million gigatonnes of annual emissions.

Carbon Capture and Storage (CCS) requires utilisation of geosciences and many of the key skills employed by the oil and gas industry.



Diversification

Some majors are taking portfolio diversification in their stride, repositioning themselves as integrated energy companies. Transitioning to a more generalised energy focus presents opportunity: diversified portfolios allow majors to shield themselves from fluctuations in oil and LNG prices, which have been shown to be particularly sensitive to geopolitical situations. In some cases, however, climate commitments from majors have been lacking; ExxonMobil, for example, plans to increase emissions by 17% from 2017 to 2025. Other oil companies have moved to position themselves as role-models outlining long-term commitments towards decarbonisation and net-zero operations. BP, Equinor, Total and many other majors have adopted net-zero targets with ambitious plans to offset end-user emissions, declaring a desire for net-zero status by 2050 in line with the Paris accords. Clear strides to reduce the carbon output and bolster green credentials in the oil and gas industry are refreshing, and some companies are making a concerted effort to act in key areas of green investment and low-carbon operations.

However, the reality remains that oil and gas companies are currently under no global obligation or pressure to change their operations. There currently exists no international oversight, tax-initiatives or global, industry-specific carbon targets. Multilateral initiatives such as the Paris climate accord are a welcome step in the right direction, although the previous US administration's attempted withdrawal dealt a setback to global cooperation. The lack of oversight and enforcement of strong emissions targets makes it easy for governments and corporate entities, particularly those in the developed world, to offshore emissions to countries with more relaxed environmental laws through the use of carbon credit exchanges and the geographic reallocation of operations.

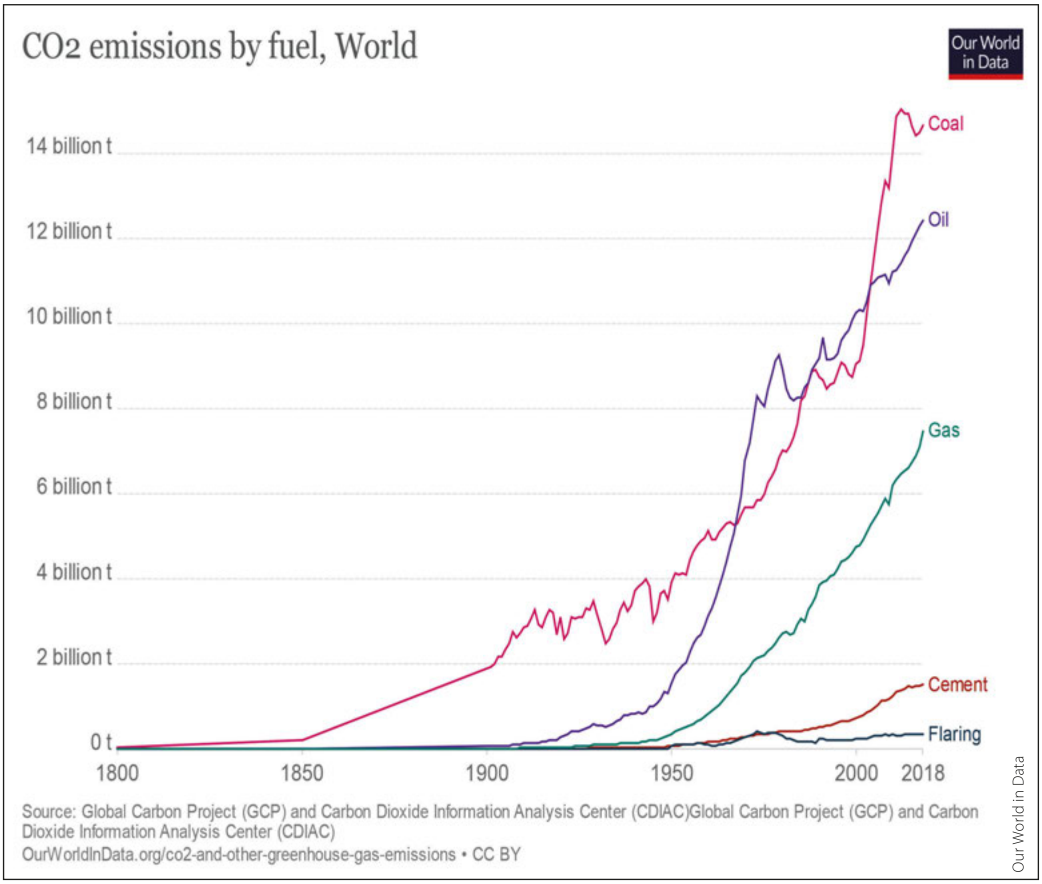
The industry remains divided. On one side there is an imperative to be prepared for climate change by ensuring that the sector is adequately skilled and retooled. Sitting on the other side of the table lies a more complacent group of actors who are banking on softer regulations and less impactful regulatory changes. If a stricter regulatory environment is imposed on the industry over the next ten years, it will be the companies that have made large investments in clean emissions technology and portfolio diversification which will thrive. However, there still lies the worry that carbon reduction innovations and action is being outpaced by the rapid growth in annual emissions, and humanity is running out of time to remain below the critical 2-degree mark.

Petroleum Geologists in the New Frontier

Petroleum geologists can unfortunately have a somewhat unsavoury image in the public eye; a 'profession of the past'. Oftentimes it can feel as if there is a dark cloud lingering over the horizon for those working in the industry, especially after the substantial job losses globally following the oil price collapse in early 2020. Hope is not lost though, since the same skills which allow geologists to find and extract oil can also be used for experimental and industrial CCS projects, and in the shorter term they still play a key role in assisting in the global transition away from coal. Geologists can play a leading part on the frontline of the inevitable green economy transition, but this is poorly publicised. There is an imperative to change the public's perception of petroleum geology and to promote an image of how the industry will help enable the energy transition. However, with university enrolments in geology programmes declining, it is vital that the geological community unite to reinvigorate the image of the 21st-century petroleum geologist; someone who is forward looking, environmentally conscious, innovative and ready to embrace the challenging times the industry inevitably faces.

References available online. ■

Reducing global reliance on coal in favour of more efficient oil and gas will be an important transitional step in reducing global carbon emissions, particularly in developing nations.



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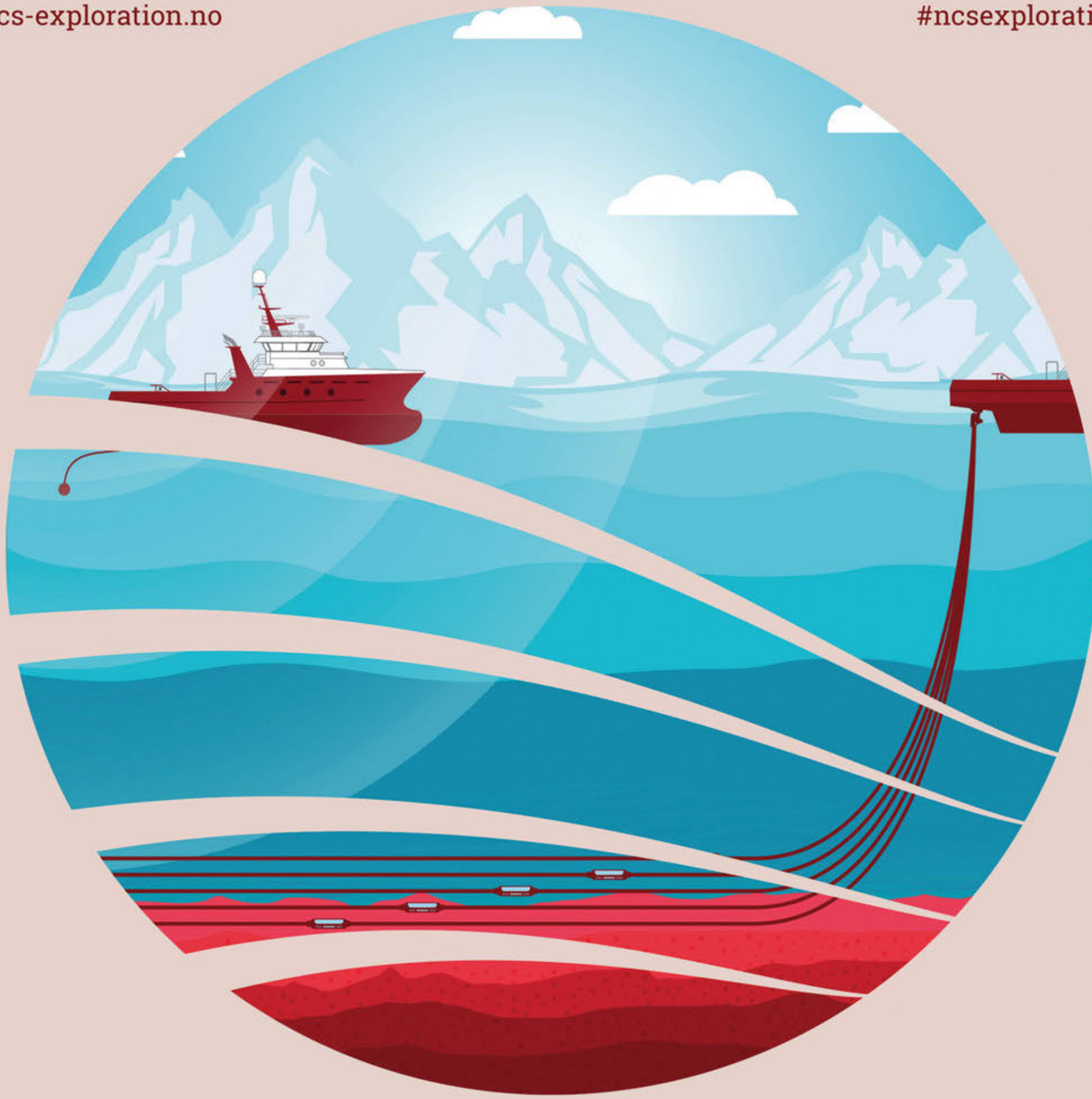

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The Tide Turns

Global wildcatting poised to go from ebb to flood.

PETER ELLIOTT, NVentures Ltd

Global exploration operations have stalled over the last year, resulting in a backlog of drill candidates and a great impetus to test world class prospects across the full range of global basins. Whilst companies like BP, and to a lesser extent Shell, have 'written off' some of their high-risk prospects in frontier basins, driven by poor investor sentiment for hydrocarbons, a great many well-defined targets remain, in settings from rank frontier to new leads in mature basins. Indeed, a lot of these 'wells to watch' targets are bursting with promise, having been refined with more data and technology over the fallow drilling months.

Significant Reserves Drill Ready

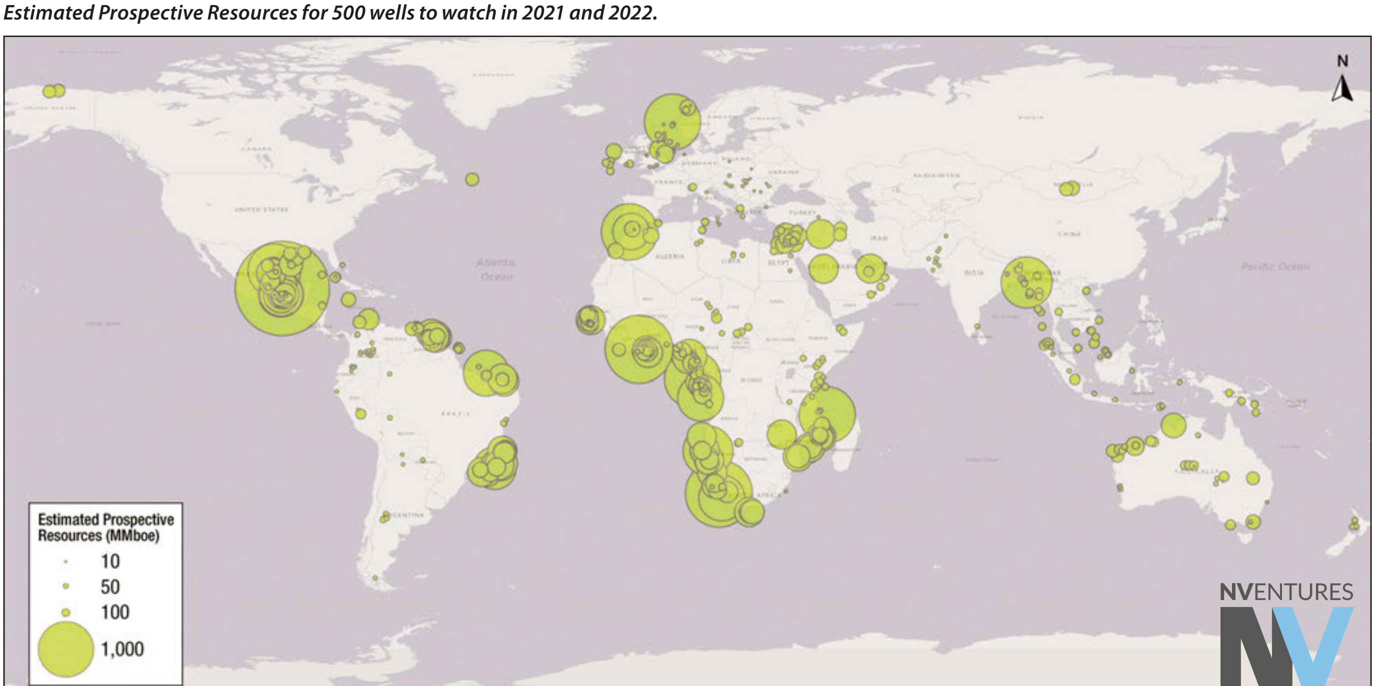
After the oil price drop in 2015, followed by a few years of low exploration dollar spend, frontier drilling for hydrocarbons hit new lows as global travel and operations restrictions accosted the industry in 2020. As we emerge from this hiatus, the dam is set to burst on a range of exciting prospects. A summary review of the global wells to watch scene, excluding poor data areas in China and Russia, suggests over 50 Bboe Prospective Resources can easily be mapped in the top 100 global prospects (of over 500 currently mapped), perhaps representing a reasonable chance of 7.5 Bboe of commercial additions over the next 12 months (using a frontier success rate of 15%). Hotspots (as illustrated on the map) include likely high-impact basins in Mexico, Brazil, US Gulf of Mexico and the Middle East, but mature provinces in Angola, Gabon, the UK North Sea and Egypt still have very significant potential, and newcomers Namibia and Suriname amongst others are gearing up to impress. Gaps are also appearing. The North Atlantic margin basins are poorly represented, perhaps reflecting the new policy-driven exploration strategy of oil and gas players.

World Class Prospects

Standout target prospects include the Venus well in Namibia (Total), which could crack open the vast Orange Basin of Namibia and South Africa. The Ondjaba-1 well in Angola likewise could broaden the ultra-deep play there, drilling in a record breaking 3,628m water. The Levant basins host two major gas targets in Zeus (Energean) offshore Israel and Block 9-1 (Eni) offshore Lebanon. The Brazilian pre-salt play is expected to keep on giving, with ExxonMobil amongst others targeting very large volumes with Opal and Titan. The remarkable success of Guyana is slowly migrating to Suriname as the true extent of the 'Canje' trend is revealed, with at least five new field wildcats planned along trend from the recent Maka Central discoveries. In south Asia local NOC firms are lining up major gas targets onshore Bangladesh (Kanchan-1, OVL), India (ONGC) and Myanmar (Woodside and Posco). The Dorado trend in NW Shelf Australia will be targeted by the likes of Santos (Apus-1) while Repsol will test the large Rencong gas prospect in Indonesia. Many of the major oil companies have continued through 2020 with large 3D surveys in offshore basins in Senegal (Total) and Egypt (Total, Shell, BP) with major new prospects being rapidly matured on the back of these new data.

The challenge then is to pin down this high value drill queue and ramp up new reserves to meet the inevitable increasing global demand post pandemic. ■

Estimated Prospective Resources for 500 wells to watch in 2021 and 2022.



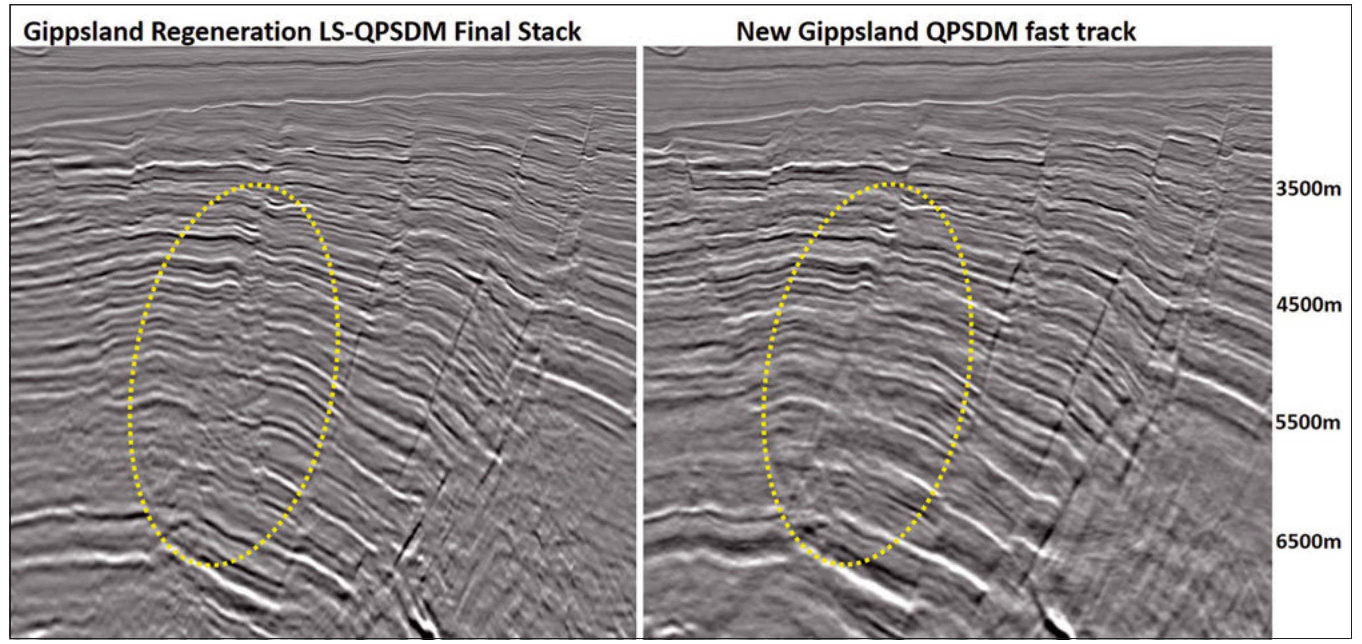
Gippsland Basin, Australia:

New Data Reveals Further Potential in a Mature Basin

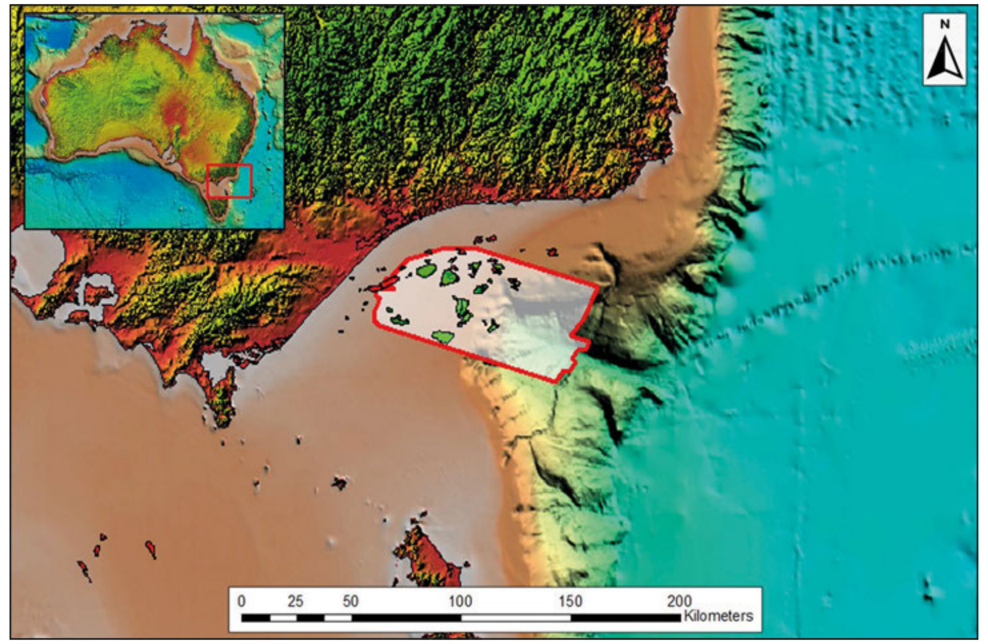
To help the industry identify new and previously overlooked prospects in Australia's Gippsland Basin, CGG acquired a new basin-scale 3D seismic multi-client survey in 2020. The 12,000 sq km dataset covers a significant offshore area, including known plays, and extends 3D coverage beyond the shelf break into unexplored deepwater acreage.

The new data is currently being processed with CGG's latest proprietary imaging technology, including 3D joint designature, P-Z deghosting and Time-Lag FWI, to enhance image quality for optimum results.

Preliminary interpretation of the recently completed fast-track data volume has already revealed enhanced insights into previously explored areas, as well as unexplored deepwater areas.

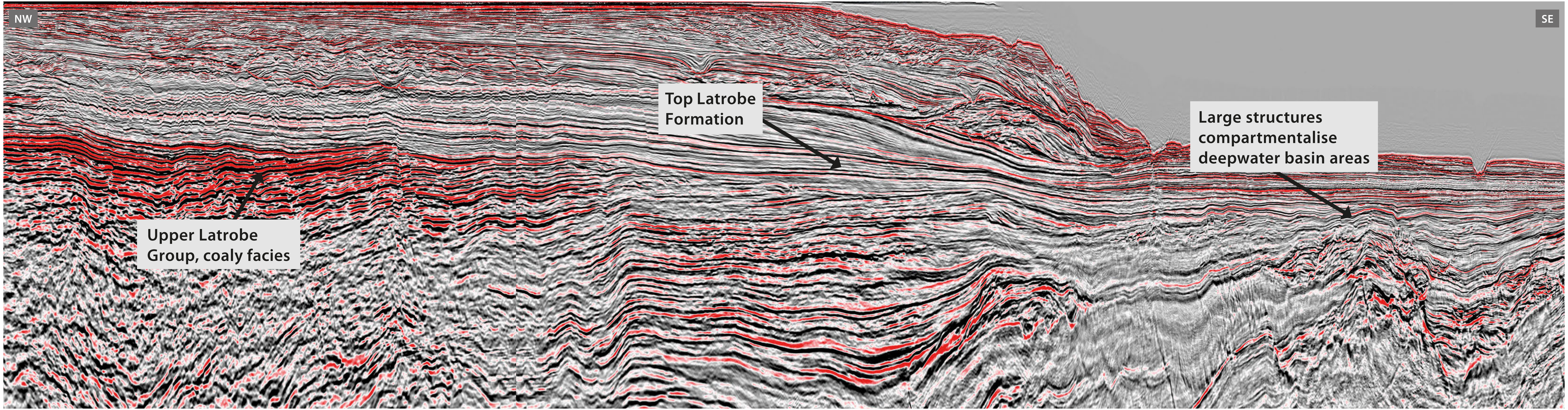


Fast-track data: comparison of Gippsland ReGeneration (left) and new Gippsland QPSDM Fast Track (right) shows improved imaging with different azimuth, longer offset and improved intermediate model.



Map showing location and coverage of new Gippsland 3D survey.

Gippsland Basin fast-track 3D data. The seismic line intersects the main Central Deep and extends beyond the shelf break into the unexplored deepwater area.



New Data, New Insights

New Gippsland Basin dataset sheds new light on a mature basin.

JARRAD GRAHAME, KEAT HUAT TENG and IAIN BURNIE; CGG

Production from Gippsland, Australia's primary oil-producing basin covering 46,000 km² onshore and offshore south-east Australia, is in decline. After the success of CGG's *ReGeneration* reprocessing project, designed to produce a high-quality, contiguous dataset from vintage 3D seismic, CGG acquired a new basin-scale 3D seismic dataset in 2020 to further enhance data quality and coverage.

New interpretation of the recently completed fast-track data is revealing enhanced insights into previously explored areas, as well as unexplored deepwater areas.

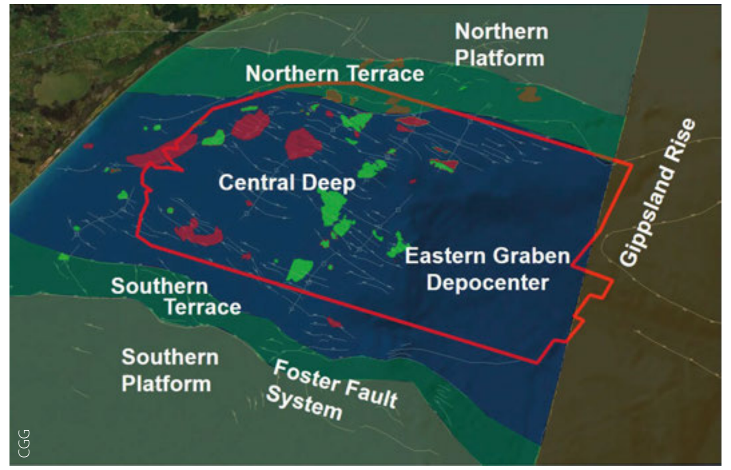
Basin Overview

The present-day structural configuration of the Gippsland Basin developed through three main tectonic phases: the initiation of rifting between Australia and Antarctica, the opening of the Tasman Sea, and finally, compression brought about by the convergence of the Australian and South East Asian plates (Power et al., 2001).

The offshore area of the Gippsland Basin is flanked to the north by the Northern Terrace and the Northern Platform. To the south, the basin is bounded by the Southern Terrace and the Foster Fault System. The central basin area comprises the Central Deep, which hosts all of the major fields. To the east of the Central Deep lies the Eastern Graben Depocentre, beyond which exist large structural highs that compartmentalise the deepwater areas.

The main source rocks are primarily upper coastal plain coals and coaly shales which have charged accumulations in shallow marine reservoirs (Bishop, 2000). In the unexplored deepwater areas there is potential for turbidite deposition where submarine channels have transported large volumes of sediment.

Gippsland Basin – structural elements and new acquisition coverage.



The primary reservoir is the Late Cretaceous to Paleogene sandstones of the Latrobe Group, which provide the reservoir for all the major fields (Rahmanian et al., 1990). A secondary reservoir is the Late Cretaceous sandstones of the Golden Beach and Emperor Subgroups, which provide the reservoir for secondary fields (Weber et al., 2004).

New Data Acquisition

Historically, most of the major fields in the Gippsland Basin were discovered on vintage 2D seismic data, dating back to the 1960s. In 2019, CGG's *ReGeneration* reprocessing project, comprising 16 vintages of 3D seismic data, resulted in a step-change in data quality and interpretation insights, which led to the development of a new basin-scale 3D acquisition project.

The new Gippsland 3D acquisition provided an opportunity to apply the latest in production-quality towed-streamer acquisition technology and extended 3D data coverage beyond the shelf break.

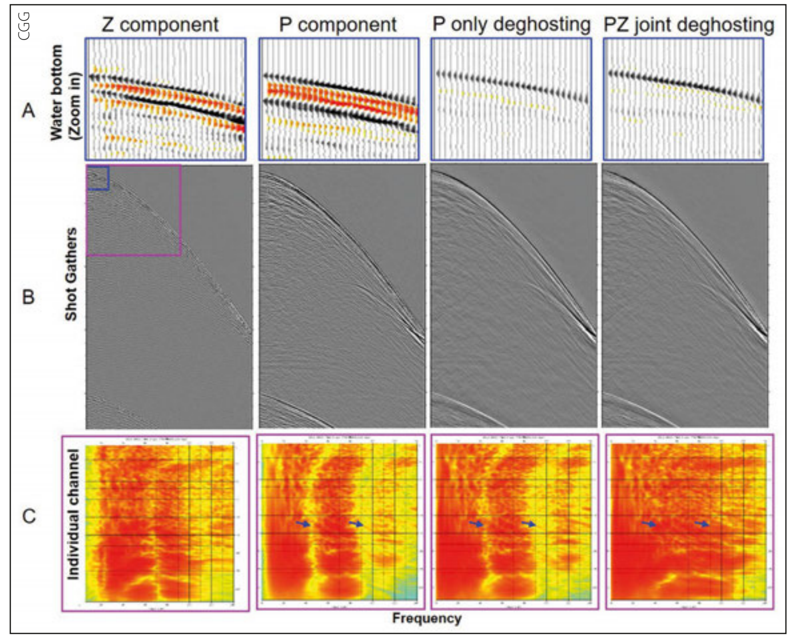
The 2020 survey utilised deep-tow multicomponent streamers, to allow for full bandwidth recovery, which is critical for penetration and imaging beneath complex overburden. A narrow streamer spacing of 75m coupled with a 200m wide-tow triple source creates a natural crossline bin size of 12.5m and minimises the impact of near offsets on shallow imaging. Diving wave analysis on the Gippsland *ReGeneration* dataset confirmed that a 7000m streamer was optimal for Full Waveform Inversion (FWI) results.

The new acquisition was oriented orthogonally to many of the legacy datasets, and in the strike direction to many of the main structures. This acquisition orientation provides a multi-azimuth (MAZ) dataset with multiple benefits, such as optimal velocity modelling for better Pre-stack Depth Migration (PreSDM), and stable Q estimation for improved absorption corrections.

Processing Technology

A number of advanced proprietary processing techniques were applied to the Gippsland fast-track data to achieve optimal imaging for the subsequent final data volumes.

These included 3D joint designature and P-Z deghosting to enhance frequency bandwidth and advanced Time-Lag FWI (TLFWI) technology with longer offset to achieve greater velocity resolution and accuracy at target levels. In addition, longer offset and continuous coverage for the survey provide greater stacking fold and improved signal-to-noise ratio.



Fast-track processing – P-Z joint deghosting.

Below is an example of how the multi-sensor data and P-Z joint deghosting compensates for the receiver ghost. From left to right, Z component, P component, P-only deghosting and P-Z joint deghosting shot gathers are displayed in row B. Row A shows the zoom-in display around the water bottom (blue rectangle window). The receiver ghost from the Z component and P component was recorded with reversed polarity, which compensates for the receiver ghost notch. This is illustrated in the P-Z deghosted shot Frequency vs individual channel plot (row C, computation window of pink rectangle). By contrast, the residual ghost notch (indicated with blue arrows) is still visible from the P-only deghosted result.

A number of iterations of tomographic update and one round of TLFWI were also applied. A comparison of the fast-track Q Pre-stack Depth Migration (QPSDM) and previous *ReGeneration* Least Squares-QPSDM can be seen on the main foldout, which demonstrates the extent to which the new data has shown improvement. This model will be further updated through a second iteration of TLFWI and dual-azimuth tomography. Further velocity updates, using both the *ReGeneration* reprocessing and the new data, will be completed by the end of 2021, with further uplift expected.

Prospectivity Insights

CGG interpreted the preliminary volumes in parallel with the early processing sequence, to provide inputs for velocity modelling, and to derive new prospectivity insights. The key methodology was to apply seismic attribute analysis techniques to identify depositional features and seismic amplitude responses potentially associated with hydrocarbon generation and accumulation.

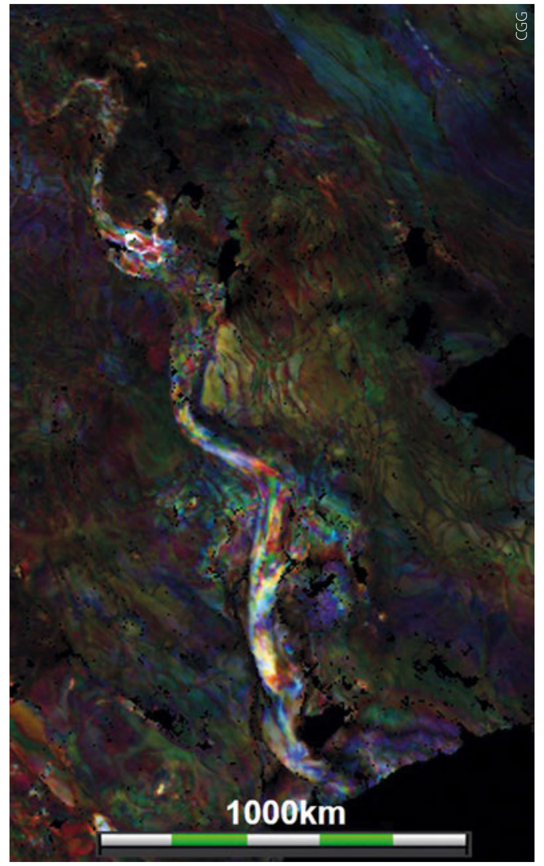
A key focus was to identify depositional features associated with sediment transport into the deeper water areas. Given the scarcity of coarse clastic sediments in these environments and paucity of pre-existing data throughout this area, the new data has provided the opportunity to evaluate these features. A number of paleo-depositional features had been identified using the *ReGeneration* dataset, beneath the present-day shelf break, within the Latrobe Group successions. These include a paleo-shoreline/offshore barrier setting in close proximity to lagoonal coaly facies.

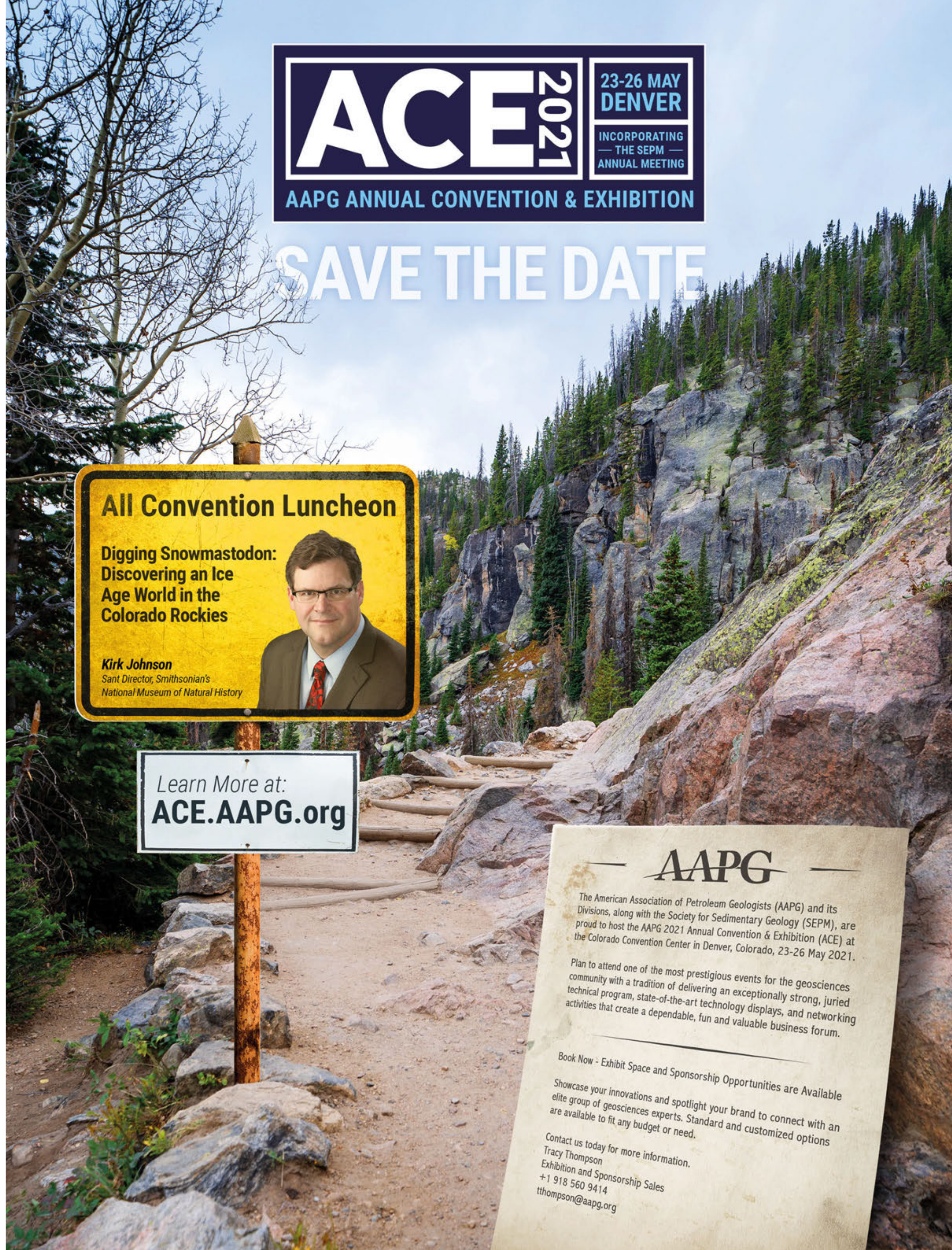
Beyond the paleo-shoreline environment, a large-scale channel complex has now been shown to extend a significant distance outboard of the shelf break, using the new data. The image below is from a spectral decomposition volume generated from the new fast-track data. This prominent, distributary channel system can be seen to extend beyond the easterly limit of the survey, highlighting the presence of large-scale sediment transport systems into deepwater areas. The new data coverage has already demonstrated the opportunity for detailed evaluation of these depositional systems for a better understanding of reservoir distribution.

The new data and preliminary interpretation have enabled CGG to identify important depositional features, particularly in the deepwater areas. These insights will be further evaluated and expanded upon with completion of the final processed volume in late 2021 and will be key to evaluating new potential in this mature basin.

References available online. ■

Spectral decomposition surface – Intra-Latrobe Group sinuous submarine channel.





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Sustainable Geophysics

In what ways can geophysics be said to add value to society, economic systems and the environment?

JANE WHALEY

This was the question three Society of Exploration Geophysics (SEG) members asked themselves recently. To determine the answer, they mapped various different geophysical applications and practices to the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015, in order to illustrate the value geophysics brings towards achieving these goals and to provide examples of specific applications and collaboration strategies. The idea was to help geophysicists understand how they can contribute to sustainability and to identify opportunities for the geophysicists of the future.

The aim was "to create a shared vision among stakeholders in geophysics about how to enhance the science's value in all components of its practice, including research and development, entrepreneurship, business operations, academia, and humanitarian engagement."

UN Sustainability Goals

The UN defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The 17 UN SDGs are a call for action by all countries to promote prosperity while protecting the planet, recognising that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs, including education, health, social protection and job opportunities, while also tackling climate change and environmental protection. The goals are independent but interconnected, selected to try to give everyone on the planet a better future, with a number of targets to be achieved by 2030. They are simply stated and aspirational, ranging from 'end poverty' and 'zero hunger' to 'decent work and economic growth' and 'responsible consumption and production' and they are directed at encouraging both businesses and individuals to adopt practices that will assist the goals.

The three SEG members – Maria A. Capello, Anna Shaughnessy and Emer Caslin – published a paper* in early 2021 in which they aimed to "raise awareness about steps and conditions that should be implemented by individuals and organisations in geophysics so they can remain relevant in the long term, serving society and preserving the planet". The result is a Geophysical Sustainability Atlas, in which they established relationships between the geosciences, and geophysics in particular, to each of the SDGs, in order to highlight the benefits to be gained from these connections.

The authors invited a large number of people from academia, industry and humanitarian organisations to form focus groups to analyse and discuss the

UN sustainable development goals for 2030.

United Nations

application of geophysics to each of the SDGs. They found geophysics to be intrinsically involved in all of the goals, and in many cases to have direct applications, while they also recognised collaboration and expansion opportunities and identified specific geophysical enablers for each goal.

Mapping the SDGs

As an example, the first Sustainable Development Goal is 'No Poverty'. The paper discusses how geophysical monitoring is vital to reducing the vulnerability of communities to natural disasters like earthquakes and is also important to ensuring the sustainable management and utilisation of the earth's resources. The closely-related second goal, 'Zero Hunger' can be supported through the use of geophysical tools to find and monitor water resources and assess soil properties, among other things. For both these SDGs the authors recognised that tools such as seismic, borehole geophysics, gravimetry and magnetometry, and ground penetrating radar can all be used to advance the targets.

A number of the goals are particularly relevant to the oil and gas industry. SDG 7, for example, discusses access to affordable and clean energy for all, with objectives that would be recognisable to many in the industry, such as optimising exploration and production and extending a field's lifecycle through geophysical techniques. However, communicating the crucial role geophysicists play in these areas, as well as in decarbonisation strategies, is an opportunity for the geophysical community. The worldwide nature of the oil and gas industry means it can also play an important role in, for example, SDG 5, 'Gender Equality', by promoting geophysics as a career for women, highlighting female role models and promoting a non-biased gender equality intake in the recruitment practices.

The use of geophysics in a number of what one could describe as non-traditional fields was promoted, with suggestions as to techniques which could be used to promote sustainable use of terrestrial ecosystems, to manage forests, combat desertification and halt land degradation and biodiversity loss (SDG 15). Drones and satellite monitoring were some of the enablers suggested to achieve this goal.

Although some of SDGs could not be directly related to existing geophysical uses, the authors identified many areas for collaboration and expansion to support each specific goal. For SDG 4, 'Quality Education', for example, there are opportunities such as ensuring knowledge transfer between industrialised and developing nations and in highlighting geophysics as a science with a broad range of applications and career paths. Within the oil and gas industry there are often specific opportunities to encourage the training, support and recruitment of local geophysicists.

Three important uses of geophysics for each SDG were identified. SDG 13, 'Climate Action', for instance, was summarised by 'reduce emissions, transition to clean energy and improve climate mitigation', while the most import tasks for SDG 12, 'Responsible Consumption and Production', were condensed into the need to reduce industrial contamination, enhance community mindset and monitor landfills. Finally, these uses of geophysics for each SDG were identified in a simplified infographic (the geophysical sustainability wheel), which the authors hope will be used to help 'spread the word'.


GWB Myanmar Water project team

Training of trainers field training group in Mon State, Myanmar.

Future and Present Geophysicists

The profession of geophysics is changing, with many opportunities for successful careers emerging not just in traditional extractive industries but also in the spheres of water resources, engineering and renewable energy, among others. The new generation of potential geophysicists will want to know how their science can contribute towards sustainability, so this project is an important step towards encouraging them towards the discipline.

At first glance it would be easy to conclude that most of the opportunities for promoting the UN SDGs through geophysics will fall on companies, professional organisations and the academic community. While they definitely have an important role to play, the Geophysical Sustainability Atlas is also designed to motivate and inspire current geophysicists, since many of the initiatives to support the SDGs can be undertaken at the individual level. Communicating the challenges and excitement of your science in easy language is something we can all engage in, and by understanding the scope for sustainability and humanitarian goals we can help promote them.

** https://library.seg.org/doi/10.1190/tle40010010.1*

Photos courtesy of Geoscientists Without Borders® ■

Masters students from the University d'Abomey-Calavi, Benin, acquiring DC resistivity data on a professional instrument.


Dana Sirota

Mature Fields: Easing into Retirement or a Second Career?

How can fields extend their productive lives and are there opportunities to repurpose our fields, our facilities and ourselves?

DOUGLAS PEACOCK, GaffneyCline

Many basins throughout the world, including those in Asia-Pacific, are experiencing declines in hydrocarbon production with fields maturing and approaching abandonment. Growth in production is coming either from unconventional reservoirs or from relatively immature and emerging basins.

In Asia-Pacific, the scale and cost of offshore decommissioning is likely to involve hundreds of platforms, thousands of wells and tens of billions of dollars. Other mature basins such as the North Sea face similar challenges. Throughout the region, processes have been underway (in some cases for many years) to allocate, clarify, and properly fund abandonment obligations. Some jurisdictions have carried out wide-ranging consultation processes to gather stakeholder views. Others have strengthened regulations in successive licence contracts. Such clarity is essential to allow governments and operators to estimate the net revenues from oil and gas operations and the liabilities associated with decommissioning and abandonment.

Other regulatory developments have recognised the challenges of mature field economics and offered improved fiscal or contract terms to incentivise Improved Oil Recovery, Enhanced Oil Recovery, asset rejuvenation, or field redevelopment.

Keeping Productive

Oil and gas fields can have lives much longer than initially envisioned. Fields may be relinquished or proposed for abandonment when the operator's perspective does not allow the full potential of the field to be exploited. Organisational barriers, regulatory or commercial issues, capital or manpower allocation constraints, technology limitations, cost structures, and other factors may exist that, if resolved, can extend the productive life of a field or production area.

An excellent regional example is seen in Thailand, where the nation has been producing oil and gas at a Proved Reserves/Production (R/P) ratio of 10 years (or less) for the past 14 years, and an R/P ratio of 4 years (or less) for the past 5 years (source: BP Statistical Review of World Energy) – with only small new field developments coming on stream in that period. This means that every year Operators are finding or maturing new volumes from existing fields to extend field life.

Several classes of activity can be considered to extend field life while maintaining safe and profitable operations. These include cost management, incremental production, operational improvements and fiscal and commercial improvements.

Cost Management

A detailed understanding of operating costs, and where and why they are incurred in a production system, allows uneconomic elements of the production system to be abandoned, improving the economics of the remaining system. This can take place at the well level (high-water-cut wells) or the satellite-production-system level by consolidating production streams into a single processing facility. The overall objective is to reduce costs by ceasing uneconomic activities. This approach also may require decommissioning activities to be carried out to remove redundant infrastructure (e.g., wellhead platforms) where the continued existence of these facilities would incur costs to maintain a minimum level of structural integrity and safety. The unit costs of essential activities or services can be reduced by contract renegotiation; furthermore, alternative and lower-cost approaches to deliver the same production service may exist.

Cost-reduction opportunities also may be found in rethinking contract strategy and moving activities from in-house to contracting out (or vice versa) to take advantage of lower-cost structures for shared services. Similarly, contracting strategies can be used to move costs from capital expenditure to operating expense (or vice versa) through equipment leasing or sale and leaseback, where such steps offer fiscal or cost advantages.

An operator of mature fields often will start with a detailed review of all available field subsurface and operational data to identify ways of generating early cash flow to finance further development. A range of incremental production opportunities can be generated and ranked for implementation, including surface facilities debottlenecking, review of existing wells to identify behind-pipe opportunities and development of new infill wells that take advantage of new technologies to exploit by-passed pay, attic, field-flank, or tight zones previously considered unproducible.

These incremental volumes can extend economic life, allowing a previously sub-economic 'tail' of the legacy field to be economically produced.

Figure 1 shows an example from a field which has been through three distinct life stages. The field was initially operated by an IOC under a Production Sharing Contract. The National Oil Company then took over, maintained production but with minimal investment. Later, an alliance with a service company resulted in a detailed study, significant investment and increased production.

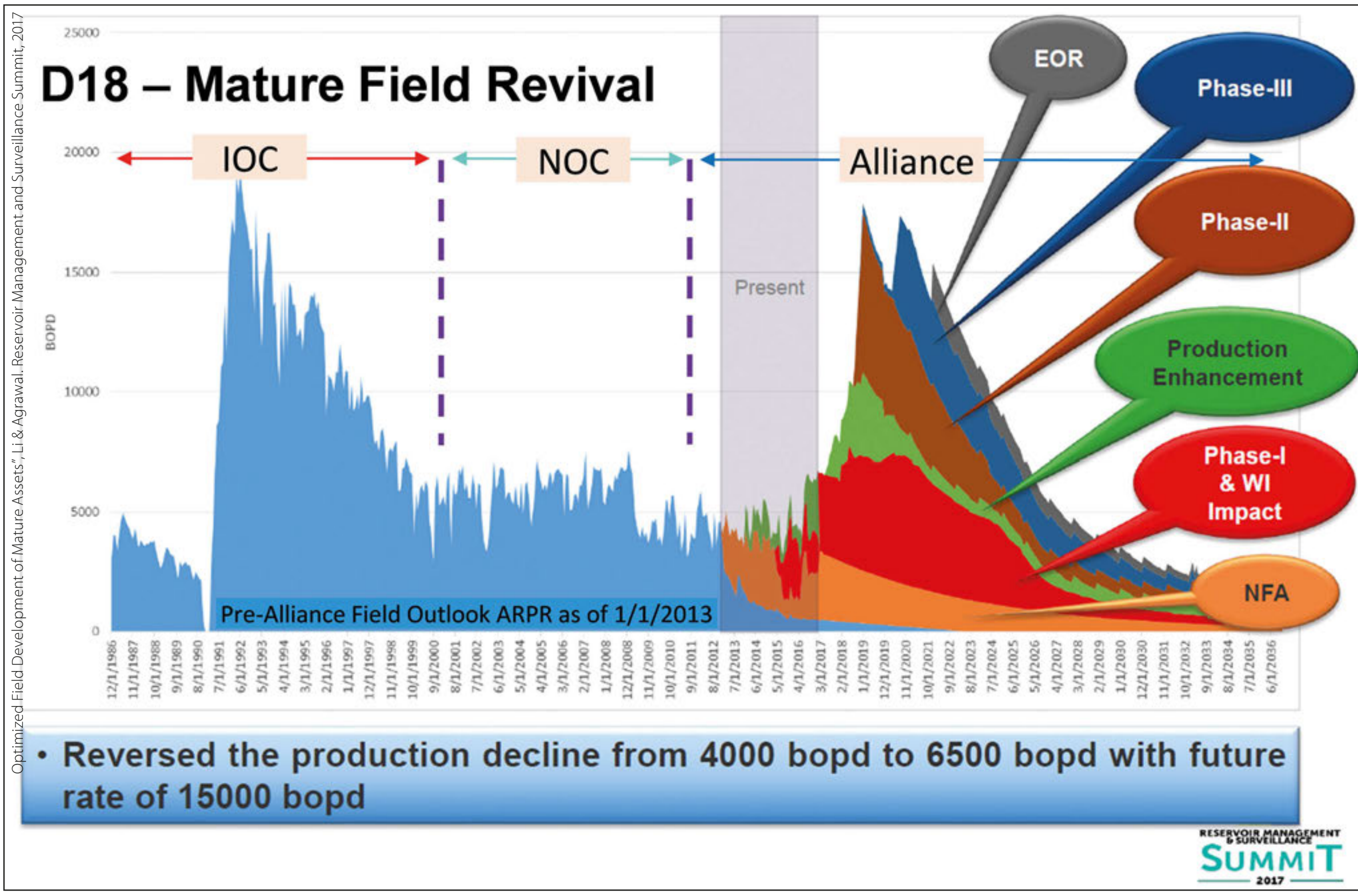


Figure 1: Oil field example with three life stages.

Fields like this will inevitably decline if neglected and treated as 'cash cows'. It may be necessary to invest time and money to achieve production improvements and extensions to field life. Many mature fields are just waiting for such attention.

Operational and Commercial Improvements

Field economic performance may be improved and extended by attention to operations. Additional gas sales can be achieved through constrained facilities by attention to planned and unplanned downtime. Attention to metering accuracy, and sometimes to system-reallocation algorithms, may offer marginal improvements in metered (and sold) volumes at minimal or no cost. Delaying field shutdown and abandonment by renegotiating commercial or fiscal terms may be in the best interests of off-takers (e.g., gas buyers) and host governments.

Gas prices, netted back to the producer, can be improved by addressing gas price, indexing terms, delivery specifications, embedded transport costs, capacity charges, or swing factors. Value may exist in a gas stream from its potential to mix away other below specification gas. Attention to the calibration of fiscal and calorific value meters can offer small but worthwhile improvements.

Oil prices generally are linked to a regional reference crude and, therefore, to Brent; however, the producer can improve net price by addressing the transport and quality offsets that are applied to the benchmark price. Attention to oil marketing and meeting with a range of buyers and traders can help a producer materially improve net prices.

Government take, over and above the rates of general corporate taxation, also may be negotiable where the alternative is field abandonment.

Reserves Extensions

Assessment and management of Reserves in mature fields is a key aspect of late life field planning. The economic limit is defined within the Petroleum Resources Management System (PRMS) as the time when the maximum cumulative net cash flow occurs for a project. The entity's entitlement production share, and thus net entitlement resources, includes those produced quantities up to the earliest truncation occurrence of technical, licence, or economic limit. The economic limit is an undiscounted operating net-cash-flow calculation, the inputs of which are production and cost profiles together with relevant fiscal terms.

The PRMS allows for interim periods of negative cash flow to be accommodated. This allows for periods of development capital spending, low product prices, or major operational problems, provided that the longer-term cumulative cash flow becomes positive and that the negative cash flow is more than offset by the positive. There may be situations where production is continued beyond the economic limit e.g., delaying abandonment expenditure, keeping shared facilities running, strategic reasons; however, any such sub-economic production cannot be classified as Reserves under PRMS.

Figure 2 shows field extension from two activities. The field is declining and the No Further Activity (NFA) case shows the field reaching its economic limit in Year 5. However, the Operator commits additional Capex in Year 5 (A) to increase production, perhaps through infill drilling, resulting in an extension of the economic field life until Year 10. In Year 10, an Opex reduction programme (B) improves cash flow (but not production) and results in another extension of economic limit until Year 15. The field finally reaches its economic limit in Year 15 (C), but production continues beyond that with negative cash flow until the field is abandoned in Year 21. The production associated with this period cannot be classified as Reserves, even though there may be good reasons to continue production as noted earlier.

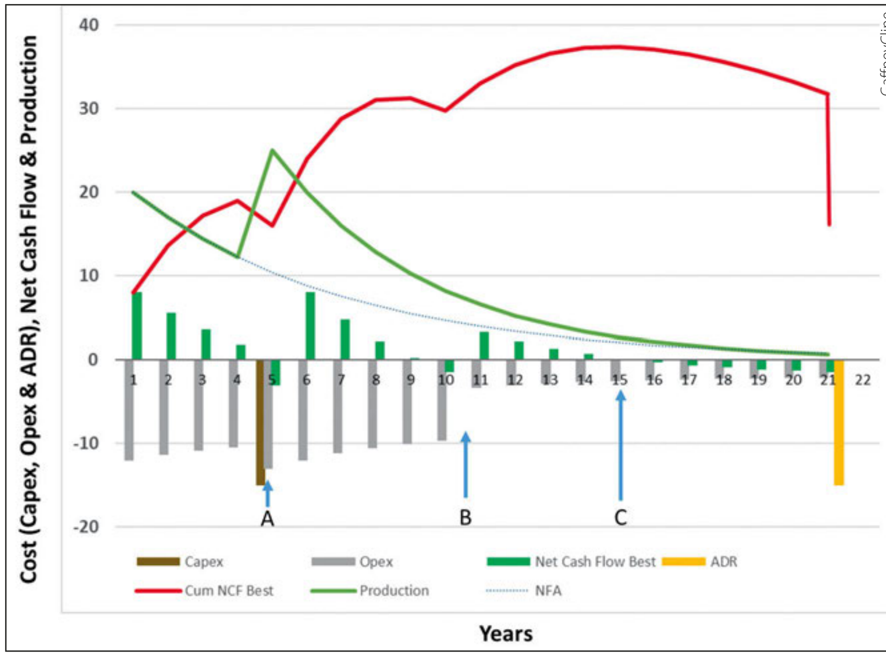
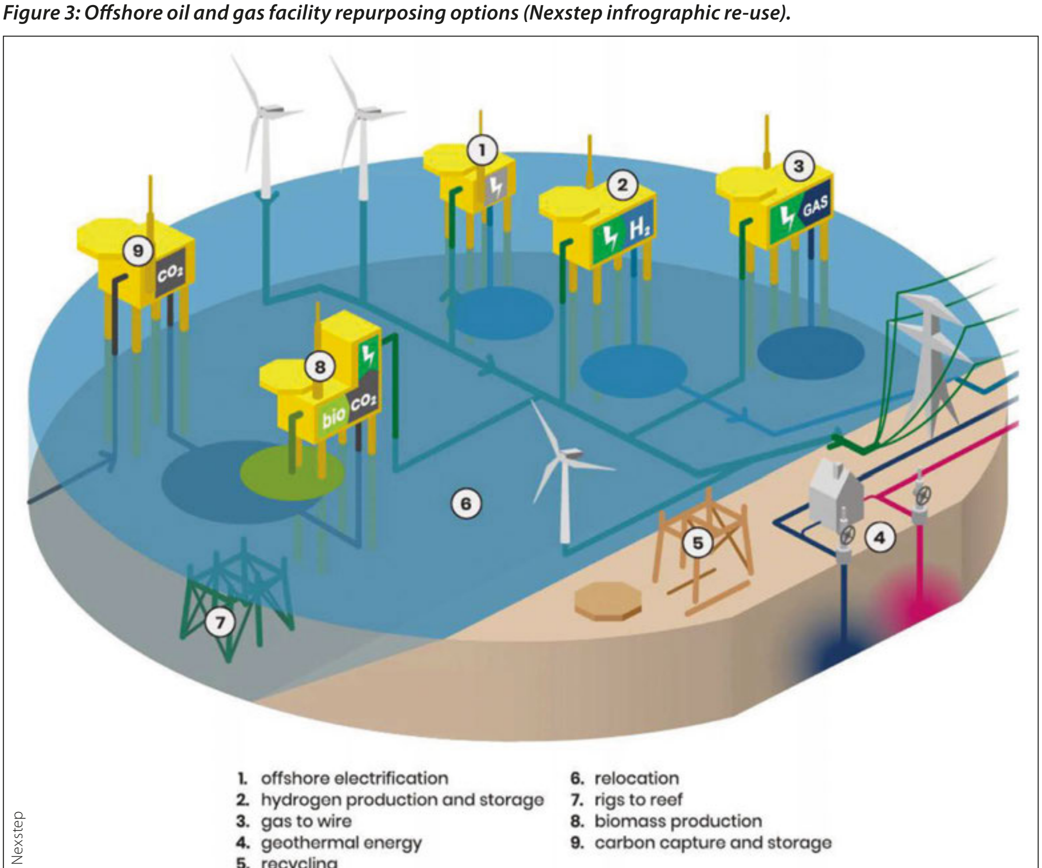


Figure 2: Example of field extension activities.

A recent study on a field cluster in South East Asia evaluated combining several of the elements described above. Elements evaluated included: IOC exit from block and Operatorship taken over by small independent with lower cost structure, reduction in Opex, additional development (which did not meet investment hurdles under previous Operator), operational and fiscal improvements. As a result, there was potential to extend economic field life by 10–15 years with a large increase in asset value.

Other options available include reducing carbon intensity of oil and gas production. In South East Asia, gas flaring is a major component of high carbon intensity in some fields. Projects which involve monetising gas can reduce carbon intensity and provide economic returns, especially as carbon pricing is expected to increase in coming years and decades.

Figure 3: Offshore oil and gas facility repurposing options (Nexstep infographic re-use).



Rebirth or a Second Career?

Depleted hydrocarbon reservoirs can be used as sites for carbon capture and storage. Deep saline aquifers nearby existing fields and facilities can also be used as potential carbon capture sites. Old facilities can have a wide range of potential uses. Suggestions include transition of offshore platforms into aquafarming hubs or recreational use such as offshore hotels and diving resorts; such reutilised platforms already exist in South East Asia. Nexstep, a joint venture between the Dutch state and the oil and gas industry, envisions various potential repurposing options including: transformer locations for wind farms, power to gas and other renewable or geothermal energy activities. Some examples are shown in Figure 3.

Oil industry professionals, from geologists with subsurface knowledge to facilities engineers with offshore construction and operations experience, will be an important part of the transition. Who understands the storage capacity, surface risks and potential for CO_2 leakage better than subsurface professionals who assess and develop oil and gas fields?

Subsurface technical assessments, such as those that assess seal capacity and hydrocarbon trapping mechanisms are useful for exploration and production, but can also be vital for carbon capture. Geological Society Memoir 52 records not only the extraordinary 50+ year journey that led to development of oil and gas fields, but is also useful for potential CO_2 sequestration projects.

These opportunities also come with several challenges. Regulatory issues related to decommissioning are already a concern in many parts of the world, including South East Asia. Providing a regulatory pathway to re-use of facilities is an additional challenge.

Timing may also be a key concern. With a large wave of decommissioning expected, providing a regulatory framework, technical capability and economic incentives may come too late to be of use for many fields and facilities. Lessons can likely be learned from basins such as the North Sea and the US Gulf of Mexico which may be more mature in the life cycle.

Prolonging economic field life until an appropriate second life can be identified may be an ideal solution to multiple problems.

The Last Economic Barrel

Imagine the conditions under which the 'last economic barrel' would be produced from a field – for maximum benefit to both the host government and to the licence holder. That barrel (or gas boe) would be produced when the marginal cost of production equals sales revenue, with no excess government take (beyond normal corporate tax), and all production services are provided by 100% local businesses. At cessation of production, a properly funded general arbitration provision is available to cover decommissioning and restoration.

Managing mature oil and gas fields is both a challenge and an opportunity. The challenge is how to manage transition to that last economic barrel, while maintaining equitable returns to business and society throughout the field life cycle.

There are a range of approaches and technologies available to extend economic operations, and a new group of operators and commercial structures emerging to implement these. The challenge to host governments and to the existing Operators is to carefully manage the fiscal, regulatory, and commercial framework of field management to allow these activities to take place, while assuring responsible field decommissioning.

Opportunities for repurposing, and a second life, should be investigated and screened. The last barrel may not be the end, but a chance of a new beginning. ■

From Arrhenius to CO_2 Storage

Part XI: How Earth's IR Photons are Transferred in the Atmosphere in the Presence of CO_2

LASSE AMUNDSEN* and MARTIN LANDRØ, Bivrost Geo/NTNU

Skydive with us into the quantum world and find out how Earth's IR radiation is transferred in a plane-parallel troposphere in the presence of CO_2 molecules.

"At quite uncertain times and places,
The atoms left their heavenly path,
And by fortuitous embraces,
Engendered all that being hath.
And though they seem to cling together,
And form 'associations' here,
Yet, soon or late, they burst their tether,
And through the depths of space career."

James Clerk Maxwell (1831–1879), From 'Molecular Evolution', *Nature*, 8, 1873.

Figure 1: "Boy in Thought", a granite sculpture sitting under the Northern Lights in Tranøy, Hamarøy (Norway) is well aware how the green lights are created 100–250 km above him. Charged particles from the solar wind first bump into diatomic nitrogen, ionising N_2 into N_2^+, making N_2 lose an electron. This electron bumps into and excites a nearby oxygen atom. To de-excite, the oxygen atom emits a photon of visible light with wavelength of about 550 nm. Our eyes and cameras interpret this colour as lime green.

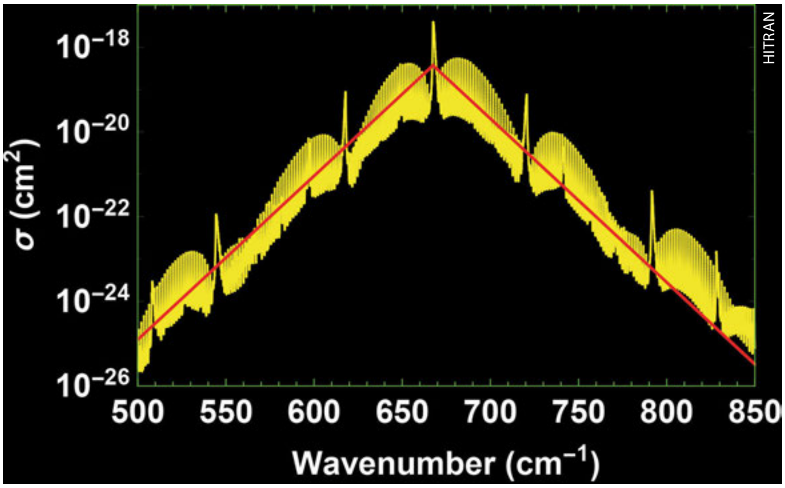


Figure 2: Absorption cross-section, in cm², for a CO_2 molecule as a function of wavenumber from the HITRAN database (http://hitran.iao.ru/home.overview), shown at 1 atm and 285K; note the logarithmic scale. The red line shows an approximation to the cross-section, used in calculations. Although the unit is given as an area, it does not refer to an actual size, because the density of the CO_2 molecule will affect the probability of absorption. For further detail see the HITRAN database (http://hitran.iao.ru/home.overview).

The absorption spectra of greenhouse gases and the physics of radiative transfer in the Earth's atmosphere are a key to understanding changing climate. For Earth's greenhouse effect, the CO_2 molecule's absorption of radiation (photons) close to 667 cm^{-1} (15 μm) is of particular interest since those wavenumbers are near the peak radiation wavelength for Earth's temperature and thus important for terrestrial radiative transfer in the atmosphere. If infrared (IR) absorption took place *only* at 667 cm^{-1} it would have negligible climatic effect. But collisions between CO_2 molecules and other molecules remove or add energy during radiative transitions and this process, called pressure or collisional broadening, allows absorption and emission to take place over a broader range of photon energies. Therefore, pressure broadening is a key source of IR opacity in the troposphere.

In fact, the CO_2 absorption spectrum shows thousands of separate lines between 500 and 850 cm^{-1} (Figure 2). The CO_2 absorption cross-section denoted by σ is a measure for the probability of absorption, or the ability of a CO_2 molecule to absorb a photon of a particular wavenumber. The density or number n of absorbing CO_2 molecules per unit volume must also affect the probability of absorption.

Absorption Coefficient

The absorption coefficient is the product of CO_2 density and CO_2 cross-section, $\alpha_\nu = n\sigma_\nu$. A simple way to calculate α_ν follows. The yellow line in the absorption cross-section (Figure 2) seen by the IR photon can be simplified by the red line given by $\sigma_\nu = \sigma_0 \exp(-r|\nu-\nu_0|)$, where $\sigma_0 = 3.71{\cdot}10^{-19}$ cm^2, $r = 0.089$ cm and $\nu_0 = 667.5$ cm^{-1}, close to an approximation suggested by Wilson and Gea-Banacloche (2012). We assume the absorption spectrum is independent of height. This is an approximation, since the broadening and the strength of the spectral lines depend on both pressure and temperature.

We also need a formula for how n changes with altitude; we use the 'exponential atmosphere' $n(z) = n_0 \exp(-z/L)$ with 'scale height' of $L = RT_0/mg \approx 8{,}000$m. Here $R = 8.31447$ J/(mol K) is ideal gas constant, $m = 0.0289654$ kg/mol is the molar mass of dry air and $g = 9.80665$ m/s² is Earth-surface gravitational acceleration. We have used the temperature $T_0 = 273$K. The exponential atmosphere takes the simplifying assumption that T is constant with altitude (T varies by only 20% below 80 km so this is acceptable). For every rise in altitude L, the air density and pressure drop by a factor e = 2.7; thus, L provides a convenient measure of atmospheric thickness.

CO_2 is heavier than air, but is well-mixed throughout the atmosphere, so that its density can be taken to decay with the same characteristic constant as air itself, $2.5470{\cdot}10^{19}$ molecules/cm³. Then, n_0 is the number density of CO_2 molecules near the surface of the Earth. When the concentration is given in ppm as $[C]$, it becomes $n(z = 0) = n_0 = 2.5470[C]{\cdot}10^{13}$ molecules/cm³.

Transfer for Spectral Radiance

We now have an approximation for the absorption coefficient in the troposphere due to the presence of CO_2. To find how Earth's IR radiation is transferred upwards (ignoring convection), we need an equation of transfer which recognises an atmosphere that is simultaneously absorbing *and* emitting. We invoke the plane-parallel approximation, where pressure, temperature and composition are assumed to be functions of height only. Suppose that, between z and $z + dz$, the absorption coefficient is α_ν at wavenumber ν. The emission coefficient is equal to the absorption coefficient as a result of Kirchhoff's law (see *GEO ExPro* Vol. 17, No. 1, 2020). In this interval, suppose that the spectral radiance, often called intensity, increases from I_ν to $I_\nu + dI_\nu$ along a path s at an angle θ to the vertical; geometry gives $ds = dz/\mu$; $\mu = \cos\theta$ (Figure 3). The radiance on its way upwards (+) will be reduced by absorption and increased by emission described by a source function J_ν. Thus, it has the differential form:

$$dI_\nu^+ = -\alpha_\nu (I_\nu^+ - J_\nu) d(z/\mu) \quad (1a)$$

Losses and gains in intensity must obey the second law of thermodynamics: for any term that introduces a loss there must be a term that introduces a gain. The formal solution to this equation for radiative transfer in the upward direction is:

$$I_\nu^+(Z) = I_\nu^+(0) Q_\nu(Z,0) + \mu^{-1} \int_0^Z dz\, \alpha_\nu(z) J_\nu(z) Q_\nu(Z,z) \quad (1b)$$

where $I_\nu^+(0)$, being a boundary condition, is the upwards radiation rate at the surface of the Earth, which we take to be equal to Earth's blackbody radiation:

$$I_\nu^+(0) = B_\nu(T(0))$$

with $T(0)$ = 288K, the average surface temperature. Further, Q_v is the function which transfers intensity upwards from height z to height Z where we imagine an observer is looking down on our planet:

$$Q_v(Z, z) = \exp(-\mu^{-1} f(Z, z))$$

where:

$$f(Z,z) = \int_z^Z dz' \, \alpha_\nu(z') = \sigma_\nu n_0 L(\exp(-z/L) - \exp(-Z/L))$$

The physics of the source function is crucial for radiative transfer. We assume that the atmosphere is in local thermodynamic equilibrium. The emission of energy from a volume element can then be specified in terms of the Planck spectral energy distribution and the radiative absorption coefficient, regardless of the spectrum of the flux passing through the element. Thus, the source function acts according to Planck's radiation formula:

$$J_\nu(z) = B_\nu\big(T(z)\big) = 2hc^2\nu^3 \left(\exp\left(\frac{hc\nu}{kT(z)}\right) - 1\right)^{-1}$$

which tells the power radiated per unit area, per unit solid angle of emission, per unit wavenumber by the surface of a blackbody at temperature T. To proceed with the source function, we need to specify how the average equilibrium temperature changes with height, taking as a guide the 'International Standard Atmosphere', which has a temperature lapse rate of 6.49 K/km from sea level to 11 km (the tropopause) so that $T(z) = T(0)$-6.49K·z/1,000m.

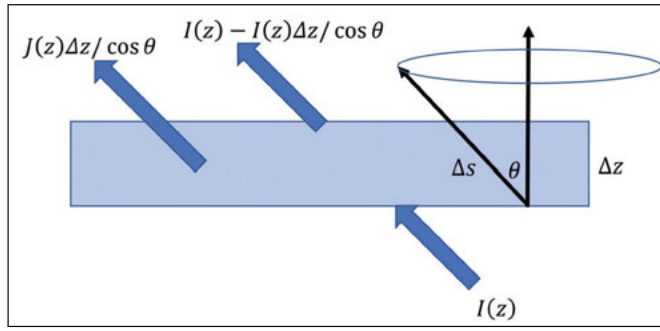


***Figure 3:** Sketch of the radiative energy balance for a slab of atmosphere illuminated by incident radiation from below. When the beam is inclined at zenith angle θ (from the vertical), the elemental path along the beam is related to that along the vertical path Δz by geometry as cos θ = Δz/Δs HITRAN.*

The first term of the solution in equation (1b) is simply the exponential attenuation of the emission from height 0 to Z. The second term is the sum of the emissions from each level z along the path from 0 to Z, each emission exponentially attenuated by the path length from z to the observer at Z.

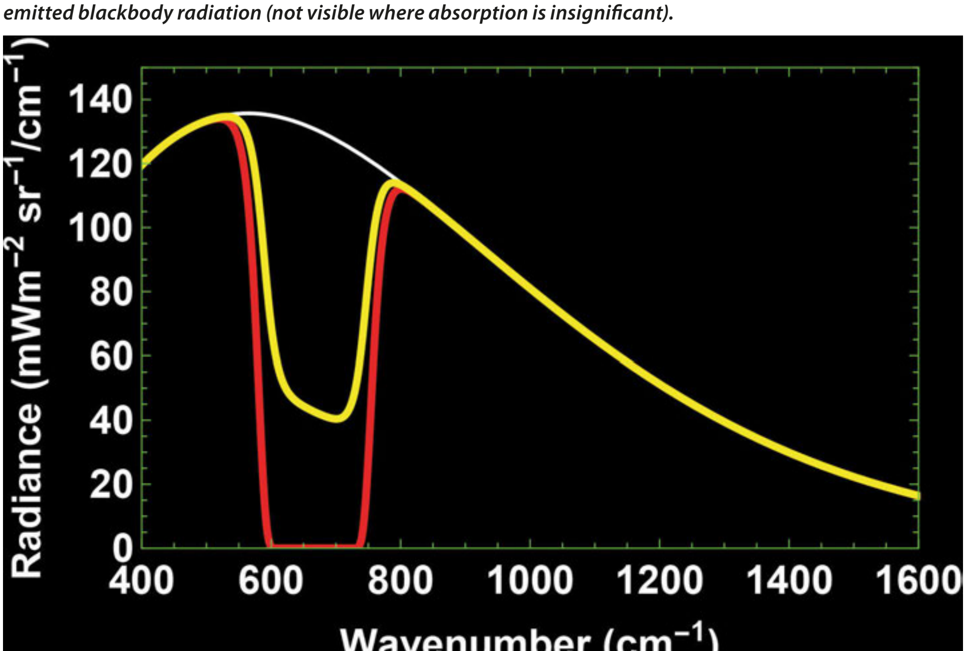
Upwards Transfer with Absorption

Let's investigate the first term of the solution, $I_v^+(Z) = I_v^+(0) \, Q_v(Z,0)$, which transfers Earth's blackbody radiation to height Z without including the effect of emission. Let μ = 1. Of course, keeping only the first term is unphysical; if the Earth were allowed to continuously send IR energy upwards into the atmosphere without any emission from the atmosphere, CO_2 photon absorption would make the air get increasingly hot. But this kind of analysis provides some learnings.

In the exponential atmosphere where its composition is assumed to be function of height only, the transfer function becomes $Q_v(Z,0) \approx \exp(-Z/l_v)$, where the approximation holds when $Z << L$. In physics, l_v is the absorption or attenuation length, being the distance l_v into the atmosphere when the probability that the photon has *not* been absorbed has dropped to 1/e≈1/3: l_v is also called the mean free path because it equals the mean distance travelled by a photon before being stopped. Mathematically, $I_v^+(0) \, Q_v(Z,0)$ is the probability of finding the photon at height Z into the atmosphere.

To explore this equation's implications, suppose a photon close to the centre of the absorption band, between 650–690 cm^{-1}, is emitted upwards at the surface of the Earth. The CO_2 concentration is assumed to be [C] = 400 ppm. How high will it travel before it is absorbed? The

***Figure 4:** The transmitted spectral radiance from Earth's surface through the troposphere with presence of CO_2 for the model in this article, with scale height L = 8 km, to top of troposphere at height 11 km. Red line: transmission upwards with absorption only, which is impossible, since the atmosphere would overheat. Yellow line: transmission upwards with absorption and emission, which allows Earth to cool due to upward travelling emission, but at the same time heat due to downward travelling emission. White line: Earth's emitted blackbody radiation (not visible where absorption is insignificant).*



absorption length is $l_0 = 1/n_0\sigma_0$ = 2.65m – not very far at all! In fact, the bottom of the troposphere might be seen as an impenetrable wall of CO_2.

Clearly, the probability of absorption is different for IR radiation at wavenumbers towards the edges of the band, below 580 or above 760 cm^{-1}, where σ is much lower, so the mean free path is 100s of metres to a kilometre. These photons make their way to a substantial height. The density of CO_2 reduces at higher altitudes, thereby increasing the probability of them travelling even higher before absorption. Radiation at these wavenumbers is most sensitive to changes in the atmospheric CO_2 level. An increased CO_2 concentration yields a reduced absorption length.

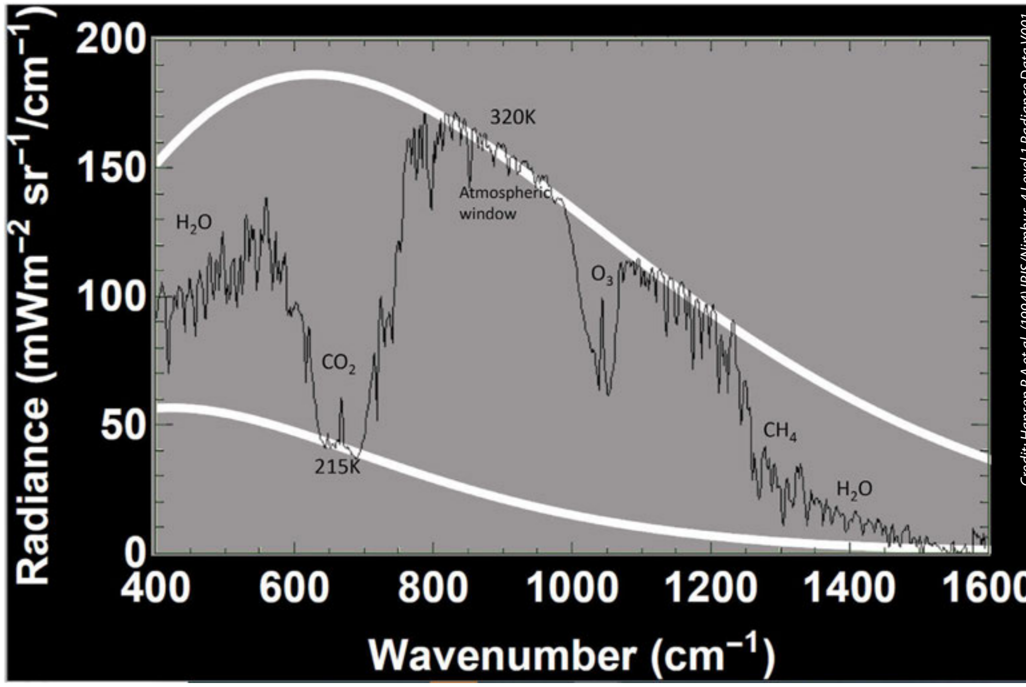


Figure 5: Thermal emission spectrum of the Earth's atmosphere and surface from 400–1,600 cm^{-1} recorded over a hot Sahara on 5 May 1970 by infrared interferometer spectrometer IRIS-D on Nimbus 4. Calculated blackbody curves for temperature 320K and 215K are superimposed. The greenhouse effect of CO_2 is visually manifest by the bite taken out of the IR spectrum near 667 cm^{-1}. This feature agrees nicely with the numerical calculations based on the equation of radiative transfer. The maximum temperature measured in the atmospheric windows between 850 and 950 cm^{-1} indicates surface temperatures around 320K. If residual atmospheric absorption is ignored, this temperature refers to the top layer of exposed soil or vegetation.

Transfer with Absorption and Emission

This discussion disregarded much of the real physics of the transfer solution: to avoid being continuously heated, the atmosphere must emit radiation, as taken into account by the second term of the solution. The term is a 'source term' for generating photons, which acts continuously at every height above Earth. Every upward-going radiation at some height Z (first term in equation (1)) according to Kirchhoff's law will be the source for new radiation with local emissivity equal to local absorptivity, half of which will radiate downwards. The rest will go upwards, and this effect is included in the source term in the radiative transfer equation (1).

The complex form of Planck's formula does not allow a straightforward analytical solution of the transfer solution, but we can calculate the integral over height numerically for every wavenumber to the altitude of top of troposphere (TOT) at 11 km. Doing so for $\theta = 0$, we find the intensity curve shown in yellow in Figure 4. If we disregard emission and only include absorption, we get the intensity curve display in red.

In an atmosphere with emission equal to absorption for every wavenumber, the model shows that parts of Earth's blackbody radiation in the presence of atmospheric CO_2 is allowed to escape to the TOT, thereby carrying thermal energy away from Earth and cooling it. However, what does not go up will have to go down to Earth, to be absorbed by the surface and converted to heat, followed by blackbody IR photon emission in accordance with an adjusted thermodynamic equilibrium.

Over the long term, for the Earth-atmosphere system to be in equilibrium, top of atmosphere emission must match the solar incoming radiation. In this article, we have analysed the one-way differential equation for radiative transfer upwards. There is, of course, also a one-way differential equation for radiative transfer of IR radiation downwards, which has opposite signs to the equation we have worked on.

Terrestrial Radiation Spectrum

Satellite measurements show the real spectrum above Earth. An example (Figure 5) is the radiation spectrum measured from a satellite over the Sahara in 1990. This spectrum is a combination of blackbody spectra for temperatures ranging from 220 to 320K for the day of measurement. The bottom of the dips in the curve indicate the effective temperature of the emission where photons are emitted not from the surface but a cooler atmospheric height. The bottom of the CO_2 band at 667 cm^{-1} emits at about the tropopause temperature of 215K. The spectrum over the IR atmospheric window has the appearance of a blackbody curve at around 320K surface temperature. In this window there is relatively little absorption of terrestrial thermal radiation by atmospheric gases.

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

Unlocking Potential in South East Asia

Geological fieldwork is important to help us gain a better understanding of the development and potential productivity of the offshore Natuna basins of the South China Sea.

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Conducting geological fieldwork in South East Asia can be challenging for multiple reasons, including often remote and difficult to access locations and tough conditions. Despite this, it can also be incredibly rewarding, providing a wealth of geological knowledge in an underexplored region. Fieldwork-based studies in South East Asia have already improved our understanding of the world's deepest forearc basin (Pownall et al., 2016), developed detailed tectonic reconstructions of the region (Hall, 2012), and even helped discover when and how fossil hominid species lived (e.g., *Homo floresiensis*; Sutikna et al., 2016). However, what makes continued fieldwork in South East Asia so exciting, and indeed very profitable both scientifically and in terms of hydrocarbon exploration, is that there is still so much left for geologists to discover.

The Link Between Onshore and Offshore

Just as Charles Lyell famously said "the present is the key to the past", it could be said that the onshore geology of a basin holds the key to sediments deposited offshore. Nowhere is this truer than in South East Asia, where the links between onshore and offshore geology can be observed in present day systems as well as in the geological record.

South East Asia has been one of the most tectonically active parts of the world for about the last 40 million years, with consistent high sediment yields leading to deposition of thick successions that form productive hydrocarbon plays throughout the abundant basins of the region. One such example is the Salin sub-basin in Myanmar, with over 18 km of sediment deposited throughout the Cenozoic (Hall and Morley, 2004). The relatively recent formation of these basins means that both the source region lithologies and tectonic regimes that deposited sediment into them can still be observed in adjacent onshore areas.

Recent studies focussed on characterising the geology of Myanmar and its potential for sourcing the Nicobar Fan and other regional basins (Gough et al., 2020; Webb et al., 2021), have shown the complex link between onshore source regions and the offshore subsurface. They have also demonstrated the importance of a fieldwork-based understanding of basin bounding highs for the reconstruction of both sedimentary pathways and basin evolution, especially in South East Asia. Few places in this region exemplify this intrinsic link between the onshore and offshore realms more than the small Indonesian tropical island of Natuna, off the north-west coast of Borneo, where the links between sediment source, depositional environment, and tectonic evolution of surrounding basins can be studied in outcrop all within a few miles of each other.

Natuna Island: Complete Source to Sink Package

As you fly into the island's capital, Ranai, you can see long stretches of white sand beaches fringing a dramatic central peak, surrounded by turquoise seas hosting a series of actively producing hydrocarbon basins. These features provide an early indication that Natuna Island is a perfect location to observe the links between onshore and offshore geology.

The island lies within the Indonesian Riau Archipelago in the South China Sea. It sits atop the Natuna Arch, a structural high

The Granitic basement of Natuna erodes away into white sand beaches.

East Natuna Field

The East Natuna Gas Field (previously known as Natuna D Alpha) is the largest undeveloped gas field in Southeast Asia. It was discovered in 1973 and is located in the Natuna sea, approximately 860 km northeast of Singapore and 1250km north of Jakarta.

Gas-in-place is estimated in excess of 220 Tcfg and with total proven reserves of approximately 46 Tcfg but with CO_2 content in excess of 60–70%. The reservoir is the Miocene Terumbu carbonate, sealed by the Pliocene Muda shale.

Should the East Natuna Field be developed, the scale of the resource will have a significant impact on Indonesia and the regional Asia Pacific gas market, either through LNG or piped gas exports. The commercial and technical challenges involved (attributed to the high CO_2 and H_2S content) make it unlikely however that the East Natuna Field can be brought onstream before 2030. Given the very significant volumes of CO_2, it is highly likely a CO_2 sequestration solution would be required in order to be able to exploit the field. ■

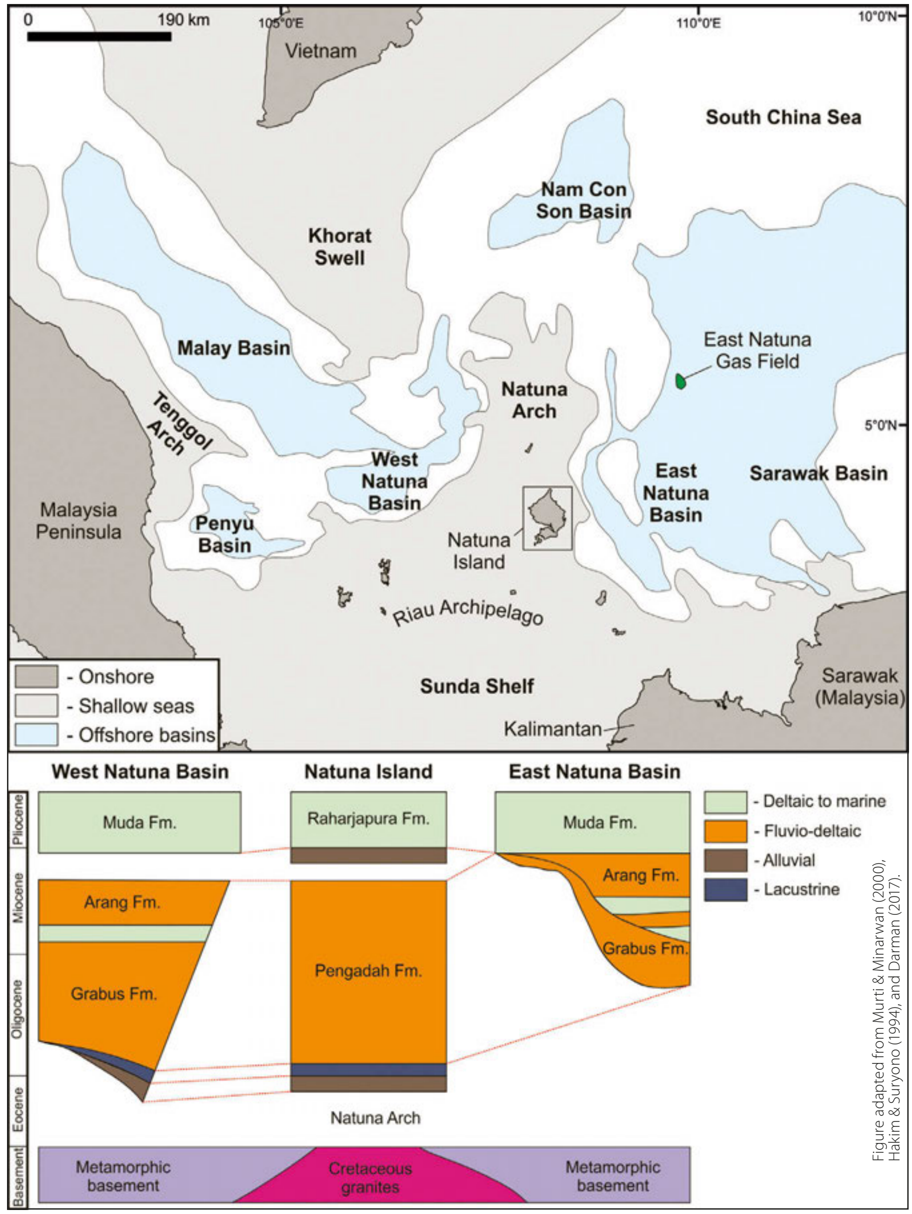
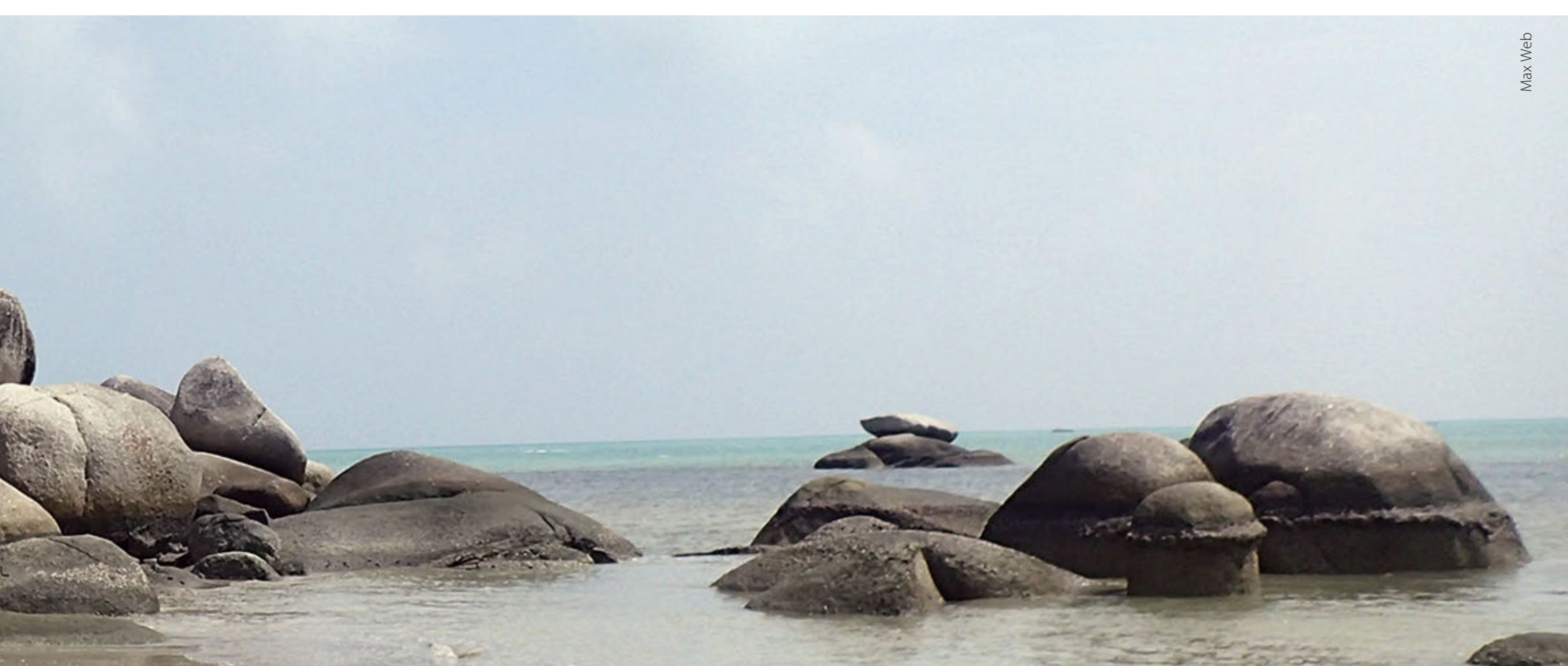


Figure adapted from Murti & Minarwan (2000), Hakim & Suryono (1994), and Darman (2017).

Map of the South China Sea and the Riau Archipelago showing Natuna Island, East Natuna field and the surrounding offshore basins shows correlation between the sedimentary rocks of Natuna and equivalent sequences in the West and East Natuna basins,=.



Max Web

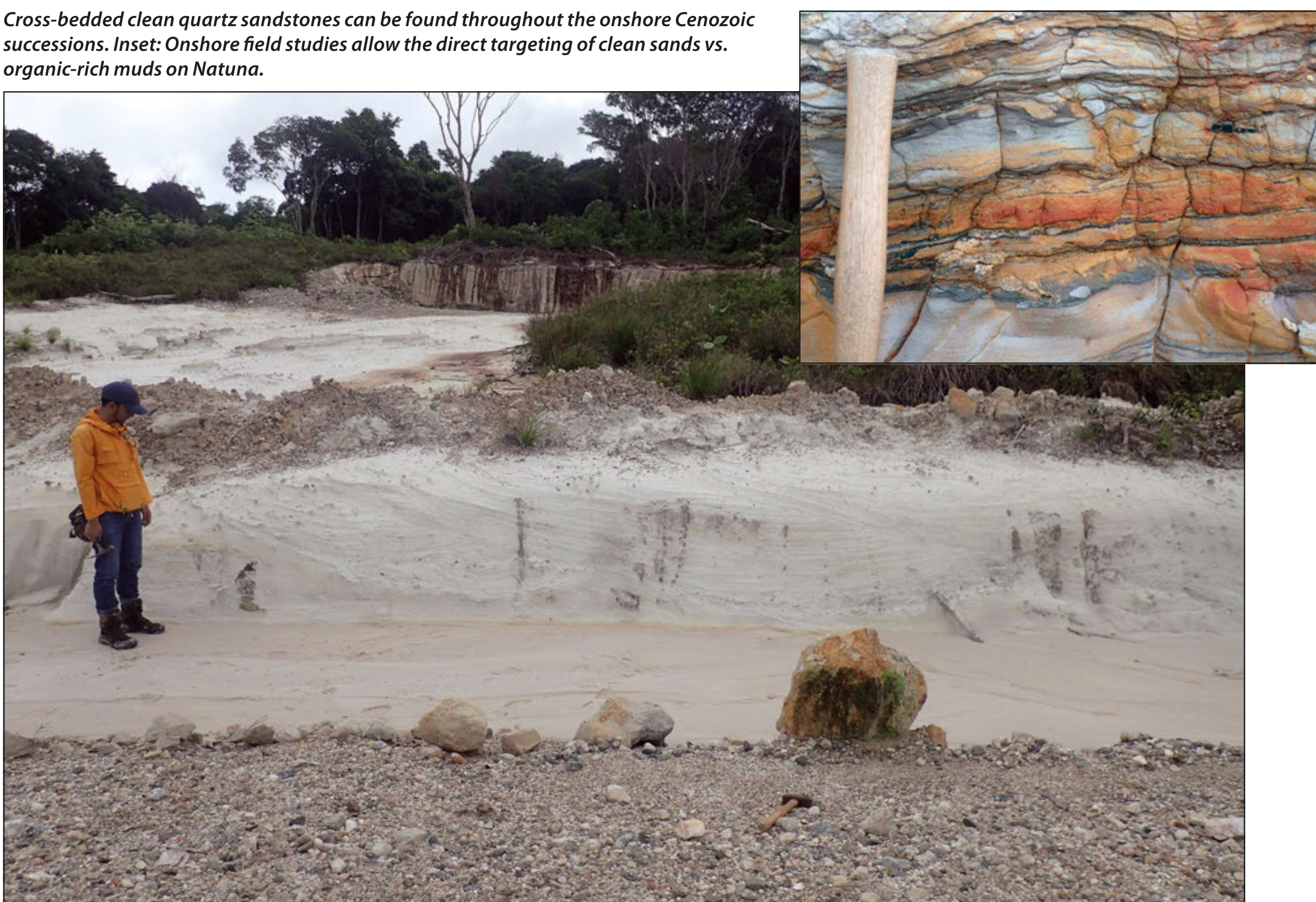
Fieldwork in South East Asia often involves boat travels through the tropical seas.

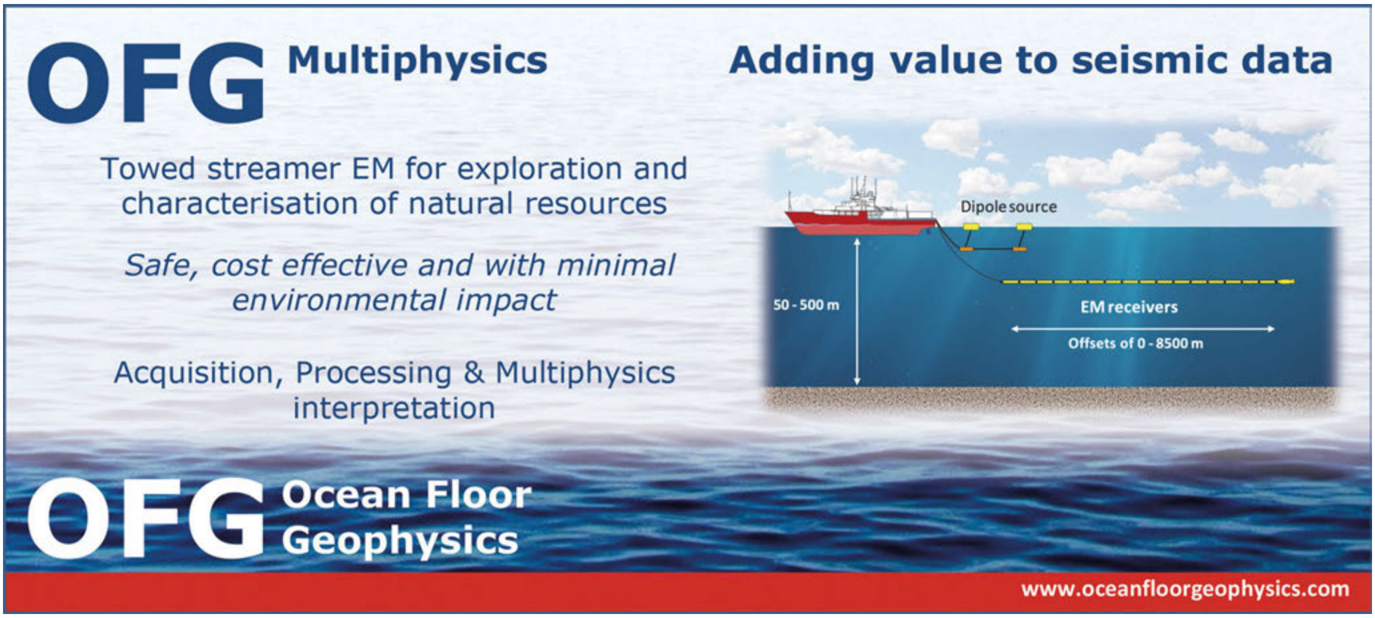
that straddles the East and West Natuna basins and represents a typical example of how we can use fieldwork campaigns to better understand subsurface geology. A recent South East Asia Research Group (SEARG) fieldtrip to the island, for instance, revealed a perfectly preserved source-to-sink package including an uplifted granitic basement shedding sediment into conglomeratic and clean quartz sandstones deposited in deltaic and beach environments throughout the Cenozoic.

Ranai Mountain (Gunung Ranai), the central granitic peak of the island, formed as part of an extensive subduction-related arc in the Cretaceous. Periodic uplift of this mountain and the Natuna Arch during basin inversion events since the Oligocene has led to the erosion of this granitic peak to create a series of quartz-dominated sandstones that now form the lowlands of the island, known as the Raharjapura and Pengadah Formations. These onshore sandstones correlate directly in both age and sedimentology with Oligocene to Pliocene successions in the West and East Natuna basins that flank the island, such as the Grabus, Arang, and Muda Formations (Darman, 2017).

The exposure of these sediments onshore with direct access to their source material at Ranai Mountain provides us with an unparalleled analogue for studying the hydrocarbon producing sequences in the subsurface. A detailed fieldwork-based understanding of the depositional environments, sedimentary provenance, and uplift history of this fascinating island would provide key insights into targeting the clean quartz sandstones shed off of the Natuna Arch and into the surrounding basins. Indeed, whilst both oil and gas are being actively produced from the West Natuna Basin (via the Grabus and Arang formations,

Cross-bedded clean quartz sandstones can be found throughout the onshore Cenozoic successions. Inset: Onshore field studies allow the direct targeting of clean sands vs. organic-rich muds on Natuna.





respectively) vast natural gas reservoirs of the underexplored East Natuna Basin are yet to begin production. These include the East Natuna Gas Field, which is one of the largest fields in SE Asia (see insert). With this in mind, can a better understanding of the onshore analogues exposed on Natuna Island, including records of both the sedimentology and structural history of the region, aid future production and exploration offshore?

The Future of Fieldwork

Natuna Island provides a snap-shot of the potential of comparatively cheap fieldwork studies for de-risking exploration throughout this region, especially in comparison to expensive seismic and drilling campaigns in frontier regions. As such, fieldwork remains a vital skill in the exploration of offshore basins where the onshore geology so faithfully mimics the rocks, structural styles, and depositional systems found at depth. Universities in the region, such as Institut Teknologi Bandung, among many others, are renowned for training excellent field geologists through immersive fieldwork programmes who will be leading the future of exploration in the region. Furthermore, as we shift into the global energy transition, fieldwork still has a vital role to play throughout the world. In South East Asia, the continued exploration of rare earth mining projects, for example along Vietnam's eastern coast and northern border, will assist the discovery of new rare earth element resources that will produce renewable energies. Fieldwork can also aid our understanding as to where these renewable projects can be best utilised, including, for example, in the placement of hydroelectric dams.

'Boots on the ground' geologists will always be vital to understanding this geologically complex but incredibly exciting part of the world.

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Natuna Island with the large granitic peaks of Gunung Ranai in the distance.

The Supercontinent Cycle: Patterns and Impacts

Plate tectonics comprises three inter-linked mega-cycles: the Rock cycle, the Wilson cycle (see *Geo Expro*, Vol. 17, No. 6, 2020), and the supercontinent cycle, which is explored here.

RASOUL SORKHABI, Ph.D.

The geography of continents and oceans has changed through geologic time. The supercontinent cycle describes the assembly, duration and fragmentation of the largest landmasses on Earth as a result of large-scale, long-term plate tectonic processes originating within the mantle and the crust. While its causes and patterns are little understood, the supercontinent cycle has first-order impacts on sea levels, climate, ecology, evolution, and mineral resources.

Continents and Oceans

There are, depending on how you count, five or seven continents and five to seven oceans in the world. For the geographer, continents and oceans are respectively the largest landmasses and water bodies in the world. For the geologist, they also represent different types of crustal rocks. Continents are mainly made of quartz-rich (typically granitic) rocks with a density of 2.7 g/cm^3. They include the emergent lands as well as adjacent continental shelves under water depths of 200 metres or so. Oceanic crust is mainly made of denser basalt (2.9 g/cm^3). That is why oceanic curst easily subducts beneath continental plates, while continental crust, once formed, may last for billions of years.

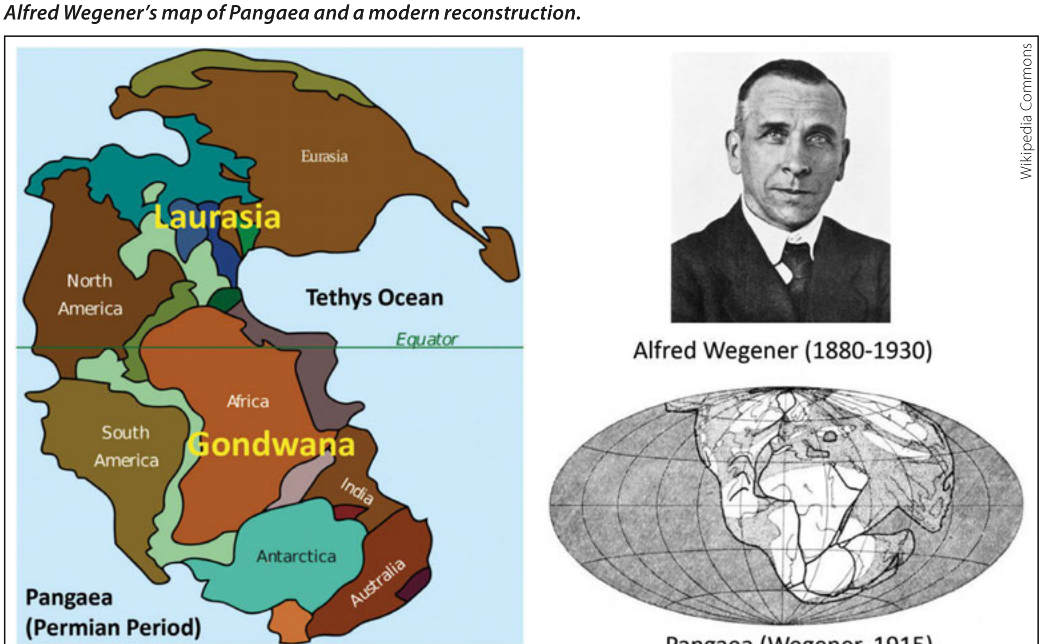
Continental margins are important not only for land–ocean interactions but also for mineral resources. In passive continental margins, both the continent and adjacent ocean are parts of the same tectonic plate, while in active continental margins, the ocean floor is a separate plate subducting beneath the continent, and producing a volcanic arc with active seismicity.

Suess, Wegener, and the Path to Pangaea

The jigsaw fit of coastlines on opposite sides of the Atlantic Ocean drew the attention of several scientists as far back as the 16th century. It appeared that South America and Africa were once together but were later torn away. In the 19th century, geologists believed that as the Earth cooled and shrank, the crust underwent collapse. Therefore, land bridges for example between South America and Africa sank and gave way to the South Atlantic Ocean. Based on this thinking ('contractionism') and using similarities in rock formations and fossils on continents currently far apart, the Austrian geologist Eduard Suess in his influential book *Das Antliz der Erde* (*Face of the Earth,* 1904) postulated the existence of at least three supercontinents in the geologic past: Gondwanaland (comprised of India, Africa, Australia, South America, and Antarctica, and named after the Gond tribes of central India), Laurentia (North America and Europe, and named after the Laurentian mountains in Canada), and Angaraland (East Siberia and parts of China, named after the Angara river). Nevertheless, Suess still believed that the present continents were always where they are now ('permanentism' or 'fixism').

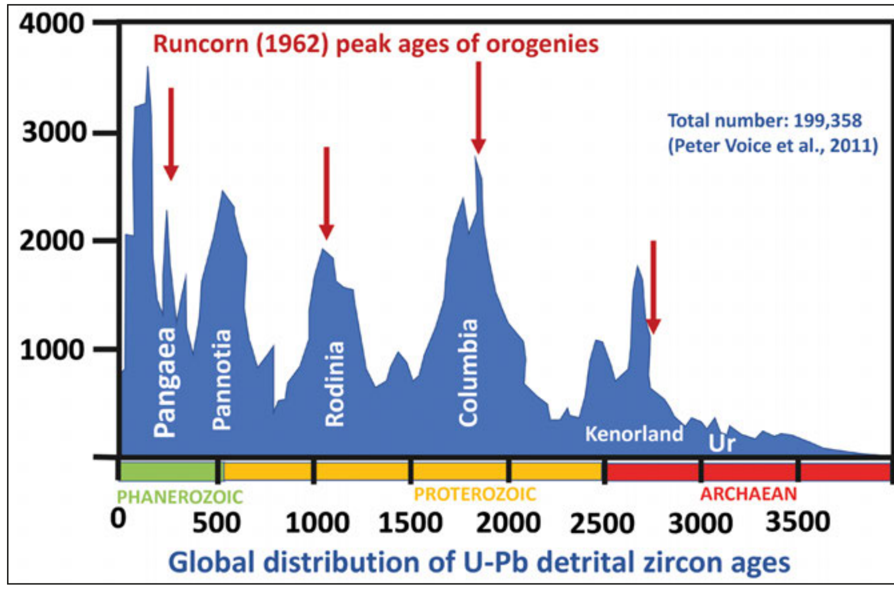
By the 1910s, three findings discredited both contractionism and permanentism. First was the discovery of radioactive elements in rocks, which implied the Earth's crust was actually heated by radioactive decay. Second was the principle of isostasy, suggesting that the Earth's crust was floating on a denser and mobile layer. Third was the observation that the oceanic crust was not made of continental rocks but of basalt. The German

Alfred Wegener's map of Pangaea and a modern reconstruction.



scientist Alfred Wegener embraced these findings and expanded on Suess's geologic comparisons of continents; but unlike Suess, he concluded that continents had drifted apart. He envisioned that during the Permian all the continents were united as a supercontinent he called Pangaea ('all earth') surrounded by the Panthalasa ('all ocean'). Pangaea consisted of Gondwana in the southern hemisphere and Laurasia (combined Laurentia and Angara) in the north. Wegener published his ideas in his 1915 book *Die Entstehung der Kontinente und Ozeane* (*The Origin of Continents and Oceans*, 1924). Wegener had all the evidence for continental drift but could not explain what forces could enable it.

Although rejected by the majority of geologists in the first half of 20th century, the discovery of seafloor spreading and subduction zones in the 1950s–60s validated Wegener's idea in the form of plate tectonics. Today, we can even measure the movements of tectonic plates from remote sensing and GPS technologies.

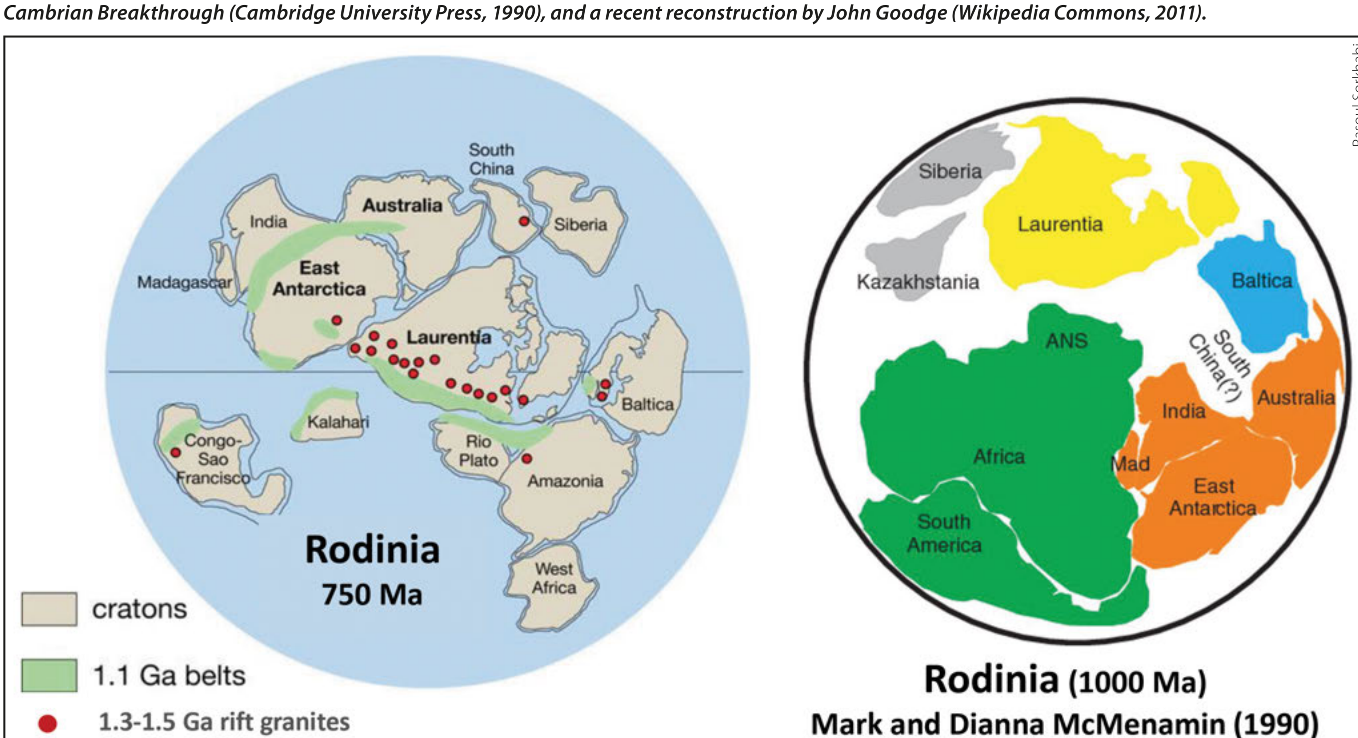


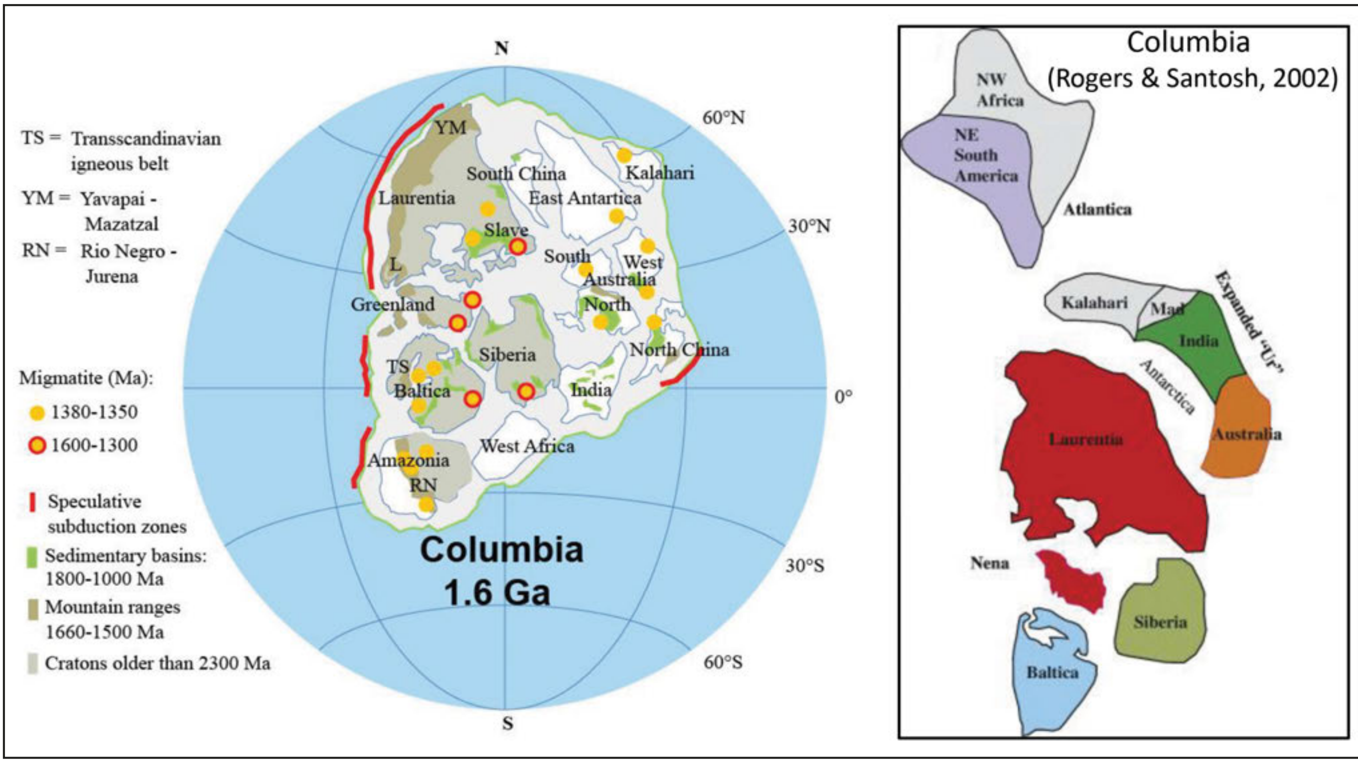
Histogram of detrital zircon ages determined by U-Pb indicating crystallisation ages of rocks from various parts of the world (compiled by Peter Voice et al., Journal of Geology, 2011) coinciding with ages of widespread mountain-building events (orogenies) suggested by Keith Runcorn.

Pulse of Earth

Plate tectonics is a continuous process although not at constant rates. Is global tectonics random, or is there some order and cyclicity in its operation? Several geologists reflected on these questions even before the birth of plate tectonic theory. The culmination of these thoughts was a 1942 book, *Pulse of the Earth*, by the Dutch geologist Jan Umbgrove, who compiled various data on tectonic, magmatic and sedimentary records for the Phanerozoic Eon worldwide, and suggested that there were two 'pulses' of widespread tectonic activities. This line of thinking was taken up by Thomas Worsley of Ohio University at Athens and his colleagues R. Damian Nance and Judith Moody (his wife) in the 1980s. They argued that tectonic and magmatic activities, as well as climatic shifts, sea-level changes, biogeochemical

Reconstructions of Rodinia at 1 billion years ago as originally suggested by Mark and Diana McMenamin in their book The Emergence of Animals: The Cambrian Breakthrough (Cambridge University Press, 1990), and a recent reconstruction by John Goodge (Wikipedia Commons, 2011).





Reconstruction of Columbia originally suggested by Rogers and Santosh (Gondwana Research, v. 5, 2002) and a recent reconstruction (Alexandre DeZotti, Wikipedia Commons, 2016).

signatures, and biological evolution observed during specific intervals are related to the assembly, duration or breakup of supercontinents, and that Pangaea was the last of a series of supercontinents Earth has witnessed. Based on clustering of radiometric ages, Worsley and colleagues identified five supercontinents at 250 million years, 650 million years, 1,100 million years, 1,600–1,800 million years, 2,100 million years, and 2,600 million years ago, consistent with similar geochronologic patterns recognised by Gordon Gastil, Keith Runcorn, and John Sutton in the early 1960s. Other geologists such as Kent C. Condie and John J.W. Rogers have also contributed to tectonic episodicity and formation of supercontinents.

Supercontinents Before Pangaea

To identify supercontinents, geologists correlate the ages and facies of rock formations, tectonic deformation, and sedimentary and fossil records across the continents. Collisional mountain belts (and their structural and metamorphic signatures) and geologic parallelism between the Precambrian 'shields' or 'cratons' (continental cores) provide particular clues to the former supercontinents. Today's geologists are also equipped with radiometric dating, geochemical analyses, and paleomagnetism which gives paleo-positions of rock samples (if remained undisturbed or corrected for tectonic tilting).

The Permian–Triassic Pangaea underwent fragmentation in the Jurassic, thus opening the present Atlantic, Indian and Antarctic oceans. Pangaea, being the most recent supercontinent, is well documented. As we go back in time, our knowledge of the size, configuration, and timing of supercontinents diminishes because the geologic records are destroyed by tectonic and erosional processes. For 4.5–3.0 billion years of Earth's history, the term 'supercontinent' may even lose its meaning, and we perhaps better use the term continental block or blocks.

In 1976, Andrew Button identified Kaapvaal craton in southern Africa and Pilbara craton in Western Australia as remnants of an Archean continent; he called it Vaalbara (Kaapvaal + Pilbara). John Rogers extended this continent to include several cratons in southern India and Madagascar; he called it Ur (after the world's oldest city in Mesopotamia), dating back to 3.1 billion years ago. This seems to be the oldest continental block we know of. Next came Kenorland (named after the Kenoran orogeny) at 2.8–2.2 billion years ago, which included the core of North America, Greenland, Baltica (north-west Europe), and also possibly extending to Ur.

Rogers also envisioned the formation of Arctica (cratons of North America, Greenland, and Siberia) at 2.5 billion years ago and Atlantica (consisting of West Africa and South America across the present Atlantic) at 2.0 billion years ago.

For the period 2.1–1.7 billion years ago, there is evidence for a supercontinent, initially called Nena (after North Europe and North America) or Nuna (an Eskimo word for 'lands bordering the northern oceans'). Paul Hoffman, who gave the name Nuna, included Laurentia, Baltica, and Angara (Siberia). John Rogers extended it to an all-inclusive supercontinent called Columbia (from the geologic records in the Columbian river area of western North America). Columbia fragmented during 1.7–1.4 billion years ago. Continental fragments came together again at 1.2–1.0 billion years ago to form Rodinia, so named by Mark and Diana McMenamin after the Russian word *rodit*, meaning 'to give birth', on the assumption that this supercontinent gave birth to all subsequent continents. Rodinia broke up from 750–600 million years ago.

During 600–500 million years ago, Greater Gondwana or Pannotia ('all southern lands') in the southern hemisphere formed. It merged with Laurasia to create Pangaea at 300–250 million years ago (the Permian period). Pangaea was the largest supercontinent ever.

John D.A. Piper has given the names Neo-pangaea (250 million years ago), Paleo-pangaea (1,000 million years ago), and Proto-pangaea (2,500 million years ago) to the supercontinents Pangaea, Rodinia and Columbia, respectively.

Supercontinents Columbia, Rodinia and Pangaea encompassed more than 75 percent of Earth's continents. Taking their median ages at 1.8 billion years, 1.1 billion years, and 0.3 billion years old, respectively, there seems to be intervals of 800 million years between them. This 800 million period is divided into three phases of assembly, stability, and breakup, each lasting 200–300 million years.

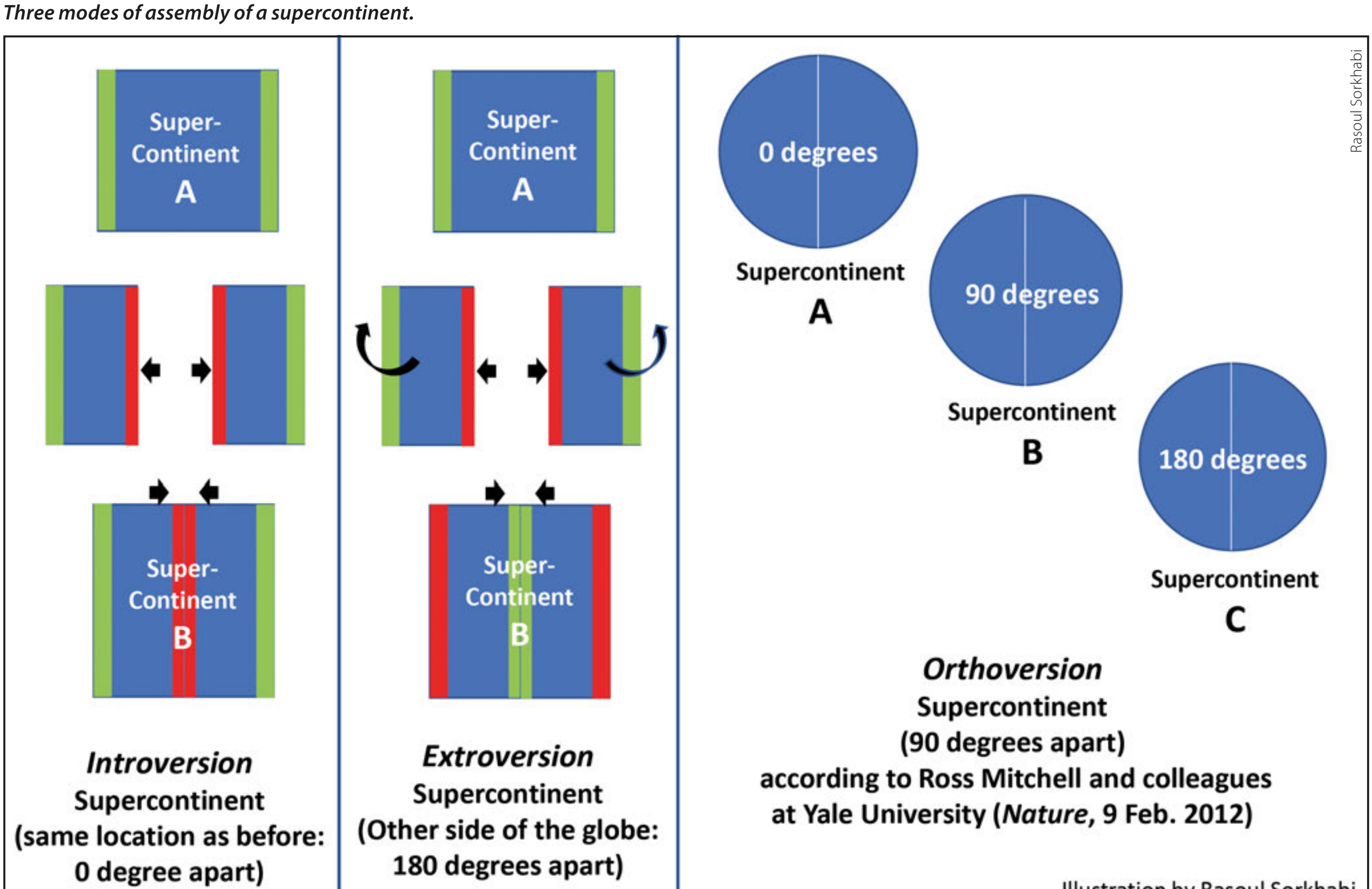
Causes and Patterns

Supercontinent cyclicity is related to several major puzzles in tectonics including the growth of continental crust through the geologic time and the birth of plate tectonics. Earth's oldest rocks (Acasta Gneiss of the Slave craton in Canada) are dated as 4.0 billion years old, and the oldest minerals (detrital zircons from Australia) are 4.2–4.4 billion years old. Tectonists like Kent Condie believe that plate tectonics on Earth was operational by at least 3 billion years ago. Prior to plate tectonics, Earth's earliest lithosphere was possibly a single stagnant plate ('lid tectonics') as we also observe on the Moon, Mercury, Venus, and Mars. Geologists have also debated whether the continental crust grew progressively though the eons, or the bulk of Earth's crust formed in the Hadean Eon – the first 500 million of Earth's history.

Is a supercontinent cycle periodic? For tectonic episodicity, Umbgrove considered a 250 million-year cycle for the Phanerozoic, and Worsley and his colleagues suggested a 440 million-year cyclicity. However, a regular periodicity is not necessary for a cyclic process, especially given that Earth's heat budget from both internal and radioactive sources has decreased through time.

The driving forces for supercontinent cycles lie within the mantle, related to the physical heterogonies, evolution and large-scale circulations in the mantle. However, we do not have a clear understanding about these hidden mechanisms. Worsley and colleagues postulated that the assembly of a supercontinent is facilitated by the subduction of dense and cold basaltic oceanic crust beneath continents (slab pull), thus closing the oceanic basins; while the long stability of a supercontinent, because of its thickness and radiogenic heat, leads to accumulation of heat beneath the continental lithosphere as the granite-rich crust is less conductive and more insulative of heat. This

Three modes of assembly of a supercontinent.



thermal contrast causes 'epeirogenic upwarp' or thermal doming of the supercontinent that may eventually lead to its extension and rifting. Relating these ideas to the deep mantle processes, it seems that 'avalanches' of subducting slabs from the upper to the lowermost mantle, the so-called 'slab grave yard' at the core-mantle boundary, facilitates the assembly of supercontinents. In contrast, the rise of hot mantle plumes, especially superplumes from the 'large low velocity provinces' in core-mantle boundary, leads to the supercontinent breakup.

The assembly of supercontinents may take place according to a geographic pattern: Introversion (same location, 0 degree), Extroversion (the opposite side of the globe, 180 degrees), or Orthoversion (90 degrees from the previous location).

Consequence and Impacts

The assembly, duration, and fragmentation of supercontinents have first-order impacts on sea-level changes, climate, biogeochemical cycle of key elements, evolution of life, formation of minerals, and so forth. Here we look at their impacts on petroleum resources.

Works by T. Worsley, R.D. Nance, and J.B. Murphy show that with an elevated supercontinent (epeirogenic uplift), global sea level falls; during the supercontinent breakup with young oceanic crust, the sea level rises; and as the continental drift matures into old ocean basins the sea level falls again.

Supercontinent breakups and ocean-floor spreading are associated with intense volcanic activities, which emit large quantities of carbon dioxide into the atmosphere and warm the climate via greenhouse effects. The plankton, which live in the upper 200 metres of the oceans and seas (the photic zone), source the bulk of hydrocarbon resources worldwide. Therefore, periods of high sea levels and warm climates flourish the plankton populations and expand their geographic area coverage. The Jurassic–Cretaceous 'hothouse', which accounts for more than two-thirds of petroleum reserves, is the best example of this phenomenon.

The assembly of a supercontinent is associated with continental collisions and increased rates of chemical weathering and erosion which remove carbon dioxide from the atmosphere and cause climate cooling. If the supercontinent is situated close to the pole, as happened in the case of the Permian Gondwana, it leads to a glacial age.

The vast majority of oil and gas fields are found in rift basins and passive continental margins (Atlantic-type margins) during the supercontinent breakup, while active subduction margins (Pacific-type margins) have not been proven to be favourable sites for oil and gas fields.

Future Supercontinents

By projecting the present direction and rates of plate motions, geologists have postulated future supercontinents. Such projections for the next 50 million years or so may be reasonable, but beyond that, they are highly speculative as plates may undergo different deformation trajectories. In 1982, Christopher Scotese envisioned Pangaea Ultima (later called Pangaea Proxima, 'Next Pangaea') that will form 250 million years in the future. Paul Hoffman in 1992 suggested Amasia that will bring Asia and North America together as the intervening Pacific completely subducts. In the late 1990s Roy Livermore suggested Novapangaea ('New Pangaea'). In 2016, João Duarte and colleagues at the University of Lisbon published a more circular tight configuration called Aurica, with Australia joining the Americas, Africa, and Antarctica close to the equator.

As the Earth's interior is gradually losing heat, plate tectonics will eventually stop. When that happens in an estimated two billion years' time, our planet will possibly end up again with lid tectonics. In the meantime, we have more immediate problems to worry about.

For more information:

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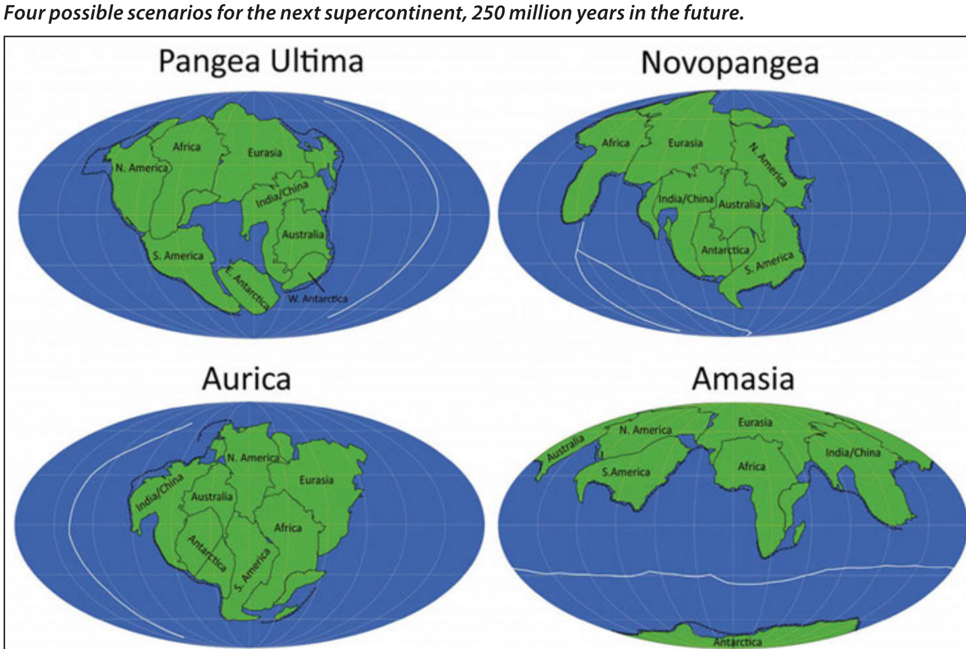
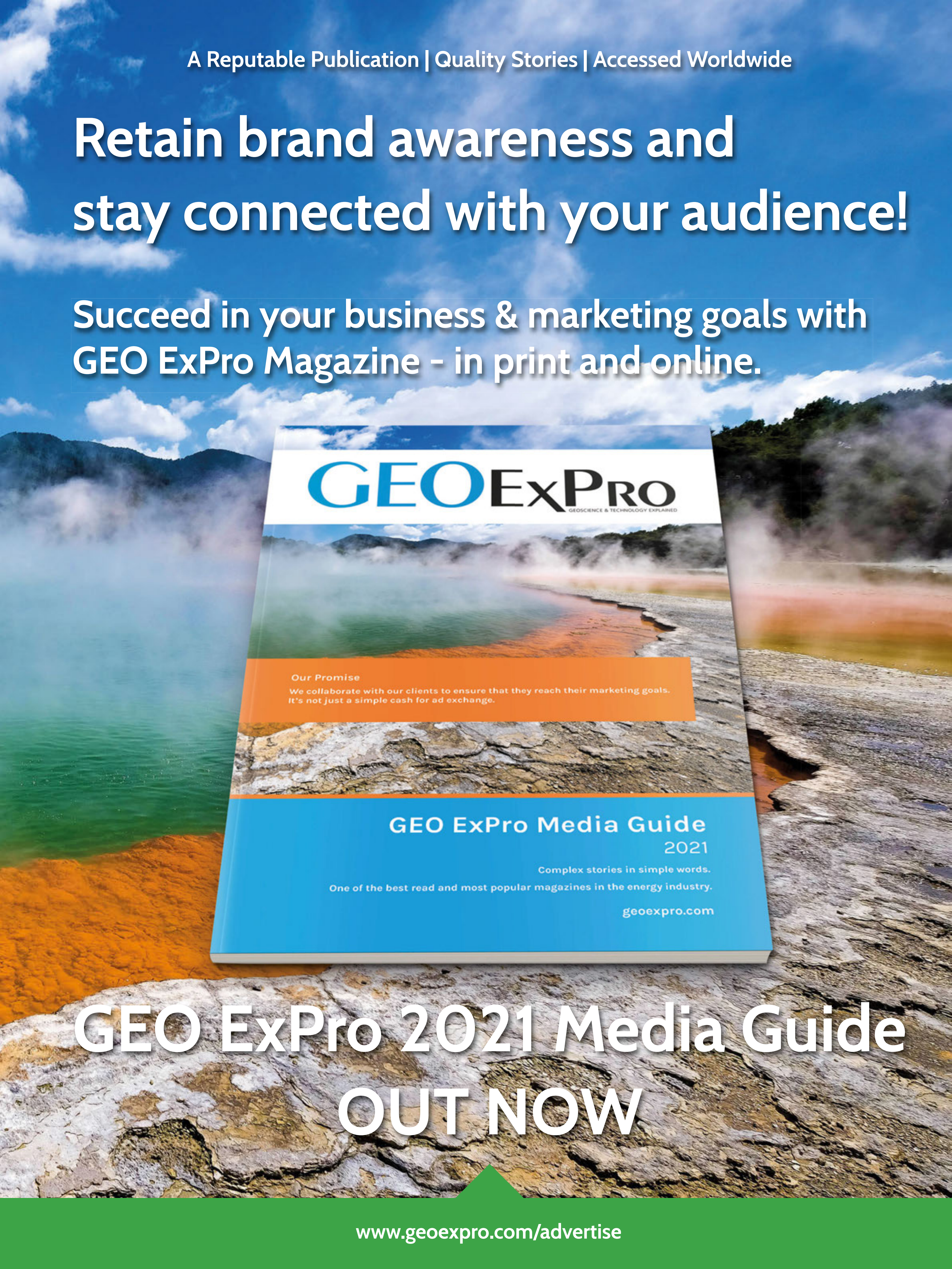
Four possible scenarios for the next supercontinent, 250 million years in the future.



Hannah S. Davis, Lisbon University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Dr Katerina Garyfalou: Geoscientist to Green Pioneer

Katerina Garyfalou explains how her career in upstream eventually led her to the circular economy and Greentech.

IAIN BROWN

Katerina grew up in a business-oriented and entrepreneurial family coming from the Greek island of Andros. Andros, one of Greece's shipping capitals, had an impact on her personality from a very young age. The female-dominated island and its international outlook due to shipping, enabled her to feel empowered and fuelled her appetite to see the world.

A Young Entrepreneur!

"My father was the first to introduce computers to Greece back in the 1970s, and as a kid, I remember growing up in a house full of creativity, risk and love of maths! I believe this shaped my 'entrepreneurial' side."

Katerina clearly had a head for business at a very young age and started her 'first job' at the age of five. "I was spending all my summers at my father's company and while waiting for them to finish work, I started making coffees for the employees while charging them for my services! I continued a few years later by publishing the only school newspaper as a student of my primary school. What I learnt from my family is to work and learn with every opportunity I get in life and if there isn't one, to create it."

A Dramatic Introduction to Geology

On September 7 in 1999, a 16-year-old Katerina was having lunch with her family in Athens, Greece. A student who excelled in maths and physics, she was still having trouble choosing what to do with her life. It was just after 2pm on the same day that a magnitude 6 earthquake hit Athens near Mount Parnitha with a maximum Mercalli intensity of IX (Violent). "It was the very first big magnitude earthquake that I had ever experienced," she said. "It was not the fact that the entire apartment of a seven-floor building was moving right and left, but the deep sound that came with it that captivated me!" It was her first introduction to plate tectonics, and she was utterly impressed by Mother Nature. This event contributed to her decision to study geology at the Greek University of Patras.

With a brother already living abroad in London, Katerina was determined to continue her studies in the UK. Immediately after her Bachelors, she started her PhD in Geoscience at the University of Aberdeen in Scotland. "Working as part of a Consortium, the PhD gave me early experience of working with major oil companies. I travelled the world for months while I was doing my fieldwork, and I was privileged to study areas that no one had even been to before."

"My main field area was in north-west Argentina, looking at a seismic scale outcrop of deep-water mass-transport deposits, turbidites and fluvial deposits.


Stelianour Sani – Photography.

Being the youngest and the only woman in the team, I was excited by driving through the river beds every day to get to the field area. My fieldwork experience expanded to many exotic and remote places such as Mexico, Africa and even though working under 45–50°C of heat while carrying equipment was exhausting, these are still some of my best memories".

Katerina soon realised that she didn't want to be an academic. She was getting impatient and working with the major oil companies was extremely appealing at a time when the oil price was averaging over $70/barrel. At this point she switched from being a full-time to a part-time student, although she didn't know at that time how hard it would be to keep on top of a challenging career and a PhD at the same time.

Fieldwork in Baja California, Mexico.

Variety and Diversity

"The word that can characterise best my work experience is 'diversity' and people will either love or hate the variety of roles I have had so far. I have worked for a service company, for a privately owned oil and gas company, for a major state oil and gas company and now a start-up. I have had roles from deep technical, to setting up a new business in West Africa, to strategy and portfolio, managing small and large teams, contract negotiating, and building partnerships. Most importantly, what has shaped my career is my thirst for learning new things and making decisions. What gives me immense satisfaction is inspiring the people around me. What has changed since the earlier years is that now, more than ever, I need to feel that I contribute actively to society and work for something bigger; for an idea that inspires me to do something good for the world. I will always be a geoscientist at heart, and I think it is one of the most beautiful sciences that one can do."

"I joined a Norwegian geophysical company, as a North Sea seismic interpreter," Katarina continues. "Early on, I decided that I wanted to be 'closer to the action' and so soon afterwards I joined their newly formed Reservoir Characterisation Group. I dived into hardcore geophysics, interpreting seismic data in ways that suited my mathematical brain. As the only geologist in the group, I had the freedom and luxury to develop my own depositional models. However, my frustration at not seeing the outcome of 'my' prospects led to my decision to leave and join an operator."

Making new friends in Senegal.

Greek Heritage and the NOC Ladder

As a proud Greek, Katerina decided to move back to her home country and join Energean, which at that time was a privately owned small oil and gas company and is now one of the most successful mid-cap companies. "What I learnt through my years with Energean is 'all for one and one for all'. In a small company with aggressive ambition to grow, you simply have to do a bit of everything: exploration, production, new ventures, admin, technical support etc."

More than three years later, her desire to see more wells drilled and be exposed to broader operations, led to the decision to join Nexen, a Canadian oil company which, a few weeks after she joined, was acquired by CNOOC. "We then became CNOOC International, and I spent eight years changing roles on average every 18 months," she explains. "Within CNOOC, I made my first career transition from technical to non-technical roles when I moved from Senior Geoscientist for West Africa Captured Basins to be the New Country Entry Manager for Senegal."

Katerina spent many weeks in Senegal and learned to love the country. "Over the years I was travelling to Senegal, I was impressed by the progress that this nation achieves steadily and progressively. Every time I visited Dakar, I saw new buildings, new roads. One time I was fortunate to spend a little more time there and experience the beautiful Senegalese hospitality. I met many locals, and I made new friends. The energy industry can give the opportunity to transform the structure of the economy creating prospects for growth and employment, and I wish Senegal and its beautiful and colourful people the best of luck in this new era.

Katerina presenting at the Africa E&P Summit, 2019.

Cultural champion at CNOOC.

Management Role

"This was one of the most unforgettable parts of my career. I left technical work to coordinate a team of over 50 non-technical individuals. Trying to navigate the corporate ladder while the oil price was falling, in a state-owned company, with a different culture from Europe and within a very male-dominated industry, came with its challenges".

"Being addicted to personal development and keen to show my company that I was serious about moving to more commercial roles, I decided to go back to studying and do an executive MBA at the London Business School. I thought that would be the same as when I did my part-time PhD, but it was not, for two simple reasons: I had moved further in my career, and the responsibilities were much greater, plus I was ten years older. When I started my MBA, I was absolutely optimistic that I would go back to the corporate ladder and advance a few steps by the end of it. I didn't anticipate that the academic environment and the exposure to so many exciting people would lead me to a significant change of mindset."

Green Shoots

By the end of this course, Katerina realised that what she wanted to do was make a difference and have a job with more meaning and to take more risks. "The opportunity to join my current company, Clean Planet Energy (CPE), a UK based company which converts non-recyclable plastics into ultra-clean fuel, came at the best time possible. I always follow the advice that I was once given: 'don't run away from your current job, but run to your dream job'. CPE had offered me a role where I knew I could make a difference to the world, exploiting my creativity while allowing me to grow more by taking considerably more responsibility. This is why I decided to make the transition from Upstream to the Circular Economy and Greentech."

"I'm really proud of my years in the oil and gas Upstream industry because it allowed me to develop the critical skills I now need in this new phase of my career." Katerina is currently the Commercial and Business Development Director for CPE. Her job is to secure long-term partnerships for both feedstock and offtake, while promoting CPE and determining short- and long-term commercial strategies. "My role is diverse, as expected with any start-up. Sometimes I may miss the structure that is usual in larger organisations, but at the same time, this allows me to make a difference and set my own standards to many different aspects of the business. I am initiating exciting new partnerships, dealing with multiple contracts and agreements, communications, PR and strategy while I'm actively doing something to help the environment!"

"Reflecting on my career so far and the different positions I've held, I believe that a fresh start is not a new place, but it's a new mindset and it's within everyone's ability to make a new start every day if they wish to. I am excited about the energy sector's future, and I believe everything can be achieved with hope and confidence," Katerina concludes. ■

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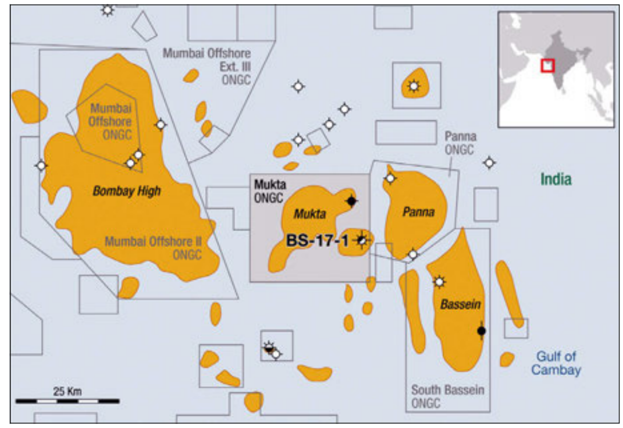
India: Returning to the Mumbai High

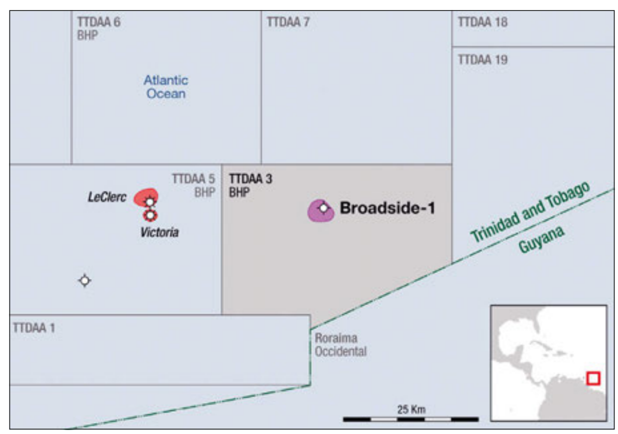


Despite a mid-year interruption due to Covid-19, **ONGC** completed **BS-17-1** on the **Mumbai High** as an oil, gas and condensate discovery in late 2020. The discovery, in the West of Bassein Mining Lease, held 100% by ONGC as Operator, is a satellite to the **Panna** and **Mukta fields**.

The Panna and Mukta fields, discovered in the 1990s by ONGC and operated over the years by a number of companies including BG Group, produce from several zones within the Eocene Bassein Limestone Formation, which has undergone reservoir enhancement via significant solution porosity, often concentrated along faults. The **BS-17-1** discovery, located between the two fields, flowed oil, gas and condensate from three separate zones. Flow rates ranged from 5.5–7 MMscfgd and oil/condensate 272–326 bopd. Although the stratigraphic units for each zone are not reported, the discovery is said to open up the Mukta and Heera Formations for exploration. These Lower Oligocene formations overlie the Bassein Limestone and are considered lateral equivalents of the 'Alternations' succession which contains the gas cap at the structurally higher Panna field.

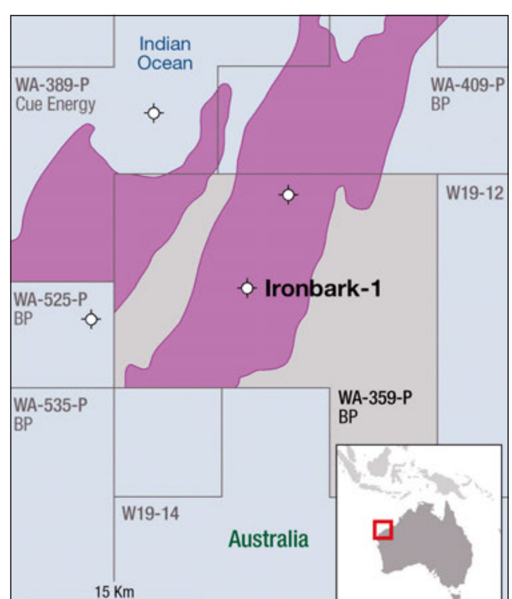
Stacked pay in this satellite is an attractive outcome if the fluids are compatible with ongoing production at Panna/Mukta, enabling ready tie-in to extend field life. At the beginning of 2020, the fields were producing about 10,000 bopd and 4 MMscfgd. ■

Trinidad : Elusive Deepwater Oil



In southern offshore **Trinidad**, **BHP** have had modest encouragement the last few years in increasing water depths with two gas condensate discoveries, but have come up unsuccessful in their most recent deepwater attempt with an additional deeper oil target. **Broadside-1**, spudded in September on **TTDAA 3** Block in over 1,800m water, targeting gas and deeper oil in Miocene sands, met with disappointing results after initial drilling difficulties and was finally plugged and abandoned as a dry well. BHP had touted recently some petroleum system similarities with the **ExxonMobil** major discoveries some 300 km to the southeast in **Guyana**. In recent years in the southern deepwater BHP have drilled the Le Clerc and Victoria gas discoveries and the dry hole Conception-1, all somewhat inboard on **TTDAA 5**. Also, BHP have drilled four gas discoveries and one dry hole in the north deepwater, but no announcements of commerciality or development plans have been forthcoming. ■

Australia: Key Farm-in Well Comes Up Dry

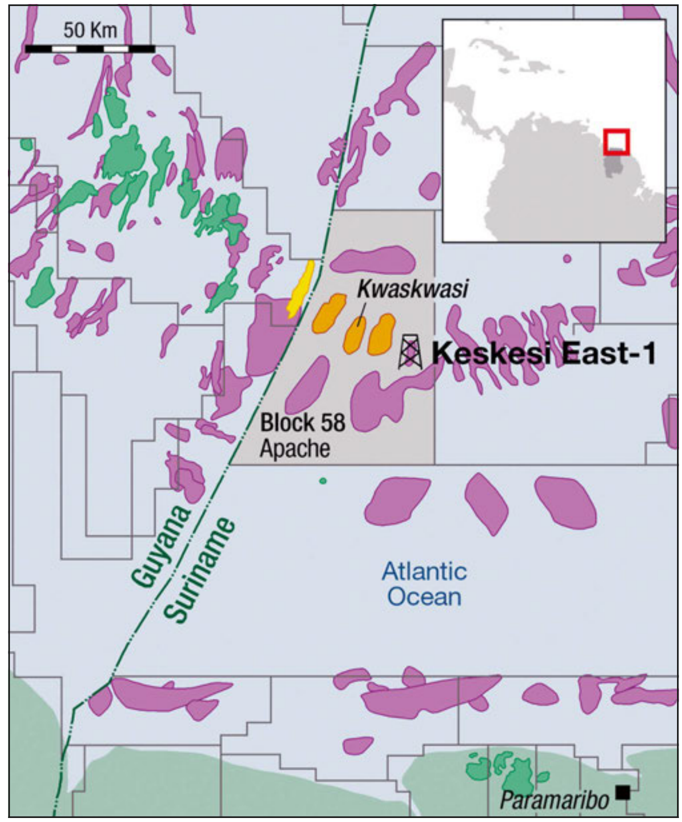


BP with partners **Cue Energy, Beach Energy and NZOG** have completed drilling the **Ironbark-1** wildcat in **Block WA-359** offshore in the **North Carnarvon Basin**. The well held huge potential for up to 15 Tcfg gas reserves within 50 km of major LNG infrastructure on the Australian NW Shelf. The well was drilled in 300m of water between 31 October and 29 December 2020 and was subsequently plugged and abandoned as a dry well. Ironbark-1 intersected the primary target of the Triassic Mungaroo Formation at 5,275m, without encountering any significant hydrocarbons. Cue Energy had worked up the play over a number of years, focusing on the fluvio-deltaic clastics of this very deep Mungaroo target formation, which does work in other fields nearby. Cue successfully farmed out to BP, Beach and NZOG in 2019. The result may have significant repercussions for the nearby North Rankin LNG platform, where Chevron is looking to exit and BP may now decide to sell. ■

Suriname: Further Success in the Upper Cretaceous

Apache and **Total** Block 58 **Keskesi East-1** has encountered 63m net hydrocarbon pay, with 58m net 27–28° API oil, volatile oil, and gas pay in good quality Campanian-Maastrichtian reservoirs, and 5m net of 35–37° API volatile oil pay in Santonian reservoirs, where wireline logging has been completed. The well was spudded in September 2020, having previously been side-tracked due to instability. The deep wells along this trend (**Maka Central**, **Sapakara, Kwaskwasi**) routinely TD below 6 km MD. Drilling is still ongoing for deeper Neocomian-aged targets, a major new target for the Lower Cretaceous which could have ramifications for the Mauritania, Senegal, Gambia, Guinea-Bissau and Guinea-Conakry (MSGBC) conjugate margin basins. Work is being carried out by the Noble Sam Croft drillship, which will be released following completion of the well.

The fourth well in the block, **Keskesi** is 14 km south-east of **Sapakara West-1**. All three previous wells in the block have encountered oil and condensate (in Upper Cretaceous marine clastic formations). Apache continue to operate the well until release of the drillship, whereas operatorship of the block was transferred to Total on 1 January, 2021, as agreed in their December 2019 farm-in. No acreage relinquishments are required until mid-2026. Total plan an appraisal campaign to begin in 2021, along with additional exploration drilling. ■



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■ Opportunities in the Eastern Mediterranean
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Event plans at www.findingpetroleum.com and www.d-e-j.com

The Azolla Story

F.M.GRADSTEIN

The Azolla Story is the fascinating account of the evolution, life and global potential of a freshwater plant called Azolla. Azolla, a symbiotic organism using photosynthesis and nitrogen fixation; not with specialist leaf shapes and surfaces as with the Roraima carnivorous plants, but with 'built-in' cyanobacterial filaments and bacterial mass. Azolla, a water-surface weed obstructing small boats on Dutch canals, or a super fertiliser, super CO_2 fixer, super water cleaner, super heavy metal remover, super too many things to name.

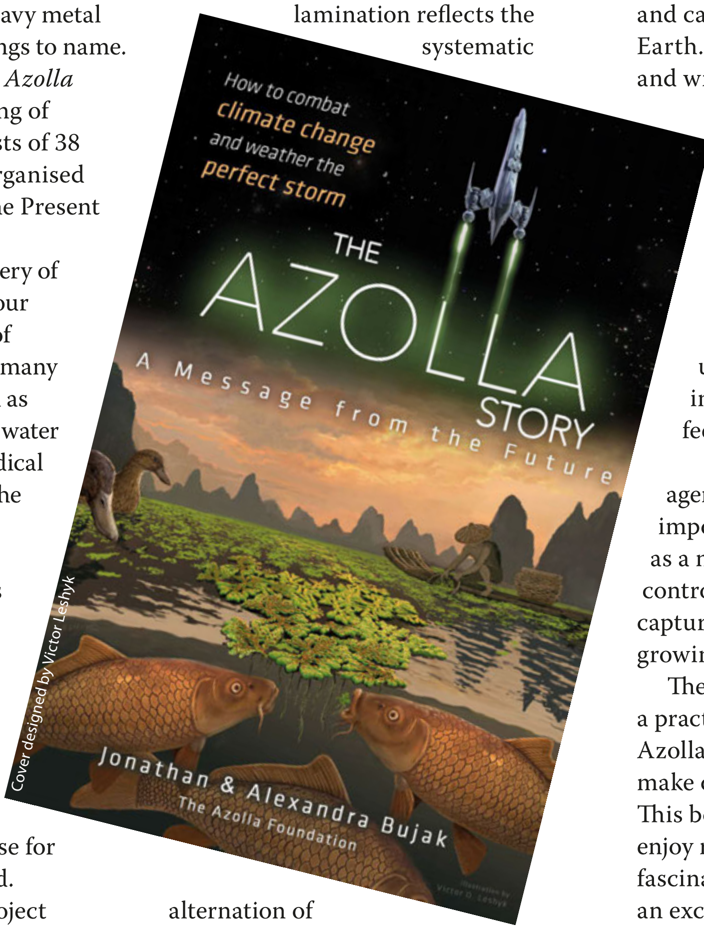
With over 400 pages, *The Azolla Story* has an impressive listing of reference sources and consists of 38 richly illustrated chapters organised temporally into: The Past, the Present and the Future.

The Past covers the discovery of Deep Time, the evolution of our biosphere and the evolution of Azolla. The Present contains many fascinating pages with Azolla as biofuel catalyser, as fertiliser, water and air cleaner and as biomedical facility. The Future outlines the Azolla Biosystem on Earth as well as in extraterrestrial endeavours and in mankind's other new missions.

Let us briefly look at one of the central and early chapters in this book that portrays the discovery of a 50-million-year-old Azolla 'lake', whose plant properties can be of much use for our current and future world.

The Deep-Sea Drilling Project (DSDP) and its successor the International Ocean Drilling Project (IODP), had long been frustrated in not having one or more drilling expeditions penetrating the Arctic Ocean floor. Finally, in August 2004, IODP Leg 302 with a team of two icebreakers, one from Sweden and one from Russia, allowed a special drilling vessel called Vidar Viking to be stationary long enough to drill the Lomonosov continental ridge between Russia and Greenland in the iced-over Arctic Ocean.

In over 1200m of water, now covered by metres of thick sea ice, the selected team of invited geoscientists discovered that almost 50 million years ago the then isolated Arctic Ocean, whose history we still poorly understand, for almost 1 million years had an almost freshwater cap. With sufficient input from riverine phosphorus, this special surface environment allowed Azolla to thrive and deposit metres of thick laminated strata on the sea floor. The lamination reflects the systematic alternation of tropical dark and tropical light half years. It had been known that both northern Canada and Siberia had a subtropical to tropical climate and corresponding biosphere in Paleocene and early Eocene times. The almost monotypic and near-freshwater Azolla flora is a special local phenomenon.



Unfortunately, the Vidar Viking drill sites revealed absence of the post-Azolla era (43 to 18 million years ago, Middle Eocene to Early Miocene) sedimentary record on Lomonosov Ridge, probably due to erosion by Miocene geostrophic bottom currents. Hence, the transition from global greenhouse to icehouse in the Arctic Ocean itself is not documented. But it is the discovery and coring of this unique floating fossil flora deposit, just after the Paleocene–Eocene Thermal Maximum (PETM), that led to a series of international workshops discovering and establishing what role Azolla played geologically, and what role it has and can have in the Anthropocene on Earth. It inspired the Bujaks to weave and write the present book.

The many chapters following on from the spectacular discovery of the Eocene Azolla event, cover in some detail how the little Azolla plant helps to make our world greener and better. The reader is introduced to how Azolla is used for purifying water and in biofertilisation and livestock feeding.

Azolla also is a valuable agent for saving mangroves, has important uses in cultivation of rice, as a mosquito controller, germplast controller, biofuel maker, for carbon capture and storage, and potential for growing and harvesting in space.

The Bujaks are realists and outline a practical bottom-up strategy of local Azolla Hubs for Azolla Biosystems to make our world greener and better. This book is perfect for those that enjoy real-time science in action with fascinating results. *The Azolla Story* is an excellent combination of art, science, technology, and social philosophy with a splendid and clever message in a handy pocket e-book format for all of us who want to improve life on Earth. It is recommended reading in 2021.

Edited by Jonathan and Alexandra Bujak The Azolla Story ebook is now available on Amazon for £9.99 and for £0.00 if you subscribe to kindleunlimited.

Read more about Azolla in the GEO ExPro website. ■

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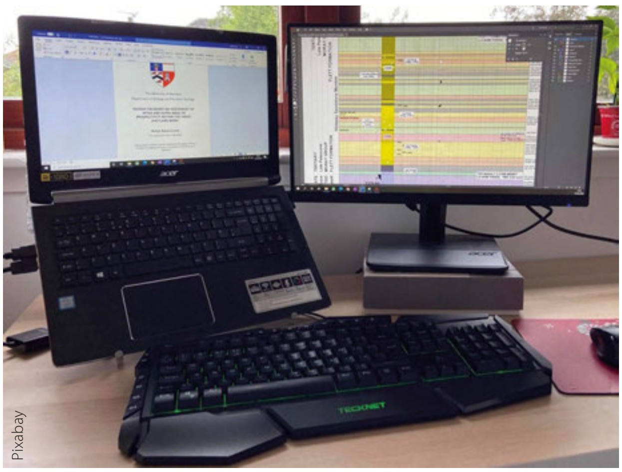
Completing a Masters in a Pandemic

Young geoscientists need resilience to succeed in their studies during these difficult times. Kirsty Lewis, a recent graduate of the Masters programme at Aberdeen University, explains the challenges she faced and overcame to obtain her MSc and a job with an oil company.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What inspired you to study Geology?
Some of my earliest memories are me as a young child getting told off for constantly bringing home various rocks and what I thought were 'dinosaur bones' (actually it was driftwood!). I grew up watching the Discovery Channel as well as renting videos from the local library about volcanoes and earthquakes. Having been brought up on the west coast of Scotland, I have developed a strong connection to nature and the outdoors. My affinity for nature and exploring, as well as a tendency to question the world around me, led me to a career in geosciences. For me, geoscience is the perfect mix of nature, science, creativity and innovation. It is also an exciting yet turbulent time to specialise in geosciences. During this time of the energy transition, the energy industry is pushing the boundaries and innovating at an exponential rate to achieve a low-carbon future. I look forward to seeing what the future holds for myself and my fellow geoscientists.

Why did you decide to do a Masters in Integrated Petroleum Geoscience?
Having completed my BSc at Aberdeen University, it was the natural route for those who wanted a career in the oil and gas industry. From looking at the LinkedIn profiles of successful geoscientists in industry, a significant majority had completed an Integrated Petroleum Geosciences MSc at Aberdeen. The field trips and hands-on experience were also a very attractive aspect.

2020 has been a difficult year for everyone, particularly for students having to study and work from home. How did you cope with this?
We didn't have much choice. Our whole world had been turned upside down. I did struggle at the start; I think we all did. One day, however, I just got up and decided to put my all into my work and thesis. I couldn't control what was going on in the world around me but I could control my work and my learning, so I used it as a distraction. I almost feel lucky now as it allowed me to focus solely on my work as well as occupying my time during the first, long lockdown. I'm just grateful now that we got a significant part of our MSc completed before the pandemic hit. Although we didn't make it to Utah as planned, our field trip to the Pyrenees in Spain was filled with memorable experiences.

Kirsty Lewis on location in the Spanish Pyrenees.


Kirsty Lewis

Industry projects and data weren't readily available for your thesis projects this year: how did you approach and solve this major issue?

In the first few weeks of lockdown, my internship, together with nearly all the student industry projects, were cancelled. The university, however, managed to produce projects which they believed were possible to fully research online. Although designed as primarily literature reviews at first, it was amazing to see the innovation and new information we were able to produce with 'old data '. We are lucky in the UK to have access to the Oil and Gas Authority's National Data Repository as well as a wealth of academic papers online. 'Google Scholar' was a life-saver for the thesis project!

What insights do you think you gained from the 'back to basics' approach required?

I think this project opened my eyes, as well as those of our lecturers and industry mentors, to just how much freely available information and data there is online. Our class produced over 30 thesis projects with no industry-donated data, while confined to our homes. A lot of companies these days tend to throw machine learning at projects and purchase expensive data. This can cause an over-reliance on data such as seismic, which may skew interpretations. Our back-to-basics approach encouraged fresh ideas to long-held assumptions, without the bias that complex data might encourage.

What advice would you give recent graduates considering a further degree?

My advice would be to find your passion before you pick your Masters. It is a significant step up from your BSc. If you find something you are passionate about, enjoy doing and can see yourself working in for the next 20 or 30 years, then do it. Working in something you are passionate about makes the long, hard nights of studying all that much easier. A geoscience degree can open a lot of doors to a wide variety of industries, not just energy!

Now that you've successfully completed your degree, what does the future hold?

I have been very lucky to land a place on the Equinor 2021 graduate scheme as a researcher in petroleum systems in Bergen, Norway. It is my dream job and hopefully the beginning of a long, interesting and international career in Geosciences. If Brexit doesn't cause any more issues, I hope to move there, in February. I will also undergo rotations into other departments within the company over the course of my graduate scheme, which will run for two years in total. In the future, I would like to see my skills as a geoscientist applied to other forms of low-carbon energy production such as geothermal or carbon capture programmes. Of the main energy operators, I have admired Equinor for being an environmentally conscious organisation, as well as a forward-looking one. I am eager to begin working with them solving the world's energy needs in an environmentally responsible manner. Also, 2020 was a crazy year and I am looking forward to starting my career and hopefully, a bit of normality. ■

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Putting a Prize on Carbon Capture

Everyone likes a pat on the back, a bit of credit now and then, but do big prizes really work? Elon Musk must think so as he's offering $100 million (about 0.05% of his net worth) to any team that comes up with the best way to capture carbon. Carbon capture and storage (CCS) of course remains a serious challenge on the road to net-zero, but for Mr Musk the publicity alone must be worth the offer. After all, he now runs the biggest car company in the world by market cap and if the experts are to be believed, sales of his 'zero emissions' Teslas are set to go through the roof this year.

When it comes to carbon capture, Elon Musk is in good company. Big oil has long recognised that CCS has to be part of its transition future. But just to put the Musk offer in perspective, a new CCS plant can cost around $1 billion in investment and so far, most governments have been reluctant to do their bit with subsidies. This may change of course as climate change commitments are upgraded at COP26, the UN Climate Conference which is due to take place in Glasgow in December this year and because the Biden administration is already talking and acting tough on the environment. As part of its $2 trillion climate plan the US government is offering generous tax breaks for CCS projects and there are already more than 30 of these off the starting blocks.

In the meantime, oil and gas companies continue the painful process of transition with business confidence down and more consolidation in the offing according to the latest industry outlook report by the consultancy DNV GL. The name of the game of course is still transition, CCS included, but amid all the doom and gloom there are positive notes in the report, aptly entitled *Turmoil and Transformation.*

Firstly, big oil and gas companies know a lot about managing big projects, be they oil and gas, or indeed renewable energy. Secondly, just over 20% of senior oil and gas professionals maintain that their companies will actually increase their investment in oil and gas projects during 2021. Thirdly, the report says the digital revolution is set to continue apace which should mean even more AI-driven, less carbon intensive operations. According to DNV GL Vice President Hans Kristian Danielsen, "there are signs that our sector may invest to transform rather than cut its way out of the present crisis." Surely there's an O&G candidate for that Elon Musk prize? ■

Nick Cottam

Teslas only really run on 'clean' energy if carbon capture is part of the equation.

Conversion Factors

Crude oil

1 m^3 = 6.29 barrels

1 barrel = 0.159 m^3

1 tonne = 7.49 barrels

Natural gas

1 m^3 = 35.3 ft^3

1 ft^3 = 0.028 m^3

Energy

1000 m^3 gas = 1 m^3 o.e.

1 tonne NGL = 1.9 m^3 o.e.

Numbers

Million = 1 x 10^6

Billion = 1 x 10^9

Trillion = 1 x 10^{12}

Supergiant field

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

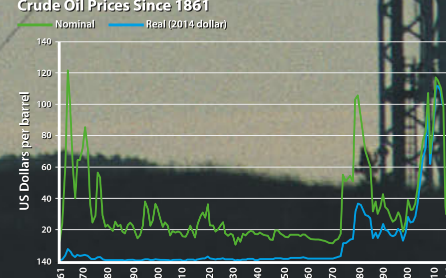
Giant field

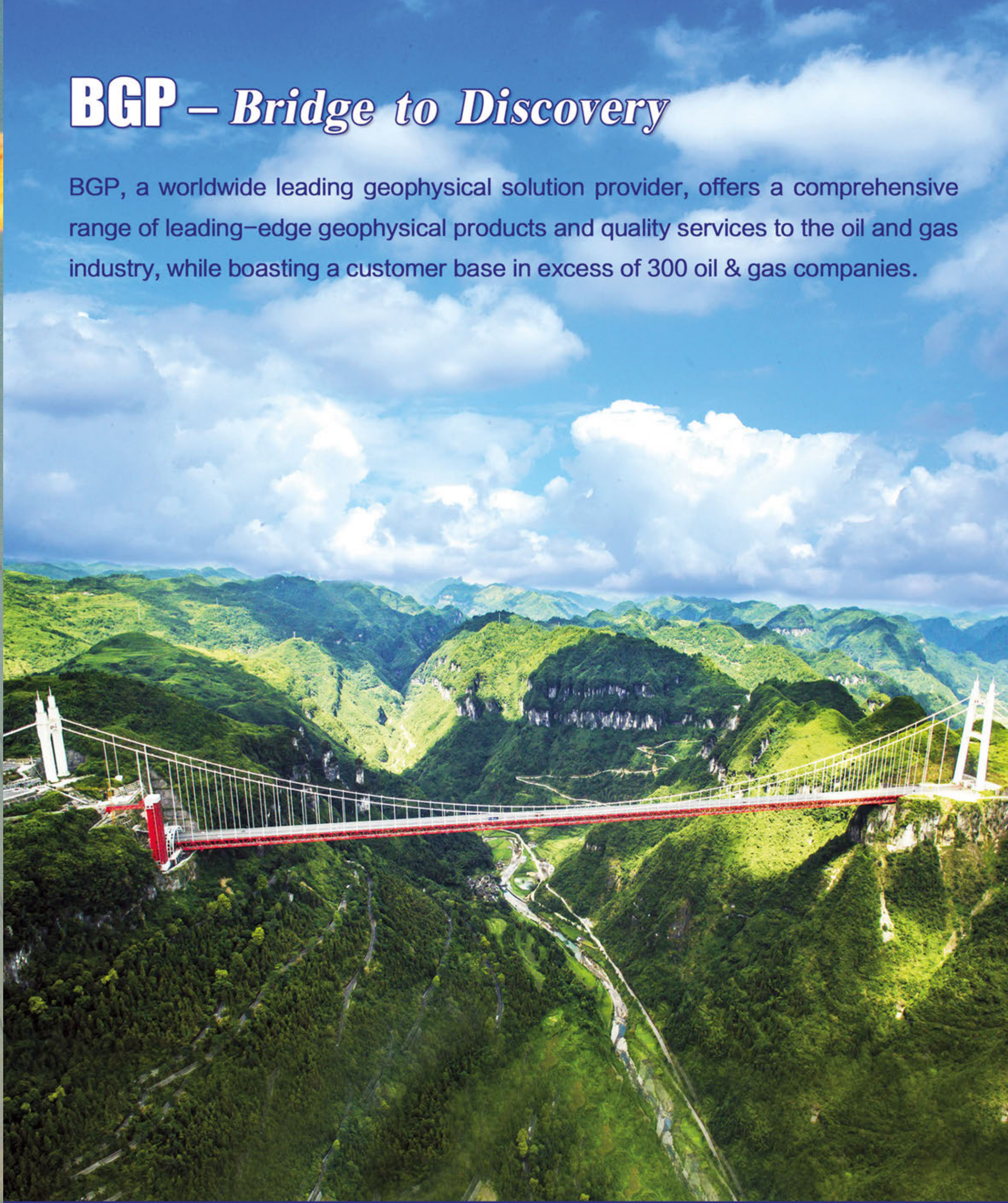
Recoverable reserves > 500 million barrels (80 million Sm^3) of oil equivalents

Major field

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

Historic oil price





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