VOL. 18, NO. 6 – 2021

GEOExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

GEO HISTORY
Mexico:
Onshore to Offshore

TECHNOLOGY EXPLAINED

Vintage Maps Reborn

ENERGY TRANSITION
A Sleeping Giant

GEOPHYSICS
Gradiometry – The New Standard

GEO EDUCATION
Big Questions and Challenges in Geoscience

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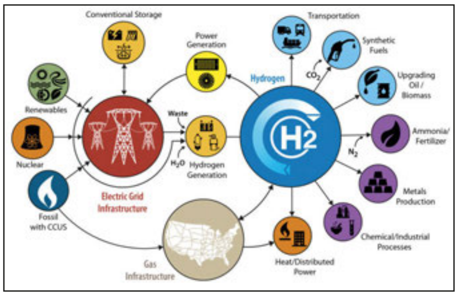

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The Texas Gulf Coast is already the No. 1 producer of hydrogen in the United States. Using its existing infrastructure, the area is primed to become a top producer of clean hydrogen.

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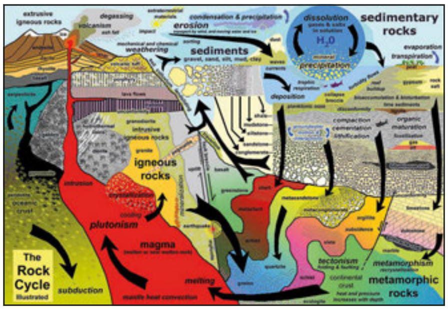
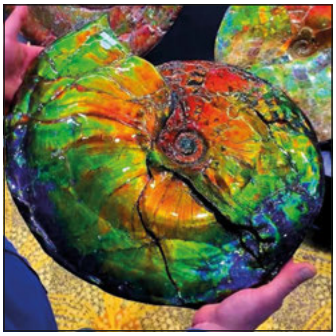
Geoscience is facing major challenges in terms of college enrolment, research funding, job market and public perception. One way to address these challenges is to turn them into opportunities and articulate big questions that geoscientists can study and contribute to.





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GEO ExPro is running a new series of fascinating articles on fossils. Avid collector James Etienne kicks things off with an introduction to this captivating hobby and field of serious scientific study.

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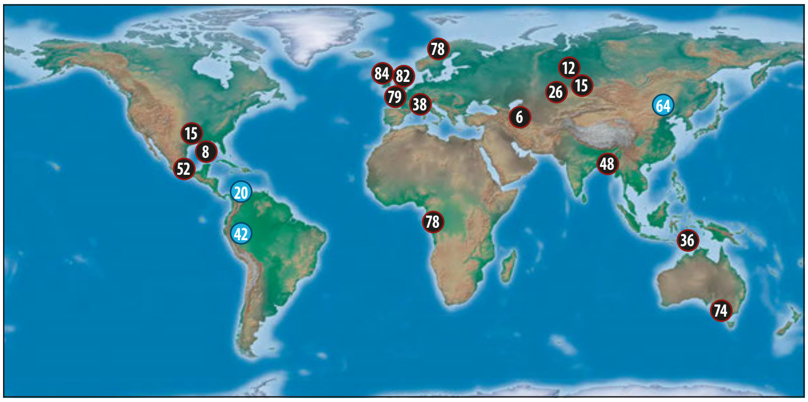
What is airborne gravity gradiometry and why is it such an important tool for frontier resource exploration? We explore the development of this technology from its origins to the most recent advances.



Contents

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This issue of *GEO ExPro* focuses on The Gulf of Mexico; Russia and the FSU; Non-Seismic Geophysics and Carbon Capture, Storage and Usage:

Aspects of Transition

The COP26 climate summit in Glasgow concluded with a pact that its UN backers still insist keeps alive the goal of limiting temperature rises to 1.5°C. One of the most important outcomes was that over 190 countries agreed to phase out burning coal, the most intensive CO_2 polluter, and strengthen emissions-cutting targets for 2030 by the end of next year as part of the bid to limit warming.


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Mary Anning's plesiosaur on display at the Natural History Museum, London.

In Glasgow, there was disappointment at the level of engagement shown by Russia and China. Although Russia is heavily dependent on its huge fossil fuel resources (more than 50 percent of the government's revenue), it has significant potential for renewables. Hydropower, geothermal and wind are all known technologies there and much of Russia is ideal for the development of wind farms. There have been recent moves to develop hydrogen for both transport and export, viewing it as a possible long-term replacement for the gas it now exports to Europe.

In the US Gulf of Mexico, hydrogen may be the 'sleeping giant'. The area is already the top producer of hydrogen in the country, having long produced the gas through steam methane reforming. With much of the infrastructure in place already from the existing oil and gas business, West Texas's expansive solar and wind farms could become the top producers of the cleanest hydrogen. The direction of travel of the Biden administration is clearly in alignment, and developments in offshore licensing are supportive of more wind power development in the gulf.

Whilst 'fossil' fuels dominate the current headlines with COP26, rising oil and gas prices, and Russian politicking, fossils more familiar to palaeontologists feature prominently in this issue. We kick off a new series with an article introducing this fascinating field of study and profitable collecting. The global market for fossils is a multi-billion-dollar global business, with individual dinosaur skeletons such as Stan (*T. Rex*) fetching US$31.8 million in a Christie's auction in London last year.

Mary Anning, the famous British amateur palaeontologist, whose life was portrayed in Francis Lee's recent award-winning film 'Ammonite' (reviewed in our GEO Media article), would have been astounded at the sums commanded today for full dinosaur skeletons. Her most famous specimen, the world's first complete plesiosaur, found in 1823, if sold today would no doubt be worth a small fortune. This amazing woman is finally being more widely recognised for her contribution to science with the unveiling of her statue in Lyme Regis, Dorset, next year. ■

Iain Brown
Editor in Chief

VINTAGE MAPS REBORN

With the advent of 3D modelling and access to detailed surface model data covering the entire globe, shaded relief maps generated from 3D animation software have given cartographers the ability to create 2D maps with a hyper-realistic 3D appearance.

Inset: President Cardenas (centre) at the Mexican General Congress, September 1938.

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Caspian Sea

The Caspian Sea is shared between Iran, and the four former Soviet republics of Azerbaijan, Kazakhstan, Russia and Turkmenistan. In August 2018, in a landmark deal between the five countries, the Convention on the Legal Status of the Caspian Sea was signed in the Kazakh city of Aktau. After more than 20 years of negotiations, this establishes a process for dividing up the Caspian Sea's resources and prevents powers from establishing a military presence. So far, only Russia, Azerbaijan, Kazakhstan and Turkmenistan have ratified the Convention and it is understood that the government of Iran has yet to send the draft law to the legislature.

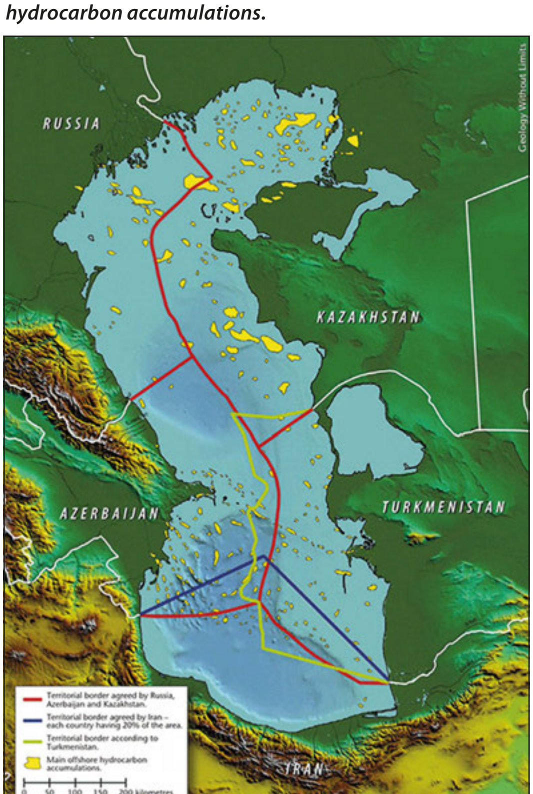
Up until 1991 the situation was less complicated as the Caspian Sea was shared between Iran and the Soviet Union. Iran treated the body of salt water as a lake, but the other countries did not agree and recognised it as a sea. Thus, it is considered by the former Soviet Union countries as under the 1982 United Nations Convention on the Law of the Sea (UNCLOS). However, if the Caspian Sea is legally classified as a 'lake', then international law concerning border lakes would apply.

The disagreement between the former Soviet Union countries over its legal status has prevented a gas pipeline being built across the Caspian between Turkmenistan and Azerbaijan. A direct pipeline would have allowed Turkmen gas to bypass Russia on its way to Europe rather than by other costly routes. In principle the international maritime law convention allows pipelines to be built under agreements between affected countries, rather than needing approval from all five nations.

There are two main disputes in the Caspian Sea involving hydrocarbons. One involves the Araz-Alov-Sharg oil and gas fields between Iran and Azerbaijan. The second is the dispute between Azerbaijan and Turkmenistan over the Serdar/Kapaz oil field. The field is referred to as Kapaz by Azerbaijan and Serdar by Turkmenistan. In a positive move in January 2021, Azerbaijan and Turkmenistan signed a Memoradum of Understanding (MoU) for the joint exploration of the Serdar/Kapaz and renamed it the Dostluk ('Friendship') field.

LUKOIL is the biggest acreage holder in the Caspian Sea followed by KazMunaiGas, SOCAR, Rosneft and Yuzhmorgeologiya. Through its position in Azerbaijan, BP is the biggest international acreage holder. Since opening its office in Baku in 1992 it has invested almost US$80 billion in the Azeri-Chirag-Gunashli (ACG), Shah Deniz, Baku-Tbilisi-Ceyhan (BTC) and South Caucasus Pipeline (SCP) projects.

Map of Caspian Sea showing territorial borders and main hydrocarbon accumulations.



In September 2021 BP announced it had agreed to sell a 25% participating interest in the Shallow Water Absheron Peninsula (SWAP) Production Sharing Agreement (PSA) in the Azerbaijan sector of the South Caspian Sea to LUKOIL. BP will remain operator of the SWAP PSA during the exploration period, holding a remaining 25% interest. The first exploration well in SWAP was spudded in the North Khali Prospective Area in August 2021. The well is designated NKX01 and is being drilled by the jack-up rig Satti in 22m of water. The well is thought to target a large anticline with Pliocene Productive Series sandstones as the main objective. Two further exploration wells are planned in the Qarabatdag and Bibiheybat prospective areas. ■

Ian Cross, Moyes & Co

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
stoiip: stock-tank oil initially in place

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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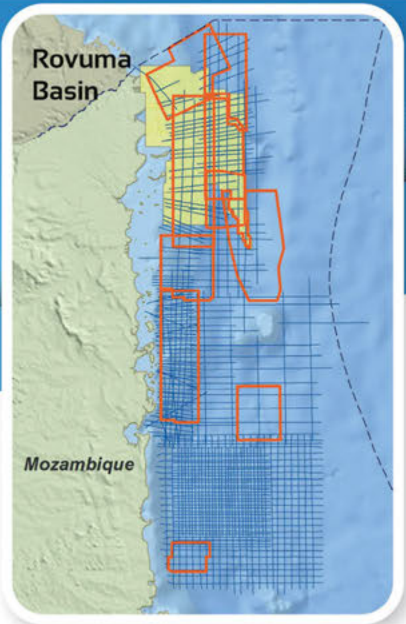
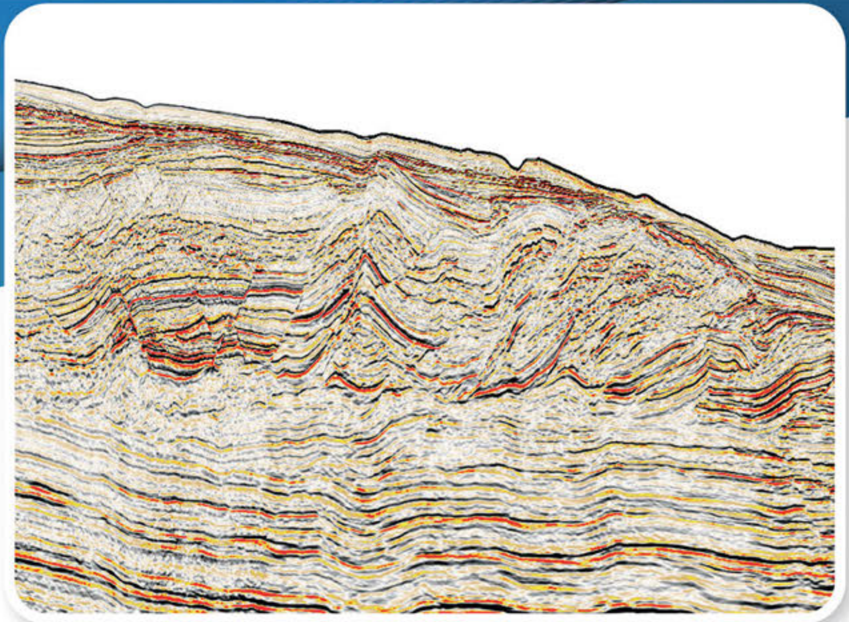
MOZAMBIQUE 6TH LICENSING ROUND

ROVUMA BASIN OFFSHORE – Legacy Seismic Data

RovumaMerge21 – 2D & 3D Data Reconditioning



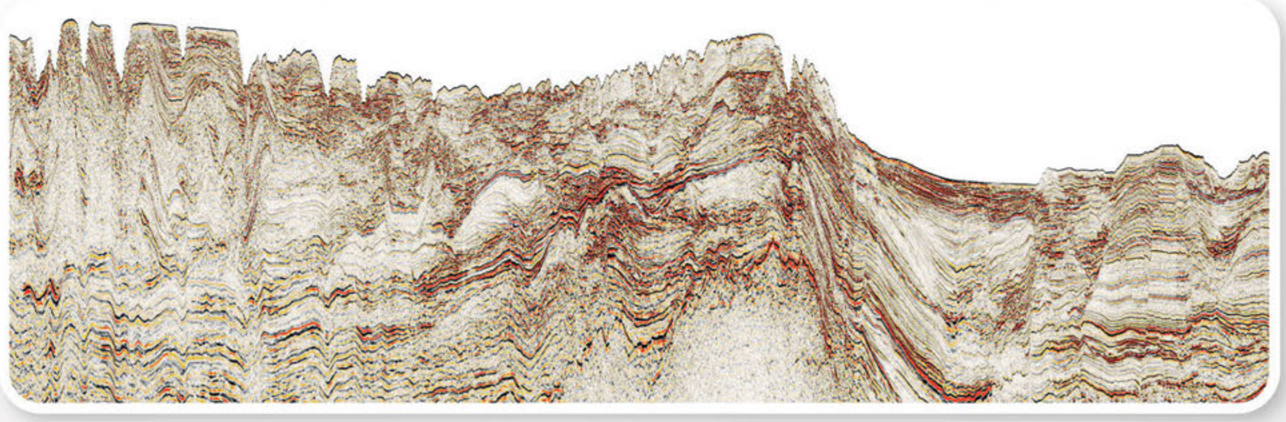


For the imminent Mozambique 6th Licence Round, the Institute of National Petroleum (INP), on behalf of the Government of the Republic of Mozambique, is making available legacy technical data for Multi-Client licensing. This includes 2D and 3D seismic, well data and interpretation reports for all areas included in the round.

GeoPartners are providing assistance to INP for the Multi-Client licensing of the 2D and 3D seismic datasets and has an exclusive agreement to license these datasets to interested companies. The data volumes available through GeoPartners total over 42,000 km of 2D seismic and 23,000 sq. km of 3D seismic.

In order to provide a regionally consistent data volume across the whole of the offshore Rovuma Basin area, GeoPartners has merged and reconditioned the existing 2D and 3D seismic surveys into a single matched data volume, comprising over 20,000 sq. km of 3D seismic and over 16,000 km of 2D seismic. Full offset and angle stacks are available over an area of over 45,000 sq. km.

For the latest information regarding the 6th Licence Round and available technical data, interested parties should visit the INP website, www.inp.gov.mz. To arrange a viewing of the new RovumaMerge21 dataset, please contact either Jim Gulland, GeoPartners or Alessandro Colla, Trois Geoconsulting.



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Alessandro Colla, Trois Geoconsulting • alessandro.colla@trois-geo.com • +31 621143173

Gulf of Mexico: The Wind of Change

The Bureau of Ocean Energy Management (BOEM) announced on 17 November that the Gulf of Mexico Lease Sale 257 generated $191,688,984 in bids for 308 tracts covering 1.7 million acres in the federal waters of the Gulf of Mexico. A total of 33 companies participated, submitting $198,511,834 in total bids.

The Biden–Harris administration is continuing its comprehensive review of the offshore and onshore oil and gas leasing programmes, with more environmental, social and governance (ESG) pressure expected to be applied on hydrocarbon explorers.

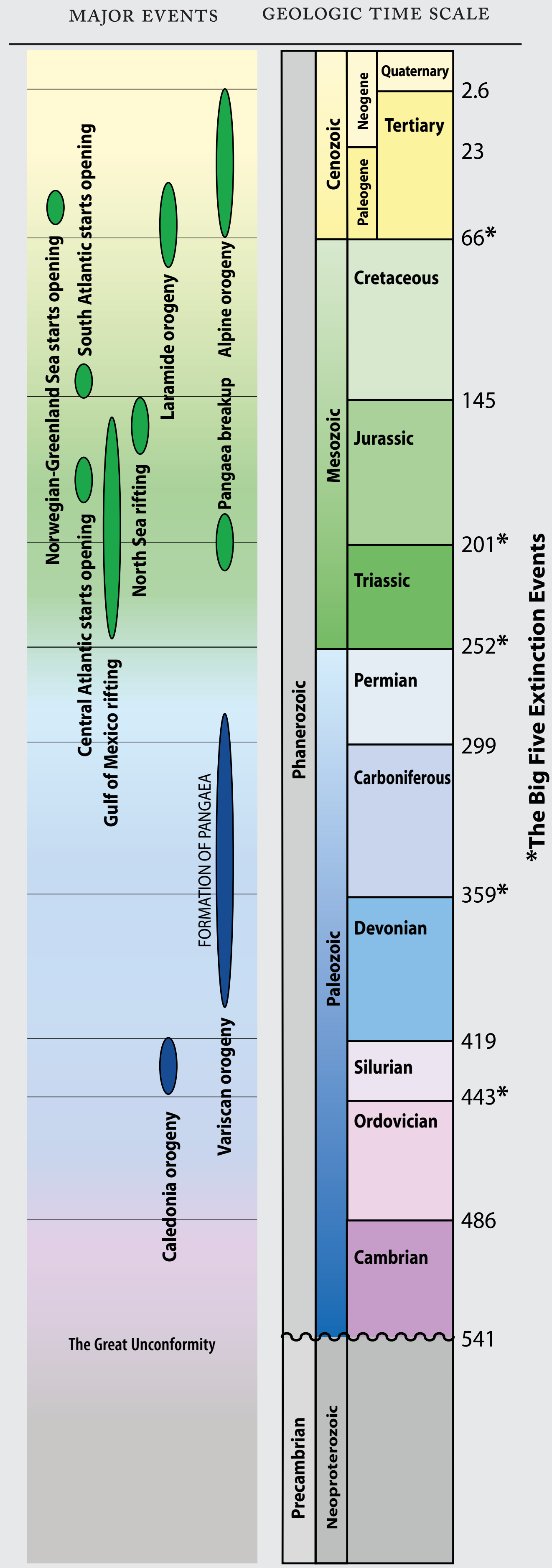
The Gulf of Mexico Outer Continental Shelf (OCS), covering about 160 million acres, is estimated to contain about 48 billion barrels of undiscovered, technically recoverable oil and 141 Tcf of gas, but there is considerable uncertainty about how much of this resource will ultimately be allowed to be exploited.

BOEM will include lease stipulations to protect biologically sensitive resources and avoid potential conflicts between oil and gas development and other activities in the Gulf of Mexico – which may shortly include renewable energy producers.

Several environmental groups sued the Interior Secretary in August to prevent the sale, and in a move that was possibly more acceptable to some of the environmental activists, the Biden administration announced in late October, its plans to extend the fledgling offshore wind sector's footprint deeper into the Gulf of Mexico by taking the first steps to offering lease sales off the coasts of North Carolina, Louisiana and Texas.

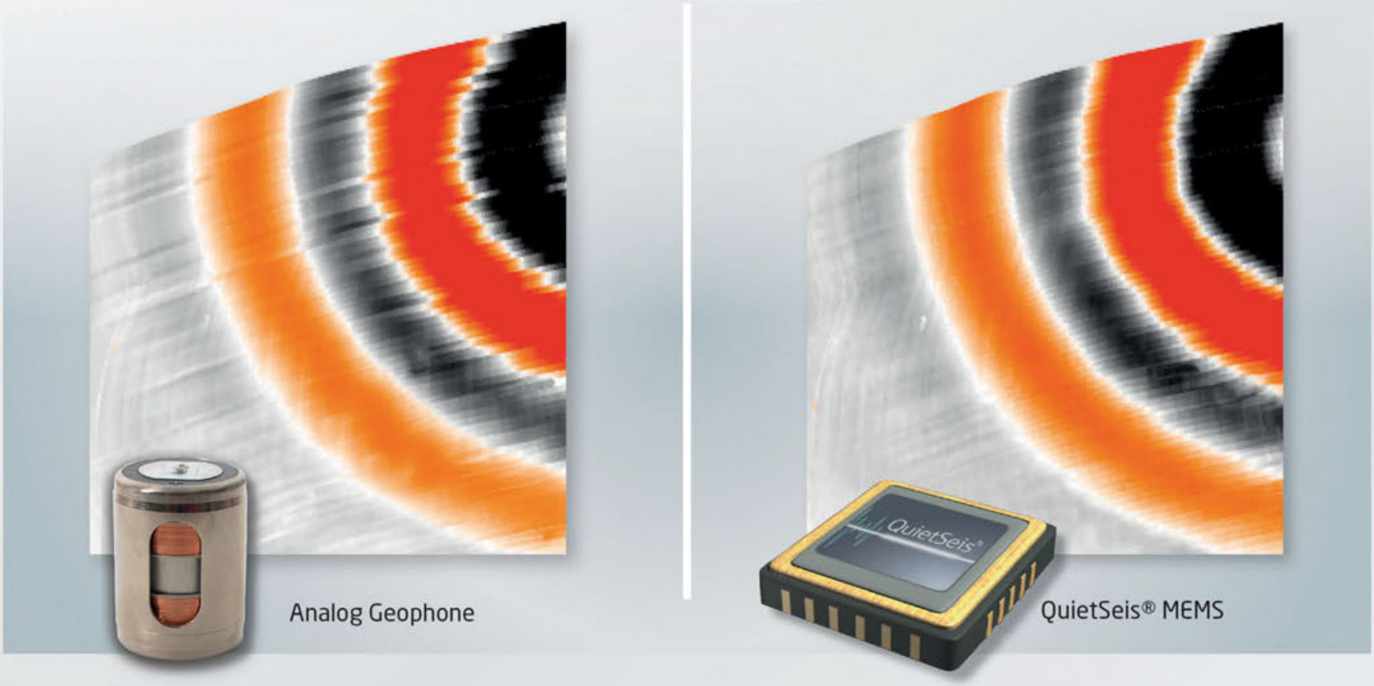
The White House has promised to support deployment of 30 gigawatts of offshore wind power by 2030, part of its larger climate-focused decarbonisation efforts. The commitment could result in the federal government's approving 16 major offshore wind farms in US waters, where currently just two pilot-scale projects are in operation. The proposed area for lease includes 127,865 acres, which is much of the Wilmington East Wind Energy Area, enough to support up to 1.5 GW of power. BOEM is also inviting the offshore wind industry to propose areas for potential leasing across a 30-million-acre swath of the Gulf of Mexico, following the coastline from south Louisiana to the Mexico border. ■

Wind farms like Thornton Bank in the North Sea could become a common sight in the Gulf of Mexico.



WiNG[NT]

WANT TO GET RID OF DATA JITTER?



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Powering the Energy Transition to 2050!

With a pandemic receding and an energy transition journey ahead, what will our wells and fields look like going forward? **DEVEX 2022** will examine how the pandemic has changed the way we work and will provide a platform for organisations to share the new technologies being developed and new skills required in order to meet the net zero 2050 targets.

This annual technical conference, organised by **SPE Aberdeen**, **PESGB** and **AFES** is in its 19th year and will take place in-person on 10–11 May in Aberdeen, Scotland.

As well as presentations and case histories focusing on the full E&P project cycle, core material and data will be on display, and we will yet again host a Field Trip. The Young Professionals group will have a dedicated event also focusing on the energy transition and skills required for the future.

Whether you are a geoscientist, geophysicist, geologist, reservoir engineer or petroleum engineer, this conference provides an opportunity for you to come together, network and share knowledge.

For more information on the programme and how to book, visit the SPE website. ■

Robots on the Seabed Advance

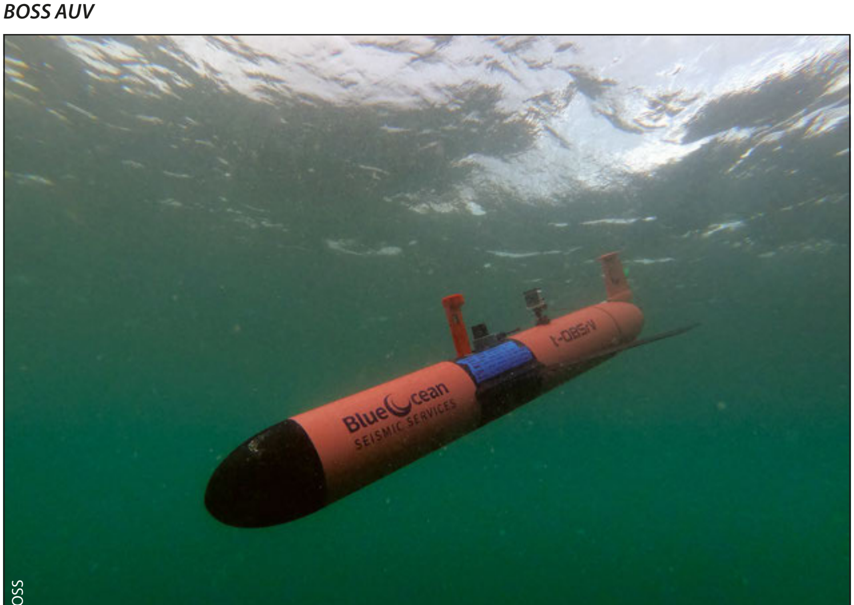
In October, **Blue Ocean Seismic Services (BOSS)**, the UK-based pioneer of autonomous robotic seismic nodes, successfully completed a series of passive and active trials in the North Sea.

When tested at various weights using a DP2 class Multi Role Vessel, BOSS's autonomous underwater vehicle demonstrated the ability to successfully and consistently couple to the seabed whilst acquiring high quality ocean bottom seismic (OBS) data for offshore exploration.

The results achieved represent a significant milestone towards validating the efficacy of this new technology and the marine seismic survey disruptor will now progress to additional seismic trials in multiple locations, followed by pre-commercial sea trials commencing in the first half of 2022 and continuing throughout the year in preparation for entering commercial operations.

Backed by investment partners **BP Ventures**, **Woodside Energy** and **Blue Ocean Monitoring**, the Company's underwater vehicles are focused on making the offshore seismic sector cheaper, faster, safer, and significantly less carbon intensive. ■

BOSS AUV



International Energy Week: Focus on the Energy Transition

Convened by the Energy Institute's sector experts, International Energy Week (IEW) 2022 will be the energy industry's first global meeting to assess the outcomes of **COP26** alongside the continuing recovery from the Covid-19 pandemic.

This conference builds on the renowned legacies and strengths of the world-renowned **IP Week**, bringing together senior figures from across oil, gas, and the wider world of energy, to explore the changing technologies, business models, and skills required to meet the energy needs of the world's populations and to achieve global net zero emissions by 2050.

With over two days of virtual engagement and one day of face-to-face presentations, **IEW** is essential for those leading on corporate strategy, business development, technological innovation and seeking to retain a competitive edge as the global energy transition accelerates.

Learn more about all aspects of the event at the IEW website. ■

CCUS: Be Part of the Future and get Involved!

CCUS (Carbon Capture Utilisation and Storage) is an essential component of delivering the UK Government's 2050 Net Zero promises. From **21–24 February 2022, SPE Aberdeen** and **PESGB** will host their second annual virtual CCUS Conference.

Designing wells for the different challenges of CO_2 injection is a relatively undeveloped skill set for most, so drilling and completion engineers face a range of new challenges which will be explored at the conference. Material selection and the qualification of completion equipment will require the supply chain and operators to collaborate closely.

What are some of the innovative ideas out there that can accelerate the adoption of CCUS with attractive business models? How do we choose storage locations and balance the conflicting benefits and challenges of repurposed 'brownfield' versus undisturbed 'greenfield' reservoirs and aquifers? What are the challenges of operating and monitoring CCUS facilities? What are the material and fluid property challenges?

We will share experience from capture sites through to transport infrastructure, enhanced oil recovery and injection facilities. All of these issues and more will be discussed in February so make sure you get involved, to be part of the future!

For more information, visit the SPE Aberdeen website. ■

More Data, More Detail, Higher Frequency

This month C&C Reservoirs have announced that they will be improving their content structure in 2022 to meet the needs of the energy transition in the upstream subsurface oil and gas industry. After more than 25 years, C&C Reservoirs' **Field Evaluation Reports** will be replaced with two new innovative report types: **Reservoirs Evaluation Reports** and **Basin Synopses**.

C&C Reservoirs

These changes will allow users of the **Digital Analogue Knowledge System (DAKS™)** to quickly and conveniently access the data that is most important to them, enabling a more efficient benchmarking of oil and gas assets against global analogues. DAKS users can expect to find more focused, detailed reports, along with a higher frequency of new and updated reports.

This transformation will begin to take effect from January 2022 when C&C Reservoirs will release the first batch of their new and improved reports. Over the next few years, C&C Reservoirs aim to convert all existing reports into the new formats whilst updating their contents to ensure their new Reservoir Evaluation Reports and Basin Synopses contain the most up-to-date information available.

For more information visit the C&C Reservoirs website. ■

NAPE 2022: Returns in Person

NAPE

The 2022 NAPE Summit returns as a live event to the **George R. Brown Convention Center** in **Houston**, Texas **from 8–11 February.** As the world's largest exploration and production expo, NAPE Summit provides a platform for buyers, sellers and investors in the energy industry to make deals and build relationships. On average there are 23 million prospect acres on display, 13,500 attendees, 850 exhibits and 36 countries represented every year. A variety of events will also be available for attendees at NAPE Summit including the Global Business Conference, Prospect Previews, Renewable Energy Pavilion, NAPE Week Seminars, Job Fair, and the Energy Innovation Case Competition. These events allow attendees the opportunity to augment their NAPE experience by hearing from industry leaders, continuing energy education, and connecting with young talent from all over the country. NAPE looks forward to welcoming everyone back to Houston and a total in-person experience for 2022. For more information on NAPE, please visit their website at NAPEexpo.com. ■

The Bear in the Room

Russia and European Natural Gas – Threat or Opportunity?

IAIN BROWN

A perfect energy storm has been brewing during 2021. A cold winter around the world in 2020 saw gas demand rising, severely depleting gas stores. Those reserves would normally be replenished over the summer, but gas output has declined because many major producers have been catching up with maintenance postponed during the Covid-19 pandemic lockdowns. This has meant natural gas storage in Europe is currently low at around 76 percent, according to Gas Infrastructure Europe. This time last year, it was at around 95 percent.

A Perfect Energy Storm

To add to this, calm weather reduced the amount of electricity generated by wind power, especially for countries like the United Kingdom and as a result, wholesale gas prices have more than quadrupled over the last year. This rise in global wholesale gas prices has been felt across all of Europe and countries that rely heavily on imported gas, such as Italy and Spain, have been particularly hard hit. Their governments have directly cut gas prices and raised taxes on energy company profits to try to address the situation.

For the UK, as one of Europe's biggest consumers of natural gas (over 85% of homes using gas central heating, and with around 30% of electricity generation from gas), the challenge is clear. Given the current supply issues, a harsh winter in Europe dramatically increasing demand could have very significant consequences.

Flexing Supply Muscle?

Russia has the largest natural gas reserves in the world (47,800 Bcm) and supplies much of the gas used by Europe (around one-third of the EU's gas consumption) and by 2035, the EU will need to import about 120 Bcm more gas per year. In terms of supply, Russia and Europe are somewhat co-dependent in that Europe is Russia's main market, and as long as its gas remains competitive, Russia is likely to remain Europe's main supplier and demand for gas is expected to continue, owing to its lower CO_2 emissions compared with coal and oil. This suggests that in the medium term at least, the EU will need to import more gas, especially as the European production outlook for the major gas producers such as the Netherlands and UK, as well as Norway, are falling.

How much Russian gas Europe imports in the future will depend on competition between Russian gas and other sources such as LNG. Suppliers from many different countries now compete to supply the EU internal market. In addition to import pipelines, there are currently 22 LNG terminals in the EU which can receive LNG from anywhere in the world. With a capacity of 216 Bcm, these terminals could import 50 percent of the EU's current demand, but they are currently only utilised at some 27 percent of capacity.

When Russian President Vladimir Putin indicated in early October that Russia could be ready to ease Europe's energy crisis, the markets breathed a collective sigh of relief, but some European politicians and experts are concerned that Russia is attempting to pressure regulators to approve the newly completed Nord Stream 2 pipeline, which will have the capacity to meet about one-third of the EU's import requirement. Other experts argue that Russia doesn't have sufficient spare gas and is trying to fill up its own storage facilities ahead of winter.

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Pipeline Politicking

Nord Stream pipelines. Nord Stream 1 (yellow) and Nord Stream 2 (green).

Nord Stream 2 will deliver gas to Europe from the vast natural gas field Bovanenkovo, located in Northern Russia's Yamal Peninsula, which holds some 4.9 trillion cubic metres of gas reserves and is expected to produce gas until at least 2028. This field alone holds more than twice as much gas as the total proven reserves of the EU (1.9 trillion).

The pipeline will travel 1,230 km through the Baltic Sea, starting from the Russian coast at Narva Bay and reaching landfall near Greifswald in Germany. It will run roughly parallel to the existing Nord Stream pipeline.

Some experts argue that Putin wants to pressure the European Union to rewrite its gas market rules and to push the EU away from spot-pricing toward long-term contracts favoured by Russia's Gazprom. Seeking rapid certification of the Nord Stream 2 pipeline to boost German gas deliveries could be part of the strategy.

Why is Nord Stream 2 such a sensitive issue? Part of the challenge is Ukraine's concern that the new pipeline will tighten Moscow's grip over the region's energy supply and further strengthen its influence. During German Chancellor Angela Merkel's final visit in October to Kyiv before leaving office, she acknowledged Ukrainian President Volodymyr Zelensky's concerns over the project. As well as unease about the regional energy supply balance, Mr Zelensky is worried about what happens in three years when the contract to deliver Russian gas through Ukrainian pipelines terminates. The loss of billions of dollars in transit fees would hit Ukraine's economy hard.

Mrs Merkel, who also held talks with the Russian President, promised to provide more than a billion dollars to help expand Ukraine's renewable energy sector but also said sanctions could be used against Moscow under an agreement between Germany and the US, if gas was "used as a weapon".

Healthy Scepticism or Not?

These complex factors may also be overprinted by a degree of paranoia around Russia's intentions should Europe become too reliant on Russian gas. But is this concern premature? According to the statistics that Gazprom has been publishing over the last few quarters, it seems that they are close to their full productive capacity, and it could therefore be very challenging for them to simultaneously meet domestic demand, replenish their own storage facilities, and meet their export commitments to Europe in the short term.

The concerns around Ukrainian gas transit fee losses are not clear cut. In 2018 Gazprom delivered more than 200 Bcm of gas to Europe (including non-EU countries), of which 87 Bcm transited through Ukraine. With forecast sales of over 200 Bcm to Europe beyond 2019, Gazprom sees a continuing role for Ukraine and looking further ahead, the steep decline in European gas production will leave a supply gap to be filled by increased imports of approximately 120 Bcm per year. Nord Stream 2 will be able to transport 55 Bcm per year, so even at full capacity it could not meet all the extra demand, theoretically retaining a need for Ukrainian pipeline capacity. This does not mean that Russia couldn't put pressure on Ukraine by restricting gas supplies through their territory, but it would be a lose-lose scenario.

There has also been concern that Germany undermines EU energy solidarity by supporting Nord Stream 2, but because of the increasingly integrated and interconnected nature of the EU internal gas market, this is a project that could benefit all of Europe. The offshore pipeline will be connected to the EU internal market at the German landfall, from which gas can flow anywhere it is needed in Europe, at prices set by the market.

The reality is that with EU gas production projected to decline by half in the face of continuing demand for gas, Europe's future energy security will depend on reliable imports and this supply gap will need to be closed by Russian gas and LNG in competition with each other – or some other supply. The EU has created a functioning internal energy market in which natural gas competes with other energy sources – and gas-exporting countries compete to supply the market.

A Short-term Problem?

The EU may be hoping the current gas crisis is a short-term phenomenon, but it would be unwise to assume so. A very mild winter might allow Northern European countries to limp through until gas demand slackens in the spring and gas stores replenish, but longer term, secure gas supplies will be needed. If less reliance on Russian gas is considered a good thing, then perhaps working to improve Europe's indigenous gas supply situation might be sensible – though environmental, social and corporate governance barriers seem to be an impediment to progress here. At least until the lights go out. ■

A Sleeping Giant

HEATHER SAUCIER

The Texas Gulf Coast is primed to become a top producer of clean hydrogen.

As the United States pours funding into the development of clean, reliable energy, the competition among candidates – including geothermal, nuclear and batteries – seems like a horse race as each resource perfects its competitive game. Yet a pocket along the Texas Gulf Coast appears to have a leading edge when hydrogen comes into play.

The area, abundant in refineries and petrochemical plants, is already the top producer of hydrogen in the country, having long produced the gas through steam methane reforming. The hydrogen is transported through hundreds of miles of pipelines and ultimately sold by companies such as Linde, Air Products and Air Liquide. Located along the Gulf Coast, these companies all have access to the area's geologically unique and vast salt caverns – the world's largest subsurface hydrogen storage site.

While the 3.6 metric tonnes of hydrogen currently produced in Texas creates CO_2 emissions, many believe the state is primed to become the leader in the production of clean hydrogen for wide-scale energy use. By integrating Carbon Capture Utilisation and Storage (CCUS) to the reforming process, a product called 'blue hydrogen' can be produced when the CO_2 by-product is stored in the sandstone reservoirs near the Gulf Coast.

To make 'green hydrogen', or hydrogen produced from renewable energy, Texas emerges as a potential leader once again. The state is the No. 1 producer of wind energy and in some estimates the No. 2 producer of solar energy in the country. Practically surrounded by depleted oil and gas reservoirs and natural gas pipelines – all which have potential for storing and transporting hydrogen – West Texas's expansive solar and wind farms could become the top producers of what many consider the cleanest hydrogen.

"Texas is geared for a hydrogen surge that could revolutionise its already thriving energy industry by providing a clean fuel that will cut emissions, and the state can export to others in need," states the Fuel Cell & Hydrogen Energy Association. "By bringing hydrogen into the fold and proving its viability, Texas has the potential to spread the technology to surrounding states and be integral to a nationwide hydrogen economy."

Hydrogen Economy

To fill the gaps inherent in intermittent renewable power, blue or green hydrogen is the only large-scale energy storage solution that can provide carbon-free, commercial scalability, said Brian Weeks, senior director of Business Development for GTI Energy, which is a partner in a government-funded initiative with the University of Texas at Austin (UT) to demonstrate clean hydrogen projects.

The US Department of Energy (DOE) reported that last year, 99 percent of hydrogen produced in the United States was 'grey hydrogen', named as such because of its CO_2 by-product.

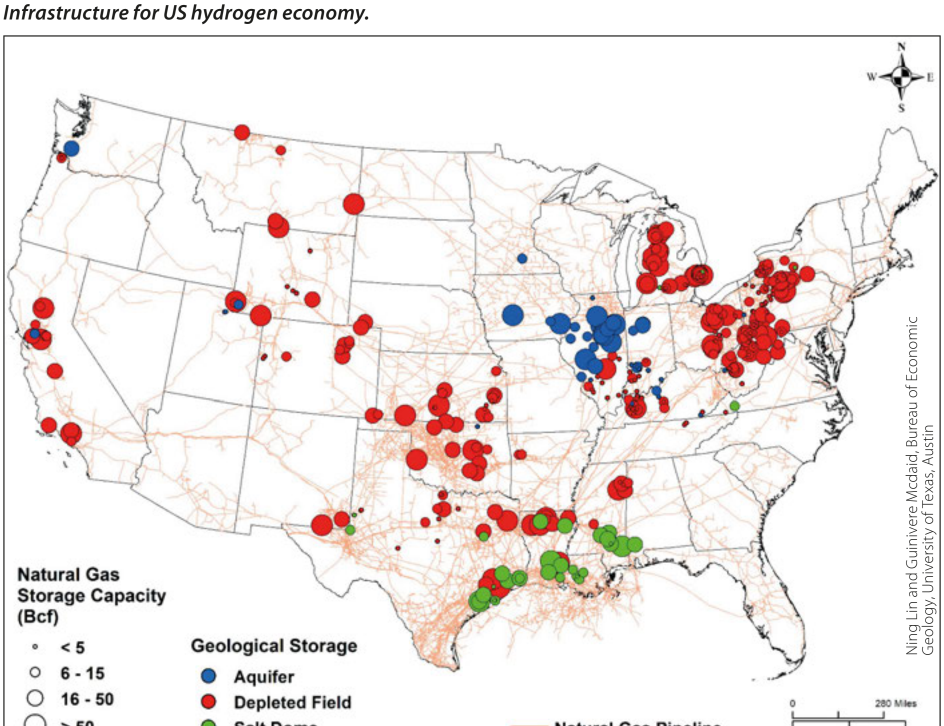
Hydrogen production is anticipated to rise. By 2050, the hydrogen economy could lead to an estimated $750 billion per year in revenue and a cumulative 3.4 million jobs, according to a 2019 'Road Map to a US Hydrogen Economy' study commissioned by the Hydrogen Fuel Cell Trade Association.

If technology and the markets can support clean hydrogen, there is potential for a 16 percent CO_2 emissions reduction by 2050, provided there is a five-fold increase in clean hydrogen use, states the DOE.

The US government has funded tens of millions in projects to advance next-generation clean hydrogen technologies, and $400 million in hydrogen-related projects has been requested in the President's Fiscal Year 2022 budget, up from $285 million in FY 2021.

Currently, hydrogen is predominantly used in the petrochemicals industry, but blue

Infrastructure for US hydrogen economy.



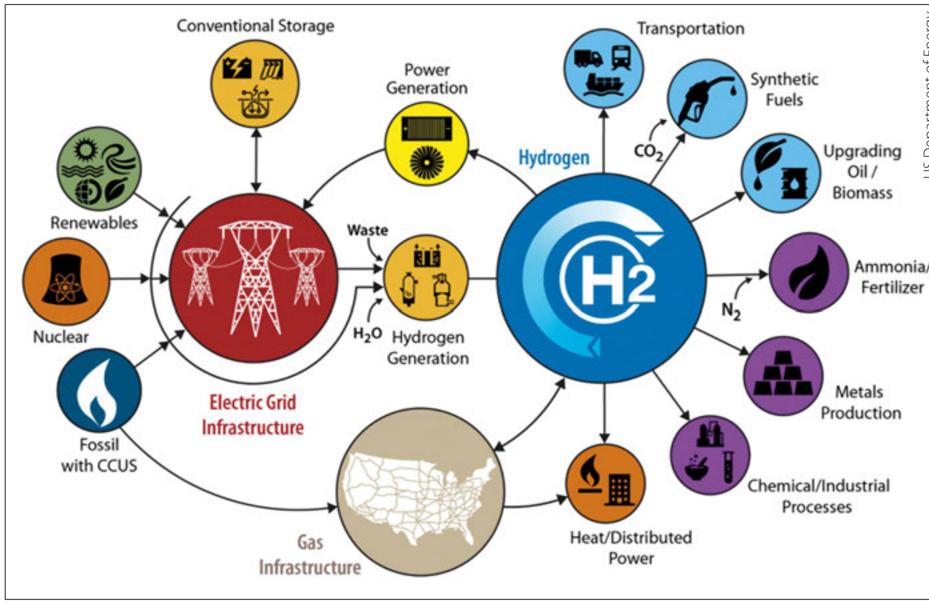
or green hydrogen could expand the gas's use as a clean replacement fuel for the manufacturing of steel, cement and green ammonia. It also has the potential for fuelling heavy trucks and shipping vessels. And, hydrogen can be burned in gas turbines or run through fuel cells to generate cleaner electricity.

Along the Gulf Coast, a transition to blue hydrogen seems an obvious first step in the eyes of Andy Steinhubl, a former production operations engineer for ExxonMobil, energy consultant, and chair-elect of The Center for Houston's Future, a non-profit organisation that addresses matters of high importance to the Greater Houston region.

"Greater Houston is a sleeping giant," he said. "We make a lot of grey hydrogen. But we could start converting grey to blue by tapping existing CCUS surface and subsurface assets and could readily scale such a system."

He believes the infrastructure developed by Denbury for enhanced oil recovery via CCUS could potentially be linked by pipeline to Texas's steam methane reforming plants to capture CO_2 emissions and jumpstart production of blue hydrogen. "If we start making blue hydrogen, we can start supporting existing and new markets while we begin incentivising and driving down the costs of production of green hydrogen," Steinhubl said, explaining that current estimates place a higher cost on green hydrogen.

In line with this vision, companies including ExxonMobil, Calpine and Dow recently announced a consortium to develop a regional CCUS system once a viable economic framework is established.



The Hydrogen Economy and Infrastructure.

Upscaling to Blue

While the Gulf Coast's salt caverns – which allow for rapid injection and production – have long been used for hydrogen storage by the petrochemicals industry, storing hydrogen for large-scale energy needs will likely require that the gas be stored in other geological formations, including sandstone and carbonate reservoirs, said Mark Shuster, deputy director of the Energy Division for the Bureau of Economic Geology (BEG) at UT.

Large-scale CCUS activities will require extensive CO_2 storage as well. Currently, pilot projects led by the DOE and the BEG both onshore and in state waters are looking at potential storage sites.

"Hydrogen made from natural gas through steam methane reforming and autothermal reforming is the cheapest way to generate blue hydrogen, even if you make cost assumptions about carbon storage," Shuster said. "We (the United States) can generate plenty of hydrogen – 10 million metric tons per year – but we do not have large-scale CCUS. That is the critical next step to producing blue hydrogen."

Many believe it's only a matter of time before government incentives – such as the tax credits offered for CCUS in accordance with Section 45Q of the Internal Revenue Code – make large-scale CO_2 storage economically feasible. In fact, the DOE is currently funding initial engineering of a commercial-scale advanced CCUS system from steam methane and autothermal reforming plants.

In order to move hydrogen beyond the Gulf Coast and into larger markets, Shuster said there is potential for blending hydrogen into the country's extensive oil and gas pipeline network – totalling roughly 3 million miles of pipelines with 4.25 Tcf of storage.

"The gas infrastructure system in the US is the most expansive and connected gas network globally and could be used to transport and distribute renewable methane and hydrogen," Shuster wrote in a May 2021 publication of Oil & Gas Journal. "If it were, it would be a bridge to a full-scale hydrogen economy in the United States."

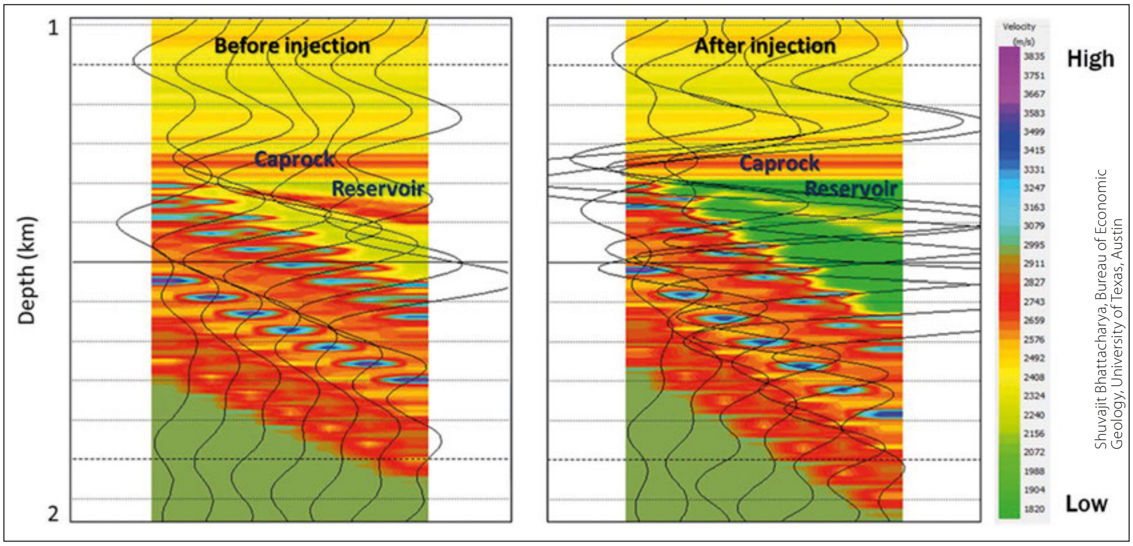
Furthermore, large turbine manufacturers are looking at hydrogen blends for their equipment to improve emissions profiles, Weeks said. "That's another application along the Texas Gulf Coast."

A blend of natural gas and no more than 10 percent hydrogen produced alongside CCUS would have an "appreciable impact" on reducing emissions, Shuster said.

Based on an average daily natural gas consumption rate of 85 Bcf, with each Bcf containing approximately 53,000 tonnes of CO_2, a 10 percent blend of blue hydrogen could remove 450,000 tonnes per day of CO_2 from natural gas emissions, he said. This represents roughly 3.2 percent of total CO_2 emissions in the United States in 2019.

Going Green

In West Texas, where the wind blows hardest at night, peak energy production often crosses paths with periods of low consumption, creating an excess of low-cost energy that cannot be



Migration of CO_2 within reservoir must be monitored through 4D seismic and other methods to ensure cap rocks are not breached and the gas remains in place.

stored. As a result, utility companies are becoming interested in converting this energy into hydrogen via electrolysis and storing it for future use.

"Electric and gas utilities were never interested in hydrogen before until recently," Weeks said, adding that storing hydrogen will allow more renewables to come online, and the natural gas grid can help the electric grid store energy.

This power-to-gas concept is being explored in several ways: transporting the hydrogen by pipeline, truck or rail to more populated areas of Texas, and storing it on site in depleted oil and gas reservoirs and natural gas pipelines, Weeks said.

"If we want to have a significant hydrogen market in the near term, we need to build on our existing assets," he said. "That is the quickest way to get to zero carbon goals."

Similar to blue hydrogen, green hydrogen does not come without challenges. Current electrolysis technology is considered outdated and costly, practically mandating that the production of hydrogen occur during times when renewable power is cheapest.

To store greater volumes of hydrogen, optimisation in existing salt caverns may be needed in addition to testing other geological reservoirs for large-scale storage, Shuster said.

However, with California leading new hydrogen market development in fuel-cell vehicles and hydrogen fuelling stations, there is potential to transport hydrogen via pipeline by repurposing an existing pipeline corridor from Texas to the West Coast, Steinhubl said.

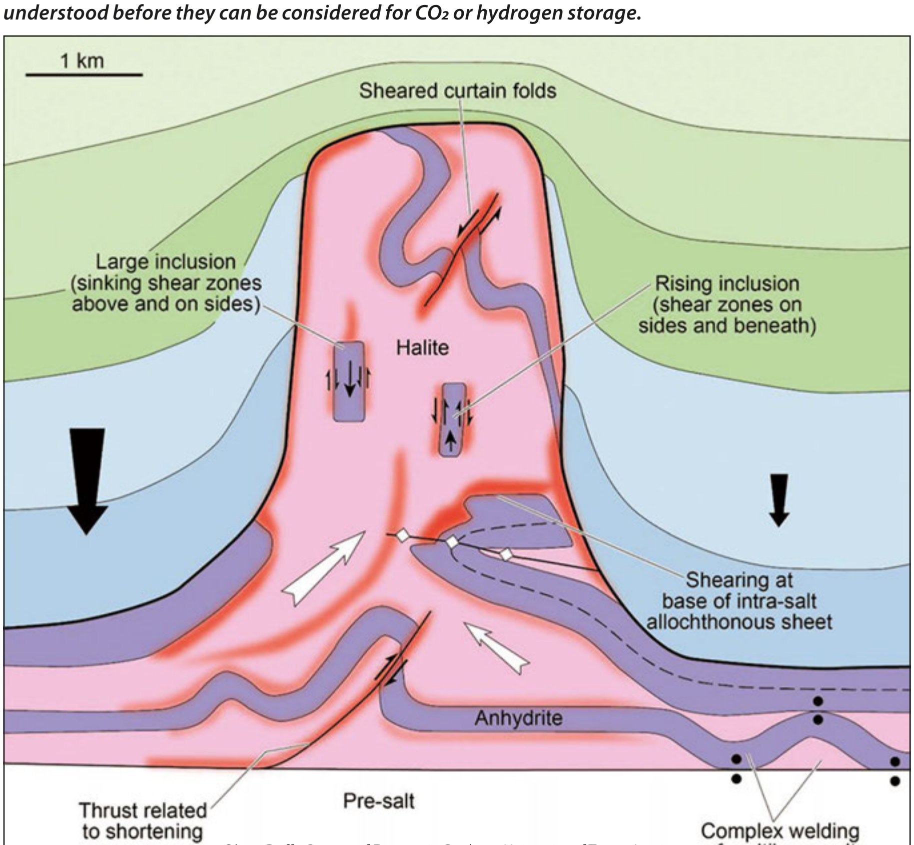
Early market potential also exists in Europe. "The Netherlands, Germany, they are all trying to find qualified suppliers," he added. "They can't get nearly the hydrogen they need to meet intermediate and 2050 objectives. The world is going to need exporters."

Emerging Market

Realising the Gulf Coast's potential, the DOE, through its H2@Scale initiative, has invested $5.4 million in a two-part project to better understand the potential for integrating hydrogen with multiple platforms throughout the economy.

The project, currently taking place at UT, includes a demonstration of clean hydrogen production from electrolysis and from steam methane reforming using renewable natural gas from a landfill. The hydrogen is then used as a power source for a data centre on campus.

The geology and internal structure of salt domes and caverns must be fully investigated and understood before they can be considered for CO_2 or hydrogen storage.



Furthermore, the University is home to Texas's only hydrogen fuelling station, which is being used to help demonstrate to local legislators the benefits of fuel cell vehicles as part of the project.

"People trained in oil and gas are very well suited for applying hydrogen and using their skills in the Houston economy and decarbonisation machine. Texas is very well suited for that," said Alan Lloyd, a research associate at the University's Center for Electromechanics (CEM) and former secretary of the California Environmental Protection Agency under Gov. Arnold Schwarzenegger, a supporter of hydrogen.

From a broader scope, the H2@Scale project includes developing a framework for leveraging Texas's wind power, its natural gas resources and hydrogen infrastructure at the Port of Houston and Gulf Coast region.

When Steinhubl looks at Houston's bustling port – the nation's No. 1 port in total foreign and domestic waterborne tonnage – he sees an ideal point of entry for clean hydrogen in heavy trucking.

Located among a sea of steam methane reformers, with hydrogen supplies practically on site, the port is a major hub for transport trucks. When compared to diesel fuel, both grey and blue hydrogen are competitively priced, lower emitting, and they can boast being lighter weight and faster fuelling with high ranges compared to an electric battery, he said.

"Tapping high density trucking corridors minimizes the infrastructure required to achieve meaningful scale regionally, thereby improving the economics of market entry and expansion," Steinhubl said.

According to the International Energy Association, fuel cell electric vehicles could reach 8 million by 2030 in developed nations and a 25 percent share of road transport by 2050.

Mountains and Milestones

While the potential for clean hydrogen abounds, there are large hurdles to overcome. Hydrogen can be stored indefinitely as a compressed gas, but ample and effective storage for hydrogen and CO_2 must be identified and sufficiently tested.

Transporting hydrogen beyond the region will require additional hydrogen-dedicated pipelines or effective blends with natural gas into existing natural gas pipelines. Both scenarios will require extensive modelling to determine their feasibility, Shuster said.

In addition to the need for large-scale CCUS systems and more efficient electrolysis, the majority of hydrogen proponents in Texas agree that a major missing piece to a clean hydrogen market is policy.

"You've got a lot of activity from the corporation side, but where are policy drivers?" Lloyd asked.

Unlike California, where the Low Carbon Fuel Standard is leveraging a clean energy market, Texas – which is not a policy mandate-driven state – trails by comparison. If the federal government would notch up 45Q tax credits, for example, "we could unleash all kinds of blue hydrogen," Steinhubl said, adding that forming a coalition of players across the hydrogen value chain could break open the budding industry.

"Government investments in R&D enable the private sector to advance a lot faster," said Bob Hebner, director of UT's CEM. "There is great interest in inventing new market structures. I would not be surprised to see changes well within the next decade or half that time. But progress requires money on the table."

Lloyd believes the large budget items for clean hydrogen in the current infrastructure bill will shift things into gear. "If this infrastructure bill gets signed, money will be coming," he said.

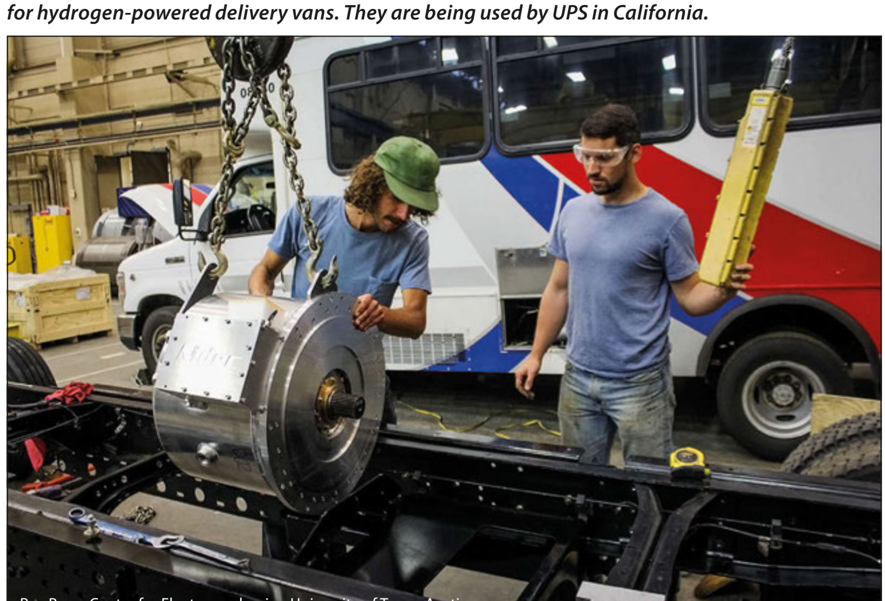
The Center for Houston's Future has applied for funding from the DOE's Energy Earthshots initiative to help create a clean hydrogen hub in the Greater Houston area for heavy trucking and exports of blue and green hydrogen.

Yet the energy industry is already breaking barriers. New technology to decrease the cost of steam methane reforming and produce pure streams of hydrogen and CO_2 – bypassing the need for carbon capture – is on the horizon, Weeks said, noting that CO_2 storage would still be required.

Utility Global, which has reported the development of an electrolyser that is less costly and more effective than current technology, has announced plans to relocate to Houston from Utah. And, the utility Entergy is developing a power plant near Bridge City, Texas, that will be capable of burning a combination of natural gas and hydrogen for electricity.

"The more I look at Texas, I say, Wow, we've got solar, wind, caverns, the ability to have world-scale hydrogen production," Steinhubl said. "We can be the energy transition capital of the world and the low carbon leader as well. It's clear we have a path. When it happens, it's going to be quite powerful here." ■

Students from the University of Texas at Austin have been designing a fuel cell hybrid powertrain for hydrogen-powered delivery vans. They are being used by UPS in California.



Roy Pena, Center for Electromechanics, University of Texas, Austin

Offshore Colombia:

Discovering New Value in Legacy Data Using Modern Workflows

ION's newly reprocessed ~60,000 km 2D seismic data provides the ideal platform to support renewed exploration efforts in Colombia after recent gas discoveries. The Pre-Stack Time Migration (PreSTM) seismic section, seen below, is the result of modern, proprietary workflow applications. Eighteen vintage surveys that make up this project are now a single, contiguous survey. This work has revealed key details of the Caribbean Large Igneous Province (CLIP) and the southern transition to the South American margin. Key regional units and unconformities can now be mapped with a higher confidence for a better understanding of the tectonostratigraphic framework. In the southern region of the basin, internal features are now imaged in the structurally complex Sinu Prism and the South Caribbean Deformed Belt. Initial observations include a well-imaged Moho across the Colombian Basin, which now allows for a better understanding of the CLIP's crustal architecture.

Colombia Caribe Reprocessing Regional Transect

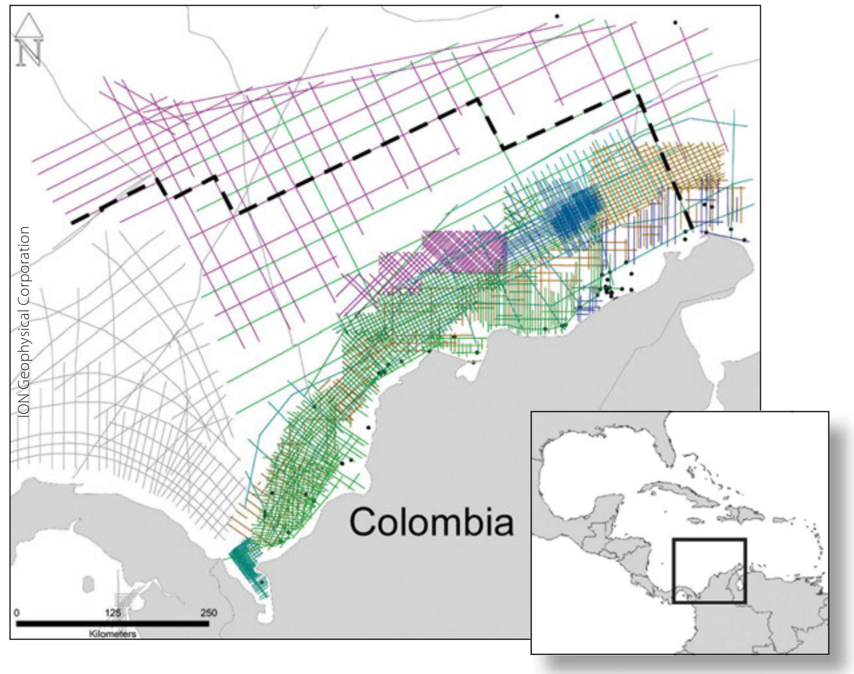
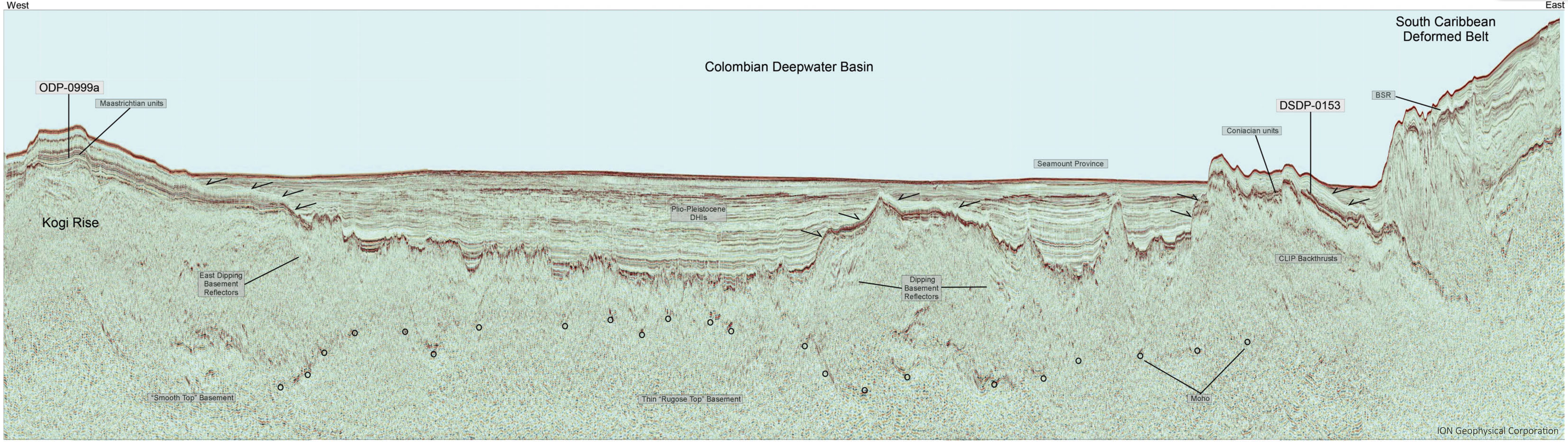


Figure 2a: Basemap showing ION's Colombia Caribe Reprocessing project, highlighting the 18 vintage surveys in offshore Colombia, PanamaSPAN and AntillesSPAN of the western Caribbean.

Figure 2b: Regional transect line across the Colombian Basin, tying the ODP-0999a and DSDP-0153 research boreholes.



Newly Integrated 2D Data Highlights the Prospectivity of Offshore Colombia

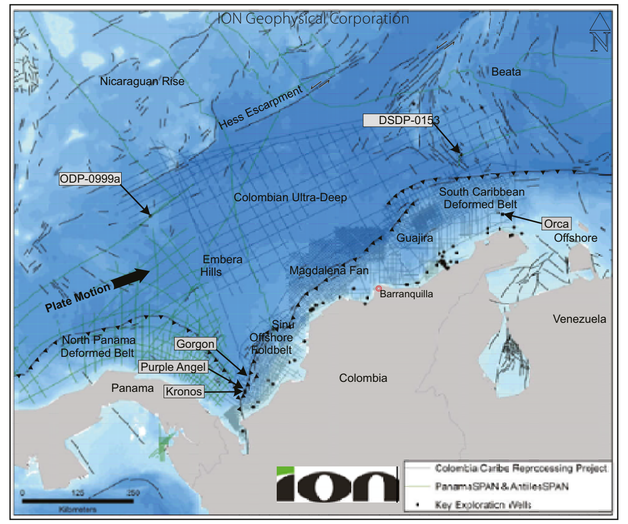
KYLE REUBER, ANTARA GOSWAMI, DARREN JUDD and SHIHONG CHI; ION

Colombia's offshore potential has been highlighted by recent discoveries in the deepwater sector. Petrobras's Orca gas discovery was the first significant find in 2014, followed by Anadarko's Kronos, Gorgon, and Purple Angel gas discoveries from 2015 to 2017. These exploration successes have renewed the interest in offshore Colombia with many operators targeting analogue structures along the margin in the hope of similar discoveries.

Recently, ION partnered with Colombia's National Hydrocarbons Agency (ANH) to reprocess and depth image the entire 2D seismic database in offshore Colombia. This undertaking has resulted in significant uplift of the data quality and has revealed new insights about the northern margin of Colombia and the Caribbean Plate.

The project extends over 60,000 line-km from 18 surveys acquired between 1982 and 2014 with varying record lengths and acquisition parameters. The Colombia Caribe data covers much of the central and western Caribbean (Figure 1). The contiguous framework provided by this project now seamlessly connects the major exploration areas and play fairways. Unlike many offshore basins, the Caribbean is highly complex and is considered to have active margins on all sides. This setting results in the formation of fold and thrust belts and subduction zones (Figure 1). The transcurrent motion of the Caribbean Plate along the Colombian margin has created the Sinu Accretionary Prism and the South Caribbean Deformed Belt (SCDB). The Colombia Caribe data covers the majority of the central and western Caribbean (Figure 1).

Figure 1: Regional tectonic framework map of the western Caribbean. Seismic coverage for the region is also shown: Colombia Caribe (grey); and ION's existing Caribbean data (green).



Exploration in the Caribbean has always been challenged by the lack of ability to constrain data points across the basin. The regional transect (Figures 2a and 2b in the main foldout) highlights the basin architecture between the ODP-0999a and the DSDP-0153 boreholes and the importance of constraining data points across the basin. This is a significant step forward, as these are two important locations that provide stratigraphic ages for the region. Additionally, understanding the basement framework has been hampered by the lack of crustal-scale imaging using vintage data. By using the reprocessed data, a complete and accurate assessment may be performed.

Legacy vs. Reprocessed Data

The approach to the reprocessing of vintage seismic data has been proven repeatedly as a strategic means to revisit and de-risk frontier basins. The processing can be split into separate parts for the Colombia Caribe Project: signal processing and velocity model building/imaging to produce the pre-stack time migration (PreSTM) and pre-stack depth migration (PreSDM) products. The two key factors within the signal processing stage to help improve the data quality were: 1) ION's experience with reprocessing older, multi-vintage surveys and 2) the application of modern demultiple and deghosting techniques to produce cleaner, broader frequency sections when compared with the legacy data. During the PreSDM velocity model building, the aim is to produce geologically consistent velocity models that would tie across all surveys and lines over the region. ION's 2D imaging workflow takes into account all the line ties and pseudo 3D velocity models that are created during model building to ensure lines tie correctly at intersections. This, along with incorporating well and gravity data and the interaction between ION's geologists and geophysicists, were key in producing the PreSDM images.

Legacy data near the SCDB captures the down-going Caribbean Plate at the South American margin (Figure 3a). This vintage seismic profile illustrates the exploration challenges associated with using legacy data that lacked a high quality image of the subsurface.

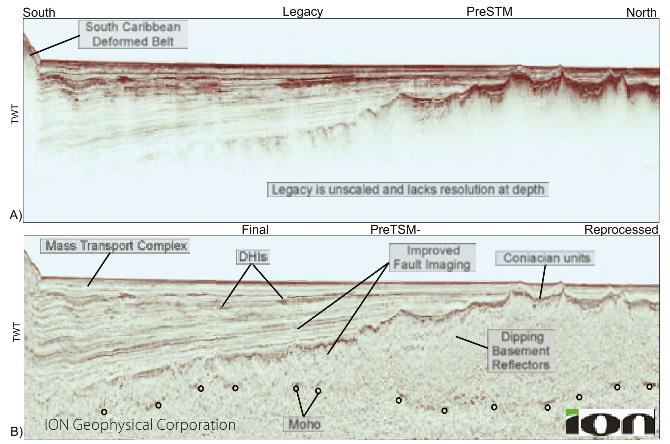


Figure 3: a) Legacy dip-line from offshore Colombia at the SCDB and down-going CLIP. b) The reprocessed data reveals many details within the data, including crustal features and high-frequency stratigraphic units.

Figure 3b is the 2021 reprocessed two-way-time (TWT) version of the line. The uplift of the data is clearly visible and exemplifies the value in the reprocessing approach. Figure 3b shows a traceable Moho at the base of the CLIP being obliquely subducted under South America – a feature that has been absent from 2D seismic data in the Caribbean, until now. Intra-basement faulting of the down-going Caribbean Plate is now imaged and the variability of crustal thickness can be assessed across the basin. Crustal flexure in this oblique subduction setting can now be more accurately assessed with the basement architecture details revealed.

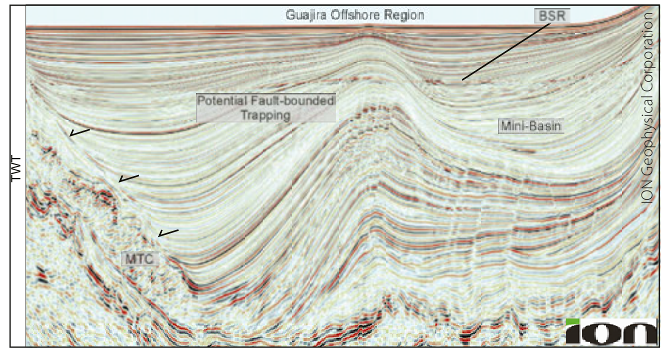


Figure 4: Example line from the SCDB. These units show normal faulting at the anticlinal crest, a bottom-simulating reflector (BSR) and potential trapping mechanisms.

Included in the processing uplift is a clear basal-stratigraphic-unit/basement interface. This contact boundary is critical to understanding the Caribbean region, as nearly all of the CLIP is capped with volcanic flows related to the Galapagos Hotspot interaction in the Pacific Ocean.

The northern margin of Colombia hosts very complex geology in terms of stratigraphy and structure. Figure 4 highlights the intensely structured region of the Guajira region where mini basins were formed between folds and thrusts. The bottom-simulating reflector (BSR) is also a common feature, possibly indicating the presence of gas hydrates. Progressive deformation occurs as the Caribbean Plate continues to move eastward relative to the South American Plate and creates excellent trapping geometries for exploration along the entire transition zone.

DHIs and AVO Analysis

Direct hydrocarbon indicators (DHIs) are a common feature in offshore Colombia represented by seismically bright amplitude anomalies, as shown in the Sinu Offshore example (Figure 5a). These anomalies are commonly present at fault discontinuities, pinch-outs or on structural features. An AVO (amplitude variation with offset) analysis is the next step to determine the presence of hydrocarbons in a reservoir-bearing unit through qualitative interpretation of these DHIs. This is performed through a seismic gather-scaled evaluation to differentiate between a brine and an oil/gas-filled reservoir. In this case, a more accurate interpretation of the results is aided by the improved quality of the conditioned seismic gathers and the integration of well

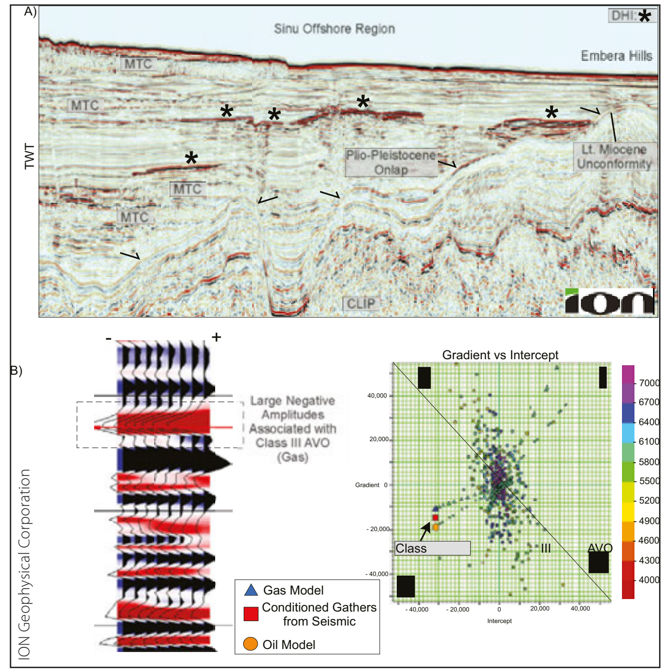


Figure 5: a) A Sinu Offshore example area that features multiple mass transport complexes (MTCs) and seismically bright DHIs in the stratigraphy. A prominent Late Miocene unconformity is present across the region. b) AVO analysis indicates a strong oil/gas signature of a Class III AVO.

data. Results from one analysis shows a strong Class III AVO, indicating the presence of oil/gas within a reservoir unit (Figure 5b). This is an important result, as it further supports continued exploration in Colombia and modernised seismic indicate that these targets are plentiful in the basin.

The benefits of a regional scale, internally consistent and cohesive seismic and velocity framework have been proven repeatedly. The success of the vintage seismic reprocessing efforts and the AVO results presented here, illustrate the potential for continued exploration successes in the coming years from the Colombian Basin. ■

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A Carbon-Free Russia: Barriers and Opportunities

JANE WHALEY

Russia has ample oil and gas reserves to both supply energy to all its people and earn huge revenues from exporting fossil fuels, so what incentives are there for it to opt for a carbon-free future?

Russia is deeply dependent on its bounteous fossil fuel resources. Oil, gas and coal account for more than half the central government's revenue, and the associated industries are responsible for a fifth of the country's GDP. As a result, Russia is the fourth biggest emitter of greenhouse gases in the world.

This vast country also possesses huge renewable resource potential, including hydropower, solar and wind, green hydrogen and huge swathes of forest and arable land for bioenergy. It has the level of technological development required to foster an energy transition towards renewable resources, yet it lags behind other world powers in its deployment of renewables. In 2020 solar, wind, geothermal, and small-scale hydropower accounted for just 1% of the nation's energy supply.

Little Interest in Climate Policies

Russia possesses the world's largest natural gas resource, the second largest reserves of thermal coal, and arguably the sixth largest oil reserves, going a long way towards explaining this apparent lack of interest in renewables. It globally exports more gas than any other country, and in 2021 it is expected to produce about 9.6 MMbopd, over half of which will be exported. This is a huge economic input and the signs are that Russia intends milking it for as long as possible.

The economic reliance on fossil fuels is tied closely to political and cultural issues, including climate change denial. For many years the Kremlin suggested that other countries would suffer more from climate change than Russia, who could consequently benefit economically, although with approximately 60% of the country in the vulnerable permafrost zone, this argument is unsustainable. Public support for an ambitious policy of reducing emissions and transitioning to a carbon-neutral energy system is low and therefore politically not a high priority.

Russia was one of the few countries not to submit an ambitious climate strategy ahead of COP26, but this year President Vladimir Putin did pledge that Russia would achieve net zero carbon by 2060. He also introduced the first ever Russian greenhouse gas emissions legislation, with a planned cut of 79% by 2050. In recent years there have also been some more encouraging pronouncements supporting cleaner energy sources including, since 2013, incentives for renewable

Sayano-Shushenskaya, in the south-western part of Eastern Siberia, is the largest hydroelectric project in Russia. It went online in 1978 and has an average annual production of 23.5 TWh.

The BN-800 commercial fast breeder reactor at the Beloyarsk nuclear power plant in central Russia.

energy developers, with a tariff system to encourage the use of Russian-made components.

History of Alternative Energy

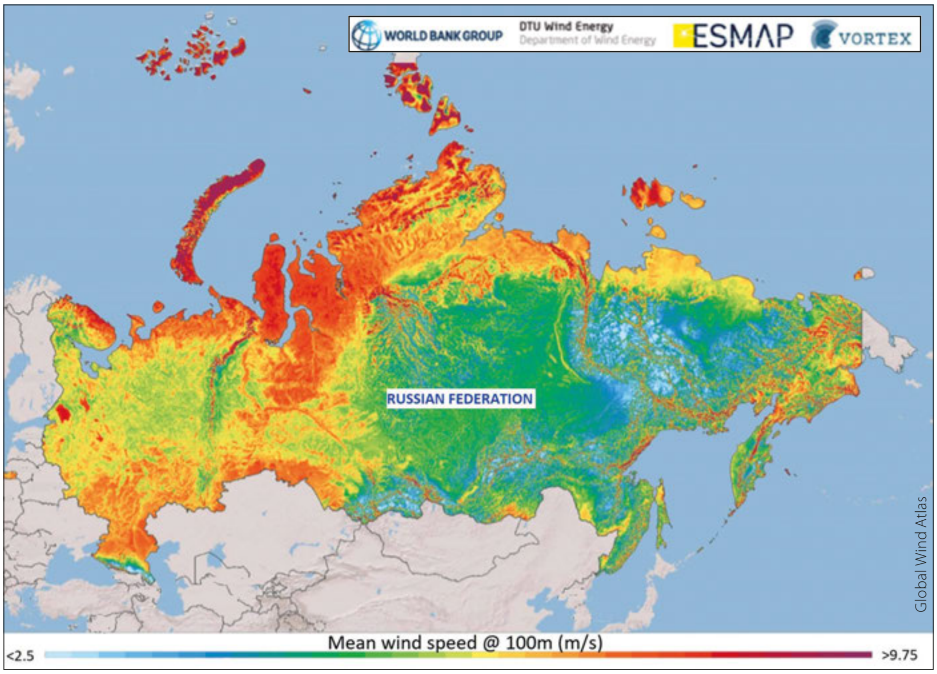
Despite the emphasis on fossil fuels, Russia has been actively harnessing non-fossil fuel energy sources for many years. Hydroelectric projects began in the 1930s and a number of large dams were built in the '50s and '60s, although many fell into disrepair in the post-Soviet recession. The country currently has about 100 hydroelectric plants with a capacity of over 100 MW, and ranks fifth in the world for hydropower production. Around 20% of Russian power is sourced from hydropower but it has been estimated that only a fifth of Russia's hydropower resource, potentially up to 852 TWh, has been accessed, although much of this yet-to-be exploited potential is found in areas far from major user centres.

Geothermal energy has also been tapped in Russia for over 60 years. The first geothermal station was built in 1966 in Kamchatka, where the power is used for heating buildings, whilst in other areas geothermal energy is used directly, in cattle and fish farming, drying agricultural products, and heating greenhouses and swimming pools. Many regions have potential for this resource, with hot geothermal liquid accessible in the northern Caucasus, the Baikal Rift area and Western Siberia, as well as Kamchatka, where thermal water reaches temperatures in excess of 300°C.

Another non-fossil fuel energy source, nuclear power, has long been important in the Russian energy mix. Possessing plentiful uranium resources, Russia actually built the world's first nuclear power plant, a 5 MW reactor, in Obninsk, about 100 km south-west of Moscow, which was connected to the grid in 1954. Currently, the country operates 38 nuclear power reactors and sees the role of nuclear, which at present accounts for about 20% of Russian power, increasing in the future, with research concentrated on the development of new reactor technologies and also in building floating nuclear power plants, primarily in the Arctic.

Wind and Solar Potential

Russia's first windmill for generating electricity was built in 1941, but progress in this sector has been slow, although the production of electricity from wind has increased by 30% since 2000 – reportedly nearly 70% in 2018 alone. There is huge potential for development in this area; it has been estimated that wind power could produce as much as 17,000 TWh and it could account for 11% of total energy capacity by 2030. Much of Russia is ideal for the development of wind farms, especially the North-western, Southern, Siberian, Ural, and Far Eastern Federal Districts, where there are large amounts of unoccupied land. In the more remote areas, which tend to rely on old diesel power stations, it would seem an obvious solution. The slow pace of wind energy development is partially due to the harsh climate, as well as logistical issues and technical problems, like a lack of proven solutions for integrating wind generators with diesel power stations.



Mean wind speed map for the Russian Federation showing potential for wind power. Very little has been harnessed to date.

Solar power has been particularly slow to develop. The first plant opened in 2010 but installed capacity has since increased quite rapidly to about 1.3 GWh by 2019. A number of projects are now under construction, with the tariff system encouraging several recent joint ventures, including a 45 MW solar power plant that opened in March 2021 in the Buryatia region, close to the Mongolian border, which boasts 300 sunny days a year. It has been estimated that the country has a gross solar energy potential of over two million tonnes of coal equivalent, with the Black and Caspian Sea regions, North Caucasus, Far East and Southern Siberia being the areas where solar energy could be most readily accessed. It is suggested that even Russia's many Arctic settlements could benefit from hybrid solar-diesel power stations that would cut costs and solve supply chain and shortage problems.

Further Green Potential

With its vast uninhabited land area, including about 20% of global forests, and large quantities of agricultural waste, Russia is thought to possess the world's largest biomass resources. It is one of the biggest producers of wood pellets and the industry is expanding fast, although it should be remembered that the forests are an important carbon sink. It is thought that the country currently only makes use of 12% of its bioenergy potential.

Tidal power also has potential. One of the world's largest tidal power plants, Kislaya Guba in the Barents Sea, with a total capacity of 1.7 MW, was built in 1968 and there are plans to develop a huge 87 GW project at Penzhin Bay in the sea of Okhotsk, which has an average tidal height of 10m.

In addition, harnessing the country's biomass, solar and wind resources will help Russia create more green hydrogen. There have been recent moves to develop the use of hydrogen for transport, often using blue hydrogen produced from gas, but the potential for green hydrogen is high. The government has plans to produce and export hydrogen, seeing it strategically as a possible long-term replacement for the gas it now exports to Europe.

What Are the Barriers?

Without a doubt, Russia has the potential to be a world leader in the renewable energy field; so what is holding it back?

The abundance of fossil fuels and the traditional reliance on them and on nuclear power to meet the country's energy demands is a major factor, as is the centralisation of the energy sector, allowing for limited discussion on the topic. The oil and gas lobby is very powerful and there is as yet very little push towards lower carbon options from the populace, who are probably not prepared to accept cost increases arising from switching to a greener economy. Although energy demand is increasing in Russia, there is a surplus of installed capacity, so there is little pressure to add to it, despite the fact that much of the present power comes from inefficient, outdated coal-fired heat and power plants which are heading towards obsolescence. Even though alternative energy sources are included in plans and future programmes, there is a lack of coordination between regulations and implementation, and the development of fossil fuels has remained the top priority. Russian official post-Covid recovery packages, for example, omitted any stimuli for the green sector, and few Russian banks will invest in renewable and decarbonisation projects because of the long payback time.

Limited attention has been given by the government to the development of the technologies required for alternative energy solutions, making their costs higher than elsewhere; the insistence on local content technology does not help. The harsh environmental conditions in the country are another factor, especially the long, hard winter. Ice has a particularly detrimental effect on wind turbines, while snow covering a solar panel stops it working and freeze-thaw effects can cause major problems, all making maintenance more expensive. Extensive research is needed to resolve these issues.

Energy transition will be expensive; a top Kremlin aide said before the COP26 summit that it could cost Russia's economy roughly $1.2 trillion by 2050. To achieve the goal of cutting greenhouse gas emissions by 79% by 2050, Russia would need to invest about $45 billion per year into alternatives to fossil fuels.

Opportunities Ahead

While there are obstacles facing a transfer to a low carbon future for Russia, recent announcements have suggested that the government is aware it may be in danger of losing out economically and technologically if much of the rest of the world turns its collective back on fossil fuels. Threats of an EU carbon border tax, for example, could seriously impact Russian exports.

In a change from his 'denial' stance, President Putin recently acknowledged the danger posed by permafrost melt. He has also designated the Far East territories and Sakhalin as net zero areas. There are promising developments in the transport sector; Moscow's state-owned bus fleet includes 300 electric vehicles, while Russian Railways has issued green bonds and has plans for the production of trains using hydrogen fuel cells. The hurdles that face many countries sourcing the rare earth and other minerals needed for a low carbon future are reduced by the fact that Russia is the world's largest nickel and seventh largest graphite manufacturer. It has recently bought into a Chilean lithium project to ensure supply for its domestic renewable and EV markets.

While Russia's Energy Strategy to 2035, published in 2020, talks up innovation, digitalisation and technology, it still demonstrates that the priority is not the climate, but maximising crude imports before the country hits its expected peak production towards the end of this decade, with a concentration on gas and nuclear for domestic use.

Russia has the resources to become a world leader in alternative energy but for the moment at least, it would appear that the existing barriers are overcoming the opportunities.

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Renewable energy potential in Russia.

Big Questions and Challenges in Geoscience

RASOUL SORKHABI, Ph.D.

What are the big questions that geoscientists can study and contribute to science, technology, economy and policy?

During 2019–2020 I undertook a survey of the most important questions in geoscience and crucial challenges facing the geoscience community. The survey was conducted through emails sent to hundreds of geoscientists and also posted through community websites of the Geological Society of America, American Geophysical Union, and American Institute of Professional Geologists. The scientists were asked to suggest up to five most important questions in geoscience (including geology, geochemistry, geophysics, and applied geology, but not regional geology) or issues facing the geoscience profession. A total of 136 scientists (75% from the USA, and 75% from academia) responded, and together they suggested 370 questions, many of which overlapped. This article is based on the survey results but written in a thematic style.

Global Warming

A large number of respondents suggested that global warming is the most critical issue of our time. This complex issue involves many areas of research including in-depth understanding of climate change, carbon budget and cycle, CO_2 sources, fluxes and sinks, climate change drivers and feedbacks (both negative and positive feedbacks), better forecasts and modelling of the impacts of global warming on ecology and societies, and more importantly working out technological and policy solutions to reduce the emission of greenhouse gases from fossil fuels into the atmosphere.

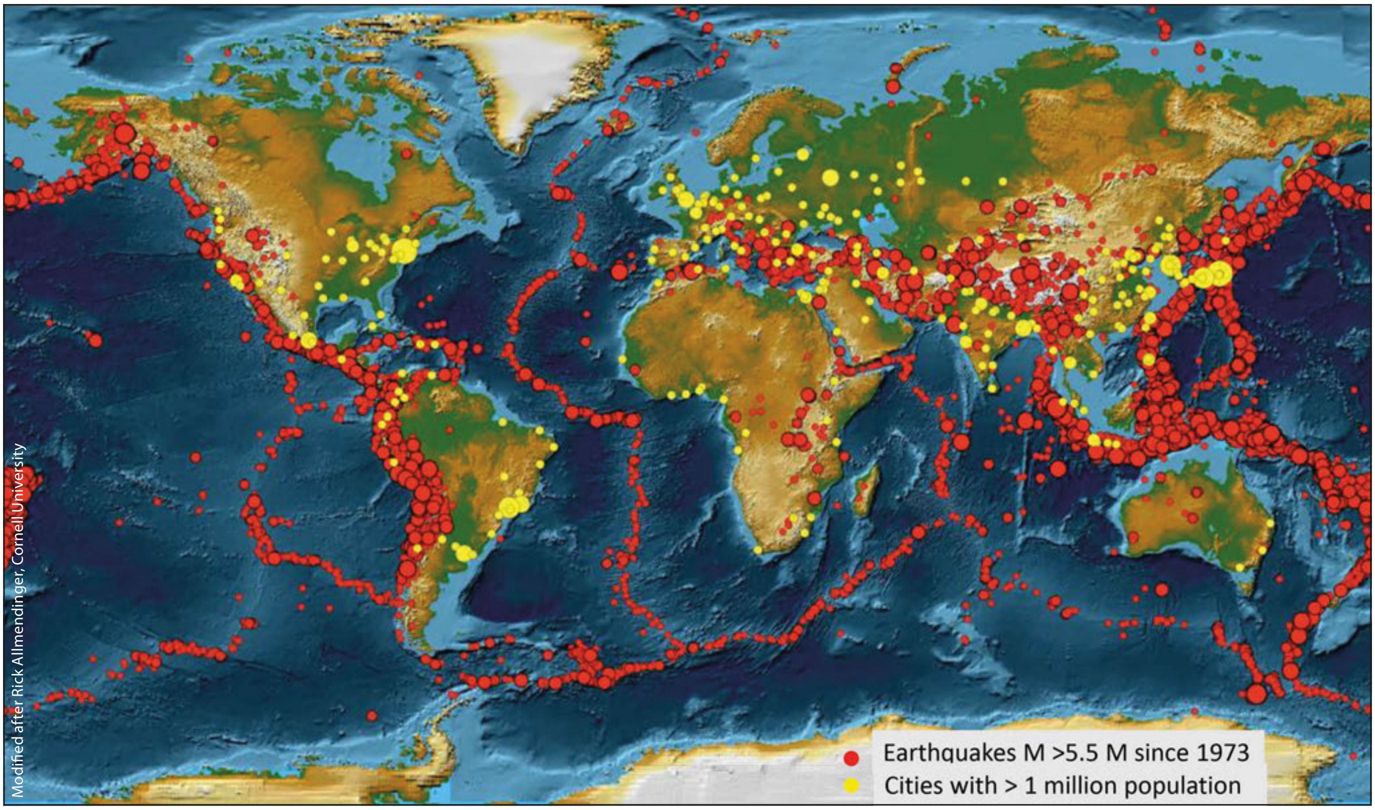
Future Energy and Petroleum Industry

Closely related with the global warming is the status and future evolution of the petroleum industry. Historically, the petroleum industry has funded numerous research studies and hired a large number of geology, geophysics, and engineering graduates. Given worldwide movements to combat global warming, the future of the oil and gas industry is not clear. Will the industry evolve and reinvent itself, or will it gradually give way to other energy, mineral and environmental industries; and if the latter, will these industries be geoscience-intensive and highly supportive of research and education?

The petroleum industry needs to address both environmental sustainability and financial challenges. To be environment friendly and reduce its carbon footprint, the industry has to invest in the science and technology of carbon capture, reuse or storage, avoid gas flaring, and control methane emissions from shale oil and gas fields. To reduce its costs per barrel of oil production and be profitable for its stakeholder, the petroleum industry must utilise smart data


Human civilisation has become a geological force.

NASA's Marshall Space Flight Center



Earthquakes and megacities along the active tectonic plate boundaries.

science and more efficient technologies for better subsurface imaging and improved recovery of oil and gas.

The world (as well as the geoscience community) is facing a big dilemma. On the one hand, the catastrophic threat of global warming is a genuine reason to move towards energy sources with the smallest carbon footprint. On the other hand, energy-dense fossil fuels currently account for 85 percent of the world's energy supply, and a rapid transition to replace fossil fuels will have its own political, economic, and technological challenges and consequences. Added to this dilemma is the fact that global energy demand will grow (not decline) in the coming decades because the flow of affordable and abundant energy is critical to the living standards of the developed world and development of low-income nations. These trends provide geoscientists with both challenges and opportunities in developing new energy technologies.

Earthquake Prediction

Seismology and plate tectonics have made great strides in our knowledge of earthquakes – how and where they occur. Nevertheless, predicting the timing of earthquakes remains a most serious problem, despite the recognition that certain physical precursors provide helpful clues. Given that a large number of megacities are situated along the tectonically active circum-Pacific and Alpine-Himalayan belts, big earthquakes are indeed silent 'time bombs' and require intense studies.

Plate Tectonics

Plate tectonics was a revolutionary discovery in 20th-century science. It has provided a unified theory, a new paradigm, to explain various, seemingly unrelated, geologic phenomena from the rock cycle and mountain uplifts to mineral deposits and earthquakes. Nevertheless, many aspects of plate tectonics still remain poorly understood and require sophisticated studies. For instance, we still do not know when and how plate tectonics began in the Precambrian Earth; how our planet functioned before plate tectonics; and what critical mass of conditions triggered plate tectonics. We also need to know detailed mechanisms of how plate tectonics affects the oceans, the atmosphere, and the biosphere, and how plate tectonics controls the generation and distribution of mineral resources. Volcanic eruptions occur at the boundaries of tectonic plates as well as at the hotspots of mantle plumes. But how exactly does an explosive volcano start and end, and how can we model these two conditions?

As far as we know, Earth is the only planet in our solar system that displays active plate tectonics. How long will the plate tectonics last? What might cause its cessation?

Mantle Dynamics and Plumes

Our geologic knowledge largely pertains to the crust accessible to us; but the crust is merely a thin skin of the global volume. Lithospheric plates are controlled by dynamic forces in the mantle, from the asthenosphere immediately below the lithosphere all the way down to the low shear velocity provinces surrounding the outer core. The mantle remains terra incognita and thus a new frontier. Our physical access to mantle plumes is restricted to hotspot magmatism on the Earth's surface. Where do plumes rise from? How can we classify plumes, physically and compositionally, to understand processes of their formation? How can we study the evolution of the mantle over geologic time as we do for the crustal rocks?

Earth's Magnetic Field

The Earth's magnetic field originates from the circulation of liquid iron and nickel in the outer core, and its influence reaches beyond the solid Earth and protects life from harmful solar and cosmic radiations. We also know that the Earth's

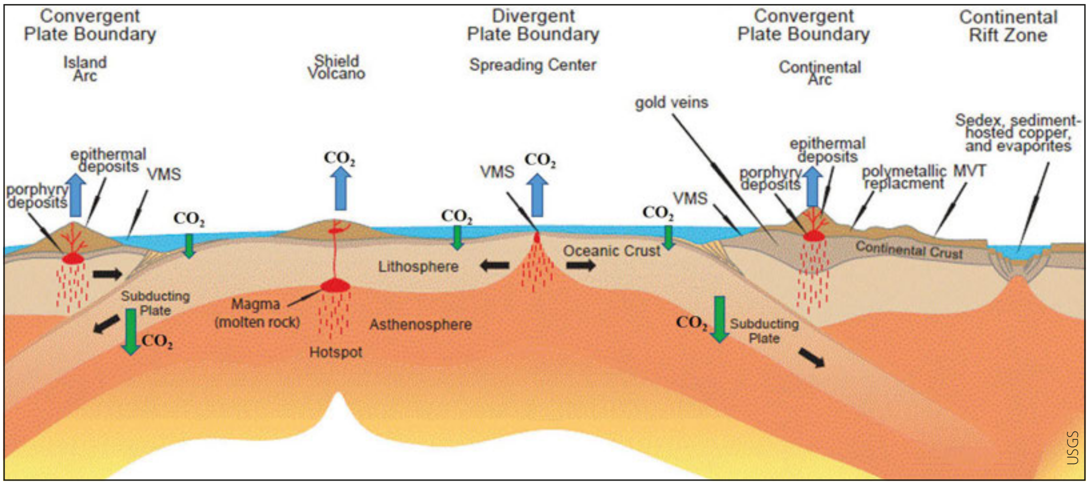


Plate tectonic cycle and its relation to mineral deposits and carbon cycle.

for 'theories of life' aids exploration of life on other planets and also deepens our understanding of survival mechanisms of microorganisms in extreme environments.

Cambrian Explosion

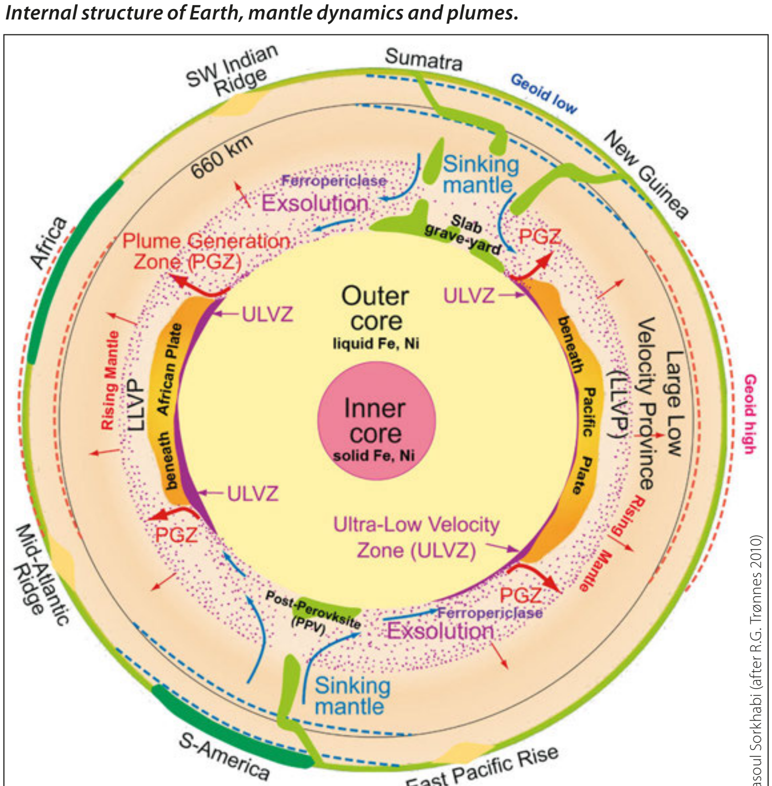
The Precambrian–Cambrian transition marks a benchmark in the history of Earth. It marks a time of drastic changes in the atmosphere (oxygenation), tectonics (assembly of Gondwana), and evolution (proliferation of multicellular organisms or what has been dubbed as the Cambrian explosion). Understanding the nature of this time interval and the interconnected phenomena leading to the Cambrian explosion of life is an important question in the history of our planet.

magnetic poles have reversed their position through geologic time; however, we still do not know exactly how and when these reversals take place.

Origin of Life

Life begets life, and life forms on Earth have evolved; but how, when and in what environment did the first cells and the earliest microorganisms emerge? Did life originate independently on Earth some four billion years ago (if not earlier) from a 'primordial organic soup' (abiogenesis) in the Earth's early oceans, or were biological molecules brought to Earth from outer space by asteroids and meteorites? The genesis of life on Earth, like other phenomena, has a naturalistic explanation, but it still remains a mystery in science. Nevertheless, the search

Internal structure of Earth, mantle dynamics and plumes.



Climates of the Past

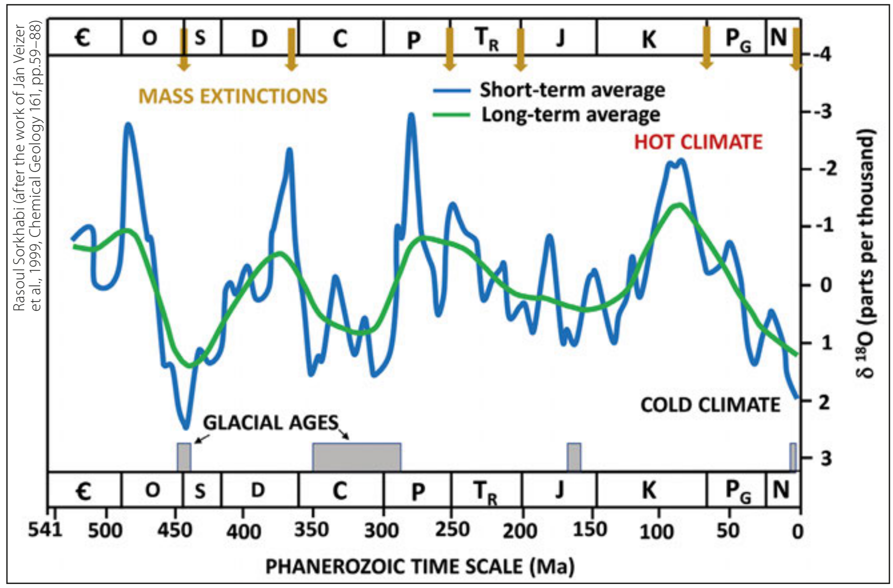
Studies of the history of Earth's palaeoclimate involves a wide range of questions such as: What were the causes and effects of drastic variations in the atmospheric composition (especially O_2 and CO_2) over geological time? What factors determined the onset and termination of greenhouse periods and glacial periods? How did the biota respond to such drastic climate changes? Some of these geologic periods are particularly attractive for geoscientists, such as the 'Snowball Earth' of the Cryogenic period, mid-Cretaceous hothouse, Palaeocene–Eocene thermal maximum, and Quaternary ice ages.

Mass Extinctions

In a mass extinction, a large percentage of higher taxa in several biological groups vanish within a brief interval of geologic time either due to 'bad genes' (natural selection) or 'bad luck' (catastrophic events) – to quote David Raup's 1991 book. Extinction is a rule rather than an exception and at the species level, over 99 percent of life forms have become extinct over geologic time, with the 'big five' events in the Late Ordovician, Late Devonian, Late Permian, Late Triassic, and Late Cretaceous each wiping out more than two-thirds of species. Obviously, understanding the causes and consequences of these mass extinctions is not only a matter of curiosity, but also importance for our own survival. Sadly, humankind in recent decades has also been responsible for the 'sixth' big mass extinction through natural habitat destruction.

Exploration of Mineral Resources

Mineral exploration has always been at the heart of geoscience because everyday life, industries and economies all depend on a vast number of minerals and elements. This field is expected to grow as global demand for minerals increases, and strategic (critical) minerals including rare-earth metals will dominate national security and geopolitics. Improved knowledge of reserve estimates, geographic distribution, geological concentrations, and industrial recovery of critical minerals and elements will be important tasks for economic geologists.



Climate changes through the Phanerozoic Eon based on oxygen isotope record of calcitic shells. Also shown are the global glacial periods and mass extinctions. It seems that the five mass extinctions are related to rapid global climate changes whether the cause was terrestrial (for example, volcanic eruption) or extraterrestrial (meteorite impact).

Natural Hazards

Natural hazards are routine geologic processes; however, their tragic impacts on human life, structures and properties have increased due to population growth and concentration in megacities prone to natural hazards as well as unpreparedness especially in developing countries. Natural hazards include a diverse set of events resulting from tectonic, hydrological, meteorological, and climatic processes, and many of them are interrelated, such as offshore earthquake-tsunami coupling. During 2000–2009, more than 7,000 geophysical disasters killed approximately 1.23 million worldwide. Geoscientists and engineers can greatly contribute to studies of the precise mechanisms of natural hazards, risk assessments and mapping, warning systems, mitigation and construction of hazard-resistant structures.

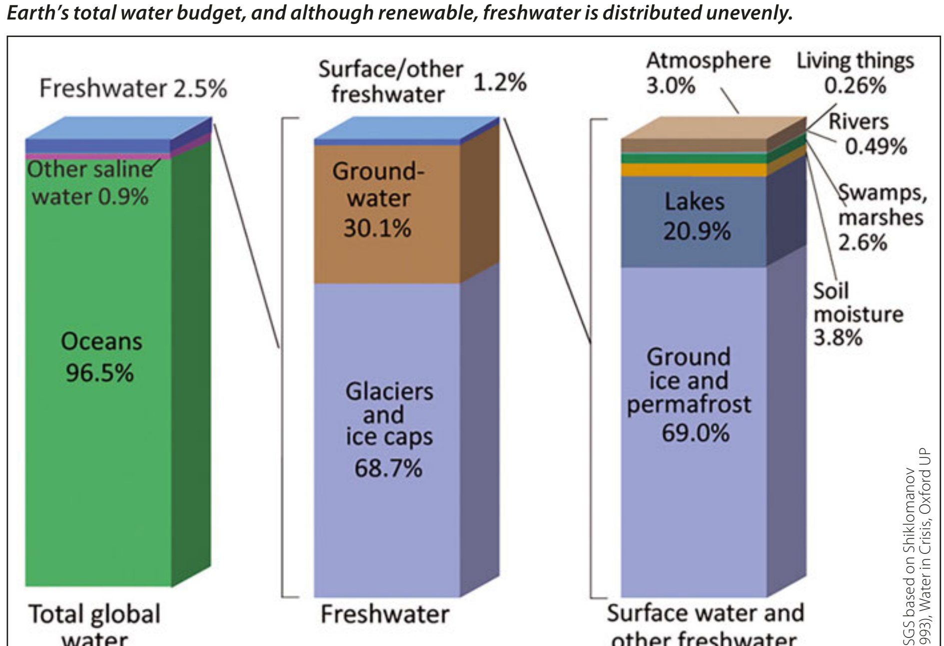
Water Resources

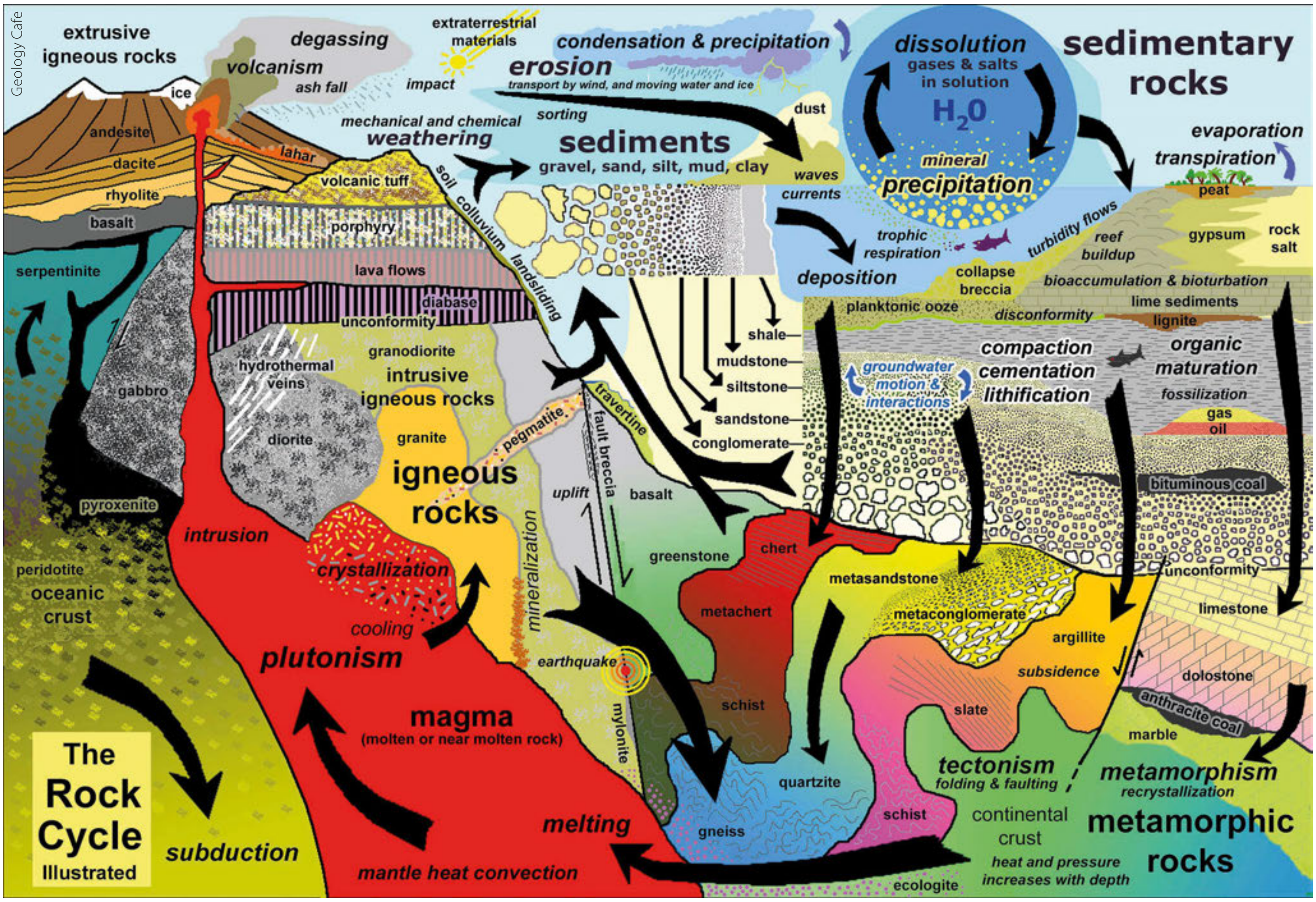
Underground and surface freshwater resources used for drinking, irrigation and other residential or industrial needs constitute only one percent of the global water budget. Although water is a renewable resource, freshwater resources are unevenly distributed both seasonally and spatially, depending on terrain and climate. Geoscientists and engineers will play an important role in detailed studies of the hydrological cycle and water budget, reservoir mapping and extraction of groundwater, water resource management especially in arid environments, optimal practices of watershed modification, desalination projects, and so forth.

Environmental Geology of the Anthropocene

Human health intimately depends on the quality of the air, water and soil. Rapid and reckless industrialisation of the world has caused environmental destruction and pollution of various types. The recent designation of the Anthropocene as a geologic age (beginning at around the 1950s) is a testimony to our (often adverse) impacts on almost every part of the planet from the atmosphere and the oceans to landscape and forests. Loss of biodiversity due to destruction of forests (with species that will never come back), desertification, silent erosion of topsoil (that will take centuries to recover), plastic pollution of the oceans, are tragic records of the Anthropocene. Environmental geology is thus a great contribution of geoscientists to society, and the significance of this field and the workforce needed for its multitude of tasks are expected to rise in the coming decades as human–Earth interactions will intensify.

The oceans cover 71% of the Earth and contain 97% of Earth's water. Liquid freshwater is only 1% of Earth's total water budget, and although renewable, freshwater is distributed unevenly.





The rock cycle shapes many features and resources of the Earth's crust.

Meteorite Impacts

There are 190 confirmed impact structures on Earth, ranging in age from 7 years to 2.4 billion years and they are found on all continents except for ice-covered Antarctica. (Antarctica, however, is a hunting ground for meteorites themselves.) All of the impact structures have been recognised since 1950 and are thus a very tiny portion of impact events whose records have been obliterated by erosional processes. Impact structuring as preserved on the Moon has been closely associated with the early history of planets including Earth. The disastrous consequence of extraterrestrial impacts on ecosystems is obvious, although its details require in-depth studies. At least in one popular case – the Cretaceous–Palaeocene boundary – impacting seems to be responsible for a global mass extinction. This necessitates monitoring large asteroids or meteors approaching Earth head-on, and if necessary, destroying them or diverting their courses physically. Another question is: Do large impacts affect the Earth's surface only or do they also cause perturbations in the mantle, perhaps even as deep as the core–mantle boundary?

Earth–Moon Relationship

Earth's only natural satellite is a unique feature in the Solar System. Isotopic signatures indicate that the Moon resembles an early lifeless rocky Earth, and according to a widely held hypothesis the Moon's materials were split off from Earth as a giant body, Theia, hit the proto-Earth. Whatever the mechanism for the origin of the Moon, the Earth–Moon companionship has been a long story of mutual gravitational influences. Aside from the tidal waves on Earth, we also know of moonquakes produced by Earth's gravity. Does the Moon's gravity also influence earthquakes and exert tidal stresses on Earth's topography and fluid pressures in rocks? We also need a better understanding of the day-length and Earth–Moon distance over geological time – a field of research that amazingly relies on coral palaeontology developed in the 1960s.

Geoscience in Public Education and Policy

Most people, including young children, are interested to learn about minerals, fossils, life of the dinosaurs, how mountains uplift, and other geological lore. Ironically, however, earth science is relatively underrated in our high schools and the public mostly remains unaware of the remarkable progress geoscientists have made in the past century. How can we communicate the value of geoscience to the public, school boards, and policy makers? This is a crucial challenge for the geoscience community; it is also a task that only geoscientists should perform. We should also present a new public image of the geologist beyond one who mainly digs for fossil fuels and studies earthquake incidents.

Big questions in science are not limited to the Big Bang and black holes. For geoscientists, understanding the evolution and operation of our one and only planet and providing humanity with vital resources are of utmost importance.

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Timor-Leste: Exploration Renaissance

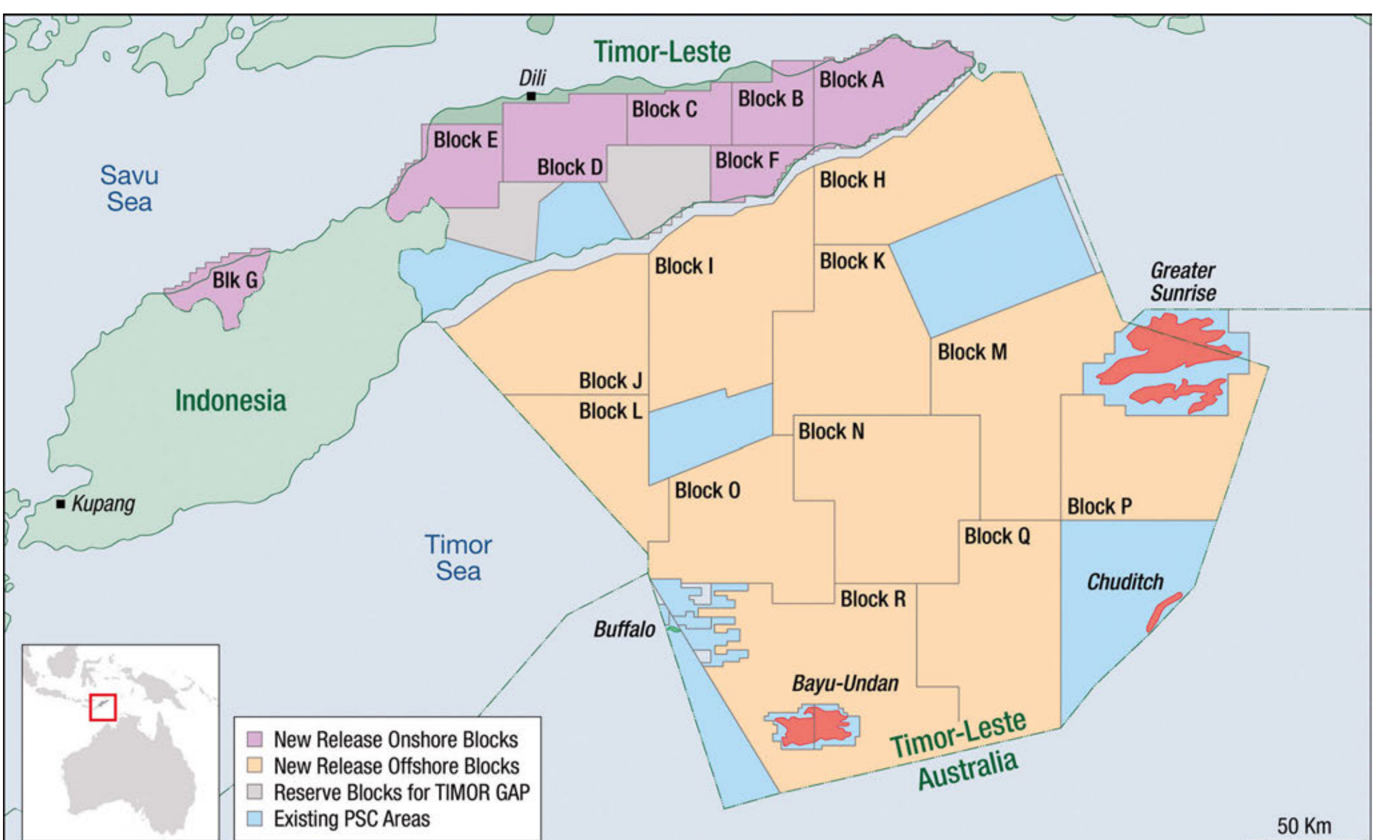
PETER ELLIOTT,
NVentures Ltd

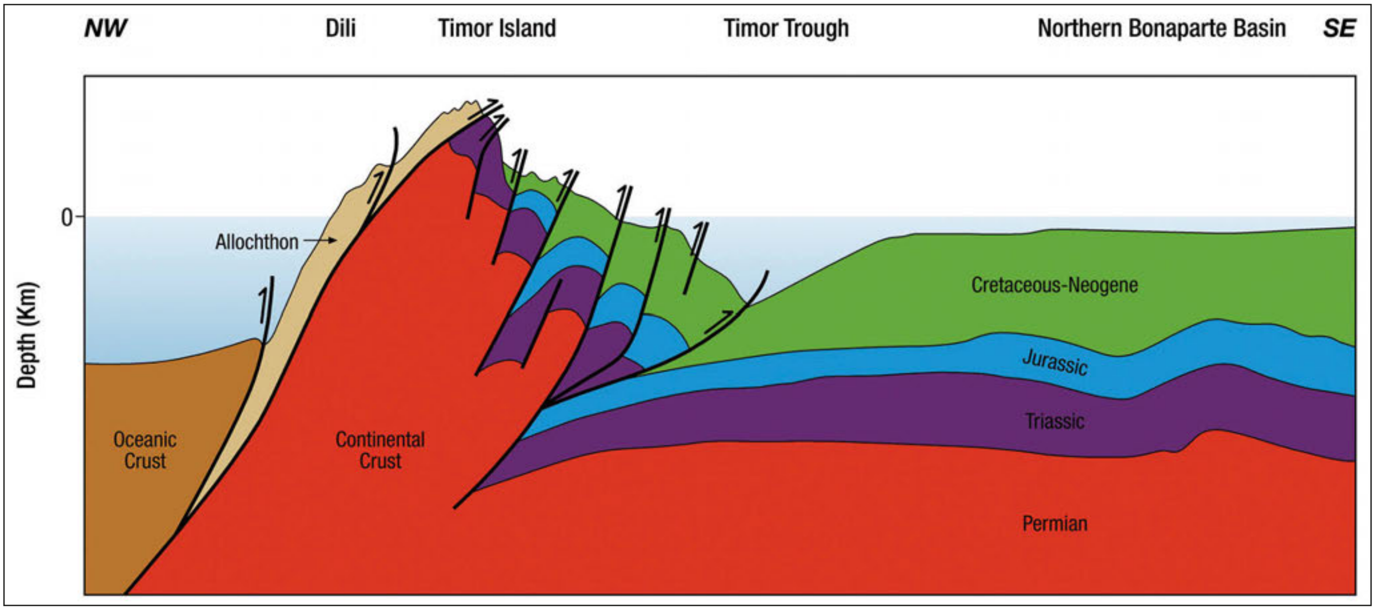
The island of Timor-Leste between Indonesia and Australia is the subject of some intense scrutiny these days, delivering opportunities for an oil and gas industry focused on low-risk and fast returns. The regulatory authority Autoridade Nacional do Petróleo e Minerais (ANPM) is currently promoting a major bid round for new acreage. Several offshore discoveries are moving closer to development, notably large gas reserves at Greater Sunrise and Chuditch, while conventional oil fields in the western offshore area are being targeted for redevelopment, including Buffalo, with several other oil accumulations ready to be developed or redeveloped. The local firm Timor Resources and national oil company Timor Gap have just commenced a three-well drilling campaign onshore, raising interest in a long-neglected oil play on the coast.

Timor-Leste and its offshore extension represent an interesting structural margin with proven hydrocarbons either side of the Timor Thrust. Running along the coastal area north-east to south-west, this major thrust, part of the eastern Banda Arc, divides the region into a large accretionary prism to the north, with Palaeocene to recent deformed sediments of the Viqueque Basin sitting on top of the remnant Triassic to Cretaceous platform, now thrusted to the south.

Imaging is poor in this upper prism and almost impossible below, but small fields have been proven through both plays (e.g., Macia). South of the thrust, the Australian Foreland Basin stretches from the Timor Trough to the North West Shelf of Australia, dipping gently upwards to the south east and creating major anticline and fault-bound gas plays (Greater Sunrise, Bayu-Undan, Chuditch) and smaller faulted oil plays to the west (Kitan, Buffalo). Here seismic imaging is much improved, and the major fluvio-deltaic sandstone of the Jurassic Plover Formation can be mapped across the offshore region, with secondary plays in the Mesozoic. The great majority of reserves so far have been found south of the major thrust belt, partly due to better imaging, and also a simpler source-migration-trap geometry.

ANPM are currently running an open bid round, with ample acreage across seven onshore blocks (A to G) and 11 offshore blocks (H to R). Large amounts of seismic and well data are available, with data packages from EZ Data Room and Searcher Seismic. This is the third bid round in Timor-Leste and they have a reasonably good track record; in 2003 the first round resulted





General NW-SE cross-section from the Savu Sea, through Timor Leste to the Australian Northern Boneparte Basin.

in the Bayu-Undan discovery, and the second round in 2006 led to the discovery and subsequent production from the Kitan field (Eni). Since 2019 the entire offshore area has moved into Timor-Leste jurisdiction, with the original Joint Petroleum Development Area (JPDA) being abandoned, resulting in simpler taxing and regulation (Greater Sunrise retains a small tax split for the Australians, once developed). This has clearly improved the level of interest in both the current bid round and the investment climate here for future field developments. The current licensing regime utilises the production sharing contract (PSC) model, and terms are comparably favourable for this region, with no signature bonus, a high oil and gas cost split and a healthy 60% contractor split on profit for oil and gas. Companies are obliged to prequalify, with the current prequal deadline set for 14 January 2022. Bids are expected by 4 March 2022. Timor Gap, the state entity, should participate at 20% in each PSC.

Several significant hydrocarbon projects remain to be developed offshore. The Kitan field was shut by Eni in 2015 due to low oil prices, as was Buffalo several years previously by Nexen. Carnarvon and partner Advance Energy are about to spud Buffalo-10 to test the attic oil volumes at Buffalo, with a field development programme in place for 2022 if drilling is successful. The 3.4 Tcf plus 400 MMbbl condensate Bayu-Undan wet gas field previously operated by ConocoPhillips now resides with Santos and partners INPEX and SK, providing gas feedstock for the Darwin LNG 500 km away in NW Australia. A three-well redevelopment programme is nearing completion with the first well flowing an impressive 178 MMcfgd plus 11,350 bcpd. Santos has now reached financial investment decision (FID) on the Barossa gas development in the North West Shelf (Australia), and the Australian firm is seeking to achieve carbon-neutral gas and LNG facilities across its portfolio. This could include carbon capture and storage (CCS) at Bayu-Undan, an exciting development for Timor-Leste.

To the east, the large gas reserves at Greater Sunrise and Chuditch are also the subject of appraisal and development planning. Woodside are working towards FID on the Greater Sunrise gas field, which would either export gas to the Liquefied Natural Gas (LNG) projects on the North West Shelf, or could involve a pipeline to Timor-Leste for liquefaction, bolstering their LNG prospects in the region. Woodside are also heavily engaged in planning for a carbon-neutral footprint across their LNG portfolio. The UK firm Baron Oil is finalising a major 3D reprocessing project over the 3.4 Tcf Chuditch gas discovery complex to the south, whereby the firm will be looking to firm up an appraisal drilling campaign. With several development scenarios available, LNG backfill is expected to feature heavily.

Onshore, the Timor-Leste firm Timor Resources, in partnership with Timor Gap, are ending a 50-year hiatus for onshore exploration drilling, having recently spud the first of three wells. The Feto Kmaus well will target multiple potential reservoirs from the Jurassic to Triassic, including the Plover Sandstone Group. The chance of success is considered reasonably high, with the Triassic Aitutu Formation underpinning many source kitchens onshore. A third well, Rusa-1, may also test the sub-thrust play deeper into the Triassic and older.

Given the number of existing and planned developments in Timor-Leste, the strong relationship between large offshore gas reserves and LNG in the region, and a broad licensing round with good terms and favourable geology, there is no doubt Timor-Leste will figure strongly in the regional hydrocarbon dynamics going forward. With net carbon targets being pursued by the regional majors, and CCS technology actively being considered, this island nation will find itself literally at the crossroads of the future oil and gas landscape between South East Asia and Australasia. Domestic growth and local content development are set to benefit in parallel, with an exciting onshore drilling campaign kicked off, and future infrastructure opportunities for the island. ■

Delivering a Geological Service for Europe

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It is a misconception that abandoning fossil fuels reduces the importance of the subsurface – whilst the use of it will materially change, it continues to play a crucial role in every aspect of human life.

The long-term security of mineral resource, energy supply and storage, and the protection of potable water supplies are central to economic growth. Growing populations and demographic changes add to the pressure on the availability of natural resources, such as geo-energy, raw materials and groundwater.

The subsurface provides the raw materials for wind, solar and other possibilities for the energy mix, including geothermal, and the possibilities for storing vast amounts of energy. Climate change is of critical concern, and as a significant part of our economies is linked to utilising fossil reservoirs of CO_2 as industrial feedstock, returning CO_2 permanently to the subsurface also becomes part of the sustainability portfolio, as does the protection of potable water in aquifers. These are examples of the trilemma between security of supply, environmental sustainability, and accessibility and affordability.

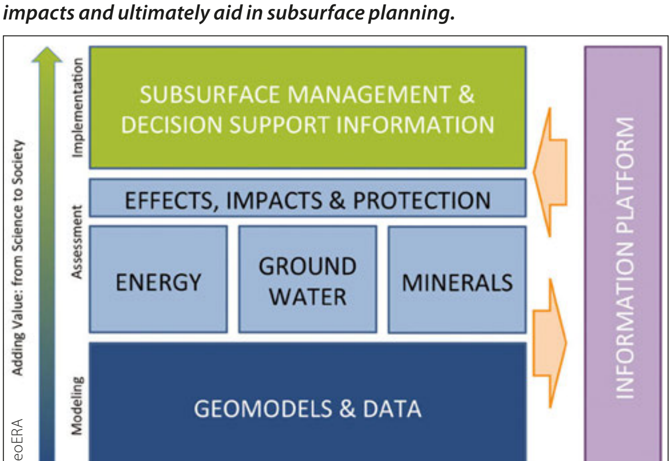
The subsurface plays a crucial role and provides many opportunities in supporting the global UN Sustainable Development Goals and the implementation of the European Green Deal and EU policies in general.

The GeoERA Concept

The myriad of solutions, often unique to the subsurface, is extensive. Including them in national or European development planning, or simply managing exploration and exploitation requires an understanding of the geology and processes. Subsurface solutions are rarely implemented generically and involve a degree of custom tailoring to local natural geological constraints (Gessel et al., 2018; Vidovic et al., 2019).

GeoERA has identified and outlined these challenges and developed a research strategy that builds on fundamental geological understanding as the basis for thematic research. While each of these levels provides insights by themselves, the ultimate goal is to bring this applied research together to assess the combined effects, impacts and protection.

Figure 1: GeoERA projects respect the philosophy of building thematic research on shared knowledge, and further apply those results to study impacts and ultimately aid in subsurface planning.



While Geological Surveys perform this role in varying degrees, at the national level, geology does not stop at borders. This brings in a European component and the need to harmonise data and methodologies.

GeoERA is a five-year project, (Jan 2017–Feb 2022), co-funded by the EU under the Horizon 2020 programme (731166-GeoERA-H2020-LCE-2016-2017/H2020-LCE-2016-ERA) and is an establishment of the European Geological Surveys Research Area, essentially a collaboration of 47 partner organisations, both national and regional Geological Survey Organisations, from 31 countries, co-ordinated by TNO, and is the first step in delivering a future Geological Service for Europe.

Worthy Objectives

The objectives of GeoERA are to contribute to the optimal use and management of the subsurface, by maximising its added value for energy, raw materials, and groundwater, while minimising environmental impacts and footprint. A stable information platform is a prerequisite to link all levels and communicate between experts, as well as deliver data to stakeholders. GeoERA has funded 15 projects, focused on four key areas.

Geo-Energy

Secure, clean and efficient energy are at the heart of the Horizon 2020 Societal Challenge 3. In response to this, the geo-energy theme seeks to develop transparent, harmonised and science-based pan-European information and knowledge on:

- Subsurface potential to deliver energy resources and storage capacities
- Potential hazards and environmental impacts associated with exploitation of the subsurface
- Competition, interference and synergies between different uses of subsurface space

The projects in this theme cover the entire value chain from resource exploration and capacities with 3D models, to subsurface management and stakeholder support (Figure 1).

Project 3DGEO-EU delivers best practices on how to build cross-border 3D models with examples on how to deal with heterogeneous datasets and inconsistent models in several pilot areas. It also highlights the evaluation and visualisation of uncertainties.

Projects HOTLIME and MUSE take a next step towards exploring and developing geothermal resources in Europe. HOTLIME focuses on de-risking deep-geothermal potential in carbonate rocks and the role of faults in highlighting potential for successful exploitation. MUSE tackles shallow geothermal energy use in urban areas, addressing stakeholder challenges and limitations related to densely populated areas and summation of anthropogenic effects and impacts.

GARAH evaluates the remaining potential for conventional and unconventional hydrocarbon resources in the North Sea as well as the presence and potential risks related to gas hydrates at European continental margins. The information from GARAH also delivers insights into the potential for the geological storage of CO_2.

HIKE delivers a first-of-its kind pan-European database of faults in the subsurface. This information is key to understanding and determining subsurface resources and capacities such as hydrocarbons, geothermal energy and CO_2 storage.

GeoConnect³d develops and tests a new approach in preparing and disclosing geological information for policy support and subsurface management in the form of a Structural Framework, one of the cornerstones for future communication and deployment of geological information and responsible valorisation of subsurface potentials.

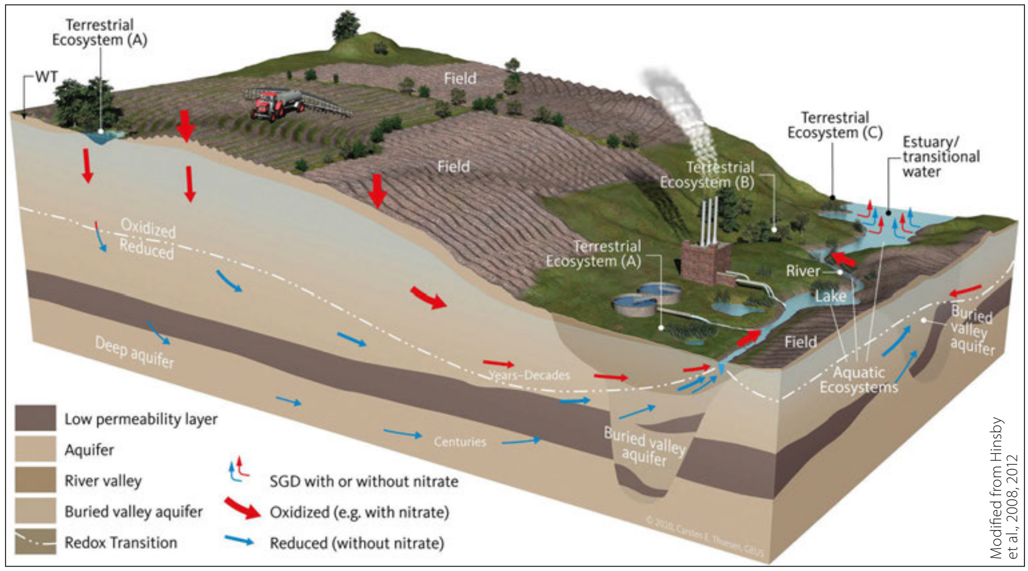


Figure 2: Conceptual model illustrating the impact of agriculture on groundwater and ecosystems and groundwater age and travel times.

Groundwater

By jointly developing effective tools and methodologies for monitoring, modelling, data management and visualisation, the understanding of groundwater systems and their interaction with surface water and ecosystems has improved. New information includes valuable data on groundwater quantity and quality across Europe.

The HOVER project covers natural groundwater quality controlled by geogenic processes as well as groundwater polluted by mainly nitrates, pesticides and emerging contaminants. Investigations included groundwater age, travel times and vulnerability to surface pollution.

The VoGERA project investigates the vulnerability of groundwater resources from deep energy related activities and provides a decision support tool for vulnerability classification.

The RESOURCE project is the new digital pan-European groundwater resources database and quasi 3D map including information such as, volume, depth, hydraulic parameters, aquifer types, salinity and age.

The TACTIC project developed information and provided access to tools for assessment of climate change impacts on groundwater and adaptation strategies with more than 40 pilot studies. Projects include estimating groundwater recharge at borehole, and integrated assessments of climate change impacts on groundwater and surface water, including groundwater dependent ecosystems.

Raw Materials

GeoERA is looking to Europe's long tradition in quarrying and mining, re-evaluating the potential of historical and new

Figure 3: Manual measurement of groundwater depth, temperature and electrical conductivity in a borehole with a well dipper.

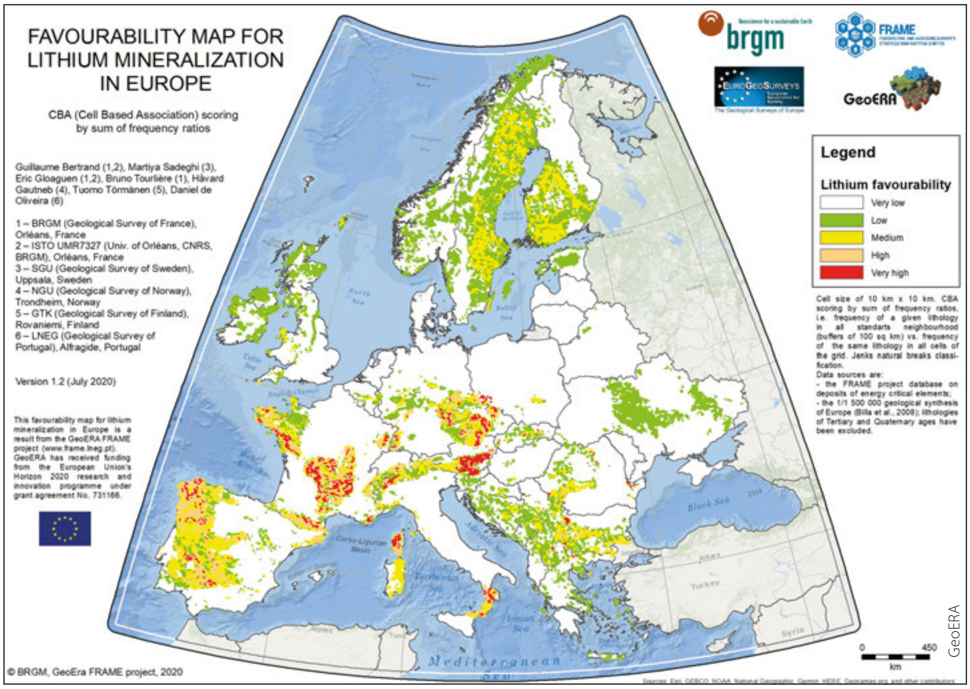


Figure 4: Lithium prospectivity map (product by FRAME).

mining sites for security and sustainability of mineral raw materials supply from EU domestic sources at the beginning of the value chain.

The four GeoERA Raw Materials projects, EuroLITHOS, FRAME, MINDeSEA and Mintell4EU share expertise and information on European onshore and offshore resources to take responsibility for ensuring domestic sourcing. The project seeks to understand and evaluate the raw materials and to visualise these results in accessible databases, maps and publications.

Information Platform

The geo-energy, groundwater and raw materials themes share the common objective of providing and disseminating spatial information on their respective resources and the underpinning geological data. As cross-thematic integration of information is vital, a key deliverable has been the 'Information Platform' that effectively integrates all ICT-related and technical issues (database and dissemination) from the three challenges.

The common geoscience information platform can integrate up-to-date data, interpretations and models, across the three main geoscientific themes of GeoERA. The platform is based on the European Geological Data Infrastructure (EGDI), first implemented in 2016, and is the basis for follow-up initiatives towards the Geological Service for Europe.

Looking to the Future

GeoERA has been as successful – providing exciting insights and results – as it has been challenging; a pioneering project, aimed at harmonising cross-thematic information by the geoscientific community to provide a stable backbone for a future European geological service.

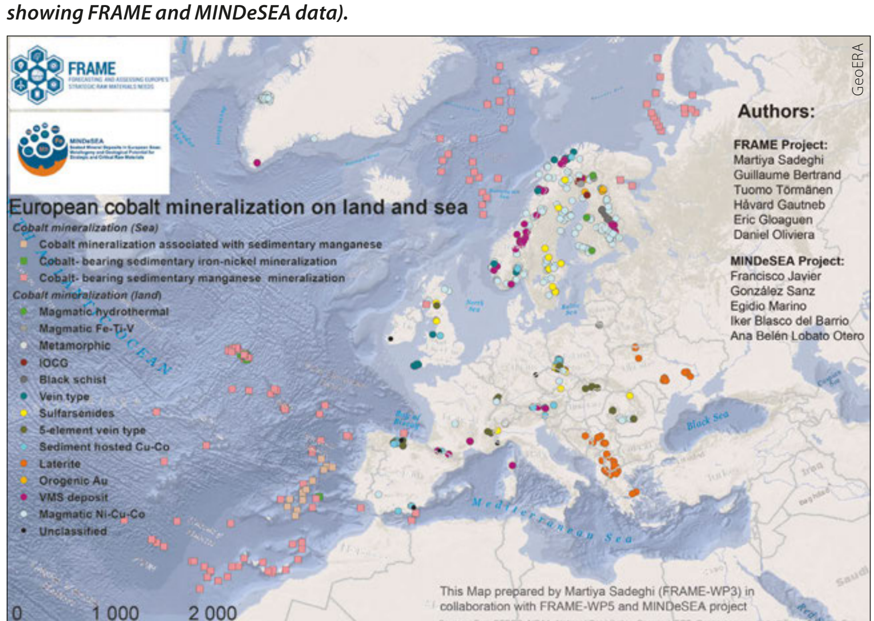
GeoERA did not set out to be a communicative project. However, social media was embraced, including extensive blogs, resulting in a dedicated audience and well-attended stakeholder outreach events, even under unforeseen Covid-19 restrictions. GeoERA has also grown beyond the borders or Europe, involving organisers, audiences and collaborators from across the globe.

Whilst the relevance of the subsurface to society, and the importance of subsurface management have been convincingly brought forward, the work is far from finished. Even as the conclusion of GeoERA is being celebrated, the next phase is in full preparation. Future projects will focus on strictly defined topics set out by the European Commission, focusing efforts on building a permanent structure and integration at European and national levels.

The subsurface has enabled humanity to jump forward, but not sustainably. In rethinking the welfare of society, the changed role of the subsurface requires attention. The Geological Surveys are answering that need, with GeoERA as the first, vital step.

References available online, ■

Figure 5: Co-mineralisation map – both in the European waters and on land (GIP-P portal showing FRAME and MINDeSEA data).

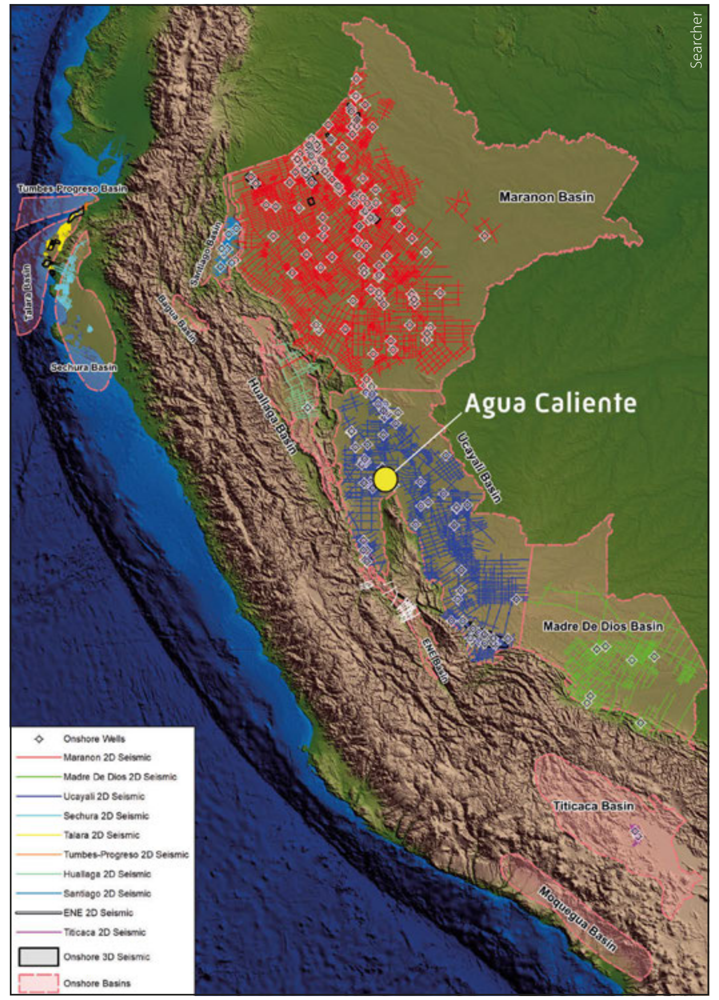


From Agua Caliente ('Hot Water') to Aceite Caliente! ('Hot Oil!')

83 years ago, the first oil exploration well east of the Peruvian Andes was spudded on a large surface anticline near the Pachitea River in Peru's Ucayali Basin. The feature drilled in this pristine rainforest, part of the greater Amazon Basin, was identified on early surface mapping and the presence of 'boiling rivers'. Only 2 kilometres from the well location hot spring water rose to the surface giving the area, the well, and subsequently the oil field its name: Agua Caliente ('Hot Water').

Searcher

Perú petro



Map showing the location of Agua Caliente and Searcher's rectified seismic dataset.

South-west – north-east section across the Agua Caliente Structure. The surface unconformity across the dome is evident. Bright reflectors correlate to limestones in the sequence showing the deep structure, the thrust decollement at basement level of Neoproterozoic age (Reyes Rivera, 2005), and the sub-thrust play.

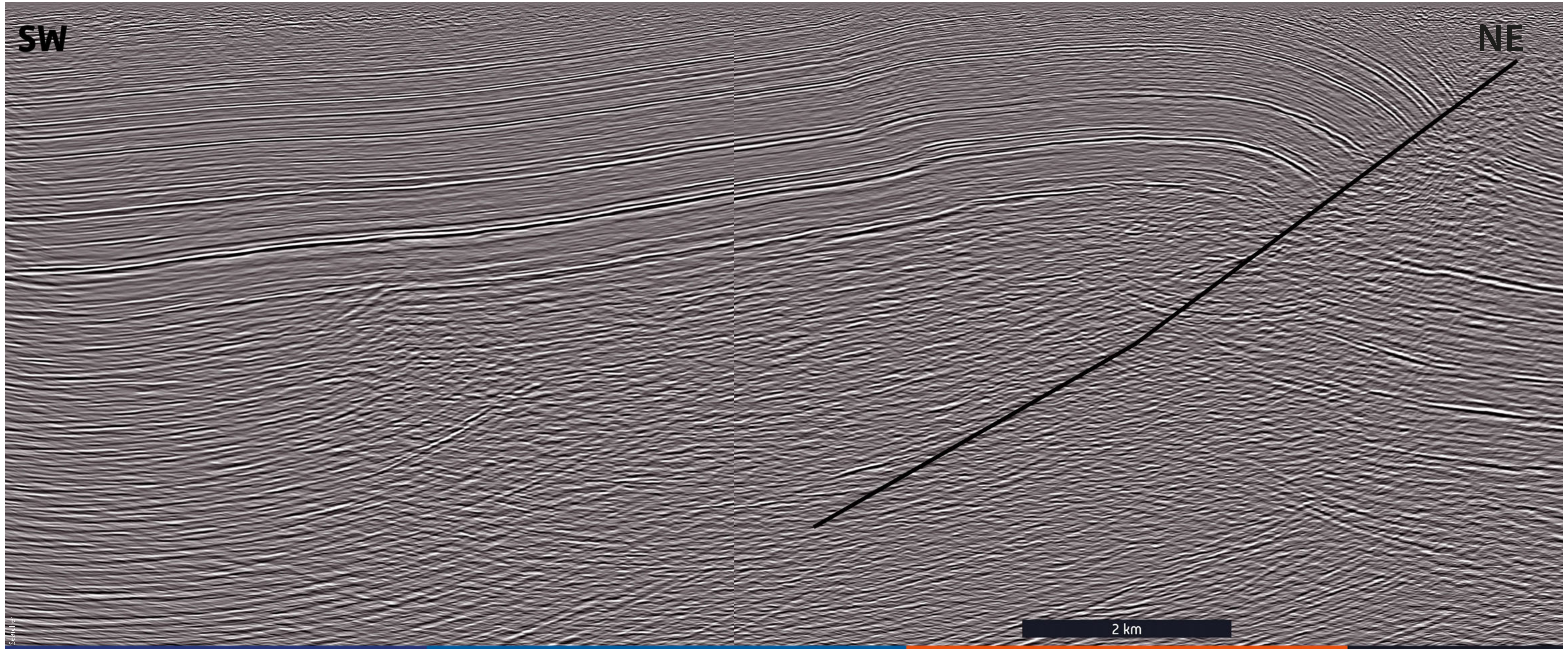


Figure 1: Agua Caliente beside the Pachitea River on Google Earth and the outcrop that caught Robert Moran's eye and imagination.

A Story of Oil Exploration in the Rainforests of Peru

The heroic story of Peru's first oil discovery east of the Andes and the passion and determination of the entrepreneurs who made this happen has been brilliantly captured by Simon Lunn in his book *Agua Caliente* published by Amazon.

NEIL HODGSON, KARYNA RODRIQUEZ, DENNYS UYEN, SEARCHER; JULIA DAVIES and LAUREN FOUND, Discover Geoscience

In his book, *Agua Caliente*, Simon Lunn tells the story of Robert Moran, a geologist who had grown up during the Californian oil boom in the early 1900s and understood that anticlines and domes were good places to look for oil. Surprisingly, this story starts with Moran on a twin prop airplane, flying over the rainforests of Peru where he saw sandstone outcrops through the tree line defining a large, oval-shaped four-way dipping dome (Figure 1). Moran had read of first settlers and early explorers finding oil seeps in the mountains to the west and realised that if there were reservoirs to match these indications of source and structure he may have discovered a Peruvian Eldorado – but this one would be a city of black gold.

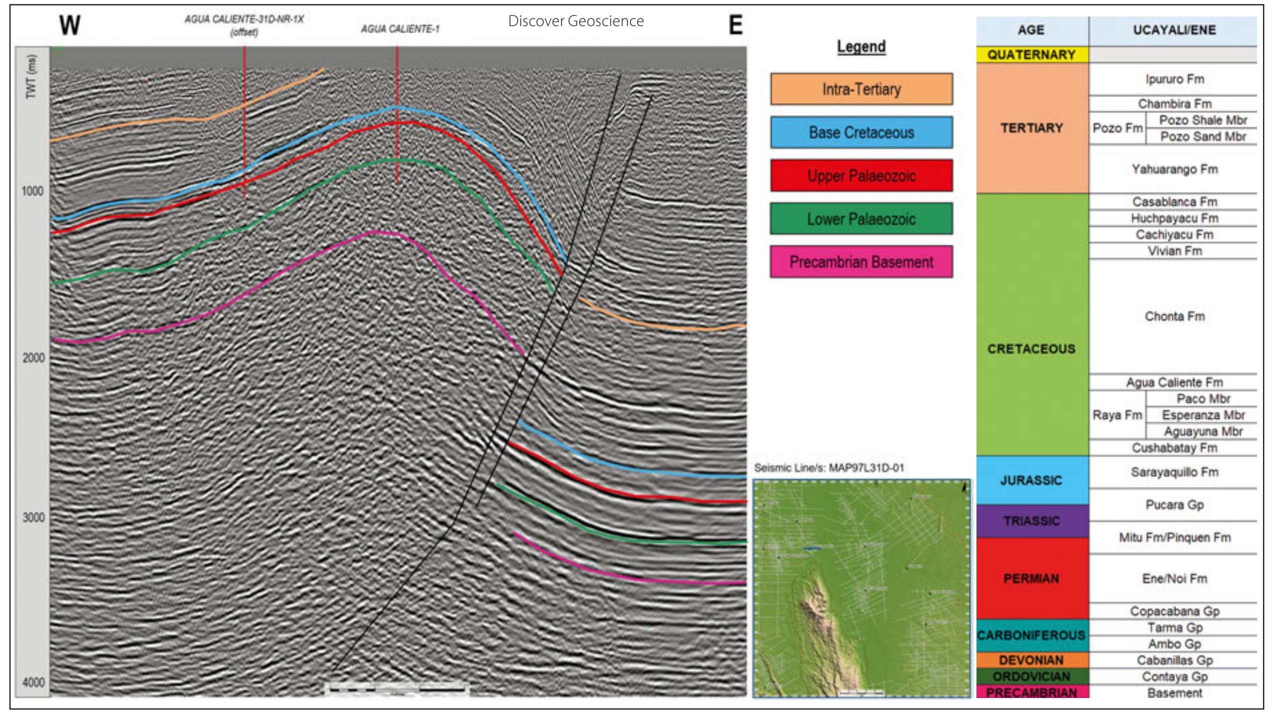
Simon has diligently researched the history of Moran and his co-investors by deciphering their diaries and letters to give an account of the hardships of geological field work in the early 1930s. These men were made of stern stuff – paddling wooden canoes on the Pachitea River through pristine unmapped rainforests, whilst camping and coping with the heat, rain, inquisitive wildlife and swarms of flies and mosquitos, with poor supplies of food and of course no GPS or mobile reception. Thankfully, these courageous adventurers did what most of us today would struggle with, mapping the lithology and dip of outcrops, and collecting fossils (for biostratigraphy) along the river to constrain the geology of the Agua Caliente dome.

From Moran's first 'remote sensing' flight over the area, it took eight years of struggle before the discovery well was drilled. We should all read this book and salute our predecessors of exploration. It is a frank, well-told and amazing story, and we highly recommend Simon's book to you.

Today, one can see the Agua Caliente anticline on Google Earth at 8° 49′ 52″ S and 74° 43′ 16″ W. The exposure that caught Moran's eye from the air is highlighted in Figure 1 (but better imaged on Google Earth in 3D mode).

Whilst we can see the forest around the field has now been ingressed for agriculture, it is still very verdant around the field. The field is now operated by a small, focused company that is taking its environmental responsibilities seriously. Yet the area needs protection and there are groups who one can work with to facilitate that (such as the non-profit 'Boiling River Project' dedicated to the protection of the Boiling River of the Amazon and its surrounding Jungle).

Figure 2: West–east section across the Agua Caliente structure showing the deep structure and the untested sub-thrust play (see foldout).



Today we have something that Moran never had: the availability of excellent quality seismic. Searcher has accessed around 80,000 km of legacy seismic data in the interior of Peru and has 'rectified' it into a consistent dataset where navigation is checked, lines tied, amplitudes balanced and phase-corrected, creating one large contiguous dataset. This data is available at low cost via subscription, and accessible via the cloud under the brand of 'sAIsmic', enabling regional exploration to be undertaken quickly and cost effectively.

As one can see from the foldout section, the seismic data over the Agua Caliente field is extraordinarily good quality. Figure 2 represents an interpreted west–east line crossing the dome, showing clearly not only why the structure is expressed as an anticline at outcrop on the surface, but also revealing the origin of the structure – a deep east-verging thrust in front of the Andean ranges. When the Agua Caliente exploration and development wells are tied to this data, they illustrate the very shallow nature of the trap and reservoir (Figure 2). The field is sourced from the Permian Ene Formation/Devonian Cabanillas Group, and reservoirs are the Cretaceous Paco and Aguanuya Members of the Raya Formation and the Cretaceous Cushabatay Formation.

The discovery of Agua Caliente instigated a wave of exploration in the Ucayali Basin that resulted in two more oil discoveries before 1960 (Maquia and Pacaya fields) and 13 gas condensate fields to date in this play (the Camisea gas and condensate fields, located to the south of the Ucayali Basin and the Candamo field in the Madre de Dios Basin, are related to the Early Carboniferous Ambo Formation source rock). Since the 1960s there have been several periods of minimal activity, partly politically driven and partly due to attention being focused elsewhere in Peru. This leaves the play hugely under-explored despite its low risk with proven source and reservoir.

Indeed, there are several underexplored plays close on Figures 2 and 3. Firstly, undrilled deeper stratigraphies are all within closure, such that new hydrocarbon systems could await deeper drilling. Source rocks are found throughout the section from the Devonian Cabanillas Group, Early Carboniferous Ambo Formation, Permian Copacabana and Ene Formations and the Triassic to Jurassic Pucará Group.

However, a second, more exciting prospectivity can be found below the Agua Caliente anticline and indeed below the thrust that formed it. The sub-thrust play is a common target in other parts of the Sub-Andean foreland basin regions along the East Andean margin from Colombia to Argentina (Fuentes et al., 2018). Depending on the depth and deformation of the decollement horizon, this sub-thrust play may be simply thrust-sealed or indeed have imbricate stacked targets in what is known as a 'triangle zone' below the thrust.

The analysis of a number of similar structures in the Ucayali Basin in a 'Well Atlas and Play Analysis' by Discover Geoscience, suggests it has not featured as a target in many wells in this basin so far, perhaps suggesting a remarkable opportunity exists across the entire basin. For example, the Aguaytia, Los Angeles and Neshuya structures to the west of Agua Caliente (and for that matter the La Colpa structure to the east of Agua Caliente) are all drilled on surface antiforms and do not reach the sub-thrust play. Whilst very clear on vergence parallel lines, some structures have subtle relief, requiring good seismic to correctly site valid tests. However, the more recent discovery of the Los Angeles field (2012) shows what can be done.

Were the sub-thrust play in the Ucayali Basin to be opened up, it will be a testament to the courage and doggedness of the early explorers, and the imagination of the generation that stand on their shoulders, except this time using large cloud-based seismic datasets. The next generation of explorers, empowered with environmental responsibilities and a willingness to work closely with local communities will bring the excitement back to exploration in the hot play – looking for 'Aceite Caliente' (Hot Oil) in Peru's Amazon Basin. Searcher would like to acknowledge Perupetro for their contribution to the text and for allowing us to show the seismic data.

References available online. ■

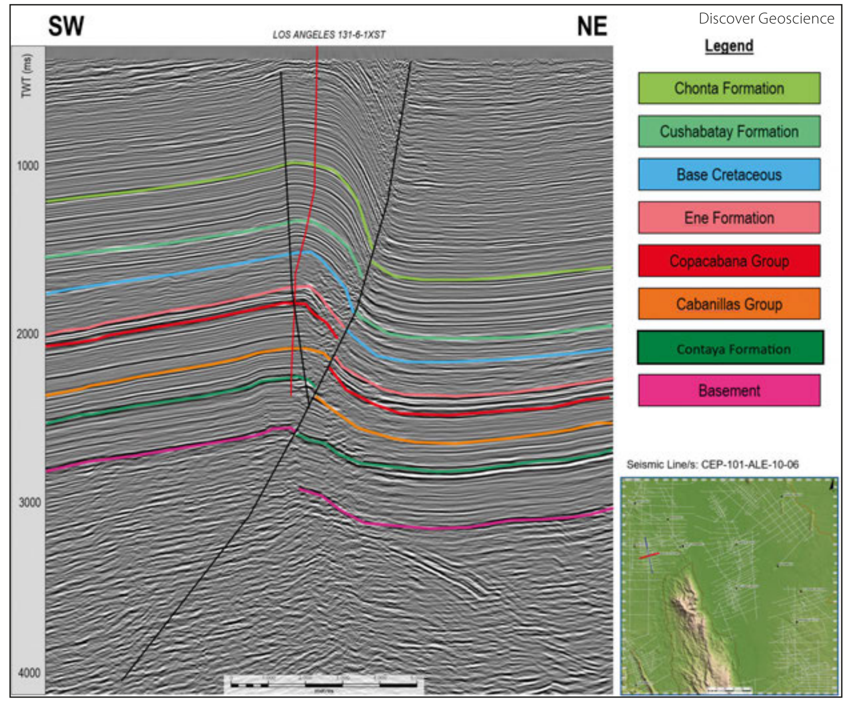


Figure 3: West–east section across the Los Angeles Field structure showing the deep structure and the untested sub-thrust play.

Natural Gas: Underexplored in Bangladesh?

THOMAS L DAVIS, Geologist, Ventura, CA, and BADRUL IMAM, University of Dhaka

Increasing demand, decreasing supply, untested high-potential plays, and much-needed exploration.

Natural gas (NG) is the principal fuel for electrical generation in Bangladesh and the foundation for the nation's rapid economic growth during the last two decades (World Bank, 2020). During this period NG supply grew through the further development of pre-2000 field discoveries. Abundant supply encouraged growth and was the parent of strong economic expansion (~4.5% GDP since 2004). Concurrently, Bangladesh has successfully managed economic development and climate change adaptation with its NG cornerstone (Roy, 2021).

Demand and Supply Mismatch

NG demand, presently at ~3,950 MMcfd (million cubic feet per day), will grow to an estimated ~4,850 MMcfd in 2030 (Figure 1). Supply from local gas fields declined from a peak of ~2,750 MMcfd in August 2018 to ~2,430 MMcfd in October 2021 (Petrobangla, 2021). This is a direct response to the small number of exploration wells drilled since 2000: only 22. A further drop in local NG supply is projected out to 2041 (Figure 1). Over the last two decades the country consumed about 13 Tcf (trillion cubic feet) but added only 2 Tcf from new discoveries (Imam, 2021).

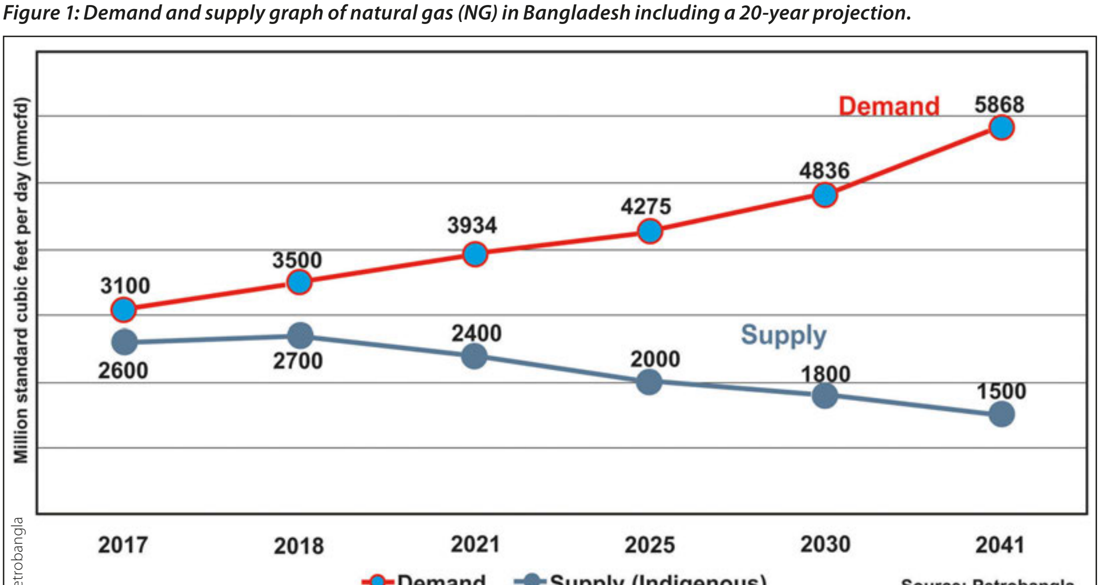
Since late 2018, Bangladesh has imported liquefied natural gas (LNG) to supplement NG supply to meet increasing demand. The declining supply from presently operated local gas fields means that the share of expensive imported LNG is expected to increase in the future from the present level of 4 MMtpa (million metric tonnes per annum) to 21 MMtpa in 2030 (Wood Mackenzie, 2021). In-country gas fields with reserves of about 12 Tcf, and more expensive LNG imports should provide the energy for moderate to high growth until 2030; if demand remains below about 2.5–3.0 Tcf per year. However, the recent price hike in the LNG spot market from less than \$10 to more than \$35 per MMBtu (metric million British Thermal Unit) means that Bangladesh must bear added pressure on its economy and must survive on the price uncertainties of LNG in the international market. After 2030 the energy supply and dependent economic growth will become even more precarious. Preventing economic decline will require a combination of new NG discoveries and reserve growth from existing fields, or expansion of other reliable and resilient base-load energy sources such as carbon-intensive coal or development of carbon-free nuclear power.

As noted by in-country experts including Shetol et al. (2019), "The possibility of natural gas being exhausted within a decade and half worries us all…Bangladesh is likely to exhaust its gas reserve by about 2030." Imam (2021) states, "…Bangladesh's gas exploration has apparently been stalled because of a lack of dynamic vision." NG exploration needs to dramatically increase over the next few years to avoid potentially severe economic contraction after 2030.

High NG Potential but Underexplored

Today, many onshore and offshore exploration gas opportunities are available in Bangladesh. Only a few blocks (Figure 2) are held by international oil companies (IOCs). Under its charter, Petrobangla has the right to enter into petroleum agreements with any IOC for the purpose of any petroleum operations and explorers must joint-venture with the Bangladesh Petroleum Exploration and Production Company Limited (BAPEX), a subsidiary of Petrobangla, to obtain licences.

Figure 1: Demand and supply graph of natural gas (NG) in Bangladesh including a 20-year projection.



A 2001 US Geological Survey estimate of mean-undiscovered, conventional-play NG in Bangladesh totals 32.1 Tcf and is divided into six assessment units (Figure 3). Another estimate of mean undiscovered NG resource in Bangladesh by the Norwegian Petroleum Directorate (NPD) indicated local Hydrocarbon Unit (HCU) totals of 41.6 Tcf (HCU-NPD, 2001). Today, there are 27 gas fields (Figure 3), all located within three of the USGS assessment units that forecasted 28.9 Tcf of undiscovered NG. As of the end of 2020 the proved plus probable NG reserves were 28.2 Tcf (Petrobangla, 2020) and nearly equal to the earlier USGS assessment. To date, only 95 exploration wells have been drilled and much of the country remains remarkably underexplored given its extensive and rich petroleum systems (Curiale et al., 2002). Much of Bangladesh is favourably located for NG accumulations as shown by the extent of the actively generating source-rock pod (Figure 3; USGS, 2001). Underexplored areas are the offshore, the western half of the onshore, and the two USGS assessment units with existing gas fields in the central and south-east. Geochemical modelling shows peak generation for NG occurs at depths of 18,000–20,000 feet (5,500–6,100 metres) or more, and subsurface geologic and geophysical mapping reveals that active NG generation pods should occur under all of central and eastern onshore Bangladesh and all of offshore Bangladesh (Figure 3; USGS, 2001).

Several high-potential gas plays are present across much of Bangladesh due to an active petroleum system, a thick sedimentary basin with rich, mature source rocks (Curiale et al., 2002), and various geologic settings developed across the basin provide a range of depositional and structural trap styles. Since the 1920s, only 10 exploration wells have been drilled in the extensive eastern fold belt that has surface hydrocarbon seeps and numerous large anticlines as shown by surface mapping (Figure 4) and cross-sections (Figure 5). Another very promising gas play is the numerous, untested stratigraphic traps developed in the complex depositional system that resulted from Bangladesh's location along an evolving plate margin (Indian and Eurasian Plates collision), high-uplift and erosion rates (Himalayas) that resulted in high-depositional rates and complex depositional patterns in the Ganges-Brahmaputra Delta.

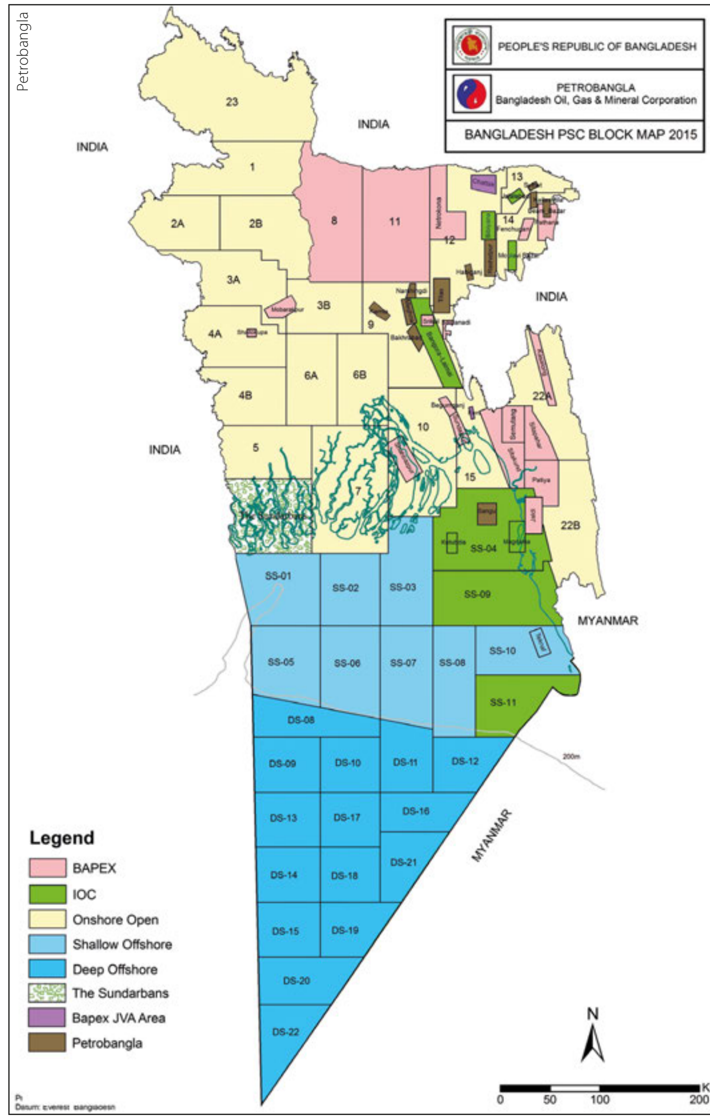


Figure 2: Bangladesh PSC Block Map (Onshore and Offshore).

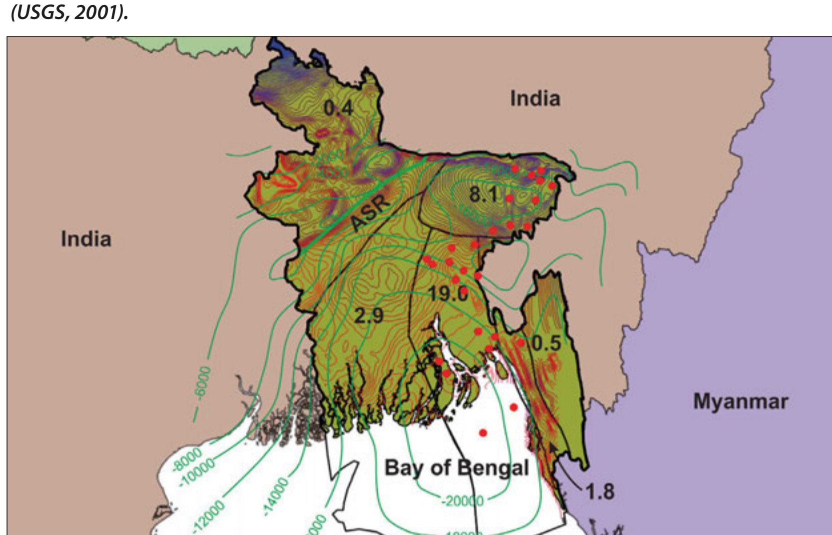


Figure 3: Map of Bangladesh showing the six USGS (2001) NG assessments units (black numbers in Tcf). There are 27 gas fields (red dots), all located within three of the USGS assessment units. The extent of the actively generating, source-rock pod is the large area south-east of the green heavy line labelled ASR. Green-coloured contours are depth to the base of the sedimentary rock section, and red to blue contours are the Bouguer gravity field (USGS, 2001).

A Range of NG Plays

The low frequency of exploration drilling obscures the true potential of Bangladesh's gas resources. As one of the world's largest delta deposits, highly influenced by tectonic plate movements, its structural and stratigraphic gas plays are abundant and warrant more attention (Imam, in press).

The play types can be broadly categorised as follows:

Structural plays:

Undrilled anticlinal plays: The geological map (Figure 4) and generalised cross-sections (Figure 5) across the eastern fold belt (EFB, aka Tripura-Chittagong Hill Tracts) show many untested and partially tested anticlinal and other convergent structural traps plus the potential for sub-thrust traps that are not obvious at the surface. Our structural work favours about 4–5 Tcf of undiscovered NG in the EFB that is similar to the high range of the 2001 USGS estimate for the two assessment units within the EFB.

Previously drilled anticlinal plays with inconclusive tests: Heavy mud used in the drilling of several exploration wells in the 1950s (Patya and Jaldi anticlines for example), may have deterred gas shows and retesting of these anticlines with conventional, lighter muds has yet to occur.

Synclinal plays – lessons from Tripura: Synclines are not normally considered as petroleum traps, but in the Indian Tripura fold belt, a northern continuation of the EFB fold belt, several discoveries have been made in broad synclinal valleys between the anticlines. Low-angle fault-detachments, angular unconformities in growth-strata, or relict structures (buried hills) probably explain the existence of these concealed traps. It is reasonable to expect that an analogous synclinal play exists in the adjacent EFB of Bangladesh.

Rollover anticline: Seismic evidence exists for the occurrence of listric faults in north-central Bangladesh and the development of hanging-wall, rollover anticlinal traps (Lohmann, 1995), and onshore blocks 8 and 11 contain prospective areas for such traps.

Deepwater fold-belt play: Geologic and geophysical studies indicate the deeper portions of the Bay of Bengal (Hatia Trough and

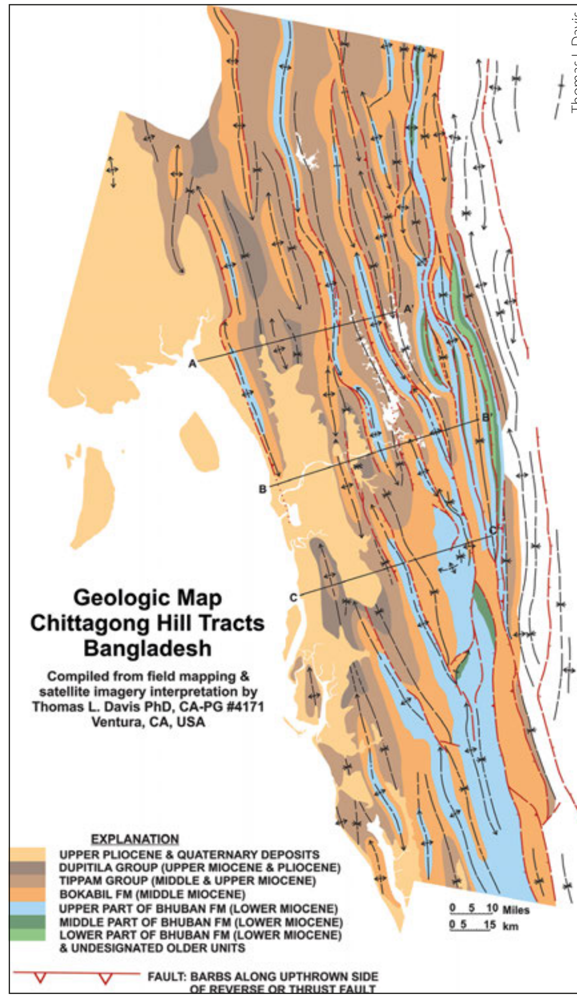
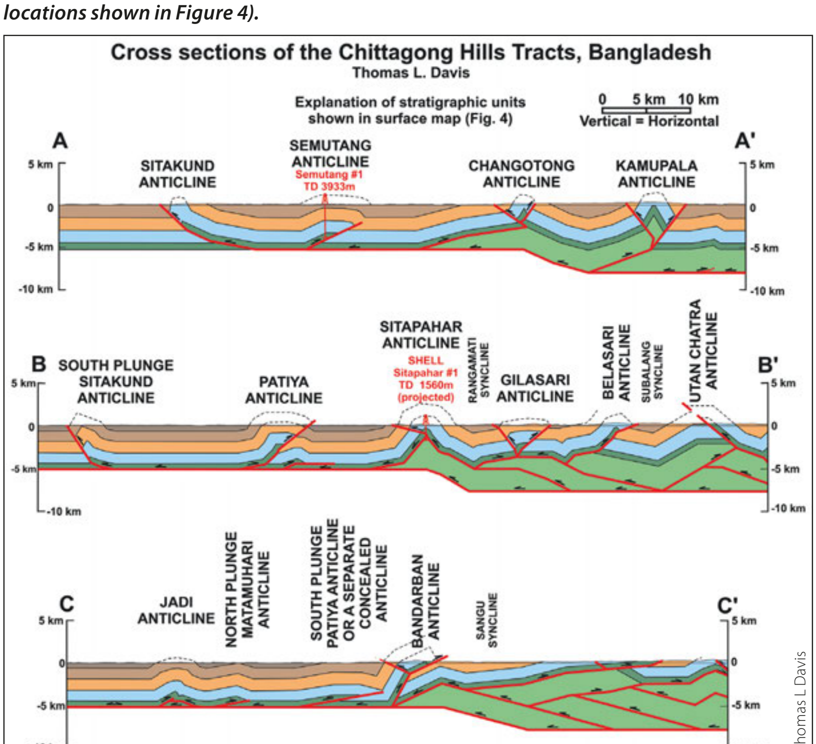


Figure 4: A generalised geological map across the eastern fold belt (EFB, aka Tripura-Chittagong Hill Tracts).

Figure 5: Three generalised cross-sections across the eastern fold belt (EFB, aka Tripura-Chittagong Hill Tracts) showing subsurface interpretations of the fold and fault geometry tied to the surface geologic mapping (cross-section locations shown in Figure 4).



Rakhine Sub-basin [Xu et al., 2015]) show the likelihood for well-developed, gravity-controlled, deepwater fold-belts and their associated hydrocarbon traps. World-wide deepwater fold-belts have become significant, commercial oil and gas provinces during the last three decades (e.g., Gulf of Mexico and Niger Delta).

Stratigraphic plays:

Deepwater turbidite play: One of the most high-potential plays consists of stratigraphic traps in the Mio-Pliocene deepwater, turbidite-deposits that occur across a wide area of Bangladesh. A variety of turbidite sand facies are described as prospective reservoirs (Bowles et al., 2019). These are primarily channel-levee complexes and basin-floor fan-lobes that include sand facies in the feeder channel deposits, channel levees, crevasse splays, distributary channels, and fan lobes. Large gas finds with turbidite plays are known from the offshore Rakhain Basin (Myanmar), adjacent to south-eastern offshore Bangladesh in the Bay of Bengal i.e., Shwe, Shwe Phyu, Mya, Thalin and others

(Figure 6). Offshore Bangladesh, adjacent to the maritime boundary with Myanmar is the most likely place where the next round of large gas fields are likely to be discovered.

Channel and incised valley plays: Seismic evidence depicts the Mio-Pliocene sections of Bangladesh as displaying erosion-induced intense channelling (Najman et al., 2012). Channels are either sand-filled or clay-plugged and in both cases stratigraphic traps are formed.

Drape over basement horst and fault: In the north-west stable shelf area of Bangladesh, deep-seated fault blocks or basement horsts are associated with overlying drape folds forming potential plays.

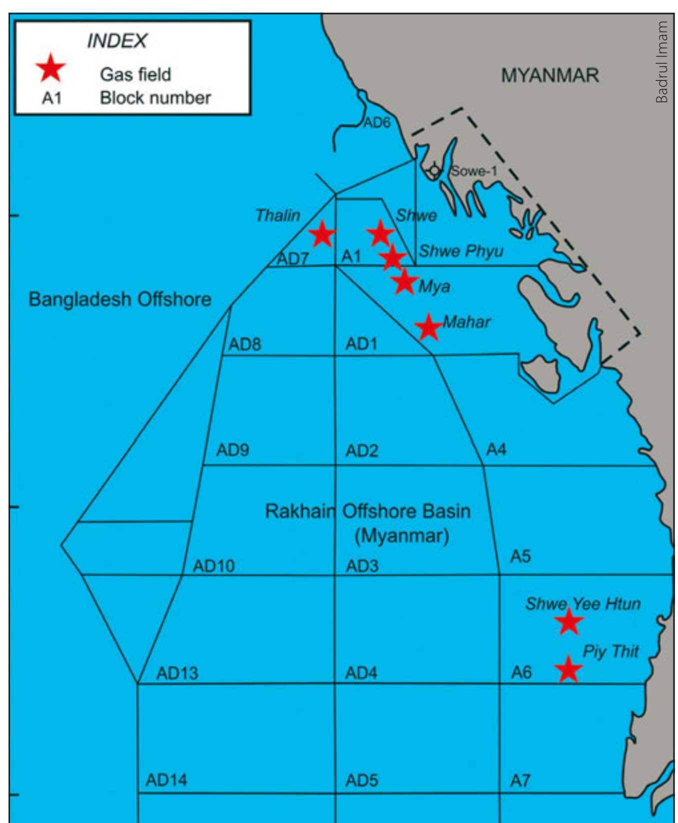
Onlap pinchout: The onlapping seismic facies are interpreted as high energy transgressive coastal sandstones pinching out against the slope (Salt et al., 1986) and such sediments should have excellent reservoir qualities.

Carbonate build up and shelf-margin reef prospects: A potential carbonate play is the shelf-margin carbonate reefs developed in the Eocene Sylhet Limestone Formation (Moore and Leyenburger, 1992).

Several unconventional NG plays exist but remain untested, including Change to tight sand reservoirs, thin-bedded sand sequences, and shale source bed accumulations. Over-pressuring is known to exist in the deep basinal areas and could assist production in these unconventional plays.

References available online. ■

Figure 6: Gas exploration blocks and discovered gas fields in the offshore Rakhain Basin, Myanmar (Imam, in press). The Myanmar blocks and gas fields lie adjacent to Bangladesh's south-eastern maritime boundary.



Mexico: Onshore to Offshore

From the 16th-century Spanish conquistadors to modern times, Mexico has been bound to oil. Although no longer in the top ten of the world's leading producers, shale gas may change this picture in the future.

M. QUENTIN MORTON

The Spanish explorers and conquistadors who came to Mexico in the 16th century saw many oil springs and asphalt deposits there. For centuries, the indigenous people had used asphalt to seal their canoes, for medicinal purposes and as incense in religious ceremonies, and collected blocks of bitumen from beaches along the Gulf Coast to provide fuel for their fires. By the late 19th century, the oil prospects of Mexico were attracting a wider interest. In 1884 a new mining law gave landowners the right to exploit petroleum in their lands but, with a lack of capital and technical expertise in the country, it fell to American and European companies to take up the challenge of exploration.

The Golden Lane

Prospecting began in earnest in May 1900, when oil tycoon E.L. Doheny and his business partner Charles Canfield arrived from California. They had first struck oil in Los Angeles in 1893, triggering an oil boom and enabling them to attract the capital needed for their Mexican venture. With the assistance of Mexican geologist, Ezequiel Ordonez, they made their first commercial discovery at Ebano near Tampico. Over the next few years, operating through the Mexican Petroleum and Huasteca Petroleum companies, they drilled numerous wells in the area. In February 1916, the Azul No. 4 well in dense jungle produced a gusher bigger than the famous Spindletop in Texas, exploding nearly 600 feet into the air and blowing 260,000 barrels of oil on the day it was capped. By the end of 1921, it had produced a total of 57 million barrels of oil.

Meanwhile an English firm, S. Pearson & Son Ltd, was completing a railway in the Isthmus of Tehuantepec, connecting the Atlantic and Pacific coasts. Headed by Weetman Pearson (later Lord Cowdray), the company diversified into the oil business in 1901 after Pearson missed a train connection and was stranded in Laredo, Texas. There he saw at first hand the 'oil mania' that was sweeping Texas after the Spindletop discovery. Knowing that oil seepages had been found around the Tehuantepec railway, he cabled his manager to buy up "all land for miles around". He also employed Captain Anthony F. Lucas, who had brought in the Spindletop well. Although initial results were disappointing, the company switched operations to the area around Tampico and hit a gusher at the San Diego de la Mar No. 3 well in 1908. It was later revealed as part of an aligned group of oil fields known as Faja de Oro, the 'Golden Lane'.

Incorporated as Mexican Eagle ('El Aguila') in 1909, the company made further discoveries at Potrero del Llano No. 4 and Juan Casiano No. 7, bringing a new wave of prospectors, drillers and fortune hunters to Mexico – by 1920, there were 155 separate companies and 345 individual enterprises operating in the country. Tampico was the thriving centre of the oil industry with the 'Southern Fields' (the so-called Golden Lane) being the most prolific producer. Next in importance were the 'Northern Fields' situated west of Tampico which included Panuco, Topila and Ebano as the main oil fields, but these were not quite so productive.

Inspecting an oil seepage near Chautla, Mexico, 1911.


The American Geographical Society Library, University of Wisconsin Milwaukee Libraries

The third main player, Waters Pierce Oil, was a former affiliate of Standard Oil. It had established a monopoly over petroleum sales in Mexico and moved into the drilling business under its Mexican Fuel Oil brand. In 1913 the company struck oil at Topila, an area that Mexican Eagle had previously dismissed as unpromising. By 1914, Mexico was the third largest oil-producing country in the world and Mexican Eagle controlled about 60 percent of production, expanding into refining, distribution and selling.

The Road to Expropriation

A difficult terrain, climate and lack of infrastructure all conspired against the oilmen. Even when oil was found, the number of high-pressure blowouts remained high. There was a lack of experienced labour, and working conditions were poor. The American geologist Everette Lee DeGolyer, who worked for Mexican Eagle between 1909 and 1919, noted the predicament of Mexican workers:

> "Men came down from the hills, brought a meagre supply of food with them, worked for a few days, slept in the brush, received their wage and went back to their homes. Skilled labour, almost altogether American drillers, their helpers, mechanics, and engineers, on the other hand, were properly housed, well fed, received medical attention, were paid a higher wage than at home, and generally received superior treatment."

Everette DeGolyer (seated) at Potrero del Llano with geologist Leon Russ in 1911.

During the Mexican Revolution (1910–1918), rebels occupied Mexican Eagle oil camps and workers were killed. In the face of threats to foreign oil workers, DeGolyer was forced to evacuate in April 1914, returning in October to compile a report on the geology of the Mexican oil fields, although the revolution rumbled on.

In 1917, article 27 of a new constitution restored ownership of the subsoil to the state, although this was amended in 1928 by the Calles-Morrow agreement which allowed the oil companies to retain the rights they had previously held. By then Mexican Eagle was a subsidiary of Royal Dutch Shell, with the remaining share of the country's oil business dominated by US majors such as Jersey Standard and Standard Oil of California. More than 4,300 oil wells were drilled between 1920 and 1929, contrasted with the 442 drilled during the preceding 20 years.

In the 1930s, the Great Depression and a glut of oil on the global markets saw prices tumbling; government revenues fell, and labour unrest followed. On 18 March 1938 President Cardenas signed an order expropriating the oil industry, effectively nationalising the assets of the foreign oil companies. Shell and Jersey Standard led an international boycott and a battle over compensation that lasted several years. Although agreement was reached, the oil companies were not allowed back into Mexico and oil operations were exclusively managed by the state oil company, Petroléos Mexicanos (Pemex). Many firms moved to Venezuela, where conditions were more favourable.

The Mexican Oil Boom

With technological advances in marine drilling, it was inevitable that exploration would go offshore. Pemex drilled its first offshore wells in the 1950s, but the breakthrough came in 1972 when a fisherman named Rudesindo Cantarell Jimenez led Pemex geologists to a location some 50 miles off the coast in the Bay of Campeche where an oil slick had fouled his nets. Named Cantarell after the fisherman, the supergiant oil field was hailed by Mexican officials as 'el salvador del pais', the saviour of the country.

The Cantarell field was formed from carbonate breccias deposited by a massive asteroid impact which created the Chicxulub crater – an event that scientists believe caused the extinction of the non-avian dinosaurs some 65 million years ago. The complex comprised four oil fields, the largest being Akal (named after a Mayan god), which held about 90 percent of the reserves.

Offshore drilling brought its own risks. Tropical storms and hurricanes could disrupt production, as well as blowouts and fires. In June 1979 the Ixtoc I platform exploded and, at the time, caused the largest oil spill in peacetime. This was an exploratory well being drilled in the Bay of Campeche and resulted in almost 3.3 million barrels of oil escaping into the sea before Pemex could plug the leak. A harbinger of the more serious Deepwater Horizon disaster in 2010, its environmental impact was wide-ranging and local industries, especially fishing communities, were hit hard. "The amount of fish to catch was never the same as before the spill," remarked one fisherman.

The 1970s and 80s witnessed the dominance of OPEC (the Organisation of Petroleum Exporting Countries), when oil embargoes and price shocks hit the global markets. In search of energy security, the United States turned to non-OPEC countries like Mexico as alternative energy sources to the Middle East. The Mexican offshore discoveries brought an oil boom to meet this demand. Between 1977 and 1981, the country's petroleum output rose from 400 million barrels to 1.1 billion barrels.

Mexico was rapidly transformed from an importer of oil to one of the world's leading petroleum exporters, with the promise of massive growth in the future. President Portillo used burgeoning oil reserves as collateral for massive foreign loans, most of which were reinvested in Pemex. But when the United States raised interest rates, a debt crisis followed, together with a succession of economic blows that saw Mexico's oil production stagnate until the mid-1990s – only then did it regain its 1982 level.

The Ixtoc I oil spill, June 1979.

The Long Decline

The Cantarell complex reached a peak of about 0.8 billion barrels in 2004. Gas pressure in the reservoir accounted for its remarkable oil flows but, when that declined, production rates dropped. Pemex used various enhanced oil recovery (EOR) techniques such as nitrogen injection to increase yield from the exhausted field. In 2004, output suddenly revived to an astonishing 2.1 million barrels per day; however, this was a momentary blip and production dropped back to 10 percent of its peak.

The KMZ development adjoins Cantarell and was discovered between 1980 and 1991. Its name is an acronym of the three main producers – Ku, Maloob, and Zaap – in a five-field complex of 207 producing wells. In 2007 a floating production storage and offloading (FPSO) vessel, the *Yuum K'ak'nab*, was added to the field, the first of its kind in the Gulf of Mexico. KMZ's output peaked at 900,000 bopd in 2016 and has since fallen to 784,000 bopd, which accounts for 46.5 percent of Pemex's total production.

Meanwhile, back on land, Pemex had made steady progress. It struck oil at a depth of 13,775 feet beneath the jungle in the Reforma area of Tabasco State in 1972. After mapping and petroleum systems analysis, between 125 and 150 potential oil prospects were identified, and many of these went on to become prolific producers. By 1979, 96 out of 216 wells were producing oil, although some of those suffered from reduced pressure. Other discoveries were made in the Chicontepec and Sabinas Basins, and the largest onshore unit was the Samaria-Luna oil field in the south which was producing 145,000 bopd in 2015.

Overall, output was in decline. The smaller fields could not make up the shortfall entirely, even though new fields had come on stream.

There was a lack of refineries to process the heavy oil known as Maya crude produced by the two main offshore fields. Much of it was sent to the US Gulf Coast refineries and then exported back to Mexico as petroleum products for domestic use. By 2016, increasing domestic demand had returned the country to the status of net importer of refined petroleum products.

In 2014, under President Nieto, reforms allowed competition from foreign private oil companies, with the result that international companies began exporting oil to Mexico, as well as prospecting for oil. Today, Mexico is ranked 14th among the world's leading oil producers.

A New Perspective

The Eagle Ford shale play extends into Mexico where it is known as the Burgos Basin. According to an Energy Information Administration (EIA) assessment of 2013, it had technically recoverable shale resources of 545 trillion cubic feet (Tcf) of natural gas, and 13.1 billion barrels of oil and condensate. Pemex has drilled some 20 exploratory shale gas wells, but progress has stalled. President Obrador promised to ban fracking soon after his election in 2018, but a recent cold-weather crisis was a reminder of Mexico's energy dependence on the United States, and Pemex has included shale exploration in its future projects "in the event that policy may change".

Thanks to Peter Morton for his kind assistance. ■

Mexican oil and gas fields (modified from EIA map 2012).

The Incredible World of Fossils

***GEO ExPro* is running a new series of fascinating articles on fossils. Avid collector James Etienne kicks things off with an introduction to this captivating hobby and field of serious scientific study.**

DR JAMES ETIENNE

I fell in love with fossils like many others, as a child, hunting on the world-famous Jurassic Coast in Dorset in the UK, a UNESCO World Heritage site, and location of many SSSIs (Sites of Special Scientific Interest). I will never forget a family holiday where my father Paul helped me rescue a small but well-preserved ichthyosaur vertebra as the tide came rushing in one day on the beach at Charmouth in Dorset. I have been collecting ever since (Figure 1).

Fossils have fascinated, inspired and left us awestruck for centuries. They provide the foundation for stratigraphic science and hint about how the Earth, and life on it, has evolved, conjuring incredible images of great beasts in ancient landscapes (think for example of Henry de la Beche's famous 1830 painting *Duria Antiquior* based on fossils found by Mary Anning; Figure 2). Fossils have inspired popular culture (e.g., the Jurassic Park movie franchise and the recent film 'The Meg') and feed a thriving multi-billion-dollar global business in trade (the annual Tucson Show in Arizona attracts an international audience of tens of thousands of people who regularly spend in excess of US$100 million in and around this two-week event alone)!

Fossils are ingrained in our culture and folklore – did you know that the Jurassic ammonite genus *Hildoceras* is named after St Hilda, who was thought to have turned a plague of snakes around Whitby (UK) to stone and sent them flying over the edge of the local cliffs? *Dactylioceras* (Figure 3), *Hildoceras* and *Eleganticeras* ammonites are so common along this stretch of the Yorkshire coastline, it is hard to walk along the beach and not find them. As recently as the early 1900s this superstitious view of the origin of these so-called 'snakestones' was still held by some townsfolk!

Other fossils such as belemnites were thought to represent the remains of lightning bolts that had struck the earth, and echinoids which are prevalent in the British chalk were thought to be 'thunderstones', delivered to Earth during thunderstorms. The latter have been collected for thousands of years and have been used to decorate graves as early as the late Neolithic to early Bronze Age (Figure 4) as well as churches during the Middle Ages and even the windowsills of kitchens and dairies in the 20th century to stop milk from curdling (thunder was thought to cause milk to go sour)!

While we now have a much better understanding of the origin of fossils such as ammonites, belemnites and echinoids, to this day, fossils continue to challenge the way we think about the past and there may be some lessons we can learn from them, especially around the sensitivity of groups of animals and plants and the ecosystems that depend on them in response to changing environments. In some ways, turning Lyell's famous maxim on its head, the past may be the key to the present!

Nearly everyone will have heard the theory that the extinction of the (non-avian) dinosaurs occurred at the Cretaceous to Tertiary (K–T) boundary because of the Chicxulub asteroid impact on the Yucatan Peninsula. Approximately 75 percent

Figure 1: Just a small sample of some of the fossils in my personal collection including ammonite, nautilus, crinoid, fish, crocodylomorph, ichthyosaur, plesiosaur and pliosaur remains and coprolites from ichthyosaurs and the Jurassic shark Hybodus.

Figure 2: The classic watercolour 'Duria Antiquior' painted by Henry de la Beche in 1830, inspired by the fossils collected around the area of Lyme Regis by Mary Anning and others in the early 1800s.

of the known flora and fauna on Earth became extinct around this time because of the resulting change in climate (likely also influenced by other factors such as the Deccan Traps volcanism). The older Permian mass extinction 252 million years ago is thought to have led to the eradication of as much as 96 percent of all known marine life because of environmental change resulting from the outpouring of the Siberian Traps, which was the biggest volcanic eruption in the history of the planet. This disaster lasted for hundreds of thousands of years and there are numerous other examples throughout the Phanerozoic where major faunal turnover has occurred.

In the present, global awareness of the impact of climate change has never been greater, and I write this as the critical COP26 meeting is in full force. But over geological timescales, Earth's climate has been in a constant state of flux, long before the arrival of hominids. This change has driven natural selection, species evolution, and incredible diversity in the fossil record which makes the sciences of palaeontology and biostratigraphy essential tools for the geoscientist.

Figure 3: Dactylioceras ammonite from the Yorkshire coast – nodules like these are plentiful and collected daily in the area around Whitby.

Utility in Geological Interpretation

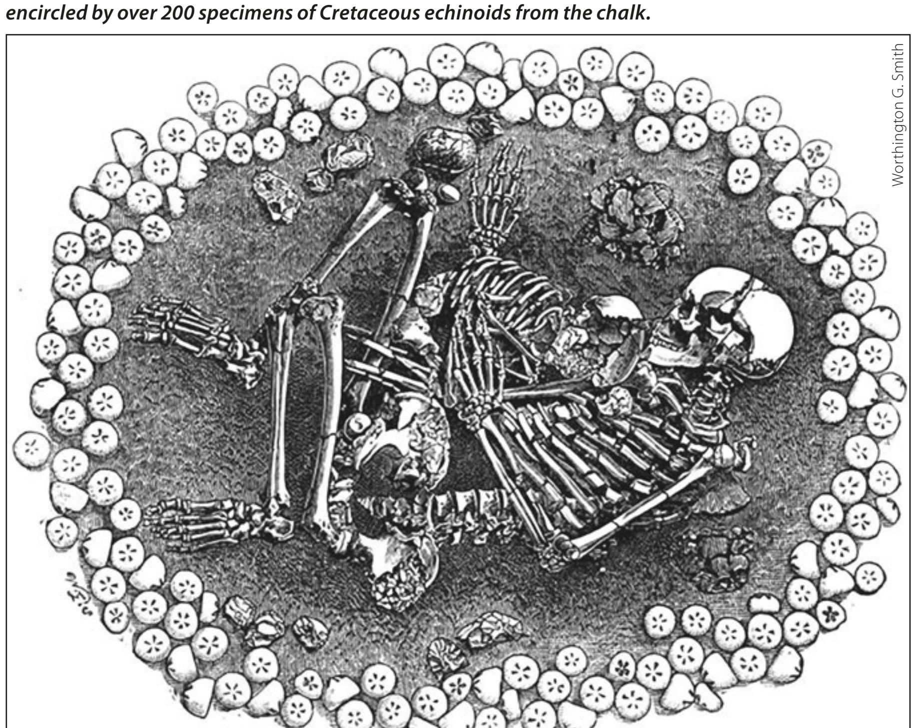
Fossils are the fundamental basis for defining the ages of sedimentary rocks. We can use diagnostic species (preferably those with short stratigraphic ranges) to define bioevents, biozones, assemblages and first and last appearance data to facilitate stratigraphic correlation (Figure 5). Some fossils provide important proxies for determining past palaeoenvironmental conditions (e.g., climatic zones from floral assemblages, air temperature from leaf stomatal indices and seawater temperature, salinity, chemistry and bathymetry from a range of different organisms based on occurrence, morphology, or measurements of the chemical compositions of their shells).

It does not end there. Different fossil groups can be useful for understanding the thermal maturity attained by sedimentary rocks following deposition, burial and diagenesis. A range of indicators including Graptolite and Conodont Alteration Indices, Spore Colour Index and Vitrinite Reflectance analysis have been extensively used in basin-modelling to understand the potential thermogenic maturation of hydrocarbon source rocks.

The degree of endemism and radiation of species can even help contest or validate conflicting geodynamic models. Did you know that the observed occurrence of radiolaria in the Barbados accretionary prism is important to debating the competing plate tectonic models for the Caribbean, or even that cosmopolitan frog radiation is useful for reconstructing the timing of the India break-up from Pangaea (Gondwana) assembly, and the evolution of the Palaeotethys and Neotethys Oceans?!

Some groups of fossils have broader utility and scientific value than others – the identification of diagnostic zone fossils, particularly in microfossil groups such as foraminifera,

Figure 4: Fossils have been collected for thousands of years – even used to decorate graves, such as the famous late Neolithic to early Bronze Age Dunstable discovery where a woman and child were encircled by over 200 specimens of Cretaceous echinoids from the chalk.



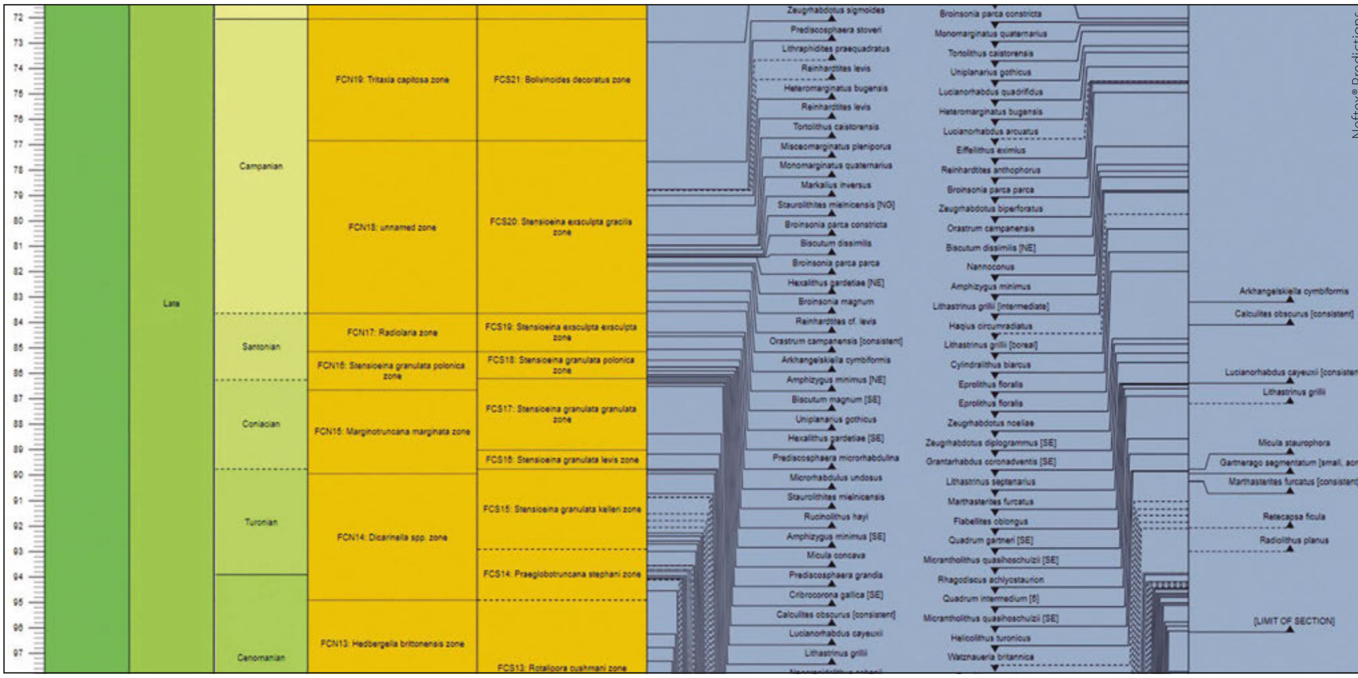


Figure 5: Biostratigraphic range charts are critical tools in stratigraphic correlation – they allow biozones, bioevents, and assemblages of fossils to be compared from different fossil groups to drive the best possible understanding of age. This is essential for sequence-stratigraphic analysis in understanding subsurface reservoir architecture, useful not only for petroleum geology, but also carbon capture and storage projects.

calcareous nannofossils, dinoflagellate cysts and other palynomorphs, are particularly well suited for borehole analysis and are an important instrument in the hydrocarbon industry.

However, there are many challenges with the several hundreds of thousands of taxa now described in the scientific literature. Taxonomically identical specimens have been described more than once (leading to many synonyms), original type-specimens were not described at a level to be truly diagnostic (*nomen nudum*) and some have since been destroyed or lost (a number of early type-specimens did not survive the air raids of World War II for example). Many fossils have also been arbitrarily assigned to taxa that have lost any real taxonomic value (so-called 'wastebasket taxa') – this is particularly problematic for some Jurassic marine reptiles and fossil fish.

Commercial World

Many key fossil groups are best represented in macrofossil specimens, such as ammonites which are revered as much for their beauty as for their stratigraphic value. Trade in fossils is big business, ranging from cottage industry in local fossil shops (typically close to the collecting localities), to large international enterprises. Do you have a slab of fossil fish on your wall? Chances are it probably comes from the Eocene Green River Formation in the United States. If you have purchased a trilobite, spinosaur tooth or mosasaur jaw in a fossil shop in recent years, they probably originated in Morocco. The fossil trade in Morocco alone is thought to be worth US$40 million a year and provides employment to more than 50,000 people.

Globally it's a multi-billion-dollar industry, but fraught with complexity on legal rights, with some very high-profile cases where illegal trade has been halted by government intervention (most notably over the last decade for dinosaur eggs and other scientifically important dinosaur specimens from Mongolia and China). In Mongolia, for example, fossils are regarded as cultural items and have been protected by law from export since 1924. Even before this time, the commercial auction of a dinosaur egg collected on one of the Roy Chapman Andrews expeditions raised consternation from the then-ruling Chinese government which invoked a year-long delay to the next planned expedition of the American Museum of Natural History. At the time, Andrews' expeditions were ground-breaking in the discovery of clutches of dinosaur eggs at the Flaming Cliffs which were associated with *Protoceratops* dinosaur remains at the site. Exceptional specimens are now known today from elsewhere in the Gobi Desert, which include embryos, allowing species level identification to the ornithischian dinosaur *Oviraptor philoceratops*.

When high-quality legitimate specimens come to market, they can attract huge interest (and vast prices). Last year, one of the most complete *T. rex* skeletons ever found – nicknamed 'Stan' (Figure 6) – sold at Christie's auction house in London for a record US $31.8 million (including fees), eclipsing the sale of 'Sue' (another *T. rex*) which sold for US$8.36 million in 1997 (roughly US$13.5 million in today's money). Even an individual well-preserved *T. rex* tooth can command prices in excess of US$20,000! Slightly more affordable fossils include megalodon teeth (a thriving industry in its own right), and stunning green and red iridescent gem-grade ammolite ammonites from Canada which are commercially mined in Alberta from the Cretaceous Bearpaw Formation (Figure 7).

Exceptional Preservation

The stunning aragonitic Bearpaw ammonites are just one example of fossils from several sites in Canada where exceptional preservation has led to the discovery of important specimens. The Cambrian Burgess Shale in the Canadian Rockies is another, with many weird and wonderful early marine life forms including *Hallucigenia*, or the Lagerstätte of the Mistaken Point Formation in Newfoundland which preserves some of the best Ediacara fauna from the Precambrian. The latter are named after the Ediacaran Hills in Australia, another exceptional location which shows the proliferation of soft-bodied marine life prior to the Cambrian Explosion which led to the evolution of many of the most successful phyla which comprise modern life today. Ediacara fossils can even be found in the U.K., where *Charnia masoni* has been known since the 1950s, named after Charnwood Forest in Leicestershire where it was first discovered.

Figure 6: A cast of the incredible T. rex fossil 'Stan' at the New Mexico Museum of Natural History.

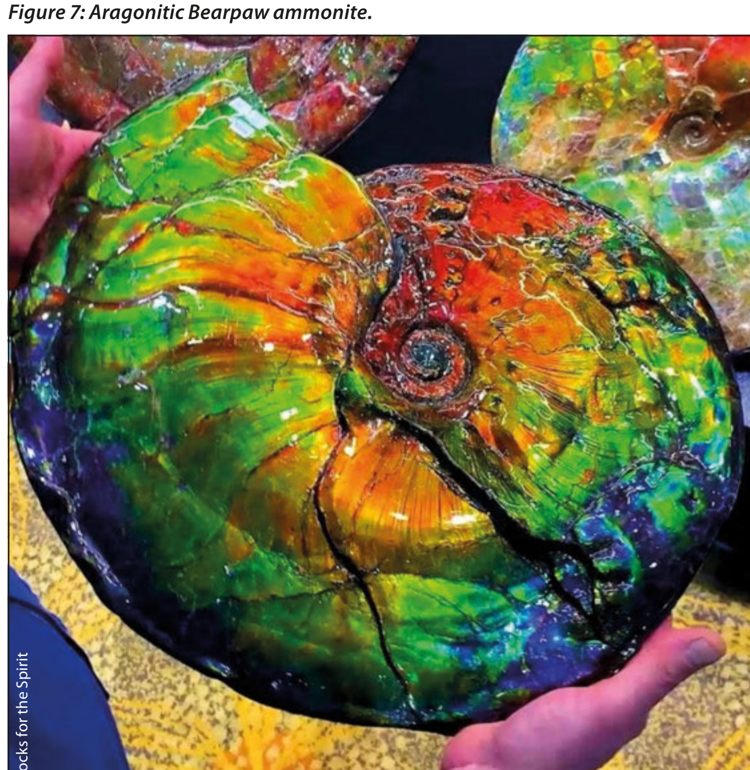
Returning to the Jurassic Coast, exceptional fossils continue to be recovered, long after Mary Anning set the bar for remarkable finds here. One such example was the recent discovery of a new species of ichthyosaur by Chris Moore, the subject of an excellent BBC documentary – 'Attenborough and the Sea Dragon'. The specimen preserves fossilised skin which has been analysed using modern technologies like electron microscopy to examine the melanosomes, which provide information on the skin pigmentation, suggesting countershading on ichthyosaurs, as observed in modern sharks. Moving further to the east (and up into the Middle Jurassic), in Kimmeridge Bay, Steve Etches MBE has donated his world-class collection of Kimmeridgian material to establish the Museum of Jurassic Marine Life which includes some very important discoveries, not least fossil ammonite eggs!

Community

The vast amount of information now available about fossils on the web, through online museum collections, dedicated websites, research papers, and social media continues to significantly improve the accessibility of fossil collecting, palaeontological and biostratigraphic sciences to all. Even a casual look will reveal literally millions of specimen images! There is a thriving and strong community of contributors, private collectors and outstanding preparators that share how and where to find amazing fossils, how to prepare them, and how to build a safe and effective preparation space to make it all happen. Modern preparation standards are now so advanced that museum-grade specimens are becoming the norm, even in private collections.

I hope you have enjoyed this brief introduction to the fascinating world of fossils. Follow the series of articles over the next several issues for more insights on these incredible artefacts that tell the story of our planet – we still have a lot to learn from them! ■

Figure 7: Aragonitic Bearpaw ammonite.



Vintage Maps Reborn

STEVE PARKER,
Visual Geomatics Ltd

Using 3D animation software and surface models for new hillshade mapping techniques to produce hyper-realistic 3D-like maps.

A new trend of map-making has recently evolved and changed the way we look at traditional topographic maps. With the advent of 3D modelling and access to detailed surface model data covering the entire globe, shaded relief maps generated from 3D animation software such as Blender have given cartographers the ability to create 2D maps with a hyper-realistic 3D appearance. These eye-catching maps are not only aesthetically pleasing and hard not to stare at, but they also provide us with the ability to visualise terrain details that can be difficult to interpret with traditional mapping methods such as contouring (Figure 1).

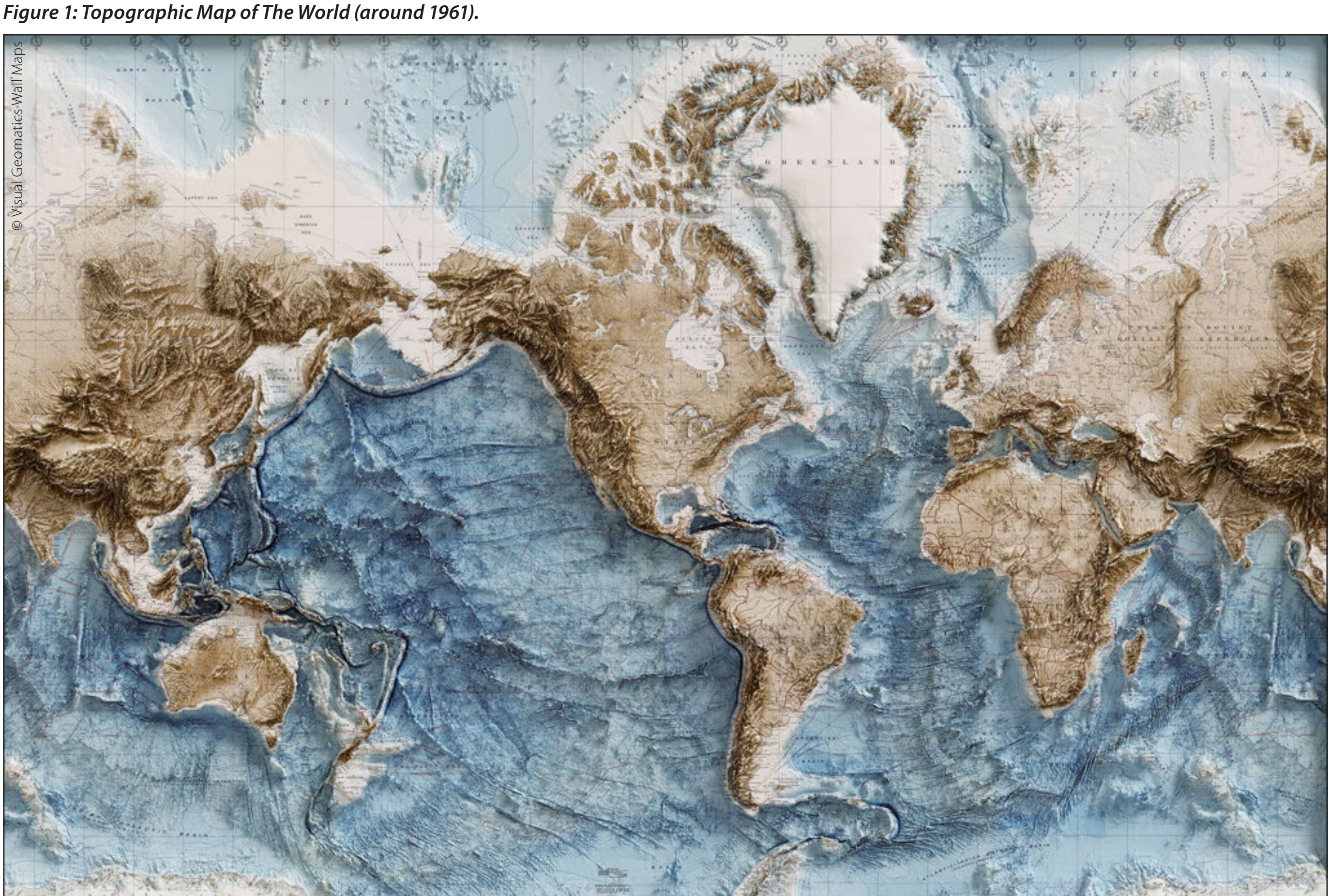
Mapping Re-Visioned

Although hillshading using 3D animation software is quite a new technique, shaded relief displayed on maps has been around nearly as long as map-making. Cartographers from centuries past shaded-in shadows by hand to display relief on maps; a skill that required great artistic sketching abilities. In more recent years where map-making has turned digital, common GIS software has been able to generate hillshaded maps that cannot be discounted in their effectiveness for topographic relief visualisation. The advantage that 3D animation software provides over these traditional techniques is a combination of an advanced hillshading algorithm and having much more control in the artificial light source(s) casting the shadows on the terrain model. Traditional hillshading algorithms used within GIS software only account for light in one constant direction whereas the 3D animation software takes a more realistic approach by accounting for how the light bounces and reflects off objects such as mountains and river valleys within the surface model. This approach results in a much more realistic shading that shows clear differences and advantages (Figure 2).

A Work of Art

Surprisingly, the most popular use of this hillshading technique to date has not been driven by the scientific

Figure 1: Topographic Map of The World (around 1961).



community for topographic interpretations, but rather for new age artwork that can be hung on the wall of a home or office.

Shaded relief maps also have the advantage of rendering 2D maps created in the past. Maps created by early cartographers from as far back as the 18th century can easily be reborn into eye-catching wall maps when shaded relief is added (Figure 3). With archival access to a massive database of scanned historical maps, new age cartographers are creating a wide variety of vintage shaded relief maps covering all corners of the globe. One does not need to search too far within social media platforms such as Reddit, Instagram and Twitter to find impressive works of art (try #shadedrelief).

Relief maps vary from a broad range of mapping themes. Maps displaying surficial geology, or physical maps showing landscapes are common for undergoing the 3D render makeover. But simple shaded relief maps that show nothing more than a colour ramp or simple tint on top of the surface model can still produce an impressive image to look at. Figure 4 displays a surface model generated from LiDAR data obtained from the United States Geological Survey's (USGS's) 3DEP database. The surface model was clipped to the mountain's lowest contour and a simple green colour ramp that lightens at higher elevations was compiled into a shaded relief render that brings out an incredible amount of detail. Notice that even the crevasses of Mount Rainier's 25 glaciers are visible on the shaded relief.

The Process

Compiling shaded relief maps starts by preparing two key components: the cleaned vintage map, and the surface model data otherwise known as a Digital Elevation Model (DEM). Although shaded relief maps can be created straight from a surface model alone as mentioned, the process of rendering from a vintage map starts by taking the high-resolution digital scan of the map and using GIS software to align or georeference the map to its correct geographic location. Properly georeferencing a vintage map can be one of the more time-consuming tasks in the process; capturing hundreds of control points to tie the map to the surface. One can imagine maps that were created before the advent of GPS can tend to have a reasonable amount of spatial distortion where the map does not align perfectly to the spatially corrected surface model data.

Figure 2: Comparison of Traditional vs Modern Hillshading – Ireland.

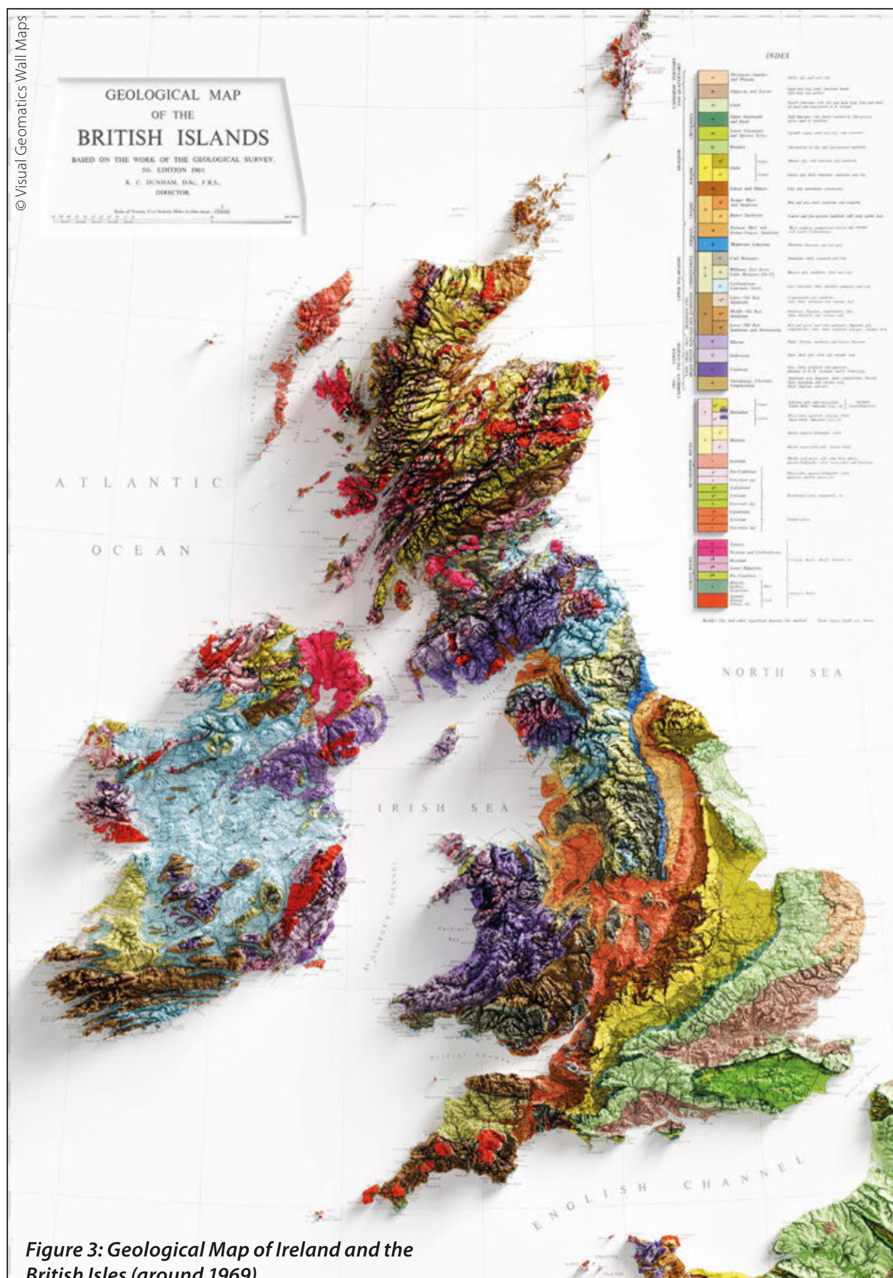


Figure 3: Geological Map of Ireland and the British Isles (around 1969).

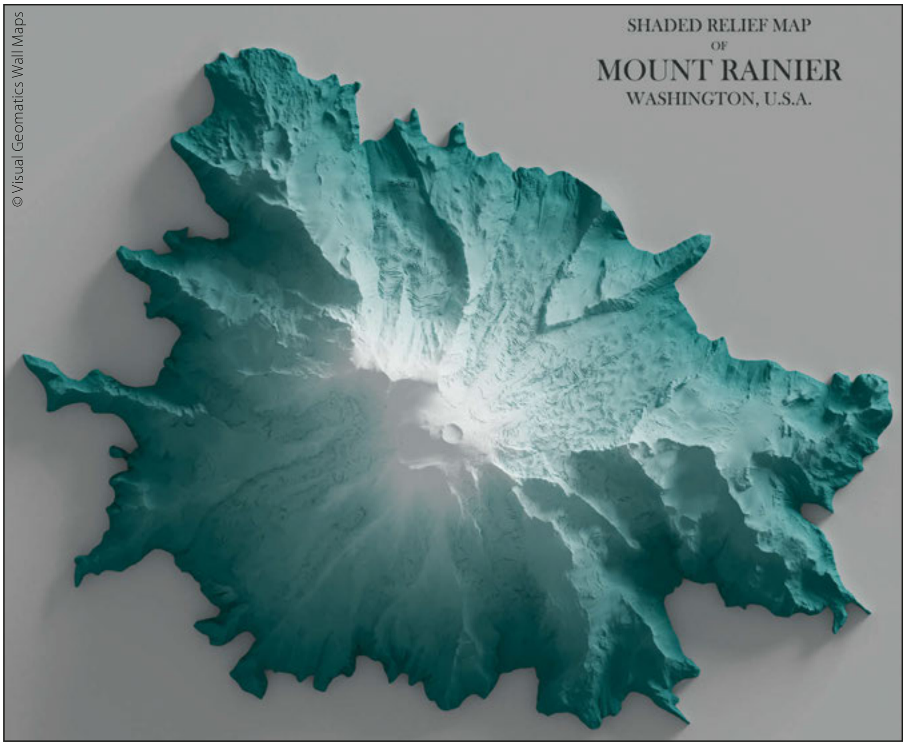


Figure 4: Simple Shaded Relief of Mount Rainier, Washington, USA.

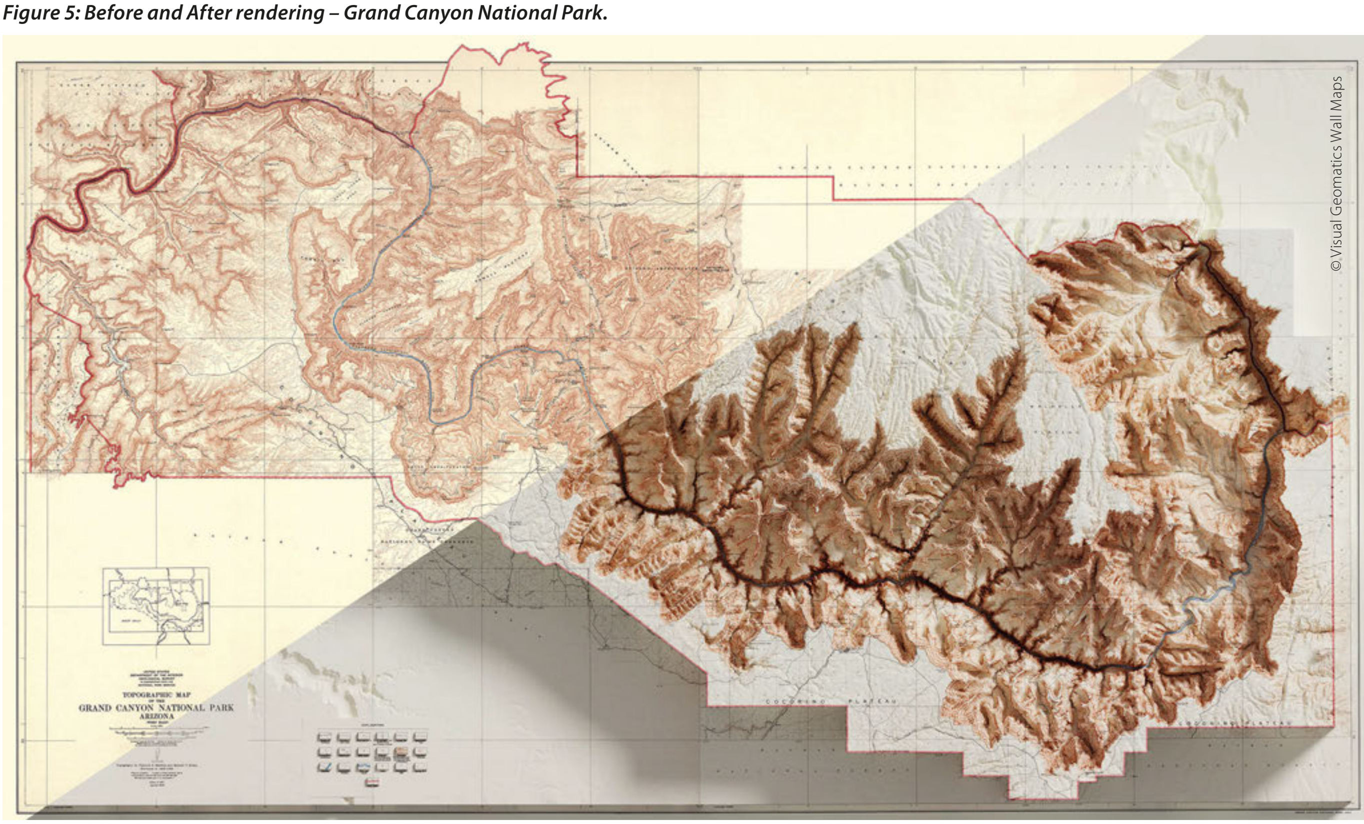
Typically, a boundary of the map's content such as a country border or island shoreline is then used to clip or extract the surface model data. This surface model data is the key component in rendering the hillshading within the 3D animation software.

This of course is oversimplifying a process that requires a moderate level of GIS expertise to perform. Most data preparations will involve manipulating multiple surface models, reprojecting data into various geographic projections and rectifying hand-drawn maps that can skew in spatial accuracies.

Once the vintage map and surface model have been cleaned and aligned it is time to reference them into the 3D animation software. Within the 3D animation software, a flat planar object is added to an empty scene. The object has a multitude of settings to configure for adjusting the material properties and behaviour of the object. Characteristics such as roughness, sheen and emission strength can be adjusted to change the appearance of the object. Ultimately the planar object references the surface model to displace or protrude it from a flat surface. A vertical exaggeration can be adjusted to increase or decrease how much displacement is applied to the surface model. Too much exaggeration and suddenly a shallow river valley can look like the Grand Canyon. Not enough vertical exaggeration and

Surface model data covering the map extent is extracted from a source such as NASA Shuttle Radar Topography Mission (SRTM), General Bathymetric Chart of the Oceans (GEBCO) or even Light Detection and Ranging (LiDAR) when available. The higher resolution the surface model the more realistic the render results will be.

Figure 5: Before and After rendering – Grand Canyon National Park.



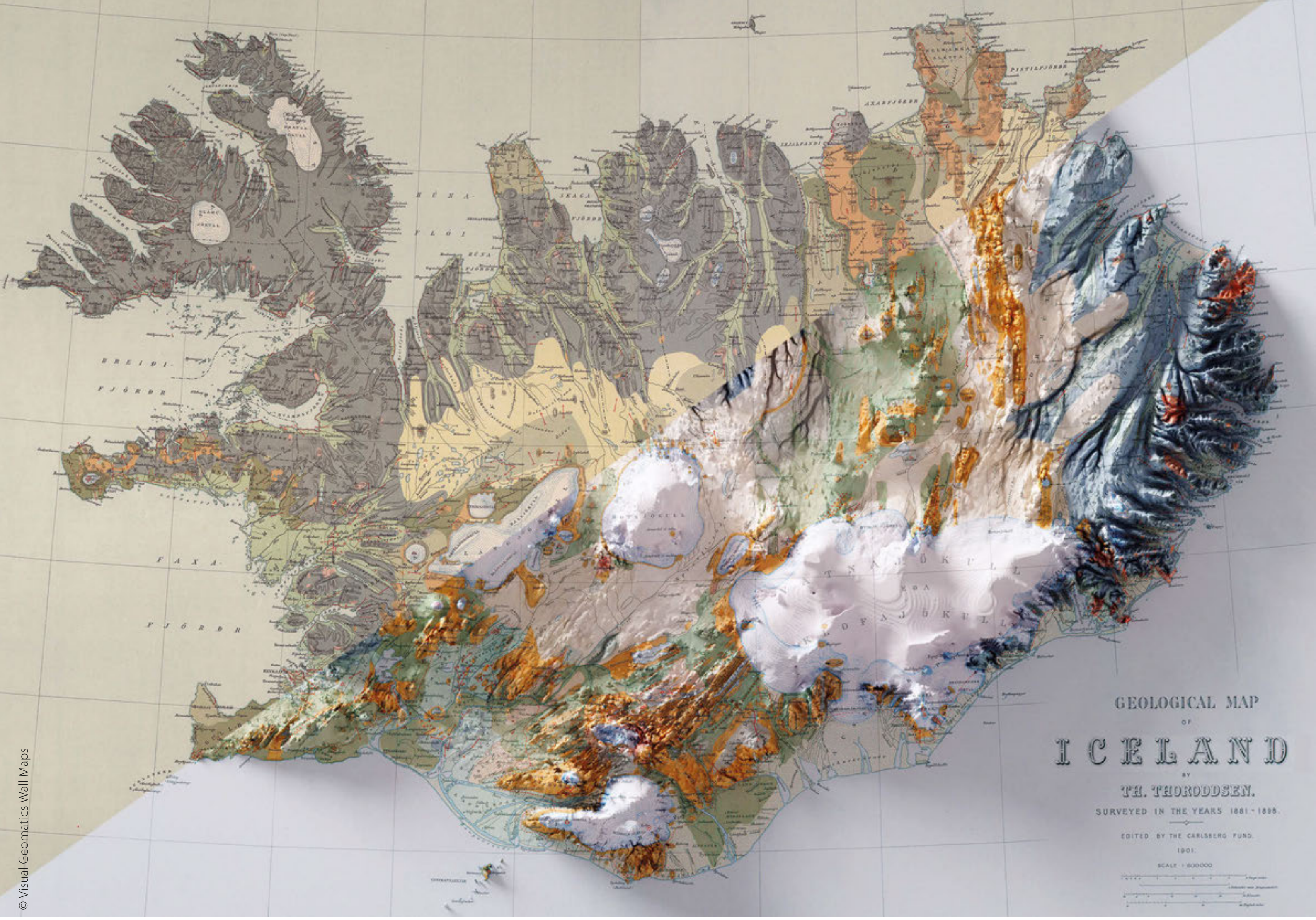


Figure 6: Before and After rendering – Iceland.

the relief map will simply look like a traditional hill-shade map without the visual appeal.

The original 2D map is referenced as the material texture of the object and when combined with the surface model's displacement a 3D object is created within the Scene. Then, a light source (or sources) is added to simulate the sun casting light on the surface from an oblique angle. It is critical to properly adjust the sun's azimuth and altitude to be in an optimal position that highlights the dominant features within the surface model. The strength of the sun can also be adjusted to either darken or soften shadows based on preference.

Lastly, is the placement of the camera. The Scene has been configured with an object and now the last step is to take a picture of it. Since maps are top view orthographic projections, the camera is placed into position directly above the centre of the object and oriented straight down.

Once all the settings are configured, the rendering can take place. As one would expect with 3D animation software, rendering is quite resource intensive and is best performed with a well-equipped processing computer that has plenty of RAM and GPU. Renders can take hours and sometimes even days, depending on the complexity of the surface or if additional objects are added (Figures 5 and 6).

The long render time is also the main reason why this technique has not displaced traditional GIS hill-shade maps where a map is generated within seconds. Though with the growing popularity of this shaded relief technique, it is not unrealistic to assume that it is only a matter of time before popular GIS software has this capability as well.

The End Result

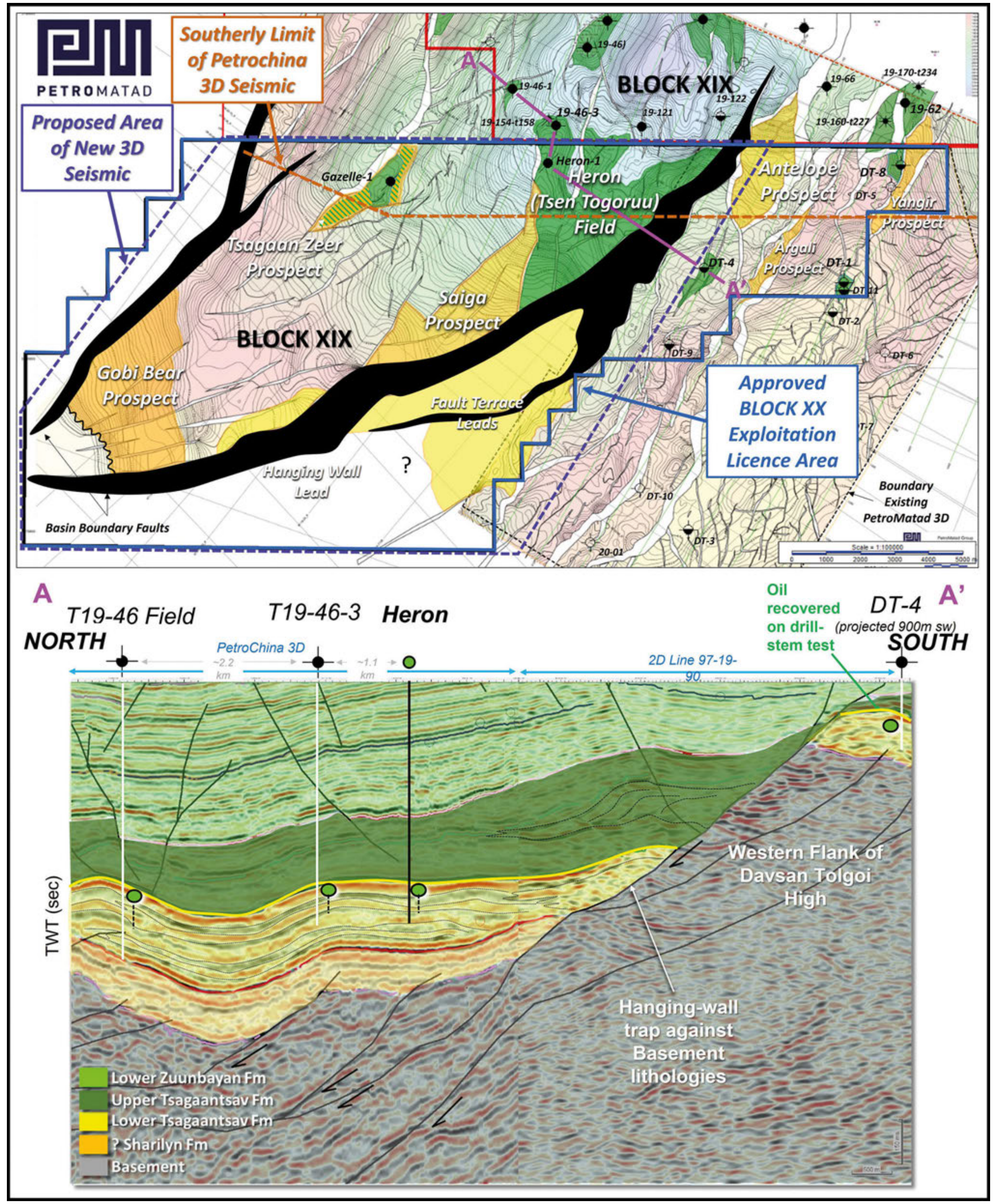
Once the render has finalised, the result is a hyper-realistic image that tricks most observers into thinking it is actually 3D at first glance. When the maps are printed on fine art paper and placed behind glass it can be deceiving, when they are actually 2D.

Since these are generated with 3D animation software, we can also take advantage of incorporating 3D animation objects such as realistic clouds.

One drawback to shaded relief maps is that in some areas of the map where elevation change is abrupt, the darker shadows cast can inadvertently render overlapping labels as illegible. Hence the popularity for these maps as wall art as opposed to maps that serve a technical, geographical purpose.

In the near future do not be surprised to see these maps as actual 3D printed models. The data already exists as 3D files and as soon as 3D printing technology can translate the map details on top of the physically printed model, you will start to see raised relief hanging on walls. ■

NE Mongolia (Tamtsag Basin) Block XX Exploitation Licence



Since 2018, Petro Matad's new management team has switched the company's focus from exploration to lower risk appraisal/development. This includes the immediate extension of the proven-producing play area and extension of the proven fields into Block XX, which led to the 3D seismic defined Heron-1 and Gazelle-1 discovery wells in 2019. Interpretation of the 2D seismic data to the south now suggests the Heron closure extends into a much larger undrilled hanging wall trap. This lies immediately downdip of oil recovered on test from one of Petro Matad's older wells (DT-4), now interpreted to have been drilled on a fault terrace where wells defined high quality shows, but appraisal drilling proved limited reservoir development.

The Heron closure alone has estimated resources of between 160 and 200 MMbbls STOIIP if its south-westerly extension (Siaga prospect) is confirmed by the planned appraisal work.

Petro Matad was granted an Exploitation Licence (EL) in June 2021 over the northern part of Block XX over an area of 218 km² covering all the Heron and Gazelle discoveries and importantly all identified upside closures within the Toson Uul Sub-basin. The initial plan is to drill several production wells within the vicinity of the Heron-1 discovery and existing 3D footprint, complete Heron-1 as a production well and acquire a new 3D seismic survey across the rest of the EL. Revenues from the initial development phase will fund further production wells in the following years across the then fully 3D seismically defined Heron structure to access the total resource potential of 32 MMbbls (P50) within the Heron closure. Full field development includes a water injection well programme and construction of a central processing facility that will export crude directly to the Mongol refinery via a planned pipeline, both of which are scheduled for completion by 2024. The resources quoted above have been independently assessed by Leap Energy in a Competent Person's Report (CPR) completed in February 2020.

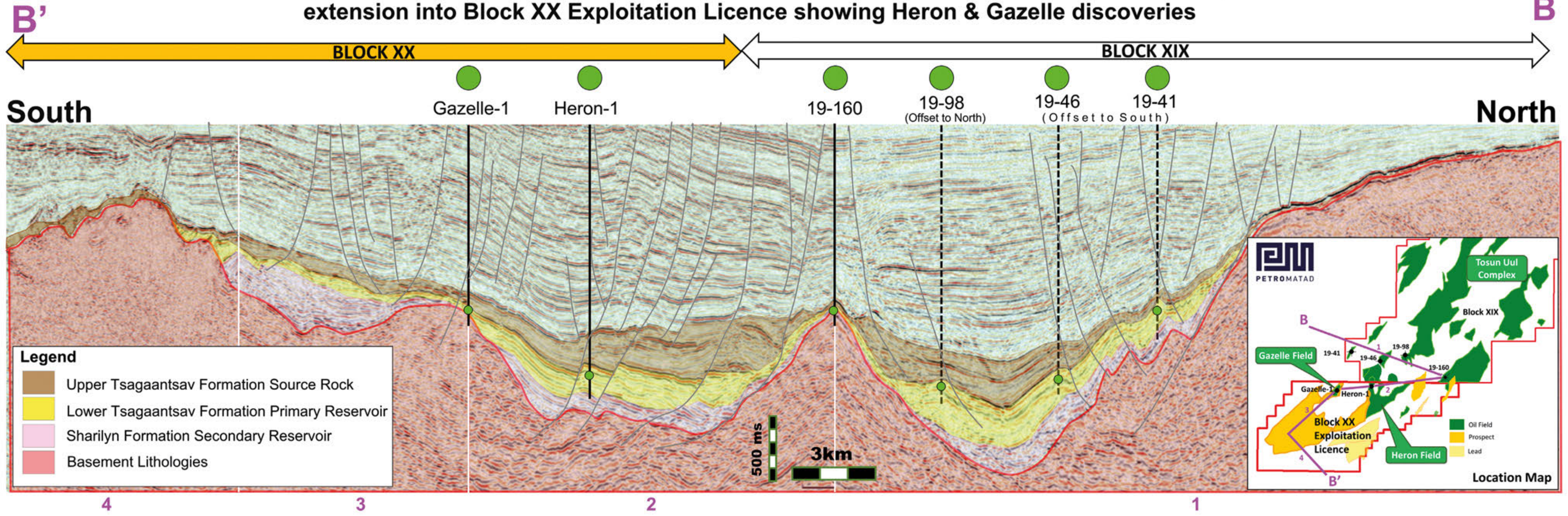
First oil is possible in 2022 if current plans can be progressed, with the oil being exported via truck on the existing road that runs through Block XX. This is already used to export the production from PetroChina's Block XIX to a pipeline terminal in the Aershan Oilfield in the Erlian Basin across the border to the south in China and sold at market prices under a contract with China National United Oil Corporation.

With the new 3D seismic survey across the entire EL, Petro Matad will, in parallel with development activities, develop well locations for the defined near-field appraisal and exploration prospects with a view to drilling these within the next few years to establish the total resource potential within the EL. In the case of success and subject to the discovered volumes, these are potential tie-back developments to the Heron facility or standalone developments benefitting from synergies with the existing Heron infrastructure. Included in this activity is the Gazelle-1 discovery which is now interpreted to have defined the periphery of the closure on the edge of the Toson Sub-basin play trend, which offers an additional 30 MMbbls of upside resource potential that can follow the initial Heron development.

Despite Mongolia's remoteness, drilling and associated facilities costs are low by comparison with elsewhere in the world. A 3,000m exploration well can be drilled for as little as US$2 to US$4 million.

Petro Matad is now seeking a strategic partner to join them in the planned development and appraisal programme and earn material equity in the new exploitation licence by contribution to the initial Heron development drilling programme, estimated to cost up to US $15 million plus up to US $5 million for the new 200 km² 3D seismic also being planned to unlock new potential to the south of the existing Heron field.

Composite Seismic Section N-S through proven Toson Uul Fields in Block XIX & Southerly extension into Block XX Exploitation Licence showing Heron & Gazelle discoveries



Upstream Projects for the Global Transition

MIKE LAKIN, Envoi Ltd

A Mongolian opportunity with local markets, appraisal/development and exploration upside, and generating fewer emissions than coal.

Whether the world likes it or not, hydrocarbons will still be needed even envisaging the most optimistic energy transition. At the time of writing, with COP26 under way, the world's leaders are still trying to agree what measures they should be targeting by 2050 (or in China's case 2060), in order to limit the rise in global temperatures. Limited progress seems to have been made in agreeing exactly how they intend to achieve this, other than a phasing out of coal over the coming decades.

Future Demand for E&P Projects

The transition will need to include hydrocarbons, and in particular gas, to bridge the gap until alternatives which are both achievable and affordable, are developed to replace them in the next 30 or so years. Gas is clearly significantly less emissive than coal which still powers some of the largest economies and by switching one for the other would come very close to reducing the emissions by the 30% climate change experts consider is necessary to keep global temperature rises below 1.5°C by 2050.

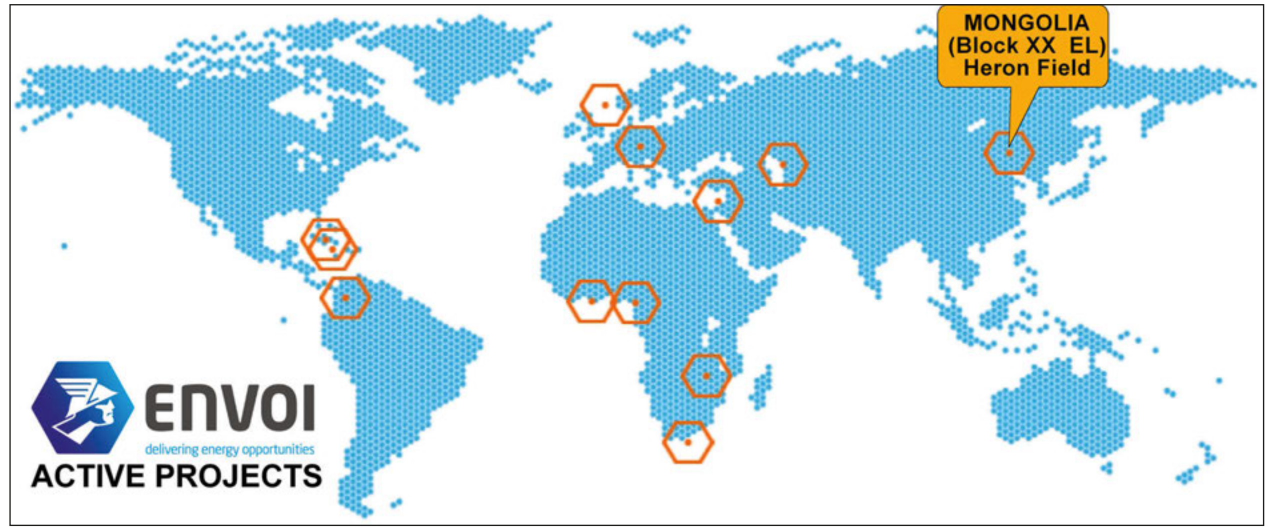
The lack of funding following the commodity price crash in 2014, increasing environmental, social and governance (ESG) influence on investors and the last two years of the Covid-19 pandemic has significantly dented the global upstream sector's traditional exploration capability. The key question is whether the remaining capability can meet the future demand and unlock the new oil, and increasingly gas resources, that will be needed for the transition. As commodity prices inevitably increase with tightening supply and new upstream investment returns with improved profitability, it is expected that market money will again become available to fund the search for the hydrocarbons needed to achieve the energy transition.

Lower risk, near-term cash-flow projects (albeit ESG compliant) will almost certainly be the first investments to attract funding, and there are many projects available now that would already have secured funding in a more buoyant market. Associated exploration will also return in time, assuming prices stay high, as investors seek the financial 'blue-sky' rewards that exploration and production (E&P) can generate. This is likely to include a contribution from E&P companies as their cash flow and profits increase and can again be risked to replace and grow resources.

The Asian Opportunity

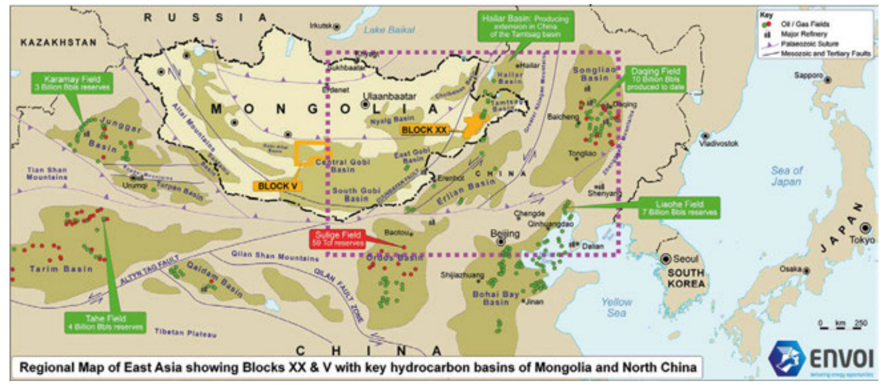
In some of the world's fastest growing economies with the highest energy demand growth (currently reliant on the most emissive fossil fuels including coal), Envoi has already seen evidence of renewed interest in E&P projects and recognition that now is an excellent time to participate before a new exploration cycle gathers pace. In this regard, Envoi's client, Petro Matad, has recently been awarded an Exploitation Licence for their Block XX in Mongolia which allows them to focus on development of their Heron and Gazelle discoveries with existing nearby infrastructure. These assets will benefit from immediate access to the strong, local, Chinese market just across the border. Surely this would be better for the environment than using coal upon which much of the region currently relies.

Petro Matad Ltd, the London AIM-listed company, has commissioned Envoi to identify a strategic partner to join them in the appraisal and development of two discoveries made in 2019 in the northern part of their large, 100% owned and operated, Block XX Exploration Licence. Situated in the Tamtsag Basin of NE Mongolia, which is historically the most productive part of the country, Block XX lies at the southern end of the basin where Petro Matad's successful Heron-1 discovery in 2019 was in effect an appraisal of the existing T19-46-3 discovery made in 2009 immediately to the north in the adjacent Block XIX Licence operated by PetroChina. This was the southernmost discovery in the Toson Uul Sub-basin where the first of many discoveries were made by SOCO in the late 1990s and sold to PetroChina in 2005. They have since drilled numerous wells and defined new closures as well as fully developing the Cretaceous-aged Tsagaantsav and Zuunbayan Formation plays of the existing fields found in the Tamtsag Basin. Regionally, these are a geological extension of the proven Hailar Basin that has been producing oil across the border in China since the 1980s, following exploration dating back to the 60s (Regional maps). ■



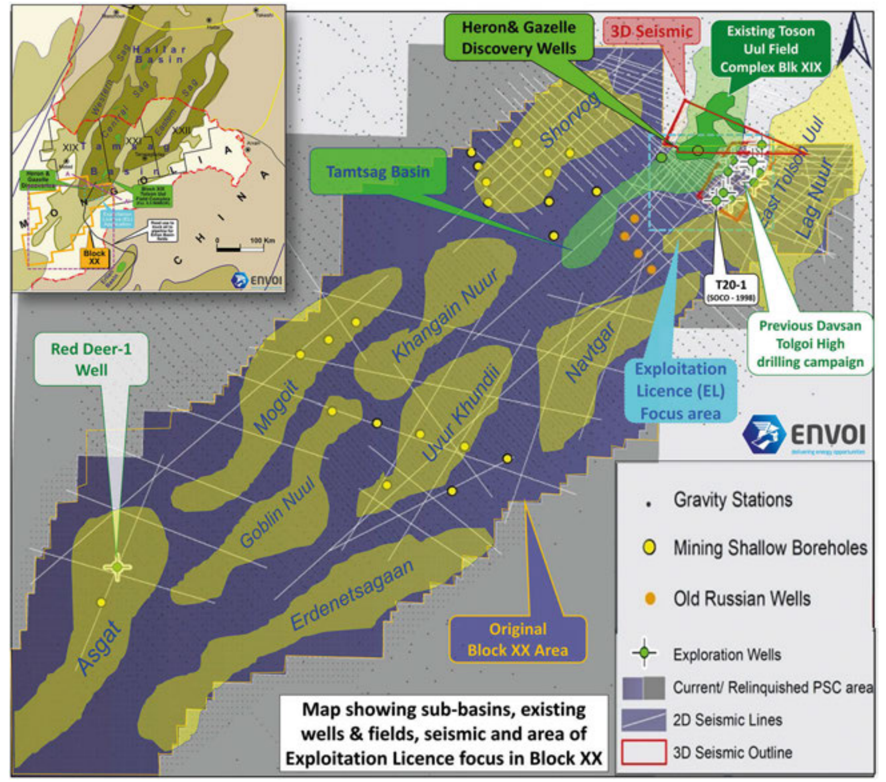
NE Mongolia (Tamtsag Basin) Block XX Exploitation Licence: Key Information for Investors

- Development of 3D defined 2019 Heron-1 discovery (flowed 821 bopd on test) at the southern end of the Tamtsag Basin.
- Established export route from existing fields ensures early revenue potential (2022) from CPR defined 19 MMbo contingent resource potential in Heron-1 discovery well.
- Combined 32 MMbo (P50) contingent and prospective (with 200+ MMbo upside) resource in Heron and Gazelle discoveries, and large additional upside in several undrilled leads.



Regional Map of East Asia showing Blocks XX & V with key hydrocarbon basins of Mongolia and North China

Map of Sino-Mongolia Border Region Infrastructure



Map showing sub-basins, existing wells & fields, seismic and area of Exploitation Licence focus in Block XX

From Arrhenius to CO_2 Storage

Part XIII: The Temperature Profile in a Grey Atmosphere

LASSE AMUNDSEN* and MARTIN LANDRØ, Bivrost Geo/NTNU

> "Outer space is not far at all; it's only one hour away by car if your car could go straight up!"
>
> Sir Fred Hoyle (1915–2001)
> British mathematician and astronomer

With an educational emphasis we demonstrate the physical essence of radiative transfer in the atmosphere by using a simple vertically continuous radiation model. It includes the grey model which accounts only for radiation while other processes of energy transfer (most importantly convection) are neglected. We derive the thermal profile for an atmosphere in radiative equilibrium, where by definition, the net flux is constant with depth.

Our goal is to determine the atmosphere's vertical temperature profile that would arise if radiative processes acted alone. In Part III (*GEO ExPro* Vol. 16, No. 4) we looked at this problem for the simple single-layer atmosphere model which assumes a constant atmospheric temperature. So, the next step is to consider a model of the atmosphere, which is vertically continuous, but still transparent to visible radiation and grey in the infrared (IR). Imperfect emitters are called grey bodies if their spectral shape matches that of a true blackbody but the magnitude is less than one. To do so, we need the equation of radiative transfer.

With reference to the figure on page 71, assumptions we make are:

1. The atmosphere is transparent to the Sun's shortwave radiation which peaks in the visible part of the spectrum (around 500 nm). The incoming solar radiation is $S/4$, where S = 1,365 W/m^2 is the average annual solar radiation arriving at the top of the Earth's atmosphere. The Earth reflects a portion $aS/4$, where a = 0.3 is the Earth's albedo.
2. The Earth heats and radiates as a blackbody with $B_\star = \sigma_B T_\star^4$, where σ_B is Stefan-Boltzmann's constant and $T_\star$ is the surface temperature in Kelvin. For today's temperature $T_\star$ = 289K (16°C), then $B_\star$ = 395.5 W/m^2. This radiation is at a wavelength which peaks at around 15 µm and that can be absorbed by IR-active molecules in the atmosphere. In the reference case of no atmosphere, the Earth's blackbody radiation is denoted by $B_0 = \sigma_B T_0^4 = (1-a)S/4$ = 239 W/m^2. Then, T_0 = 255K (-18°C).

There are of course a lot of differences between the vertically continuous model and the Earth. For example, we neglect that part of the incoming solar radiation is absorbed by the atmosphere. We also neglect energy components like conduction, convection and evaporation which transport heat from Earth's surface. When we calculate numbers from the multi-layered model, we cannot expect to reproduce the energy budget numbers that are measured by instruments. In the following, we ignore this aspect of reality.

A green flash seen from Morro Bay, California. Green flashes occur regularly on the Pacific horizon when the atmosphere, acting as a prism, scatters the light at sunset, allowing only the greens and sometimes blues or violets to survive their trip to the observer's eye.

The Equation of Transfer for Total Radiative Flux

In Part XII of this series (*Geo ExPro* Vol. 18, No. 2), we derived an approximate equation for radiative transfer of spectral flux in the atmosphere. The equation depends on the absorption coefficient $\alpha_\nu = n\sigma_\nu$ being the product of the CO_2 density n and CO_2 absorption cross-section σ_ν; ν being the wavenumber.

Going from spectral flux to flux requires us to integrate over wavenumbers. To avoid numerical integration, one may invoke the so-called grey approximation, where the thermal opacity and thus absorption coefficient of the atmosphere is assumed to be independent of wavenumber and is represented by a single, broadband value. Letting $\alpha_\nu = \alpha = n\sigma$ one obtains the differential system for upward and downward fluxes

$$dF^+/dz = -\alpha(dF^+ - \pi B) \quad (1a)$$

$$dF^-/dz = -\alpha(dF^- - \pi B) \quad (1b)$$

where $\pi B = \sigma_B T^4$ and T is the Kelvin temperature; this equation is the empirical radiation law derived by Stefan and Boltzmann, stating that the total energy radiated per unit surface area of a blackbody in unit time, or the radiated energy flux, is proportional to the body temperature into the fourth power (see *GEO ExPro* Vol. 16, No. 3).

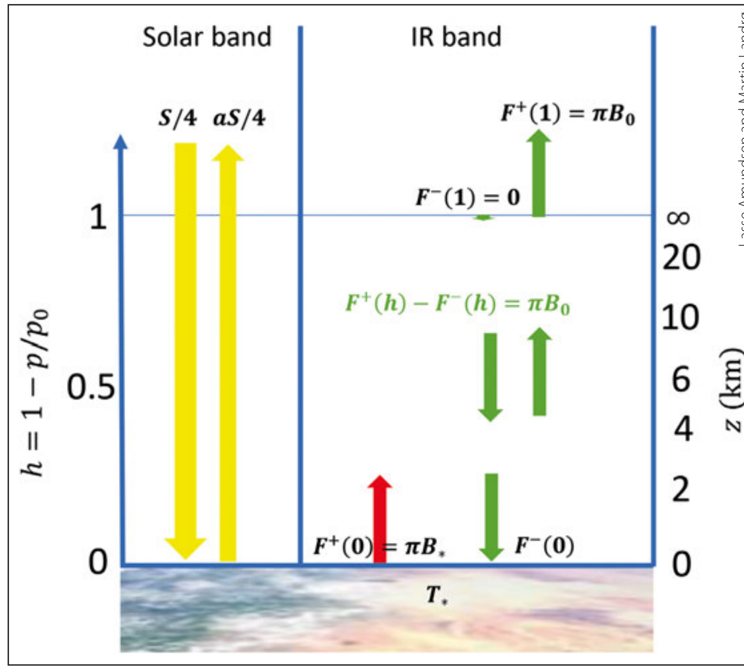
The downgoing radiation, which is the back radiation from the atmosphere, causes heating of Earth's surface. The upward radiation contributes to cooling by ensuring that the absorbed energy from the Sun and the terrestrial radiation can be rendered back to space; thereby, stabilising Earth's temperature.

Goessling and Bathiany (2016) suggest introducing a new vertical coordinate, the relative pressure deficit $h = 1 - p(z)/p_0$, where p is pressure and p_0 is the sea-level pressure; h is zero at sea-level and one where pressure is zero, in outer space, commonly accepted to be the Kármán line at 100 km. Then, using the hydrostatic equation $dp/dz = -\rho g$, where ρ is density of air and g is gravitational acceleration, one has $d/dz = (\rho g/p_0)\, d/dh$. Therefore, equations 1a and 1b can be written as

$$dF^+/dh = -\beta(dF^+ - \pi B) \quad (2a)$$

$$dF^-/dh = \beta\,(dF^- - \pi B) \quad (2b)$$

with absorption coefficient $\beta = np_0\sigma/(\rho g)$; β is the only parameter of the grey model and describes the atmospheric opacity in the IR band. From the hydrostatic equation, using the ideal gas law $p = \rho RT$, where R is the gas constant, which is the universal gas constant divided by the molecular weight of the gas or mixture in question, the atmospheric pressure and density can be shown to fall off exponentially with height. By eliminating ρ from the hydrostatic equation and the ideal gas law one gets $dp/p = -dz/L$, where $L = RT/g = 8$ km is the scale height. While T is not a constant with height, but assuming it is, gives a simple expression for p as a function of height, $p = p_0 \exp(-z/L)$. For an isothermal atmosphere, the density profile is simply $\rho = p_0/(gL) \exp(-z/L)$. Since CO_2 density and air density have the same dependence on height, β is constant. This property of β makes equations 2a and 2b analytically solvable, given boundary conditions, which are: (1) Earth's surface at depth $z = 0$ radiates as a blackbody $F^+(0) = \pi B_\star = \sigma_B T_\star^4$, and (2) at the top of the grey atmosphere there is no downgoing radiation, $F^-(1) = 0$. Furthermore, energy balance at $h = 1$ requires that $F^+(1) = \pi B_0 = \sigma_B T_0^4$. With these conditions, we find the fluxes as given in equation A-4; see Box, where the basic maths is derived.



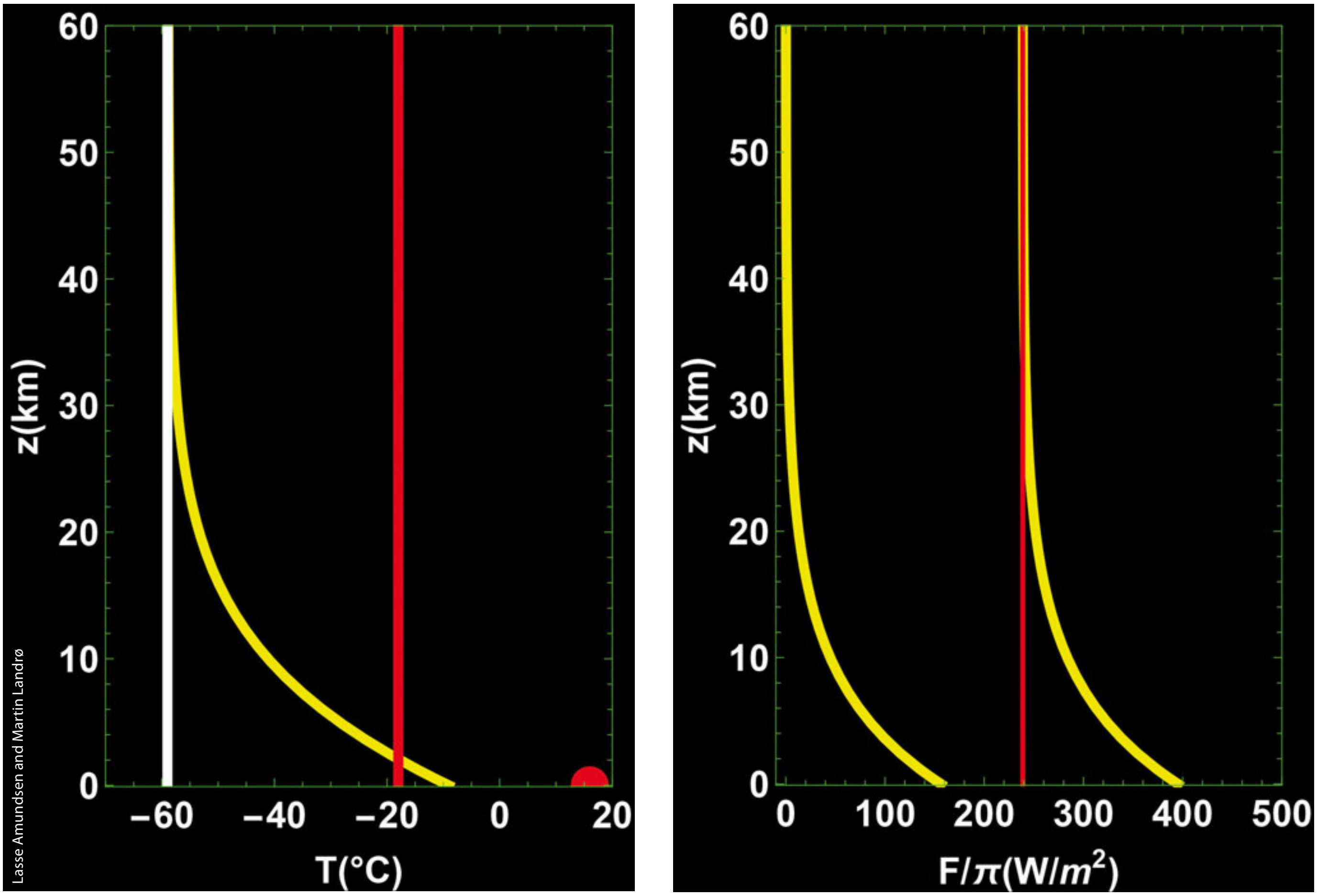
Sketch of the grey atmosphere model. The atmosphere is transparent to the Sun's shortwave radiation in the solar band. The Earth heats and sends upwards longwave (IR) radiation, which is absorbed by thin layers in the atmosphere. The layers heat and re-radiate energy to space and back to the surface. F^+ and F^- denote upward and downward fluxes, respectively. Earth's surface at depth z = 0 radiates as a blackbody with flux $F^+(0) = \pi B_\star$. At the top of the grey atmosphere there is no downgoing IR radiation, $F^-(1) = 0$. The Earth is in energetic equilibrium between the radiation it receives from the Sun and the radiation it emits to outer space. Energy balance at the top of atmosphere requires that $F^+(1) = \pi B_0$, where B_0 is the blackbody radiation in the absence of atmosphere. The condition of radiative equilibrium requires that the net flux at any given depth, $F^+(h) - F^-(h)$, remains constant.

Blackbody Temperature Relations for Earth in Thermal Equilibrium

In the Box, equation A-5, the blackbody radiation as function of the relative pressure deficit variable h is derived. It determines the blackbody temperature as function of the absorption coefficient β:

$$T^4(h) = T_*^4 \,\frac{\beta(1-h)+1}{\beta+2} = \frac{T_0^4}{2}\,(\beta(1-h)+1)$$

The temperature profile given above is identical to the profiles given in the literature, e.g., Goessling and Bathiany (2016), Thomas and Stamnes (1999), Pierrehumbert (2010), and Salby (1992). Observe the discontinuity in temperature



The vertical coordinate z is approximate height, calculated from h = 1-exp(-z/L) with constant scale height L = 8 km. Left: Vertical temperature profile (yellow line) of a grey atmosphere in equilibrium for surface temperature $T_\star$ = 289 K (16°C) (red dot) and β = 1.31. The atmospheric temperatures at the bottom and top are –9°C and –59°C, respectively. The vertical red line is Earth's temperature (255K = –18°C) with atmosphere absent. The vertical white line is the temperature for β = 0. Right: Downward (left yellow line) and upward (right yellow line) fluxes. The red line displays the net flux, which is constant with depth.

at Earth's surface, where the atmospheric temperature just above is always lower: $T(h = 0) < T_\star$. This is a result of the negligence of all mechanisms of energy transfer other than radiation in the model; in reality, diffusion of heat removes the discontinuity.

The second part of the above equation reveals that, for Earth-atmosphere in overall thermal equilibrium, an increase in absorptivity of a grey atmosphere leads to a temperature increase everywhere except at the top of atmosphere (TOA) where the temperature is independent of β.

Flux and Temperature Profiles

The upward and downward fluxes and the temperature are all linear in the relative pressure deficit variable h. To get the solution in height, we need to know h as a function of z. Assuming that the pressure is exponentially decaying with depth, from the definition of the relative pressure deficit one gets $h = 1\text{-exp}(-z/L)$. The figure above shows the solutions for the temperature profile and upward and downward flux profiles as function of depth for $\beta = 1.31$. In the limit of an almost completely transparent atmosphere, β tends towards 0, the atmosphere attains one single equilibrium temperature, and the surface temperature attains the effective equilibrium radiative temperature T_0 of the planet.

Absorption Coefficients

The constant absorption coefficient β can be determined from the present-day blackbody radiation from Earth's surface ($B_\star$) and blackbody radiation with atmosphere absent (B_0) according to equation A-6, $\beta = 2(B_\star/B_0\text{-}1) = 1.31$. The depth-dependent absorption coefficient α involved in equation 1 reads

$$\alpha = n\sigma = \alpha_0 \exp(-z/L)\ ;\ \alpha_0 = \frac{p_0 C}{g M_{air}} \frac{\sigma}{L}$$

where we have used that the number density n of the absorbing gas is $n = n_{air}C = \rho C/M_{air}$ with the volume mixing ratio $C = n/n_{air}$, and number density n_{air} and the molecular weight M_{air} of air. Further, we assume that the density profile of air is exponentially decaying with depth.

For a gas with uniform mixing ratio such as CO_2, α has an exponential decay with L equal to the scale height.

Acknowledgement

The authors have enjoyed many helpful discussions with Tore Karlsson.

References available online.

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

SOLUTION OF FLUX EQUATIONS

Equations 2a and 2b present two differential equations, one for the upward flux and the other one for the downward flux. It is convenient to introduce the net flux across an atmospheric layer, $F_d = F^+ - F^-$, and the total flux $F_s = F^+ + F^-$. Equation 2 then can be restated as

$$dF_d/dh = -\beta F_s + 2\beta\pi B \qquad \text{(A-1a)}$$

$$dF_s/dh = -\beta F_d \qquad \text{(A-1b)}$$

In the first equation, on the right-hand side, F_s times dh is the amount of energy absorbed and $2\pi Bdh$ is the amount of energy emitted. Equation A-1b tells that the total flux F_s can change with h only when there is a net flux. If there is no net flux, then there is symmetry, $F^+ = F^-$, and the total flux gradient is zero.

The condition of radiative equilibrium (expressing conservation of energy) requires that the net flux at any given depth, $F^+(h) - F^-(h)$, remains constant. The boundary condition at top of atmosphere, $F^-(1) = 0$, along with energy balance which requires $F^+(1) = \pi B_0$, yield

$$F^+(h) - F^-(h) = \pi B_0 \qquad \text{(A-2)}$$

The boundary condition at the bottom of atmosphere, tells $F^+(0) = \pi B_\star$, and $F^-(0) = \pi(B_\star - B_0)$.

Equation A-1b can be integrated as

$$\int_h^1 \frac{d}{dz}(F^+ + F^-)\,dz = -\beta\pi B_0 \int_h^1 dz$$

yielding $F^+(1) - F^+(h) + F^-(1) - F^-(h) = -\beta\pi B_0(1-h)$. By inserting boundary conditions, we find

$$F^+(h) + F^-(h) = \pi B_0\,[1 + \beta(1-h)] \qquad \text{(A-3)}$$

Solving equations A-2 and A-3 we obtain solutions for the fluxes,

$$F^+(h) = \frac{\pi B_0}{2}\,(2 + (1-h)\beta) \qquad \text{(A-4a)}$$

$$F^-(h) = \frac{\pi B_0}{2}\,(1-h)\beta \qquad \text{(A-4b)}$$

The way to proceed to find $B(h)$ is simple. Since F_d is constant, the left-hand side of equation A-1a is zero. The right-hand side of equation A-1a then immediately gives the sought-after blackbody radiation,

$$B(h) = \frac{B_0}{2}\,(1 + \beta(1-h)) \qquad \text{(A-5)}$$

which is used in the main body of the article for determining the temperature structure in the atmosphere as a function of h.

Equation A-5 can be combined with equation A-4a for $h = 0$, that is, $F^+(h = 0) = \pi B_\star = \pi B_0(1 + \beta/2)$, to give $B(0) = B_\star - B_0/2$. Note the jump in $B(0)$ at the surface from $B_\star$.

The equation for $F^+(h = 0)$ finally determines β as

$$\beta = 2(B_\star/B_0 - 1) \qquad \text{(A-6)}$$

We have solved the differential equations for the fluxes and blackbody radiation in h-coordinate, where solutions are linear in h.

Gradiometry – The New Standard

CHRISTOPHER VAN GALDER and ALESSANDRO COLLA, Xcalibur Multiphysics and DAN DIFRANCESCO, Niagara Gravity Consulting

The Evolution of Airborne Gravity Gradiometry for Oil and Gas Exploration.

The use of Airborne Gravity Gradiometry (AGG) for oil and gas exploration has expanded significantly since the year 2000, particularly in frontier areas. In some geological environments the use of this technology has become an essential tool and has been given the credit for some of the most important discoveries of the last decade. The ability of the AGG technology to cover very large areas in a short period of time has allowed explorers to optimise the amount of seismic acquired prior to drilling while significantly shortening the exploration cycle. In frontier evaluation the use of AGG remains an essential component of exploration programmes and has almost completely replaced conventional gravity acquisition.

But what exactly is AGG, how does it work, and why has its application become an essential component of any exploration programme? We will try to explain it by sharing a bit of history of the development of this technology from its origins to the most recent advances.

AGG – A Long Development History

Since the introduction of the torsion balance in the 1890s, it has been recognised that gravity gradient information is very valuable, yet difficult and time-consuming to obtain. Baron Loránd von Eötvös developed the first torsion balance instrument for field use with an accuracy of 10^{-9} per sec^2 (this CGS unit ultimately received the name Eötvös or E). The only problem was that the measurements were very time consuming. Improvements in torsion balance design led to the introduction of the Oertling and Askania torsion balances in the 1920s, with similar accuracy as Eötvös's early instrument, only smaller in size.

Until its discontinuation in the late 1930s, the torsion balance contributed to the discovery of 79 oil fields in the Gulf coastal region of Texas and Louisiana. It is estimated that these fields contained petroleum reserves of approximately one billion barrels. Unfortunately, torsion balance field surveys were laborious and expensive. The instrument had to be housed in an insulated portable hut to reduce temperature variations while mounted on an aluminium baseplate for stability. Readings were required at three instrument orientations, at 120-degree intervals, with one orientation repeated. After each rotation, one hour was required for the beams to stabilise before readings could be made. A total of four hours were required at each measurement location or station. In 1930, about 125 of these instruments were in use in oil exploration worldwide. These became obsolete, not because they produced inferior results, but because the operational challenges were so great, and the use of spring gravity meters were easier and more efficient for the field operator.

Fast forward to the 1970s when the need for gravity gradient measurements re-emerged – not for exploration purposes, but for assisting with missile launch and navigation functions. The US Air Force and US Navy and Ballistic Missile Defence Organisation (BMDO) all recognised the benefit of being able to make moving-base measurements of gravity gradients. The result of this interest was the deployment, in the 1980s, of the Gravity Sensors System (GSS) for the US Navy Fleet Ballistic Missile Submarine (Trident II) Navigation programme and the Gravity Gradiometer Survey System (GGSS) for the Air Force Geophysics Lab (AFGL). These systems incorporated the Bell Aerospace (now Lockheed Martin)-designed gravity gradiometer systems using full-tensor gradiometers (FTG) which measured all the independent gravity tensor components with accelerometers housed in three discrete instruments.

Figure.1: Digital Falcon AGG ready for installation.


Xcalibur Multiphysics

Commercial uses for the gravity gradiometer came to the forefront in the early 1990s, when Bell Geospace Inc. (BGI) conducted the first Gulf of Mexico marine hydrocarbon surveys using the US Navy ship USNS *Vanguard* – and its installed FTG gravity gradiometer system. These surveys, which began in 1994, demonstrated the ability to collect meaningful gradiometry data from a moving marine platform.

BHP Sees Potential

At the same time, BHP engaged in an R&D effort with Bell/Lockheed Martin to develop a unique gravity gradiometer system for mineral exploration applications (e.g., diamonds). The intention was to build the next generation of equipment – one that would be a game-changer in resource exploration. The project began with a thorough investigation of existing exploration techniques and equipment. The one that showed the most promise was gravity gradiometry and the equipment was the FTG built by Lockheed Martin. BHP knew there were limitations for the technology when deployed on an aircraft. The dynamic airborne environment is orders of magnitude more turbulent than that of a submerged submarine. This vertical acceleration causes significant errors in the FTG data that vary based on the level of turbulence. BHP understood that they did not need to measure most of the tensor components to determine all of them. With this understanding, the joint development project with Lockheed Martin focused on modifications that would dramatically decrease noise and increase repeatability. The first modification was to move to a near-horizontal disc on which to mount the accelerometers. This change significantly reduced the impact from vertical acceleration caused by turbulence.

Falcon™ Takes Flight

BHP trademarked this design Falcon™. The results showed near-constant noise levels from the Falcon systems at all levels of turbulence. The next major modification was to build-in a second set of accelerometers, as well as increasing the sensor separation distance (baseline), to reduce noise further. This enabled the design to yield two near-independent gradiometers in one instrument. This allows for every data point to be a repeatability measurement. These changes allowed BHP to improve the gradiometer into a revolutionary exploration tool for mineral exploration. During their exclusive ownership of the equipment, they acquired nearly 2,000,000 line-km of exploration data. They made countless discoveries until they exhausted all their mineral properties. BHP then divested the technology to Fugro Airborne Surveys, and subsequently to CGG. Xcalibur Multiphysics is now the proprietor of this technology. Numerous improvements to the Falcon systems over the past 25 years have yielded significantly better operating performance. These include Falcon Plus: a digital design which improves upon the original analogue functionality of Falcon (this was first deployed in 2005); Heli-Falcon: installation of the digital Falcon into a B3 helicopter for lower and slower data collection surveys

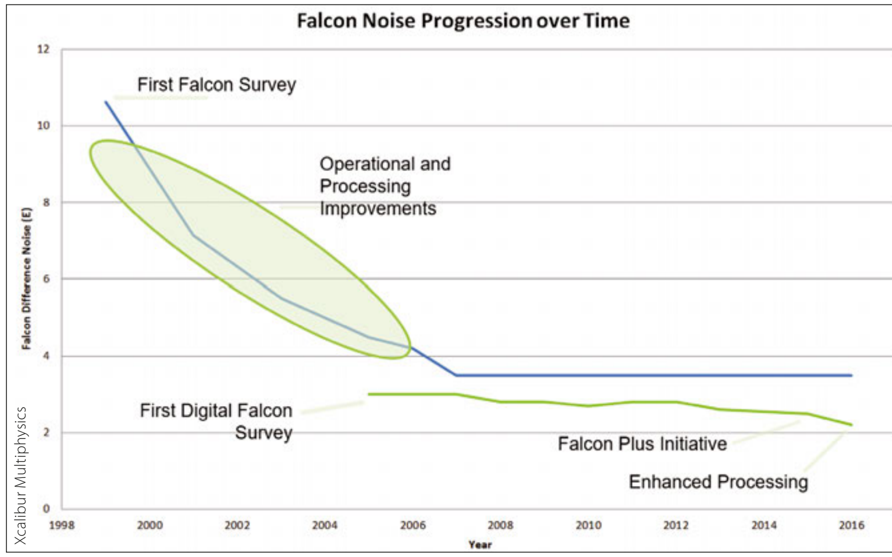
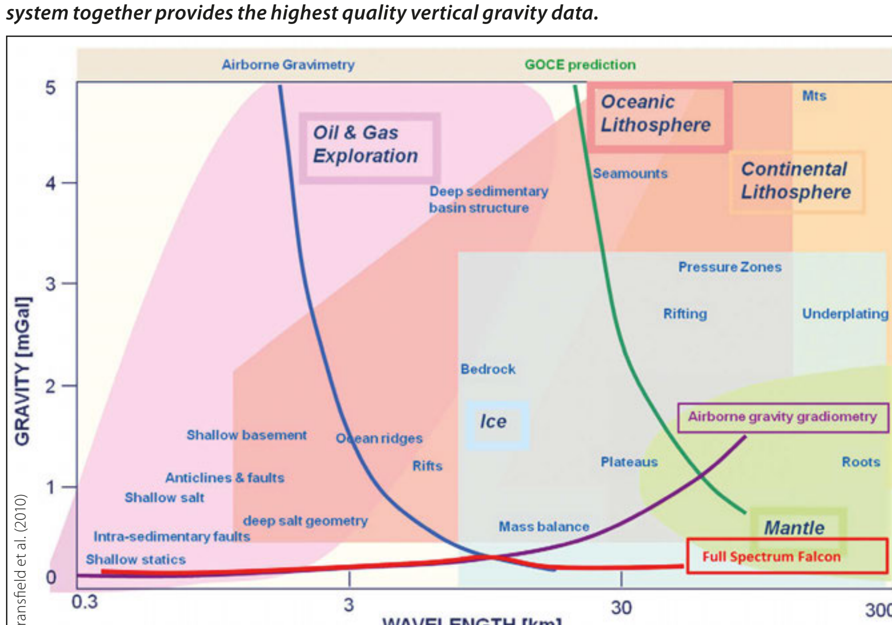


Figure 2: Improvement of noise levels with time obtained with equipment development and enhanced processing techniques.

Figure 3: This plot illustrates the error profiles for airborne gravity, airborne gravity gradiometry and satellite gravity. The geologic features shown above the error curves are detectable at indicative wavelengths and anomaly amplitudes. The AG error curve decreases with increasing wavelength; the AGG error curve increases with increasing wavelength. Combining an AG and AGG system together provides the highest quality vertical gravity data.



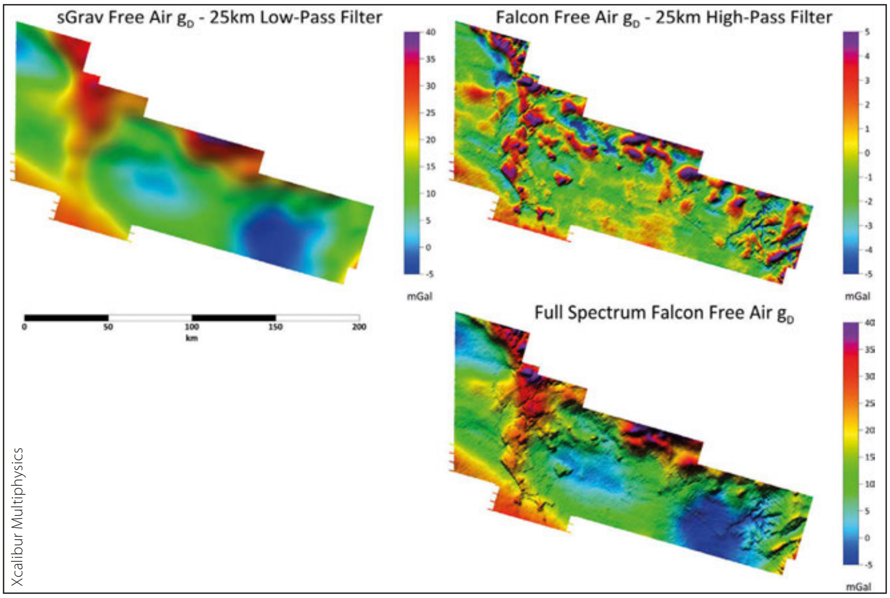


Figure 4: The Full Spectrum Falcon solution combines the medium to long wavelength data from the sGrav system (upper left) and the short to medium wavelength data from the Falcon AGG system (upper right). These data are added together to give the Full Spectrum Falcon product (lower right).

yielding higher resolution data; and Full Spectrum Falcon: an integrated system that melds the inputs from the gradiometer with an on-board gravimeter to assess all wavelengths of interest.

In addition to improvements noted for the Falcon systems, Lockheed Martin also embarked on an ambitious design called the Enhanced FTG (eFTG) that included the best features of Falcon integrated into a full-tensor configuration. This larger, more capable system is currently deployed by Austin Bridgeporth for airborne surveys. Lockheed Martin remains the sole commercial supplier of gravity gradiometer systems (e.g. Falcon, FTG and eFTG) to the resource exploration industry.

Both airborne gravity (AG) and AGG systems (Figure 1) measure derivatives of the gravity potential. While the noise in AG-acquired vertical gravity data decreases as wavelength increases, the noise in AGG-acquired vertical gravity increases as wavelength increases. Figure 3 illustrates the relationship between noise and wavelength for AG, AGG and satellite gravity. The optimal combination of both AG and AGG data can result in high quality gravity data with low noise across the entire acquisition spectrum.

The Falcon AGG system, after its initial development by BHP, has been progressively improved over the last two decades with the many enhancements described above. Most recently the industry recognised the need to measure both short and long wavelength to improve the detection of the wide bandwidth gravity anomalies of geological interest. It is to fulfil this need that equipment like the Xcalibur's sGrav (gravimeter), measuring AG, has been developed and deployed simultaneously with the Falcon AGG systems.

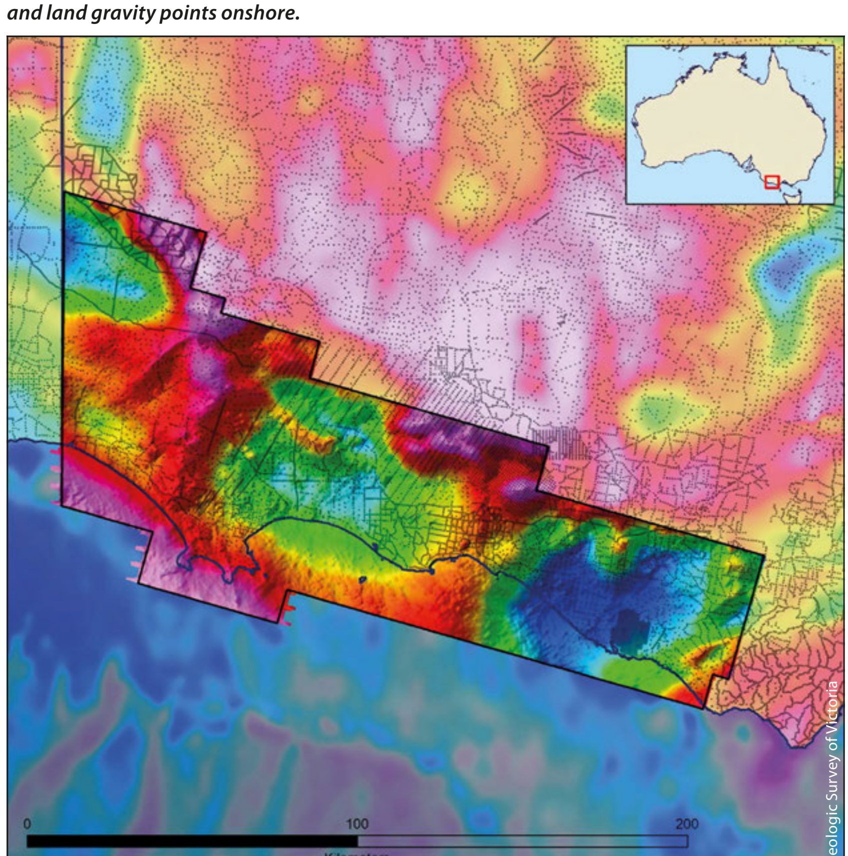
Each dataset is processed separately to obtain vertical gravity. For the AGG data, vertical gravity is derived from the measured gradients either via integration in the Fourier domain or an equivalent source process. For the AG data, standard gravity processing methods are used to obtain the vertical gravity. With the AG and AGG vertical gravity products, error curves for AG and AGG are derived as a function of wavelength as illustrated in Figure 3.

These two error curves allow the determination of the ideal cross-over wavelength. Plotting these estimated errors together allows the visualisation of results to find the wavelength at which the two error curves intersect. The wavelength at this intersection is the ideal cross-over point for merging the AGG and AG gravity. Once the centre wavelength of cross-over filters is determined, the two datasets are merged to obtain the optimal dataset of low noise, wide bandwidth gravity.

Victoria (Australia) Case Study

To demonstrate the result of the combination of AG and AGG we show data examples from a recent survey flown for the

Figure 5: Final image of Full Spectrum Falcon AGG Data superimposed to public domain data and land gravity points onshore.

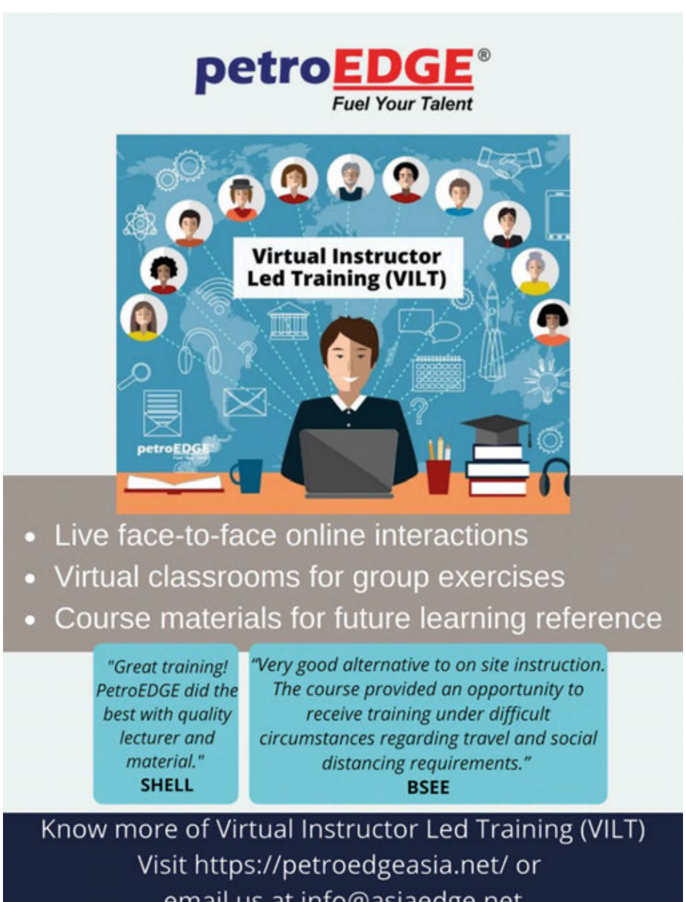


Geologic Survey of Victoria in Australia. The survey covered an area of about 15,000 km^2 at a line spacing of 500m along the southern coast of Victoria. Both AGG and AG data were collected at the same time on the same aircraft. The AGG system was a Falcon AGG and the AG system was an sGrav. From these two datasets, it is possible to estimate the AGG and AG gravity errors to determine the optimal cross-over wavelength to merge them.

Using a 25 km cross-over wavelength, the sGrav data (after application of a low-pass filter) and Falcon data (after application of the high-pass filter) were added together to create the Full Spectrum Falcon product. These results are shown in Figure 4. The noise estimate for this survey was 0.3mGal.

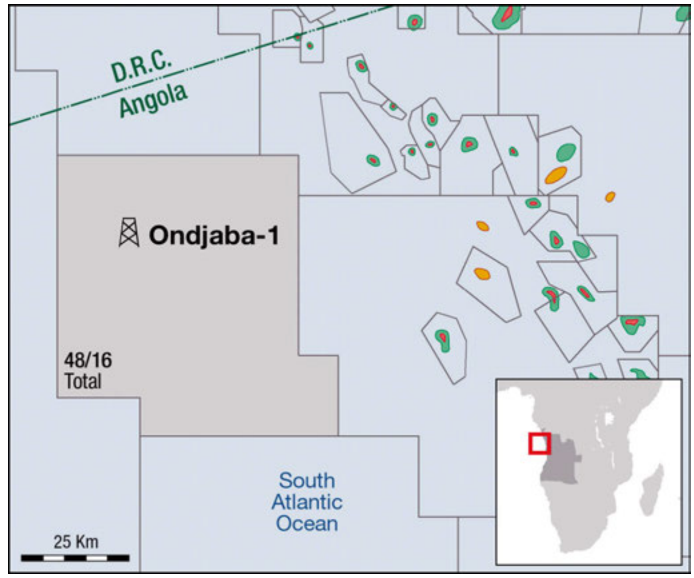
The survey was acquired as part of the 'Victoria Gas Program' and covered both onshore and offshore regions, providing full coverage across the transition zone where little or no other data had been acquired. The resulting anomaly map (Figure 5) clearly shows both deep basement structures, where the sedimentary sequence is thicker, as well as more subtle intra-sedimentary or shallow geological structures.

Since the initial deployment of AGG, there has been a continuous improvement of data quality as a result of both equipment development and processing techniques. The acquisition of data covering the full spectrum of geological responses of interest has been of increasing importance for oil and gas exploration. Collection of the highest quality vertical gravity data across a broad bandwidth is best done by utilisation of both a conventional AG and an AGG system. Each of these system types has its advantages and weaknesses, but together they make a powerful exploration tool. ■



NVENTURES

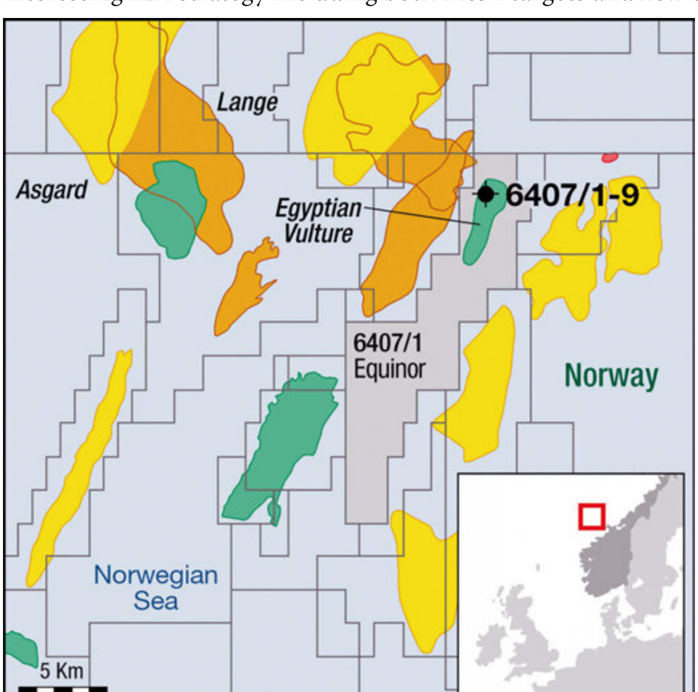
Ondjaba-1: Total Energies and Maersk Explore New Depths



Total Energies have drilled the **Ondjaba-1** wildcat offshore **Block 48, Angola**. Along with **Maersk**, and this time using the Maersk Voyager, they beat their previous record (offshore Uruguay at 3,400m water depth), spudding in 3,628m water depth. The Lower Congo Basin at this distal position has two potential play types: late rift phase carbonate mounds, and drift phase deepwater turbiditic sands. The nearest well, **Manjericao-1**, is located some 30 km to the east and is a suspended drift phase oil discovery. The pre-salt section is not well imaged on seismic, but basement horsts and tilted fault blocks may be present over which late rift phase carbonate mounds could have been emplaced in shallower waters. Primary carbonate porosity may have been enhanced through dolomitisation if subaerial exposure occurred. These reservoirs would be equivalent to those of the giant Tupi field (on the conjugate margin, offshore Brazil), and to similar discoveries made in the Kwanza Basin of Angola (**Blocks 21 and 23, Cameia and Bicuar**). Drift phase reservoirs targets may include Upper Cretaceous, Paleogene and Neogene channel / fan turbidite complexes, and it is not clear yet of these are being targeted post-salt, or indeed if the well is west of the Aptian salt distribution. **Total Energies** and partners **Qatar Energy** estimated a target volume of 823 MMbo, with a chance of success of 20% and a dry hole cost of US$46 million. The Maersk Voyager appeared to move off prospect without testing. The national authority in Angola, ANPG, recently announced a bid round of eight offshore blocks including **Block 32** to the east, so the industry will be focused on the timing of the well results and the bid round deadline. ■

Egyptian Vulture: Longboat Circling Success in the Norwegian Sector

Longboat Energy, the emerging full-cycle North Sea E&P company has announced a material discovery at the **Egyptian Vulture** exploration well in **PL 939**. The firm, established by the ex-management team of Faroe Petroleum, have an interesting ILX strategy including both M&A targets and new barrels from the drill bit. Exploration well **6407/1-9** encountered light oil in the primary target in the **Lower Cretaceous Intra Lange Formation**. Top reservoir was reached at 3,684m with 13m net sand in a 37m oil-filled gross interval. Net to gross is reportedly high in the upper part of the formation, with porosities around 16%. The operator's preliminary estimate of recoverable resources is 19 to 63 MMboe (with STOIIP at 220 to 440 MMboe). A good flow rate prediction for the wells (subject to further study) will significantly increase the resource estimate for this laterally extensive discovery measuring approximately 80 km^2 as defined by the seismic amplitude anomaly. Egyptian Vulture sits within a mature area with dense infrastructure, being 20 km from the **Åsgard field** and 23 km from the **Kristin field**, both of which are also operated by **Equinor** and which offer development options for Egyptian Vulture. Equinor operated the well and this is the second well by Longboat, in a fully funded seven well campaign. The firm have since announced a small sub-commercial discovery at **7/11-14 S** in the Southern North Sea (operated by **AkerBP**). Next up are **Ginny** and **Hermine** later this year and **Kveikje** and **Cambozola** in 2022. ■



Ammonite: A Missed Opportunity

Mary Anning's story is fascinating in its own right – so why make it up?

JANE WHALEY

The film *'Ammonite'*, described as 'loosely inspired by the life of British palaeontologist Mary Anning' and written and directed by Francis Lee, had its world premiere at the Toronto International Film Festival in 2020. It is beautifully shot and highly atmospheric, with the cold winds coming off the sea on the south coast of England almost felt by the viewer. It also features fantastic performances from the two female leads, Kate Winslet and Saoirse Ronan as Mary Anning and Charlotte Murchison, with support from the veteran actor Gemma Jones as Mary's mother, quietly mourning the death in infancy of eight of her ten children.

A Romantic Drama

Ammonite, described as a 'romantic drama', tells the story of Mary, who spends her life walking under the cliffs of Lyme Regis in all weathers seeking out fossils and other interesting rocks to sell to tourists, and Charlotte, wife of gentleman scientist and aspiring geologist Roderick Murchison. They meet when Charlotte is staying in the town in the hope that sea air will help her recover from depression. Through a number of slightly unlikely circumstances, Charlotte ends up staying with Mary and her mother in their cold and basic cottage on the sea front, where Mary and Charlotte, in between a bit of desultory fossil hunting, embark on a passionate but doomed love affair.

A film centred on women and their relationships, with very few male actors appearing even fleetingly, is to be celebrated in the modern environment, especially when it is as well acted and produced as this one, and I would recommend viewing it, although with the warning that it does contain some very explicit scenes. My main problem with the film, however, is that Mary Anning is not a fictional character. She is an important, if frequently overlooked, player in the history of geology and there is a much more important true tale to be told here; there is no need to invent a romantic story for Mary Anning's life to be interesting.

Lionsgate Films

Self-Educated Fossil Expert

As many people reading this will know, Mary was the self-taught, working class woman from Lyme Regis on the south coast of England who, while collecting fossils for a living, became an expert on Jurassic fauna at a time when the science of geology was in its infancy and the significance of fossils was just being recognised. As mentioned in the movie, at the tender age of 11 she discovered (with her brother, a character conveniently wiped from the film's story) the first known ichthyosaur, which the family sold and which can still be seen in the Natural History Museum in London. Her most famous find was of the first complete plesiosaur, in 1823, and she also made the first discovery of a pterosaur in Britain and a new type of fossil fish, *squaloraja*, in 1829. There were probably many more that were not attributed to her, with the purchaser often taking the credit.

Mary was well known and respected as an excellent fossil finder, and many aspiring 'gentleman scientists' visited her in Lyme to understand her techniques for finding and preserving fossils – including both Roderick Murchison and his wife Charlotte, who she stayed with on her only trip to London (a key point in the film). But despite acknowledging her skill and knowledge and frequently visiting and corresponding with her about the fossils she had found and the geology of the region, with a few exceptions the scientific establishment did not really accept her because of her gender and humble background. She never published any scientific papers, while several learned gentlemen made their name by plagiarising her work and thoughts; she is reputed to have commented that: "these men of learning have sucked my brains and made a great deal by publishing works, while I derived none of the advantages." Belatedly, a few years before she died of cancer at the age of 48, she received some annuities from the scientific community in recognition of her work, including from the Geological Society of London, which had refused to allow her to become a fellow because she was a woman (a rule they only changed in 1919).

Surely there is enough in all this for a good film about Mary Anning's life?

Poorly Served

Anyone viewing this film with no knowledge of geology will leave it knowing little more, except that it seems a hard, cold and rather muddy field of study, as Mary and Charlotte fight the tide, rain and rockfalls as they search for fossils on a windswept beach and then spend hours chipping away at them by candlelight. The importance of the fossils is never discussed, and the non-geologist may only pick up a single geological fact from this film; namely that coprolite is fossilised poo. In fact, Mary Anning was one of the first people to recognise these fossils as such, a point not mentioned.

Charlotte Murchison is also served poorly by this film. Rather than being a shy little mouse much younger than Mary Anning, as she is, at least initially, portrayed in the film, she was a strong, well-educated woman, at least ten years older than Mary. Charlotte had encouraged her husband Roderick Murchison to develop an interest in geology and subsequently accompanied him on all his travels, taking part in geological discussions and using her artistic skills to illustrate his writings. She and Mary certainly wrote letters to one another, none of which hinted at any strong affection and most of which were rather business-like, as Charlotte acted as a conduit between her wealthy friends and Mary in the sale of fossils.

It appears Mary had a lot of friends, male and female, and was not the monosyllabic misanthrope Kate Winslet so ably personifies, although the quote above implies she was obviously quite forthright. She shared her knowledge and skill generously with many people. Whether she had any sexual relationships, female or otherwise, is not relevant to her story. Film-makers are at liberty to make things up, but dwelling on this aspect to make an imaginary romance the centre of the narrative loses so many more important aspects of this remarkable woman's life. Francis Lee is quoted as saying that he gave Mary a romance with a woman because she had been served badly by men throughout her life, without seeing the irony of the fact that he was yet another man pushing aside the things she considered important in her story: her scientific knowledge and contributions to the science of geology.

Mary Anning deserves better. ■

Portrait of Mary Anning with her dog Tray and the Golden Cap outcrop in the background, Natural History Museum, London. Credited to 'Mr. Grey' in Crispin Tickell's book 'Mary Anning of Lyme Regis' (1996).

Remembering Mary Anning

Although Mary Anning remains relatively unknown, since she died in 1847 there have been a number of attempts to commemorate her life and legacy. In addition to *Ammonite*, fictionalised accounts of her life include the book *Remarkable Creatures* by novelist Tracy Chevalier and *Curiosity* by Joan Thomas, which, unlike the film, put her work centre-stage, as well as a number of children's books with titles like *The Dragon on the Cliff* and *Mary Anning and the Sea Dragon*, which have hopefully encouraged a number of youngsters to take an interest in geology. Biographies include an article reputed to be by Charles Dickens, although that has now been discounted, as well as several books, including *The Fossil Hunter* by Shelley Emlin and *Jurassic Mary:* by Patricia Pierce. The Natural History Museum in London showcases several of Mary Anning's spectacular finds, including her ichthyosaur, plesiosaur and pterosaur, with a guide explaining the fossils. There was even a recent effort to have her portrait featured on the new UK £50 bank note to be released this year.

Perhaps one of the most interesting campaigns to commemorate Mary is 'Mary Anning Rocks' (maryanningrocks.co.uk). This aims to build a statue of Mary in Lyme Regis to "give her back a physical presence in her Lyme Regis… and give the people of Lyme and the thousands of tourists that come to visit every year a focal point of remembrance and respect. ….to inspire and show people, young and old, locals and visitors alike, that great things can be achieved from almost impossible circumstances." The charity hopes the statue will be erected in 2022, according to Evie Swire, the 14-year-old girl who started the campaign when she was only 10. A campaign spearheaded by a young girl – now that sounds like something Mary Anning would have approved of.

The Need for Joined-up Thinking to Optimise Use of the North Sea to Achieve Net Zero Targets

In the run-up to the COP26 climate summit, John Underhill, Professor of Geoscience & Energy Transition at Heriot-Watt University, highlights the importance of an integrated approach to energy transition.

JOHN UNDERHILL

The UK has been highly effective in decarbonising the UK electricity system through the use of renewables in general and wind power in particular. The contribution made by wind power has risen four-fold in a decade – from 5.4 GW in 2010 to 24 GW in 2019 – and it contributed 24.8% of UK electricity supplied in 2020, having surpassed coal in 2016 and nuclear in 2018. Although initially dominated by onshore sources, the contribution made by offshore wind installations has rapidly caught up to be roughly equal now and will provide most of the electricity in the future.

The appetite for offshore wind remains high and there have been demands for more wind farm licences to be awarded. The next round (Phase 4) of awards promises to be the largest yet with substantive areas of the continental shelf becoming hubs for wind energy. It is also providing a tidy green-energy windfall income stream.

Despite the undoubted positive contribution that wind has made to decarbonise the electricity system, there are unintended consequences that impact our ambition to decarbonise other sectors. In particular, since most wind farms are fixed to the seabed, it is much harder to visualise, characterise, monitor and hence, utilise the subsurface below them, something that is required if we are to locate and evaluate safe storage sites and monitor the carbon dioxide injection needed to decarbonise the UK's industrial hubs.

Subsurface imaging is primarily through the acquisition of seismic reflection data that produces an accurate 3D 'body scan' of the buried geology. The data is usually obtained by towing a long streamer of sound wave receivers. Unfortunately, wind farm installations preclude this method since it's akin to the boat and its recorders having to navigate a large 'ski slalom'.

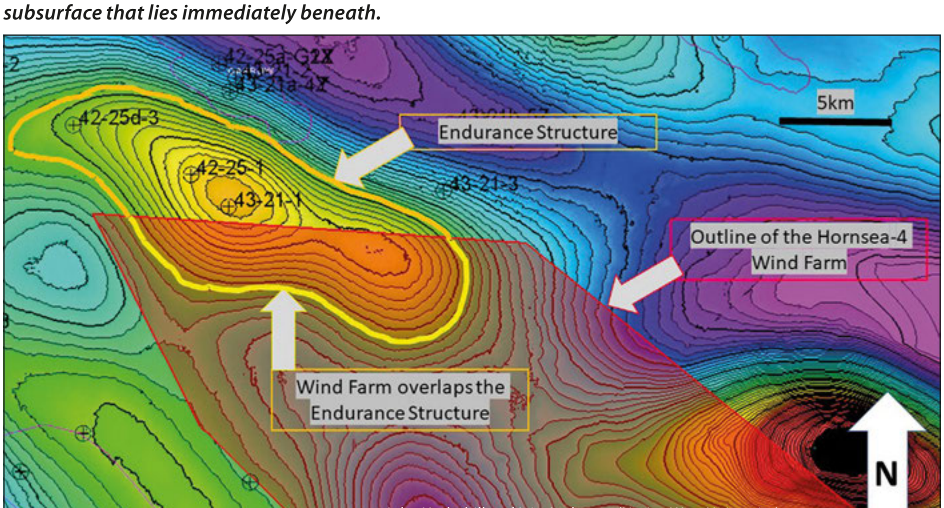
The competition for offshore seabed and subsurface 'real estate' has come into sharp focus with the publication of the Net Zero Strategy and the green light for two carbon storage licences. One of the prime sites (Endurance) that underpins the East Coast Cluster carbon store will be covered by the Hornsea-4 wind farm. As a result, it may prove necessary to use sea-bottom sound recorders, something that could add an order of magnitude of cost to the project (from £5 million to £50 million) meaning it and other projects may no longer be viable.

Wind farms are undoubtedly a valuable technology for the energy transition and a crucial part of our efforts to decarbonise. However, holistic, joined-up thinking is needed to ensure the best and most appropriate use is made of the seabed and subsurface geology. A collective failure to understand the dependencies and the impacts that their blanket coverage has may rule out other promising technologies and hold back the UK's pathway to net zero.

The occurrence of wind farms and significant monitoring issues will affect our ability to build a blue hydrogen capacity because of the spatial association needed between a producing gas field, carbon store and hydrogen export route to shore (and storage), any one of which might be precluded by the competition for space.

Judicious management of the offshore areas is urgently required that involves collaboration between the regulatory bodies (Crown Estate and the Oil & Gas Authority) and the various wind farm, gas and carbon storage operators to avoid unhelpful competition. Only by doing so will the UK have choices for the low-carbon technologies and re-purposing of the North Sea for the low-carbon energy transition. It is essential to get the optimal use of our offshore subsurface resources if we have any chance of achieving our net zero targets. ■

A top structure map of the Triassic Bunter Sandstone Formation (in TWTT) showing the location of the Endurance closure that is the foundation of the recently awarded East Coast Cluster carbon store and the Hornsea-4 wind farm. The overlap between the structure and the wind farm makes measuring, monitoring and verification of carbon dioxide injected into Endurance all the more difficult and costly. The map underlines the need for regulators, wind farm operators and those pursuing carbon storage to be more aligned to avoid unintended consequences resulting from a competition for the seabed and subsurface that lies immediately beneath.



Good COP, Cleaner Fossil?

At the time you are reading this column, COP26 will be a recent memory and the postponed World Petroleum Congress (WPC) in Houston should be underway. While, dear reader, you have the advantage over me as to the latest news buzz surrounding each event, let's just hypothesise for a moment, shall we?

COP26, we can surmise, produced a cobbled-together agreement for meeting a new and even more ambitious net zero target and keeping temperature rises to 'well below 2°C' this century. This is despite the warming and even heated pre-conference debate about global emissions still heading in the wrong direction and bad boy coal still in the warm embrace of the likes of China, India and even First World Australia. And how many leaders failed to show up for the event in Glasgow with the perhaps feeble excuse that they were simply cutting their own personal carbon footprint?

This year's postponed WPC looks as if it will be an altogether more bullish affair. At the time of writing, the oil price is still rallying from its pandemic low of around $40 a barrel to more than double that. And if, as Einstein suggested, everything is indeed relative, then fossil oil is a better bet in our short-term reality than fossil coal – and both get trumped by gas.

The elephant in the room of course is energy security. Will the wind of fortune blow consistently on renewables? What are the geopolitics of gas and how do you decarbonise without hurting the poorest countries of the world? COP26 may have done something to frogmarch the laggards on coal and even on getting developed countries to sign up to the promised $100 billion a year to help poorer countries reduce emissions and adapt to climate change. All 197 COP26 delegations (some minus their leaders) will have noted the UN report which described the $100 billion target "as a floor and not as a ceiling," and that it should be surpassed this year "to sustain trust between developed and developing countries." Anyway, don't bet on that.

WPC meanwhile returns face to face to the US for the first time in more than 30 years. The theme of this year's event is 'Innovative Energy Solutions' and you can bet your bottom oil barrel dollar that cleaner production will figure strongly. Fossil fuel in the short to medium term at least has its relative part to play in the climate emergency. ■

Nick Cottam

Shutterstock

Conversion Factors

Crude oil
1 m³ = 6.29 barrels
1 barrel = 0.159 m³
1 tonne = 7.49 barrels

Natural gas
1 m³ = 35.3 ft³
1 ft³ = 0.028 m³

Energy
1000 m³ gas = 1 m³ o.e.
1 tonne NGL = 1.9 m³ 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 Sm³) of oil equivalents

Giant field
Recoverable reserves > 500 million barrels (80 million Sm³) of oil equivalents

Major field
Recoverable reserves > 100 million barrels (16 million Sm³) of oil equivalents

Historic oil price