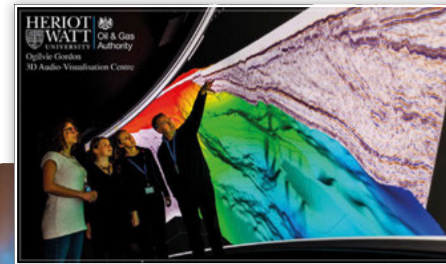
VOL. 18, NO. 2 – 2021

GEOExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED



GEO EDUCATION
Geoscientists for the Energy Transition

INDUSTRY ISSUES
Gas Flaring

EXPLORATION
Alaska Anxiously Awaits its Fate

GEOPHYSICS
Nimble Nodes

ENERGY TRANSITION
Increasing Energy While Decreasing Carbon

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GEOSCIENCE & TECHNOLOGY EXPLAINED

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West Texas! Land of longhorn cattle, mesquite, and fiercely independent ranchers. It also happens to be the location of an out-of-the-way desert gem, Big Bend National Park. Gary Prost takes us on a road trip and describes the geology of this beautiful area.

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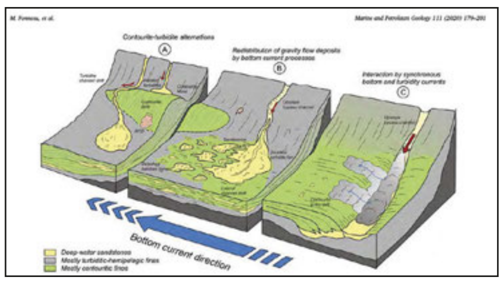
The effects of contourite systems on deep water sediments can be subtle or even cryptic. However, in recent years some significant discoveries and the availability of high-quality regional scale seismic data, has drawn attention to the frequent presence of contourite dominated bedforms.



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Seismic node systems developed in the past decade were not sufficiently compact to efficiently acquire dense seismic in any environment. To answer this challenge, BP, in collaboration with Rosneft and Schlumberger, developed a new nimble node system, now being developed commercially by STRYDE.

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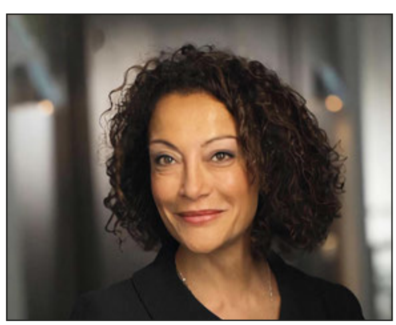
Iman Hill, the new Executive Director of the International Association of Oil & Gas Producers (IOGP) talks about her latest leadership role and the future of oil and gas in a transitioning world.



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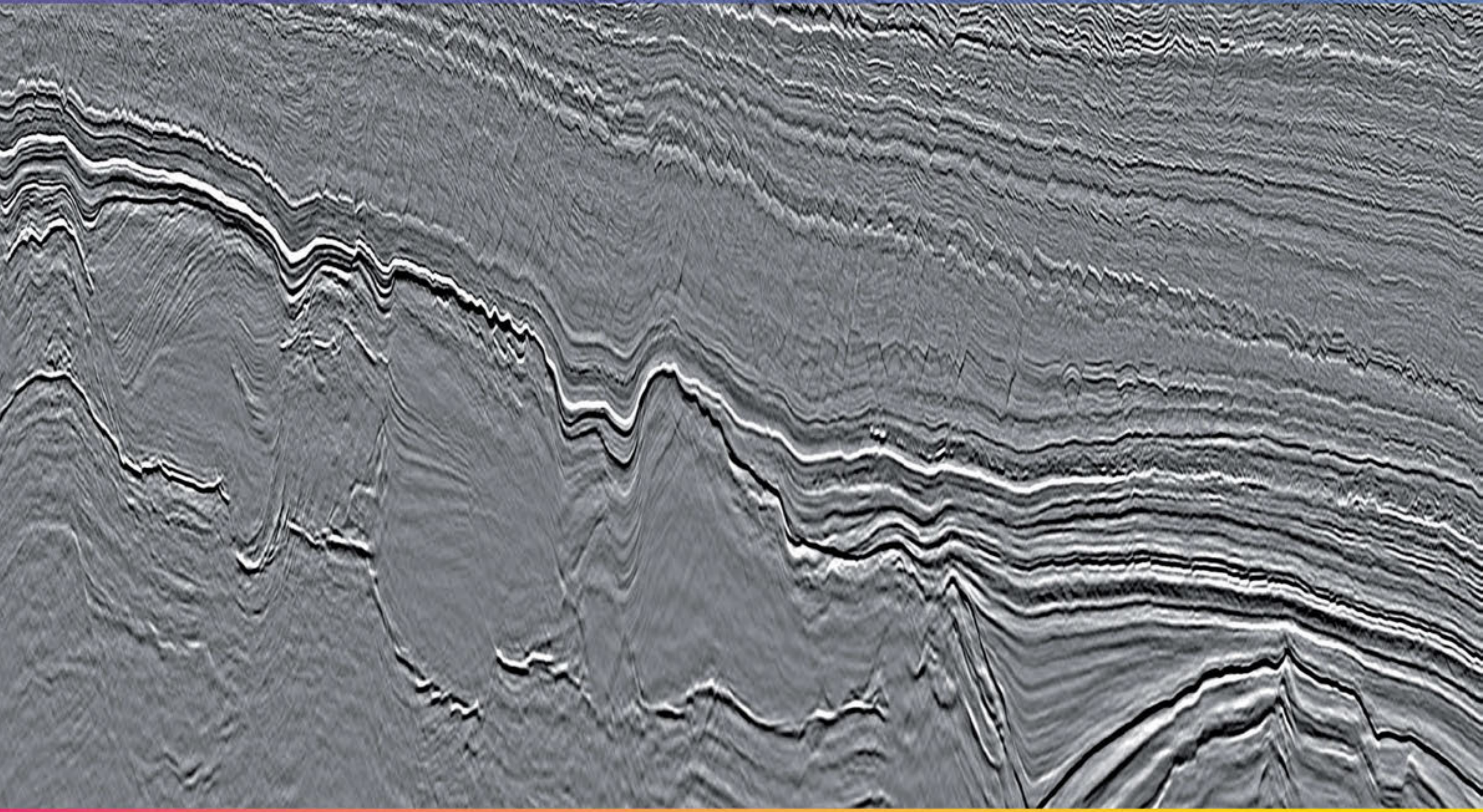

US Energy Refocus?

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The UN Climate Change Conference (UNFCCC-COP26) will be hosted in the UK later this year and will bring together heads of state, climate experts and campaigners to agree coordinated action to tackle climate change. In our cover story we examine the issue of gas flaring, its prevalence, how this gas might be captured and utilized and the lack of progress on this problem since COP21. The statistics suggest that rather than mitigating this wasteful practice, gas flaring from 11 countries that specifically identified flaring as a significant component of their COP21 Nationally Determined Commitments, showed an increase of 6%, rather than an expected decrease.

President Biden's new administration has a very different view of climate change from the Trump Government. Early indicators are that there will be a significant focus on renewables. The US offshore wind industry has trailed development in Europe, and lags behind the country's onshore industry. The new administration's goal of 30 GW of offshore wind capacity by 2030 looks achievable with capital spending of $12 billion per year on projects to reach that milestone. For European oil companies diversifying into renewable energy and seeing a chance to transfer their capabilities in offshore operations to a new sector, the opportunities in the US look attractive and companies such as BP and Equinor have formed a strategic partnership for US offshore wind and are jointly developing the Empire Wind 1 and 2 and Beacon Wind 1 projects, which have a combined capacity of 3.3 GW. All these developments will weigh heavily in the minds of oil industry professionals, as illustrated in our article on the outlook for Alaska.

Keeping the lights on and homes heated for the foreseeable future relies heavily on hydrocarbons and particularly natural gas. Iman Hill, the recently appointed Executive Director of the International Association of Oil & Gas Producers (IOGP) points out in our Q&A that over the next 20 years the global energy demand will rise by around 20%, mainly in non-OECD countries. This in the context of global oil and gas production declining by an average of 8% per year. So, investment in both existing and new fields seems inevitable. The transition to cleaner energy is a journey we are already on, but like it or not, it is probably going to take a few decades before we can wave goodbye to an energy source that has lifted hundreds of millions of people out of energy poverty. ■

Iain Brown
Editor in Chief

GAS FLARING

Gas flaring, the deliberate combustion of natural gas at oil and gas fields, refineries and processing plants is a significant economic and environmental waste. Yet much of this gas can be recovered with technically proven and commercially viable solutions.

Inset: A 3D Audio Visualization Centre at Heriot Watt University in Edinburgh provides an immersive environment for PhD students to investigate sub-surface models.

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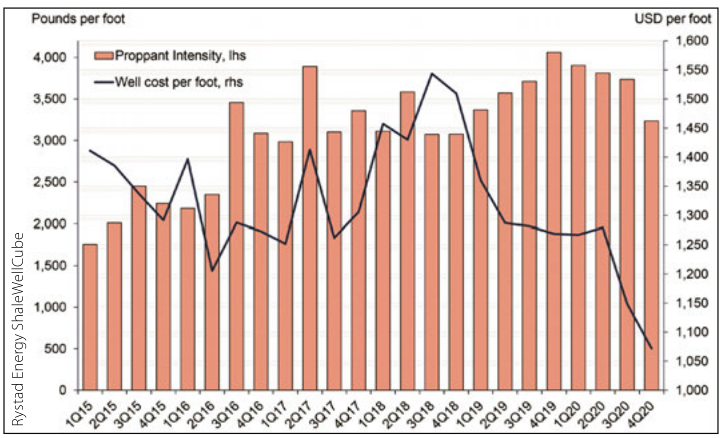
The Third Growth Phase of the Haynesville Play

Structural cost efficiencies help extend the Haynesville's core.

The Haynesville Shale's small 'consortium' of dedicated operators has credited the optimization of well design and completion efficiencies as the key to the renaissance of the basin in recent years. A hallmark of the second growth phase of the Haynesville play has been the steady increase in the intensity of completions. In the first quarter of 2015, the average completion in the play used less than 1,800 pounds of proppant per foot, only a few hundred pounds per foot more than the first growth phase, several years prior. By the second quarter of 2017, that number more than doubled, but was accompanied by a rise in well costs as activity began to pick up again.

However, since 3Q, 2018, operators have been able to steadily reduce their average well cost to about $1,072 per foot as of the fourth quarter of 2020. While some of this decline can be attributed to cyclical service price deflation, the consortium of operators has clearly captured efficiencies, as the average completion intensity hit an all-time high at over 4,000 lbs/ft in the fourth quarter of 2019.

Haynesville Shale: Average well* proppant intensity and D&C capex per lateral foot. *Includes horizontal wells TIL in each quarter



It appears for now that most producers have found their 'sweet spot' at between 3,000 and 3,500 pounds per foot. Furthermore, the efficiency gains captured by Haynesville operators are evident from the changes seen between 2018 and 2020 in the average frac speed per well, measured in lateral feet stimulated per day. The play average reached 617 feet per day in 2020, up from 537 in 2018, with some companies, such as Comstock, Rockcliff and Goodrich posting major gains. While geological factors and operational strategies, such as proppant intensity and the number of frac stages, can influence the ability to complete frac jobs faster, more lateral feet stimulated per day, generally indicates the more efficient use of capital in completing wells.

Rockcliff Energy, active in the East Texas portion of the play, saw increases in both frac speed and fluid per foot in 2019 and 2020, completing frac jobs faster and with more fluid per foot. Key factors in driving the westward extension of the play's core. The Haynesville rock in the northwestern part of the play is shallower than elsewhere, but thicker and less pressured than the traditional core, resulting in it being largely neglected in the play's first boom period.

However, thanks to the aforementioned completion efficiencies, producers have been able to see improving well results at a fraction of the cost of the Louisiana core and (albeit deeper) the Shelby Trough. Although productivity in north-western Haynesville, still lags behind the core, these trends bode well for the area's significant future development potential. This view is corroborated by continued rapid production growth in the Texas Haynesville (prior to the Texas freeze in February) for key operators including Rockcliff, Comstock and ExxonMobil.

While the cost efficiencies and improvements in well design and completion techniques may have reached a peak in 2020, Rystad Energy believes that the Haynesville still has room to grow over the course of the next five years. Using an average 2020 well decline curve, analysis concludes that production can grow by another 5 billion cubic feet per day (Bcfd) in the play over the next five years using an average of 54 rigs, and that growth can be maintained even if the number of rigs were to drop to 35. ■

Matthew Bernstein; Rystad Energy

ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids

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

Licensing Update

PETRONAS Launches Malaysia Bid Round, 2021

At, a virtual event held on 26 February 2021, with over 250 potential and existing investors, PETRONAS successfully launched the annual Malaysia Bid Round (MBR) 2021 which is themed 'Grow Your Energy Portfolio with Us'. A total of 13 exploration blocks are offered in offshore Malaysia.

Following the launch, PETRONAS will host a virtual data room which will be accessible until 6 August 2021, allowing data room reviews within the bid round period. Subsequently, the bid evaluation exercise should take place between August and September 2021. PETRONAS expects to award the Production Sharing Contracts (PSCs) to successful bidders before the end of the year

Out of the 13 blocks, three are situated in the Malay Basin (PM340, PM327 and PM342), four in the Sabah Basin (SB409, SB412, 2W and X) and the remaining six are in the Sarawak Basin (ND3A, SK4E, SK328, SK427, SK439 and SK440). Included in blocks PM342, SK4E, SK328 and SB409 are six discovered fields. MBR 2021 also features four deepwater blocks (ND3A, 4E, 2W and X) off the coast of Sarawak and Sabah which saw prominent discoveries in recent years.

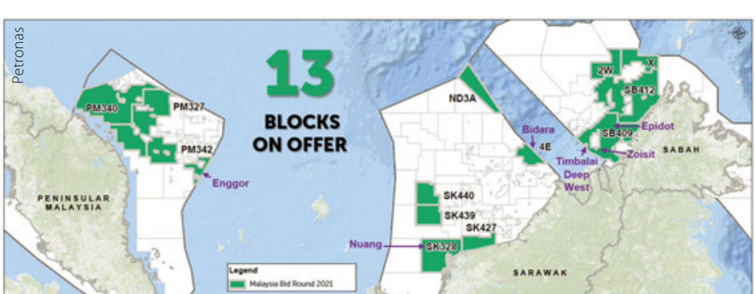
Whilst the MBR 2021, focuses on exploration blocks, the opportunities around late life assets and undeveloped smaller discovered fields will be made available in the second half of this year.

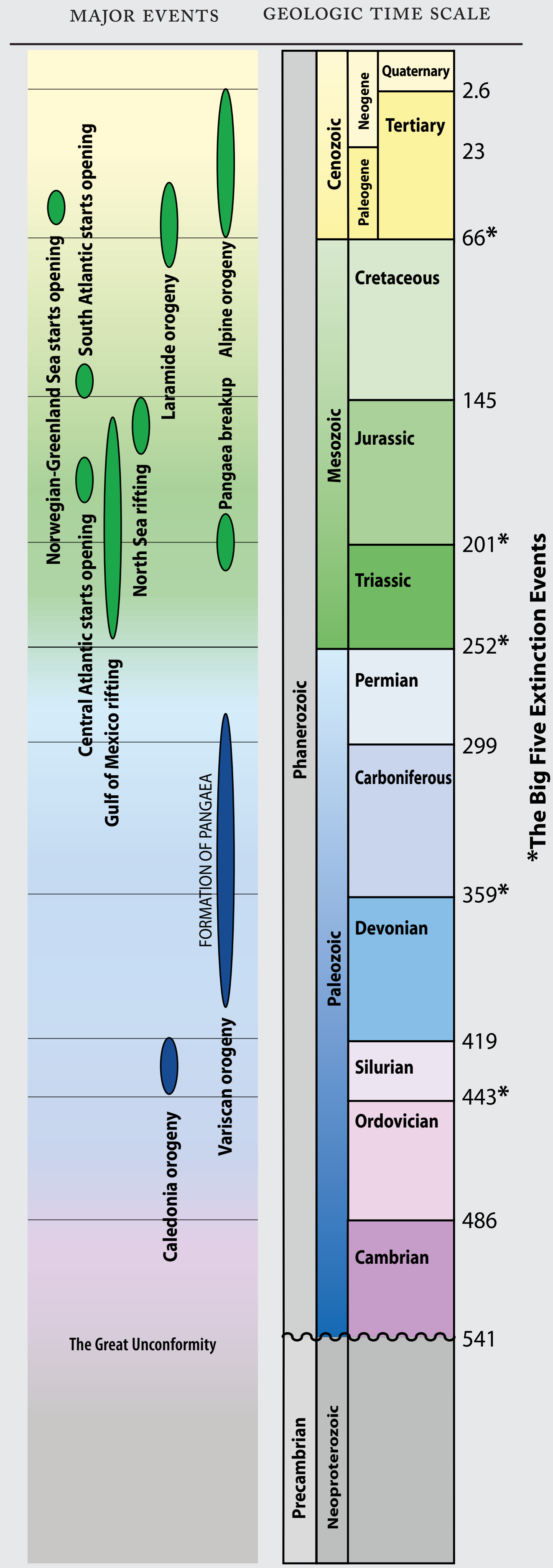
As part of this year's bid round, PETRONAS has introduced three new PSC terms. The first is the Enhanced Profitability PSC Terms (EPT) which will be applied to nine shallow water blocks, out of the 13 blocks offered. The EPT terms are formulated based on the feedback received from oil companies to provide more attractive returns under current challenging market conditions. The new Small Field Assets (SFA) and Late Life Assets (LLA) PSC Terms introduced recently were also developed to provide opportunities for companies with capability to extract greater value from discovered resources and LLAs.

PETRONAS has also incorporated several non-fiscal enhancements for the exploration blocks being offered and a phased exploration period.

At the same time, PETRONAS is offering three large areas for study arrangement. First is the area to the south of the Malay Basin in Peninsular Malaysia with emerging Pre-Tertiary and basement plays yet to be explored. The second and third areas cover the deepwater north of Luconia that extends north-easterly to Sabah and which could have extensions of proven plays.

Details of MBR 2021, can be found on the PETRONAS MBR website. ■





Energy Transition Takes Centre Stage at SPE Offshore Europe 2021

As the backbone of global energy supply, the transformation of the oil and gas industry is critical to cut carbon and remain relevant. Working together to deliver a decarbonized, net zero future will form the theme and direction of **SPE Offshore Europe 2021** being held in Aberdeen, Scotland, **September 7–10, 2021**. Two years on from the first edition to be held at Aberdeen's new state-of-the-art event complex P&J Live, preparations are underway to showcase the direction and innovation needed to realize a lower carbon future.

A dedicated Energy Transition Theatre and Zone will shine a light on the ongoing challenges E&P has regarding the transition to a net zero future, with exciting opportunities for discussion, technology showcase and thought leadership insights.

"The future of oil and gas is in our hands and working together is crucial to remain relevant and in the energy mix," said Neil Saunders, conference chair of **SPE Offshore Europe 2021** and Executive Vice President of Oilfield Equipment at Baker Hughes.

Taking place just eight weeks before COP26 in Glasgow, SPE Offshore Europe 2021 is already being seen as the 'curtain opener' to critical energy talks and the platform for the energy industry to galvanize action. ■

Blasto: A Remarkable Discovery

The recent **Blasto (31/2-22S) discovery**, possibly containing as much as 120 MMboe, on a downthrown Jurassic fault-block just north of the Troll field in the North Sea stands out for two reasons. Firstly, Shell drilled a wildcat on the same structure in 1982, but despite what was reported as 'very good oil shows' in the Sognefjord Formation, the well was classified as dry. Secondly, the current Operator, Equinor with partners Vår Energy, Idemitsu and Neptune Energy de-risked the prospect using 4D seismic.

Blasto turns out to be the fourth discovery in what Equinor has termed the Fram area (Fram was the name of the vessel that Norwegian explorer and scientist Fridtjof Nansen used when trying to reach the North Pole during the 1890s.) The strategy to explore close to infrastructure in a mature area of the NCS is clearly paying off and these resources should be brought into production quickly, proving that infrastructure-led exploration remains a profitable venture for companies brave enough to invest.

Oil-stained core from the Shell 1982 wildcat on the Blasto prospect.

At the forthcoming conference, **NCS Exploration – Recent Advances in Exploration Technology**, in May, in a session called 'Expanding the Exploration Toolbox' the de-risking of Blasto will be presented. In the same session, Equinor will also give a keynote on the 'Greater Fram – The Ship that Never Sinks'.

For further details see NCS exploration 2021. ■

Drone Strikes on Saudi Installations

Saudi Arabian oil infrastructure remains vulnerable to terrorist attacks as witnessed recently by the failed Houthi militants' drone attacks in March, when over 20 drones and missiles were launched at strategic targets including **Ras Tanura**, the critical oil export terminal.

Since the 2019 attacks on oil installations in Saudi Arabia which took almost 50% of the country's oil production offline, Saudi Arabia has strengthened its defences against missile and drone strikes. Those efforts appear to be paying off with the new defence systems preventing the weapons from reaching their intended targets. With Saudi Arabia remaining a key global oil supplier, the continuing military activity in this region remains a thorny problem and governments are nervous and remaining vigilant about the possibility of further threats to oil supplies.

The 2019 attacks caused crude oil prices to jump as much as 10% and disrupted 5.7 million barrels of crude oil production, representing half of the kingdom's output. With relatively unspecialized commercial drones now capable of carrying considerable payloads, this is a subject of ongoing interest and concern, not only in the Middle East but in the wider global community. ■

APPEX 2021: Digital Exploration Deals


APPEX

The dust is still trying to settle on the stage of **APPEX 2021**, but the buzz created by this digital event continues. Set just a year after many people's last physical industry meeting before the 'Covidocene', the undertaking this year was breathtakingly bold: to hold a meeting whose success had been based on face-to-face networking and idea sharing and hold it digitally.

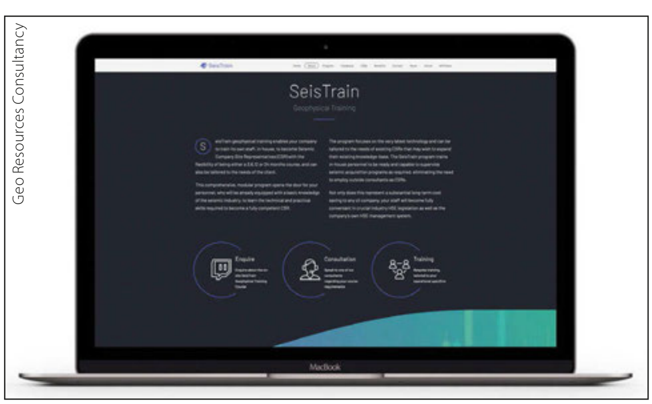
The AAPG Europe team enjoy a challenge, so **APPEX 2021** started a week early with a daily round of digital 'International Pavilion Showcases'. Here, representatives from around the world set out their stalls with excellent technical presentations and updates from Uruguay, Sudan, Greenland, Peru , South Africa, Belize, Morocco and Tunisia. Whilst normally such presentations might only have been seen by oil executives who attended the APPEX venue, these talks were reaching out to the industry across the world.

During the APPEX event itself the International Pavilion had virtual booths for all the showcase countries in addition to Albania, Australia, Israel and Newfoundland, for networking and arranging one-to-one meetings, and a business lounge where service companies could demonstrate their latest technologies and oil companies could meet and catch up. A favorite event this year was the grand auditorium of talks with a spectrum of presenters from government representatives talking about licensing rounds, information analysts and providers looking at trends in the industry, oil companies presenting new ideas and acreage opportunities, new data to examine and new technology to investigate afterwards. Some presentations were recorded and some live digital action, but all kept to schedule and to time, which is pretty much an APPEX first.

Credit is due to the AAPG professional team for designing and executing such a powerful event, and to the sponsors and the participating businesses who keep APPEX strong and focused through Covid-19 and the energy transition. Next year APPEX will be back in person, but perhaps with a digital footprint too, so that the event can continue to bring a high value networking, informing and collaborative product to a yet larger audience across the world. ■

CSR Training Course Fills Critical QC Gap

Seismic exploration, whether it is land or marine, is the principal method used by oil companies to search for oil and gas reserves. The success of seismic surveys depends on the quality of the data acquired to be able to identify and delineate potential horizons of interest. Acquiring the data is the responsibility of seismic acquisition contractors. Industry trends, the low cost of oil, ensuring high HSE compliance, and the ongoing requirement to acquire 'more for less' can lead to shortfalls along the way that may impact the quality of the data acquired.



Geo Resources Consultancy

The role of a Seismic CSR (Company Site Representative), or Seismic Acquisition Supervisor, is to act as the bridge between company and contractor to ensure that both data quality and HSE are of accepted industry standards. Historically the role of a CSR has been filled by someone with many years' experience working for a seismic contractor.

Seismic contractors have now, by necessity, moved to employing a more cost-effective work force with fewer people having the required experience and knowledge to become a CSR. This comes at a time when experienced supervisory skills on a seismic crew are even more important. Where there used to be one CSR on a seismic crew, there are now typically two or three focusing on different aspects of the operation.

Geo Resources Consultancy's SeisTrain modular training program aims to fill this gap by enabling persons with a basic knowledge of the seismic industry to learn the technical and practical skills required to become a competent CSR. It is primarily targeted at oil companies to train in-house personnel to be ready and capable to supervise their often-infrequent seismic acquisition programs when needed. This would then fully or partially negate the requirement to employ outside consultants as CSRs, thus saving costs. ■

EAGE Annual 2021 Makes a Strong Return

The 82nd EAGE Annual Conference and Exhibition aims to help the industry and academia re-engage after a very challenging year. EAGE strives to come back from the pandemic and, as always, bring the world's largest most comprehensive geoscience and engineering event to its attendees between **October 14–19, 2021** in Amsterdam, the Netherlands. Additionally, anyone unable to travel to Amsterdam will get to enjoy the best of the live show online, via EAGE's virtual platform.

The program will consist of over 1,300 technical presentations covering a wide variety of disciplines. The event will also organize a series of Forum Sessions, gathering leaders of the industry to discuss the most pressing issues in the wider geoscience and engineering field. However, for those interested in looking for more focused educational sessions, a variety of Workshops, and Field Trips will be available.

Additionally, the EAGE Annual will bring together around 200 exhibitors showcasing their innovations, new product launches and valuable industry services. Attendees can also maximize networking opportunities by all our social events. Stay up to date on everything the Conference and Exhibition has to offer by visiting the EAGE website. ■

US Fossil Fuels Program Review

The **United States Interior Department** hosted a virtual forum on March 25 to collect input from industry representatives, labor and environmental organizations and natural resource advocates, on how to best manage America's natural resources.

The information gathered at the livestreamed event will help inform an interim report that will include initial findings on the state of the federal conventional energy programs, as well as outline next steps for the Department and Congress to improve stewardship of public lands and waters.

Fossil fuel extraction on public lands accounts for nearly a quarter of all US greenhouse gas emissions. Multiple bills in Congress have been introduced in recent years to reform the program, including those to better ensure public participation in land management and leasing decisions; to address the growing clean-up and remediation costs of orphan wells scattered across the country; and to ensure a fair return to taxpayers for the use of their resources.

Over the last few years, the oil and gas industry has stockpiled millions of acres of leases on public lands and waters. Onshore, over 26 million acres are leased to the oil and gas industry, with over 50% designated non-producing. Offshore, of the more than 12 million acres of public waters under lease, over 75% are non-producing. Onshore and offshore, the oil and gas industry currently hold approximately 7,700 unused, approved drilling permits.

The Trump administration offered for lease more than 25 million acres of public land onshore and more than 78 million acres offshore for oil, gas and mineral development. While only 5.6 million onshore acres were purchased and 5 million offshore, the authorities have decided it is time for the Interior Department to review future stewardship of public lands. ■

Green Hydrogen – Next Steps

Renewables-generated hydrogen could have a huge impact on energy supply in the coming decades, as reducing costs allow Green Hydrogen to displace both Blue and Grey varieties, according to a new report by **BloombergNEF (BNEF)**.

BNEF forecasts that Green Hydrogen could become cheaper than natural gas by 2050 in 15 of the 28 markets modeled. As much as a third of the global economy could be powered by clean energy if government support is forthcoming. This is a huge 'if', as policy-supported investment is crucial to the roadmap, as is a very significant fall in the cost of renewable electricity. At present, the focus is on producing hydrogen from fossil fuels with associated carbon capture and storage. BNEF suggest it will be around ten years before the expected falling cost of photovoltaic electricity undercuts Blue and Grey Hydrogen. With many of the integrated oil companies transitioning to integrated energy companies (Shell will double the amount of electricity it sells within a decade) perhaps these developments will arrive faster than anticipated. ■

Shell's First Solar PV Plant in the Middle East

Wood, the global consulting and engineering company, recently completed its first utility-scale, photovoltaic (PV) solar project in the Middle East, for **Shell**, designed to cut emissions from industrial activities. The development will supply renewable electricity to a large ferrochrome production facility, displacing the equivalent gas-fired power generation taken from the grid and saving more than 25,000 tonnes of CO_2 emissions annually. The 25 MWp **Qabas Solar Plant**, consisting of more than 80,000 solar panels, is located within the **Sohar Free Zone** in northern Oman. The landmark project is focused on improving the utilization, energy efficiency, and carbon intensity of energy production operations, accelerating solar energy development in the Sultanate of Oman.

This project was awarded following Wood's work on Shell's 27 MWp Moerdijk Solar PV Plant. As one of the largest facilities of its kind in the Netherlands, it is generating power for the onsite chemical facility, which manufactures base chemicals from the petroleum fractions naphtha, hydrowax, gasoil and LPG. ■

Seismic Businesses Refocus

Although **CGG** completed its withdrawal from the seismic acquisition market last year as part of its transition to an asset-light technology company, its geophysical equipment division, **Sercel**, continues to advance solutions for data acquisition. Sercel, together with **Kappa Offshore Solutions** recently launched **PIKSEL**, a compact marine seismic solution designed for acquiring seismic data for high-resolution 3D imaging of targeted offshore areas. Building on Sercel's Sentinel® streamer technology, and Kappa's expertise in equipment integration and hydrodynamic modeling, PIKSEL can acquire high- and ultra-high-precision seismic data, meeting the requirements of the market for high-resolution site surveys. With its hydrodynamic design, towing speeds are high, and the system can be containerized to enable quick installation onboard a range of vessel types.

Norwegian **PGS** continues to integrate seismic acquisition and multiclient, winning a slew of recent projects in the eastern Mediterranean. PGS also has made its first foray into the combined node and streamer market, and says it may consider similar hybrids in the future. The new project will commence in the **Barents Sea**, in late May 2021 with an anticipated duration of 75 days. PGS will deploy drop-nodes from **Geospace Technologies** and operate its own streamer and separate source vessels with an ultra-wide multisource configuration. The survey covers approximately 3,600 square kilometers, including a sparse node-grid for velocities, in an area with moderate water depth.

In another interesting development, Peter Zickerman, former founder of **Polarcus** and now founder-director of start-up **PXGEO Seismic Services**, is growing a new company. In an agreement with **Fugro**, PXGEO has agreed to purchase certain assets and the related business of Fugro's subsidiary, Seabed Geosolutions. PXGEO is a marine geophysical service provider looking to capitalize on the strengths of combined ocean-bottom and towed streamer seismic data acquisition. ■

Gas Flaring

A quick win decarbonization lever.

JOHN-HENRY CHARLES, BRIAN HEPP and MARK DAVIS; Capterio

Gas flaring, the deliberate combustion of natural gas at oil and gas fields, refineries and processing plants, is a significant source of economic and environmental waste. Yet much of this gas can be recovered with technically proven and commercially viable solutions. As the world works to decarbonize, we urgently need to improve transparency on this avoidable source of pollution and deliver material reductions.

Hot Topic

Over the last 130 years the oil and gas industry has been instrumental in driving economic growth and improving living standards. No part of our daily lives is untouched by hydrocarbons. Yet this same industry is facing an existential crisis brought about by climate change and partly by the development of low-cost renewables.

The world is racing towards a low carbon future. Governments and corporations around the world have committed to net zero by mid-century. But as we progress to this point and for the considerable remaining time that hydrocarbons will power and drive our economies, we need to address the issue of flaring of natural gas.

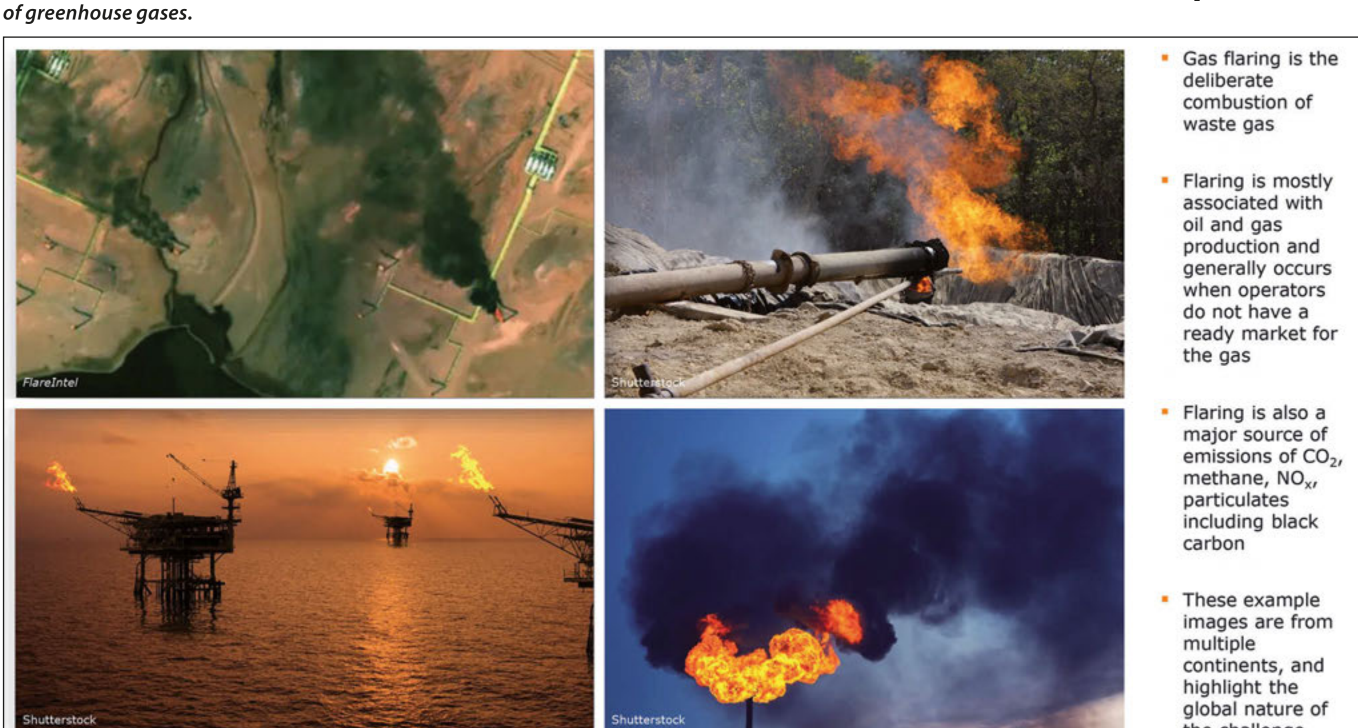
Globally, 150 billion cubic meters (Bcmg), or 14.5 billion cubic feet (Bcfg) per day of gas was flared in 2019, according to the World Bank's Global Gas Flaring Reduction Program, which estimates flaring from the thermal anomalies observed by satellite. Flaring is at its highest level for a decade, and is up by 3% since the 2015 Paris Agreement. That is 4% of gas consumption and is sufficiently large that, if it were a country, 'flaring' would be the fifth largest gas-consuming country globally (after US, Russia, China and Iran). It is also 100 gigawatts (GW) of continuous power (almost 3% of all power generated in 2019) and could displace up to 9% of all coal-generated power.

Apart from the environmental damage, flaring also leads to an annual revenue loss of up to $18 billion and direct emissions of 276 million tonnes of CO_2 per year. And when the 'methane slip' which is associated with incomplete combustion of flares is included, these are probably at least three times higher at 1.2 billion CO_2-equivalent tonnes (some 2% of global emissions), and could be significantly higher.

Flaring, the most visible of the sources of loss in the oil and gas supply chain, is a close sister to 'venting' (the deliberate, known release of methane from storage tanks, pumps and compressors) and 'fugitives' (the accidental release of methane from leaking infrastructure). Together, using numbers provided by the International Energy Authority's (IEA's) Methane Tracker, these three sources amount to an estimated 7 billion CO_2-equivalent tonnes. Whilst venting and fugitives, collectively known as 'methane leakage', are increasingly in the public awareness, flaring is somewhat overlooked.

Yet to meet the IEA's sustainable development scenario (which predicates a 90% reduction in flaring by 2025) and to deliver net zero by mid-century, flaring must be firmly in the spotlight. We estimate that the upstream E&P industry would need to invest a modest 2–3% of its $450 billion capital expenditure (some $10–15 billion) over the next three to four years to meet this target.

Figure 1: Examples of gas flares from Europe, Africa and the Middle East. Over 10,000 gas flares globally emit more than 1.2 billion CO_2-equivalent tonnes of greenhouse gases.



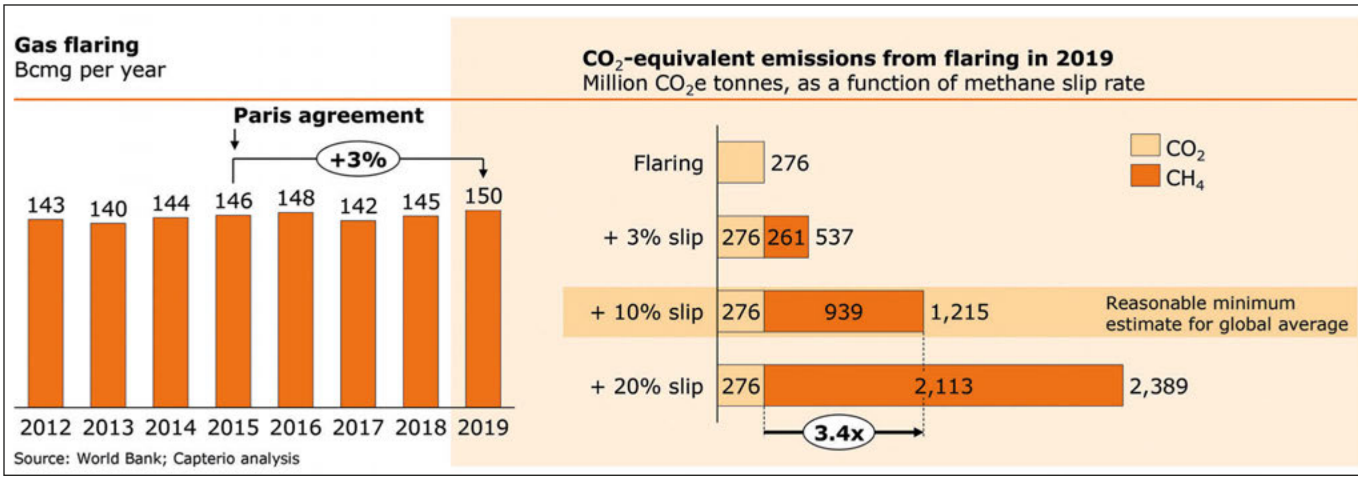


Figure 2: Flaring profile over time: Flaring also emits methane through 'methane slip' generated by incomplete combustion. Efficient flaring achieves around 97% combustion, but the global average is much lower, with a global weighted average combustion efficiency of 90%, leading to CO_2-equivalent emissions of 1.2 billion tonnes per year. Note we use the IPCC's Global Warming Potential (GWP) of 84, meaning that methane is 84 times more potent than CO_2 over a 20-year period.

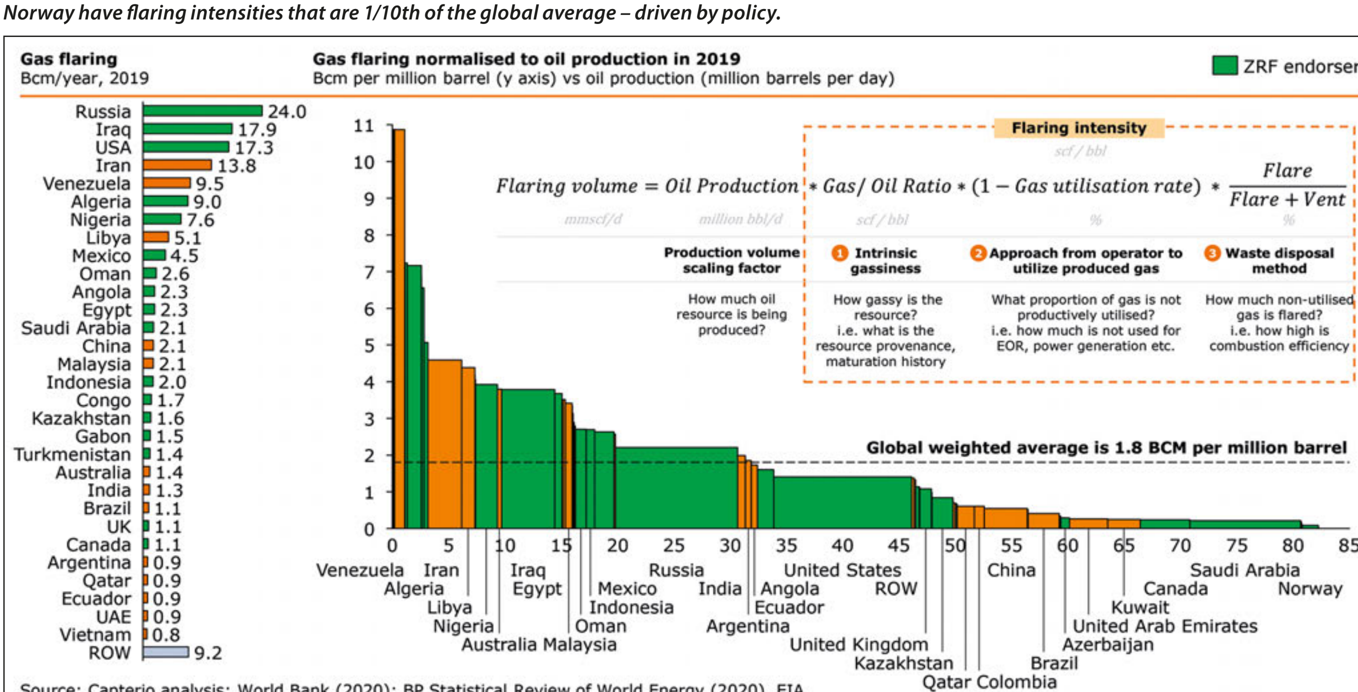
Flaring varies significantly by country, with the top five countries accounting for over 50% of flaring. It is promising to see that 34 governments that represent 70% of all flaring have endorsed the World Bank's 'Zero Routine Flaring by 2030' initiative (Figure 3). Each of these countries could be more ambitious with their nationally determined contributions during the upcoming negotiations in Glasgow for COP26.

Perhaps more interesting, when flaring is compared to its primary driver (oil production) in our 'flaring intensity' metric, countries with high 'flaring intensities' are generally those dominated by unlisted National Oil Companies. Venezuela, Algeria, Iran and Libya stand out with very high rates, whereas Saudi Arabia and Norway have very low rates, 10–20 times lower than the global average. It should be noted that we cannot rule out that our estimates of flaring are underestimated if countries vent unburnt gas to the atmosphere, often without detection and with huge environmental consequences.

Flaring intensity is a big deal, not least because consumers are becoming aware of the emissions embedded in their supply chain and are increasingly looking to buy products that are certified as low carbon on an end-to-end basis. The EU, as part of the recently-launched EU Methane Strategy, for example, is considering imposing a carbon border tax potentially as early as 2023. Countries with high flaring rates need to act to preserve the competitiveness of their gas, or risk losing revenue and influence.

Flaring intensity is a function of the source rock provenance (the gas–oil ratio), the gas utilization rate, and the combustion efficiency of flares. The most important driver of flaring is the utilization rate.

Figure 3: Illustration of the league table of nation-states, for flaring in absolute terms and relative to oil production. Countries such as Saudi Arabia and Norway have flaring intensities that are 1/10th of the global average – driven by policy.



On associated gas utilization, Saudi Arabia has shown leadership, following a government decision in the 1980s to create a new petrochemicals business from waste gas. Norway is similarly successful (and flares 10 times less than the UK) showing that decades of focused policy, well-developed infrastructure and carbon taxation, delivers results.

This variation also talks to the causes of flaring. Companies flare natural gas in three main situations: when disposing of unwanted or 'associated' gas accompanying oil production, during operational upsets or trips, and for safety purposes during routine operations. Whilst the latter two situations are somewhat inevitable, the former is of significant concern. A detailed inspection of satellite data highlights, firstly, that most flaring is 'continuous' in nature, debunking the myth that most flaring occurs from upsets, and secondly, that moderate and large flares (those above, 3 million scfg/day) account for almost two-thirds of the flaring. Figure 4 has the details.

Why Operations Flare

So, given that gas is intrinsically valuable, why is so much of it flared? For the most part, we think it is due to a system failure, underpinned by lack of focus, economics, resources or regulation (see Table 1). Sorting out the system failure can be very challenging, but with the industry's reputation on the line, it is imperative that we find collaborative solutions.

Our research shows that flare capture projects can often be intrinsically commercially attractive. The key is to unlock the barriers and ensure that the revenue split rewards each party appropriately. Often creative thinking, such as potentially 'aggregating' flares with other operators, helps.

Potential for flaring	Comment	Solution
Flaring is not sufficiently "on the radar" or in focus of operators and governments	Most flares are not metered and often ignored, or worse, denied. Often flaring is "towards the bottom of the to-do list"	Increase disclosure and reporting – using public domain data as a backstop.
Fixing flaring is perceived not to be economically attractive (and/or infrastructure is missing)	High costs (or high taxes) certainly make some flare projects unattractive. But often creative solutions can be found to deploy technology more effectively or at greater scale (by aggregating flares of others).	Many flares do have commercially-attractive solutions. Operations need to be more creative and agile technically and commercially to find structures that work.
The industry lacks resources (expertise and financing)	In today's lower CAPEX world, allocating capital to non-core projects (which flaring is, for most operators) is hard and often requires specialist understanding of low pressure gas systems	Open up flaring to third-party players who can bring technical know-how, financing and innovative operating models
Regulators are ineffective (and often 'fly blind' with no independent view of flaring)	Few governments have stringent anti-flaring policies – and many of those that do lack enforcement mechanisms	Regulators and governments must use available data, encourage metering and define and enforce penalties

Table 1: Overview of the main reason that operators flare gas today.

Flare Capture, a Win-Win

There are two broad solution categories for gas flaring: use the gas in local operations, or export the gas (either directly, or as a product) to the market. In all cases, the industry is moving to deploy standardized units that are skid-mounted and are mobile, meaning that solutions can be deployed quickly and redeployed as required. Since many flare solutions are considered as small capital projects, they will likely require fit-for-purpose solutions delivered by agile and specialist solution providers.

Since flares are often rich in C_2+ components (which often causes the thick black smoke), monetization options can also capitalize on the recovery of valuable liquid products such as LPG (Liquefied Petroleum Gas), NGLs (Natural Gas Liquids) or condensate, which can significantly enhance the economics.

The main monetization options for local operations include reinjection for enhanced oil recovery, storage or disposal.

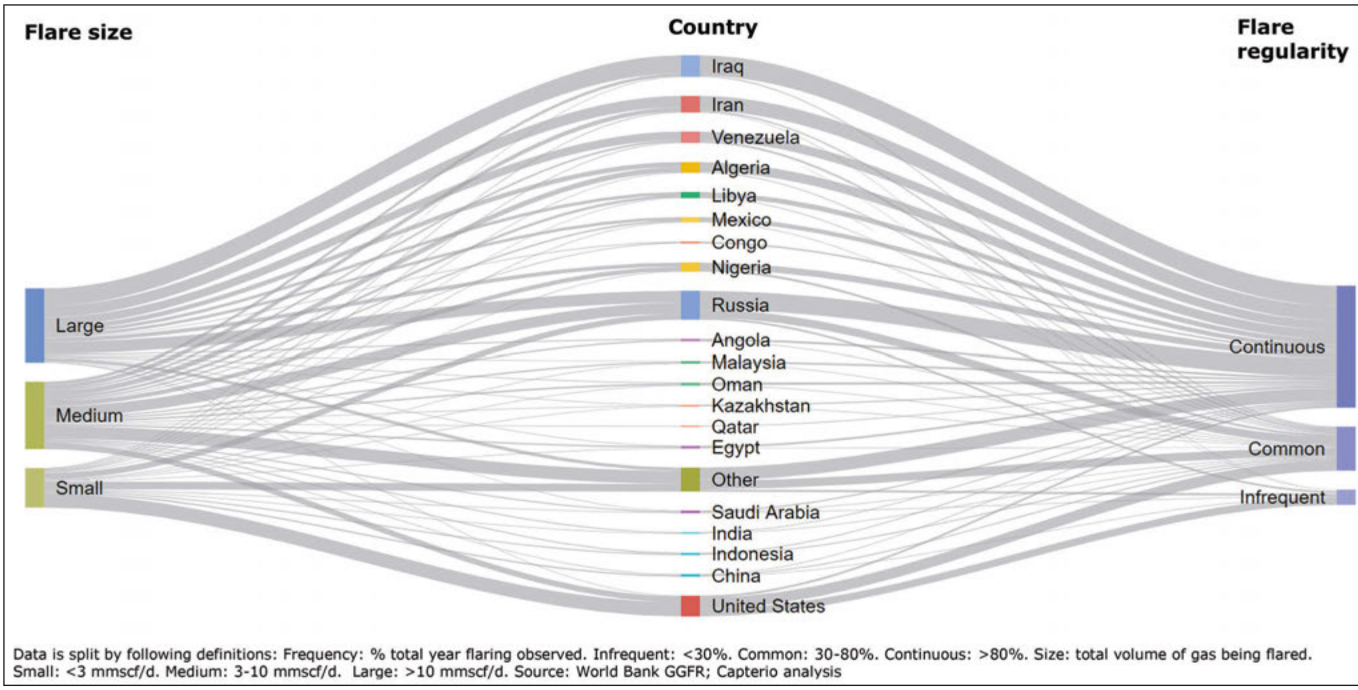


Figure 4: Sankey chart of the volume of flared gas by size of flare, nature and country. Flaring in countries such as Iraq or Iran are dominated by flares that are not only 'large', but are also operating 'continuously'. Conversely, flares in (e.g.) USA are mostly small, and many are not operating continuously.

DNO and Genel, for example, have recently reduced flaring by 20–30 million scfg/day in their Peshkabir/Tawke fields in Kurdistan whilst also increasing gas drive, leading to increased oil production. Also, it is possible to use the gas to generate electricity for oilfield operations. A surprising number of oilfields are powered by electricity generated from diesel, when abundant and cheap flared gas is available.

The main market-based monetization options include sending the gas to an existing gas pipeline. We have analyzed the proximity of every flare to its nearest gas pipeline globally, and identify that 58% of gas flares are within 25 km of a gas pipeline. Another option is to transport the gas via a 'virtual pipeline' to the market as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), or as methanol or synthetic diesel ('Gas To Liquids'/ GTL). Small-scale plants, which typically handle volumes as low as 2–5 million scfg/day are viable, and small-scale CNG and LNG plants in particular are already being deployed at scale in several countries. Our analysis highlights that 63% of gas is within 25 km of an existing gas demand centre. Other options include generating power for the grid and delivering computing services by using flared gas to power-run data centres, or to enable cryptocurrency mining. Such systems have been deployed commercially at scale in the US with considerable success. Equinor is the latest major oil company to have announced a Bitcoin project. Another option is to generate value-added products such as petrochemicals or fertilizers, or potentially synthetic proteins for use as animal feed.

Sound Investments

We estimate that approximately a third of flared volumes (50 Bcmg per year) can likely be monetized with attractive IRRs in the 20–50% range, post tax. These projects deliver significant new revenues to owners and their host governments (in some cases, boosting GDP by up to 1%), improve health, create jobs, improve reputations and contribute towards emissions reductions targets. Another 50 Bcmg would likely be roughly value-neutral – meaning that only a third of the total flaring is likely to be seriously 'out of the money'.

Whilst most gas flaring solutions lead to the gas being burned with associated CO_2 emissions, unless sequestered, they deliver two environmental advantages. Firstly, the end product, which is often gas-fired power, could end up displacing lower-quality power sources, such as coal. Secondly, total emissions are dramatically lowered by eliminating venting of methane at inefficient flares (offset by marginally increased CO_2 emissions from more efficient combustion). The result is a net emissions reduction of up to 77% for a typical flare (Figure 5).

Flare capture projects, therefore, are 'low-hanging fruits' that not only create real economic value, but also significantly reduce emissions and help to accelerate the energy transition. Investors that are seeking sound investments that deliver against their ESG metrics and have negative marginal abatement costs, are increasingly interested in these opportunities.

Making Flaring Glaringly Transparent

It is however disappointing that, five years on from the 2015 Paris Agreement, global gas flaring has increased by 3% from 146 Bcmg to 150 Bcmg in 2019. The cumulative waste is some $100 billion in lost potential revenue.

It is particularly disappointing that flaring from the 11 countries that "specifically identified flaring as a significant component of their NDCs" has increased by 6%, to 60 Bcmg. Eight of the 11 countries now flare more than in 2015, which is not good enough. We must do much more and quickly. To help this situation, Capterio has launched a new and open-access tool

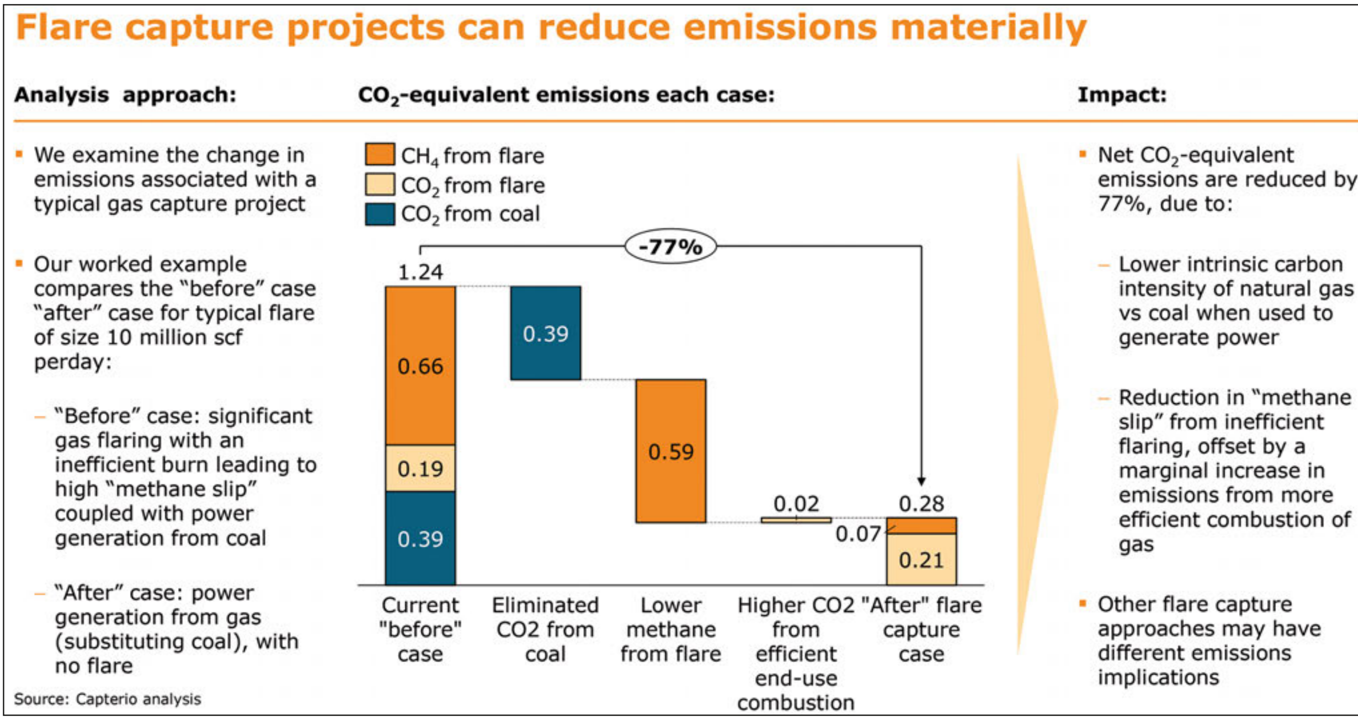
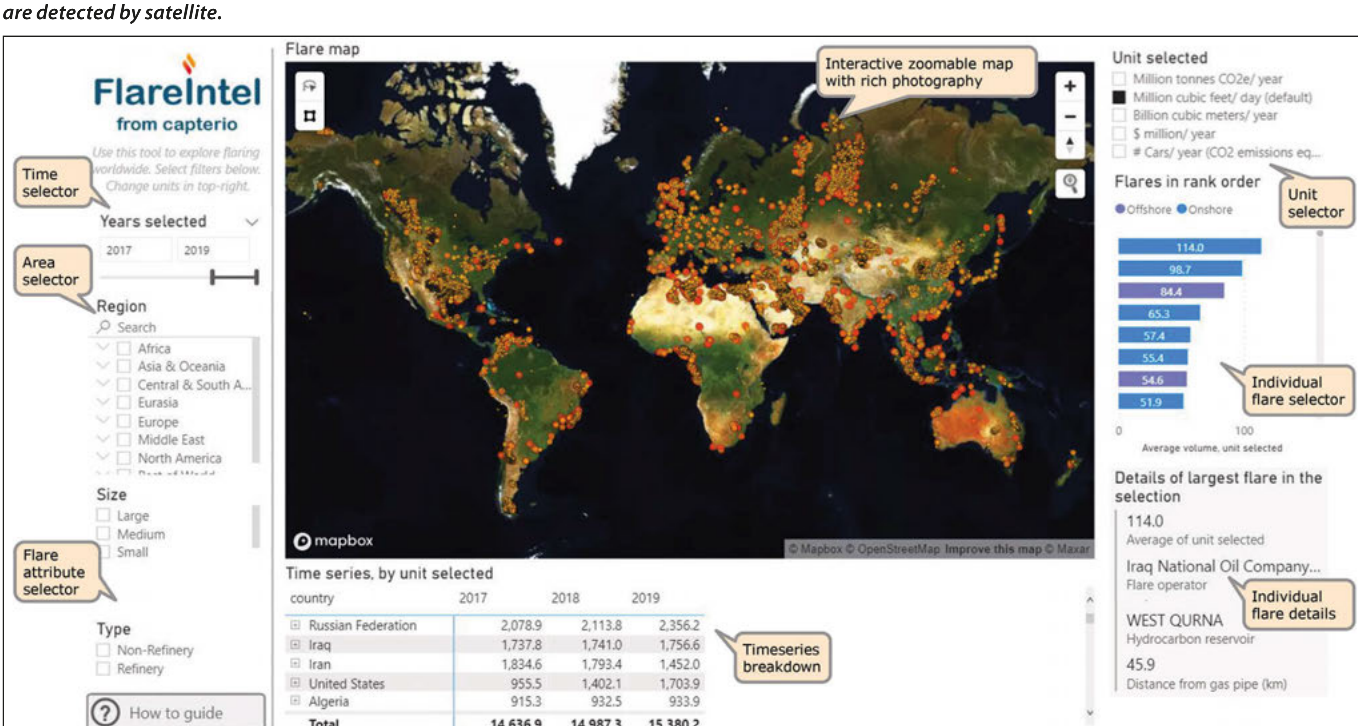


Figure 5: Emissions impact resulting from a 10 million scfg/day flare where recovered gas replaces coal-fired power generation. We calculate CO_2-equivalent emissions of methane over a 20-year basis.

'FlareIntel', which enables users to explore each of the 10,000+ flares globally for free (Figure 6). The tool, which is available on the Capterio website, integrates the last eight years of flaring data at the level of the individual flare with recent satellite imagery and metadata (such as the field name). We hope that by bringing this data into the public domain, we can improve awareness, accountability and assist in identifying and accelerating the delivery of on-the-ground flare capture solutions.

Geoscientists have long been interested in and understood environmental change. Our natural tendency for big-picture, integrative thinking has a direct application to flaring, whether by minimizing it by design through better cross-discipline integration from project inception or by holding our industry to account. The upcoming COP26 is the moment for governments to raise ambitions. Let's use our influence to make sure it happens. ■

Figure 6: Screenshot of a new, free to use, public-domain 'Global Flaring Intelligence Tool' which enables users to explore each of the 10,000+ flares that are detected by satellite.



The Greater Orphan Basin: Unraveling Newfoundland's Emerging Energy Plays

Recent discoveries (e.g., Cambriol and Cappahayden) at the Grand Banks, offshore Newfoundland reconfirm the increasingly promising hydrocarbon potential along the shelf and slope sections of this emerging North Atlantic basin. These discoveries, along with proven petroleum systems, evolving play concepts and ongoing 3D seismic acquisition campaigns, open up exciting running room for hydrocarbon exploration and potential to capture step-out opportunities for near-field developments. The new multisensor 3D seismic acquisition and processing technologies enabling effective demultiple, offer complete imaging of the rift-related petroleum systems and reveal new opportunities in the overlying Tertiary passive margin sequences.

The Grand Banks shelf platform offshore Newfoundland was affected by three major divergent plate tectonic systems associated with the progressive opening of the Central and North Atlantic, respectively. The eastern Grand Banks shelf edge marks an intermediate stage in the northward migration of the Atlantic system. It is dominated by the separation of Iberia from Avalonia, which completed after a Jurassic to Cretaceous rift stage, documented throughout the Grand Banks subsurface. Regional seismic data from the outer Orphan Basin, provides tectonic evidence for a pull-apart basin that is transient into Riedel-shear dominated arrays of extensional faults, towards the prolific hydrocarbon domain of the Grand Banks distal shelf.

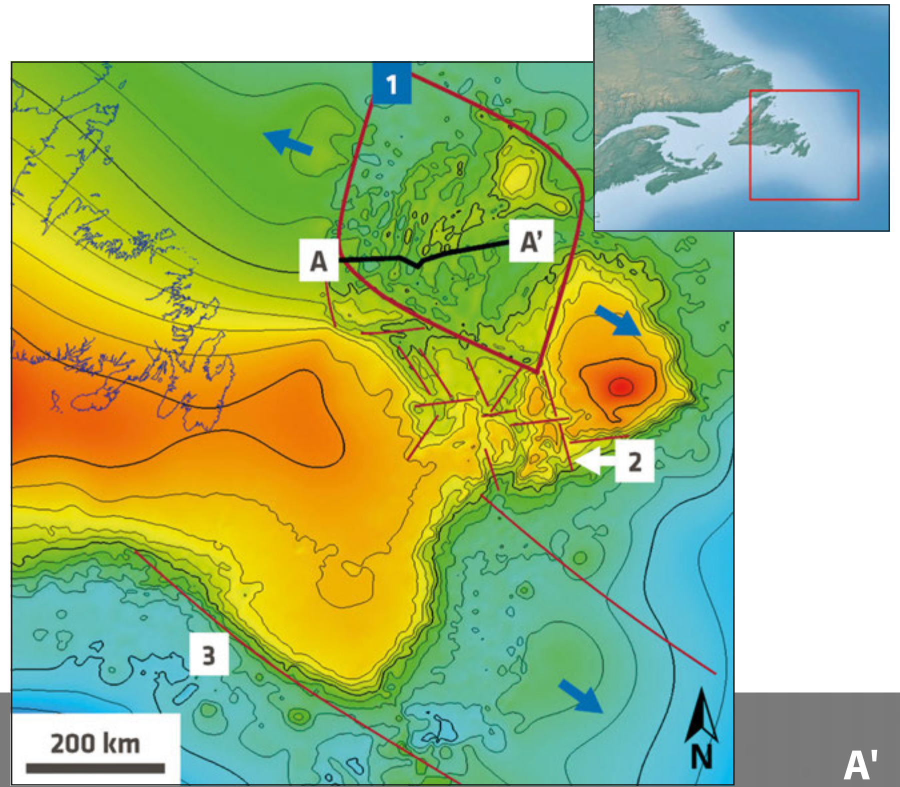


Figure 2: Major tectonic and structural elements of the Grand Banks. The pull-apart geometry of the Orphan Basin is well outlined by the breakup (Cretaceous) unconformity as well as the rift pattern of the adjacent basins. 1. Pull-apart basin 2. Riedel shear fault zone 3. Newfoundland fault zone. Blue arrows indicate crustal extension.

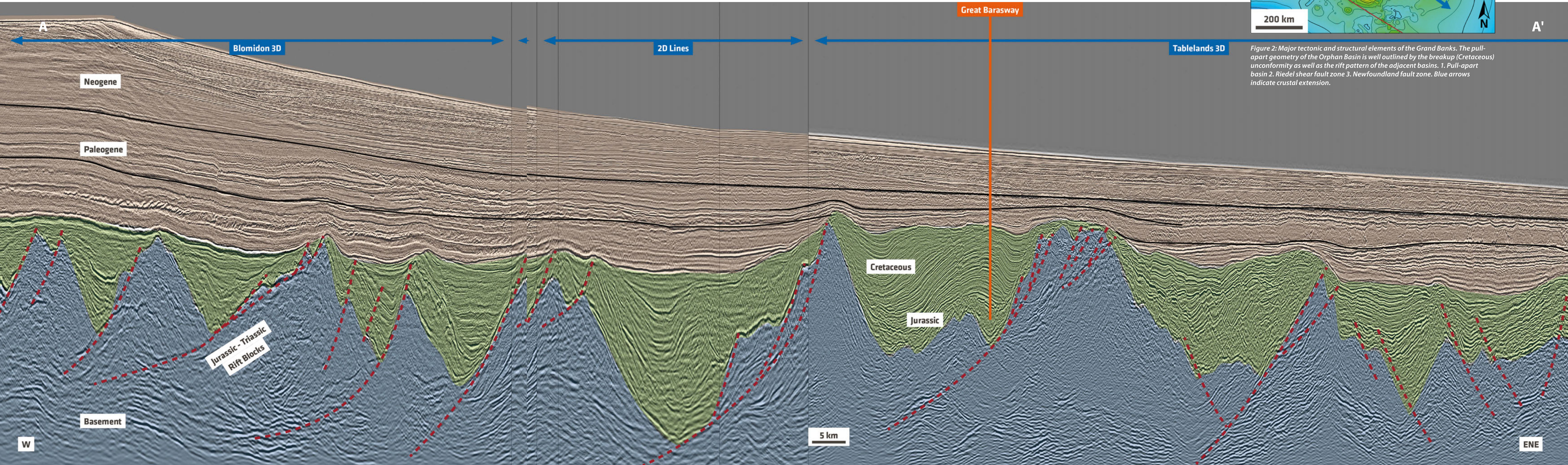


Figure 1: Regional section through the Orphan Basin from a combination of 3D seismic surveys and interconnecting 2D seismic line sections. The 3D images reveal details of rift character of the extended continental crust affecting the basement, potential Paleozoic, and Mesozoic pre-rift sediment. The Jurassic to Cretaceous syn-rift deposits are well-delineated petroleum systems and reservoir sequences.

Open Running Room in an Emerging Basin

HERMANN LEBIT, YERMEK BALABEKOV and TAYLOR BUCKLEY; PGS

Three divergent plate tectonic systems control the offshore Grand Banks shelf platform. To the south, the Newfoundland–Gibraltar fracture zone limits the Triassic to Jurassic opening of the Central Atlantic. The northern shelf edge reveals a complex tectonic evolution related to the Cenozoic opening of the North Atlantic Basin and subsequent development of the southern Labrador Sea. The eastern Grand Banks shelf edge documents an intermediate stage in the northward migration of the Atlantic system and is dominated by the separation of the Iberia micro-plate from Avalonia, which completed after a Jurassic to Cretaceous rift stage. The rift-related extensional tectonics is prevalent throughout the Grand Banks subsurface (Figure 1) and underneath its present-day slopes. Extensional structures are the major element of the proven petroleum systems in terms of source rock presence and its maturity, due to the variable overburden in extensional systems. It further controls the reservoir distribution relative to structural highs and associated trapping mechanisms. Reliable seismic data significantly contributes to reservoir risk mitigation and improves the success rate for exploratory drilling.

Subsurface Integration with Modern 3D Seismic Data

Regional seismic data analysis, based on 2D lines and extensive 3D multisensor broadband seismic coverage, suggests that the Orphan Basin formed as a pull-apart arrangement that is transient into Riedel-shear dominated arrays of extensional faults towards the prolific hydrocarbon domain of the Grand Banks distal shelf (Figure 2 inset). The grain of the rifting architecture at the Grand Banks subsurface is evident from the morphology formed along the base of the passive margin sequence (Cretaceous Unconformity). This reveals a NW–SE principal extension direction for the Orphan Basin based on the consistent regional trend of the underlying half-graben highs, while the Flemish Cap represents a rifted basement block that has been displaced by the Orphan extension. That rift pattern forms a rhombic shape, bound by a northern lineament that was presumably reactivated as a transform system during the Cenozoic North Atlantic opening, while the western lineament forms the conjugate to the Flemish Cap. The southern lineament marks the transition into an array of horst and grabens that indicate a crustal extension system with a Riedel-shear component, which is compatible with the simultaneous extension in the adjacent pull-apart. The Jeanne d'Arc or Flemish Pass sub-basins formed early in this system, while the Tableland Basin reaches into the pull-apart section of the Flemish Cap.

The Grand Banks basins have a prolific, rift-related petroleum system in common, which is primarily sourced by Kimmeridgian to Tithonian shales. The Great Barasway well, which successfully encountered an

Figure 3: The annotated 3D Seismic line (acquired post-drill) illustrates a syn-rift roll-over anticline associated with a system of low angle extensional faults. A well targeting the anticline crest encountered Tithonian source rock in a relatively shallow position but can be easily tracked to adjacent synforms on the 3D seismic. Hydrocarbon indicators (e.g., orange circle) along keystone normal faults suggest a working petroleum system

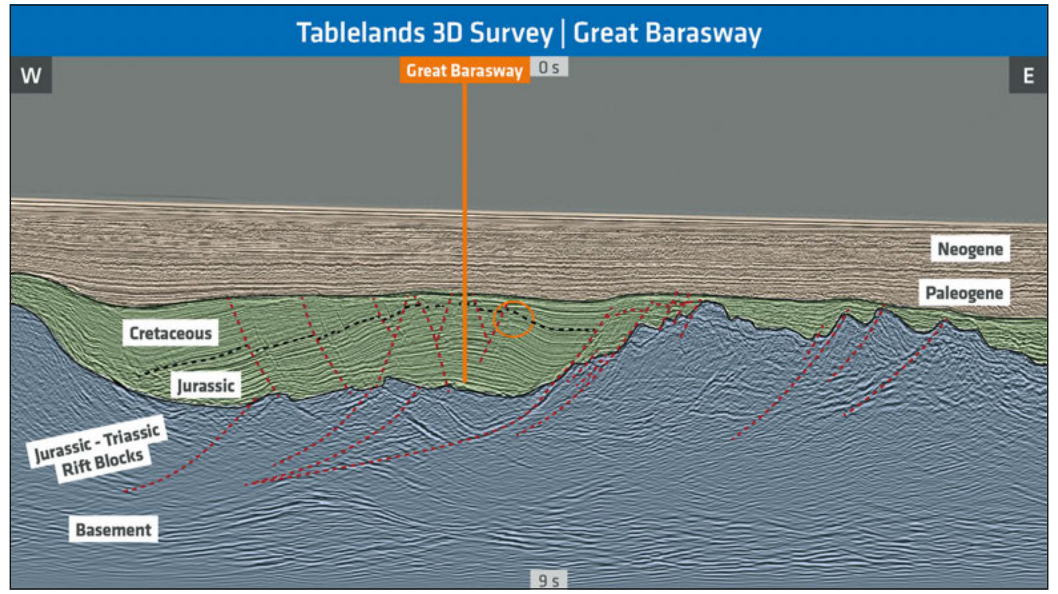
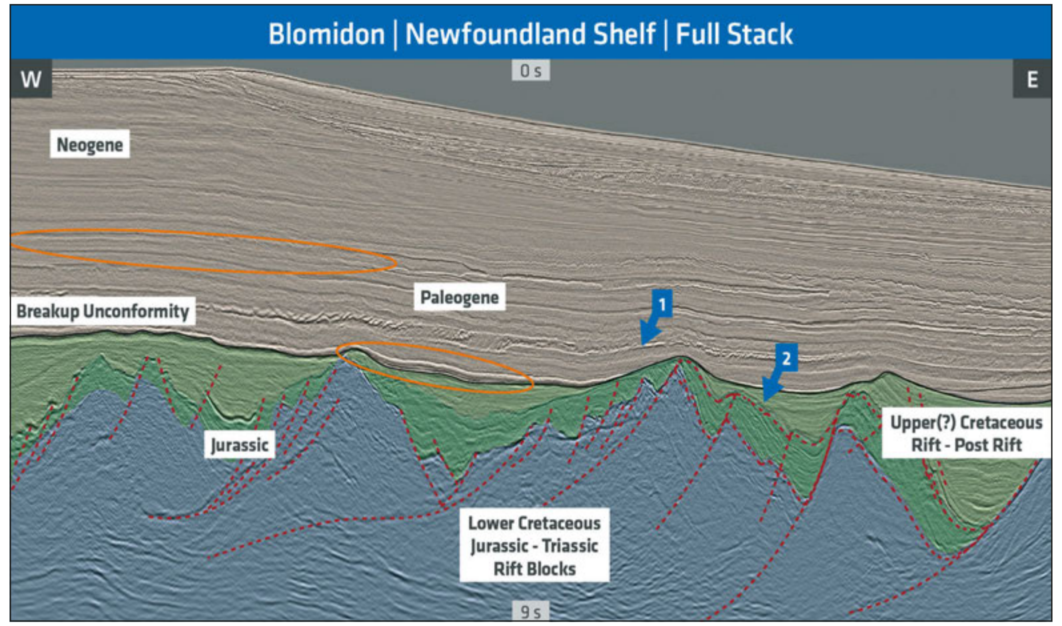


Figure 4: High quality 3D seismic resolves the depositional and structural architecture of the Orphan Basin including the outline of various rift stages due to the depositional signature. The ellipses highlight sequences with clear amplitude responses in the 3D seismic data, which are indicative of hydrocarbon reservoirs in the Paleogene of passive margin cover sequence and on-lapping in the Jurassic to Cretaceous syn-rift sequences and overlying post-rift cover. 1. Indicates draped /ponded sand complexes, 2. On-lapping reservoirs at half grabens.



Upper Jurassic source rock sequence in the greater Orphan Basin, is illustrated on post-drill 3D seismic data (Figure 3). The seismic section reveals an extensional roll-over anticline driven by an eastward dipping low angle detachment fault, with the exploratory well targeting the crestal structure. Underneath the passive margin unconformity, the drilling merely found a reduced Cretaceous section before encountering the Upper Jurassic source rock sequence at a relatively shallow and immature depth. The 3D seismic allows for reliable tracking of the source rock intervals into the deeper roll-over syncline or half-graben where higher thermal maturity levels are likely. Evidence for up-dip hydrocarbon indicators are present on the 3D seismic line with anticlinal keystone faults forming the critical trapping mechanism for potential sandstone reservoirs (e.g., Figure 3).

The locus of crustal extension in the greater Orphan Basin may have shifted during the Jurassic to Cretaceous as indicated by migrating depocenters for the sedimentary syn-rift accumulations (Figure 1). High quality 3D seismic imaging of the rift architecture and syn- to pre-rift sedimentary signature offers a complete picture of the depositional/burial history and provides enhanced control for modeling the petroleum system. Figure 4 illustrates an east–west section from a recent 3D survey in the Orphan Basin that resolves the structural elements of the rift section in conjunction with the imaging of an early syn-rift or pre-rift sediment sequence, possibly of Jurassic age, followed by a well-imaged syn-rift half-graben fill, presumably Cretaceous of age. The seismic data highlights amplitude responses for potential hydrocarbon reservoirs in the Cretaceous sediments on-lapping onto the structural highs and in late to post-rift deposits draping the structures. The assessment is based on the semi-quantitative analysis of potential exploration objectives and a quick, automated horizon interpretation to help screen the interval of interest. The analysis also comprises the passive margin sequence which gradually builds Paleogene to Neogene cover sequences of progradational sedimentary wedges, as illustrated on Figure 4.

New Play Concepts

The passive margin slope sequences of the Grand Banks reveal a promising play concept comprising Upper Cretaceous to Paleogene slope to basin-floor fan sand fairways. Prolific play analogs have been documented elsewhere along the margins of the greater Atlantic system. This play type differs from the proven petroleum systems of the various sub-basins covering the Grand Banks area and it is assumed to be primarily sourced by organic-rich Albian, Cenomanian, Turonian (ACT) shales that have been penetrated and analyzed in research wells of the International Ocean Drilling Program which were located at the distal sector of the basin. The ACT source rock interval is associated with the separation of Newfoundland and Iberia and was presumably deposited in partially restricted marginal basin settings during the early drifting stage, while the developing slope of this basin received clastic input from the Canadian Shield via sand channel and fan complexes.

De-risk Emerging Orphan Basin with Optimized Imaging

PGS and partners (Nalcor & TGS) classify the Grand Banks region as emerging hydrocarbon basins and acknowledge its exploration and production potential. This is the primary driver for our continuous commitment to high quality GeoStreamer 3D seismic acquisition campaigns accompanied by innovative time and future depth processing of the seismic data. The major focus of the seismic program aligns with the industry demand to optimize seismic imaging to completely capture the petroleum system and assess the reservoir potential of the rift play and the overlying passive margin sequences. The broadband multisensor seismic products offer a reliable database for appropriate exploration risk mitigation and potential drilling hazard assessment in this emerging basin. ■

Critical Minerals From Sedimentary Basins

A view from North America.

RASOUL SORKHABI; Ph.D.

The petroleum industry is currently facing various challenges, including a global movement toward a low-carbon world. These challenges, however, also provide the oil and gas industry geoscientists and engineers with new opportunities for exploration and production as well as research and development. Exploration for critical minerals in sedimentary rocks and basins, briefly described in this article, is a case in point. This field is rapidly growing in the US as the country seeks to decrease its dependency on China, which has been the dominant exporter of critical minerals in the past three decades. In 2020, for instance, the US Department of Energy allocated $122 million for regional research initiatives to produce critical minerals and rare earth elements from the country's sedimentary basins.

What Makes a Mineral Critical?

Mineral economics textbooks have remarked that the terms strategic, critical and essential minerals are the outcome of war emergency in relation to supply status of minerals necessary for winning a war. However, these terms are important for peacetime as well, because modern civilization depends, more than ever, on a vast array of minerals. Indeed, we currently use all the elements of the periodic table. A cell phone, for instance, utilizes about 75 different elements.

A college textbook, similar to AGI's *Glossary of Geology*, defined a 'strategic mineral' as one that a country has little resource of its own and thus depends on imports; 'critical mineral' has some occurrence in the country, while 'essential mineral' has both fundamental usefulness and large occurrence. However, definitions of these terms vary. A 2018 US Geological Survey listed 35 critical or strategic minerals "whose absence would have substantial consequences for the US economy or national security." These minerals are "essential for the manufacture of high technology devices, national defense applications, and green energy-growth industries."

Criticality depends not only on industrial importance or economic value but also on vulnerability, risk and disruption in supply chain due to various factors such as international conflicts. Table salt was once a critical mineral for ancient peoples; today it is produced in abundance. Rare earth elements were not even known in pre-modern times; today they are among critical minerals for the industrial nations.

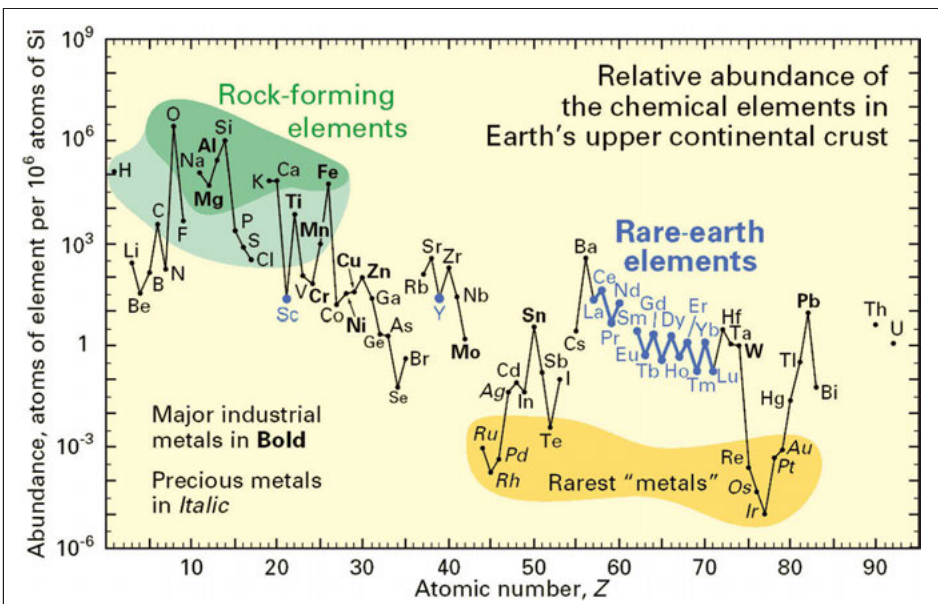
Another related term is 'energy mineral'. In a strict geologic definition, fossil fuels are not 'minerals', because they are organic. Moreover, oil and gas are not solid and are mixtures of various hydrocarbon molecules. In 1977, the American Association of Petroleum Geologists founded the Energy Mineral Division to advance the science of non-petroleum minerals that can be used for energy production, such as coal and uranium. Today, energy minerals are sometimes considered as those used to produce electricity or fuel. In this way, there are large overlaps between critical and energy minerals.

Minerals, Sediments and Basins

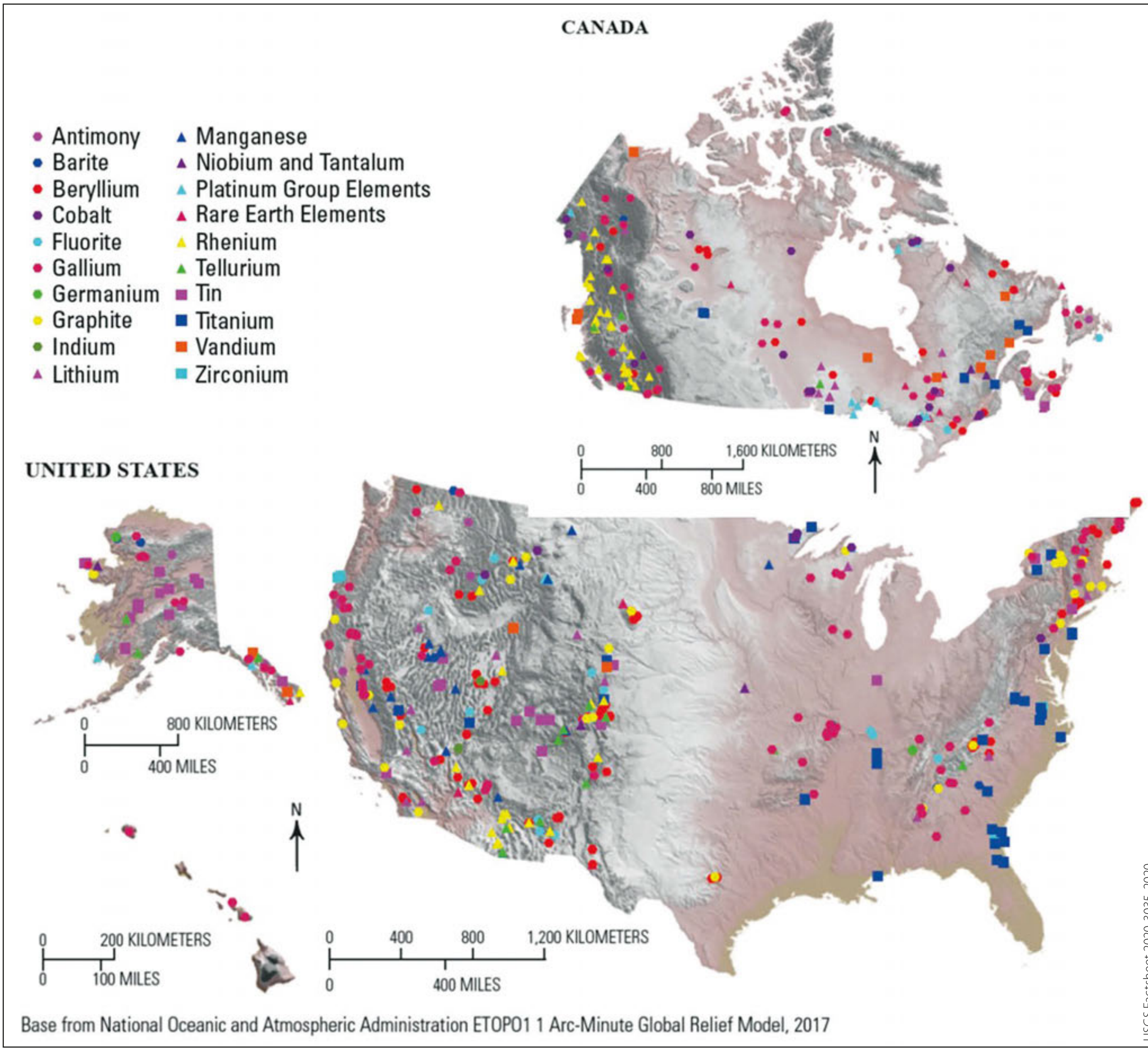
All rocks are made of minerals and they, in turn, of elements; however, their distributions are not uniform. Certain elements and minerals are more abundant in some rock formations than others. Igneous, metamorphic, and sedimentary rocks are all valuable for mining, with sedimentary rocks classified into clastic, chemical, and organic types. This classification is not merely a semantic issue; it pertains to the formation processes of sediments, and thus guides us in mineral exploration. Clastic rocks, from conglomerates to clays, are derived from pre-existing rocks; chemical rocks form by precipitation or evaporation in marine environments, and organic sediments come from plants or other organisms. Minerals occur in sedimentary rocks via various mechanisms.

Sediment-host deposits of base metals such as lead, zinc, and

Abundances of elements in the upper crustal rocks including the rare earth metals.



(Haxel et al., 2002, USGS Factsheet 087-02)



Critical mineral mines in North America.

copper are well known. Indeed, the classification of ore deposits known as Mississippi Valley Type (MVT) around the world were named after the successful extraction of such deposits along the Mississippi River in Missouri, Iowa, Wisconsin, and Illinois ('the Lead Belt') as early as the 18th century. These are high-grade sulfide bodies hosted in carbonates.

Some sedimentary rocks are also known to contain low- to medium-grade uranium-bearing minerals. Colorado Plateau-type sandstones, the site of the post-World War II 'uranium rush', are sandstone bodies of Jurassic–Cretaceous age widely distributed in Colorado, Utah, and Wyoming. These sandstone formations with alternating red (oxidizing) and white or green (reducing) layers are ideal for uranium mining because uranium is mobile in oxidizing environments and precipitates in reducing environments. Black shales may contain 50 to 250 ppm uranium. Phosphorite deposits can also contain uranium oxides within apatite and fluorite.

Although in the subsurface, dolomite may be a petroleum reservoir, dolomite layers in basin-margin exposures may also provide a major source for production of magnesium. Dolomite itself can be used as a flux for the smelting of iron and steel. Magnesite ($MgCO_3$), another industrial mineral, occurs in shales and limestones, in association with salt and gypsum, or within regolith above ultramafic rocks. In the US, sedimentary magnesite mines are located in California, Nevada, Idaho, Texas, and Florida.

Vanadium used for production of steel alloys, for glass coating, and as a catalyst, is present in considerable concentrations in black shale, coal, crude oil, oil shale, and oil sands.

Sedimentary basins sometimes host igneous intrusions which create ideal conditions for ore deposits. For instance, in Salt Lake City, Utah, there is an open-pit copper mine called the Kennecott or Bingham Canyon mine, which is the second largest of its kind in the US and the deepest excavated mine in the world. This huge deposit of copper (as well as gold and silver) was formed by a 35-million-year old quartz monzonite porphyry that intruded Late Paleozoic sediments of the Oquirrh Mountains.

Rare Earth Metals

Rare earth elements or metals (REEs) include the entire lanthanide series (with atomic numbers from 57 to 71) as well as scandium and yttrium, because of their similar chemical and physical properties. REEs are classified into light (atomic numbers 57 to 64) and heavy (atomic numbers 65 to 71). Yttrium is included in the heavy REEs because it also has paired electrons. REEs have a wide range of applications in electronics, glass and other industries and they are used as permanent magnets, alloys, and catalysts (including petroleum-refining catalysts).

REEs are not really ‘rare’ on Earth, but unlike the base metals such as chromium and zinc which are found individually in ore deposits, REEs occur together in a limited number of minerals. Moreover, their mining results in toxic substances which must be properly dealt with.

Although igneous rocks, especially carbonatites and alkaline magmatic rocks, are the major sources of REEs, sedimentary deposits can also yield REEs. Major REE minerals include bastnaesite, monazite, apatite, and xenotime. The presence of REEs in sedimentary rocks largely depends on the provenance of the sediments as REEs are insoluble in water.

Placer deposits, especially monazite, in Ontario’s Elliot Lake mining district, contain heavy REEs and the Alberta black shale deposits in Canada are also attractive for REE mining.

Phosphorite deposits from Idaho to Florida are proven sedimentary sources for REEs. Bastnaesite, the major mineral for REEs, has been found in karst bauxite deposits in the Balkan region of Europe.

Laterite deposits are intensely weathered bedrocks in tropical to sub-tropical climates. More than 250 laterite deposits containing REEs have been mapped around the world. One particular type, ion-adsorption clays (formed by the intense weathering of granitic rocks) are massively mined in southern China as the world’s main source of heavy REEs. These elements are adsorbed to the surface of kaolinite, halloysite or illite.

Minerals From Brines

Formation waters in oil fields are often brine with high concentrations of dissolved salts and thus contain various minerals. These toxic waters must be treated, stored, disposed or reinjected into the wells. However, formation waters also

A view of solar evaporation ponds in the Silver Peak lithium mine extracted from brine wells in Clayton Valley (a dry lakebed), south-west Nevada.

Wikipedia Commons, 2010

offer important sources for mineral extraction. These waters may be classified as four types: reservoir water associated with oil and gas, bottom water at the base of hydrocarbon column, edge water to the sides of the hydrocarbon column, and water in barren traps. Compared to hard-rock mining which is time-intensive and has adverse impacts on the land surface and likely on groundwater, formation waters are easier to exploit.

Lithium is one of the valuable metals that can extracted from brine. A successful US example is Albemarle Corporation's Silver Peak mine that has been in operation since 1966 (it is North America's only lithium brine mine).

Lithium-ion batteries power many devices from cell phones to electric cars. Global demand for lithium is expected to increase and Goldman Sachs Group has called lithium-rich formation waters 'the new gasoline'. Moreover, lithium processing also yields other critical elements and minerals such as cesium and rubidium as residues.

In 2017 the Canadian mining company, MGX Minerals, acquired the Lisbon Valley Petrolithium Project in the Paradox Basin of south-east Utah, that is designed to extract lithium and other minerals and salts from brine waters in the Lisbon Valley oil and gas fields. Lithium content in these formation waters is as high as 750 ppm.

Tesla Eyes Opportunity

In the 1970s, several authors reported lithium in various clays, with concentrations from several ppm in some montmorillonites to as high as several thousand ppm in hectorites.

In 2020, the electric car company Tesla announced obtaining lithium mining rights in 10,000 acres in Nevada where lithium has been proven abundant in vast and thick tracts of clay deposits. Tesla plans to extract lithium from claystone by the weak acid leach technique. Laboratory experiments have shown over 80% recovery within several hours; the leftover clay would be put back in the land. Tesla is not the only lithium-bearing clay mining company in Nevada. Cypress Development Corp owns the Clayton Valley Lithium Project totaling 5,430 acres, in south-west Nevada.

Helium From Natural Gas Fields

Helium, the second simplest element (after hydrogen), is an inert (noble) gas. Helium is rare on earth and is also considered a non-renewable resource because it can escape into outer space. Although helium can be released by volcanic activity, it is mainly produced in the radioactive decay of uranium, thorium and elements present in both basement and sedimentary rocks. Being a buoyant gas, helium can migrate upwards and accumulate in natural gas reservoirs. As much as 7 percent radiogenic helium has been reported from gas fields, from which helium can be extracted by low-temperature fractional distillation. The Petrolia Oil Field in Clay County, Texas and the Texas Panhandle gas field are both historical sources of helium production dating back to the 1920s.

Helium has a wide range of industrial applications including cryogenics (liquid helium to cool superconductive magnets), shielding gas in arc welding, helium-neon lasers, carrier gas in gas chromatography, supersonic wind tunnels, etc.

Hydrogen

Hydrogen was first envisioned as a fuel (extracted from water) in Jules Verne's *The Mysterious Island* published in 1874. Verne knew about the abundance of water on Earth, but in his time, nobody was aware of abundant natural gas reserves. Ironically, natural gas, which has been flared for decades, is now considered a major source for hydrogen, probably a better source than the much-needed water ('green hydrogen' can be produced by water electrolysis). 'Grey hydrogen' is already produced from natural gas in places like the Alberta Basin, which is primarily used in petrochemical facilities. However, Canada now has its eyes on massive production of 'blue hydrogen' from natural gas via steam methane coupled with a carbon capture and storage system. In this way, natural gas opens up a new frontier for hydrogen fuel during the energy transition in the coming decades.

Mineral mining requires sophisticated technologies and petroleum companies, which have advanced some of the best geological, geochemical and geophysical techniques for exploration of oil and gas, are in an excellent position to explore for critical minerals in sedimentary basins. These new ventures will also demand participation of geoscientists and engineers who want to learn new techniques. Perhaps the science of sedimentary and geochemical processes in petroleum basins for critical minerals has come of age. ■

Big Bend Country

A tour of Big Bend National Park, Texas.

GARY L. PROST

West Texas! Land of longhorn cattle, mesquite, and fiercely independent ranchers. It's also the location of an out-of-the-way desert gem, Big Bend National Park. Wild, undeveloped, expansive vistas, and no crowds, is how the park is described. The area is rich in history. Roamed by Comanches and Apaches, settled by the Spanish, it was the Republic of Texas after 1836, and has been part of the United States since 1845. This is where many of the cattle drives that defined 'cowboys' began.

The region is arid, part of the Chihuahuan Desert. Mostly flat valleys are punctuated by mountains poking up through cactus and sage-strewn prairie. Summers are hot; winters are mild. Vegetation is sparse, and water is rare. None of the creeks flow all year-round.

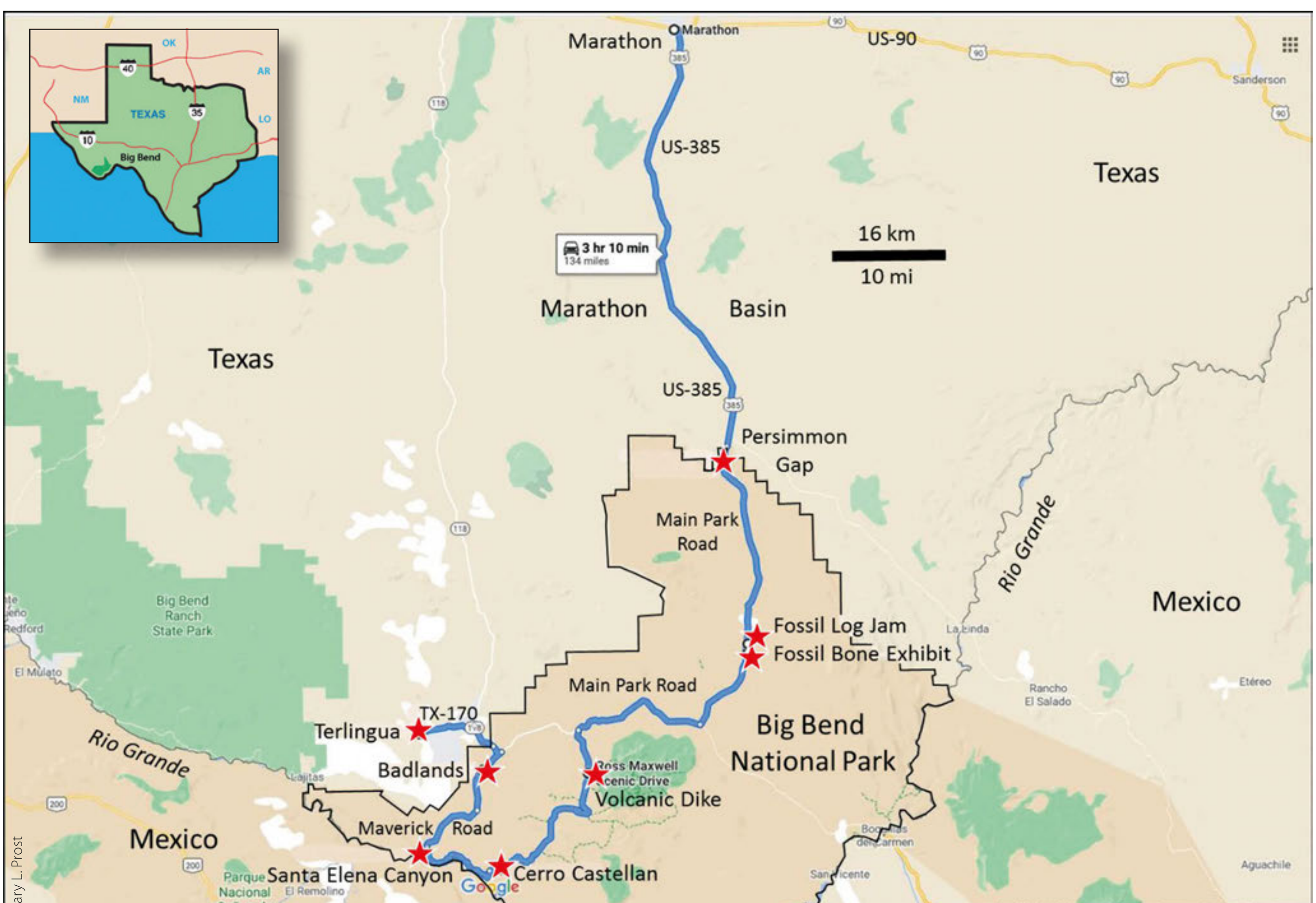
Named for the bend in the Rio Grande, Big Bend National Park covers 324,200 hectares (1,252 square miles). This park has the variety of geologic features you would expect in an area this large (Prost, 2020).

We begin in Marathon, Texas, a thriving town of 386 souls with some of the darkest night skies in the country. We traverse the Marathon Uplift and Big Bend National Park, and end at Terlingua, a mining ghost town.

Marathon Uplift

Driving south on US-385 from Marathon, you cross a topographic basin that is a geologic uplift. The Marathon Uplift exposes Paleozoic strata of the Appalachian-Ouachita-Marathon fold and thrust belt (Variscan Orogeny in Europe). This thrust belt formed during Late Carboniferous (Pennsylvanian) to Permian time, roughly 300–270 million years ago (Ma), as the northern continent of Laurussia collided with the southern continent of Gondwana to form Pangea. Late Cambrian to Late Carboniferous sediments deposited along the southern margin of Laurussia were thrust north-west over Carboniferous deep marine units. Tectonism ended in the Permian, after which the area remained quiet until the Laramide (Rocky Mountain) Orogeny (75–40 Ma), when the older folds were refolded. The area was uplifted during the Tertiary (Hickman et al., 2009).

The route from Marathon to Terlingua, Texas, with stops (stars). The entire trip is 134 miles (216 km).



Big Bend National Park

41 miles (66 km) south of Marathon you enter Big Bend Park at Persimmon Gap (29.659870,–103.173510). Big Bend Park is south of the main Ouachita-Marathon suture, on former Gondwana. Persimmon Gap lies on the 'Comanche Trail', a path used by Native Americans to move across Big Bend country. The gap is named after native Persimmon trees that thrive in the area.

This low pass in the Santiago Mountains exposes a south-west-directed Laramide-age thrust. Late Cretaceous to Eocene Laramide deformation in North America is related to subduction along the west coast and is characterized by east-north-east shortening.

Rifting opened the Gulf of Mexico, beginning in the Late Triassic. This area was then covered by a shallow sea until Late Cretaceous time and a thick limestone section accumulated on a carbonate platform. As the sea began to retreat, around 100 Ma, sandstone and shale were deposited in shallow marine and shoreline environments. Remnants of these sediments form flat to gently inclined strata throughout the park and contain fossil oysters, clams, ammonites, and a variety of fish and marine reptiles.

Laramide shortening caused north-west to south-east oriented features such as Sierra de Santa Elena/Mesa de Anguila in the south-west corner of the park. Mariscal Mountain, 16 miles (26 km) south of the Panther Junction Visitor Center, is the southernmost uplift of the Rocky Mountains.

Overlapping the Laramide Orogeny was a period of volcanism. Lava flows, dikes, sills, laccoliths (domed sediments over intrusions), and ash eruptions occurred between 46.5 and 28 Ma. These features formed the Chisos Mountains and are present in Big Bend Ranch State Park to the west.

Basin-and-Range extension began around 25 Ma and is ongoing. This orogeny created normal fault-bounded mountains and valleys. The Terlingua Fault bounding the Mesa de Anguila has about 6,000 ft (1,830m) of vertical offset. The area is presently being uplifted around 3 inches (8 cm) per 100 years.

Today, erosion cuts away at the mountains and fills the intervening valleys. Only in the last 2 Ma has the Rio Grande reached these valleys and connected them to the Gulf of Mexico, making it the youngest major river in the United States.

Laramide thrusting seen from Persimmon Gap. Lower Cretaceous Glen Rose Formation is thrust over the Upper Cretaceous Aguja Formation.

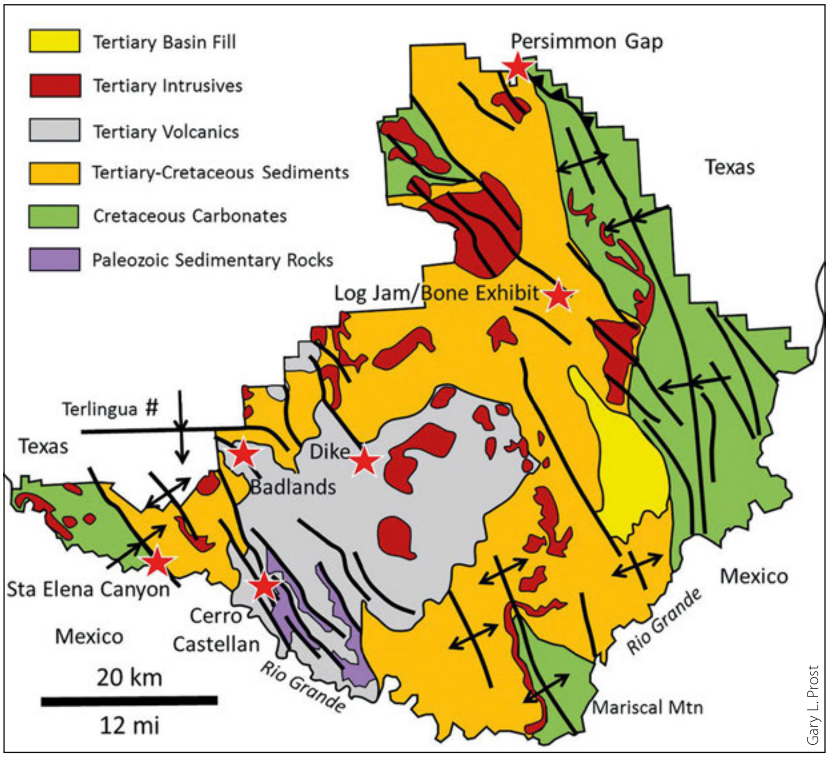
Fossil Trees/Logjam

Follow the Main Park Road 17.7 miles (28.5 km) south from Persimmon Gap to the unmarked Fossil Trees/Logjam site (29.431413,–103.136839). Between 400–500 ft (120–150m) east of the road on a low rise is a river channel sandstone in the Paleocene Black Peaks Formation. This bed contains abundant petrified logs, some up to 30 ft (9m) long. All are *Paraphyllanthoxylon abbotti,* a Cretaceous-Paleocene broad-leaf tree.

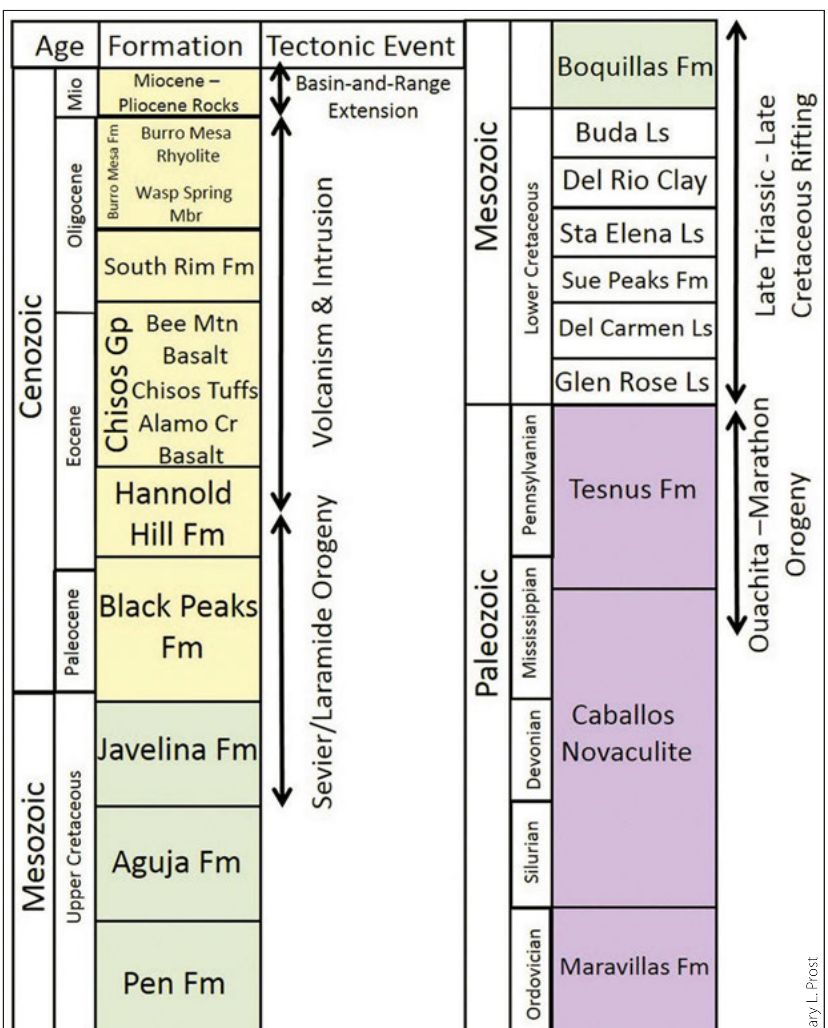
Fossil Bone Exhibit

Continuing south on the Main Park Road for 1 mile (1.6 km) brings us to the Fossil Bone Exhibit (29.418922,–103.138278). The Exhibit Ridge Sandstone member of the Eocene Hannold Hill Formation is a conglomeratic river sandstone filled with fossil bones. The Late Cretaceous Javelina Formation in this area consists of alternating lacustrine shales and stream channel sandstones. The upper part of the sandstone-capped ridges contain sauropod (*Alamosaurus sanjuanensis*) and pterodactyl (*Quetzalcoatlus northropi*) bones. This giant flying reptile had a wingspan over 10m (35 ft).

The 'volcanic dike' in the Chisos Volcanics.



Simplified geology of Big Bend National Park. Modified after Gray and Page, 2008.



Stratigraphy of Big Bend National Park. Modified after Gray and Page, 2008.

Volcanic Dike

Continue south on Main Park Road to Ross Maxwell Scenic Drive and turn south. At 25.2 miles (40.5 km) from the Bone Exhibit a pullout on the east side of the road has an interpretive plaque. The 'Volcanic Dike' (29.2676,–103.3687) forms a wall across the landscape. This Oligocene rhyolite dike was intruded into the Chisos Formation volcanics (Turner et al., 2011).

Cerro Castellan

Continue south on Ross Maxwell Scenic Drive for 17 miles (27.4 km) to Cerro Castellan (29.1486795,–103.5030757). A resistant lava flow caps this monolith. The base is the Eocene-Oligocene Chisos Group tuff, which is overlain by the Bee Mountain basalt, then more Chisos tuff. Oligocene Burro Mesa rhyolite tops the peak (Gray and Page, 2008).

Santa Elena Canyon

Continue driving 9.7 miles (15.6 km) west on Ross Maxwell Scenic Drive to Santa Elena Canyon (29.167368,–103.610305). This is arguably the most spectacular location in the park. Santa Elena Canyon is a dramatic gorge cut by the Rio Grande through the Mesa de Anguila. This north-west to south-east uplift is tilted southwest and has a towering, east-facing escarpment along the Terlingua Fault. Lower Cretaceous strata exposed in the canyon include, from top down, Santa Elena Limestone (upper cliffs), Sue Peaks Formation (slope-former), Del Carmen Limestone (lower cliff), Telephone Canyon Formation, and Glen Rose Limestone (lower slopes and ledges). A short nature trail enters the chasm from the east. At the canyon entrance the walls rise 460m (1,500 ft) above the river and a prominent rudist layer outcrops in the Del Carmen Limestone near the canyon mouth. Santa Elena Canyon is an 'antecedent river', cut downward by a combination of abrasion and chemical solution of the limestones. The Rio Grande has been grinding downward at a rate of 0.0008 inches per year (0.25 mm per year) for the last 2 Ma.

Volcanic Badlands

Return east to Old Maverick Road and turn north; drive north for a total of 10.9 miles (17.6 km) and pull over (29.2703626,–103.5224992). The valley fill here contains mostly Pleistocene volcanic material eroded off the Chisos Mountains to the east. The road crosses a 'pediment', a low-relief, gently sloping erosion surface, and 'bajadas' of coalescing alluvial fans. These colorful sediments are easily eroded and transformed into the rugged terrain known as Badlands.

Terlingua

Continue driving northeast on Old Maverick Road to the junction with TX-118; turn west onto TX-118 and drive to FM-170 in Study Butte; turn west on FM-170 and drive to Terlingua (29.320722,–103.617276), a total of 11.6 miles (18.7 km).

We end this transect in Terlingua, an old west ghost town that is seeing something of a revival (110 inhabitants in 2019). Terlingua was the main source of mercury in the United States during World War I. The deposits were depleted and the mines were abandoned by 1946. Since 1967 the ghost town has become world-famous for their annual chili cook-off that attracts as many as 10,000 visitors the first Saturday of each November.

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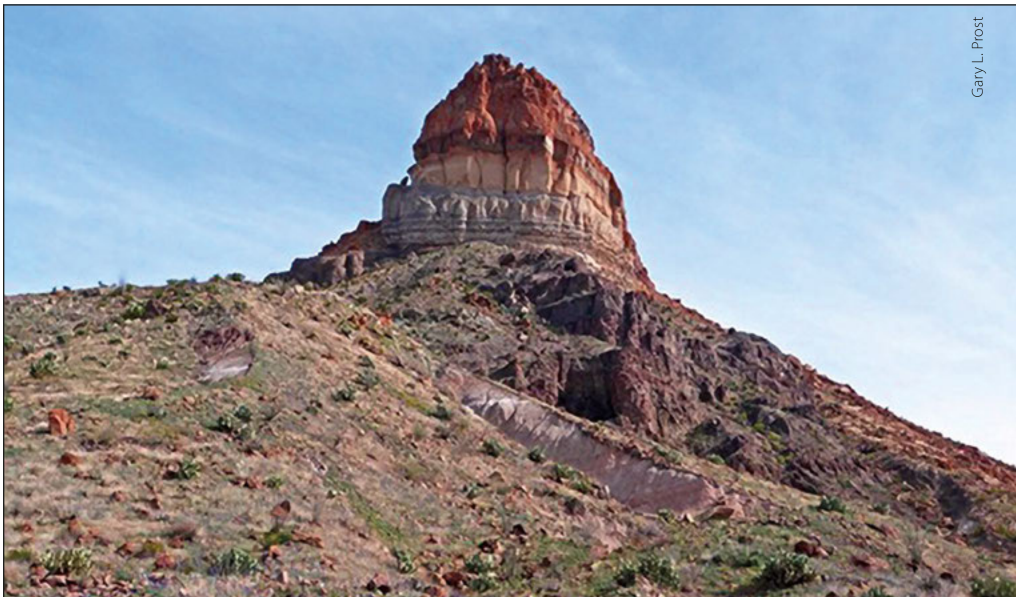
Santa Elena Canyon and the Rio Grande looking west.

Looking east from Old Maverick Road to the volcanic Badlands.

Cerro Castellan consists of a resistant lava flow over volcanic tuff.



Increasing Energy While Decreasing Carbon

JANE WHALEY

Supermajors are moving from IOCs to IECs but in different ways across the Atlantic.

The 'supermajor' oil and gas companies are changing; in different ways and at different speeds, they are making the transition from international oil companies, or IOCs, to integrated energy companies – IECs. That one letter change is very significant. And despite, or maybe because of, the distractions caused by Covid-19, 2020 seems to have been a pivotal year for this transition.

Net Zero Targets

Take BP, for example. In its annual statement it describes how 2020 was the year in which it began 'reinventing' the company, launched an ambition to achieve net zero by 2050, and committed to "deliver the energy the world needed." The company, which was one of the first to express interest in the alternative energy sector, as far back as the 1980s, has set out plans to grow in both the renewables and bioenergy spheres, primarily through acquisition or joint ventures with companies like leading solar energy company Lightsource and Bunge, a fast-growing Brazilian biofuels business. BP also announced that it is developing plans for the UK's largest Blue Hydrogen production facility at Teeside, targeting 1 GW of hydrogen production by 2030.

Shell has also been at the forefront of the supermajors' transition from IOC to IEC. The company likewise has a net zero by 2050 target and believes that its total carbon emissions and oil production have both already peaked. It intends to reduce net carbon intensity by up to 8% by 2023, 20% by 2030 and 100% by 2050, using a baseline of 2016, and claims to be the first IOC to submit an Energy Transition Plan for an advisory vote to shareholders at its AGM. Focusing on 'value over volume', the company expects a gradual reduction in oil production of around 1–2% each year, through both divestments and natural decline.

Eni, by comparison, is actively moving out of oil but into gas, which it soon expects to represent 90% of its hydrocarbon production, supporting the energy transition as a back-up to more intermittent sources. Exploration will focus on infrastructure and near-field opportunities in proven basins, particularly those with a high gas potential, targeting 2 Bboe of resources. The company also aims for net zero by 2050, in line with the Paris Agreement, with a target for absolute emissions of –25% by 2030 vs 2018 and –65% by 2040, to be achieved through increasing efficiency and the circular economy, plus the use of Blue and Green Hydrogen for bio-refining and other hard-to-abate activities, as well as carbon offsetting.

Energy Providers

As with the other European supermajors, Eni plans to hugely increase its electricity production – further evidence that these companies are becoming energy providers rather than oil producers. Eni plans to double its bio-refinery capacity by 2024 and by five times by 2050, while it proposes to increase its renewables capability to 4 GW by 2024 and up to 60 GW by 2050.

In a similar fashion, Total's ambition is to reach 35 GW of renewable electrical capacity in 2025 and nearly 100 GW by 2030. Like BP, Total is acquiring and partnering with many companies generating renewable electricity and is fast becoming a world leader in solar energy, with over 2,000 MW of solar assets in operation in India, more than 5,000 MW of solar projects in Spain and an 800-MW solar farm in Qatar. The company says that it aims to transform itself into a broad energy company by profitably growing energy production from LNG and electricity, which are the two fastest growing energy markets. As a result, it expects to see sales of oil products reducing by almost 30% in the next decade, so that by 2030 its sales mix will be 30% oil products, focusing on low cost oil projects, 5% biofuels, 50% gases and 15% electrons. In fact, at Total's next AGM it is proposed

SunPower Total solar power plant, Prieska, South Africa. Total is becoming a major player in solar energy developments.


© Total/Zylberman Laurent – Graphix Images

to change its name to TotalEnergies, to signify its transformation into a 'broad energy company'.

Shell and BP are also moving into the electricity supply sector, with the former stating that by 2030 it expects to sell twice as much electricity as it does today, while the latter is aiming to achieve 50 GW of renewable energy capacity by 2030. BP has also entered the electric vehicle (EV)-charging market with the recent acquisition of EV-charging company Chargemaster.

Different Approaches

While the European supermajors are falling over themselves to prove their green credentials, things are a little different on the other side of the Atlantic. US supermajors ExxonMobil and Chevron still consider that producing oil and gas rather than electricity are at the core of their business and they are confidently waiting for a post-Covid surge in both demand and oil prices, while actively investing in de-carbonizing their assets and reducing emissions.

Chevron has not stated an ambition for net zero by 2050 but expresses support for the Paris Agreement and to that end will concentrate on reducing the carbon intensity of its products. This will include the increasing use of renewables in association with its hydrocarbon assets, using offset mechanisms and and investing in low-carbon technologies that can enable commercial solutions. It has made some investment in geothermal energy and recently announced a 'pathway' toward net zero emissions in the coming decades, with new targets to lower emissions per barrel pumped by a third over the next seven years, but expects to be a fossil-fuel-dominated company for the next ten or 20 years.

Unlike its European peers, Exxon Mobil plans to up its oil production by 1 MMbopd over the next five years. The company came under a lot of pressure at the end of 2020 for failing to address climate change in its long-term policies. It subsequently announced a new five-year plan to reduce greenhouse gas emissions, including those from methane flaring and upstream operations, which it said was in line with the Paris Agreement. It plans to reduce the intensity of its oilfield greenhouse gas emissions by 15%–20% of 2016 level by 2025. The company has also created a division to commercialize technologies that help reduce carbon emissions and is concentrating on carbon capture and storage (CCS), although the funds available to this are small relative to its exploration budget. European supermajors have also put investment into CCS, but for the US companies it seems to be the main emissions reduction strategy route.

ConocoPhillips was the first US-based upstream company to adopt a net zero by 2050 strategy and is still the only one of the three US supermajors to do so, setting an emissions intensity reduction target of 35–45% by 2030, as well as forming a 'low-carbon team' to study energy transition alternatives.

Hydrocarbons in the Mix

While there seems to be quite a difference between the enthusiasm with which O&G supermajors are embracing the energy transition on either side of the Atlantic, it should be noted that, despite all the hype, hydrocarbons remain a significant part of their businesses. Energy demand is projected to continue increasing and all companies acknowledge that oil and, in particular, gas will be supplying part of that demand. While the US companies seem to be betting on demand for hydrocarbons to increase at least in the short term, to be largely supplied by shale gas with reduced and sequestrated emissions, the Europeans are turning themselves into energy suppliers – but even they acknowledge that the transformation from IOC to IEC will be paid for by the cash from their oil, gas and refining activities. Despite all its talk about investment in green technologies, a third of Shell's planned investment this year will be in the upstream sector, which it expects to provide the company with material cash flow well into the 2030s.

The supermajors all acknowledge the energy transition is coming – but the difference between the European and US companies is the question: how quickly? ■

North America

Meanwhile back in the United States and Canada… 'The World Turned Upside Down'.

ROG HARDY; NVentures Ltd

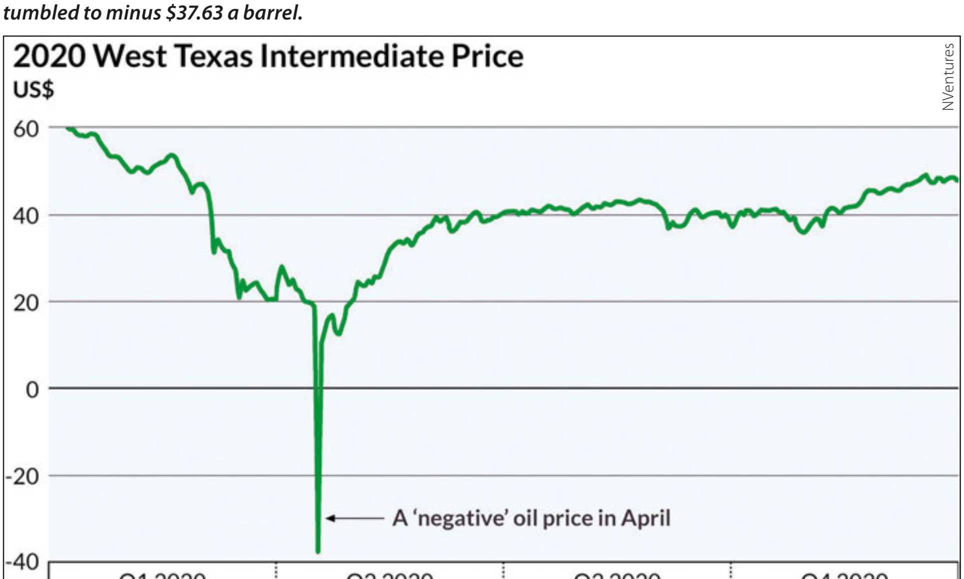
When Lord Cornwallis surrendered his British forces to the Yankees after the siege of Yorktown, ending the Revolutionary War, his band played 'The World Turned Upside Down' – an old English ballad of the day. Nothing could be truer for the US and Canadian domestic E&P community over the last year: a symbolic negative oil price blink, rig counts and production rates plummeting, a new US administration slapping moratoriums on federal land and waters while appointing 'greens' to high positions. In Canada, a liberal government, now emboldened by newly aligned policies south of the border, continues to invoke the ire of Alberta with restrictive measures. Meanwhile Texas, the energy capital of the world, is shivering in the dark, just like those bumper stickers told New Englanders to do a couple of decades ago. Traditional producers touting carbon-neutral barrels sold and endorsing a carbon market. All in all, an upstream world turned upside down.

The US and Canadian domestic upstream business has weathered many a calamity in the past, like the price shocks of Spindletop, the Depression, supply gluts and supply squeezes from overseas, and the 'shale glut'. The vibe in upstream these days is different, however. It evokes the 'end of oil' debates brought on by Hubbert's peak oil research of the mid-1950s and resultant majors' (now obviously) premature efforts to diversify. This time, however, the threatened end to life as the upstream knows it, is anthropomorphic, not 'natural'. There is plenty of oil and gas left to produce with ever-improving technology, but a heightened concern for how long demand will support this major industry. The upstream vibe is not, however, predominately doom and gloom. Upstream has the most brilliant and positive people of any industry who see challenge and opportunity in the events of the past year, as much as problems and obstacles. The shale 'revolution', enabled by innovation within this community, demanded unprecedented adaptation in domestic US and Canada, more than anywhere else on Earth. Geoscientists and engineers were defiantly able to meet these challenges. A looming 'end of carbon' moniker will not defeat this crowd.

So the past year has seen a strident move from the largest major to the smallest independent to cut carbon emissions in production and transmission and to rapidly ramp up investing in and co-venturing with start-ups in direct air carbon capture and sequestration through injection (a proven technology for enhanced oil recovery) and subterranean mineralization. Additionally, investment has been made in planning for a nationwide network of CO_2 pipelines from capture points to injection points and investment in new geothermal technology to increase the applicability of this technology. Other initiatives include 'solarizing' power generation for upstream facilities and leverage offshore technology by moving into offshore wind farms. To follow the lead from Europe, majors are also investing in Green Hydrogen in a much more substantive way. Perhaps most significantly, major oil companies are now advocating carbon trading, possibly with a view that this will be a new profit center with all the technology they can bring to bear.

And of course, with all this adaptation through resilience and innovation, activity continues. In conventional action, a busy winter drilling campaign started on Alaska's north slope by Australian and UK independents, 88 Energy and Pantheon, based on wonderful sequence stratigraphic work in Cretaceous traps with some quick success. This is tempered, however, by further major exits (BP, Shell), a legal impediment to ConocoPhillips' development work, and a lackluster showing in the last lease sale of the previous administration in the leasable portion of the Arctic National Wildlife Refuge. In the deepwater Gulf of Mexico, operators are keeping a few exploratory wells going, including Kosmos touting their short-cycle, infrastructure-led exploration near existing facilities in oil prone areas, but offshore Labrador-Newfoundland activity has ground down to bare-bones development work. On a closing note to activity, the super-resilient shale movement is holding firm in activity and production across the board, with at least talk of higher efficiencies and murmuring the old refrain "Lord, please let there be another boom … I won't mess up again." ■

West Texas Intermediate Oil Price, 2020 showing negative oil price as the future contracts for May delivery tumbled to minus $37.63 a barrel.



Geoscientists for the Energy Transition

The importance of geoscience research and training.

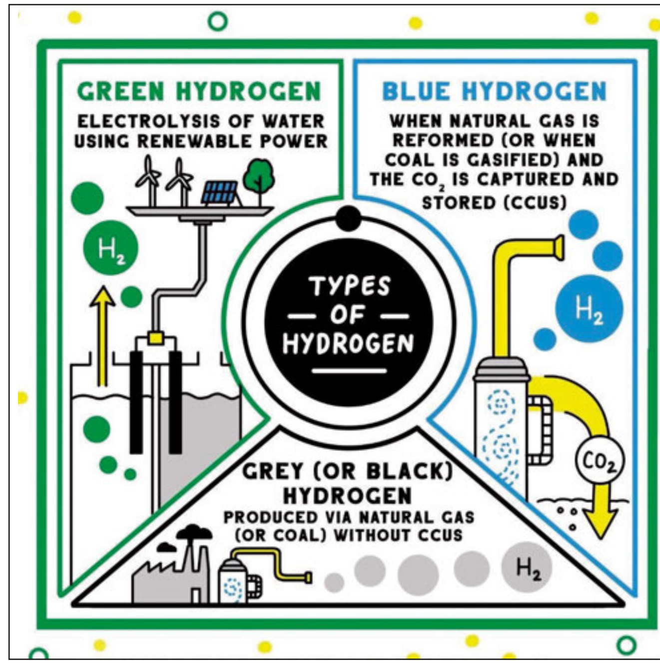
JOHN UNDERHILL; Heriot-Watt University

The industrial revolution was initially fueled by coal and the subsequent development of modern society was underpinned by oil and gas. Their use led to unprecedented economic growth and a rise in the quality of life, but it has also come at the cost of creating a carbon-intensive economy. The challenge before us now is to decarbonize, reduce greenhouse emissions and tackle climate change while simultaneously alleviating fuel poverty, meeting the energy needs of global population growth, and maintaining a prosperous, just and fair society that does not hinder developing nations. While the United Nations did not name any specific discipline, geoscience is a red thread that runs through their Sustainability Goals and has an essential role to play in delivering on these commitments.

How Geoscience will Help us to Decarbonize

Major strides have already been made in some countries to decarbonize the electricity sector with renewable sources superseding coal. There has been a drive toward hybrid and battery power replacing petrol and diesel vehicles. Doing so leads to an increased demand for a suite of raw materials (e.g. minerals and rare earth elements) for the batteries to store the energy. There is a similar need for them in the construction of the solar panels and wind turbines in power generation. Yet more are required for smartphones and other applications. Given that demand cannot be met through existing operations or recycling of materials currently in circulation, there is a need to identify new sources of critical elements, metals and minerals. Some estimates suggest that the need for metals like lithium will lead to a five- to ten-fold increase in production. The intensity of operations will mean extraction issues will have to be addressed if sustainable mining is achievable.

Parts of the energy sector like heavy industry, other forms of surface transportation, heating, cooling and aviation are far harder to decarbonize than electricity. The need to decarbonize industrial hubs is especially acute and requires the capture of emissions, transportation and their sequestration in safe and secure sites. Sedimentary basins represent obvious storage opportunities through the use of depleted oil and gas fields and saline aquifers in which fluids are trapped and transported. Inert, long-chained hydrocarbons have very different properties to carbon dioxide and the highly corrosive carbonic acid that results from its reaction with water. There is a need to test subsurface storage sites, since poor choices would undermine confidence and may lead to a promising technology not being adopted. Use of technical methods and the data acquired, processed and interpreted in the pursuit of oil and gas (e.g. seismic reflection, petrophysics, core description and pressure data etc.) are the same needed to characterize and monitor the carbon stores, meaning expertise gained in petroleum studies are well-aligned with the energy transition.



The different sources of black, grey, blue and green hydrogen. (Graphic credit: BP)

Hydrogen is being touted as an alternative fuel for domestic gas supplies and surface transportation. While some demonstrators are testing whether hydrogen can be blended into gas networks, others seek to replace the whole grid. Hydrogen is also being trialled in buses and trains as an alternative to petrol and diesel (e.g. in Aberdeen).

Historically, hydrogen needs have been met from coal or methane sources, known as Black and Grey Hydrogen respectively with their carbon emissions vented or flared. While the aspiration is to use electrolyzers to convert the electricity from wind farms to hydrogen (Green Hydrogen), the process is in its infancy and does involve putting energy in to get hydrogen out, meaning it is less efficient. Given those challenges, the transitional step being proposed is to obtain hydrogen through steam reformation of methane, which also leads to a carbon dioxide by-product (Blue Hydrogen).

Blue Hydrogen requires a close spatial association between a gas field, a safe carbon store, a hydrogen export route and hydrogen storage site, an interdependency that demands a critical evaluation of the subsurface. Blue Hydrogen as a transition fuel also underlines the continued role for indigenous gas, because local sources have a lower carbon footprint than imports and they ensure the security of supply. The absence of fields containing hydrogen suggests that its storage in porous media remains unproven. Use is currently made of man-made salt caverns to hermetically seal hydrogen. More geological stores may be needed to avoid a requirement to construct high-pressure gas cylinders at scale, but if the right sites are to be chosen, appropriate salt lithologies need to be detected.

Geothermal heat is another obvious renewable energy source. To date, efforts have concentrated on areas with higher geothermal gradients (e.g. the granites of Cornwall or volcanic areas in places like Iceland). As they are often sited in remote locations, heat loss during transportation is commonly an issue. This means an alternative ground-source for heat is required to serve large conurbations blighted by high unemployment, deprivation and fuel poverty. Since many urban areas were industrial and manufacturing centers located near coal mines, their trellised network of shafts may be a source of warm water and may provide an immediate source of low-enthalpy distinct to the needs of the stressed communities.

Existential Threat or Opportunity?

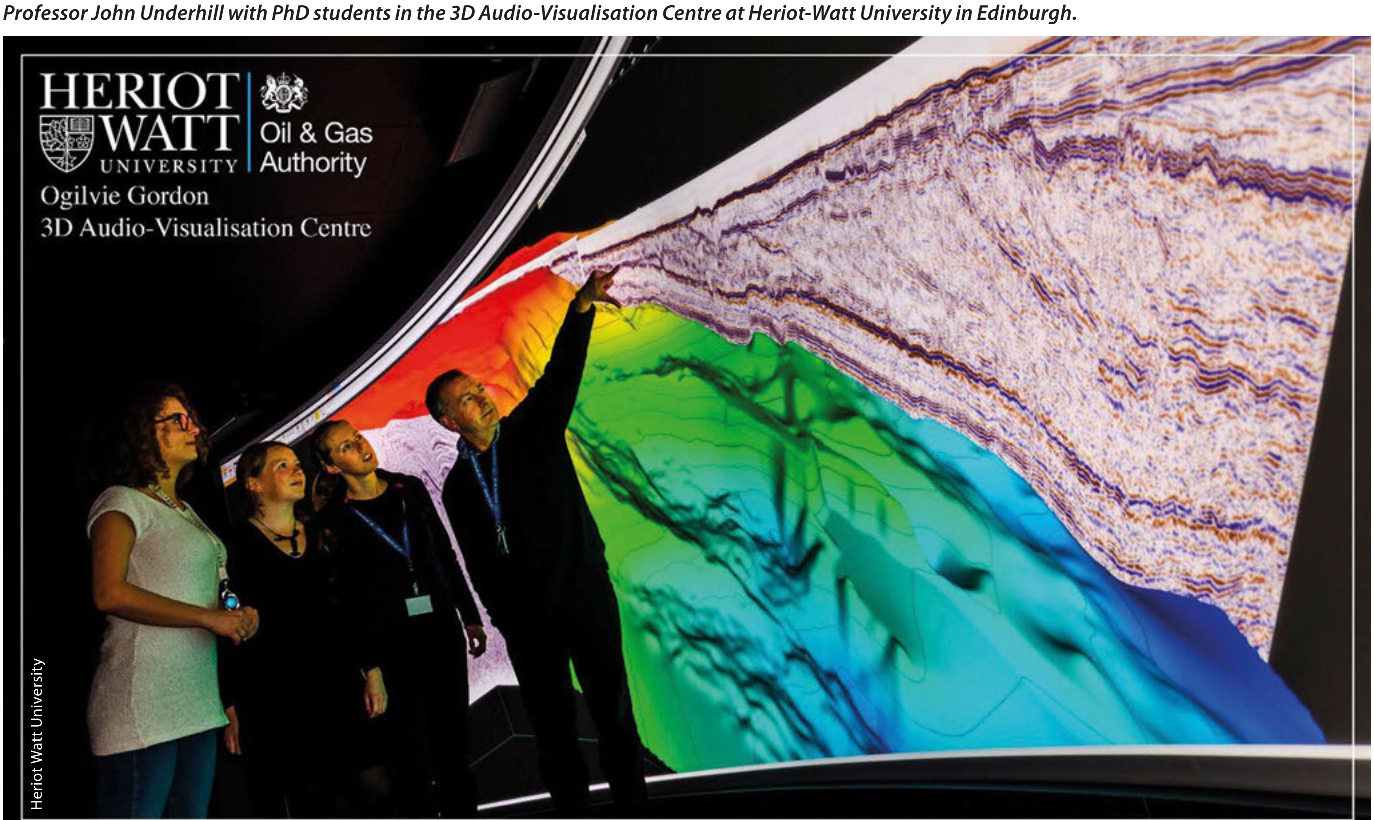
Given the critical role that geoscience will play in a low-carbon future, one would think that there would be an upsurge in interest and an appetite to undertake academic degree programs in the subject. However, all the data and evidence point to student numbers for Geology and Geophysics degrees and vocational applied Masters programs experiencing a sharp decline. In some instances, such as those in Petroleum Geoscience and Mining Geology, recruitment is at an all-time low, implying that students are finding geoscience a far less attractive career option.

One issue is the negative perception that a career in geosciences aligns with 'dirty' exploitation and extractive industries that have presented us with the global carbon problem. A second element is the demise in access, resulting from Geology being dropped from the school curriculum, making it harder for students to be introduced to, or further their interest in the natural world. Another factor is arguably a collective failure to paint the picture that shows the important role geoscience has in creating the solutions that tackle and reduce emissions.

Finally, the push for student numbers in recent years has led to an over-supply of graduates leading many to drift away from geoscience. Unless we tackle these issues, demonstrate the subject's contribution to a low-carbon future and communicate its importance effectively, a career pathway in geoscience may remain unappealing.

Efforts are underway on both sides of the Atlantic to raise awareness of geoscience and the role it plays in securing a low-carbon future. In the US, the National Science Foundation (NSF) has sought to address undergraduate geoscience education. Publication of its recent report, entitled the *Future of Undergraduate Geoscience Education,* highlighted three major tasks. It outlined the key concepts, skills, and competencies that are needed for success in graduate school and their use in the future workforce; sought to identify the best teaching practices and most effective use of technology to enhance student learning; and investigated how to recruit, retain, and ensure the success of a diverse and inclusive community of geoscience graduates and teachers to contribute to a well-informed public and dynamic geoscience workforce.

Professor John Underhill with PhD students in the 3D Audio-Visualisation Centre at Heriot-Watt University in Edinburgh.



In the UK, the Geological Society of London (GSL) have similarly been examining the issues and sought to articulate geoscience's place in addressing the key global challenges. Their work shows how the role and career pathway of the geoscientist maps on to the UN Sustainability Goals, describing career pathways that contribute to making the energy transition a reality.

A number of universities have been reviewing their undergraduate and vocational Masters (MSc) programs to see if they are fit for purpose. There is now an increasing awareness of the need to blend traditional strengths in classroom, lab-based and fieldwork with new technologies like virtual reality and novel teaching practices, something that has been an unforeseen benefit of Covid-19 and the drive for online learning in the absence of residential opportunities.

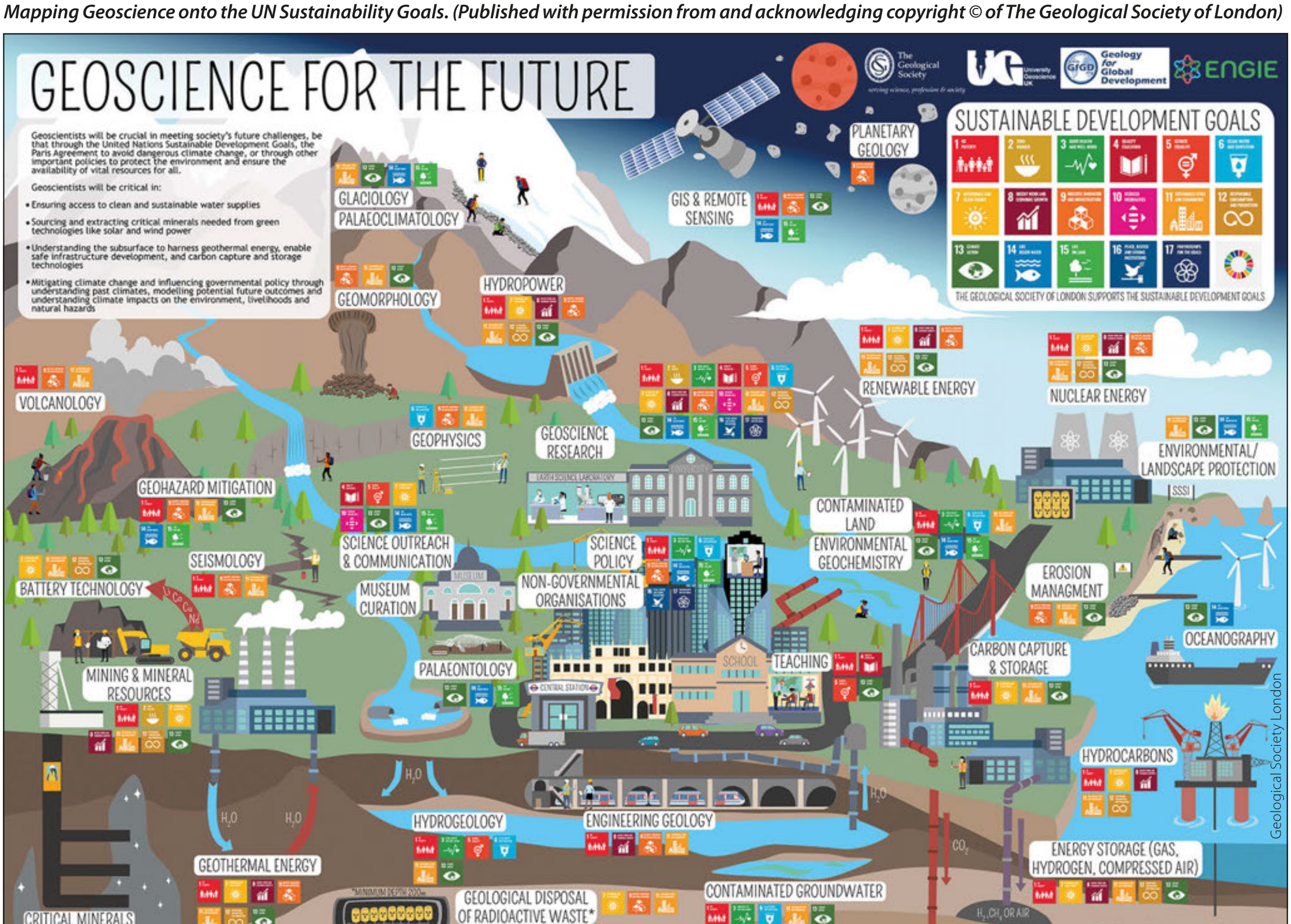
A new appreciation of the key issues associated with the energy transition and net zero have led to a change in teaching and learning content and methods to assess, accurately image, characterize, parameterize and quantify the subsurface. Where courses have been found wanting or student numbers have declined to unsustainable levels, universities are revamping them. Most notably, this has led some institutions to drop petroleum-related courses from their portfolio and others to re-evaluate what constitutes the essential component parts of their courses.

Ph.D. training and research has been particularly proactive in the Energy Transition with the launch of a Centre for Doctoral Training (CDT) in 2019. Entitled GeoNetZero (GNZ), it constitutes a Heriot-Watt-led partnership of 12 UK universities, who deliver world-class research and training that addresses geoscience and its role in the low-carbon energy transition and challenge to meet net zero emission targets. As well as undertaking Ph.D. research projects across the net zero landscape, they also receive a 20-week, GSL-accredited, industry-supported training program that enables students to appreciate the wider context of their individual projects and helps build their industry and academic networks. The CDT's purpose is to build the next generation of geoscientist practitioners equipped to meet the challenges of the energy transition and to engage and work with communities to find meaningful solutions.

Geoscience's Pivotal Role

Given our dependency on carbon and the requirement to wean ourselves off it, there is a need to ensure the Earth is in safe hands and skilled practitioners oversee the energy transition as we move to a decarbonized future. In order to do so, we need to be willing and able to make the case for geoscience, demonstrate its relevance and thereby, attract and retain a pipeline of talent. The direction of travel is clear and steps are being taken to address the current issues in geoscience training and research. The key to delivery and re-birth of geology as a valued discipline will be to show that what we do should not be characterized simply as a contributor to the climate problem, but that it has a pivotal role in society and is super-crucial in finding low-carbon solutions for the energy transition. ■

Mapping Geoscience onto the UN Sustainability Goals. (Published with permission from and acknowledging copyright © of The Geological Society of London)



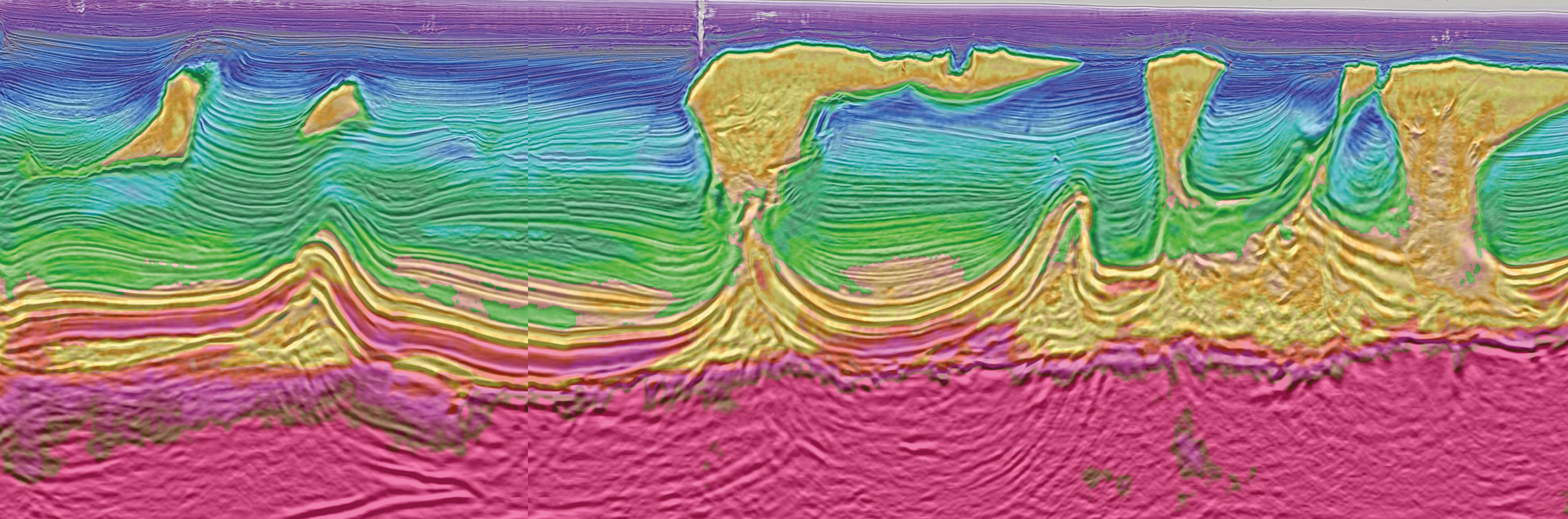
Ultra-Long Offsets Signal a Bright Future for OBN

Results from the ultra-long offset Amendment survey in the Gulf of Mexico demonstrate a step-change in high-resolution velocity model building from shallow to deep.

The US Gulf of Mexico (GoM) has always been one of the main engines for driving technical innovation in the offshore oil and gas industry. TGS's Amendment Phase 1 is the latest proof positive of this. This ultra-long offset sparse node survey was optimized to acquire full azimuth 40 km offsets, one of many industry firsts achieved by this survey. The combination of a velocity model update and long offset, full azimuth imaging, has begun to unlock previously unimaged parts of this complex salt basin. Industry acceptance that this approach will drive exploration and field development in the GoM for years to come, is rapidly growing. This development poses an interesting question: Could this survey provide a window into the future of seismic surveys in other mature basins?

TGS

The OBN survey, named Amendment, was acquired in the Mississippi Canyon area of the Gulf of Mexico.



Gulf of Mexico, a Proving Ground for OBN Technology

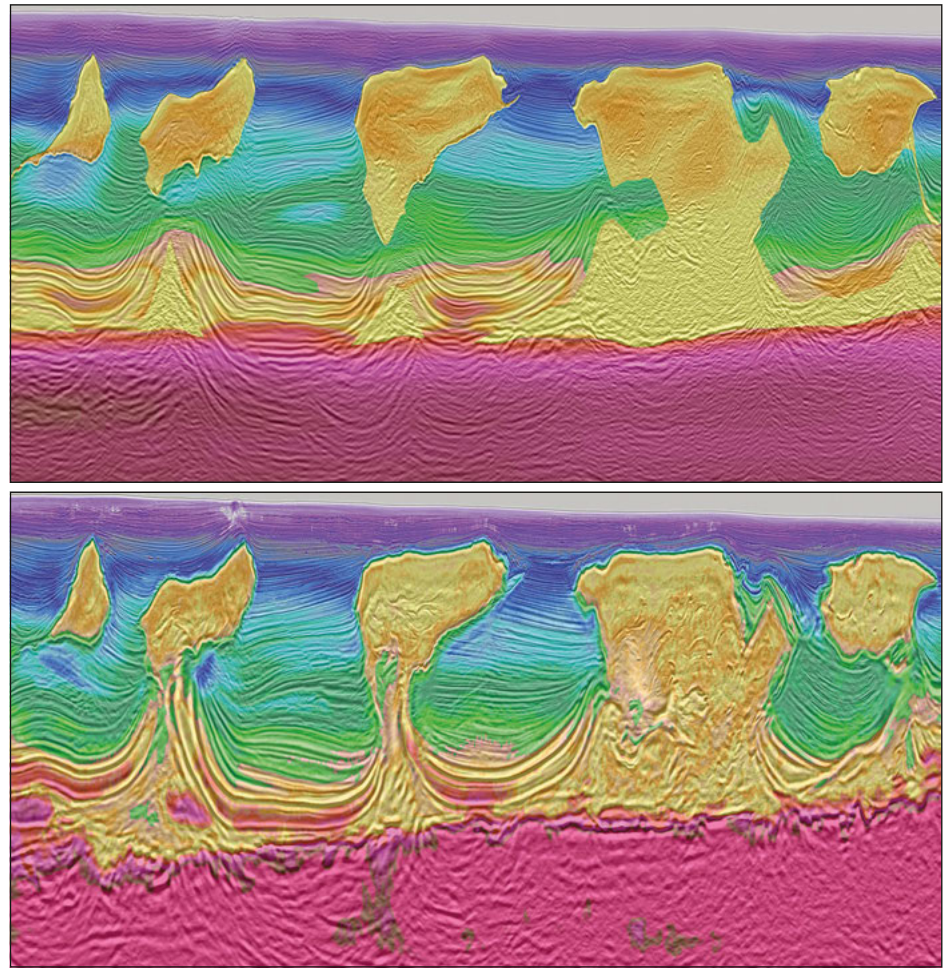
DUNCAN BATE and MIKE PERZ; TGS

Survey Design and Capture

It has been well understood for decades that Full Waveform Inversion (FWI) techniques can recover velocity information from seismic refraction and reflection data. Since the Wide Azimuth (WAZ) seismic acquisition in the US Gulf of Mexico (GoM) in the early 2000s, exploration teams have been gradually refining the velocity model with successive iterations of reprocessing. Each new update to the model has yielded an improved image. But the WAZ data lacked the offsets to use refraction-based FWI techniques at the depths of interest.

The Amendment Phase 1 survey, undertaken by TGS in partnership with WesternGeco (Schlumberger), was acquired in water depths of up to 2,070m and covers 118 OCS blocks (2,765 sq km) The acquisition took place between April and August 2019. Before acquisition, survey design modeling resulted in a 1 km by 1 km receiver spacing and a source grid of 50m by 100m. Refraction information from the Louann level at about 15 seconds TWT, or approximately 12 km, was predicted to require at least 25 km offsets and >30 km in some geological settings. The new ultra-long offset refraction information was specifically acquired to help drive FWI methods to the correct velocity model and overcome larger errors at greater depths than before.

The legacy velocity model (top) was derived from a traditional top-down interpretation and tomography driven workflow. The updated DM-FWI model (lower) shows the velocity model is more conformable to the geology and the reflection image is greatly improved.



Through this pioneering survey, many crucial lessons have been learned. Most Ocean Bottom Node (OBN) work was historically undertaken with node spacing of only a few hundred meters. Pushing the node spacing over 1 km required a whole new approach. The time spent tripping the Remote Operated Vehicles (ROVs) vertically in the water column is far less important, and conversely, the time taken to fly the ROVs between node locations becomes far more critical.

When large offsets are essential, it is hard to get away from the fact that many shot locations need to be acquired. Simultaneous source acquisition has been pushed further with either three dual-source vessels or two triple-source vessels. This requirement results in a vast quantity of raw data (1.5 Petabytes), which demanded new seismic imaging techniques to be applied and necessitated the development of a sophisticated new method of velocity model generation. Dynamic Matching, Full-Waveform Inversion (DM-FWI), used here for the first time, created a high-resolution velocity-model update that focuses on solving the kinematic difference between synthetic input data.

DM-FWI Brings Greater Subsurface Knowledge

Dynamic Matching, Full-Waveform Inversion (DM-FWI) is an iterative technique that uses seismic reflection and refraction information to enable a unique workflow to update the velocity model. The technique was designed to overcome many of the limitations of standard FWI, such as cycle-skipping, which can cause erroneous model updates and therefore, incorrectly imaged seismic data. The velocity model's data residual (the differences between observed and predicted values) were calculated in localized windows in time and space. This method produced a robust model update using the data's total energy, including refractions and reflections.

The result is superior, geologically coherent velocity models, improved subsurface analysis, and reduced uncertainty. Together, these benefits enable the end-user to cut their cycle-times and costs, in addition to their risks in complex imaging areas, particularly sub-salt.

The application of DM-FWI to the Amendment dataset with its ultra-long offsets shows the technique's capability to resolve large velocity errors and provide significant imaging uplift.

Crucially, the inversion-based algorithm can reduce imaging cycle-time and interpretation ambiguity. It works in tandem with new survey designs for ocean-bottom nodes and is also applicable to modern towed streamer survey designs.

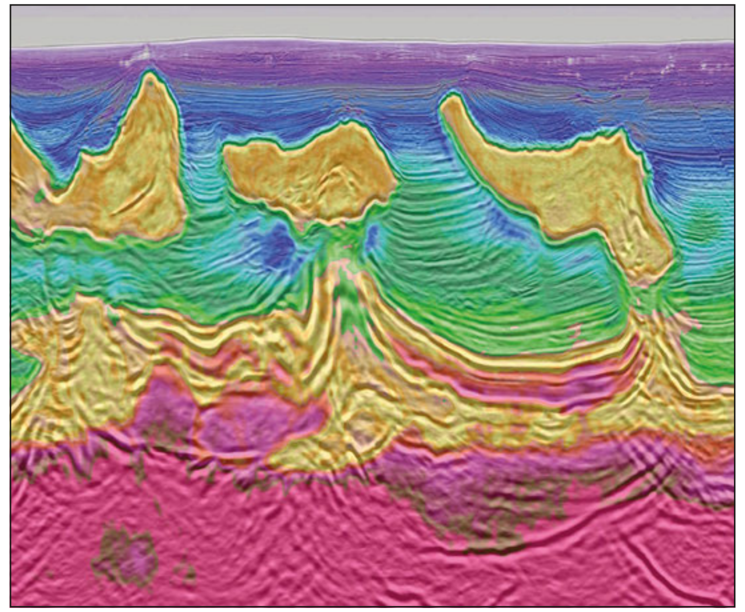
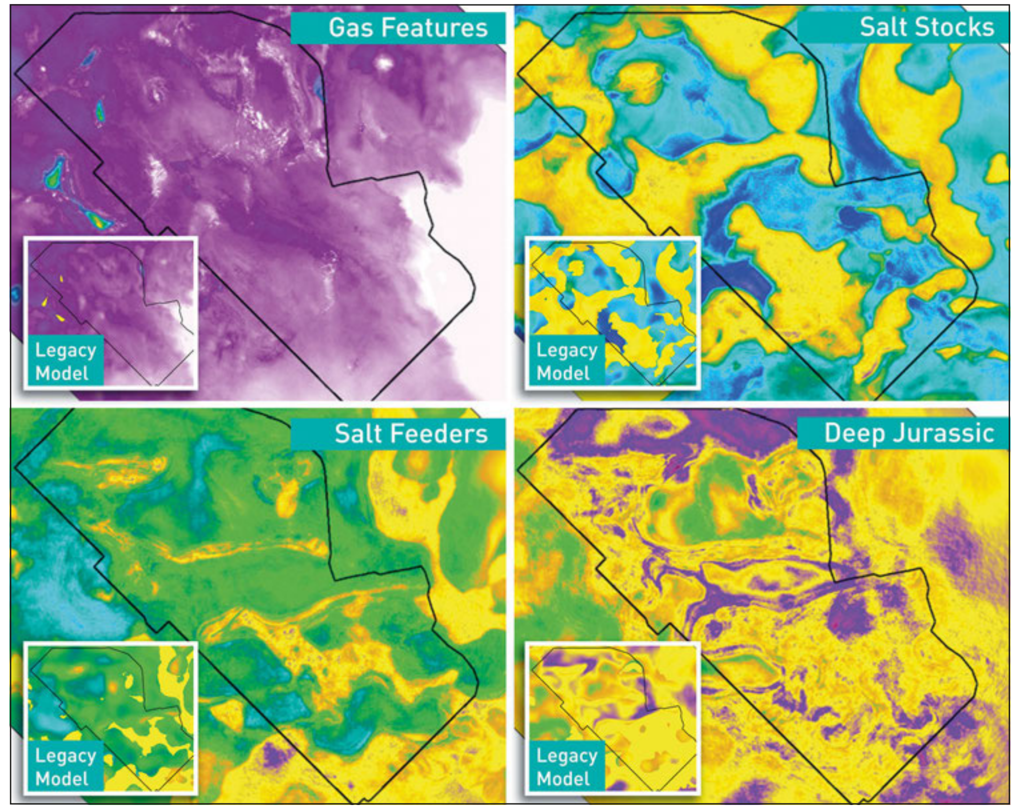


Image shows the velocity model derived from DM-FWI using the ultra-long offsets recorded as part of Amendment.

Slices through the velocity model at different depths show that the DM-FWI-derived model is highly conformable to geology. The new model has helped identify and map new features, like the salt feeders, throughout the section.



Amendment Was Just the Start

The combination of existing OBN technology, innovative survey design, and DM-FWI technology is a real step-change in high-resolution model building from shallow to deep. Following the success of the Amendment project acquired in Mississippi Canyon in 2019, TGS has completed the Engagement project, also in collaboration with WesternGeco (Schlumberger). This phase has extended the footprint of ultra-long data in the Northern Green Canyon protraction area.

Both the Amendment and Engagement projects represent a new generation of survey design and open up significant opportunities, both in the Gulf of Mexico and elsewhere, for improved subsurface analysis. There are many other parts of the world with challenging imaging conditions that could benefit from an approach similar to Amendment and Engagement. ■

Behind the Hybrid Curtain

The rise of mixed turbidite–contourite hydrocarbon systems.

KARYNA RODRIGUEZ and NEIL HODGSON; Searcher

Hybrid sedimentary systems develop where drift or coast parallel bottom currents interact with turbiditic or gravity-driven flow. There will be few places where this interaction doesn't occur, but the dominance of one type of flow over the other is hugely variable around the margins of the world's oceans and has been through time. In the oil and gas industry we have employed a default turbidite mindset to understand deeper water clastics for two main reasons, scale and sample bias.

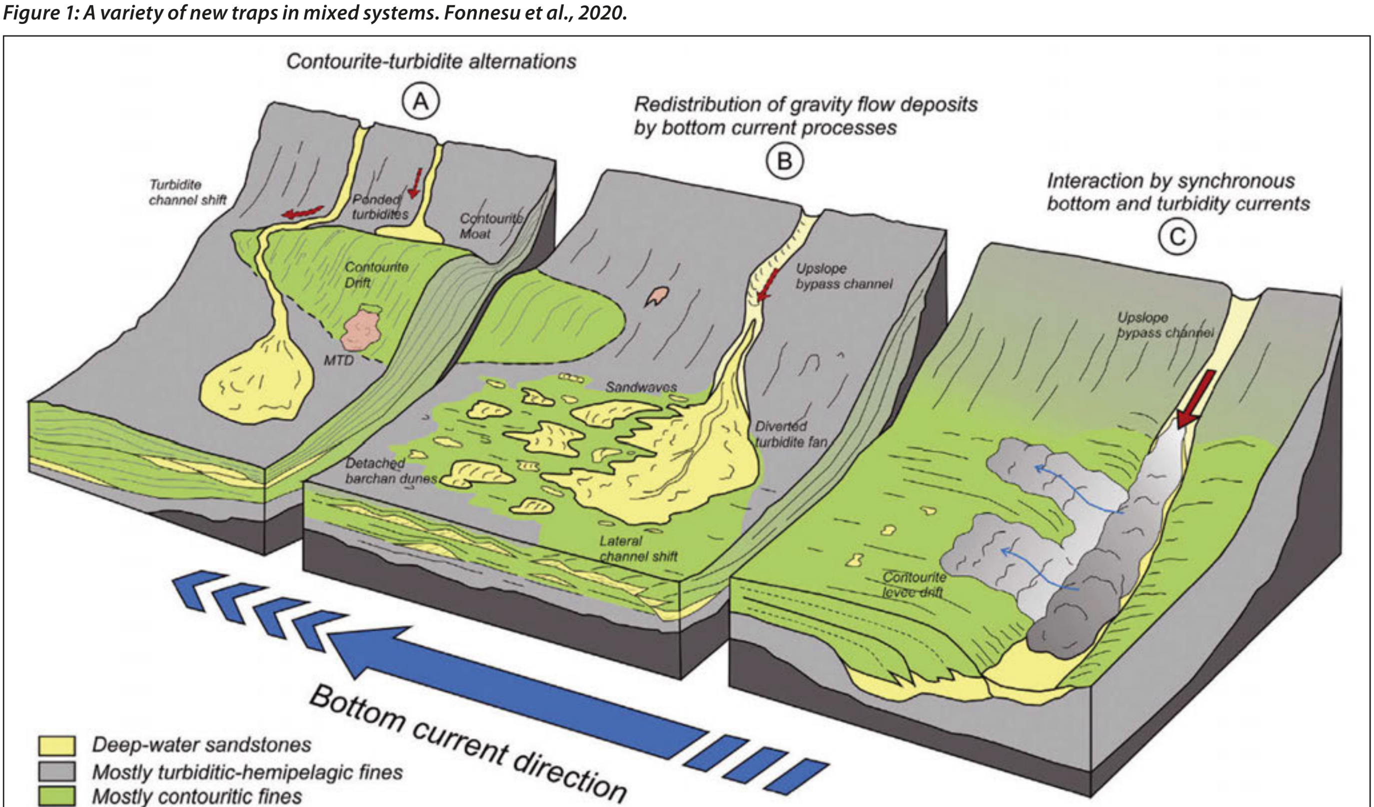
Contourite and hybrid deposits have been studied for decades, for example Stow et al., 1998, Mutti et al., 1980, 2014, Rebesco et al., 2014 and Hernandez-Molina et al., 2008. Yet in the exploration world we did not have to embrace these concepts fully until recent discoveries forced us to bridge an enormous gap in deepwater sedimentology, between what is recognized at outcrop and what is observed on seismic data.

Hiding in Plain Sight

The effects of contourite systems on deepwater sediments can be subtle or even cryptic at outcrop scale. Deepwater shales, in particular, can look conformably bedded over hundreds of meters of outcrop. Slope channels may conceal the signs of contourite activity as they are dominated by basin-ward dip, incision and construction, and basin floor fans may have few current indicators to denote current flow direction on the basin floor. For this reason, global outcrops demonstrating clear contourite deposition are conspicuously rare in comparison to the number of examples visible on passive margin, regional seismic data. Either there is a problem preserving such margins in the outcrop record, or it is difficult to recognize them. Of course, explorers looking for coarse clastic reservoirs are also drawn to fluvial input points, where flow from slope to basin floor is often dominated by currents flowing downslope: turbiditic flow. This introduces a sampling bias, in that turbidite-dominated sequences appear to adequately characterize the deepwater geology that explorers have been concerned with, without the need for consideration of the influence of contourite currents.

However, in recent years the availability of high-quality regional scale seismic images has drawn attention to the frequent presence of contourite-dominated bedforms. This mismatch between seismic expression and field studies could perhaps have been swept under the carpet; however,

Figure 1: A variety of new traps in mixed systems. Fonnesu et al., 2020.



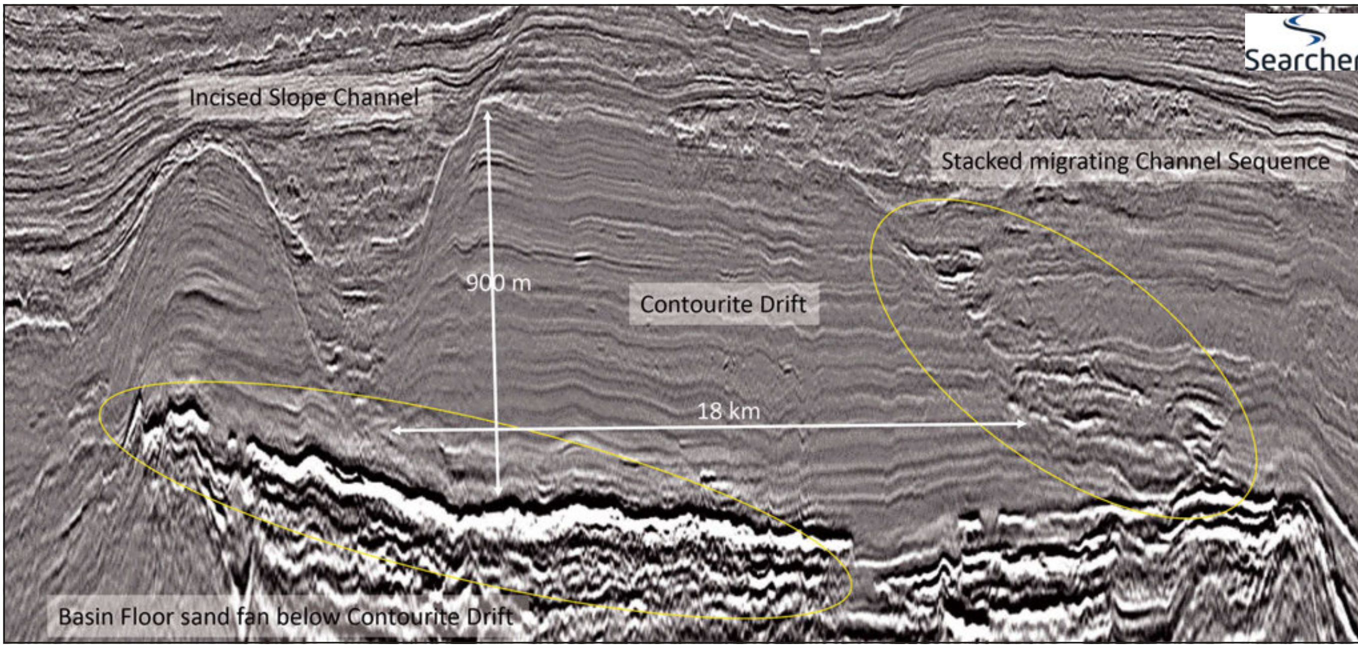


Figure 2: Hybrid migrating channel system (on right-hand side) from offshore Mexico (Courtesy Searcher). This stacking style is analogous to Rovuma. Note beneath the drift is a large bright soft reflector interpreted to be a sandy basin floor fan that the shale contourite drift has migrated over creating a reservoir-seal pair.

several recent notable discoveries in contourite-dominated sequences have required a re-evaluation of the importance of contourites' influence on deepwater exploration models.

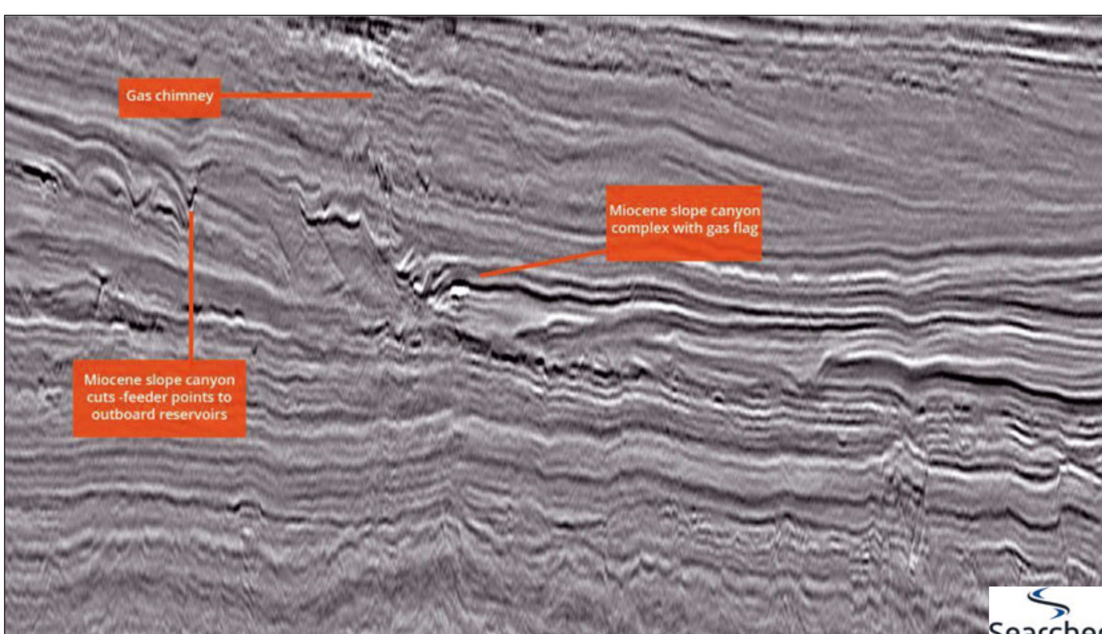
In a brilliant paper which catches the particular trapping style of the supergiant Coral gas accumulation, offshore Mozambique, Fonnesu et al., 2020, describe a number of ways that turbidite currents may interact with contourite currents to create new plays. On the left of Figure 1 (A), turbidites running down the slope (or across the basin floor) bump into contourite drifts, either depositing sand in the updip drift moat or causing the turbidite channel to meander around the drift. In the centre of the diagram (B), coarse-clastics move to the basin floor and deposit as fans, but these are redistributed by high-velocity bottom currents, creating isolated sand dunes (Mutti et al., 1980) and one supposes, migrating sand waves.

On the right-hand side of Figure 1, (C), a contourite current interacts with a turbidite flow whilst it is running down the slope, stripping away the cloud of fine mud in the flow with which it builds the far levee (generating asymmetric levees), and/or new mounded or sheeted drifts off-channel, leaving high net-to-gross sands behind. The action of these latter currents in a constructional slope setting forces the channel to migrate laterally, setting up traps and seals. There are many excellent examples of this from many margins of the world, including offshore Mexico (Figure 2) and the Malvinas Basin in Argentina (Figure 3).

Spotting 'Hybrids' on Seismic

The identification of hybrid systems relies on the recognition of a series of diagnostic criteria derived from the integration of observations (Sansom, 2018). Yet, once you get your eye in, it is hard to interpret a deepwater regional seismic line without spotting contourite influence. There are several possible

Figure 3: Hybrid migrating channel system (Miocene slope canyon complex) from the Malvinas Basin, Argentina.



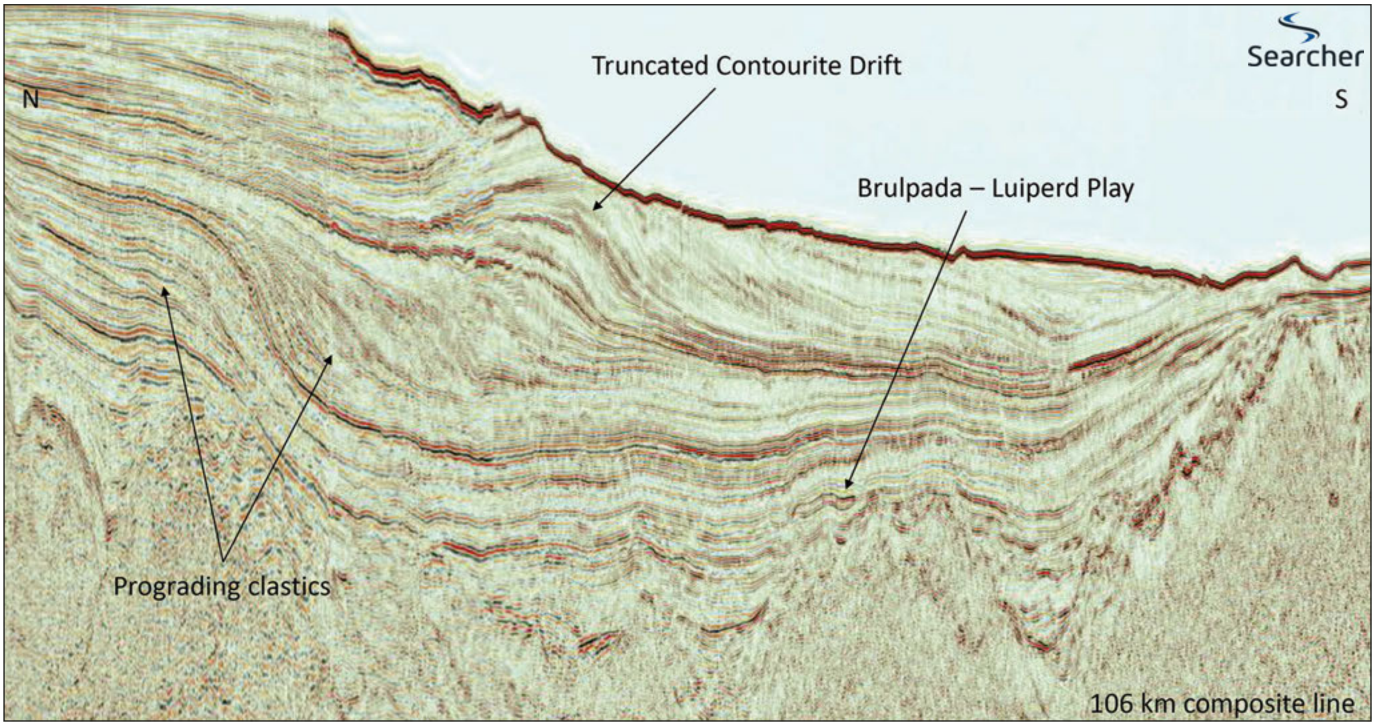


Figure 4: Giant (truncated) contourite drift, South Outeniqua Basin, South Africa. Note the bright, soft reflectors beneath the drift which again illustrate a potential reservoir-seal pairing.

contourite manifestations that have been described due to the mixing of sediment input direction, slope and basin topology, clastic grain-size and orientation.

Visible in seismic sections are different styles of drifts; either mounded when they can be of giant size (Figure 4) and either isolated or nested, or drifts that are slope-leveed or sheeted (plastered, or abyssal). Drifts are commonly comprised of silt or shale and represent the resting place for the fine-grained material shed into a basin. In the example from Mexico shown in Figure 2, a fine-grained drift has been deposited over a basin floor fan creating a classic reservoir-seal pair. This relationship is also visible on Figure 4 in the South Outeniqua Basin of South Africa and has been reported in many other contourite-influenced margins.

What is less visible on seismic is the result of clastic sediment enhancement by winnowing of fine material from turbidity currents. To deduce the possible effect of these, we need to look for the channels that move against the current, driven by contourites building levees downdip.

On the slopes of the Malvinas Basin, we observe constructional channel sand systems between large silt- and mud-rich drifts showing a distinctive crab-wise migration through time (Figure 3). In equivalent sequences in Rovuma, the quality of sand is particularly high in these drilled systems as the fines have been removed from the gravity flow and deposited around the channels as silt- and mud-rich levees and drifts.

These migrating channels (see Figure 1, C) are key in detecting the influence of contourites, and the winnowing of fines is the absolute product of this influence. A deposit of high sand content reflects more effective winnowing by contourite currents, which is often seen to be associated with a higher amplitude in the axis of the channel. Indeed, in the Tano Basin of Ghana, the tell-tale westward stepping stacking of channels in the Tweneboa, Enyenra, Ntomme (TEN) Field is due to contourite flow across the channel during deposition. The high quality of the sand in these channels will, at least in part, be due to this influence. Whereas in the past the sand content of the channel system may have been ascribed to the sand content of the sediment mix forming the turbidite flow, we now suggest that high sand content channels may have been enhanced by contourite activity, and lower net coarse-clastic content component channels have not.

This is interesting because contourite currents are not constant in time or constant down any given slope. Episodic activity through time reflects a variety of controls from the way oceans communicate, such as the opening of gateways to climatic controls such as atmospheric CO_2. Variation in contourite strength and even direction downslope, reflects the stratification of oceans with depth into 'slabs' of water of varying density (defined as isopychnal units). Practically, it means that a turbidite being winnowed upslope may not continue to be winnowed downslope, or vice-versa. This complicates but does not preclude using the presence of contourite activity to correlate stratigraphically.

A common visualization of contourite coarse clastics, are prograding units on the basin floor that comprise contourite sand waves. These occur where high-energy currents cross the basin floor and interact with basin floor sand fans. They are so striking that often they have been interpreted as prograding deltaics, but they actually represent deepwater and ultra-deepwater sand deposits. The recognition of these sand wave bodies can be astonishingly fruitful for explorationists, as they are often very thick (500–700m offshore Uruguay) and having been winnowed and redeposited, may comprise sand-rich units.

Do Contourites and Mixed Systems Help Explorers?

Key examples of prolific discoveries associated with hybrid turbidite–contourite systems include the Rovuma Basin, offshore Mozambique (Mamba Complex 85 Tcf), the Tano Basin, offshore Ghana (Jubilee and TEN Fields), the Fan-1 discovery, offshore Senegal, the Tortue and Orca discoveries, offshore Mauritania, the Yakaar discovery, offshore Senegal and the Barra Complex discovery in the Sergipe Basin, offshore Brazil (Barra complex, 3 billion STOIIP). None of these accumulations could have occurred if these deposits had not been shaped by contourite currents.

Hydrocarbon system elements analysis considers the presence, effectiveness and timing elements of source, reservoir, trap and seal. In this framework, the influence of contourite currents is particularly pertinent to reservoir effectiveness, trap and seal. Such analysis using regional seismic datasets, has led to the identification of a series of undrilled hybrid-system plays offshore Mexico, Peru, Argentina, South Africa and Papua New Guinea. The huge potential of these trapping systems indicates that this depositional system will now comprise a focus area for deepwater exploration globally.

Due to scale, sample bias and a lack of necessity, 'hybrid' turbiditic–contouritic sedimentary systems are only just beginning to be recognized as a significant new breed of exploration targets. Both, what can be seen on seismic (contourite influence bedforms) and what is inferred from contourite activity (winnowed turbidites yielding high net-to-gross sands in reservoir targets), is proving to be an essential tool in identifying these exciting hydrocarbon trapping systems.

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Nimble Nodes

AMINE OURABAH; STRYDE

Tiny seismic nodes making high density land seismic accessible to all industries.

Seismic acquisition has seldom seen such challenging times, especially onshore, where we are seeing tighter budgets and tougher environmental restrictions, whilst still requiring denser surveys and a faster turnaround of subsurface information. This situation is affecting all industries looking to acquire seismic with conventional systems.

Cable systems have dominated the seismic acquisition market for many decades, but their bulkiness and cost have limited the receiver density needed to achieve the required image quality, especially in difficult terrains or urban environments. Line preparation for laying the cables, often involving vegetation cutting, a practice that seems so contradictory to today's environmental values, is often the only solution to move bulky systems around, with their associated safety risk, environmental impact, and cost.

Cable-less autonomous nodes are natural successors for cable systems, and removed some of those constraints, but were still not small, light, and low cost enough to enable them to release their full potential in any terrain at any scale.

The Race for Denser Surveys

Higher trace density seismic surveys have been associated with a better definition of the subsurface for several decades, whether in terms of imaging or seismic attributes which are ultimately linked to rock and fluid properties (Ourabah et al., 2015). Trace density is defined by the number of pair source-receivers per unit of surface and can be increased by either increasing the source or the receiver density. In the last decades, the oil and gas industry has recognized the value of increasing trace density, and seismic surveys of tens of millions of traces per km^2 are gradually becoming the norm. This has been achieved by increasing either source efficiency or receiver channel counts to their limits.

If we look at how conventional surveys have evolved to higher densities on the source side in the last few decades, we can see that conventional vibroseis source fleets have been 'scattered' and replaced by denser single point sources, often using some flavor of simultaneous shooting schemes, bringing an increased autonomy, and delivering considerable efficiency compared to conventional source fleets (Howe et al., 2008).

The receiver side however, which often uses geophone arrays, or bulky and expensive nodes, has lagged behind, slowing down the survey as they are unable to match the speed of these new, fast-moving sources. The same philosophy needed to be applied to the receiver side. Arrays had to be replaced with independent, single point receivers and distributed on a much denser grid. However, this was difficult to achieve at scale with existing technology, as the sensors had to be smaller, lighter, and sufficiently autonomous to allow this explosion of receiver count to reach its full potential.

Industry Consortia

Fully autonomous nodes seemed to be the natural successor to cable systems in this journey toward denser receiver configurations. Early nodes were too expensive to be used in dense arrangements as they included a significant dead weight, bulky casings, limited autonomy, as well as restricted ability to charge and harvest data from large numbers of nodes simultaneously. The most recent nodal systems showed improvements in size and battery life (Dean et al., 2018) but were still not nimble enough to achieve the vision of an unlimited channel system that could efficiently acquire dense seismic in any environment. To answer this specific challenge, BP, in collaboration with Rosneft and Schlumberger, developed a new nodal system referred to in their publications as the 'nimble node' (Manning et al., 2018).

During the development phase, several field trials were performed in different environments and serving different purposes (Figure 2). The main ones being a 2D field trial in in the United Arab Emirates in 2017, comparing this nodal system to three existing commercial cable systems. This trial demonstrated the efficiency of the new system as well

Figure 1:The STRYDE node.

Figure 2: Deployment of the STRYDE nodes in a Taiga forest (left) and a desert environment (right).

as delivering identical seismic quality on a sensor-to-sensor basis (Ourabah et al., 2019). The next trial in 2018, was the first 3D survey with this 'nimble' nodal technology and was used in a production survey in West Siberia adjacent to a 12-geophone cable array system, and delivered outstanding data resolution compared to the cable system (Brooks et al., 2018). This field trial not only demonstrated the efficiency and robustness of this nodal system in an extremely cold and forested area but also its potential health, safety and environment, time and cost benefits by reducing line preparation and tree cutting for laying receivers.

World Record

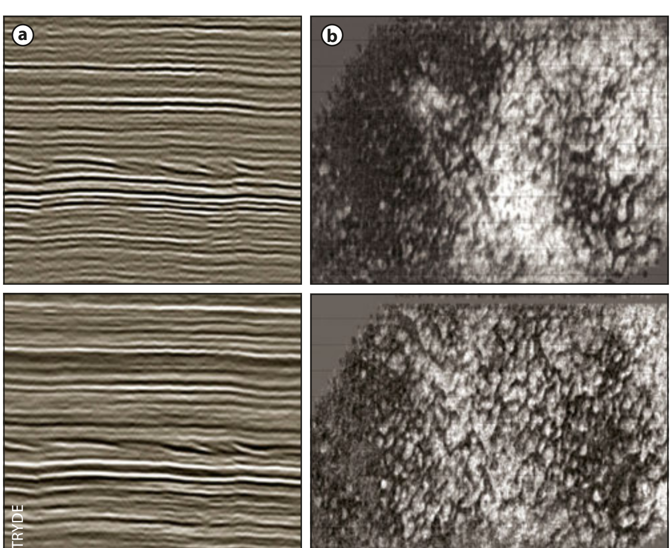
The last trial of the research and development phase was a large-scale 3D field trial completed by ADNOC in the United Arab Emirates in 2019. This was the densest nodal land seismic survey in the world, achieving a staggering 184 million traces per km^2 using about 50,000 nodes. Half a million deployments were performed in just over 50 days, where a crew of 36 people deployed and retrieved 10,000 nodes per day at an average speed of 15 seconds per station (12.5m interval). Single operators rotated between 10,000 and 20,000 nodes per day through the containerized cleaning, charging and data harvesting system. Thanks to the density achieved, the seismic delivered a significantly improved resolution at a deep target level (Ourabah and Crosby, 2020) (Figure 3).

Following these successful trials, BP established a new company called STRYDE to bring the nimble node technology to the broader seismic community with the ambition to make high density land seismic accessible to all industries.

Opportunity in a Pandemic

The new company was created in August 2019, a mere six months before the Covid-19 pandemic hit. 2020 was certainly an 'interesting' year to introduce a new nodal system to the seismic industry. The upstream oil and gas industry was already going through very difficult times even before the added uncertainty of a global pandemic. This situation

Figure 3: a) STRYDE PSTM Stack (bottom) vs Legacy Cable (top) from the large-scale field trial. b) Time slices at 900ms from the 3D test in Siberia, top: 12G arrays at 50m, bottom: STRYDE node at 5m; c) Operational results from the large-scale field trial, top: 15 sec per station (12.5m) average deployment and retrieval speed; bottom: 10,000 nodes deployed, and 10,000 nodes retrieved per day.



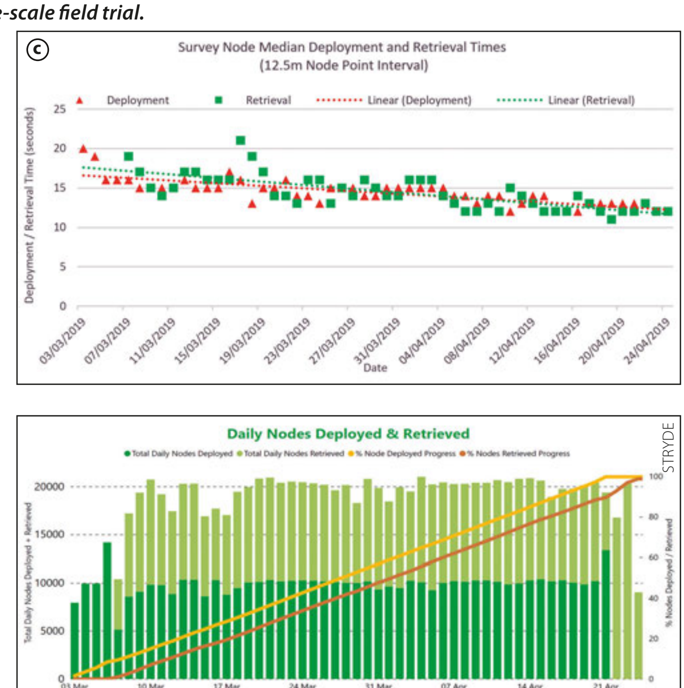


***Figure 4:** The Nimble System used for geothermal and seismic risk surveys in Europe.*

did present an opportunity for STRYDE to focus on other industries which were still using seismic but were less impacted by a weak oil price.

Geothermal was one of the first industries outside of oil and gas to understand the benefits of this system. This industry faces the same imaging challenges as oil and gas exploration but suffers from restricted acquisition geometries due to cost and access to urban and semi-urban areas. Smaller, lighter, more discrete nodes were therefore ideal to overcome these challenges, especially in reducing the crew size, which aligned perfectly to the new safety restrictions imposed by the pandemic.

This opportunity allowed STRYDE to adapt its system, which was initially targeting ultra-high-density surveys using several hundreds of thousands of nodes. They designed a new variant called the Nimble System (Figure 4), a modular and compact version for acquiring 2D or small to medium 3D surveys with up to 50,000 nodes. This variant, also used as a demo system, was very easy to ship around the world for trials in America, Europe and Asia and was typically tested against other nodal systems. These trials have delivered superior operational results and equivalent or better images of the subsurface. Before the company's first anniversary, the system had already been used for four geothermal surveys in France, Belgium, and Switzerland, as well as mineral exploration, seismic risk, micro-seismic and even archaeological surveys. STRYDE has also taken the opportunity during 2020 to collaborate with universities looking at using low-cost sensors for passive seismic and motion studies.

The company and its clients have successfully embraced remote support when traveling was restricted due to Covid-19, highlighting the importance of making this nodal system simple and intuitive to use. Oil and gas seismic projects have since started resurfacing and at the present time, more than 170,000 STRYDE nodes are used across various industries.

Energy Transition

Industries critical to the energy transition, such as geothermal, carbon capture, helium and hydrogen storage and exploration, are expected to play a key role in the new low carbon world. They will need access to the best quality subsurface information in order to achieve their goals and with the focus on renewable energies, this new nodal system will surely have a part to play.

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Alaska Anxiously Awaits its Fate

Largely dependent on the oil and gas industry, the state awaits a new administration's decision on drilling on federal land.

HEATHER SAUCIER

On the North Slope's National Petroleum Reserve – Alaska, or NPRA, a 'land rush' was expected during an early 2021 federal lease sale, as described by Senior Research Geologist, David Houseknecht of the U.S. Geological Survey (USGS). Of the 18 million acres made available for the sale by the Trump administration, 7 million included the highly prospective Teshekpuk Lake area, acreage that has rarely or never been leased.

However, all came to a halt in January when the Biden administration, known for its adverse attitude toward the industry, swooped in and suspended all lease sales on federal land for further review.

While that move was expected, it has made many question the fate of NPRA and, in a much broader context, how a strategic shutdown of oil and gas projects and infrastructure, such as the Keystone XL pipeline, will ultimately affect the country.

New Life on the North Slope

They may be in a remote, often forgotten part of the world, but operators on Alaska's North Slope reclaimed center stage after a recent series of significant discoveries, both in and adjacent to NPRA. NPRA is a 23 million-acre site set aside by the federal government a century ago for its known petroleum value (and modified in 1976 to protect environmentally sensitive areas, such as Teshekpuk Lake).

After the excitement from the historic discoveries of Prudhoe Bay in 1968 and the Alpine Field in 1994 subsided, the North Slope remained relatively quiet for nearly two decades until new discoveries were made in stratigraphic traps in the Cretaceous Nanushuk and Torok Formations.

In 2013, Armstrong Energy and Repsol announced 1.2 billion barrels of recoverable oil from its Pikka discovery, just to the east of NPRA. That was followed by ConocoPhillips' 2016 Willow discovery in NPRA, which is thought to contain up to 750 million barrels of recoverable oil.

The USGS immediately updated its assessment of the North Slope's resources in the Cretaceous Nanushuk and Torok Formations, including state waters and NPRA. In 2017, it estimated that there were mean undiscovered, technically recoverable resources of 8.7 billion barrels of oil and 25 Tcf of natural gas. According to the assessment, the estimates are "significantly higher than previous estimates, owing primarily to recent, larger-than-anticipated oil discoveries."

Essentially, prospective acreage in northern NPRA extends across 400 kilometers from east to west, Houseknecht said.

Buoyed by the possibilities, lease sales on the North Slope, in particular NPRA, soared, bringing in \$11 million in 2019, a steep jump from the \$1.5 and \$1.1 million raised in 2018 and 2017, respectively.

The 2021 sale was expected to be even more lucrative with the inclusion of areas near Teshekpuk Lake.

With the Pikka and Willow discoveries to its south-east and known oil seeps from the Nanushuk Formation to its north-west, the Teshekpuk Lake

Trans-Alaska Pipeline System

Location map showing NPRA and ANWR areas.

area is no doubt in the middle of a major hydrocarbon fairway. Yet, it has been designated a 'Special Area' by the U.S. Bureau of Land Management because it is a critical breeding ground for migratory birds, a calving area for caribou and the largest lake in Arctic Alaska that allows for fishing in winter months.

Many conservation groups believe this land should remain off limits.

"There are some places in NPRA that have globally significant ecological values and are culturally irreplaceable," said David Krause, assistant director of The Wilderness Society in Alaska. "None of Teshekpuk Lake Special Area should be leased."

In addition to the Teshekpuk Lake area, about 6 million acres in western NPRA, also included in the 2021 lease sale, are now thought to be prospective, and operators are hungry to acquire its acreage.

"Seismic data across the entire North Slope and western NPRA shows the potential for new resources, said Renee Hannon, a consultant and former

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Geologist describing sandstone in the Nanushuk Formation along the southern boundary of NPRA.

Alaska Onshore Exploration and Geoscience manager for ConocoPhillips from 2000–2017. "The Pikka and Willow fields contain shallow marine sandstone, good reservoir properties, good flow rates, are at reasonable depths, and contain light oil," she added. Both are located near existing infrastructure and will ultimately feed into the Trans-Alaska Pipeline System, or TAPS. "This is why people are so excited," Hannon explained.

"I wouldn't be surprised to see additional discoveries in the Willow to Pikka size range," Houseknecht said. "There are many, many, many anomalies in seismic data just like those associated with Willow and Pikka that have not been tested."

Trans-Alaska Pipeline in front of Albian-Cenomanian strata of the upper Torok and Nanushuk Formations (contact at base of lowest prominent sandstone bench), exposed on Marmot syncline about 100 miles south of Prudhoe Bay. Although not in NPRA, rocks in the lower Nanushuk Formation on this bluff are analogs for reservoirs in major oil discoveries in and near NPRA more than 100 miles to the north-west.

Benefits to Alaska

While the jury is out on whether the lease sale will move forward, be scaled back or canceled, any pullback would impact Alaska.

"Our state's economy and infrastructure depend on new, producing fields to offset the decline of older fields," explained Sean Clifton, Policy and Program specialist for the Alaska Department of Natural Resources' Division of Oil and Gas. "Without development of new North Slope fields, throughput in TAPS could drop low enough that the pipeline may have to shut down."

Once in production, the Pikka and Willow discoveries will account for roughly 45% of total Alaska production, keeping flow rates steady at roughly 500,000 barrels a day. Without them, volumes are expected to drop by half by 2030.

"We need the inertia of activity across the North Slope, including federal lands, to continue that development that gets oil in the pipeline, gives people jobs and keeps us growing," Clifton said.

"While oil has generated up to 90% of the state's unrestricted revenue in the past, low oil prices and declining production mean oil is projected to provide between 19 and 22% of unrestricted revenue over the next decade," he added.

When you factor in pilots, mechanics, truck drivers and cooks, Clifton said, "just about everything that everyone does in this state ties into the oil and gas business."

The Willow discovery is expected to create 2,000 construction jobs, 300 permanent jobs, and generate more than $10 billion in federal, state, and North Slope Borough revenue.

"The Pikka discovery is expected to create a similar number of jobs and revenue," Hannon said.

"When you start canceling lease sales or removing acreage, not only do you stop exploration, you stop innovation for developing newly discovered resources," she added. "And because there is such a long lead time between discovery and first oil, this is when you risk stranding these discovered resources because you may not get them into TAPS."

According to some estimates, the North Slope and offshore Arctic region still hold 50 billion barrels of undiscovered, technically recoverable oil.

A Troublesome Transition

While Alaska might be one of the first states to feel the effects of the new administration's stance on the industry, a ripple effect is no doubt coming.

If leasing is in question now, permits will be next, said Mark Myers, former commissioner of the Alaska Department of Natural Resources and former USGS director. As the Arctic continues to warm, Alaska will continue to see dramatic changes in landscape, including erosion along its northern coast, thawing permafrost and a change in vegetation. All are likely to affect how, if and when industry-related activities are permitted. "These changes will affect views on lease sales," Myers said.

If the 2021 NPRA lease sale is canceled, that sends a mighty message: "This is particularly important because it is not ANWR (Arctic National Wildlife Refuge), it is not offshore. It is an onshore petroleum reserve," Myers said. "When you pull that out of leasing, you are making a different statement. Not that you are worried about the Chukchi Sea or licensing in ANWR, it's a strong signal that they are going to pull back altogether on leasing in federal lands."

If that is the first step in distancing the nation from oil and gas as the new administration looks to renewables, what does that plan look like?

While Myers can see oil give way to natural gas as a transition fuel and renewables become greater suppliers of electricity generation and transportation fuel, there are missing links on the transition trail, namely the need for energy storage and distribution lines, and both will have environmental consequences.

For example, energy storage requires the mining of lithium and other critical minerals for batteries, and transmission lines will no doubt cross environmentally sensitive areas and habitats all over the country, including federal lands, he said.

Point of No Return

"The surface disturbance directly caused in creating the infrastructure needed for a complete transition to renewable energy could potentially be larger than that currently used in the production and transportation of fossil fuels. Federal lands will play a major role in the transition," Myers said. " Are we willing to accept more surface environmental degradation on our public lands from renewables because they decrease our dependency on fossil fuels and lower greenhouse gas emissions? It will be interesting to see how the government will make land-use decisions."

Myers embraces a transition to sustainable energy as long as a viable plan is mapped out.

"If you don't allow development or permitting of oil and gas on federal lands anymore, you are making a statement that we are at the point of no return," he said.

If projects to explore for and transport oil and gas are systematically shut down, Myers said the country is essentially playing a game of Jenga. "When you start pulling pieces out," he asks, "are you going to collapse your structure?" ■

From Arrhenius to CO_2 Storage

Part XII: Model for Radiative Transfer of Fluxes in the Temperature-stratified Atmosphere

LASSE AMUNDSEN* and MARTIN LANDRØ; Bivrost Geo/NTNU

> A group of farmers desperately trying to increase their cows' milk production call a theorist to help them find a solution. After a few months of hard work, the theorist calls back: "I found the optimal solution. Consider a spherical cow in a vacuum ..."
>
> A popular joke about modeling.

Earth's energy budget describes the balance between the radiant energy that reaches Earth from the Sun and the energy that flows from Earth back out to space. Since the launch of the first satellite instruments there has been much interest in determining radiative fluxes at the top of the atmosphere for earth radiation budget studies (House et al., 1986). Energy fluxes at the Earth's surface, however, cannot be directly measured from space, but must be inferred from measurements at the top of the atmosphere using additional empirical or physical models (Wild, 2017). Recall that radiative flux is the amount of power radiated through a given area, in the form of photons, and has unit W/m^2.

In Part XI (see *GEO ExPro* Vol. 18, No. 1, 2021) on the temperature-stratified atmosphere, we introduced the equation of radiative transfer which describes mathematically how a traveling beam of radiation loses energy to absorption and gains energy by emission processes. The fundamental quantity that describes this radiation is called spectral radiance or intensity. It might be useful to remember that intensity is the power (W) per unit wave number (cm^{-1}) (or wavelength or frequency) interval crossing unit area (m^{-2}) in unit solid angle (steradian^{-1} or sr^{-1}) in a given direction. The spectral flux simply is the intensity integrated over all directions. The total flux then is the spectral flux integrated over all wavenumbers.

The objective of this short article is to find a model for radiative transfer of fluxes in the temperature-stratified atmosphere. It can be used to model the transmitted spectral flux from the Earth's surface through the troposphere with the presence of CO_2 for the model presented in Part XI. It can be used also for simple climate sensitivity calculations (see the last section of this article). Moreover, the model that we derive in this part, will later be used as a basis for finding a simpler model for radiative transfer. It is simpler in the respect that it uses the so-called gray approximation, where the thermal opacity of the

Figure 1: Time-lapse images of the atmosphere before and after the Mount Pinatubo eruption. Mount Pinatubo is located about 55 miles (90 km) northwest of Manila in the Philippines. Top: Image of Earth's limb at sunset, in September 1984, where the atmosphere is relatively clear. Bottom: Image in August 1991, a little more than a month after the eruption, shows distinct layers of aerosols in the upper reaches of the atmosphere. The haze effect – caused by ash and gases released during the eruption resulted in temporary worldwide cooling by about 1°C over the two years following the eruption.

atmosphere is assumed to be independent of wavenumber and represented by a single, broadband value. The model couples the transfer of fluxes upwards and downwards and further allows the prediction of the temperature profile in the troposphere.

A Difficult Exercise

It is not a trivial exercise to derive the flux transfer solution from the intensity transfer solution. The reason for this is the intensity's dependence on the angle θ of a traveling beam to the vertical (see Part XI, Figure 3), manifested through a factor cosθ. To remove any angular dependence from the problem, a common assumption is to use an effective angle of the beam propagation of 60 degrees relative to the vertical, so that cosθ = 1/2. However, since there are other valid choices for this angle, as theorists we proceed without making any assumption about the angular distribution. To find the model for the upward flux per unit wavenumber our approach is to integrate the integral solution for radiative transfer for intensity, found in Part XI, over all solid angles in the upward-pointing hemisphere.

Integral Solution for Radiative Transfer of Intensity: A Recap from Part XI

In Part XI (see *GEO ExPro* Vol. 18, No. 1, 2021) on the temperature-stratified atmosphere we learnt that a bit of infrared (IR) radiation is emitted at every height (each having its own temperature) and some of this is absorbed at each intervening level of the atmosphere. The radiation comes out in all directions, and the rate of emission and absorption is strongly dependent on wavenumber and linked to the quantum transitions in IR active molecules. We supposed that the properties of the radiation field and the properties of the atmosphere through which it travels are functions of a single coordinate, which we take to be altitude.

We found the radiative transfer equation for upgoing radiance (intensity):

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

where $B_\nu(T)$ is the blackbody radiation at temperature T and $Q_\nu(Z,z)$ is the function which transfers intensity upwards from height z to height Z, where we imagine an observer is looking down on our planet, $Q_\nu(Z,z) = exp(-\mu^{-1}f_\nu(Z,z))$ where f_ν depends on the absorption coefficient $\alpha_\nu = n\sigma_\nu$ which is the product of CO_2 density and CO_2 cross-section. Finally, $\mu = \cos\theta$, where the angle θ to the vertical axis describes the path upwards of the intensity.

The physical interpretation of equation (1) is straightforward. The first part of (1) transmits to altitude Z Earth's blackbody emission which is decaying exponentially with rate of the absorption coefficient. The second part – the source term – accounts for the radiation emitted by the atmosphere itself. All thin layers below altitude Z contribute to the emission, with more distant layers given progressively smaller weights. The emission to space is most sensitive to temperatures near the top of the atmosphere.

In Part XI, for a given temperature model, we calculated the integral in equation 1 numerically to find the spectral radiance.

From Radiance to Flux

Now, our objective is to find an equation for the net upward flux per unit wavenumber, F_ν^+, by multiplying equation 1 by $\mu = \cos\theta$ and integrating over all solid angles (see Figure 2) in the upward-pointing hemisphere. The $\cos\theta$ arrives as a result of Lambert's Cosine Law which holds that the radiation per unit solid angle (the radiant intensity) from a flat surface varies with the cosine of the angle to the surface normal (see Figure 3). That means we need to integrate over all azimuths from 0 to 2π and over 90 degrees of zenith, so that $\theta = 0 \rightarrow \pi/2$. Since radiance is independent of azimuth, the spectral flux is given by:

$$F_\nu^+(Z) = 2\pi\int_0^1 d\mu\ \mu\ I_\nu^+(Z)$$

After some hard work, we find the solution for spectral flux:

$$F_\nu^+(Z) = \pi B_\nu^+(T(0))P_\nu^{(0)}(Z,0) + \int_0^Z dz\ \alpha_\nu(z)\pi B_\nu(T(z))P_\nu^{(1)}(Z,z) \quad (2)$$

where:

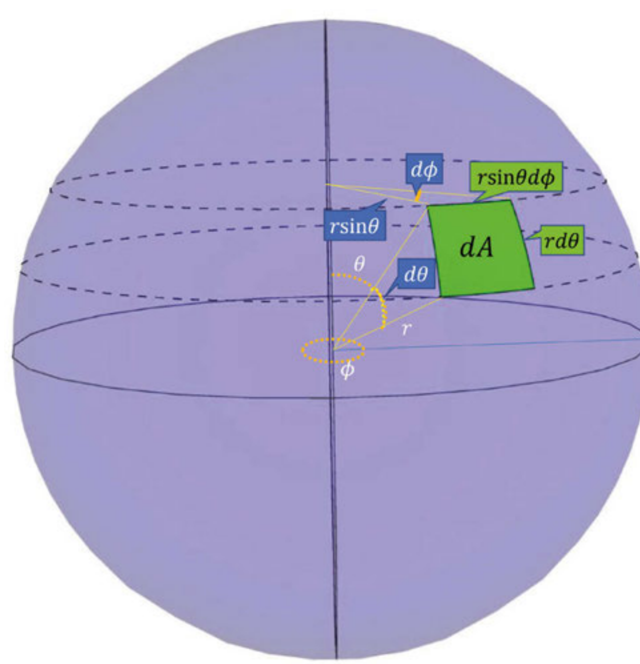
$$P_\nu^{(0)}(Z,0) = Q_\nu(Z,0)(1 - f_\nu(Z,0)) + f_\nu^2(Z,0)\left(\mathrm{Shi}\left(f_\nu(Z,0)\right) - \mathrm{Chi}\left(f_\nu(Z,0)\right)\right)$$

$$P_\nu^{(1)}(Z,z) = 2Q_\nu(Z,z) - 2f_\nu(Z,z)\,\Gamma\left(0, f_\nu(Z,z)\right)$$

$$Q_\nu(Z,z) = \exp\left(-f_\nu(Z,z)\right).$$

Here, Shi and Chi are the sinh and cosh integrals, and Γ is the incomplete Gamma function, which are special functions that occur in a variety of physical and engineering problems.

***Figure 2:** Spherical coordinate system and solid angle. The green area on the sphere of radius r is dA = rdθ r sinθ dϕ. The solid angle is dΩ = dA/r² = sinθdθdϕ. Define μ = cosθ; then dΩ = -dμdϕ.*



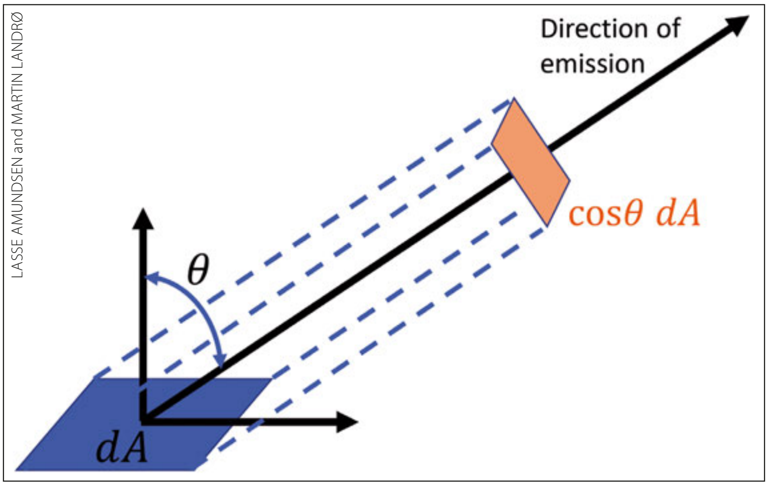


Figure 3: A Lambertian radiator is one that emits a radiance (called intensity, I, in equation 1) that is independent of angle; it emits uniformly into the hemisphere, I = constant. The radiant intensity ($\tilde{I}$), however, depends on the direction of emission, $\tilde{I} = I A \cos\theta = \tilde{I}_0 \cos\theta$. Black body sources are Lambertian radiators. In the visible spectrum, the Sun is almost a Lambertian radiator, and as a result the brightness of the Sun is almost the same everywhere on an image of the solar disk.

From Radiance to Approximate Flux

Equation 2 is a representation of a differential equation which is yet to be determined. To simplify the derivation of this differential equation, we suggest the approximate representation:

$$F_\nu^+(Z) = \pi B_\nu^+(T(0))Q_\nu(Z,0) + \int_0^Z dz\, \alpha_\nu(z)\pi B_\nu(T(z))Q_\nu(Z,z) \quad (3)$$

which is based on the approximations:

$$P_\nu^{(0)}(Z,0) \approx Q_\nu(Z,0) \;\; ; \;\; \alpha_\nu(z)P_\nu^{(1)}(Z,z) \approx \alpha_\nu(z)Q_\nu(Z,z)$$

The validity of the approximation can be demonstrated by calculating numerically the spectral flux for the exact (equation 2) and approximate (equation 3) solutions. We use the model given in Part XI where we calculated the transmitted spectral radiance from Earth's surface through the troposphere with presence of CO_2 to top of troposphere at height 11 km. The result is shown in Figure 4. We observe that the approximate equation catches the major trends of the transmitted spectral flux.

What are the differential equations for the spectral flux in the approximation given by equation 3? We will need those equations for the next part of this series, which aim at finding the thermal profile for an atmosphere in radiative equilibrium, where by definition, the net flux is constant with height.

Differential Equations for Spectral Flux

Equation 3 and equation 1 have similar forms when:

$$I_\nu^+ \to F_\nu^+ \;\; ; \;\; B_\nu \to \pi B_\nu \;\; ; \;\; \mu = 1$$

Due to the similar forms, spectral flux in the approximative representation in equation 3 must obey a differential equation similar to that of equation 1 in Part XI. Therefore:

$$dF_\nu^+ = -\alpha_\nu(F_\nu^+ - \pi B_\nu)dz \quad (4a)$$

Equation 4a is the differential equation for the spectral flux passing upwards. The differential equation for the spectral flux passing downwards is:

$$dF_\nu^- = \alpha_\nu(F_\nu^- - \pi B_\nu)dz \quad (4b)$$

A Climate Sensitivity Calculation

The total flux (in W/m²) is found by integrating numerically, the flux over all wavenumbers. Let's calculate the radiative forcing at the top of the troposphere (TOT) at two times: first at the beginning of the industrial revolution when CO_2 concentration was C = 275 ppm; and second, in October 2019 when C = 408.55 ppm. We find the warming effect $|\Delta F|$ = 2.4 W/m², which is slightly above the number ΔF = 2.06 W/m² predicted by using Arrhenius' logarithmic forcing rule (see *GEO ExPro*, Vol. 17, No. 2, May 2020). In this evaluation, we kept Earth's and the atmospheric temperature the same for both CO_2 concentrations.

References available online.

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

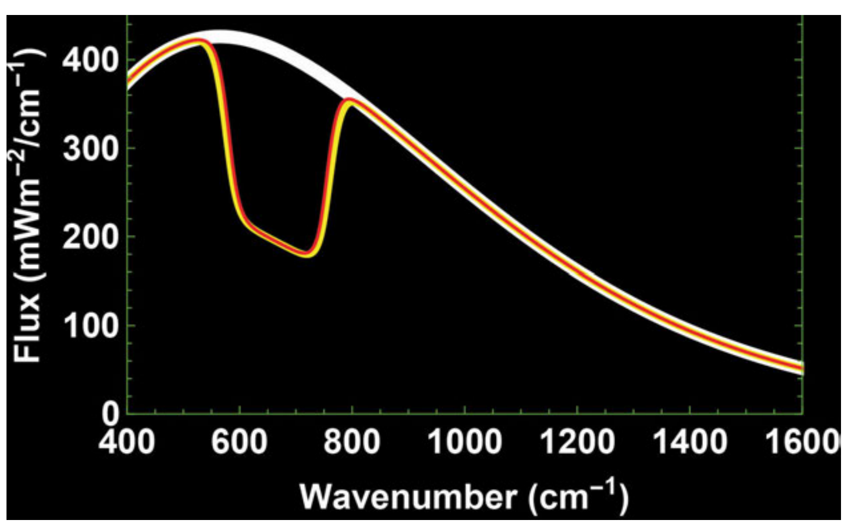


Figure 4: The transmitted spectral flux from Earth's surface through the troposphere with presence of CO_2 for the model presented in Part XI, with scale height L = 8 km, to top of atmosphere at height 11 km. Yellow line: Exact solution (equation 2). Red line: Approximate solution (equation 3). White line: Earth's emitted blackbody radiation.

Revealing the Intra-Zechstein Prospectivity on the UK Mid North Sea High

Figure 1: Interim depth section across the first phase of ION MNSH PRIME 3D. Lateral variation in intra-Zechstein seismic facies is clearly seen with important changes between platformal and basinal facies in the lower Zechstein Z1 and Z2 units. Note the unit thins to the east in this image due to decrease in accommodation space. All seismic images North Sea Normal, white is hard. INSET: detailed stratigraphic breakdown of the Zechstein showing the repeating carbonate, anhydrite and halite units and the lateral variation between more platformal areas on the left (carbonate/anhydrite dominated) and more basinal areas on the right (halite dominated), from Patruno et al., 2017.

The Intra-Zechstein plays on the flanks of the European Permian basin are complex and highly variable. The sequence includes repeating anhydrite, dolomite, and halite sequences with significant lateral facies variation. While the center of the Permian Basin is dominated by more massive halite units, the basin margins contain higher proportions of platformal carbonate and anhydrite units.

These marginal areas have proven successful in Poland, Netherlands and both onshore and offshore UK, most recently with the Ossian discovery in 2019 on the southern flank of the UK's Mid North Sea High (MNSH). Interest in the area was further demonstrated by the success of recent licensing in the UK's 32nd round when Shell, Deltic and Horizon all took new acreage within the play fairway, joining existing players Spirit, Chrysaor, Ardent, One-Dyas and Draupner.

In 2020, ION completed the first phase of the MNSH PRIME 3D survey, covering the entire Zechstein play fairway in the UK MNSH area. The second phase, which is industry supported, is currently in acquisition and will be complete later this year with products available in early 2022 (Figure 2).

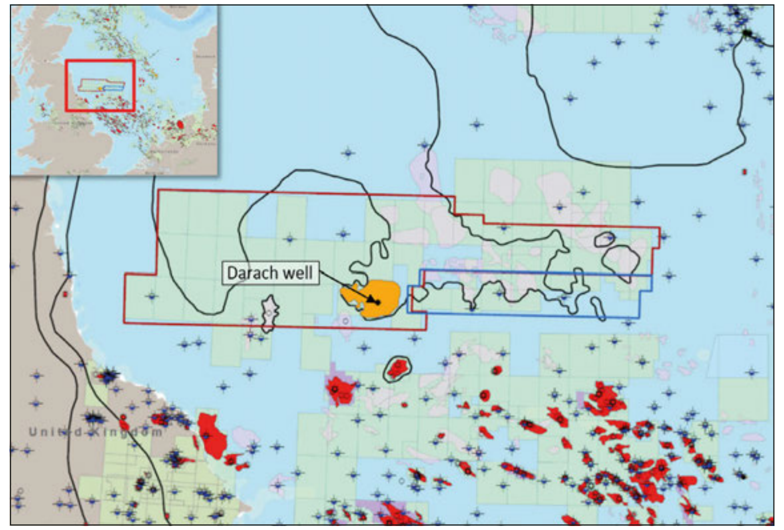
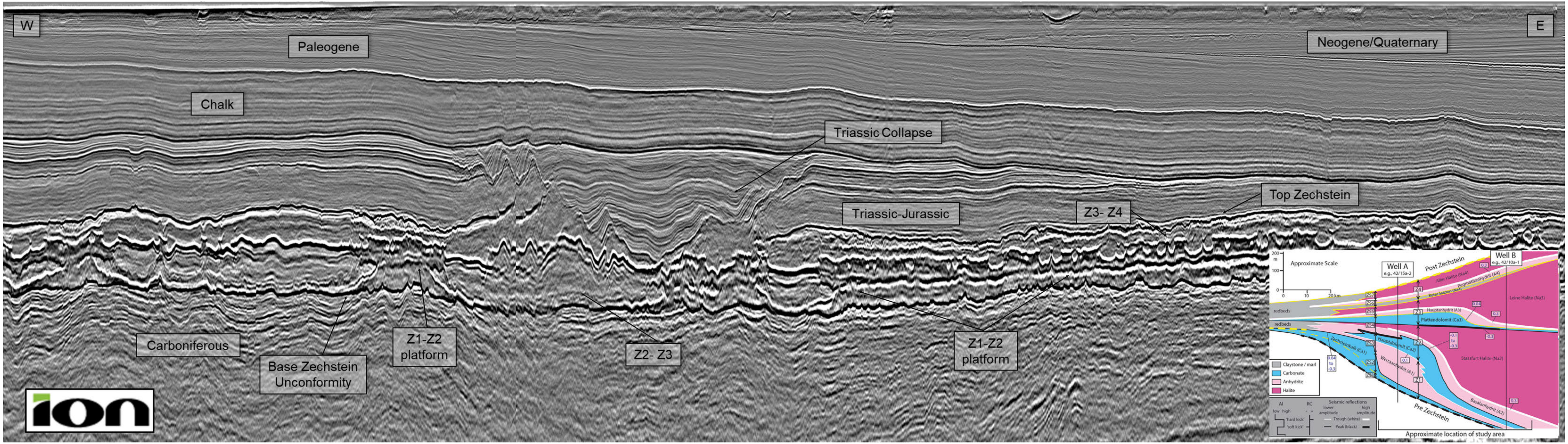


Figure 2: IONs MNSH PRIME 3D survey. The blue outline shows the first phase acquired in 2020 and the red outline shows the second phase being acquired in 2021. Held acreage is in green and previously identified prospects and leads are shown in pale pink. The black outline marks the interpreted edge of the anhydrite Z2 platform, mapped from previous seismic data, provided by Horizon.



The Zechstein: An Ignored and Bypassed Play

PAUL BELLINGHAM, WILL REID, EMILY KAY and NEIL HURST; ION Geophysical

Exploration in the Southern North Sea (SNS) and on the Mid North Sea High (MNSH) area has focused on the clastic plays of the Lower Permian Rotliegend Group and earlier Carboniferous units in dominantly structural traps. The Zechstein, in contrast, is typified by multiple thin dolomite units within a dominantly anhydrite and halite sequence with variable reservoir facies and with complex geometries (inset Figure 1, seismic foldout). With seismic quality unable to easily resolve reservoir variability, it was not the primary target for exploration, also meaning that wells through the Zechstein unit were neither aimed at the most prospective parts, nor significantly investigated.

However, there are several hints toward the potential of this unit. But exploration efforts are hampered by a lack of large, modern, high quality 3D seismic in the most prospective areas of the play. The ION MNSH PRIME 3D is therefore critical to imaging these complex repeating units, their lateral variability and building an understanding of reservoir distribution and prospectivity.

Time to Reconsider

In the UK 32nd round, 40% of the acreage was awarded in the SNS. The UK remains an attractive area for investment with one of the highest global returns per barrel. The presence of existing infrastructure, the location of future CCS (e.g., Endurance) and the location of windfarm development (e.g., Sofia and Dogger Bank), all help to lower the carbon footprint for oil and gas while maintaining profitability, making the SNS an area of industry focus.

The geology also favors the SNS/MNSH area to demonstrate the potential in the Zechstein, especially the Z2 Hauptdolomit unit (inset Figure 1, main foldout). One of the earliest discoveries offshore in the SNS was Resolution (1966) which found oil in the Z2 Hauptdolomit just offshore Yorkshire. While reservoir quality was poor and the discovery remains undeveloped, Shell have recently farmed-in with a view to further appraisal and potential development.

In 1990, the Crosgan discovery, whilst mainly targeting Carboniferous, discovered gas in the Hauptdolomit. In 2019, the Ossian discovery (Figure 2, seismic foldout) tested oil in the Hauptdolomit and will be ready for appraisal in early 2022, and onshore UK, the West Newton oil discovery was made in the same unit, targeting the platformal facies to optimize reservoir quality.

All these results and those on the margin of the Permian basin demonstrate that the Hauptdolomit is an attractive target with excellent reservoir properties in areas of platformal facies. The identification of these platform facies from the less prospective basinal facies,

Figure 3: The top of the Zechstein unit. The west (a and b) shows minor deformation of overlying Triassic and upper Zechstein units forming pronounced salt ridges. In the center and east of the survey (c and d) the upper Zechstein, which is salt dominated, has been evacuated down to the Z3 Plattendolomit, which is also faulted, and infilled with Triassic collapse structures. Significant accommodation space is created but with limited tectonic deformation; note largely undeformed base Zechstein.

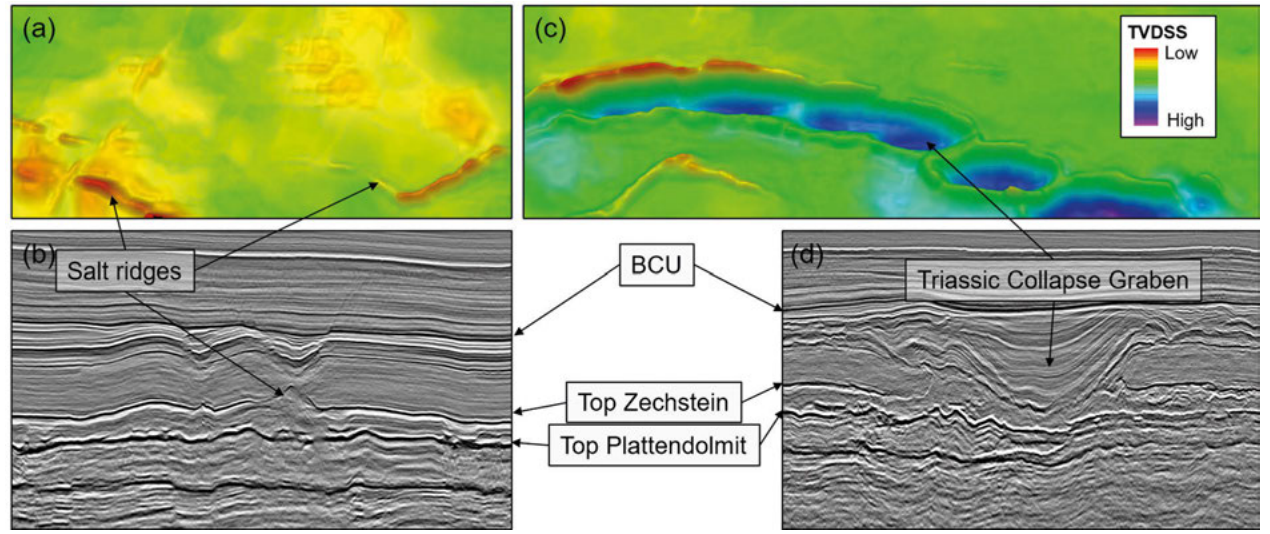
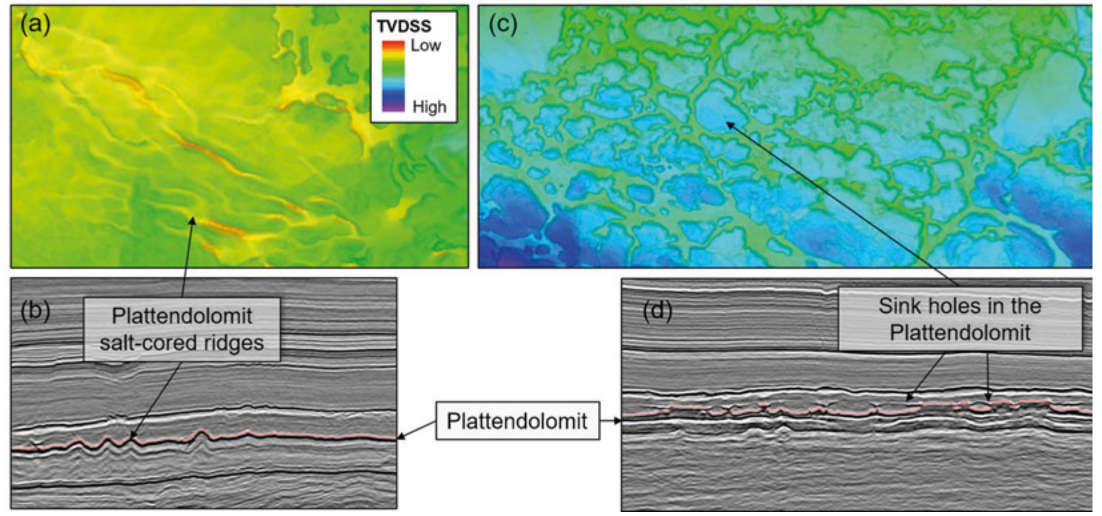


Figure 4: The Z3 Plattendolomit varies between a set of salt cored ridges on an otherwise smooth horizon in the west (a and b), and a karstified horizon with and sinkhole features in the east (c and d).



requires regional high quality 3D seismic to fully constrain the distribution. IONs MNSH PRIME 3D survey enables the explorer to do just this.

Spectacular Initial Results

Imaging of the first phase of the MNSH PRIME 3D is in progress, using a full range of modern processing and imaging techniques. Initial results show a significant improvement in imaging quality over previous datasets. Figures 3–5 show sections and horizon maps of the Top Zechstein, Plattendolomit (Z3) and Hauptdolomit (Z2) respectively.

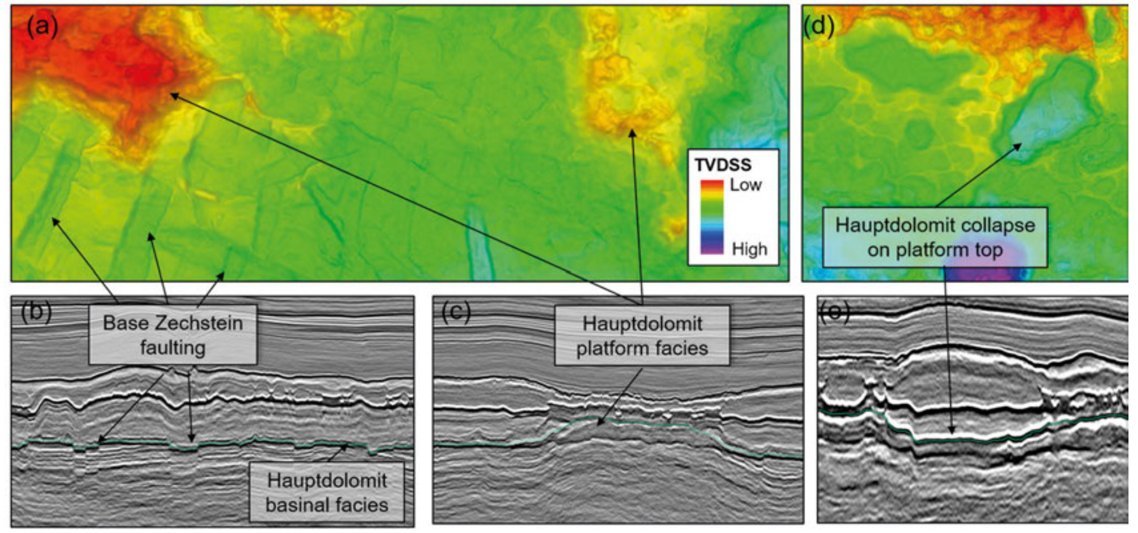
The Top Zechstein (Figure 3) shows varying amounts of halokinesis causing collapse and thickening of the overlying Bacton group Triassic strata, itself a potential target. The initiation of these collapse features is inherently related to the edges of the more platformal seismic facies units in the lower Zechstein, highlighting that movement is initiated where there are rapid changes in the amount of halite in the section.

The Z3 Plattendolomit unit is a strong seismic marker but is variable across the area (Figure 4). Where the platformal zones dominate, and the overall Zechstein is thinner in the east, the Plattendolomit is characterized by karstification and the presence of sinkhole-type features. These are not seen further west where there is a thicker sequence and the Plattendolomit is surrounded by more halite-rich units. Here we see more gentle, salt-cored ridges and no evidence for exposure or karstification. Note that the ridges form early and are layer bound.

The Z2 Hauptdolomit (Figure 5), is more enigmatic seismically but is a critical horizon to pick accurately; it is the most prospective reservoir unit where it is a more elevated, thicker platformal facies, proven by previous successes. Additionally, where it is a more basinal facies it has also been demonstrated to be an effective source rock, the 'Stink-dolomite'. In the west of the survey, the platform edge is well picked out seismically defining potential targets; in the east we see more erosion and collapse in this unit, giving the potential for karstified secondary porosity development.

Overall, our initial results from this exciting new dataset show how high quality data can illuminate and unlock the potential of this previously largely overlooked play in the UKCS. ■

Figure 5: The Z2 Hauptdolomit unit shows progression from more platformal to more basinal seismic facies in the west of the survey (a, b, c) while in the east of the survey the platformal seismic facies is more prominent with frequent collapse features.



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SAVE THE DATE

Volcanoes to Venture Capitalists

Mark Davies explains how volcanology led to new technology fit for exploration and hazard mitigation.

IAIN BROWN

November 14th, 1985 was a seminal day for a young Mark Davies. News of a volcanic eruption in Colombia was breaking on the BBC. The Andean Nevado del Ruiz volcano had exploded the previous day, killing over 23,000 people in the town of Armero, almost 40 km away from the volcano.

"I remember watching the news footage with a mixture of horror and confusion. I had no reference point with which to answer questions such as how can we put a man on the moon, but be unable to stop a volcano from killing 23,000 people, and 40 kms away from the summit?"

The Motivating Force of Tragedy

For days after the event the BBC focused much of the coverage around a young girl who was trapped in mud up to her chest. Every time the rescue team tried to get her out, the pressure of digging would slowly crush her fragile body and they would have to stop the rescue. She did not survive and that changed the course of Mark's life.

"To this day I remember seeing on TV night after night, the hope wane away. By the time she died, my emotional investment into the whole tragedy was overwhelming. I made my decision there and then, I needed to do something. What? I did not know, but I needed to understand why such a tragedy happened."

The emotional impact stuck. A decade later as a fully qualified volcanologist and while filming a BBC documentary, he would summit Nevado Del Ruiz to install monitoring equipment. Not anticipating the emotional floodgates that would open and unbeknown to Mark, the producers of the documentary organized a helicopter trip to Amero where upon his arrival, he was introduced to surviving family members of the little girl featured in the coverage.

"I was fighting back tears. To this day I don't know why I reacted like that. The family, who by this time had made peace with the volcano, must have thought I was a complete lunatic. I am 6ft 8inches and 115 kilos, they were typically central American and a fraction of my size and must have thought they were in a subplot to a Shrek movie."

Mark undertook a degree in Geology at Cardiff and was allocated a tutor, a young volcanologist who guided much of his early career. In his final year there, Mark had been discussing the opportunity of studying for a PhD with his tutor, when another opportunity presented itself.

"The PhD opportunity was amazing, but I was unsure if it was right for me, I wanted to spend my time on volcanoes, monitoring hazards rather than in a laboratory. Then everything changed. The tutor was offered a professorship at the Universite Blaise Pascal, in Clermont-Ferrand and the opportunity to study a PhD was no more."

There are only a few places in the world where you can go and study an advanced degree in pure Volcanology. Hawaii is one, and Clermont-Ferrand is another. The former lies on an active volcanic chain and the second, on an extinct one in the middle of France's Massif Central.

Rather than cutting ties, the tutor suggested Mark study for an advanced degree in volcanology at Clermont under a foreign student bursary scheme. With the language barrier, studying in Clermont was brutally hard, but worthwhile. It provided a wonderful grounding in volcanology, although it soon became evident that Mark wanted to focus on hazard mitigation and after graduating Mark secured a PhD at the Open University Earth Sciences, Volcano Research Group.

Nature's Laboratory

It's easy-to-understand Mark's fascination with volcanoes but delve

One of nature's natural laboratories – Mount Etna Volcano, Sicily.

Shutterstock

deeper and the reasons are multi-layered. A fascination with volcanoes influenced his early years, but they also continued to guide many decisions throughout his later career.

Tasked with developing a continuous microgravity monitoring station on Mount Etna, Sicily, a year into his PhD, the island of Montserrat in the Caribbean began to erupt for the first time in centuries. The British Geological Survey (BGS) was tasked with monitoring the volcano and a rapid recruitment drive occurred. Along with several young and excited scientists, Mark found himself mobilized to the Montserrat Volcano Observatory.

"It was my dream job, I was monitoring an active volcano and surrounded by clever people with a veritable smorgasbord of technology at our disposal. Although I specialised in ground deformation monitoring, I soon became interested in many other disciplines that were being deployed. The Phrase 'Jack of all trades, master of none' rings very true in my case."

Thermal Monitoring at Santiaguito Volcano, Guatemala with the Hawaiian Institute of Geophysics and Planetology.

Geological Time Scales

What captivated Mark was the 'real time' work being conducted on the volcano. There is no other geological phenomenon that affords you results in such short order when conducting research or developing equipment. Cross-over technology fascinated Mark. For example, thermal imaging cameras used by the fire service were adapted to monitor hot spots within the volcanic dome. Working with the Montserrat Volcano Observatory instilled a practice of looking to other engineering and scientific disciplines to find solutions, something that Mark activity promotes to this day as CEO of the AustinBridgeporth Group.

Montserrat was also the springboard for Mark's other passion, teaching. An advocate of knowledge transfer, Mark spent many years on the public lecture circuit for the Open University Geological Society, Royal Geographical Society, and the British Association for the Advancement of Science. The lectures were popular and led to making TV programmes where he fronted several mainstream documentaries for the BBC, Channel 4, National Geographic, and the Discovery channel.

Mark then landed a coveted tenure position as a lecturer at the University of East Anglia (UEA). A position that should have set him on an academic research and teaching pathway for life. He lasted barely one year and by his own admission hit a low point in his career. Although UEA was a dynamic place to be, and in his own words full of brilliant young researchers, he was forced into a decision to walk away.

"I was broke, I barely had two pennies to rub together at the end of each month. The job was everything I had worked towards, but I did not

Mark lecturing on the Minoan volcanic eruption. Note volcanic bomb in outcrop that has punched through eruptive layers.

and spatial awareness. Measurements must be acquired often to assess the volcano. At that time, seismic was and still is, the key monitoring tool for an observatory affording results in real time and the ability to pinpoint the location of activity in three dimensions. However, a volcano is a complex beast and mitigation becomes more accurate if other properties are monitored.

"At that time, I felt the niche research I specialized in, microgravity, was being left behind. The team at Hawaii were developing satellite remote sensing to monitor heat flow over entire volcanic provinces, significantly improving spatial and temporal sampling. Another evolving technology was GPS systems for ground deformation. They were becoming cheaper, and several could be deployed permanently to monitor movement in real-time. However, little had changed in 30 years of microgravity monitoring because instrumentation was too expensive to be deployed in numbers, permanently. This meant that manual measurements were still required, which was dangerous on active volcanos such as Montserrat and spatial coverage remained poor. What the discipline needed was new instrumentation that could be deployed remotely but with the sensitivity and resolution equal to what we were recording on the ground."

factor-in one important aspect, the salary. I was on a UK wide academic pay scale as a junior lecturer. So, something had to give and I took a position as an Associate Research Professor in Hawaii, on triple the UK salary."

The decision led to the loss of several academic friendships. However, few knew the real reason why he quit and these days he uses this example to highlight the disparity between the US and the UK when valuing scientists and engineers. A disparity that Mark points out, continues to this day.

Natural Resources

If UEA had been the perfect job, then Hawaii was the dream job. The Hawaiian Institute of Geophysics and Planetology (HIGP) is loaded quite literally with academic 'rock stars 'and Mark openly admits that he felt 'outgunned' by his peers. He did learn one very important lesson though, "if you surround yourself with people much cleverer than you, but can contribute ideas, then all is not lost."

Real time volcanic monitoring remained a strong research driver. The key to any hazard mitigation program is temporal

In an academic merry-go-round of scrambling for limited research money, Mark found it hard to secure funding to develop new technology and soon turned to industry to solve the problem.

"Look, we all know that universities are underfunded and back then, the chances of securing money were limited. Industry was a different proposition altogether. I learnt a valuable lesson when I took a job to pay bills at a company which specialized in gravity and magnetics for hydrocarbon exploration. On my first day and overconfident, I was introduced to some new software that was being developed. I felt I was hit by a speeding bus. I realized that with access to this software, what took me two years to produce on a limited academic budget, I could have finished in less than two months. It was a huge reality check. If you want progress in a short timeframe, you need the funds."

Monitoring volcano edifice fractures on the Island of Montserrat. Tropical forest destroyed by ash and corrosive gases.

That lesson wasn't lost on Mark and when a spinout from that same company approached him to join a startup team which would develop the world's highest resolution superconducting gravity instrument, Mark committed with responsibility for developing workflows and techniques to interpret the data, focusing on where to deploy the new gravity systems. The envisaged timeframe was two to three years after which his plan was to return to academia with a new airborne system he could 'borrow' to monitor microgravity on active volcanoes. So, he made a promise to the CEO, to stick with the program until the system was fully developed and operational. Little did Mark know, but it was the start of a journey that would take over a decade to complete.

No Guarantees in Life, or a Good Start-up Idea

At the core of the venture was the development of a superconducting gravity gradiometer, a system so sensitive that it would revolutionize subsurface gravity imaging. It had originally been designed to operate in space under a European Space Agency project and the engineering team assembled was exceptionally talented.

"The team assembled was truly multidisciplinary. You had PhD level low noise superconducting engineers working next to and reliant on watchmakers tasked with building micro-accelerometers. I absolutely loved the working environment and marveled at the synergy … the whole being greater than the sum of its parts."

At that time, the development focus was centered around hydrocarbons and mineral exploration and so a deal was brokered to operate the only commercial Full Tensor Gravity Gradiometer (FTG) manufactured by Lockheed-Martin. While the FTG commercial offering went from strength to strength, the superconducting project stalled, and with no sign that it would be commercialized, Mark left and a few years later created Bridgeporth.

The new company, backed by venture capitalist funding, built a solid business around the latest Lockheed 'enhanced' FTG instrument called the e FTG. This system not only demonstrated an improvement in servicing the hydrocarbon market, but also possessed the sensitivity and signal to noise to search for battery

Ali Abdelaziz

Presenting at an international conference.

minerals, water resources and geothermal energy. Over two decades on from the Montserrat eruption, an instrument that can finally provide useful airborne data for volcanic monitoring has been developed and the journey reaches full circle. Is Mark finally at peace with Nevado del Ruiz?

"Innovation comes from creative thinking, but to flourish, resources and a conducive environment are needed. That's where academia and industry need to develop a more symbiotic relationship. In the UK we don't do that quite as well as the US, but I hear the government has just appointed a science and technology tsar, so fingers crossed. At the very least let's pay scientists and engineers what they are worth and give them the funds to make some magic." ■

Know Before You Go!

Ray-based seismic modeling has come a long way and the motivation for this is simple enough: performing a modeling study is significantly cheaper than failing in the field!

LARS ZÜHLSDORFF and TROND HAUGLAND; NORSAR

Field managers are required to make costly decisions, relying on data that almost always could be improved. Entire projects are in jeopardy if the wrong questions are asked or answers are not sufficiently sound. Will a new survey be fit for purpose? Is it the data that is causing issues, or rather the processing flow? Should one try something new to improve imaging or repeat the old (for time-lapse reservoir information)? How can we improve interpretation to mitigate risk? Balancing budget and benefit may sometimes be the most challenging part. But it might not need to be. Ray-based seismic modeling might not make the decision for you, but it can provide essential information before proceeding with a gamble.

The synthetic model in this article combines a typical oil and gas reservoir with complex structures from an ancient channel and levee system (Figure 1). While this is a realistic setting, as found, for example in the Bay of Bengal, it can be considered analogous for any laterally and vertically varying velocity fields that reveal moderate impedance contrasts. The reservoir, on the other hand, contains poorly imaged tilted blocks. The poor imaging could either stem from overburden effects or target dip, a scenario often encountered in many parts of the world.

The case we are looking at here can be described as follows. There is an existing towed streamer survey (cross-strike) with 3 km maximum offset, that initially provided the basis for a drilling campaign. One reservoir is already producing oil, the other one has proven gas but requires further development. What happens in the tilted blocks between the reservoirs is unclear, as seismic interpretation is hampered by imaging issues. The key question of this study is whether careful reprocessing of existing data can save the cost of acquiring new data.

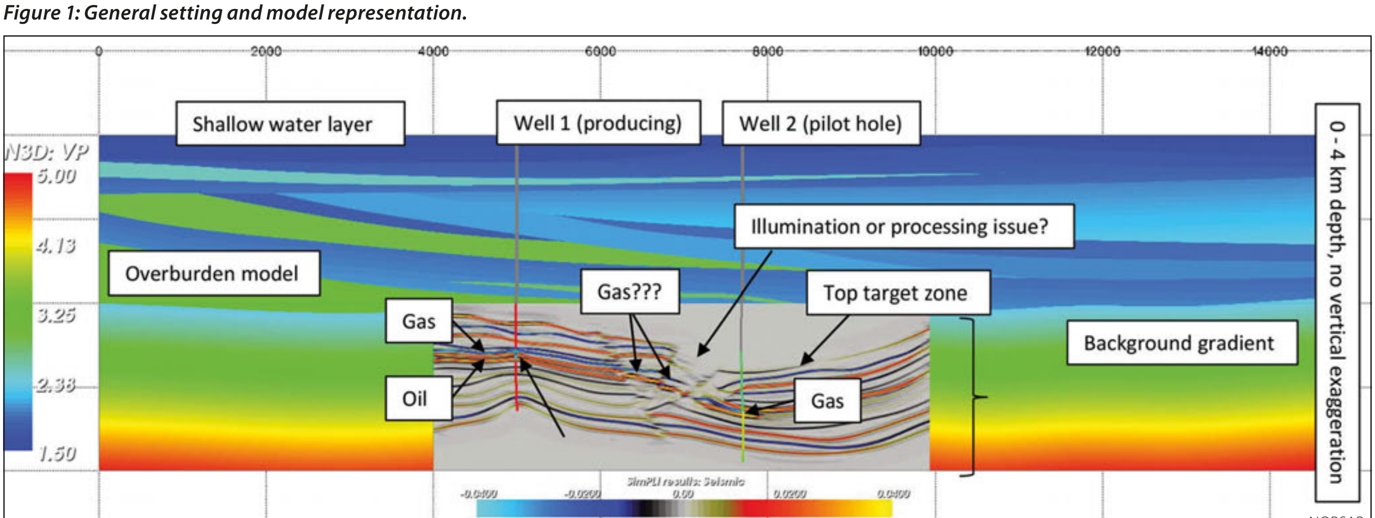
Will a New Survey Improve the Image?

The first part of this study is a classic illumination test, i.e., the existing survey is evaluated by modeling all shots within a representative depth model. Typically, the model would be built from interfaces picked from migrated seismic sections and from interval properties as determined from seismic velocity analysis, well logs, check shots, or even best guesses.

On the modeling side, a technique called wavefront construction was used in this study. In other words, wavefronts rather than rays are propagated through the model, which is much closer to what is happening in the field (and much more efficient in the presence of many receivers). As the wavefronts are constructed from rays, the rays are still available and can be displayed and utilized as in classic ray tracing. A key feature of ray-based modeling is that simulations can be limited to selected parts of the wavefield (e.g., a primary target reflection). This is fundamentally different to full wavefield data and makes the process very efficient. As reflection points are known, ray-based modeling is also suited for generating attribute maps directly on the target of interest.

In this case, the target is illuminated unevenly (Figure 2A), even though the survey was densely sampled and regular. Especially the steeply dipping top of the tilted blocks receives many 'hits', but also seems to generate a shadow zone close to its base. Ray path analysis reveals that the shadow zone is caused by refractions in the overburden, which deflect rays from the affected area. Another core observation is that illuminating the dipping section requires a large migration aperture, i.e., contributing shots and receivers are not located

Figure 1: General setting and model representation.



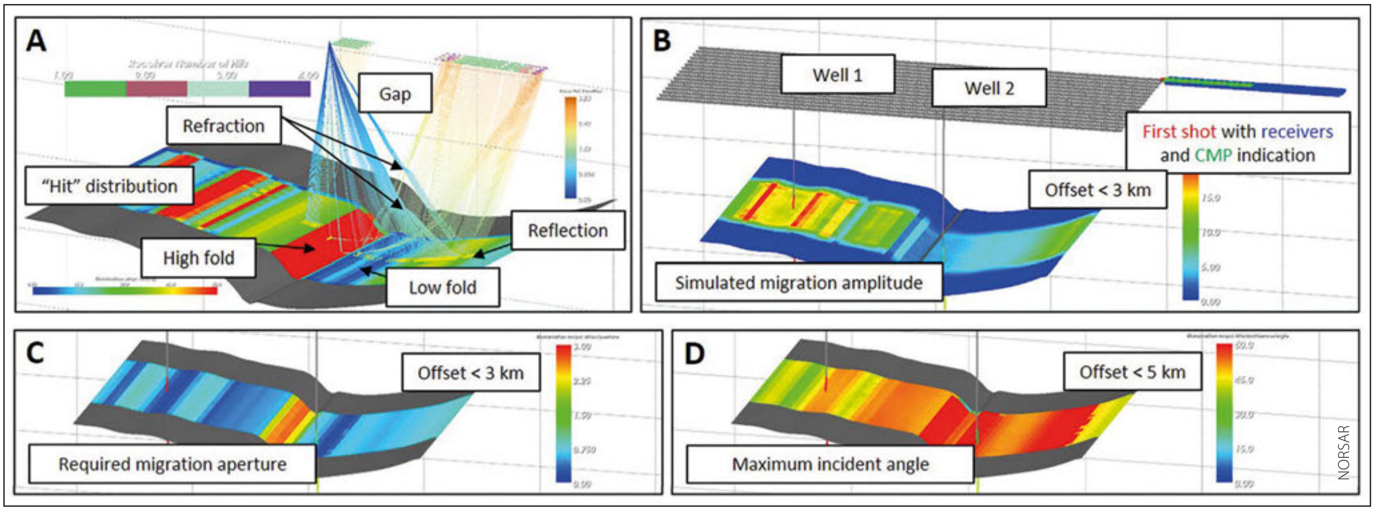


Figure 2: Selected results of the illumination study, showing A: ray paths for a single shot and a single receiver line as compared to the reflection point distribution on the target ('hit map'), B: simulated migration amplitude along the target, C: required migration aperture for seismic imaging, and D: maximum incident angle at the target (if maximum offset is increased from the initial 3 km to 5 km).

right above the slope, but further away. Consequently, ray paths are longer and both attenuation and geometrical spreading are effectively reducing amplitude. This can be visualized by using an illumination parameter called Simulated Migration Amplitude (SMA) (Figure 2B), which is generated by migrating reflection events along the target. For the given example, this mainly shows that target coverage and final reflection amplitude are only loosely related, and many 'hits' do not necessarily produce a strong amplitude in seismic sections. Also, the dipping section will be poorly imaged if migration aperture is set too small when processing (Figure 2C).

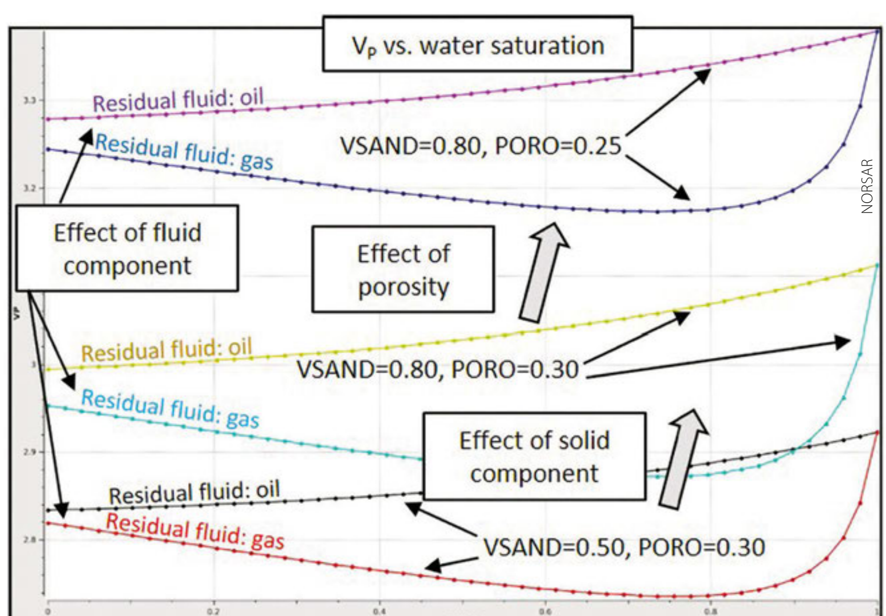
The question whether a new survey with a different geometry will do better, requires moving from survey evaluation to survey planning. Many different survey geometries could now be tested, but as the area is almost 2.5D (i.e., not much changing along strike), there are only two key options that seem to make sense: using longer offsets and running the survey along strike rather than cross strike. Checking the effect of larger offsets is simple, as typically long cables are used for modeling anyway (for exactly this purpose). It turns out that incident angles become over-critical if offsets are increasing beyond 3 km (Figure 2D). Longer cables would therefore nominally increase the fold, but not provide much extra contribution directly used for seismic processing. If only subcritical events are considered, attribute maps for an along-strike survey do not reveal any advantage to the initial survey geometry.

Thus, on initial consideration, new data may seem to be a waste. However, there may still be good reasons for shooting along strike, as the second survey azimuth could be combined with the first to increase fold and signal-to-noise ratio. There may also be good reasons for repeating the existing survey, as this could be used for monitoring the reservoir, and ideally, estimating fluid saturation and pore pressure therein. However, can we predict whether there would be a sufficient 4D signal for this?

Predicting 4D Success

Time-lapse studies typically start with a fluid simulation model that produces numerous scenarios for many different time steps. To translate fluid flow simulation into 4D seismic signals, two steps are required. The first uses rock physics to convert parameters like fluid saturation, shale content, porosity, and pore pressure into elastic parameters (Figure 3), as these are needed for calculating reflectivity. This means, rock models can indicate how reflection coefficients are changing in response to production. It is recommended that rock models are calibrated by well-log data in each specific case. The

Figure 3: Sample calculations from a rock model, indicating how fluid saturation, shale content and porosity affect P-wave velocity.



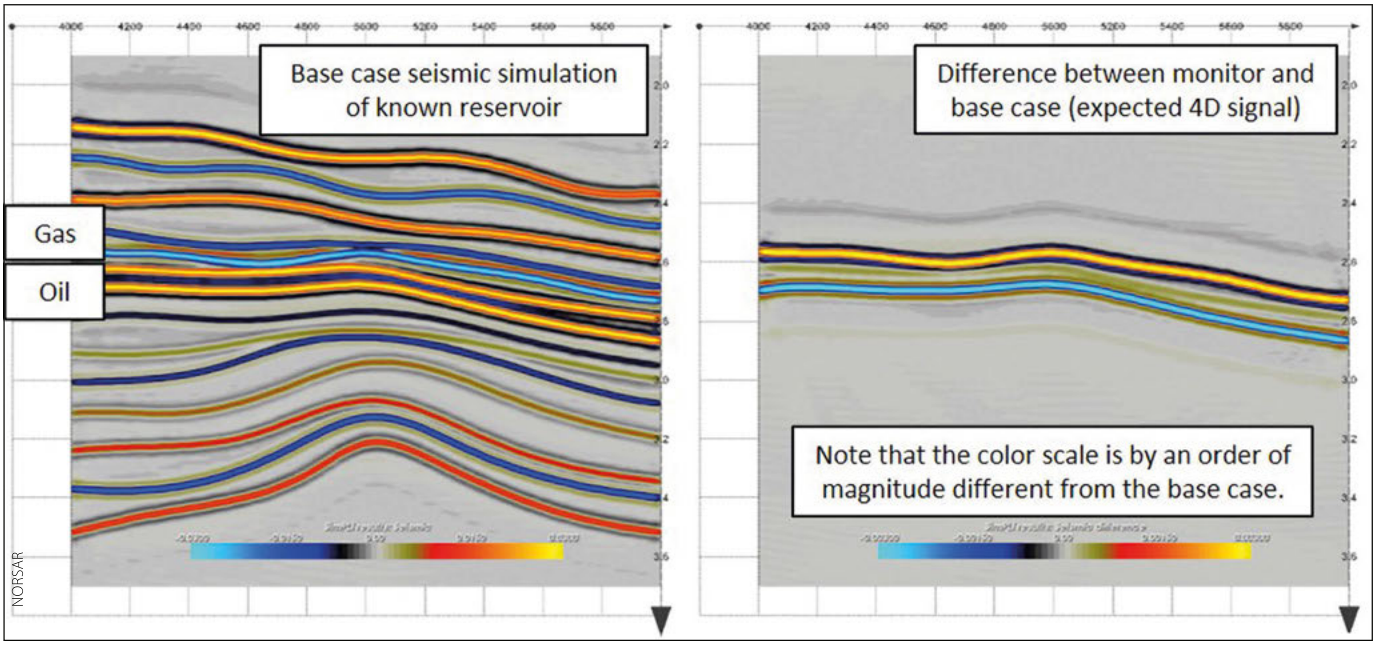
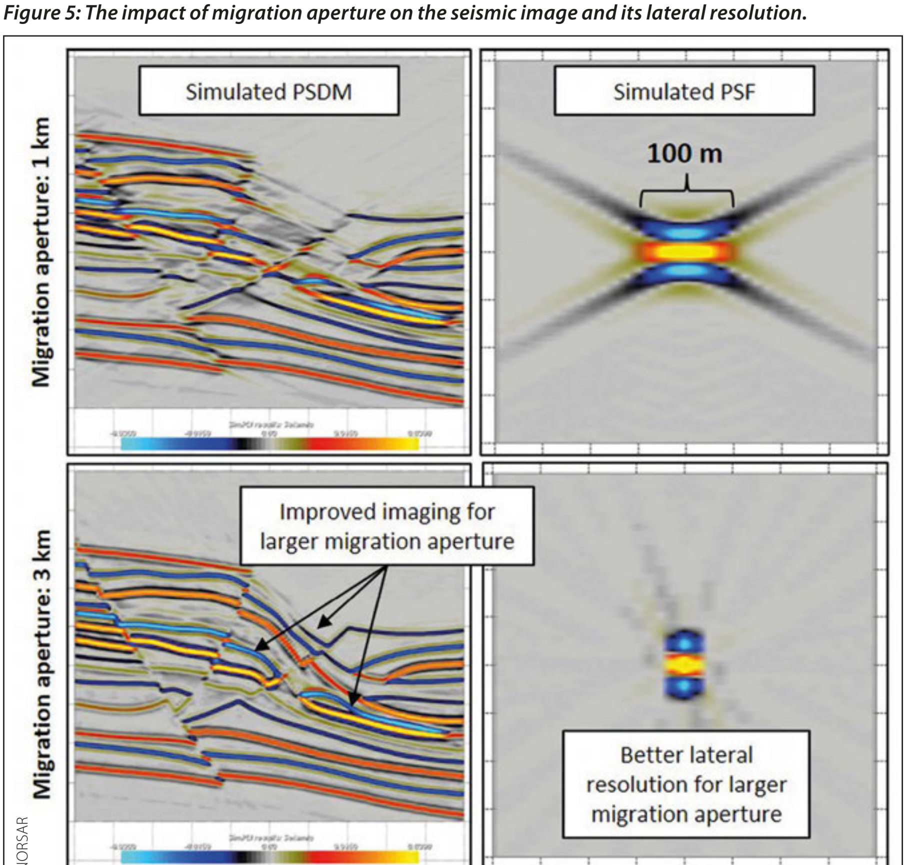


Figure 4: Estimated 4D effect from a fluid simulation model.

second uses a suitable fast-track method for Pre-Stack Depth Migration (PSDM) simulation, as many different scenarios need to be evaluated efficiently. Point-spread functions, as generated from ray-based modeling, may act as 3D convolution wavelets that can be directly applied to reservoir models (or, more specifically, to incident-angle-dependent reflectivity grids). This process is almost as quick as classic 1D convolution but considers both illumination and resolution effects. Calculating the difference between a base case and a monitor case allows for estimating the amplitude change and thus the expected 4D signal (Figure 4). In the given case, a reasonable 10% reduction in reflection amplitude seems to suggest that a monitor survey might be worthwhile.

However, there still is the issue that tilted blocks are not sufficiently imaged, which obviously cannot be rectified by choosing larger offsets or a different survey azimuth. It is therefore time to get back to the initial question of 'will it be beneficial to re-process instead of acquiring new data?'

Figure 5: The impact of migration aperture on the seismic image and its lateral resolution.



Reprocess or Not?

Traditionally, ray-based modeling data are not well suited for processing tests, as amplitudes for triplications and caustics are not well represented and may distort images by systematic artefacts. However, the approach to fast-track PSDM simulation as outlined above may help, as it indicates the impact of migration aperture on both the final seismic image, and its lateral and vertical resolution (Figure 5). In other words, if the migration aperture was too small when the initial seismic data were processed, poor imaging of tilted blocks is explainable, and may be fixed by reprocessing.

It also is worthwhile checking whether the velocity field used for seismic migration was accurate enough. This cannot be tested by a fast-track filter approach but requires migrating synthetic shot gathers. Ray-based Kirchhoff modeling as used in this study can be limited to P-P primary signals from the target volume of interest, and therefore provides an efficient alternative to more comprehensive (but also more expensive and time consuming) concepts like full waveform modeling. Synthetics generated by this process include diffractions and are therefore suitable for migration tests. Using different background models for Kirchhoff target migration, i.e., different velocity fields, the effect of upgraded velocity information on the final image can be tested directly. In this case, seismic image quality suffers a lot if migration velocity in a few overburden layers is wrong by as little as 10% (Figure 6). If updated velocity information has been made available since the data were initially processed, reprocessing would make a lot of sense. It would likely also allow for better interpretation of the tilted blocks. Ray-based modeling could then be used for identifying qualified events for accurate amplitude variation with offset (AVO) analysis, by generating shot gathers for model iterations based on assumptions of the oil or gas content in the potential reservoir. Comparing modeled shot gathers to field records will then provide additional confidence in interpretation. This may mitigate exploration and production risks, and even de-risk a potential drilling campaign.

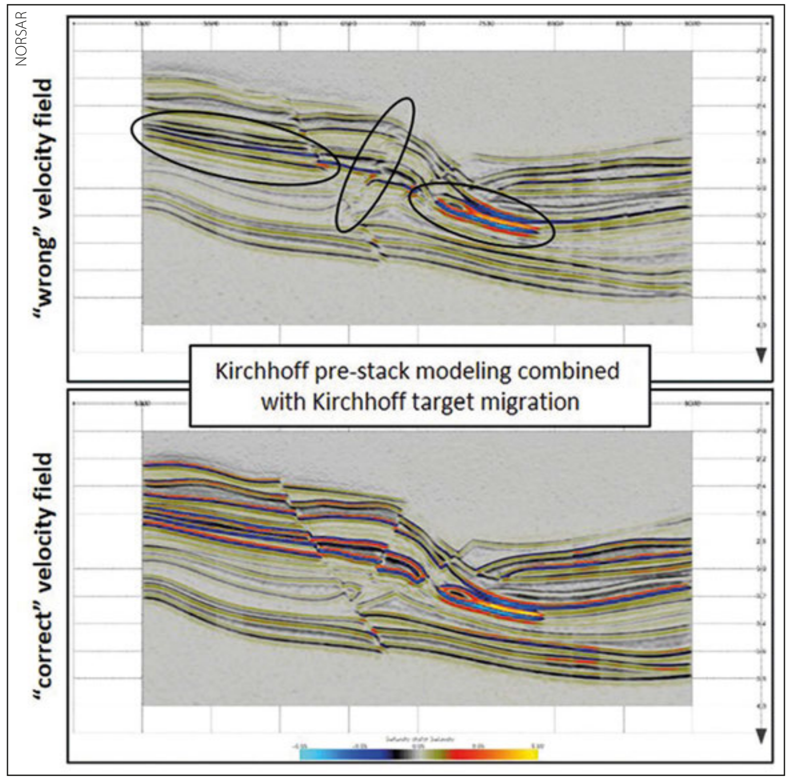
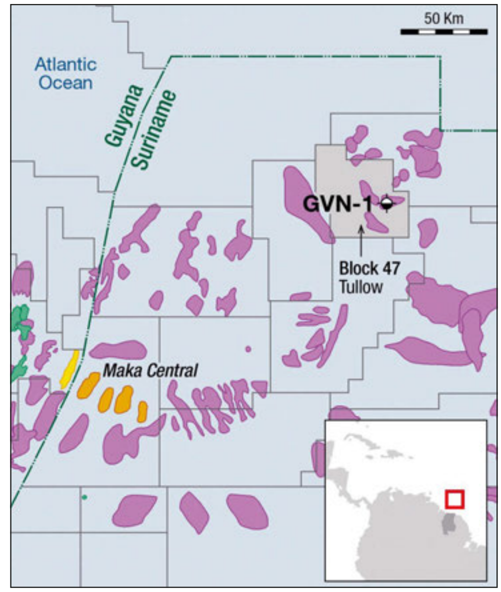


Figure 6: The impact of inaccurate velocity fields on the seismic image.

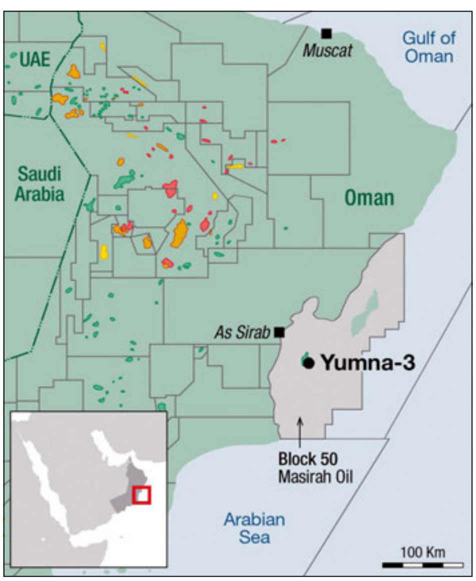
Combining different ray-based modeling approaches may not only guide new seismic acquisition, but also help to make the most out of existing data. ■

Suriname: Offshore Cretaceous Trend Falters



Tullow's Block 47 GVN-1 has reached TD at 5,060m, encountering good quality reservoir but only minor oil shows. Drilling, delayed from 2020 due to Covid restrictions, was completed using the Stena Forth drillship in 1,856m of water. Best estimate prospective resources for the well had been posted at 235 MMboe, with a 34% geological chance of success. The well tested the **Goliathberg** and **Voltzberg North** targets in the Cretaceous turbidite play. Tullow hoped to extend the **Guyana–Suriname** fairway to the northeast in a bend bordering a Cretaceous kitchen to the west and the Demerara High to the east. This has proven prolific so far, with the Canje source kitchen charging oil gas and condensate fields from Liza to Keskesi East. Tullow have a huge acreage position to follow up in this area with two other adjacent blocks in the Demerara Basin (Blocks 54 and 62) and could yet join the likes of Apache as a large independent with a major discovery after a string of non-commercial wells in Suriname. Ratio and Pluspetrol are partners on Block 47. ■

Oman: Offshore Shows More Potential

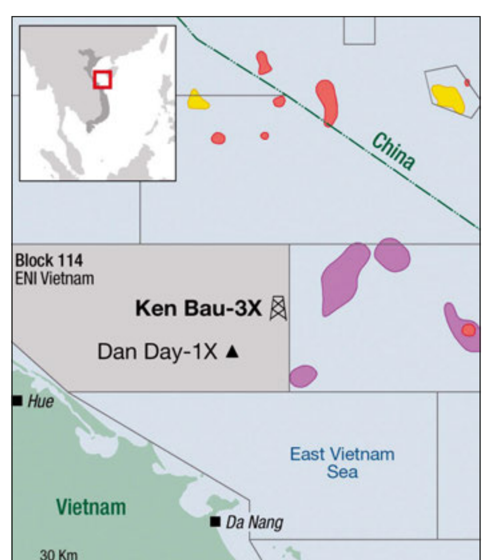


Masirah Oil Ltd, an 86.37% owned subsidiary of Rex International Holding Ltd, has had exciting results from its three well campaign on the **Yumna Field**, **Block 50, offshore Oman**. However the subsequent wells in the campaign have had less positive results, with the Zakhera prospect having oil shows and two further Yumna satellites, Yumna North and East, being water saturated.

The Yumna Field is a tilted fault block in the shallow offshore part of the Masirah Graben, a northeast–southwest trending basin along the Oman coast. The basin seems to have been historically overlooked, perhaps on grounds of materiality and challenges posed by the thrusted ophiolitic mélange in the shallow section. The field was discovered by the GA South-1 well, drilled by Masirah in 2014. The reservoir is the Upper Cretaceous Lower Aruma Formation, a transgressive sheet sand. While thickness is a modest 10–20m, the sand has excellent porosities of 21–24% and 2 Darcy permeability.

Both **Yumna-2** and **Yumna-3** have been completed as producers and a production rate of 20,000 bopd has exceeded expectations. However, the lateral extent of the good quality reservoir is now in question, as poor reservoir quality is stated as the reason for lack of commercial hydrocarbons at Zakhera. Near the Yumna Field, sand quality is high, as proven by Yumna **North-1** and **East-1**, but charge or trapping issues will need to be better understood. Either way, there is still significant potential for Masirah in the block, which covers the greater offshore part of this overlooked basin. ■

Vietnam: Eni Appraise Gas and Condensate at Ken Bau



Eni kicked off its Vietnamese 2021 drilling campaign in **Block 114, Song Hong Basin**, in early March. The KB-3X appraisal of the significant 2019 gas discovery, **Ken Bau**, was spudded some 8 km southeast of **KB-1X**, with the PetroVietnam VI jack-up in 95m water. Eni estimates resources at the accumulation at around 7–9 Tcf gas in-place with 400–500 MMbbl of associated condensates. The reservoir consists of Upper Miocene sands. Once operations at this well have finished, the much-anticipated **Dan Day-1X** wildcat will follow, situated to the south of Ken Bau. Eni and Essar are partners on the block. **Kris Energy** have **Block 115** to the east and are expected to announce a farmout on that block very soon. ■

Breakthroughs in Geology

Rather than 'Eureka' moments, a gradual development of ideas led to the major concepts that transformed the earth sciences.

JANE WHALEY

Geology, like all sciences, is continually developing and ideas behind it evolve over time, through the hard work and expertise of many people. Having said that, a number of ideas have dramatically revolutionized the science, such as uniformitarianism in the 18th century and, more recently, the theory of plate tectonics.

In his new book, *Breakthroughs in Geology*, Graham Park, Emeritus Professor of Tectonic Geology at the University of Keele, UK, describes the ideas that he believes have transformed earth science, devoting a chapter to each of his chosen concepts, moving through time to the most recent developments. As Prof. Park says in his preface, such a list is bound to be subjective and others may choose differently, but he discusses all his breakthroughs in a manner that allows you to appreciate the importance of interlinking ideas and disciplines. He goes into each in some depth, while describing them clearly in a manner that the non-specialist will understand, all amply illustrated. He briefly summarizes each new concept, and links it to previous interpretations on the topic, before indicating its impact on geological science. He also discusses the influential players involved in each breakthrough, with brief bios and descriptions of their seminal papers.

The book is a fascinating read and makes you admire the intellectual imagination and integrity required to make that first step toward a breakthrough; it takes bravery and self belief to move against accepted norms, as some of the early geologists did. James Hutton's description of the Earth as having "...no vestige of a beginning – no prospect of an end..." was at odds with the contemporary view of an unchanging Earth created in its present form over a time span outlined in the Bible. The first two chapters are devoted to those early scientists, such as Hutton, Lyell and Darwin, who used a range of disciplines to identify the main principles of the newly emerging science of geology.

The third chapter looks at the concept of continental drift, which developed as geologists wrestled with the question of how mountains formed once ideas such as 'the contracting earth' were abandoned. Although Wegener is rightly considered to have formulated and promoted the idea, the author explains the way in which his work built on that of many other geologists. Wegener's theory took time to be accepted, until a mechanism behind the drift of the continents could be found, ultimately leading to the idea of mantle convection (Chapter 4). Proving this concept illustrates how interlinked scientific disciplines are needed to develop these breakthroughs; for instance, the discovery of radioactivity by physicists enabled geoscientists to date rocks and gain insights into the make-up of the interior of the earth, further elucidated by the new science of geophysics.

Chapter 5 discusses important developments in structural geology, allowing highly strained rocks to be described and understood for the first time. This led to the investigation of shear zones and the realization of their significance with regard to major crustal displacements.

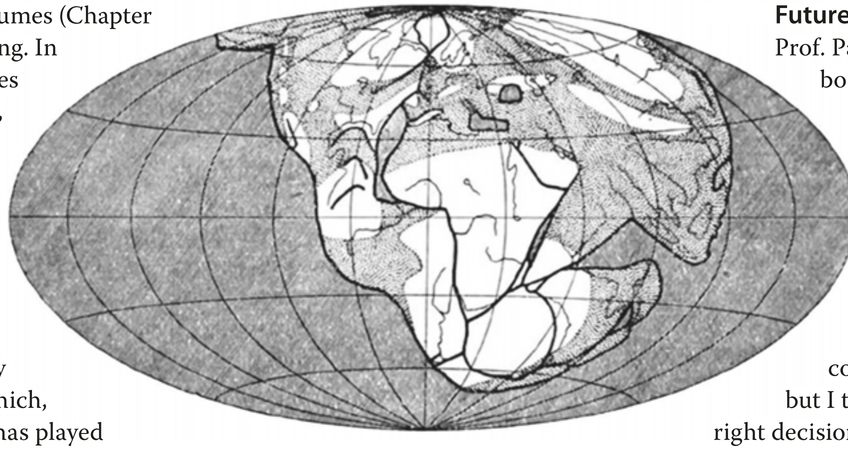
Most Influential Breakthrough

The following chapter concentrates on plate tectonics, which resolves the main issues surrounding a mechanism for continental drift and is, in Park's opinion, "the most influential breakthrough in earth sciences since Darwin." The concepts of seafloor spreading, mid-ocean ridges and subduction at oceanic tranches eventually developed through extensive seafloor mapping coupled with the use of paleomagnetic dating and some 'out of the box' thinking. This section also covers new concepts like transform faults and the growing understanding of the significance of volcanoes and earthquake zones. The author points out the large number of earth scientists involved in fleshing out the theory of plate tectonics, none of whom can take full credit but all of whom provided significant input.

Several of the subsequent chapters discuss topics that have proved important in refining and deepening the plate tectonics theory, such as ophiolites (Chapter 6), back arc basins and trench roll back (Chapter 9) plus hot spots and mantle plumes (Chapter 10); all equally fascinating. In Chapter 8, Park discusses fault system kinematics, a concept that has hugely changed and influenced the way structural geologists think about faults and faulting.

The final two chapters cover relatively new concepts, one of which, sequence stratigraphy, has played a significant role in hydrocarbon exploration. In a remarkable leap from accepted thinking, Peter Vail and his team at Exxon in the 1970s looked at the boundaries between rock layers, instead of the rocks themselves, in order to correlate distinct chronostratigraphic units on a continental or even worldwide scale. While there are limitations to the concept – it is of little use with many carbonates, for example – sequence stratigraphy combined with seismic imaging revolutionized the work of exploration geologists.

The final chapter discusses gravity spreading, and the role extensional forces generated by gravity play in tectonics, touching on salt tectonics and the more recent ideas around channel flow.



Alfred Wegener's first map of Pangea, outlining the theory of continental drift.

Future Debates

Prof. Park rounds off his book with an excellent glossary explaining terms encountered in the book, as well as a comprehensive chapter-by-chapter reference list. Initially, I was surprised by the absence of a final concluding chapter, but I think he made the right decision. Each chapter has a summary and conclusions in the form of a short Postscript outlining the significance of, and subsequent developments in the breakthrough featured, so there is no need for repetition of these points at the end.

As Prof. Park points out in several places in this excellent book, geology is constantly evolving and there will be many more breakthroughs in the future. Meanwhile, the research, the generation of new ideas, and the ensuing debates all continue!

Breakthroughs in Geology: Ideas that Transformed Earth Science
Dunedin Academic Press, 2019
Graham Park ■

Championing Secure Energy Supply

Iman Hill, the new Executive Director of the International Association of Oil & Gas Producers (IOGP) talks about her new leadership role and the future of oil and gas in a transitioning world.

You have had a very successful oil company career. What attracted you to this very different role at the IOGP?
I've been privileged to work for some of the best companies, including BP, Shell, BG Group, in every continent and in settings from desert to ultra-deep water. As you progress, you take on increasing responsibility, bigger field developments and operations, more production, more complex stakeholder relationships. The IOGP role may look to most as if it is a step out from my past but actually, it makes perfect sense. It is such a multi-faceted role and allows me to bring everything I have learnt over the course of 30 years, technical and commercial know-how, stakeholder management and advocacy for our industry, together in one role. And what a pivotal time to be trusted to lead the Association.

Negative public opinion and the current pandemic create significant challenges for the industry. How do you see IOGP helping companies address these issues and particularly those around the energy transition and the oil industry's role in this?
Supporting our member companies on their journeys towards a lower carbon future is one of the Association's core tasks and a personal commitment. There is a variety of ways in which to achieve the goals of the Paris Agreements. Our industry is not only supporting global society in its efforts – we are making a tangible difference in fighting climate change: by reducing emissions from our own operations, by providing cleaner energy, and by developing low carbon technologies. IOGP is supporting its member companies across the board in this. To give you a couple of examples: IOGP has been a supporting organization to the Methane Guiding Principles since 2018 and is contributing with a range of good practice guidance including guidelines for methane emissions target setting, quantification and reporting. Our Engineering Leadership Council is leading on the Low Carbon Agenda with a portfolio of deliverables related to electrification, flaring and venting, carbon capture and storage, and energy efficiency. Together with the Oil and Gas Climate Initiative (OGCI) and the IPIECA, the global oil and gas industry association for environmental and social issues, we are working on recommended practices for methane emissions detection. We are also developing a flaring management guideline with the World Bank's Global Gas Flaring Reduction (GGFR) Partnership, that will be relevant for governments, regulatory bodies as well as the oil and gas industry.

How do you see the IOGP adapting as integrated oil companies (IOCs) strive to become integrated energy companies (IECs)?
In every corner of our sector, every company is working daily to tackle the duality of the challenge that we face; how to meet the world's energy demand as cleanly as possible and to drive the fight against climate change. It is not only IOCs, but also NOCs; we are all in this together and IOGP member companies span the whole spectrum. So, recognizing the shifting strategies of our members, and having a principle that an association should only exist for as long as it remains relevant and delivers value. One of my first tasks as Executive Director was to oversee a broad and deep strategic review which will identify how IOGP needs to evolve to best address the challenges and transitions in the industry and across our membership. We have collected quality data and insights from a broad range of our members as well as from external stakeholders and are now developing the potential scenarios to recommend to our Board.

What do you see as the key personal challenges you will face in this role?
Firstly, I could not have asked for a warmer welcome, for a better handover or for a more talented and dedicated team that truly shares my passion for this industry. Despite the ongoing challenging circumstances with all of us working from home, we all share a common purpose, which is to take the delivery of value from the Association for its members to the next level. My biggest personal challenge is probably to remember to hold back a little and to ensure that our relatively small team does not take on too much at once.

The oil and gas industry has huge challenges in terms of public perception and license to operate. How will the IOGP help the industry project a more positive and less defensive 'persona' to the broader public?
I personally believe with a passion that we need to be a consistently louder, factual and non-emotional voice for our industry. There is just so much misconception, and downright fiction that is spouted about our industry and a widespread lack of understanding of this industry's efforts in driving the energy transitions to the lower carbon future that we all want. We have every reason to be proud of this industry, not least because without oil and gas production, not only would we not have access to reliable, affordable energy, we also wouldn't have many of the medical items that have been needed to fight Covid, or even some of the very simple every day household items that we rely on. It's easy to talk about the developing world's vast and growing need for energy from fossil fuels, but let's not forget that energy poverty is being experienced in the developed world, right here in the UK. Living in homes without power, with no money to heat or cook, sounds like a Victorian-era social issue, but it's a real problem in Britain today. So, let's stand up and speak up. No one else will do this for us. This not only requires relentless focus on improvements in the areas of mitigating emissions, reducing our environmental footprint and enhancing our safety performance, it also means that we need to engage with all stakeholders involved.

How do you see the industry tackle the immense challenge of security of energy supply whilst achieving global net zero targets?
While over the next 20 years the global energy demand will rise by approximately 20%, mainly in non-OECD countries, global oil and gas production declines by an average of 8%/year. So, we need investments in both existing and new fields. The crunch question is: can investment in oil and gas be compatible with the transition to a low carbon future? The answer is so obvious to me, of course it can, and it is. The transition to cleaner energy is a journey we're already on, but like it or not, it's going to take a few more decades. In the meantime, we need traditional sources of energy. Vilifying oil doesn't change that and trying to downplay the role of natural gas or technologies such as Carbon Capture and Storage (CCS) is plainly incomprehensible if you're really after a cleaner and reliable energy mix.

At the same time, the industry must continue to demonstrate that everything possible is being done to reduce the environmental footprint of hydrocarbon production, that we continue to mitigate methane emission from our own operations and that we are driving the development of low carbon technologies such as CCUS and clean hydrogen as well as operating safely and cost effectively. IOGP is working in all these areas in support of our members.

Loss of personnel and key skills from the industry is an important issue. What are your views on this?
Access to a talent pipeline of skills has never been more important. The world of work is changing and to remain competitive organizations across the board will have to think differently about how they manage talent. In out sector we are faced with the compounding effects of fewer entrants year on year and 1000s of years of experience getting ready to retire. So, this is very high on our agenda. More than ever, entrants into the workforce want to be sure that they will see themselves represented in the workforce of the companies they are considering joining. So, it is those organizations providing a diverse and inclusive working environment and a culture where differences, in the way we present ourselves, communicate and make decisions, are encouraged and valued that will be the winners of the talent war. Recognizing the criticality of this to the health of our industry, the Board of IOGP recently endorsed a recommendation to establish a new task force led by IOGP and in partnership with the American Petroleum Institute and other contributing organizations. 'The Energy Workforce of the Future' task force is a co-ordinated effort for our Industry aimed at addressing the root causes of the industry's attraction and retention challenges, identifying and sharing best practices on creating diverse and inclusive cultures as well as looking at the skills mix needed for the coming decades. We welcome all potential collaboration and contribution in moving this forward. ■

ESG and Those Burning Issues

What does ESG look like under the bonnet? As a company are you doing what you say you do and is it helping? The issue of how an organization manages environmental, social and governance or, in short, ESG issues seems to be more important than ever in a still pandemic-infected, somewhat fragmented global economy. For an O&G sector piloting transition it is a burning one.

Burning, as in flaring (see Cover Story in this issue), is a case in point. Speaking at an online International Petroleum Week event in February, Matt Haddon of the sustainability firm ERM, listed five steps for O&G decision makers on the road to transition. After telling his audience they had to measure and understand their carbon footprint, make the link between low carbon pressures and financial performance, set a net zero goal with near-term targets and pursue carbon removal techniques, Matt paused for breath. Step 5, he announced, was to stop routine flaring because without this measure "you have no credibility".

According to the World Bank Group, routine global gas flares emit more than 400 million tonnes of CO_2-equivalent emissions every year and in the US at least, some states are resorting to legislation. A growing number of oil companies, including the likes of Shell, Chevron and Occidental, are signing up to the World Bank's 'Zero Routine Flaring by 2030' initiative – an ESG policy which also needs to show up as ESG under the bonnet.

Speaking at another online event recently, Caspar Chiquet of BP Shanghai reminded his audience that BP was taking an integrated approach on the road to transition. That meant moving away from the previously siloed world of upstream and downstream and looking right across the value chain. "It means less volume, more value in the hydrocarbons business," he said "and it's where the cash flow comes from that enables us to do more in the renewable energy business."

That integrated approach and the ESG that goes with it is designed, in part at least, to appease the investment community. Investors want to see old fashioned O&G returns combined with real evidence of transition. Getting rid of flaring is just one part of the deal. The industry's investment in large-scale renewable projects is another but as Chiquet notes, high value, high return hydrocarbon projects must be part of the mix, certainly until 2050 and probably well beyond. ■

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.

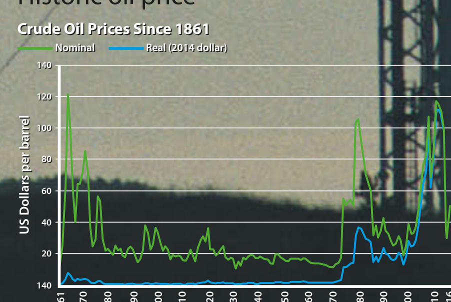
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

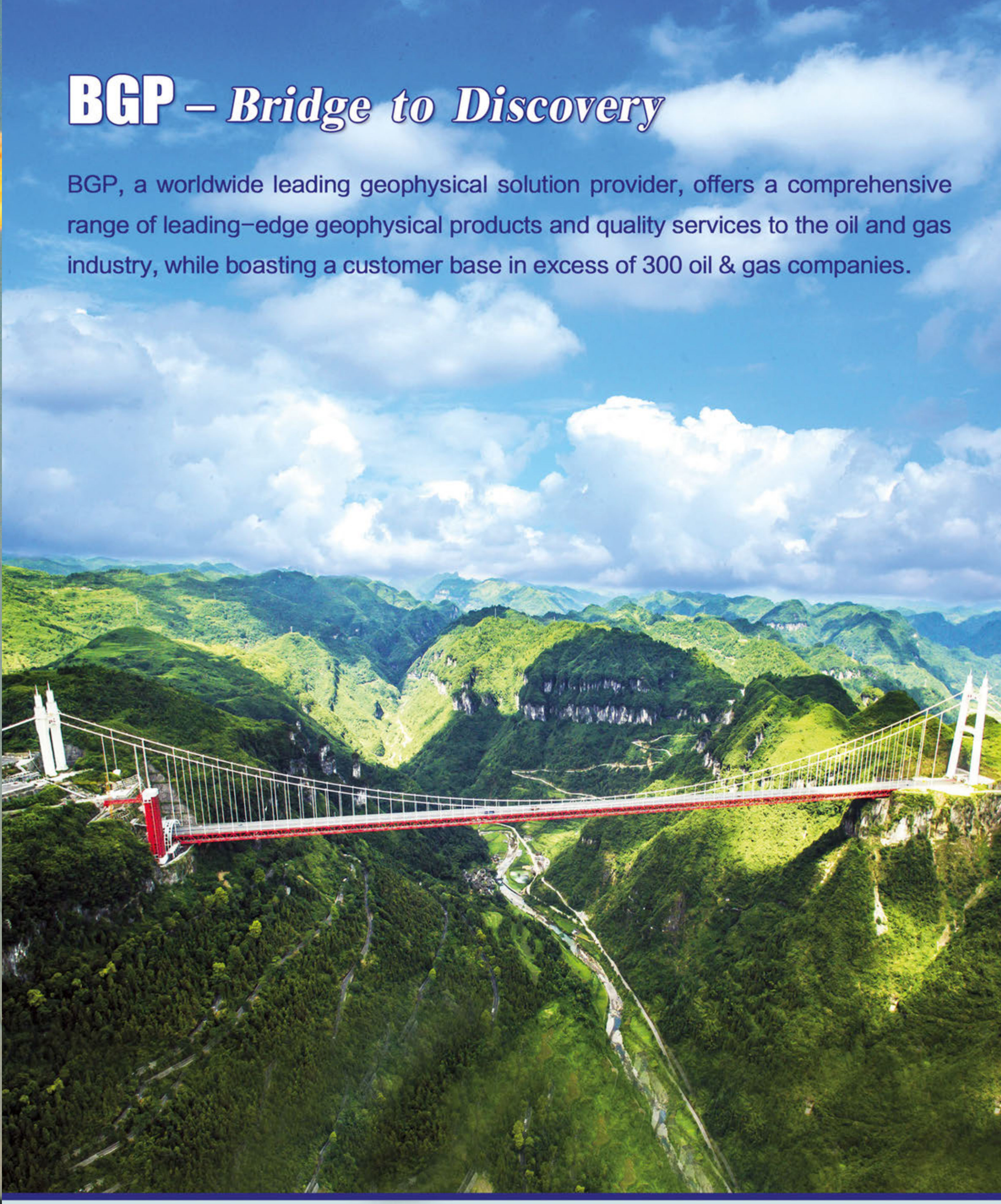
Supergiant field
Recoverable reserves > 5 billion barrels (800 million Sm³) of oil equivalents

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




BGP – Bridge to Discovery
BGP, a worldwide leading geophysical solution provider, offers a comprehensive range of leading-edge geophysical products and quality services to the oil and gas industry, while boasting a customer base in excess of 300 oil & gas companies.