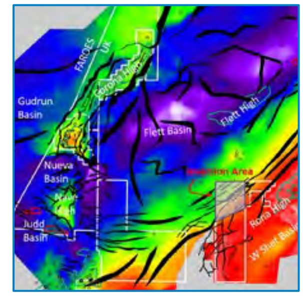
GEO ExPro

VOL. 19, NO. 1 – 2022

GEOSCIENCE & TECHNOLOGY EXPLAINED



ENERGY TRANSITION UPDATE
Brazil: Losing its Way

PALAEONTOLOGY
"Land Plants Didn't Evolve Until the Silurian!"

Q&A
Sophie Zurquiyah – Repositioning CGG for the Transition

GEOPHYSICS
A Clearer Vision with Seismic Inversion

GEO TOURISM

EXPLORING THE HEARTLAND OF THE INCAN EMPIRE

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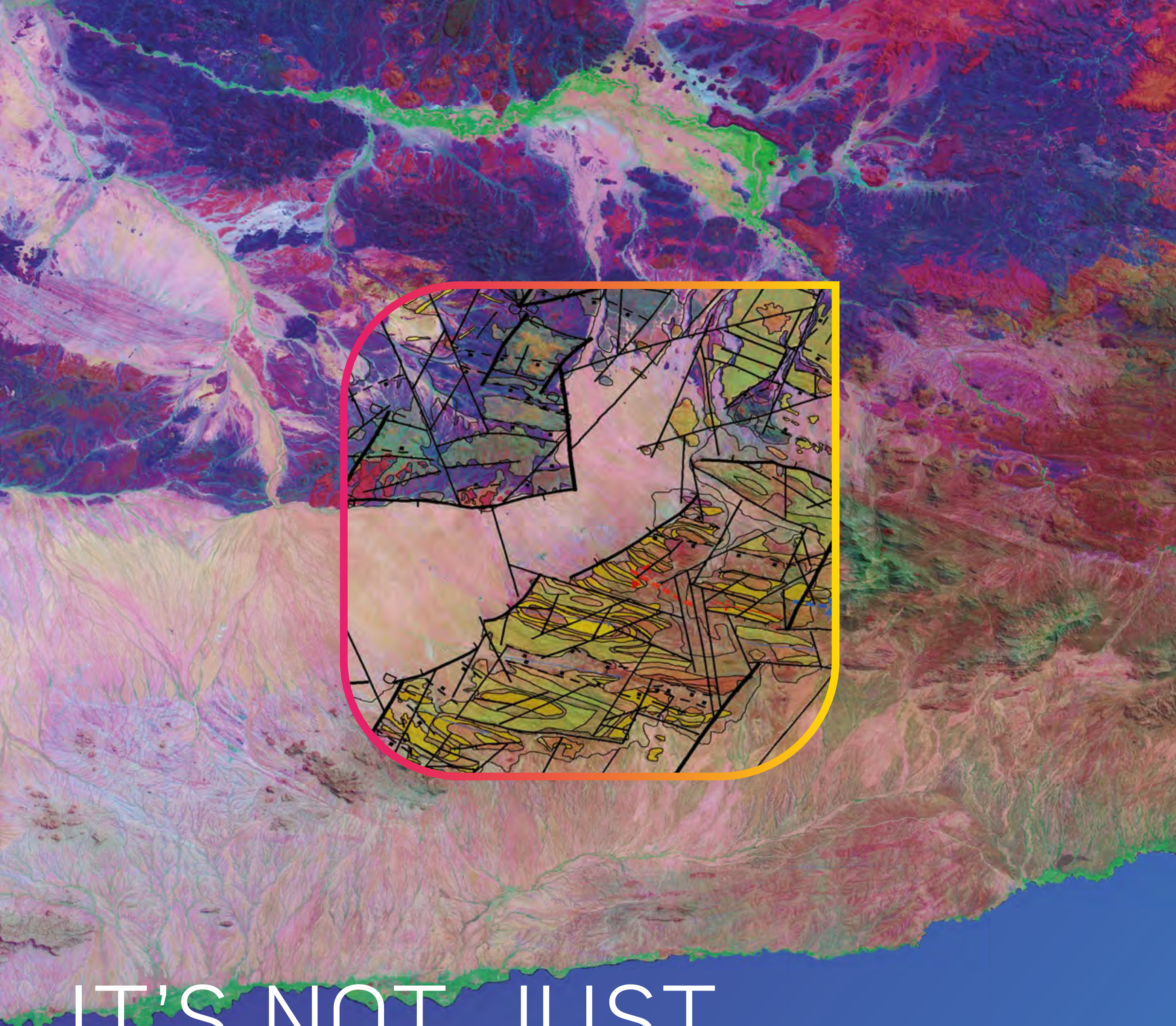

CONTENTS

Vol. 19 No. 1
This issue of GEO ExPro focuses on South America; Sustainability and the Environment; Seismic Interpretation; Increasing Efficiency in E&P.

5 Editorial

6 Regional Update: South America and Caribbean

8 Licensing Update: South America – Licensing Slows

10 A Minute to Read

15 ***Cover Story:*** GEO Tourism: Exploring the Heartland of the Incan Empire

20 Seismic Foldout: Offshore Oman: Stunning Hydrocarbon Geology from a Closing Ocean

26 Palaeontology: "Land Plants Didn't Evolve Until the Silurian!"

30 Energy Transition Update: Brazil: Losing its Way

32 Global Resource Management: Critical Minerals for Electric Vehicles

36 HotSpot: Global Wildcatting – Going with the Flow

38 GEO Education: Master's Meltdown or New Dawn?

42 Seismic Foldout: Unifying Offshore Brazil: From the Abimael Propagator to the Abrolhos Islands

48 GEO Physics: A Clearer Vision with Seismic Inversion

52 Recent Advances in Technology: From Arrhenius to CO_2 Storage – Part XIV

56 Technology Explained: AI – Its Use in Exploration and Production

60 Energy Transition: Palynology Reinvented

64 Energy Opportunity Foldout: Offshore Jamaica

70 Exploration Update

72 GEO Media: Rock Doctor

73 Q&A: Sophie Zurquiyah – Repositioning CGG for the Transition

76 FlowBack: Oiling the Culture Wars

Previous issues: **www.geoexpro.com**

GEO ExPro
GEOSCIENCE & TECHNOLOGY EXPLAINED

COVER STORY 15

Exploring the Heartland of the Incan Empire

From the iconic ruins of Machu Picchu to the ancient capital of Cuzco, the Inca's intimate relationship with some of South America's most spectacular geology is brilliantly displayed in modern-day Peru.

32 EV-CHALLENGES

When evaluating how much 'greener' electric vehicles (EV) are compared to the latest petrol-powered vehicles, we must look at the whole picture, which should include a 'cradle to grave' approach.

56 AI: OVER-OPTIMISTIC?

Artificial Intelligence (AI) has at least one feature in common with hydrocarbon exploration – a history of boom and bust. AI's boom-and-bust is probably much easier to explain – excessive optimism.


SHUTTERSTOCK


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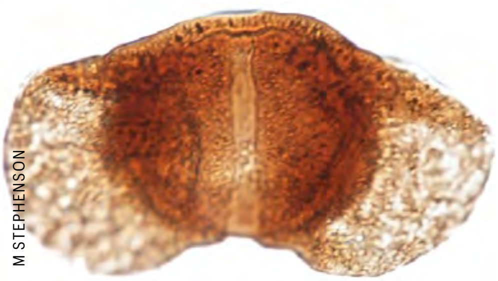
CHRISTOPHER MICHEL (CC BY 2.0)


M STEPHENSON

52 THE DOOM OF A PHOTON

The history of an individual infrared photon being emitted upwards from Earth's surface into the atmosphere is analysed as a one-dimensional random walk. Will it return to Earth, or leave into outer space, or will it stay in the atmosphere forever?

60 PALYNOLOGY AND CCS

Palynology (the study of fossil spores and pollen) would seem to be far away from the big engineering and reservoir research questions for carbon capture and storage (CCS) and the energy transition, but surprisingly may have purpose in the crucial area of reducing the uncertainty caused by geological heterogeneity.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SOUTH AMERICA – RICHES AND STRIFE

Iain Brown
Editor in Chief

The last few years have been tumultuous for the world in general but particularly so for South America. In recent times, mass protests have swept across several countries, including major oil and gas producers. Protestors are disillusioned with corruption, anti-democratic practices, inequality, and the rising cost of living. These conditions and widely varying economic models lead to uncertainty over energy policy. Especially when the energy transition is occupying the more progressive governments.

Improved technologies, cheap capital plus financial subsidies have substantially reduced the cost of renewable energy in South America. To measure the long-term costs of building an energy project, the industry often evaluates using the levelized cost of energy (LCOE). In 2019, eight countries in the world had a lower country-level weighted LCOE for new onshore wind projects when compared to the cheapest fossil fuel projects. Of those eight countries, two of them, Argentina and Brazil, were from South America. Brazil, Chile and Peru also recently announced record-low solar photovoltaic auction prices, reflecting the growing feasibility of constructing solar projects in the region.

In the conventional energy realm, oil-exporting South American countries are now benefitting from resurging global energy demand and higher crude prices providing a boost to oil nations' balance sheets. However, these benefits are not equally distributed among oil and gas exporting countries. South American nations that produce mostly heavy crude with higher sulphur contents, such as Venezuela, Ecuador and Colombia, are seeing diminishing global demand for those types of resources. They must now develop their own renewable energy portfolios, and cleaner fossil fuels, to progress as the world transitions to cleaner fuels. Guyana and Brazil, which have lighter oil and lower sulphur content, as well as relatively low operating costs, will still attract foreign investment.

Brazil and Guyana are likely to be amongst the world's top sources of oil supply growth over the coming years. The current government in Brasil has implemented policies that have brought substantial foreign investment to the oil sector and although the country needs to carry out further reforms to introduce market competition, Brazil is clearly on track for major increases in oil and gas output.

Guyana, despite its small size, is poised to become the region's newest 'petrostate'. However, it has been slow to develop the institutions and legal framework needed to govern the new oil industry and manage the significant expected revenues, and a recent political crisis has further delayed that process. Nonetheless, Guyana is set to become one of the region's top producers. It is hoped this new wealth will at least in part be used to develop its green energy potential.

SOUTH AMERICA AND CARIBBEAN

The region of South America and the Caribbean has had a mixed bag of results in the last 12 months or so. We have seen more world class oil discoveries being made, play openers, a return of bid rounds, and slow progress with deal flow.

Ian Cross, Moyes & Co

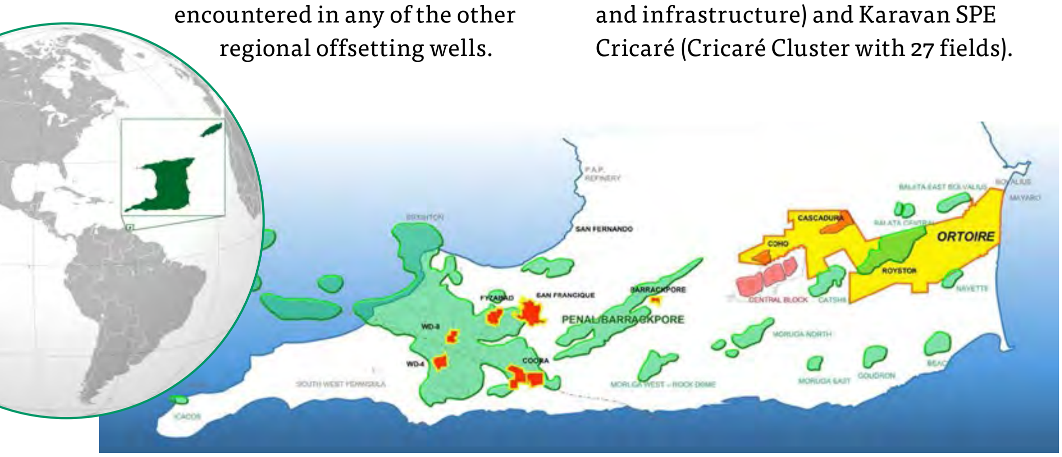
The prolific oil province offshore Guyana continues to charge ahead, with ExxonMobil announcing several more discoveries taking discovered recoverable resource for the Stabroek Block to over 10 billion oil-equivalent barrels since the Liza-1 discovery in 2015. Success has continued in Guyana into 2022 with CGX Energy announcing the Kawa-1 well as a hydrocarbon discovery, in the northern part of the Corentyne Block. Kawa-1 is a deep well reaching a total depth of 6,578m. It is located close to the maritime boundary with Suriname and adjacent to APA Corporation's (Apache) Block 58 where the play fairway extends to the south-east.

One of the discoveries made in the region which has stayed below the radar, largely because of the bigger and higher profile discoveries made elsewhere, is the Touchstone Exploration, Royston-1 exploration well, in the Ortoire Block on the eastern side of Trinidad. The Calgary-based company has had an impressive run of successes in this block along with 20% partner, Heritage Petroleum Company. Its latest well, Royston-1, confirmed a light oil discovery in the lowermost section of the well, which is understood to represent a new zone not encountered in any of the other regional offsetting wells.

Touchstone announced that Royston-1 encountered an intermediate sheet of the Miocene Herrera Formation and produced 1,786 barrels of total fluid at an average flow rate of 705 bbls/day. Interestingly, Royston-1 was targeting a deep gas prospect that an offset well, originally drilled in the 1960s, had detected gas in, but remained untested. Long-term testing of Royston-1 is planned with results due in the coming months. Touchstone is planning two additional wells, from the existing Royston-1 surface location, to target the Royston Deep Prospect and the Cretaceous Kraken Prospect. Kraken will have been de-risked with the deeper oil discovery at Royston-1.

Several countries in the region are either planning licensing rounds in 2022 or have rounds in progress. These include Argentina, Barbados, Brazil, Colombia. Cuba, Dominican Republic, Ecuador, Guyana, Mexico, Peru, Suriname, Trinidad and Tobago, and Uruguay. Some of these will include recycled acreage from previous bid rounds when lower energy prices made them look less attractive.

On the deal side, Brazil has seen almost 50% of the transaction activity in the region followed by Argentina with 15% and Colombia with 10% according to data from the Moyes database. The large number of deals concluded in Brazil has been due to ongoing Petrobras sales of onshore fields as they focus their resources on the ultra-deepwater. Buyers include PetroReconcavo SA (Remanso Cluster with 12 fields), Carmo Energy (Carmópolis Cluster with 11 fields and infrastructure) and Karavan SPE Cricaré (Cricaré Cluster with 27 fields).



Map of hydrocarbon accumulations in the Ortoire Block, eastern Trinidad.

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}

Time
Ma: Million years ago
Ga: Billion years ago

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

LNG
Liquefied Natural Gas (LNG) is natural gas (primarily methane cooled to a temperature of approximately -260 ºC.

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

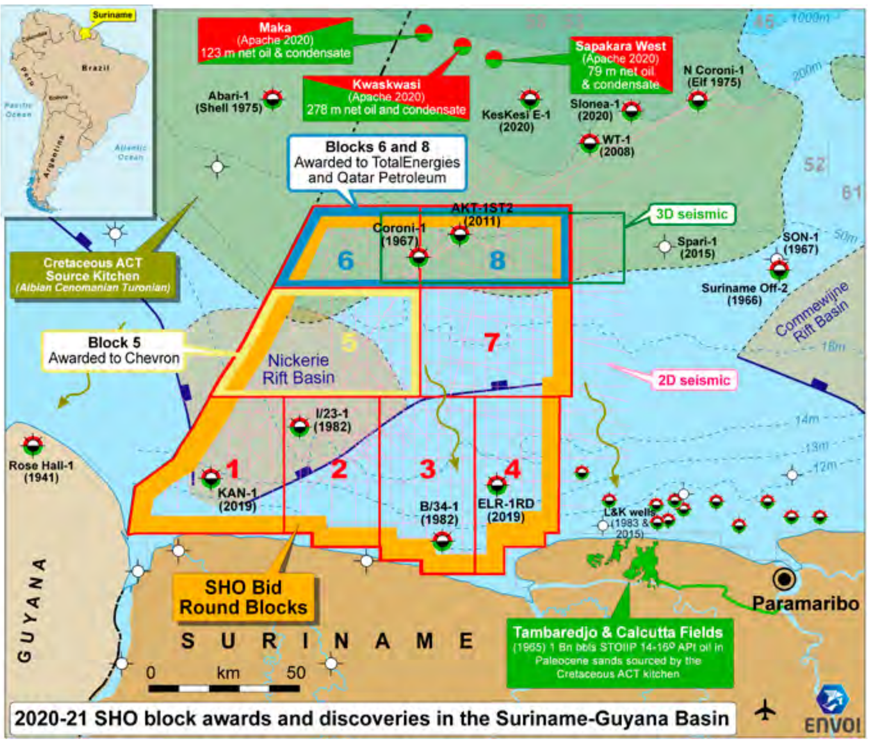
P3 reserves:

Quantity of hydrocarbons believed recoverable with a 10% probability

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

SOUTH AMERICA **LICENSING SLOWS**

South America and the Caribbean is currently seeing less licensing activity, at least partially because of the impact the Covid-19 pandemic on frontier exploration which has prompted international oil companies to focus on ILX and advantaged oil.



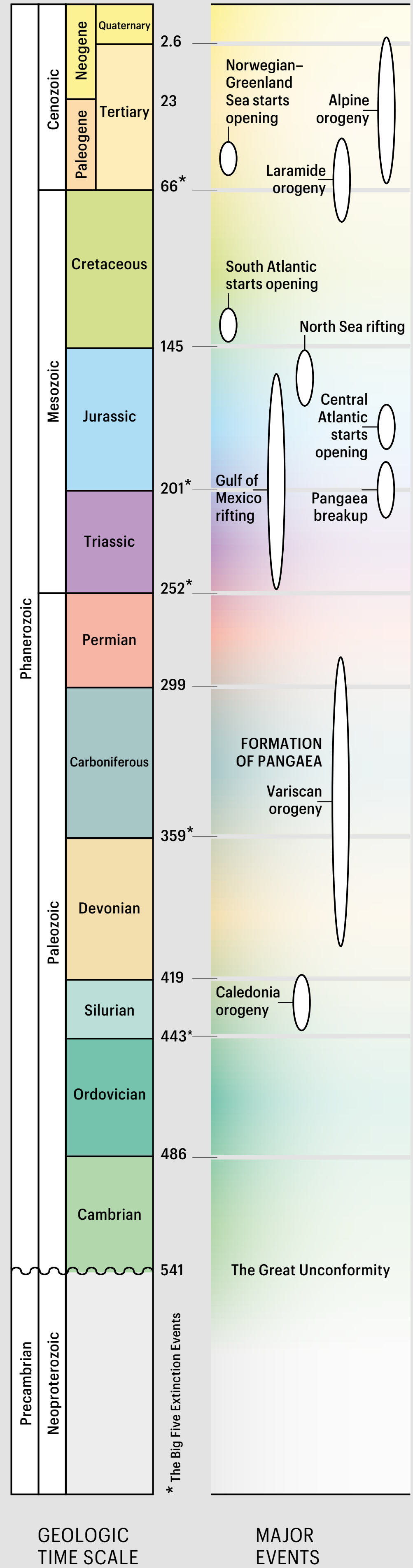
2020–21 Shallow Offshore (SHO) block awards in Suriname.

The relatively new and prolific petroleum province centred on the Guyana–Suriname Basin, has seen much of the offshore acreage already licensed. Suriname has seen seven offshore blocks awarded since 2016.

The most recent licensing activity was the 2020–21 shallow-water bid round. This attracted 10 bids for only three of the blocks which were awarded in mid-2021. TotalEnergies and Qatar Petroleum were awarded Blocks 6 and 8, which lie immediately south of Block 58, in which TotalEnergies and APA have discovered 1.7 billion barrels of recoverable resources. Chevron was awarded Block 5. All three blocks lie in shallow water depths and have a combined area of about 4,850 square kilometres.

As activity ramps up, the Government of Guyana plans to auction new blocks for offshore oil exploration by the third quarter of 2022, according to Vice President Bharrat Jagdeo.

In Brazil the public session for the submission of bids for the 17th Licensing Round was held in October 2021 but the round was not considered a success with only five of the 92 blocks receiving bids. The Brazilian government has since added 11 offshore exploration blocks located in the prolific pre-salt zone to its Permanent Offer initiative. There are now hundreds of exploration blocks that were either relinquished or never licensed by oil companies included in this initiative.



WHAT DOES 2022 HAVE IN STORE FOR THE OIL AND GAS SECTOR?

What should we all be considering in our planning for 2022 and what might the major developments impacting E&P be? If we could accurately predict this, we would all be rich but it's a safe bet that decarbonisation will continue (if not accelerate) in driving change, and this will naturally result in explorers keeping options open for the energy transition. But apart from the obvious, which key trends might be important this year?

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Oil Price to Firm

Oil and gas cash flows will remain very high with Brent at US$70–80 per barrel. The talk of $100 oil price remains hypothetical, but such a bull scenario could emerge with tighter global monetary policy if the core OPEC+ producers keep production below target levels and if Iranian crude oil remains off market. Further supply disruptions resulting from activities in Libya or the UAE could also create the conditions required for oil prices to rise above $100.

A $100 price spike would eventually be corrected by marginal production, primarily by US shale producers and other production players in Canada, Brazil, Norway and Guyana.

Project financing pressure from investors on asset managers could force some operators to choose to delist and go private. Further Covid variants are a threat to demand and prices, and remain impossible to predict.

Exploration to Remain Subdued

Conventional exploration is likely to remain subdued, continuing the trend set in 2021, despite improved prices. Spend will total US$20–25 billion, with wildcatting led by the majors and large NOCs. Deepwater plays with highly productive reservoirs will be prioritised, including giant prospects in Brazil, Guyana, Suriname, Namibia and South Africa.

Deepwater is likely to account for half of all new volumes and NOCs will lead exploration of their domestic unconventional plays in China and the Middle East. Expenditure growth will be led by well-funded Middle Eastern NOCs such as ADNOC and Saudi Aramco where there is less stakeholder resistance.

On a less positive note, in 2022, more governments could join those with existing exploration bans, though this is unlikely to include countries with basins holding substantial resources and remaining prospectivity.

Brittle Service Sector to Remain Under Pressure

The strongest service companies are already gearing up for the energy transition but the weaker ones, without the cash to invest in research, development and diversification will come under further stress. The seismic business which is still suffering from overcapacity may see further company consolidation with more vessels being permanently taken out of circulation. Increased utilisation is required before the sector can exert price pressure.

Operators are predicted to experience inflation of 5–10% in 2022, depending on the sector, and how much of this reaches the pockets of the service companies depends on the pace of the increase in activity. Global supply chain disruption, labour costs and increasing commodity prices will be passed through to operators, but this is unlikely to support increased service sector profit margins.

Carbon Capture and Storage (CCS) Will Mature

Proposed projects in Indonesia and Qatar will be sanctioned. Santos's plan to turn Bayu-Undan into a CCS hub will progress and TotalEnergies' Papua LNG redesign will facilitate CO_2 injection from the start of operations. Sizable hub developments could be sanctioned for the first time in Europe, and a proliferation of new global project proposals will emerge, driven by government policy and investor pressure. Seismic companies are now acquiring data specifically for CCS purposes, such as the recent contract award to PGS by BP to deliver CCS seismic acquisition over the Endurance reservoir off the UK east coast.

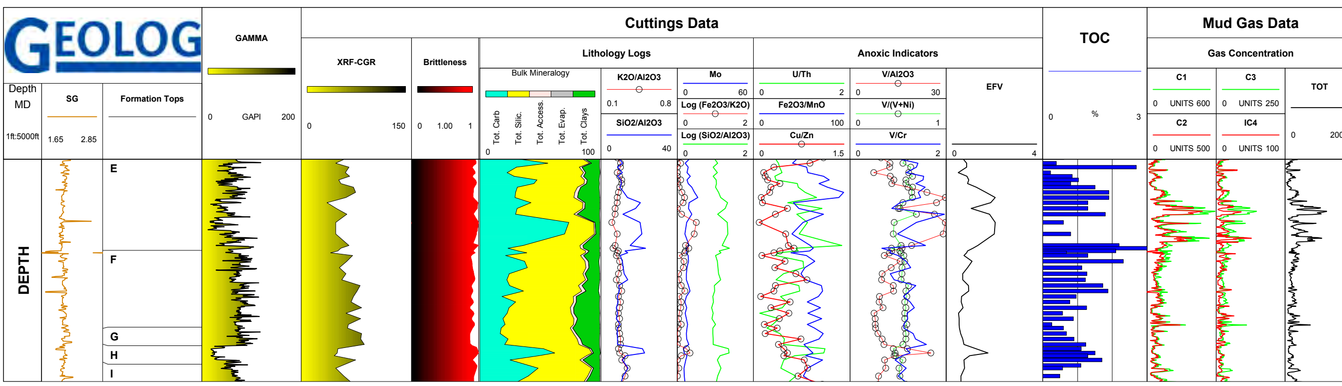
Diversification

Oil and gas operators and service companies will continue to diversify to exploit emerging areas such as renewables, CCS and hydrogen storage. Keeping options open for the future, operators will want to retain their diminished technical expertise but will apply their skills to new areas of business.

WHAT ABOUT THE DATA?

In today's world of big data and cloud-based solutions, increasing emphasis is placed on software applications enabling time and resource efficiencies when generating results. However, are we as an industry losing sight of the importance of input data quality in populating such models?

Data may derive from seismic or remote sensing (logs), along with primary rock (cuttings and core) and mud gases. Measurements from cuttings and mud gases are invaluable inputs to efficient cloud-based software applications as they are collected on almost every well, providing a framework of spatial and stratigraphic data. Assuming samples are analysed using a consistent approach, data points can be confidently compared: sample to sample, well to well.



GEOLOG

In today's exploration and production environment, surface logging companies are able to collect quantitative mud gas compositional ($C_1 - C_8$) and $\delta^{13}C$ isotopic data ($C_1 - C_3$) in real time using standardised, consistent protocols, with measurements confidently comparable well to well and providing key information regarding hydrocarbons within the petroleum system. Similarly, cuttings data, obtained at wellsite or in the laboratory, using consistent, quantitative approaches, can be utilised to assess reservoir quality and connectivity. These datasets provide key calibration points for petrophysical interpretations.

Efficiencies gained using sophisticated cloud-based software applications can only be truly recognised if the primary input data is obtained through this consistent quantitative approach, allowing end-user confidence in the data. In a world demanding ever-increasing efficiencies, the importance of good quality primary input data is paramount and cannot be overlooked.

SPE ABERDEEN

COUNTDOWN TO SEISMIC 2022

This conference will take place in person this year from 4–5 May at the P&J Live, Aberdeen.

Conference Chair, Ian Barron, Senior Geophysicist and Geoscientist at Shell explains, "This year the conference will focus on how seismic supports the UK's Energy strategy as well as sustainably support its Net Zero ambitions and the increasing development of new energies."

Covering the entire energy lifecycle, from exploration through appraisal, development and production and through to abandonment, decommissioning and repurposing, this conference is not only relevant to geoscientists and geophysicists, but also those in non-geo-related roles, such as petroleum engineers and senior decision makers in operators and service companies.

Themes will include topics such as reservoir characterisation, advances in seismic acquisition and processing and carbon capture and storage. Innovative technologies include autonomy in geophysical operations, digitalisation, big data and machine learning, mixed, virtual and augmented reality interpretation. Geophysical topics include the role of geophysics in supporting low carbon energies development, advances in near-surface seismic and 4D seismic and monitoring applications.

For more information on the technical programme and booking, visit the SPE Aberdeen website.

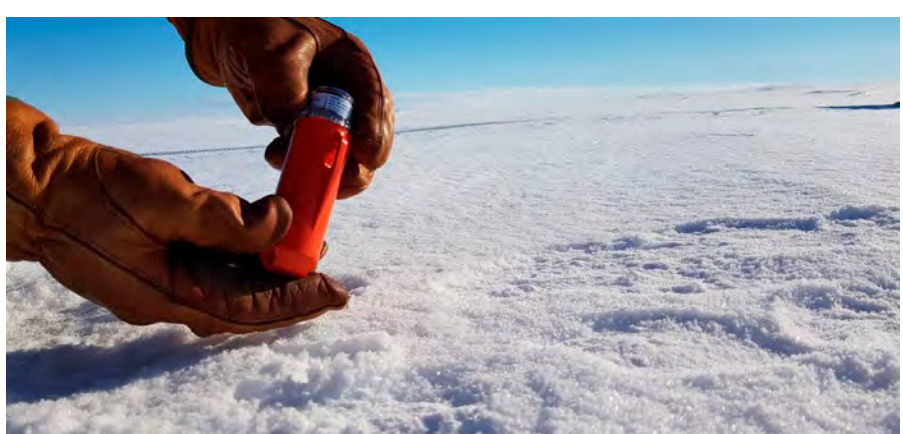
SEISMIC TECHNOLOGY USED IN ANTARCTICA AHEAD OF POTENTIAL EXTRA-TERRESTRIAL DEPLOYMENT

Scientists have deployed a network of seismometers onto Antarctica's Brunt Ice Shelf in an experiment which will test the ability of the instruments to operate on icy moons of the solar system. Twenty state-of-the-art seismic 'Nodes' built by STRYDE (the world's smallest and lightest land seismometers) have been deployed onto the ice shelf around the British Antarctic Survey (BAS) Halley VI Research Station, along with one 'short period' (SP) sensor built by Imperial College London and the University of Oxford and funded in development with the UK Space Agency. This is the first time that either of these instruments have been used in Antarctica, an environment which is the closest analogue of an icy moon found anywhere on Earth.

In addition to laying the groundwork for future space science missions, this exciting and novel experiment will also help to understand the floating ice shelf upon which the BAS Halley VI Research Station is located. The team behind the study have already started to gather useful data on seismic vibrations recorded in the ice shelf, which may help to further illuminate the evolution of cracks in the shelf and ocean conditions beneath. This data will contribute towards understanding the changing nature of the Brunt Ice Shelf which is critical to planning future Antarctic operations.

Similar SP sensors are currently recording data on Mars as part of the NASA InSight mission and a further set will be sent to the Moon as part of the NASA Farside Seismic Suite in 2024. The hope is that seismometers like these will one day be sent to the icy moons of Saturn or Jupiter, where seismological recordings will be one element of data acquisition used to explore the moons' interiors, and to establish whether conditions exist where primitive life may have evolved. This project will test the ability of seismic instruments to perform in an environment like that found on these icy moons for the first time, and in doing so will play a key role in the search for life elsewhere in the solar system.

The Nodes were deployed in mid-January, and commissioning of the SP sensor was completed at the end of January 2022. The first Antarctic deployment is expected to last 2–3 weeks, ahead of a potential longer deployment next year. The project is a partnership between BAS, the UK Space Agency, University of Oxford, and STRYDE.



STRYDE

GeoConvention 2022

This conference will take place in person and virtually from **20–22 June** at the **Calgary TELUS Convention Centre**.

Join us in person or participate from anywhere in the world with one of the largest integrated geoscience and energy conferences!

GEOCONVENTION

Why Hybrid?

The last two years of hosting virtually has allowed GeoConvention to grow international participation significantly as earth science and energy professionals and students, keen to learn and share with some of the brightest minds in industry and academia, joined us from the comfort of their home or office from hundreds of locations throughout the world. There is also a certain value in meeting, networking, and collaborating in person that just cannot be replicated through a virtual platform and hence the push to host in both formats for the 2022 programme.

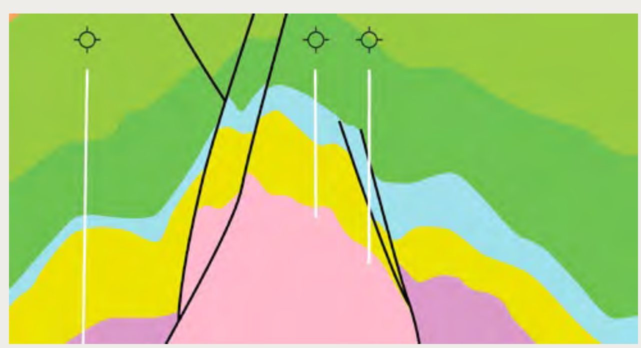
Why Attend?

With over 50 technical sessions identified, GeoConvention 2022 will feature a fully integrated programme representing a diverse collection of earth science disciplines, including geology, geophysics, petrophysics, minerals, water, earth, environment, and the energy world. From live panel discussions to targeted technical content, GeoConvention provides the ultimate opportunity to expand your knowledge and push your capabilities to the next level. Plus, with the full programme offered virtually through to the end of the year, you will not miss a thing!

We invite you to join us and thousands of geoscience and energy professionals, students, and academic leaders, as a presenter, exhibitor, or delegate, as we return to a live conference experience with simultaneous virtual execution, bringing the full event to your home or office.

For more information on the technical programme and booking, visit the **GeoConvention website**.

NEAR-FIELD EXPLORATION IS EXCITING!


GEOPUBLISHING AS

In recent years, near-field exploration has been the most important way in which new resources have been proven on the Norwegian Continental Shelf (NCS). A few more frontier wells have certainly been drilled too, such as Stangnestind in the Barents Sea and Stovegolvet and Dovregubben in the North Sea, but these have all disappointed.

Finding smaller volumes to extend the life of hubs and assets comes with its challenges and is not a trivial exercise. Even though technology has advanced, and an increasing number of offset wells are available for study, dry wells are still being drilled. This is partly because more complicated structures are being targeted, be it from a reservoir, source or sealing perspective.

This makes near-field exploration, despite its negative connotation at times, an often-fascinating arena of new technology, testing new play concepts, drilling small fault blocks and pushing the boundaries of hydrocarbon migration zones.

Learning about what went wrong and what went well in recently drilled wells is therefore a crucial part of successful exploration. The upcoming **NCS Exploration Conference**, taking place **1–2 June 2022** in **Oslo**, Norway, facilitates knowledge transfer between companies active on the NCS through a programme packed with interesting talks on recent discoveries, recent dry wells and much more.

EXPLORING THE HEARTLAND OF THE INCAN EMPIRE

SHUTTERSTOCK

Altiplano Plateau.

From the iconic ruins of Machu Picchu to the ancient capital of Cuzco, the Inca's intimate relationship with some of South America's most spectacular geology is brilliantly displayed in modern-day Peru.

Lon Abbott and Terri Cook

Incan civilisation arose in the Peruvian Andes in the 12th century. At its zenith in the early 1500s, the empire spanned much of western South America, from modern-day Ecuador to Argentina. At its heart lay the valley of the Urubamba River – the Sacred Valley – whose rich soils and mild climate are ideal for growing maize, making it the Incas' breadbasket. Today, a journey through this beautiful vale offers visitors gorgeous scenery, opportunities to marvel at the Incas' precision, earthquake-resistant stonemasonry, and tantalising glimpses of innovative ways the ancient civilisation harnessed the region's geology.

The Cuzco area's landscape is awe-inspiring, thanks to its location in the tectonically complex Andean subduction zone. Cuzco nestles in one of several pull-apart basins formed along the seismically active Cuzco normal fault system, located well to the east of southern Peru's active volcanic arc. This fault system separates the northern extremity of the Altiplano Plateau from the non-volcanic Cordillera Oriental mountain chain, which has been thrust over the Brazilian Shield. The Cuzco valley stands at 3,400m elevation on the plateau; glacier-clad peaks in the adjacent Cordillera Oriental soar to 6,300m, four kilometres above the cloud forests, sustained by moisture from the nearby Amazon, that wreath the precipitous river valleys.

Peru has been a subduction zone since the Jurassic, but today's dramatic topography only began forming about 26 million years ago as an indirect response to the consumption of the northern Farallon Plate in the California Trench. That event split the Farallon Plate's southern reaches into today's Cocos and Nazca Plates; the Nazca has been converging orthogonally with South America at about 11 cm per year ever since. Despite that steady convergence rate, shortening in the Peruvian Andes has fluctuated, with long periods of meagre, 1 mm per year shortening punctuated by brief but faster periods of 10–20 mm per year.

Scientists attribute these fluctuations to variations in the retreat rate (rollback) of the Nazca slab. During periods of rapid rollback, plate retreat has accounted for almost all the convergence. But during brief intervals of slow retreat, the bulk of plate convergence was instead accommodated by Andean shortening. These fluctuations explain the simultaneous presence of thrust faults in the foothills and normal faults in the High Andes and Altiplano: during times of rapid slab retreat, the body forces imposed by the region's great height have caused gravitational collapse amidst regional compression.

Most visitors arrive in Cuzco, but few are sufficiently acclimated to Cuzco's 3,400m elevation to enjoy tourist forays right away. For that reason, we suggest that you begin your exploration of the Incan heartland in the 2,800m-high Ollantaytambo, which is nestled in the Sacred Valley 72 kilometres north-east of Cuzco.

The Royal Estate: Ollantaytambo

Ollantaytambo, 'Olly' to most visitors, occupies a strategic location where the Sacred Valley narrows dramatically as the Urubamba River passes from Mesozoic marine rocks into more erosion-resistant Palaeozoic basement. Pachacuti, founder of the Incan Empire, made Olly a royal estate. A century later, when the Spanish conquistadors overthrew the Incan Empire and took Cuzco in 1533, they installed Manco Inca Yupanqui as the puppet emperor. Mistreatment by the Spaniards caused Manco Inca to rebel in 1536. After leading a 10-month siege of Cuzco, Manco Inca retreated to

Stonework in Ollantaytambo's Temple of the Sun.

his stronghold at Olly, where his army defeated 100 conquistadors and their 30,000 conscripted indigenous troops in 1537's Battle of Ollantaytambo.

Visitors reach Olly's pre-eminent archaeological site, the Temple of the Sun, by ascending steep staircases through stone-lined Incan agricultural terraces, passing several stone fountains. The Temple's stonework is impeccable, with many joints between adjacent stones too tight to pass a sheet of paper between them. The Wall of Six Monoliths consists of massive pink granite slabs derived from quarries six kilometres away, on the other side of the river. It is mind-boggling to contemplate how the Inca managed to transport these huge monoliths so far.

Atmospheric Machu Picchu.

Today Olly serves as the gateway to Machu Picchu. It is the staging area for spectacular four-day Inca Trail treks and the departure point for the 1.5-hour train trip through the deep Urubamba Gorge to Aguas Calientes, where most non-trekking tourists spend the night before touring Machu Picchu.

Machu Picchu: The Incan Magnum Opus

This world-famous archaeological treasure is the indisputable highlight of any trip to southern Peru. What really sets Machu Picchu apart is its dramatic setting. It is perched at 2,430m on a ridge connecting the 3,062m-high Machu Picchu Mountain with Huayna Picchu, the pyramidal peak that forms the ruins' stunning backdrop in iconic photos. The Urubamba River snakes picturesquely around Huayna Picchu in a stately oxbow, 400 metres below the archaeological site. Clouds and mist frequently obscure the middle-elevation slopes of the verdant canyon walls, making Machu Picchu the definition of an 'atmospheric' location!

Inca Trail trekkers enter the site through the Sun Gate, the complex's ancient main entrance. Those visiting by train either stay at a luxury lodge just outside the complex or take a 20-minute bus ride up from Aguas Calientes. Only day trips are allowed. The complex's most architecturally significant features are the semicircular Temple of the Sun, the Intihuatana Stone, and the Inti Mach'ay cave. All were religious sites dedicated to sun worship. The trapezoidal 'Solstice' window at the Temple of the Sun was oriented to let sunlight strike the central stone platform on the June solstice. Similarly, the pillar of the Intihuatana Stone points directly at the sun on the June solstice. Its name translates as 'hitching post of the sun' because the Inca believed the stone held the sun steady on its path across the sky. The exquisite stonework around the Inti Mach'ay cave was designed to channel sunshine through a tunnel-like window to strike the back of the cave for a few days surrounding the December solstice.

Recent research indicates that Incan stonemasons had a sophisticated understanding of earthquake engineering. Earthquakes occur regularly in southern Peru; a 1950 earthquake destroyed one-third of the buildings in Cuzco and damaged the Spanish-built Cuzco Cathedral. However, the building's Incan-built foundation was nearly unscathed; only the corners of a few blocks were chipped off, and a few others slid a centimetre or two out of place. Subsequent research has shown that these are the most characteristic features of palaeo-earthquake damage, and that even this modest amount of damage to the sturdy Incan stonework occurs only when the modified Mercalli intensity reaches level VIII–IX. A 2020 study systematically examined Machu Picchu's Temple of the Sun and another impressive edifice, the Temple of Three Windows, for such earthquake damage. The Temple of the Sun is especially amenable to palaeo-seismic study because its semi-circular construction allows detection of damage caused by waves propagating in any

Machu Picchu's Temple of the Sun.

direction, and it facilitates discrimination between earthquake damage and damage caused by downslope creep.

The study detected damage caused by two earthquakes, one whose waves propagated N20°E from a focus on an active normal fault 30 km south of Machu Picchu, and another whose waves travelled at N110°E from a similar fault that lies 20 km to the north. The researchers employed classic stratigraphic techniques to deduce that these quakes occurred during Machu Picchu's construction (sometime between 1438–1491), noting that the lower walls' high quality stonework exhibited earthquake damage, but the rough, simple stone construction (which characterised later work at Machu Picchu) does not.

A hike up either Huayna Picchu or Machu Picchu Mountain provides panoramic views of the ruins. Huayna Picchu is a shorter, more popular hike, but we loved the climb up Machu Picchu Mountain. It provides the iconic view of Machu Picchu, framed by Huayna Picchu and the Urubamba Gorge behind. On clear days the glacial cap of 6,271m-high Salkantay, Peru's 12th-highest mountain, looms to the south. A 15-minute detour brings you to the impressive Inca Bridge. Here an Incan road was hewn into a cliff, with a six-metre gap spanned by logs engineered into it. If enemies approached, the defenders needed only to withdraw the logs to protect the settlement.

Tapping a Mesozoic Sea: The Saltworks at Maras

The Sacred Valley holds many other worthy scenic attractions besides Machu Picchu. One of our favourites was the saltworks at Maras, 40 km north-west of Cuzco. Maras stands on a plateau high above the Urubamba Gorge. The plateau is capped by a Mesozoic marine sequence containing evaporites. After groundwater dissolves those evaporites it issues as a salty spring at the head of a small, amphitheatre-headed tributary to the Urubamba. The Inca built thousands of small, terraced evaporation ponds in the gorge to extract the salt, and today's villagers continue the tradition.

The salt forms in three layers. The first, pink, layer consists of highest-quality table salt, the second, white, layer is ordinary bulk salt, and a grey salt-mud mixture forms the third layer, which is sold as industrial salt. The jumble of white and pink ponds juxtaposed against the steep, red and tan canyon walls dotted with scrubby vegetation is an arresting sight. We wandered delightedly through the ponds, but the local salt cooperative has since closed them because of visitor-caused contamination. You can still enjoy panoramic views of the ponds from several viewpoints on the canyon rim.

Terraced saltworks at Maras.

Ancient agricultural research station at Moray.

An Incan Agricultural Research Station: Moray

Moray, just a few kilometres from Maras, offers visitors a scenic stop that illustrates another way the Inca harnessed the local geology to public benefit. A series of circular sinkholes up to 30 metres deep formed here in the plateau-capping Cretaceous limestone. The Inca lined the sinkholes with terraces constructed from blocks of nearby Tertiary andesite and plumbed it with a sophisticated irrigation system. They then filled the terraces with soil imported from all parts of their empire. The sinkholes' various aspects produce a range of temperatures that, combined with the regulation of water from the irrigation system, produced a range of microclimates in a small space. Archaeologists believe Moray served as an agricultural research station, where the viability of various crops was tested in soil types and climates spanning the empire.

Terri Cook

Lon Abbott

Capital of the Empire: Cuzco

Cuzco, a city of 430,000 inhabitants, bustles as much today as it did when it served as the capital of the far-flung Incan Empire. It was built about 900 CE by the Killke people, who were later conquered by the Inca. The modern city's centre, the Plaza de Armas, has served as a gathering place since Incan times. It hosts Cuzco's top tourist attraction, the Cuzco Cathedral. In Incan times it was the Kiswarkancha palace, which was razed by the conquistadors when they took control of the city in 1533. They built the cathedral on the Incan foundation, constructing it from andesite blocks they scavenged from Saqsaywaman, an Incan citadel that stands atop a hill overlooking the city.

The Cathedral is an impressive example of Spanish colonial architecture, and houses important historical artefacts, including the 'Christ of the Earthquakes', a wooden crucifix blackened by years of candle smoke that is paraded every year during Holy Week to commemorate the devastation wrought by the 1650 earthquake. The museum also hosts important works painted by the 'Cuzco School' of art, which the Spanish colonists founded to teach European-style art to the indigenous Quechua. The oldest painting, the 'Señor de los Temblores', depicts townspeople parading the Christ of the Earthquakes around the Plaza de Armas during the 1650 earthquake as they prayed for the shaking to end. Another important, and humorous to Western eyes, painting depicts the Last Supper, with Christ and the Disciples dining on roasted guinea pig, a local delicacy.

Like all visitors to Cuzco and the Sacred Valley, geologists will revel in the area's scenic grandeur and admire the Inca's incomparable stonemasonry. But they will likely get a wee bit extra satisfaction from the journey, thanks to their comprehension of the geologic forces that sculpted the landscape and their appreciation for the geologic acumen displayed by the Inca.

Cuzco Cathedral is built atop an Incan foundation composed of the dark gray stone.

SEISMIC FOLDOUT

OFFSHORE OMAN: STUNNING HYDROCARBON GEOLOGY FROM A CLOSING OCEAN

Figure 1: West to East Composite Line of 1990s Legacy Data, reprocessed in 2006 from the Oman Sea. Line length 200 km. Decollement surface in orange.

The Offshore Oman Sea lies east of obducted Oceanic crust, yet has a vast sedimentary sequence of Jurassic to recent clastics and carbonates that remains virtually unexplored. This basin contains extraordinary structures revealing compression and contemporaneous extension that has shaped the development of a hydrocarbon system. Little is known of the basin and yet, modern seismic reprocessing is poised to unlock the potential of this hidden gem.

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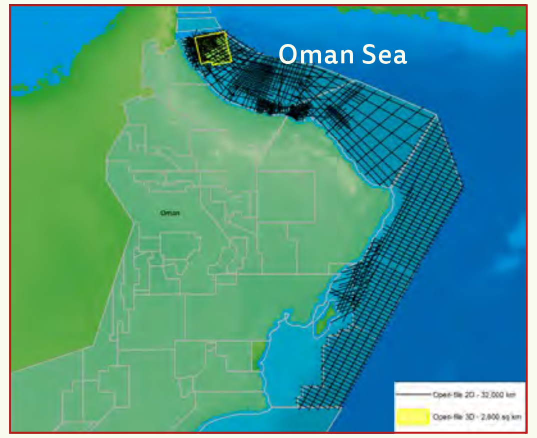
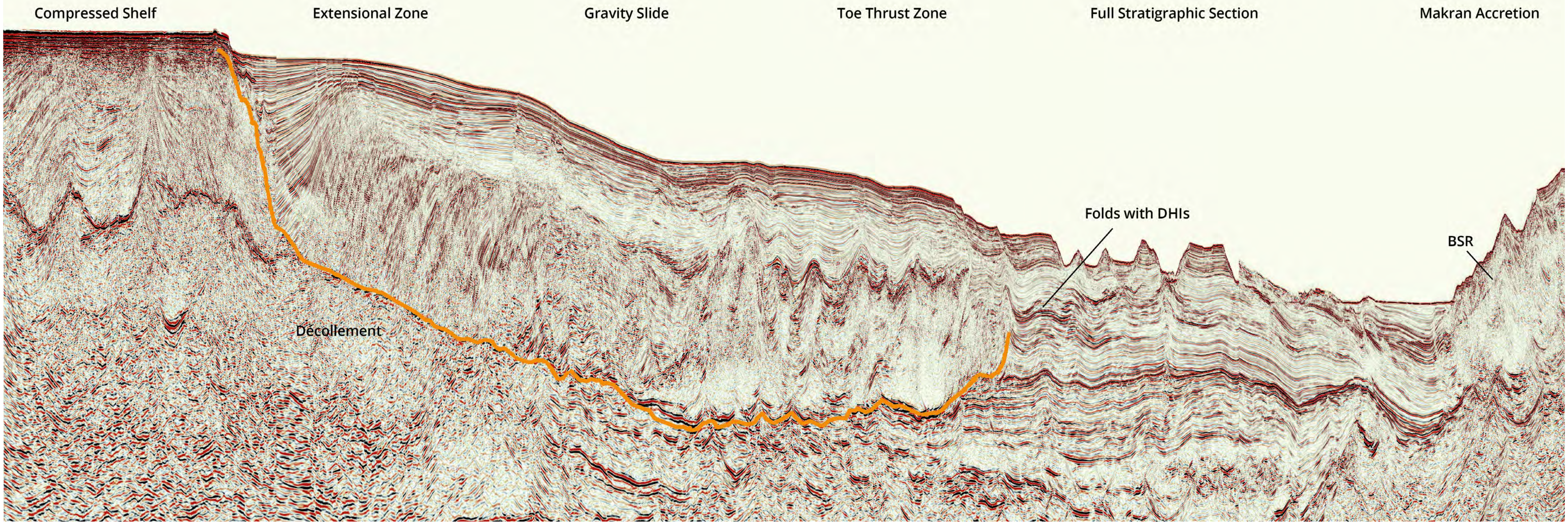


Location map showing position of composite line.



SEARCHER

OFFSHORE OMAN

Unexplored and tantalisingly prospective.

Neil Hodgson, Karyna Rodriquez: Searcher;
Julia Davies, Peter Hoiles: Discover Geoscience;
Dr. Saleh A Al Anboori: MEM

The Eastern Oman Mountains are widely known as an ophiolite range of rugged and dramatic beauty, where one of Oman's two slices of obducted oceanic crust were emplaced on top of continental crust by thrusting in the Late Cretaceous. To the west of these mountains lie multiple, prolific oil and gas basins of extraordinary variety.

To the south-east lies the Indian Ocean where the Omani continental shelf has a hydrocarbon province, shaved slim by the transform fault that eased the Indian continent on its northward Early Tertiary fly-by to its collision into Asia. The consequences of that geo-drama could not be more significant for humanity or more studied, as befits the formation of the Himalayas and significant removal of CO_2 from the atmosphere which facilitated the ice ages that arguably evolved the human species into consciousness. Yet, perhaps just as importantly, on the way north the Indian Plate blocked the exit of the Oman Sea creating a restricted marine basin – ideal for depositing an Early Tertiary source rock and clipping the edge of Oman, depositing the Semail Ophiolite onto it. To the north-west of Oman lies the Oman Sea where a far less well-known story unfolded in the last 80 million years as the normal passive margins to the Neo-Tethyan Ocean were caught in a plate tectonic vice. Here, as Africa and the Arabian Peninsula rotated into Asia and the ocean disappeared, the oceanic crust was first obducted on both sides creating mirroring mountain ranges in Oman and Iran, until subduction began, and the basin acquired a more familiar destructive margin geometry with subduction verging eastward under Iran and Pakistan in the Makran subduction zone.

It is to the Oman Sea, or Sohar Basin, that we have turned first because of the incredible geology that is illustrated on existing legacy seismic data, which we can now reveal has huge potential for image uplift on reprocessing. In the Oman Sea, south of the Straits of Hormouz that provides marine access to the Arabian Gulf, there lies a wide, shallow shelf with over 8 km of Cretaceous and Tertiary sediments, that leads through a steep slope down to 4,000m water depth and the jaws of the Makran subduction zone. The thick sedimentary section, found at depth on the Omani side of the Makran accretionary prism (*Figure 1* – main panel) is the stage for extraordinary hydrocarbon geology to play out, where access to modern seismic data allows us to see a hitherto little imagined engine of hydrocarbon generation, migration and entrapment that has hardly been considered by industry to date. Here we have new possibilities for exploration in a little-known basin with amazing geology and a friendly, sophisticated government to facilitate commercial business.

Geological Knowledge of the Oman Sea: Structures and Sources

Although there has been relatively little published this century on the geology of the Oman Sea, in just the last two years three key papers have been published: Ali et al., 2020, concerning the northern, UAE area of the Gulf offshore Fujairah; Levell et al., 2021, focusing on the Omani part of the Sohar Basin; and Ninkabou et al., 2021, focussing on the southern, relatively more stable part of the Oman Sea.

Each of these excellent papers draws upon onshore outcrop and well data integrating beautifully with the seismic and the limited wells drilled in the offshore.

The three wells in the Sohar Basin are key to understanding just how unexplored this basin is. Two of these wells were drilled 50 years ago, in very shallow water at the shelf margin. Both are remarkably well located for the time, and target tilted fault-blocks at the point of regional migration loci. Both are reported to have encountered shows, and found significant reservoirs in the Tertiary at least, reaching final depth in Late Cretaceous shales. The bounding fault for these structures appears to be an extensional fault which is active today and is perhaps the most likely reason for the lack of success of these wells.

The foldout line (*Figure 1*) shows a composite traverse across the Oman Sea and is a good foil for discussion of the geology of the basin. At the far western end (left) of this line many structures can be observed in the Miocene to Cretaceous section. These are mostly thin-skinned thrusts and compressional structures, folds, inverted anticlines, and strike-slip flower structures formed in post-ophiolite obduction by the contraction of the basin. Compression continued after the start of Makran subduction and thin and thick-skinned structuring was coeval creating features such as what Levell et al. call the Daymaniyat anticline (*see Figure 7 in their paper*). Peak deformation appears to have been at the end of the Miocene. But that is not the last of the structural strangeness, as, when subduction started in the mid-Tertiary, the slope angle significantly increased

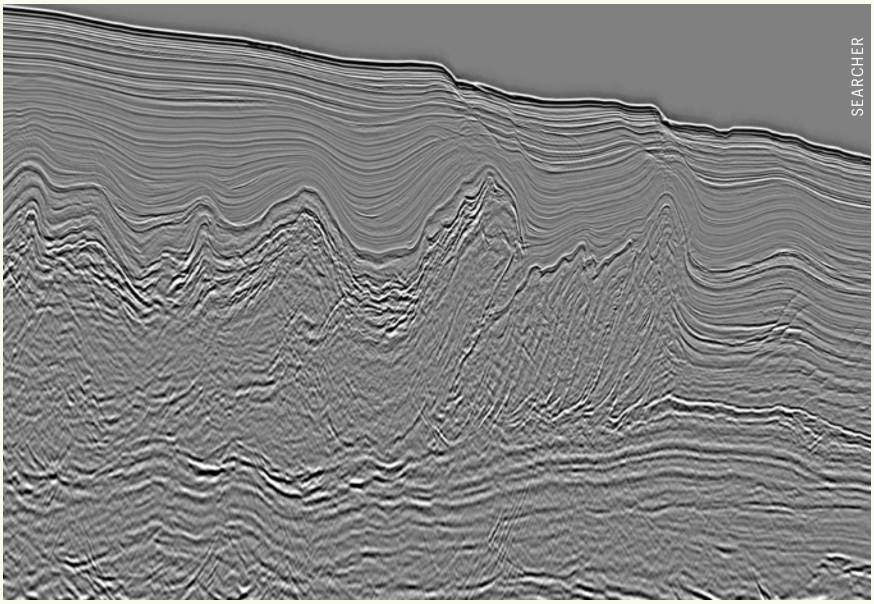


Figure 2: 2021 Reprocessed line over toe-thrust zone showing imbricate thrust structure of toe thrusts and imaging of the Cretaceous pre-decollement section. Line length 26 km.

and a large part of the thick Cretaceous and Palaeocene slope (some of which was deformed and folded by compression) began to move downslope under gravity sliding towards the subduction trench. The diachronous decollement surface appears on the basin floor to be at Palaeocene level age, contemporaneous with the eastern closure of the Oman Sea and the development of a restricted marine basin and is a candidate source rock of Pabdeh Formation age. However, up-slope Cretaceous sediments are also entrained in the slide.

The couplet of up-dip extension and sediment loading with a down-dip contractional toe-thrust set at the end of decollement is clearly seen on *Figure 1*. The mid-slide area shows drape over pre-slide compressional folds caught up in the slide. These are often associated with bright reflectors in the Pliocene.

Biogenic gas is evident in the Makran system to the east, expressed as gas hydrate 'Bottom Simulating Reflectors' (BSRs). Where BSRs can be confidently picked to the west of Makran, one can calculate a geothermal gradient at the BSR of around 35°C/km (whilst in the Makran accretionary prism this drops to 20–25°C/km). The nature of the decollement surface is uncertain, and it would be speculative to consider this as a candidate potential source rock. Yet below this lies a thick sequence of Cretaceous and Jurassic section that has not been drilled offshore, of similar age – if not depositional setting to the super-prolific Cretaceous and Jurassic source rocks of the northern Arabian Gulf.

Seismic Reprocessing 2021–2022

It is frustrating that on legacy 1990s to mid 2000s data the sub-decollement surface cannot be mapped or examined, and it is for this reason that late last year Searcher was awarded a contract by the Ministry of Energy and Minerals, Oman (MEM) to reprocess and promote as a multi-client product. Initial reprocessing with a modern processing sequence including deghosting and multiple elimination, have been extraordinarily successful in revealing the sedimentology of the pre-decollement section and the structural detail of thrusting complexity in the toe-thrust area (*Figure 2*).

Whilst exploration of the toe-thrust area has been successful in many basins globally, for example the Rovuma Basin (Mahanjanr and Franke, 2014), this has never been attempted in the Oman Sea.

To the north of the seismic line in Figure 1 (main foldout panel), the toe thrusts of the gravity slide collide with the opposite verging thrusts of the Makran accretionary prism. However, here we see the first structures outboard of the last toe thrust as simple, large anticlines in the Miocene to Pliocene as a soft-kick event associated with direct hydrocarbon indicators – flat events and positive (far-near)*far angle responses. These structures are particularly interesting because they sit where a continuous sequence can be observed from the oldest sediments lying on Oceanic crust (Jurassic and Triassic) right through to recent sediments. It is here that the Early Cretaceous older source rocks can feed directly into the shallower play systems. Experts picking natural oilslicks from satellite data have found many repeating slicks in this area; however, note the presence of active ports and shipping lanes (Clermont Blaizot, personal communication).

Unexplored and Tantalisingly Prospective

There are very few remaining thick clastic sections in moderate water depth remaining on earth that are so little known, so incredibly under-explored, and have such tantalising indications of the presence of hydrocarbons. It is perhaps ironic that the imaging power being unleased through broadband extension of deghosted data, that had always been needed to conduct efficient and successful exploration, is only now becoming available. However, this new imaging is constantly revealing new geological marvels – and here that will surely lead to a new province for exploration success in the beautiful Sultanate of Oman.

Searcher would like to thank MEM for their support in publishing this article.

References provided online.

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"LAND PLANTS DIDN'T EVOLVE UNTIL THE SILURIAN!"

A brief history of the evolution of... well everything

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If you were to ask my wife when plants first evolved, she would answer without hesitation (in a mock pompous voice) "land plants didn't evolve until the Silurian"! She is not a geoscientist but will never forget this piece of trivia after I embarrassed her many years ago by chiding a fossil vendor for trying to pass off a feathery looking fracture in Welsh Cambrian Slate as fossil fern. This phrase pops up from time to time whenever I am in danger of climbing on my soapbox! As it happens, there is some evidence that the earliest land plants may have been slightly older than this, based on fossil spores reported from the mid-Ordovician, but certainly the oldest thalloid macrofossils are known to be Silurian in age. While this attempt at fraud was not exactly the crime of the century, understanding when and how different organisms emerged, radiated, and evolved is incredibly important in understanding the rocks beneath our feet.

Searching for LUCA

Somewhere buried in my garage is a piece of Precambrian Bonahaven Dolomite from the Dalradian succession on the Isle of Islay. Collected on the beach below the Bunnahabhain whisky distillery, it contains probably the oldest fossils I have in my personal collection – some biogenic algal mounds called stromatolites. As stromatolites go, these examples are young – the oldest known are from the Strelley Pool Chert on the Pilbara Craton in Australia and at 3.4 billion years old they are widely regarded as the oldest fossils on Earth (*Figure 1*).

Recently published research on slightly older putative microbial fossils undertaken at UCLA and the University of Wisconsin–Madison utilised secondary ion mass spectrometry (SIMS) to examine the carbon isotopic signature of these organic-looking remains. Their results suggest a biogenic origin, pushing the fossil record back to ~3.5 billion years.

In fact, life may have emerged some 400 million years before this. The latest work from the Universities of Bristol and Bath leveraging molecular clock theory, now estimate the age of LUCA (the Last Universal Common Ancestor) for life on Earth at 3.9 billion years. Molecular clock theory essentially uses the mutation rate of DNA and protein sequences (calibrated from the fossil record) to derive ages of divergence between fossil groups with common ancestors.

The Great Oxygenation Event

If LUCA first appeared around 3.9 billion years ago, it took nearly another 1.5 billion years before prokaryotic organisms (cyanobacteria) evolved and proliferated enough to drive early oxygenation of the Earth's atmosphere, starting at or around 2.4 billion years. Oxygen production as a by-product of cyanobacteria photosynthesis started to convert the early reducing atmosphere to an oxidising one, paving the way for the (future) evolution of aerobic multicellular organisms.

Rapid Diversification of Life

Some 1.8 billion years later, and approximately 34 million years before the so-called 'Cambrian Explosion' (~541 Ma), complex (largely soft-bodied) multicellular life exploded. The Ediacara biota emerged towards the latter part of the Ediacaran period around 575 Ma and radiated, with thousands of specimens known from at least 40 localities worldwide including several particularly important sites in Canada, Russia,

Figure 1: Stromatolite fossils in the Strelley Pool chert (~3.4 billion years old), Western Australia.

Figure 2: A cast of the iconic Ediacara fauna Dickinsonia sp.

Namibia and Australia. The biota includes a broad variety of forms, with some complexity (e.g., Dickinsonia, *Figure* 2). While hard-shelled organisms in the Cambrian were probably preceded by soft-bodied forms, with very few exceptions, the Ediacara biota appears to have become extinct at the Precambrian–Cambrian boundary, including the first metazoan fauna with calcified skeletal material (e.g., Cloudina and Namacalathus).

The Cambrian Explosion

Practically all extant animal phyla emerged in the Cambrian including arthropods, typified by trilobites, including some important zone fossils (e.g., Bergeroniellus asiaticus) and chordates (which includes the subphylum Vertebrata to which all organisms with backbones (including us) belong). Some remarkable Lagerstätte are known, including the world-famous Burgess Shale. After many years of toil, mapping the Lower Palaeozoic of Wales and struggling to find a robust fauna to defend the establishment of the Cambrian period, Adam Sedgwick would be absolutely astonished by the tens of thousands of specimens Charles Wolcott amassed from the Burgess Shale, and the many millions of trilobites, brachiopods and other fossils collected from Cambrian stratigraphy worldwide over the last 150 years.

Reading the Writing in the Rocks

One fossil group that emerged in the Middle Cambrian and persisted into the Carboniferous was the graptolites. Graptolites are important zone fossils, and while they may appear to many as just scratches in the rock, they are actually incredibly varied complex colonial organisms that comprised an important part of the Early Palaeozoic zooplankton.

From my home office in Oxfordshire, I can just about see the village of Culham across the River Thames where Charles Lapworth trained as a teacher at the Diocesan Training College (now the European School). Born in Faringdon (famed for its highly fossiliferous Cretaceous Sponge Bed Gravels), Lapworth moved to Scotland to teach, and spent his spare time doing geology. He spent many years painstakingly documenting the graptolite fauna at a locality called Dob's Linn, now recognised as the global stratotype section and point (GSSP) for the Ordovician–Silurian boundary. His work was revolutionary, providing the framework to establish the Ordovician period, defining the boundary with the Silurian, and resolving some fierce debate about where the divide between the Cambrian and Silurian should be placed; a source of much animosity between Sedgwick and Murchison in the mid-1800s.

Greening of the Earth

All jokes aside about the evolution of land plants, the emergence of vascular plants completely changed everything – imagine the difference the 'greening' of Earth had! The first true soils started to develop and plants with roots significantly modified the behaviour of surface drainage. Some research indicates that the resulting improvements to bank stability led to more established streams and rivers, which in turn created the habitat required for larger plants such as tree ferns to thrive... cue the great Devonian and Carboniferous forests (*Figure* 3), and the development of the economically important coal measures.

> *The evolution of land plants also paved the way to colonisation of freshwater habitats*

By the Late Carboniferous/Early Permian, atmospheric oxygen exceeded 30% (significantly greater than today's 21%). Insects loved it, and they grew to colossal sizes as exhibited by some spectacular fossils. In the fossil record insect size continued to track atmospheric oxygen until the evolution of birds recalibrated the food chain (when being smaller became an advantageous evolutionary trait). The evolution of land plants also paved the way to colonisation of freshwater habitats, with the first lacustrine fish and arthropods appearing by the Late Silurian/Early Devonian and many other fossil groups such as the amniotes (the clade of tetrapod vertebrates that includes synapsids and sauropsids) by the Late Carboniferous. While plant-related palynomorphs track plant evolution, most of the major microfossil groups such as ostracods

Figure 3: Pecopteris tree fern from the Carboniferous Saar coal basin in Germany.

and foraminifera had appeared by this time. Forams with non-calcareous tests emerged in the Early Cambrian but have a relatively poor preservation record compared with later agglutinated and calcareous multilocular species that are known from the Carboniferous. Another important microfossil group representing plankton had emerged by this time – dinoflagellate cysts, although they were to enjoy much greater success from the Triassic onwards following a highly advantageous evolutionary change in the structure of the dinoflagellate wall which greatly enhanced their mobility.

The Rise of Dinosaurs and the Evolution of Birds

After Siberian Trap volcanism wreaked ecological havoc and Permian mass extinction, one of the most successful (and perhaps famous) fossil groups of terrestrial animals emerged – the dinosaurs. Before this, therapsids (stem mammals) had been the dominant terrestrial vertebrates having evolved from sphenacodonts (synapsids) in the Permian. Some sphenacodonts such as Dimetrodon incisivum (*Figure 4*) have often been incorrectly referred to as dinosaurs, even though Dimetrodon actually became extinct some 40 million years before dinosaurs appeared on the scene.

Dinosaurs evolved from archosaurs (sauropsids) which dominated throughout the Triassic. At least two further extinction events paved the way for dinosaurs to take over in the Jurassic and dominate the land through to the Cretaceous. Dinosaurs were an incredibly diverse group ranging from very small theropods like Compsognathus to the enormous sauropods like Cetiosaurus. We have a good understanding of some of the habitats they lived in, not just from body fossils, but also from their ichnofauna-like footprints (e.g., *Figure 5*).

JAMES ETIENNE

Figure 5: Natural casts of Iguanadon footprints weathering out on the beach in Compton Bay, the Isle of Wight.

Archosauria is also the clade responsible for the emergence of pterosaurs, although pterosaurs are not ancestral to birds. Birds evolved from a clade of theropod dinosaurs called maniraptorans (coelurosaurians). While the term maniraptora may not be very familiar to you, the group includes household dinosaur names like dromaeosaurs and oviraptors. The quintessential link fossil Archeopteryx is not considered to be a direct ancestor to birds based on modern cladistics, although it is probably closely related to their common ancestor. The so-called 'Berlin specimen' of Archeopteryx is so famous I did not bother to illustrate it here!

Meanwhile, in the Jurassic seas, the iconic cosmopolitan fauna of ichthyosaurs and plesiosaurs (made famous by the exploits of Mary Anning in the early 1800s) dominated. These large marine reptiles are often mistakenly referred to as dinosaurs, but they are not related. They fed on belemnites, fish and other marine organisms, as evidenced by exceptional fossils with preserved stomach contents, and their fossilised faeces known as coprolites which often contain fish scales and bones, and the hooklets from belemnites (*e.g., Figure 6*). Ammonites were

Figure 6: A large ichthyosaur coprolite I recently found on the Jurassic Coast of southern Britain. This example is packed full of fish scales, fragmentary fish bone and belemnite remains. On rare occasion it is possible to find coprolites containing ichthyosaur vertebrae demonstrating some cannibalistic behaviour.

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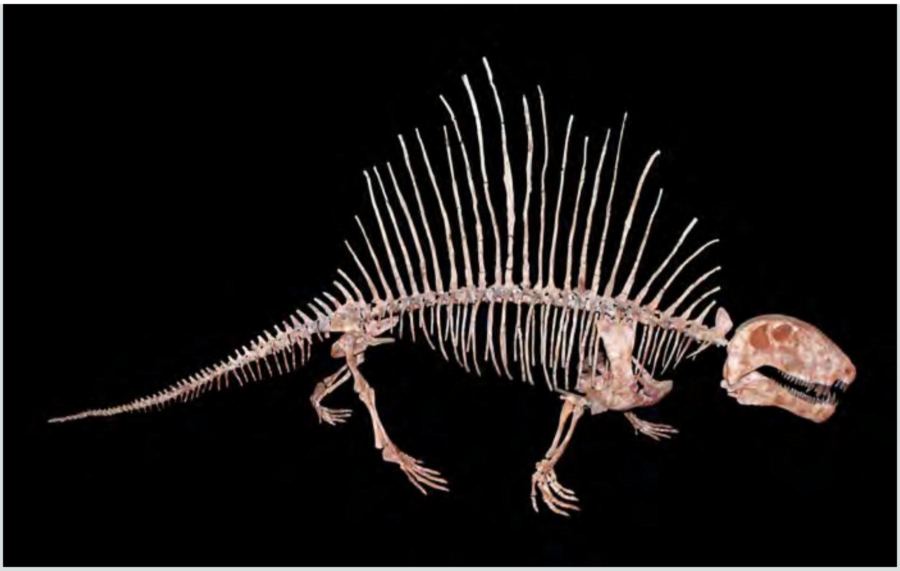

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Figure 4: The sphenocodont Dimetrodon incisivum from the Permian Basin, now in the collection of the Staatliches Museum für Naturkunde Karlsruhe, Germany.

JAMES ETIENNE

Figure 7: Psiloceras planorbis (Sowerby, 1824) ammonite from Watchet on the Somerset coast. This ammonite is an important Hettangian (base Jurassic) biostratigraphic marker.

abundant and incredibly diverse, evolving rapidly and making them ideal zone fossils in both boreal and tethyan realms, each with its unique index taxa (*Figure 7*).

Mammals

Competing for space throughout this time, the first true mammals emerged at least as early as the Jurassic if not the Late Triassic (there are discrepancies depending on which qualifying characteristics and cladistic model you choose to follow). Early mammals were mostly diminutive and nocturnal, but flourished, especially in the Tertiary (once their dinosaur competitors had demised) and are of course today one of the most successful and diverse therapsid lineages in modern ecosystems.

The evolution of modern mammals is much better understood; for example, the well-documented emergence and radiation of hominids out of Africa. Australopithicine skeletal remains dating back at least 3.2 million years give us clues to our ancestral lineage, with perhaps the most famous hominid fossil 'Lucy' (*Figure 8*). Unlike LUCA, Lucy is not an acronym, but the colloquial name given to specimen Al 288-1 after the Beatles song 'Lucy in the Sky with Diamonds' was played at the excavation site.

A couple of million years after Lucy's death, in the Middle Pleistocene, her descendants (Neanderthals and Denisovans that emerged after Homo erectus) had made it at least as far north as southern Siberia, as demonstrated by a much lesser-known fossil called 'Denny' who had a Neanderthal mother and Denisovan father. It is possible that these hominins or their relatives were actively hunting woolly mammoth out on the Russian steppe, especially as mammoth remains were also found at the site. Today Homo sapiens mine the mammoth ivory from the permafrost in Yakutia, Siberia, but the international trade (while legal) has taken a hard hit over the last few years, negatively impacted by a major clampdown on elephant ivory trade in China and tighter controls on Russian exports that protects tusks and other fossils considered to have scientific and cultural value. Some spectacular mammoth remains preserved in the Arctic permafrost are now being used by bioscience and genetic engineering companies to try and resurrect the mammoth (so-called 'de-extinction'). Advanced genome engineering technologies like CRISPR-CAS9 are making some of these attempts scientifically viable. Not quite dinosaurs, but definitely a bit 'Jurassic Park'!

120. CC BY 2.5.

Figure 8: A cast of the partial skeleton of hominid Australopithecus afarensis (specimen AL 288-1), otherwise known as Lucy. This replica is in the collection of the Muséum national d'histoire naturelle, Paris.

Flowers

The earliest angiosperm fossils date from the Lower Cretaceous with pollen in the Valanginian and macrofossils recorded from at least the Aptian onwards. As with other fossil groups, it is hypothesised that they may have appeared earlier than the direct fossil record currently captures based on their sheer diversity, and older fossils may yet be discovered. It has been posited that the evolution of flowering plants had major ecological ramifications – herbivorous dinosaurs failed to evolve a mechanism to avoid eating poisonous plants, driving disruption and collapse of the food chain which contributed to the demise of both herbivorous and carnivorous dinosaurs. Environmental change driven by the Deccan traps and the Chicxulub asteroid impact did the rest!

In the next issue...

This short article barely scratches the surface on the vast amount of knowledge represented in the published scientific literature. There are thousands of articles and books covering the taxonomy, biology, evolution and ecological analysis of the speciation on Earth over the bast 3.9 billion years, but I hope it has whetted your appetite to learn more! Darwin and other early evolutionary thinkers showed incredible insight and I expect that we will continue to see refinement in the understanding of how flora and fauna have evolved as we continue to unearth and interpret the fossil record. The next article in this series 'Gone Fossil Hunting' will cover what it takes to find amazing fossils, from initial planning to the preparation of museum-quality specimens!

BRAZIL: LOSING ITS WAY

Brazil has been a leader in the energy transition – but is now being left behind.

Jane Whaley
Associate Editor
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In many ways, Brazil is well ahead in the energy transition game. Its energy matrix is already 45% renewable and it has enough untapped resources to significantly increase that proportion. It is also a world leader in ethanol for use as an alternative to petrol and diesel.

Yet despite these green credentials, Brazil's approach to energy transition remains confused, with the present government showing little political will to make the changes necessary to keep carbon emissions at an acceptable level.

Flex-fuel Cars Rule

The oil price shocks in the 1970s motivated Brazil to develop a cheaper, alcohol-based fuel sourced from abundantly available sugarcane, requiring just a minor adjustment to regular gasoline engines. The government used loans and tax breaks to encourage everyone from sugarcane growers and distillers to car manufacturers and drivers to come on board with the initiative. The 'flex-fuel' nature of the vehicles meant that consumers could take advantage of changes in prices for commodities; a greener and cheaper solution for drivers.

Brazil has developed a highly efficient agricultural system for sugarcane cultivation and is now the world's second-largest ethanol producer, representing 25% of total ethanol used globally as fuel. Bagasse, the dry fibrous material that remains after crushing sugarcane, provides the power for the process, so most ethanol distillers are energy self-sufficient, increasing both the competitiveness and the green credentials of the process. Ethanol, which can also be made from corn, replaces gasoline/petrol in cars, while biodiesel, derived from vegetable oil such as soy and palm, can be used instead of fossil-fuel derived diesel. In 2018 over 70% of light vehicles in Brazil used ethanol fuel, and by 2040, 24% of all liquid fuel consumed in Brazil is expected to come from biofuels.

Ethanol derived from sugarcane powers the majority of cars in Brazil.

While the prominent use of biofuel is praiseworthy, it is not without issues. It stimulates sugarcane and, to a lesser extent, soy monoculture at the expense of food production, especially by large organisations, and pushes out smaller producers. There are also major concerns over using land for biomass; it is not a sustainable resource if it changes, disturbs or destroys natural ecosystems, particularly through deforestation, as discussed below.

Progress with Renewable Power

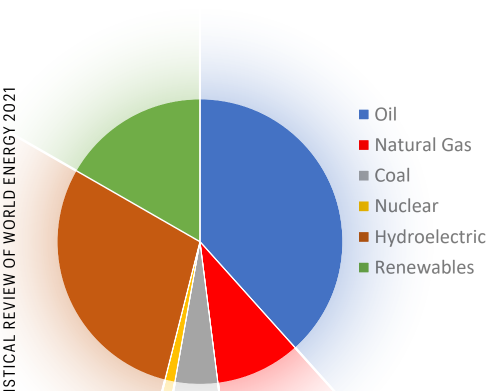
Brazil also has abundant other sustainable resources available. Hydroelectricity, for example, already accounts for over 66% of the country's electricity generation, having started in 1983 with the building of the giant Itaipu Dam on the Paraná River dividing Brazil and Paraguay. There is plenty of untapped hydro potential but the majority is in the north, while the main demand centres are in the south-east. In addition, climate change is affecting Brazil through a reduction in river flow in recent years; the percentage of electricity derived through hydroelectricity dropped by 10% in 2021 as a result of droughts. Hydropower can be a seasonal resource; but on the positive side, the use of reservoirs means it is possible to effectively 'store' electricity for use when intermittent supplies like wind and solar are not available.

Solar power is relatively new in Brazil, with the first major solar farms only opening in 2017, although at the time they

The Itaipu Dam power plant on the Paraguay/Brazil border is the second-largest by capacity in the world.

were some of the largest in the world. Total installed solar power was estimated to be about 10.3 GW in mid-2021, generating approximately 1.46% of the country's electricity demand, having doubled its share in just three years. The use of wind for electricity started in 2007 and has grown steadily, contributing 9% of the power generation supply in 2019. There are an estimated 750 wind farms and over 10,000 turbines but, like hydropower, much of the resource is located in the north-east of the country, away from major centres of population. Brazil has not yet built any offshore wind farms, but will probably include offshore areas in upcoming energy auctions as it offers good potential. Both wind and solar can provide electricity in Brazil more economically than fossil fuels.

Some energy is supplied by two nuclear power plants, but the proportion contributed into the energy mix has not changed much in recent years. A third reactor is under construction, due to be completed later this decade.



Primary energy consumption by fuel in 2020 in Brazil was fuelled 45% by renewable sources.

Brazil possesses some of the important energy transition minerals, including 20% of the world's graphite resource, second only to China. It has significant lithium reserves, predominantly from high quality hard rock pegmatites, producing 1,900 tonnes in 2020, up from 300 tonnes the previous year. It also holds about 21 million tonnes of rare earth metals – again only exceeded by China – but only a very small amount is produced.

The Rainforest is Burning

So, with a predominantly non-fossil fuel road transport system, an efficient and largely renewable electric sector, and plenty of untapped renewable resources, surely Brazil is a shining light in the energy transition pathway?

However, in addition to its plentiful energy resources, Brazil holds two-thirds of the Amazon rainforest, one of the world's most important carbon sinks. Large-scale deforestation for agriculture and logging has taken place in the Amazon for the last 50 years, with some respite between 2002 and 2016, when global outcry at this devastation resulted in the development of national parks and indigenous reserves, with protections stringently enforced. The rate of deforestation dropped dramatically.

That changed when Jair Bolsonaro came to power in 2019 with an agenda that included exploiting the rainforest for agricultural gain, predominantly cattle ranches and soy cultivation (hence the connection with biofuels). In his first two years in office alone over 25,000 km² of rainforest was destroyed, much of it in lands allocated to the indigenous people but, with no budget for park protection, there is little to stop the indiscriminate chopping and burning. Even more worrying, it appears that the Amazon rainforest is now emitting more carbon dioxide than it is able to absorb, mostly through these deliberate fires. As the rainforest declines, the forest's dry season increases, triggering further warming and drying, killing trees and potentially causing the entire ecosystem to shift from rainforest to savanna.

Bolsonaro did make some rather vague concessions at the COP26 climate conference, including committing to end illegal deforestation by 2030 – yet to be legally formalised – and moving the date for becoming carbon neutral from 2060 to 2050. However, Brazil's new climate plan, announced at the conference, is actually a step backwards compared to the previously agreed agenda; for example, the aim to reduce annual deforestation to 8,670 km² by 2022 is a 15% larger area than achieved in 2018 and a long way from the previously agreed target for 2020 of 3,925 km².

Although an avowed climate change denier, Bolsonaro did advocate expanding wind and solar energy generation and reducing the use of coal and oil – but then cut state subsidies in these fields in 2021.

Emissions Rising

This approach to the Amazon rainforest means that Brazil's emissions rose rapidly in the last couple of years. Deforestation and forest fires alone accounted for 46% of the country's total emissions in 2020, up 9.5% on the previous year, despite the Covid pandemic.

With its head start in renewables for cost-effective electricity supply and transport and its abundant natural resources, Brazil could be a leader in the energy transformation and even export clean energy to neighbouring countries. At the moment, unfortunately, it appears to be heading in the opposite direction.

References available online.

CRITICAL MINERALS FOR ELECTRIC VEHICLES

We hear that electric vehicles (EVs) are necessary to meet net zero targets but how green are EVs really and, moreover, where will the raw materials for the batteries come from?

Iain Brown

When evaluating how much 'greener' Electric Vehicles (EVs) are compared to the latest petrol-powered vehicles, we must look at the whole picture, which should include a 'cradle to grave' approach. There are significant problems with some of the materials that make up today's electric vehicle batteries. As production ramps up, these urgently need to be examined and fixed. For example, cobalt production is linked to child labour in parts of Africa and indigenous communities are resisting lithium mining on their land in places like South America.

Just How Green are EVs?

Critically, EVs run on electricity that must be generated somehow and although renewables will provide a portion of this energy, in some parts of the world oil, gas, coal and nuclear will also provide a significant contribution (for example gas produces ~35% of the UK's electricity). However, when comparing the total amount of CO_2 created by cars over their life cycle, including manufacturing, driving, recycling and disposal, EVs still come out on top, though estimates differ considerably. According to a report by Zemo Partnership, petrol cars produce around 24 tonnes of CO_2 during their lifetime, whereas an electric vehicle emits between 25–50% less.

While it is difficult to burn oil ethically and sustainably, it is possible to produce electric vehicles in ways that minimise impact. But doing this will take time – which is why companies and governments have an important role to play. Car companies and their suppliers are the key to this, and there are ways in which they can help.

Firstly, they can demand transparency from their suppliers – it needs to be possible to accurately identify which company and mine provided which material, so carmakers can choose better suppliers, and avoid bad ones.

Secondly, car companies must only work with producers that follow the highest standards for treatment of workers and the environment. Car companies are already huge buyers of materials like lithium, cobalt and nickel, and that allows them significant influence over the industry that supplies them.

Lastly, these companies need to be willing to refuse to buy their raw materials from polluting and unsustainable mining and that means some of these materials will simply have to stay in the ground. This becomes problematic, as the planet currently doesn't have sufficient mineable battery mineral resources to electrify the global transport system.

Supply Crunch Looming?

International Market analysis firm, CRU, forecasts that the 2021 lithium demand of about 450,000 tonnes will exceed supply by ~10,000 tonnes. Lithium demand is expected to more than triple between 2020 and 2025, rising to a million tonnes by 2025 and outpacing supply by 200,000 tonnes. To put this in perspective, in 2017–2018 a small supply/demand imbalance of around 10,000 tonnes occurred causing spot prices to soar by over US$20,000/tonne. This 2017–2018 event could signal further price shocks if expected shortfalls reach predicted levels. Demand for battery-grade nickel, another important component in EV cells, is estimated by Rystad will outstrip supply by 2024. This supply problem could force battery mineral suppliers to either consider previously unattractive sources of nickel in countries such as Indonesia, where there are environmental concerns or to assess alternative battery chemistries.

SHUTTERSTOCK

Indigenous communities of the Salinas Grandes protest against lithium mining on their territory.

So, if we consider these forecasts, it appears there is a clear need for a coordinated and concerted effort to address local supply of not only lithium, but also other key elements needed in EV battery production. Otherwise, it appears likely that battery and EV manufacturing in North America and Europe will be reliant on precursor materials that will continue to be imported from other regions.

Reliance on Asia and South America in the middle of the supply chain has inherent risks and is unlikely to meet national environmental and sustainability targets and ultimately promotes increased imports of finished EVs from cost effective and resilient supply chains already built in China.

Novel Lithium Extraction

There may be a way to obtain lithium which may be more sustainable longer term. US General Motors (GM) future electric cars may rely on batteries made from lithium derived from a hydrothermal fluid that rises from rocks beneath the California desert.

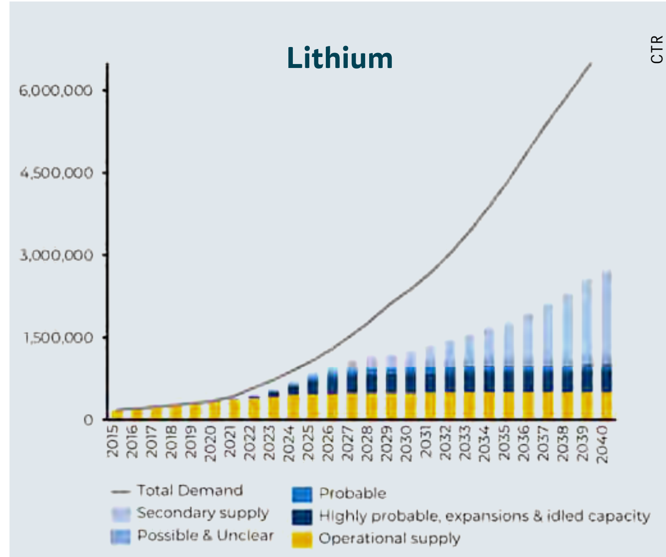
GM struck a deal with a little-known company called Controlled Thermal Resources (CTR) which was formed in 2013, to supply lithium from a desolate lake known as the Salton Sea. This is a shallow, highly saline water body in Riverside and Imperial counties at the southern end of California. It lies on the San Andreas Fault within the Salton Trough that stretches to the Gulf of California in Mexico.

The geothermal activity below the Salton Sea releases lithium so that it can be extracted. Due to increased demand for lithium for use in EV battery production, the Salton Sea area is gaining attention. CTR's Hell's Kitchen Lithium and Power development in the Salton Sea Geothermal Field is primarily electricity-generation-focused and lithium at the Salton Sea is a by-product of this. A well taps hot water underground, creating geothermal energy, and the geothermal 'brine' is then concentrated in lithium and other elements.

While the Salton Sea's lithium resource has been known for decades, it has been extremely hard to capture. It is well established that this brine, heated to over 200 degrees centigrade, can create electricity by being used to generate steam that spins a turbine and creates electric current.

The problem with extracting the lithium is that it is mixed with several other ingredients, especially silica. The lithium, present at only 250 ppm, needs to be removed along with other minerals as the water issues from the ground at thousands of gallons per minute. The heat and velocity along with the difficulty of separating the particles are each a challenge.

Many techniques and process strategies have been proposed for direct lithium extraction (DLE) from the geothermal brines, and these can generally be categorised into adsorption,



Benchmark Mineral Intelligence latest forecast lithium supply and demand graph – May 2021.

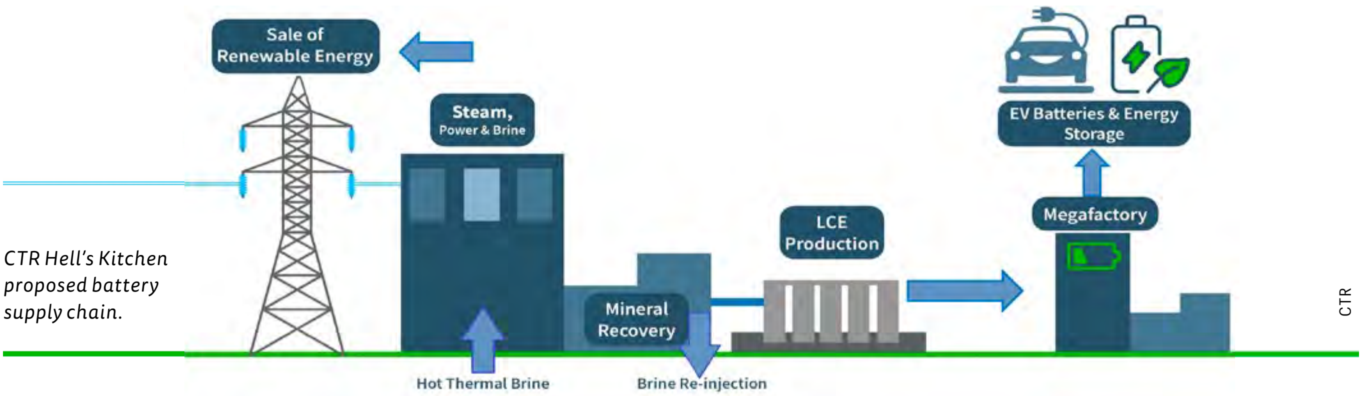
ion exchange and solvent extraction techniques. Of these technologies, the ones currently advancing to pilot- and near-commercial-scale demonstrations involve adsorption and ion exchange techniques. The end products which are used in batteries are lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$).

CTR claims that its proprietary process will produce 20,000 tonnes of lithium hydroxide by the first quarter of 2024, which if achievable would be almost 4.5% of the world's current lithium supply. Once at full capacity, CTR claims the plant could produce 300,000 tonnes of lithium which is more than Australia currently produces.

Interestingly, CTR also claim their process has the highest sustainability attributes available. Their facility utilises 100% renewable energy and steam, significantly reducing the time to produce battery-grade lithium products while eliminating all overseas processing. The operations have a minimal physical footprint and a near-zero carbon footprint. The geothermal brine, after lithium extraction, is reinjected into the geothermal reservoir.

CTR

Hydrothermal activity at the Salton Sea.



CTR Hell's Kitchen proposed battery supply chain.

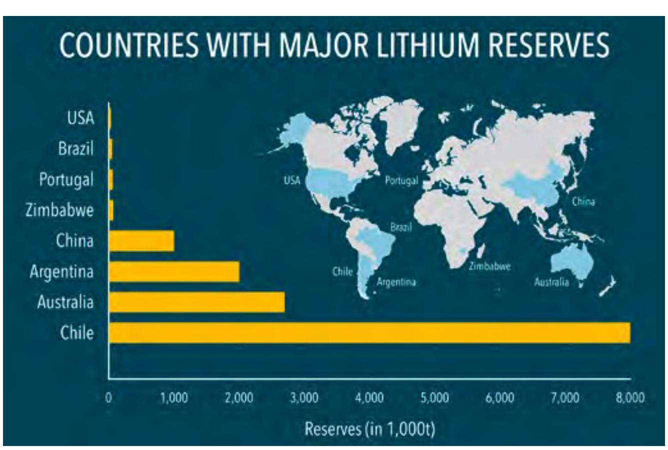
As part of the DLE process, CTR will deploy an ion exchange process developed by Lilac Solutions: a leading DLE technology group that received US$20 million in funding led by the Bill Gates company, Breakthrough Energy Ventures, and MIT's The Engine. A further $US 150 million funding was confirmed in September 2021.

Beyond the United States

Most of the world's lithium is produced in South America or Australia and shipped to China for processing into battery-grade lithium chemicals. The techniques typically used are evaporative brine processing and hardrock (spodumene) mining. Both have environmental impacts.

Today, over half of the world's known lithium sources are produced from brine water evaporation, and most of this brine water is found in the salars (salt flats) of Bolivia, Argentina, and Chile. The environmental problems with solar evaporation begin with ground water consumption in areas where water is already scarce. So much water must be pumped from the ground to create the evaporation ponds that it endangers the water supply for nearby inhabitants. The brine levels of the salars are dropping from the production processes, and the waste salts from used brine are left stacked in piles in the desert.

Spodumene mining and refining operations consume large quantities of chemicals and utilise tailings ponds and waste chemical lagoons to deal with their solid and liquid wastes.



Countries with major lithium reserves for battery production.

This practice carries many of the same issues as other operations in the mining industry, including contamination of ground water, rivers and soil.

There is currently no commercial lithium production in Europe but there is active engagement from government, industry and academia focused on lithium extraction from geothermal brines in the Upper Rhine Valley of south-west Germany, Alsace, France and in the south-west of England.

Waste salt stacks in the Salinas Grandes, Argentina.

Environmental Considerations for Geothermal Extraction

Additional considerations beyond the specific cost and performance of lithium extraction processes relate to impacts of the tail fluid on the geothermal reservoir. Injectate after lithium removal is likely to be cooler than the normal power plant rejection temperature. Also, re-saturation of the brine with lithium could be affected by injectate access to lithium-bearing rocks in the reservoir and by injectate residence time. Reservoir modelling combined with details of lithium distribution in the reservoir could clarify the importance of these potential impacts of lithium extraction from the geothermal brine.

In other words, the possible longer term environmental impacts of direct lithium extraction are not fully understood, and further research is required. However, it remains a possible solution to cleaner, more sustainable EV battery production and may alleviate reliance on a very limited number of nation state suppliers.

GLOBAL WILDCATTING

GOING WITH THE FLOW

Madeleine Slatford
NVentures
www.nventures.co.uk

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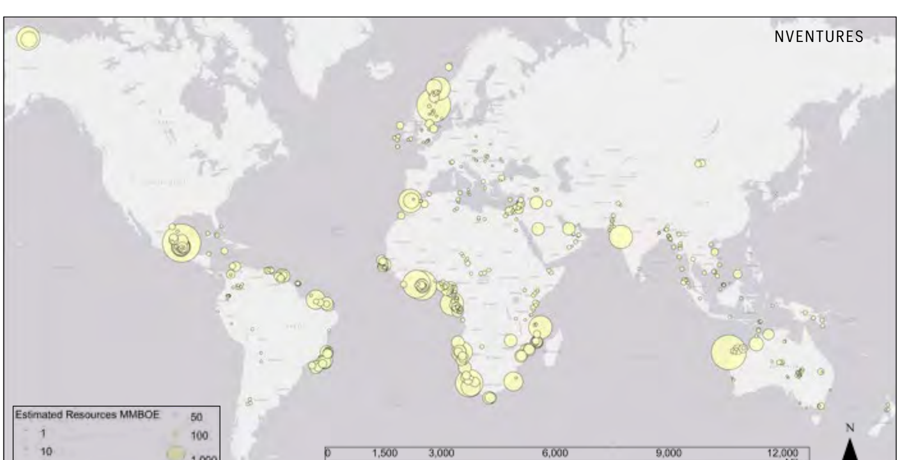
The extended impact of uncertain oil prices, combined with the Covid-19 pandemic and dwindling investor sentiment for hydrocarbons, have affected the exploration drilling scene in 2021, with a number of already deferred wildcat wells being further delayed and, in some cases, shelved. Notwithstanding the overall sentiment, 2021 had some significant exploration successes and early 2022 has followed strongly. A global review of wells to watch by reserves added (see map) indicates strong potential in the Gulf of Mexico, Atlantic margins of South America and western and southern Africa, North Sea (UK / Norway), eastern Mediterranean, west coast India, and Australia's North West Shelf (NWS). Onshore, significant reserves increases are possible in Kurdistan, Saudi Arabia, UAE, North Slope Alaska and eastern Africa.

The deadline to net zero committed to by various countries and companies, will in some cases preclude exploration in frontier basins, as the timeframe from basin evaluation through prospect maturity and drilling – to development and production – will be simply too long. While deepwater prospects drilled by the majors and larger NOCs stand most chance of adding significant reserves, there is a strengthening interest in targeting onshore, shallow water and infrastructure-led exploration prospects in emerging or mature basins and junior players are showing their niche abilities here.

Drilling deferrals from 2020 continued into 2021, such that some long-awaited wildcats such as TotalEnergies' Venus-1 well in Namibia and OVL's Kanchan-1 in Bangladesh are still ongoing in early 2022, and their outcomes are keenly awaited. Early 2022 is expected to see the spud of high-impact wells Apus-1 and Pavo-1, in NWS Australia, targeting the Triassic Dorado trend. Meanwhile, Sasanof-1 is planned near the giant Scarborough gas field, also in NWS Australia and Timpan-1 is scheduled in the North Sumatra Basin, Indonesia. In the eastern Mediterranean, there is no news on timing for the TotalENergies planned Block 9 Lebanon well and Energean's Zeus prospect offshore Israel is still in the planning stage. São Tomé and Príncipe will host its inaugural exploration well with Shell and Galp, Jaca-1, in Block 6 in the deepwater west of Equatorial Guinea. Several wildcats are planned for Guinea Bissau and Ghana in the West Africa margin, with relatively little activity in the onshore basins.



Global wells to watch by estimated reserves.

Guyana and Suriname continued to build on a notable run of exploration successes in 2021, particularly in the sweet spot of the Stabroek block offshore Guyana, with Longtail-3, Whiptail-1 and -2 and Catabacк-1 all proving additional oil reserves in deeper Cretaceous targets and continuing into 2022 with Fangtooth-1 and Lau Lau-1. In Suriname, TotalEnergies are drilling Krabdagu-1, on trend with previous successes in the block, despite disappointment with Bonboni-1. Other appetites remain lukewarm, with Tullow planning to exit Suriname, having had a presence there since 2007.

While reserves additions in the Asia-Pacific region are relatively modest, the drilling success rate throughout 2021 was between 50–60%, reflecting the maturity of the region but also the appeal of lower risk, higher return, exploration.

Turkey's 2020 Black Sea discovery, Sakarya, underwent various follow-up exploratory and appraisal operations, all of which appear to have increased reserves and highlighted the Black Sea potential, though possibly aggravating geopolitical issues in the region.

Despite a shortening timeline for the future of exploration, as the energy transition gathers pace, several countries are starting 2022 with bid rounds ongoing or opening. The appetite for companies' exploration dollars and commitments remains. If this can generate a spate of discoveries like those of early 2022, the health of the industry is more robust than it is generally presented.

MASTER'S MELTDOWN OR NEW DAWN?

THE FUTURE OF MASTER'S TRAINING IN ENERGY GEOSCIENCE IN THE UK

Professor Jonathan Redfern, *University of Manchester and*
Bernie Vining, *Visiting Professor, Royal Holloway, University of London*

All change! All change!

The energy transition is affecting all we do, be that in industry, academia or government. It is no longer a question of whether we need to act, but what we should do and how quickly, driven by the science, as well as public and market sentiment, as the scale of the challenge becomes apparent. Energy delivery, in all its forms, relies on geoscientists and engineers, whether to maintain oil and gas supply and ensure energy security in the near to medium term or to play a pivotal role in the removal of atmospheric carbon, delivering carbon sequestration (CCS/CCUS) and providing assurance it will stay sealed in the subsurface for millennia. Geoscientists also have a critical role in delivering sustainable resources, be that conducting site surveys for wind farms or subsurface characterisation for the future expansion of geothermal energy. All this activity will require a huge growth in exploration and development of strategic mineral resources, providing raw materials for many energy types, from batteries to nuclear energy.

Are we sleepwalking into a looming crisis in education?

But where will these geoscientists and engineers come from? Is there a strategy to attract and train them? Or are we sleepwalking into a looming crisis in education?

The feedstock for geoscientists into industry in the UK and globally has typically come from master's programmes, but most of these MSc courses are struggling. In the UK we have seen many petroleum geoscience and engineering courses close (*Figure 1*).

Those that survive have significantly reduced student numbers. And this is mirrored across the globe, be it in South East Asia where established MSc programmes in Thailand and Malaysia are teetering on closure, with single digit student numbers, or Australia and the US, where closures and course cutbacks are also ongoing apace.

There is a looming disconnect with potential demand for trained geoscientists and engineers for traditional and renewable resources, and the ability of academic institutions to supply.

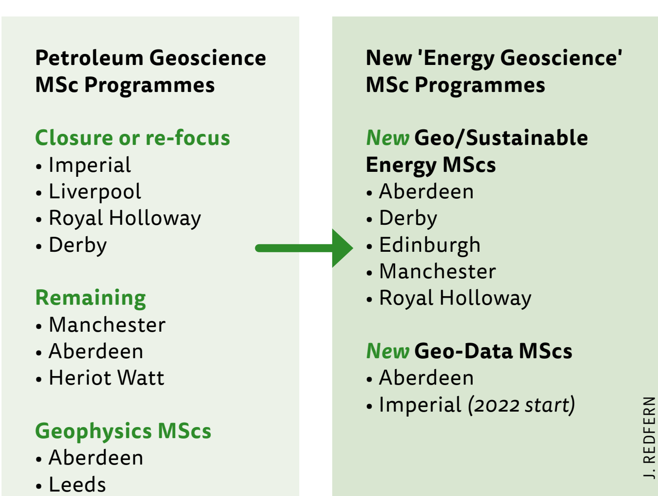


Figure 1: MSc course changes. Petroleum geoscience courses closed, with only three remaining, plus two geophysics courses. New Geo-Energy and Data courses are opening up to meet new demand.

Delivering the Right Skills

Traditionally in the UK, master's courses (12-month intensive postgraduate courses) have delivered focused, applied training to students to equip them with the knowledge and skills to join the job market, forming the backbone of the energy industry. But this pipeline of skilled geoscientists is under severe challenge from several fronts. Applicants to UK MSc programmes in subsurface geoscience have been steadily falling for the last five plus years. This reflects several possible causes.

In part, it is a function of a wider issue for geoscience. The numbers applying as undergraduates have also been falling, with UK students studying geology at university declining year-on-year since 2014, a total drop of 43 percent (UK Geoscience UK Resources). This reflects the fact that geology is rarely now taught as a separate subject in schools, instead being introduced only in other associated sciences like chemistry and physics (*Figure 2*).

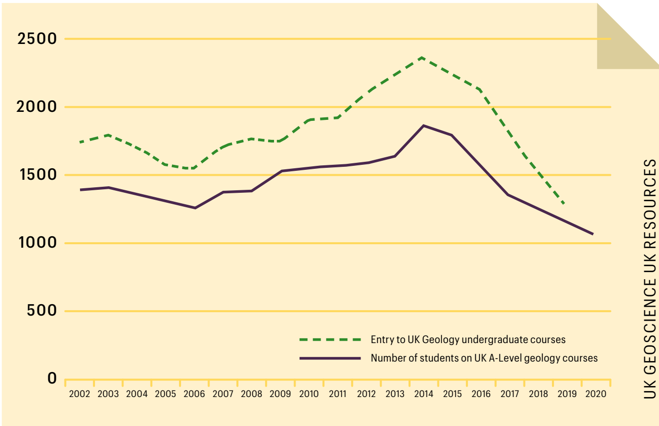


Figure 2: Comparison of falling number of A-level geology students and fall in UK undergraduates taking geology at university.

The conversion of UK undergraduates to master's programmes in energy geoscience and other sciences is worryingly low, with a notable drop in applications. The total number of students on all energy-related master's geoscience programmes in the UK has fallen by 28 percent over the last three years, with a fall in 85 percent on petroleum master's, reflecting in part the closure of programmes (*Figure 3*). In 2021 there were only 10 UK students studying petroleum geoscience at MSc level in the UK.

Cause and Affect

Cost and availability of scholarships is a key issue. After three years of building undergraduate debt, the extra financial commitment to undertake an MSc is considerable. A decade ago, there were a range of funding opportunities to support MSc students, such as scholarships from industry, government (NERC) and from organisations like the Petroleum Exploration Society of Great Britain (PESGB). This attracted the best to apply. However, most of these scholarships have been withdrawn, as companies and government cut costs.

Reduction in number of students on 'Energy-related' geoscience master's in the UK

- **Petroleum Geoscience** (UK/EU)
  2018: 65
  2021: 10 *(-85%)*
- **All 'Energy Geoscience' Masters** (UK/EU)
  2018: 65
  2021: 57 *(-13%)*
- **All 'Energy Geoscience' Masters** (UK/EU/Overseas)
  2018: 187
  2021: 134 *(-28%)*

J. REDFERN

Figure 3: Changes in numbers attending petroleum and energy-related courses over the last three years.

The perception of the job market is another important factor. Students no longer feel there is the prospect of a long, interesting and lucrative career in this field. In the past, the track record of employment for MSc graduates from most courses was very high. The majority joined the oil and gas industry, some went on to undertake a PhD, or moved into other rewarding careers. All benefitting from the broad range of transferable skills taught. Even today our courses have an enviable track record in this regard, but the recent period of low oil price and significant turmoil and redundancies in the sector, reported across the media, has hit student confidence in the energy industry as a long-term stable and attractive employer. Sectors such as IT, banking, civil engineering and environmental consultancies are all perceived to offer better employment prospects. So, there are bridges to build to communicate the exciting opportunities that still exist and to attract the best workforce.

And finally, there is wider public perception of the industry, driven by a media that often only portrays oil and gas companies as polluters, the target of many who put the blame firmly on the energy industry for climate change. An industry only regarded as the 'problem' and not part of the 'solution' is not one that graduates want to join. This view is widely held, and whatever those of us who work in energy may wish, it is a strong driver in reducing applications, and something that needs to be countered.

Evolving to Meet the Transition

How can we meet these wide-ranging challenges? To date, only three Petroleum Geoscience MSc courses remain in the UK, at Manchester, Aberdeen and Heriot Watt universities. These are bolstered by strong overseas demand, but all have smaller class sizes and falling numbers of UK applicants. Some courses have already closed and other MSc courses have re-branded and are re-focusing on a broader geo-energy or geoscience and data science curricula *(Figure 1)*. This reflects changing student demand and the need to prepare students for new roles in industry. But the challenge remains to deliver the graduates that industry will need, with the right geoscience skillset.

Collaboration is Critical

To meet future demand and to ensure the UK remains a global centre for geoscience and engineering excellence in subsurface energy requires a collaborative effort. Industry, academia and government must work together to change perceptions, improve communication, deliver innovative training solutions and step-up to lead in the search for resources globally. Recognising this, the Centre for Masters Training in Energy Transition (CMT) was founded in 2020. The CMT is an independent, international organisation and a world leader promoting geoscience training for the energy transition. Leveraging global outreach and working closely with industry, we plan to change the way we communicate and offer a platform for change. We will develop innovative modular online master's courses that will appeal to students across the world and will also open opportunities to those early career employees who, via distance learning, can continue their education in parallel with their employment. Truly collaborative programmes, in which each participating university would offer a selection of modules, enabling students to create their own bespoke master's degree.

The Centre for Masters Training in Energy Transition (CMT) **promotes access to resources** and **training for the next generation** of geoscientists and engineers to successfully meet the climate change challenge of **attaining net zero carbon emissions and delivering secure and sustainable energy** for the 21st century.

Figure 4: Mission Statement of Energy Transition CMT. For more information see the ***The Centre for Master's Training in Energy Transition****-website.*

Global Communication

We need an integrated strategy for communication. Not just talking to ourselves or those already knowledgeable about the issues, but engaging directly with young people using social media and championed by relevant role models. And we need to show we are all part of a collaborative effort to meet the climate change challenge, to be seen as part of the 'solution', emphasising the needs of energy security and sustainability, and noting that different parts of the world are at different stages along this energy transition journey.

We need to capture students' enthusiasm and show them they can look forward to exciting career opportunities worldwide across the evolving energy sector. The CMT is also focused on meeting the demand from industry to re-train its existing staff for the acceleration of the energy transition and to deliver the skilled graduates for research and development.

Flexibility, Adaptability and Agility

This is an exciting and challenging time for geoscience, that requires flexibility, adaptability and agility to change. It requires support and commitment from industry, government and academic policymakers. The key attributes of success will be improved communication and collaboration, to meet the demand for a planned and managed energy transition, and continued delivery of high-quality graduates with a strong background in geoscience fundamentals. Working together, universities can deliver curricula that provide the apropriate applied geoscience and engineering training, embracing new technologies with a cross-discipline, problem-solving mindset; all in the context of commercial acumen, leadership and management skills.

The CMT is a forum for collaboration, with engagement with the following parties:

Academia:

Bringing together leading UK universities that specialise in energy-related teaching, to build consensus and a powerful voice, and share their experience and expertise to grow the market globally and to deliver outreach as part of our commitment to meet these important challenges.

Industry:

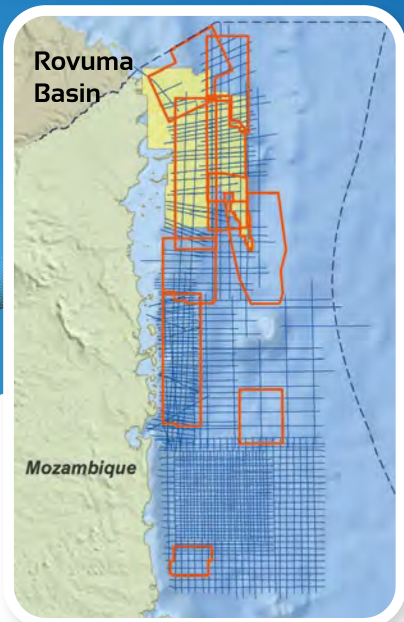
Supported by a wide range of companies from across the energy sector, contributing their own experience and expertise, supporting the next generation with knowledge, materials, mentorships, and financial support.

Government:

The UK government has recognised the critical nature of this sector, and the need to decarbonise. It is engaged with a particular emphasis on meeting the skills gap, in alignment with their commitments to net zero emissions by 2050. A recognition of the important role that master's training provides, together with apprenticeships and upskilling courses, should be followed by additional support.

Societies and International Bodies:

Involving international bodies like UNESCO, and professional organisations like the Geological Society of London, PESGB, and AAPG is important. By utilising their depth of knowledge and experience to help co-ordinate and communicate the many exciting initiatives to the target student audience.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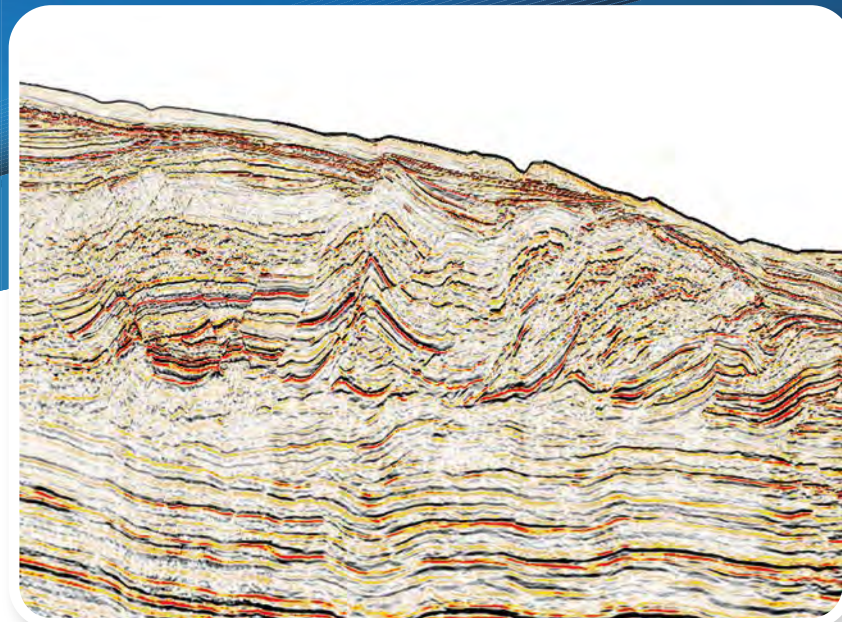
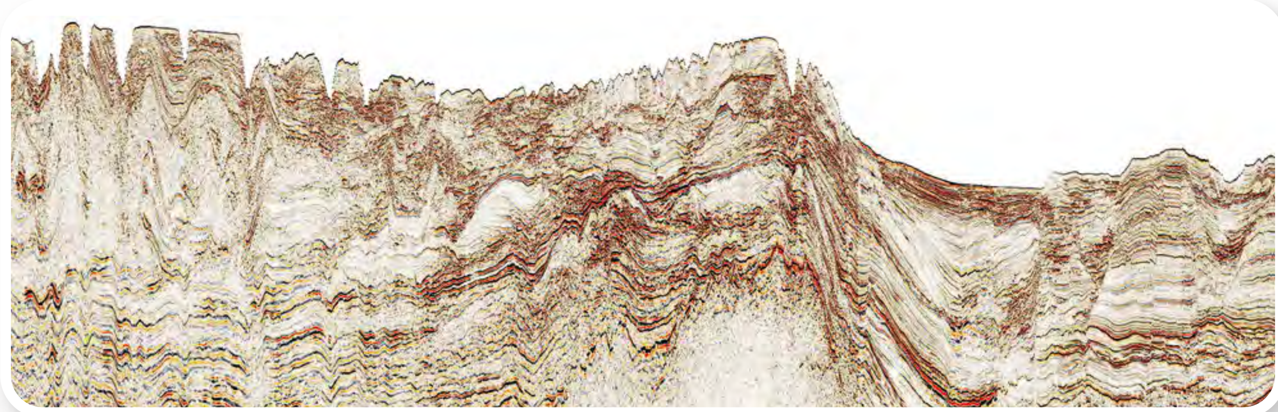




UNIFYING OFFSHORE BRAZIL: FROM THE ABIMAEL PROPAGATOR TO THE ABROLHOS ISLANDS

The ION Picanha™ 3D program reimages 275,000 km² of legacy seismic data into one contiguous data volume, enabling visualisation of the subsurface from the Abimael Propagator in the south-western Santos Basin to the Abrolhos Islands in northern Espírito Santo, more than 800 kilometres away. Regional mapping of well-tied geologic markers at major boundaries such as Albian carbonates, Aptian salt layers, and Brazil's infamous pre-salt sag sequence, reveal linkages between their geologic history and their robust hydrocarbon accumulations.

Picanha 3D Reprocessing Program

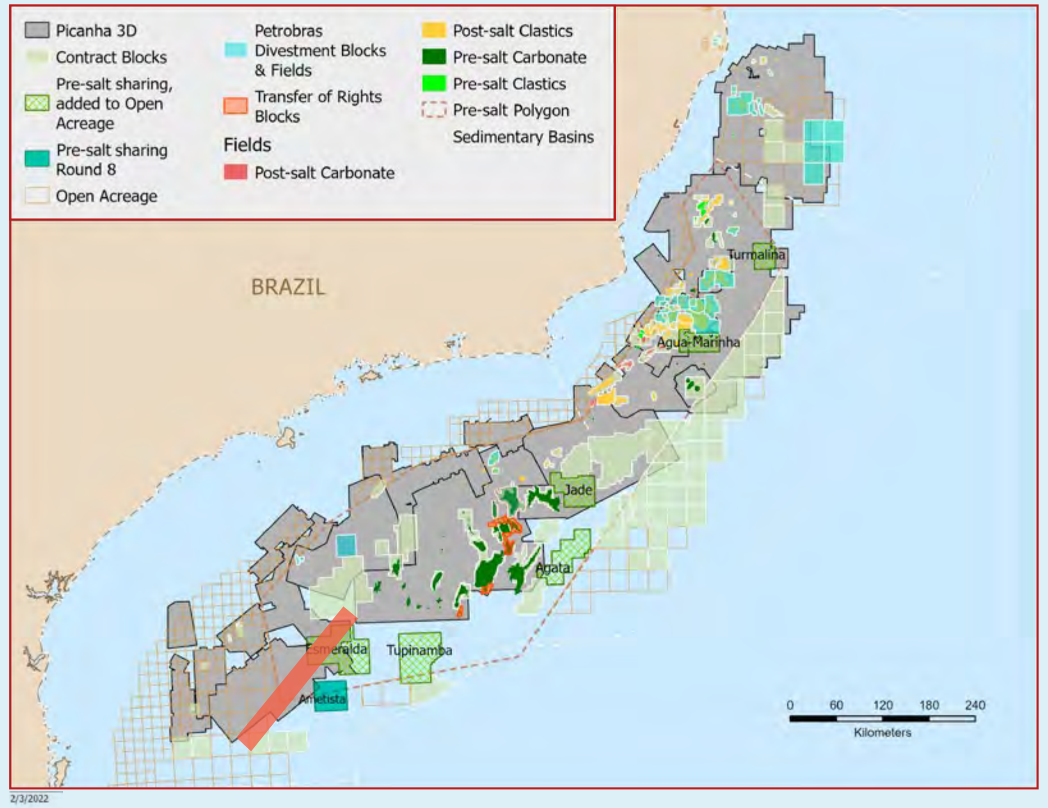
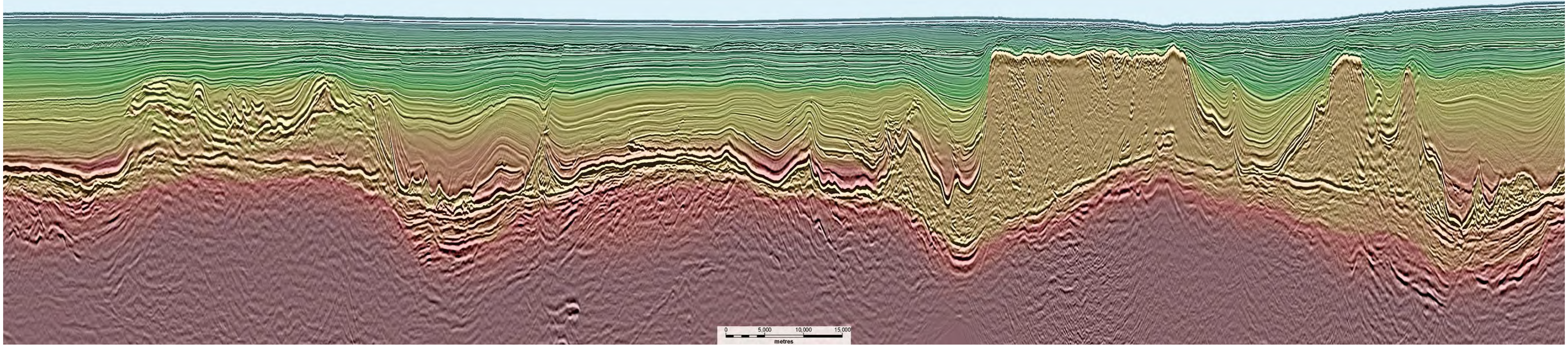


Figure 1A: Regional map with red line cross-section location.

Figure 1B: Cross-section through Picanha Phase 6 in south-western Santos, displaying a unique opportunity within the Esmeralda block. Updated imaging reveals intriguing basement structures and young development of the Ariri Salt canopy at the Abimael Propagator.



3D REPROCESSING INTEGRATES REGIONAL SEISMIC, OFFSHORE BRAZIL

The new Picanha 3D dataset provides the ideal foundation for an exploration and production strategy across a world-class petroleum province.

Andrew Hartwig, Jonathan Denly, Jeff Faw; ION

Brazil is the current epicentre of the South American oil and gas industry and ION's Picanha™ 3D reprocessing program sets a strong foundation for an offshore exploration and production strategy. The multi-client program unifies 115, previously discrete, standalone surveys into one seamless, contiguous regional 3D seismic volume. The integrated program supports national and international oil companies by accelerating exploration insight through regional mapping and prospect generation within an unprecedented 275,000 km² seismic survey (*Figure 2*).

The Picanha 3D dataset covers three of the prolific Brazilian offshore basins – Santos, Campos, and Espírito Santo – where both localised and regional studies can be evaluated for an improved understanding of the petroleum system and relationships from field to field. High-profile lease blocks such as Esmeralda, Jade, Água Marinha, and Turmalina are all within the Picanha 3D survey limits and were recently redesignated as Permanent Offer blocks (sure to garner plenty of attention as oil giants search for the next Lula field).

Broad Brush, Broadband

Starting with just four surveys, the number of input datasets has grown to its current tally of 115, acquired between the years of 1986 and 2013, each with varying acquisition parameters. Upon beginning the Picanha 3D program, the expectation was that it would grow to numerous phases and require a consistent image throughout. This necessitated that the processing, imaging, and interpretation of the data follow a robust, repeatable sequence, while allowing the flexibility to include new technologies as and when available. The benefits of this approach are evident in the seamless, high quality TTI RTM (40 Hz) and Kirchhoff PSDM (90 Hz) stack data, where direct hydrocarbon indicators at post-salt fields such as Marlim, Albacora, Roncador, and Atlanta are confirmed, and pre-salt fields such as Pão de Açúcar, Búzios, Lula, Libra, and Uirapuru are consistently imaged. The dataset includes velocity calibration from over 280 wells, resulting in improved depth imaging of steep-dipping salt flanks and deep basement structures across the region.

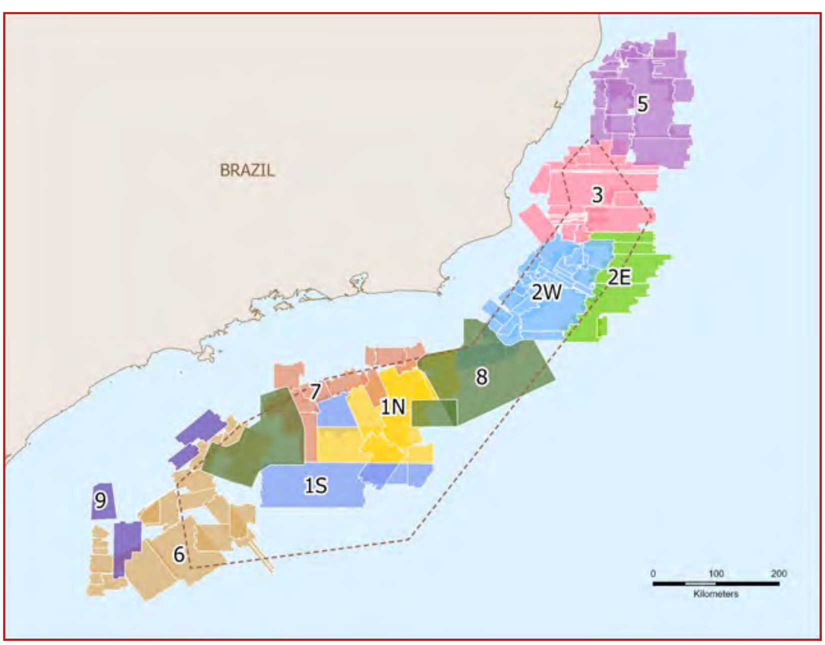


Figure 2: Map of the Picanha 3D program phases covering Santos, Campos, and Espírito Santo Basins.

Latest Datasets

To date, five phases of the Picanha 3D program have been completed with four more currently underway or scheduled to begin in 2022. The most recent program to be completed is the Picanha Phase 6 dataset. Located in the southwest Santos Basin, Phase 6 covers the inboard side of the famous Santos Outer Basement High, the Aram field, and many Permanent Offer blocks. Phase 6 data displays the potential for Brazil's shallow water, post-salt, clastic reservoirs juxtaposed against salt diapir flanks or rotated, and fault-bounded traps related to salt evacuation at the Albian Gap. Substantial pre-salt potential is also exposed through the updated imaging of base salt topography ranging from 6–12 km in depth.

Within the Esmeralda Block, shown in *Figure 3*, the updated data show unique opportunities in the pre- and post-salt carbonates. A nearby well confirms the presence of 350 m of pre-salt Barra Velha Formation and TDs in the syn-rift volcanics of the Camboriú Formation, confirming the presence of the proven reservoir components. The block is situated on the south-western side of the Santos

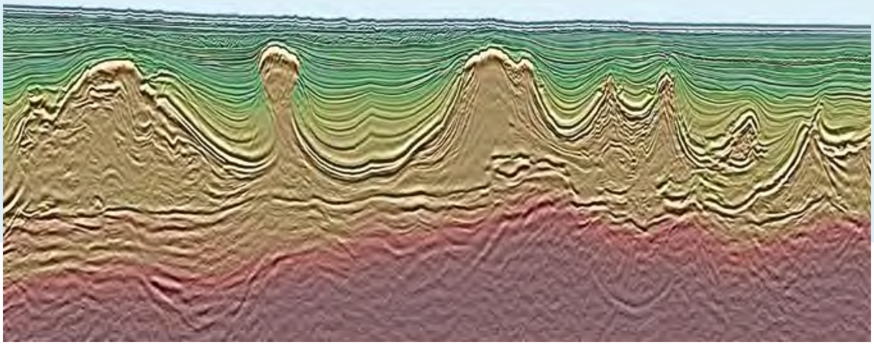


Figure 3: 40 Hz RTM with interval velocity overlay shown in cross-section view through the Permanent Offer block, Esmeralda.

Outer High with source migration from the Santos Inner Rift Kitchen where steep basement horsts and grabens display pockets of syn-rift and sag sediments. Proximity to the Florianopolis High and Abimael Propagator represent a complicated crustal regime that triggers vertical salt diapirism in the southernmost Santos, adding another unique variable to exploration in the area.

Picanha's latest addition, Phase 5 (*Figure 4*), which is scheduled to finish in August 2022, is 800 km north-east of Phase 6 in the Espírito Santo Basin. Here, Permanent Offer blocks are up for lease where updated imaging and velocity calibration techniques are expected to bring out huge upside potential within pre-salt basement onlap plays, as well as Gulf of Mexico-style allochthonous salt-flank plays. The dataset also approaches the Abrolhos Magmatic Province to the north-east. This igneous province is home to seamounts and volcanic islands and is an open area for new play concepts.

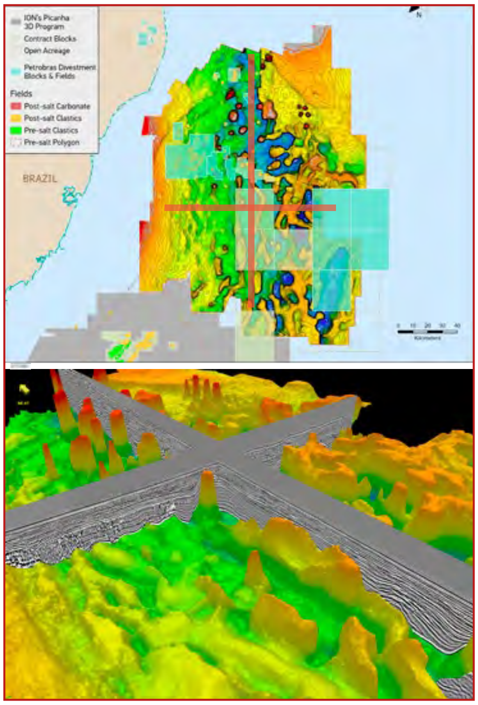


Figure 4. Above: Map of Picanha 3D Phase 5, Espírito Santo, displaying Top-Fast imaging surface, combining carbonate, salt, and volcanics for velocity constraint.

Below: 3D view of velocity constraint horizon on preliminary anisotropic sediment flood.

Regional Scale Perspective

The interpretation workflow for the Picanha 3D program has evolved from an imaging only workflow to an expanded, geologically driven evaluation of the program area's prospectivity, risk, and sustainability. The prolific Retiro and Ariri Salt Formations which were deposited during the mid-Cretaceous Aptian period are a critical imaging challenge which the interpretation team tackles using a variety of techniques. A dataset as large and contiguous as Picanha enabled the development and application of machine learning methods, reducing turn-around time by +30% and delivering an accurate starting model for follow-on, FWI-driven proprietary projects.

Albian carbonates and basement have also been regionally interpreted not only for velocity constraint, but for a measurement of the petroleum system where isopach maps can be used for pre-salt thickness and sediment depocenter mapping. Throughout the interpretation, comparisons can be made from field to field for insight to hydrocarbon migration evaluation, trap and seal styles, and regional trends which identify potential in open acreage.

Analysis of seismic attributes extracted from interpreted geologic surfaces have been used in combination with well data to interpret the geologic evolution of the petroleum system. For example, a semblance extraction from the regional basement surface (*Figure 5*) reveals patterns associated with fracture zones. High-density chaotic patterns coincidentally trend through known reservoirs, leading to a hypothesis which identifies these as lacustrine shorelines where carbonate platforms and microbialite build-ups of the Barra Velha and Lagoa Feia units are prone. The use of seismic attributes to identify basement fabric associated with volcanics, fractured carbonates, or even post-salt clastic turbidites are just a few applications for the regional dataset, while more detailed rock physics and inversion work can also be performed and tied to well data for reservoir characteristics.

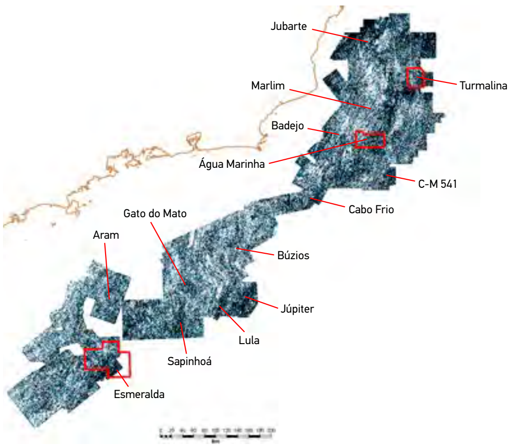


Figure 5: Semblance attribute extracted from ION interpreted basement surface, showing proximity of fracture patterns to existing fields.

Offshore Brazil Unified

The Picanha 3D program unifies offshore Brazil at an unprecedented scale, delivering high quality, regional 3D seismic data from the Abrolhos Volcanic Province, southward through the post-salt amplitude anomalies of the northern Campos, and Cabo Frio; a pre-salt flat spot at the Búzios, and the historic Lula field; then south-west to Esmeralda and the Abimael Propagator. The evergreen approach to the Picanha 3D program will continue to expand its footprint and role as a foundation for exploration insight in this prolific hydrocarbon province.

All images courtesy of ION Geophysical Corporation.

A CLEARER VISION WITH SEISMIC INVERSION

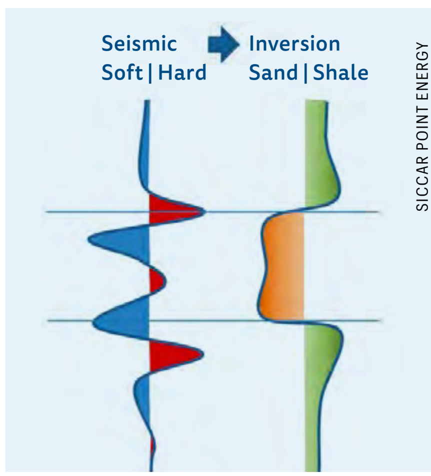
DEFINING A NEW UPPER CRETACEOUS PLAY, WEST OF SHETLAND

Christian Ellis, Abbie Morrison, Niall Mark: Siccar Point Energy; Heather Poore, Jim Jordan, Mark Pay: Spark Exploration; Santosh Kuppens, Frederik Horn and Henrik Juhl Hansen: Qeye.

It takes a lot of people to drill a well and many different disciplines working together, like the moving parts of a complex machine. It has been said that oil is a boring (but necessary) product, but that this lack-lustre commodity is obtained and supplied by some of the most interesting and complex technological and commercial processes known to man. Part of the role of geoscientists and engineers is to explain the insights and results from their own disciplines in ways that can be understood across multidisciplinary teams including non-technical stakeholders such as project investors.

It is probably fair to say that engineers' eyes often appear to glaze over somewhat when they are presented with a seismic line. It is probably easy to understand why – all those red and blue, or black and white stripes. A good seismic inversion can take that information and integrate it with other subsurface data, such as well logs, combined with more general information on the geology at hand, to generate a more meaningful display of the layers which will be encountered by the drill bit. Another really clever trick is that inversion reduces the imprint of the band-limited seismic vibration, or wavelet, thereby increasing the sharpness of the geological images compared to the input seismic. Inversion turns hard-to-interpret seismic amplitude values into rock and fluid property values, such as porosity and fluid saturation, and sharpens up the tops and bases of reservoir targets in the process.

Despite being a deeply technical process, ultimately a successful inversion project is driven by the people doing the work and a successful outcome depends on a good understanding across the team of the various components feeding the inversion. Several generic pitfalls can be avoided by careful project planning and project management. In addition to careful technical quality control of inputs, it is important to build an understanding across client, contractor and



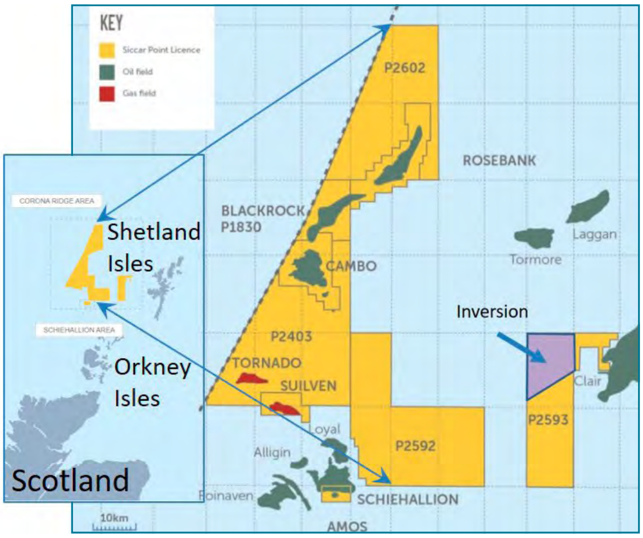
Turning seismic into rock and fluid properties.

partner stakeholders of what each party can contribute to the project and optimally to get an up-front commitment to regular (e.g., weekly) communication of how the project is progressing, what decisions are being made, and what options there are for doing things differently.

The initial stages of an inversion project are very time consuming. This is the stage at which seismic and log data is quality controlled and high-level geological concepts which will feed into the process are explored. One of the challenges at the early stages can be to balance forward momentum with the necessity from time to time to recycle. Shear velocity log quality is a common source of uncertainty and error, and existing pre-stack seismic data needs to be evaluated and if necessary optimised by applying further seismic processing. Wavelet definition is equivalent to finding the acoustic fingerprint within the seismic data and requires an equivalent forensic search since it will constrain every subsequent output. Once again, it can be time consuming.

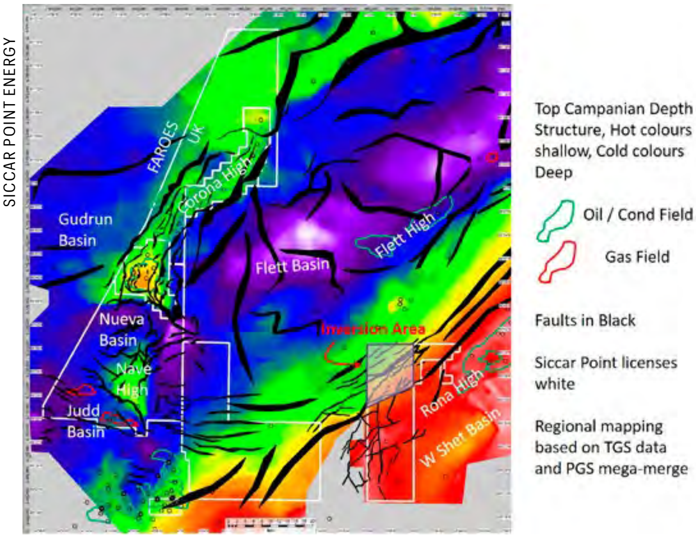
A seismic inversion is, rather obviously, only as good as the seismic data which underpins it. Put differently, if a phenomenon such as a subtle amplitude variation with offset (AVO) response (for direct hydrocarbon indication for example) is not already captured and hidden within the wiggles, the inversion process will not magically generate it and reveal it. A conventional full-stack seismic display encodes numerous hidden dimensions (compressibilities, densities etc.) which are themselves encoded within offset amplitudes (AVO) and normal incidence amplitudes. Pre-inversion analysis of seismic data can include cross-plotting seismic data in AVO / normal incidence space to establish if and where the data show the tell-tale signs that an inversion will be worthwhile. At this stage of the analysis, it will more than likely already be clear to a seismic interpreter where reservoir sands are most likely to emerge from the inversion image, and what the geological probability of success may be on mapped prospects. As the inversion project progresses it will test these pre-existing ideas.

SICCAR POINT ENERGY



Siccar Point Energy Licences (yellow) and the inverted area.

SICCAR POINT ENERGY



Structural Elements West of Shetland. Siccar Point mapping based on PGS, TGS and open-source seismic data.

The Colour of Sound – **Images of Hydrocarbons**

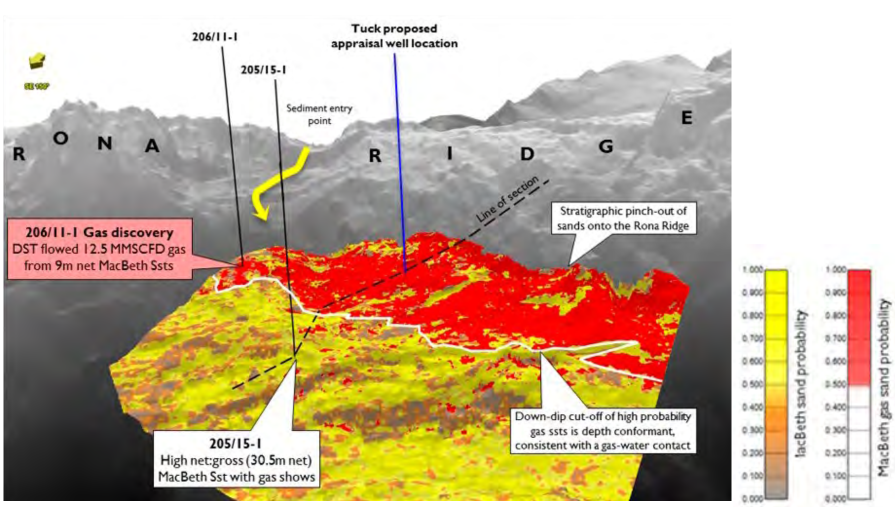
The West of Shetland (WOS) is one of the frontier provinces of the UKCS, although it is still commonly referred to as part of the North Sea in the popular press. Numerous fields within the basin are currently on production, such as Schiehallion, Clair and Laggan-Tormore, a number of material discoveries have still to be developed such as Cambo, Rosebank and Tornado, and a number of companies hold extensive exploration portfolios.

Siccar Point has partnered with several inversion companies within development and exploration work programmes in the WOS including a successful recent inversion project on the Rona Ridge, west of the Clair field, which sheds light on the likely distribution of a gas sand which has already been tagged in a nearby well. The tagged gas is within our Tuck prospect, hosted in the MacBeth Sandstone. Inversion analysis by Qeye in Denmark of data shot by PGS and TGS, and supported by Siccar Point's partner Spark Exploration, has added value to the partnership not only by generating a best-in-class inversion product, but also by acting as a platform across which the joint venture partners have communicated regularly to achieve these results.

A stepwise project roadmap was followed from early data handling and evaluation, through initial outputs, to a final set of probabilistic and deterministic deliverables with a project duration of three to four months. One of the most important steps of the workflow involves infusing pre-existing geological knowledge into the algorithm and is akin to allowing the geophysical data to shine through a shadowy existing image of the geology. This entails a balancing act determined by how good we believe the preconceived geological knowledge or 'prior model' to be, versus how good we think the geophysical uplift will be. If we get it wrong, we over-saturate the output with our erroneous misconceptions and learn little from the process.

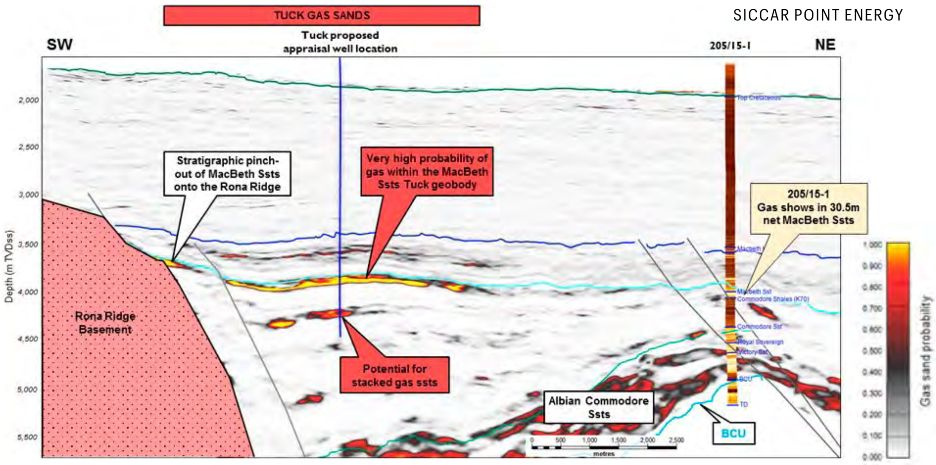
There are various ways of supplying a prior model and the algorithm used for the Rona Ridge rests on the notion that geological events facies sequences are ordered, and that if we know the general stratigraphy of a region, we can use the knowledge of where we are in the sequence to predict, to a greater or lesser extent of likelihood, what the underlying and overlying layers will be even in the absence of geophysics. We can also add such general information as the fact that gas will most likely occur above oil, and that they will both occur above brine, within the porous reservoir sequences. This type of prior model is described as a Markov Chain, with each link of the chain representing a likelihood of what will happen next as we travel downwards through the rock layers. There are several other

SICCAR POINT ENERGY



3D display of inverted gas sand up-dip in red pinching onto a basement high (grey). Brine sands are down-dip in yellow. Viewed approximately from north. Area is approximately 15 km across. Seismic data courtesy of TGS.

SICCAR POINT ENERGY



Dip line through the centre of Tuck with high probability of gas presence highlighted in yellow. Seismic data courtesy of TGS.

ways of supplying prior models used by different inversion products in the marketplace, all of which have their own strengths.

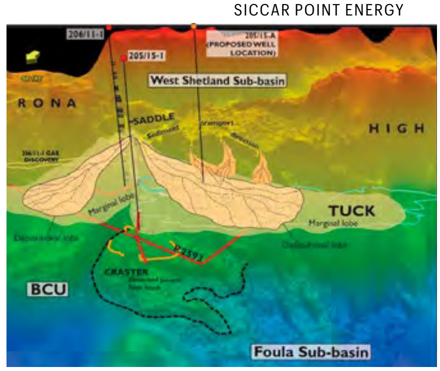
The inversion engine generates ordered wavelet scale sequences of facies consistent with the geological prior understanding. Rock physics and statistical relationships based on well data, between the compressibilities and densities of rocks and fluids as well as seismic wavelets and seismic noise models, produce a likelihood of seismic data depending on geology via facies sequences. The seismic data are then interrogated to produce a spatially varying distribution of facies sequences, consistent with the seismic data (within noise level) and the prior understanding of layered rock and fluid fill.

From Acoustic Image to Gas Sand Map

Numerous plays are present along the Rona Ridge, but our current inversion has primarily targeted just one of these. This is the known Upper Cretaceous play, which has already been intersected within the licence by a well that found over-pressured gas-bearing sands onlapping the basement, very much analogous to that found in TotalEnergies' Glendronach field, 60 km to the NE. The geological challenge is to find better quality sand than that encountered in the existing well. The geophysical challenge is to determine whether the carbonates overlying parts of the sand were masking the true seismic response of the target within a side lobe to the main seismic loop.

In fact, the mapped distribution of the carbonate layer is different from that of the seismically bright underlying gas sand loop, and the inversion has corroborated this conclusion, demonstrating a down-dip cut-off parallel to structure consistent with a gas/water contact. The mappable sand lobe sweeps from the basin back up towards the depositional entry point, with the inversion demonstrating that seismic amplitude changes which we observe are most likely related to changes in porosity between the axis of the sand depositional system and its margins. The inversion has also highlighted several secondary sand input points to the system and shows that the lateral seal for the Tuck prospect most likely occurs because of facies change.

SICCAR POINT ENERGY



3D geological interpretation showing sediment input points to sand lobe. Viewing direction similar to previous illustration.

Known lateral stratigraphic traps in the West of Shetland are numerous, not only in this play but also within the Palaeocene. When exploration of the WOS first began, geologists were concerned that it would be difficult to find good sand reservoirs this far out into the Atlantic margin. That fear has proved unfounded, but the common occurrence of lateral traps by facies change may reflect the fact that we are prospecting in deepwater systems a long way from the primary source of the sediment. The stepped over-pressure profiles in the upper Cretaceous stacked sands seen in the Tuck and the along strike Glendronach, also support lateral pinch-out as the lateral seal mechanism.

Measurements of Success

The best indication that an inversion project has been successful is perhaps that output volumes are accepted by the subsurface team as providing useful constraint to models and that they are actually used. A set of inversion volume outputs languishing somewhere on an IT system is surely the most dispiriting indication that the project has not delivered what it set out to do and has not managed to achieve a useful data synthesis. In this article we have tried to set out the ways in which the project owner is most likely to help build a successful result. This will include lots of discussion up front about what stakeholders think the project is likely to achieve and lots of short duration validation tests of ideas during project implementation. A successful inversion project will have a legacy beyond the initial project aims and will hopefully become a set of seismic volumes which future project teams will come back to again and again. When the project helps bring stakeholder companies together and enhances the working relationship, it is most likely to deliver the more tangible results of drillable anomalies.

Acknowledgements:

PGS and TGS are gratefully acknowledged for the use of seismic data in regional mapping and inversion.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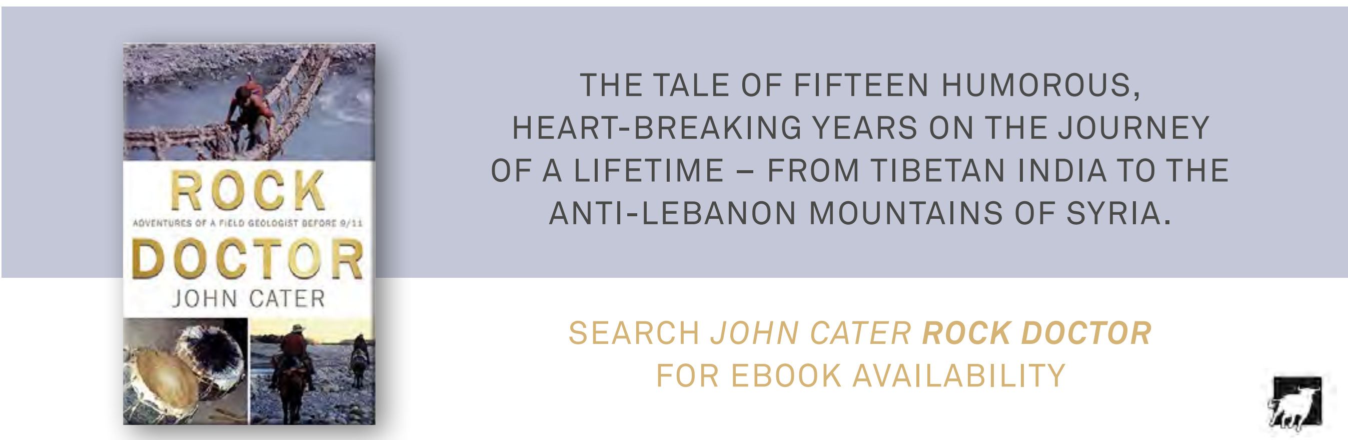
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FROM ARRHENIUS TO CO_2 STORAGE

Part XIV The Doom of a Photon on a Random Walk

Should I stay or should I go now?
If I go there will be trouble
And if I stay it will be double
So come on and let me know
— THE CLASH (1982)

The history of an individual infrared photon being emitted upwards from Earth's surface into a static atmosphere is analysed as a one-dimensional random walk. Will it return to Earth, or depart into outer space, or will it stay in the atmosphere forever? The photon's frequency and the CO_2 concentration in the atmosphere determine its fate. The random walk applied to the radiation of photons lacks essential physics but provides a simple educational model which illustrates how absorption, followed by re-emission, result in a net stream or flux of photons back to Earth's surface.

Lasse Amundsen* and Martin Landrø, NTNU/Bivrost Geo

One day when Brigitte is climbing the Haiku Stairs she meets Phôs. Brigitte, let me know, Phôs says. I've been walking the stairs for some time now. I am born from Gaia (Earth) but she destroys me if I fall onto her. I cannot go to the top since Rainbow then reaches down on me to carry me up to space. Should I stay, or should I start a random walk, in the hope that I will walk the steps forever? Brigitte says, if you go there will be trouble. The random walk will be your doom.

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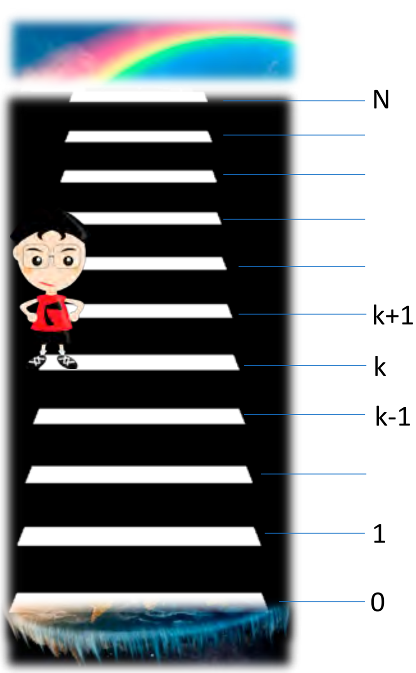
Figure 1: Hawaii's famous Haiku Stairs, known as the 'Stairway to Heaven'.



LASSE AMUNDSEN

Figure 2: Phôs on step k of Haiku Stairs. On step 0, Phôs falls onto Gaia and is destroyed. On step N, Rainbow captures Phôs and sends him into space. What is his fate if he starts a random walk?

The random walk means that you hop one step up or one step down with equal probability, independent of the direction of all your previous hops. Suppose that Haiku Stairs has $N+1$ steps. The first step 0 is close to Gaia and the top step N is close to Rainbow. We are now at step k. What you're asking me is your chance of avoiding fatality – extinguished by Gaia at step 0 or captured by Rainbow at step N.

Let $p(k)$ be the probability that you hop to the bottom step where you are extinguished by Gaia, given that you start at step k. In two special cases, the value of $p(k)$ is easy to determine. If you start at 0, you fall onto Gaia and you are extinguished immediately, so that $p(0)=1$. On the other hand, if you start at step N, you're captured by Rainbow, who will never more let you hop the stairs, so $p(N)=0$.

When Phôs starts at k ($0<k<N$), Brigitte breaks her analysis of Phôs's fate into two cases based on the direction of his first hop:

- If his first hop is down, then he lands at step k-1 and eventually he falls onto Gaia with probability $p(k\text{-}1)$.
- If his first hop is up, then he lands at step k+1 and he eventually falls onto Gaia with probability $p(k+1)$.

By the law of total probability which expresses the total probability of an outcome which can be realised via several distinct events, Brigitte expresses the probability of Phôs falling onto Gaia as:

$$p(k) = (1/2)\,p(k-1) + (1/2)\,p(k+1),\ p(0) = 1,\ p(N) = 0$$

In mathematics, this just a linear recurrence:

$$p(k+1) = 2p(k) - p(k-1)$$

with well-established methods for solution. High school students who are familiar with finite differences (*see GEO ExPro Vol. 15, No. 2*) are also on familiar territory by writing the recurrence equation in the form:

$$p(k+1) - 2p(k) + p(k-1) = 0$$

The left-hand side is seen as the finite difference (with step one) of a second derivative.

The right-hand side dictates that the second derivative be zero; therefore, the solution for $p(k)$ must be a linear function $p(k)=a+bk$ where the constants a and b are determined by the boundary conditions $p(0)=1$ and $p(N)=0$. Brigitte tells Phôs the probability:

$$p(k) = 1-k/N \qquad [1]$$

She continues: Phôs, when you start at step k in a stair with N+1 steps, then you're destroyed by Gaia with probability 1-k/N. Moreover, it is straightforward to calculate the probability that you're captured by Rainbow. Leaving it as an exercise, the answer is 1-$p(k)=k/N$.

This is bad news for you, Phôs, Brigitte concludes. The probability that you end your fate at the bottom or on the top of the stairs is 1-k/N+k/N=1. There is zero probability that you'll hop the stairs happily forever.

Phôs asks Brigitte, what is my destiny if the number of steps in Haiku Stairs is infinite? Brigitte lets N tend towards infinity in the probability equation *[1]* and she finds 1. Even for an infinite number of steps, you are extinguished by Gaia with probability 1. This is true no matter where you start.

Phôs in the Atmosphere

Before reading on, the interested reader may want to consult 'Part XI: How Earth's IR Photons are Transferred in the Atmosphere in the Presence of CO_2' (*GEO ExPro Vol. 18, No. 1*). The reader may also consult Wilson and Gea-Banacloche (2012) who have discussed, in a similar way to our attempt, the history of an individual photon when treated as a random walk, consisting of absorption and re-emission events by CO_2 molecules in a hypothetical static atmosphere.

Following the theory of Part XI, we consider the exponential atmosphere whose composition is assumed to be the function of height only. In this atmosphere, the transfer function taking the photon from the surface of the Earth to height z is $Q\nu(z,0)\approx\exp(-z/l\nu)$, where $l\nu=1/n\sigma_\nu$ is the mean free path or the mean distance travelled by a photon before being absorbed. Here, n is the local CO_2 density and σ_ν is the CO_2 cross-section which is a measure for the probability of absorption, or the ability of a CO_2 molecule to absorb a photon of a particular frequency or wavenumber. The cross-section can be approximated by the function $\sigma_\nu=\sigma_0 \exp(-r|\nu-\nu_0|)$, where $\sigma_0=3.71\cdot10^{-19}$ cm^2, r=0.089 cm and $\nu_0=667.5$ cm^{-1}, close to the approximation suggested by Wilson and Gea-Banacloche (2012). Air has $2.5470\cdot10^{19}$ molecules/cm^3. Then, when the CO_2 concentration is given in ppm by $[C]$, the local density close to Earth's surface is $n=\eta[C]$ molecules/cm^3 where $\eta=2.5470\cdot10^{13}$.

After being absorbed, the photon is re-emitted, with a 50/50% probability of being sent upwards in the atmosphere or downwards, back to the Earth. If it goes upwards, then it travels another distance $l\nu$ before it is absorbed again. The story of absorption and re-emission continues in this way. The question is what is the probability that the photon will eventually get back to Earth, where it heats Earth's surface and ends its life? Alternatively, we may ask what is the probability that it eventually escapes into space?

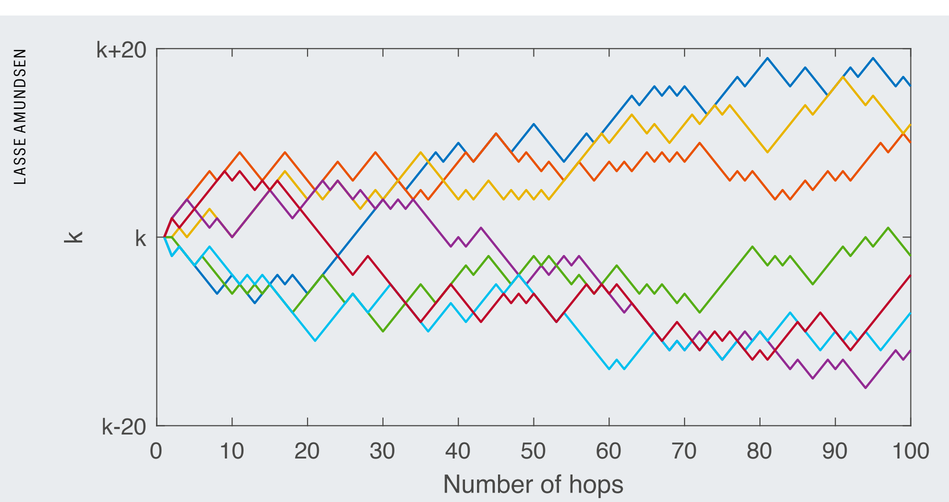


Figure 3: Seven different random walks starting at step k.

Let's use the simple random walk formula *[1]* to study the fate of a photon emitted upwards by the Earth's surface at 'step 0'. Since the photon has travelled one mean distance, it is on 'step 1' when it starts on the random walk, with probability of return:

$$p(1) = 1-1/N$$

To evaluate this probability, we need an estimate of the number of steps or 'layers' N of the atmosphere. The exponential atmosphere is characterised by the scale height L=8,000m. In the exponential atmosphere, for every L rise in altitude, the density and pressure of air drop by a factor e=2.7; thus, L provides a measure of the thickness of the atmosphere. Therefore, we may take the number of layers to be:

$$N = L/l\nu = \eta\sigma_\nu L[C]$$

Let's estimate N by supposing that the photon is at the centre of the absorption band at wavenumber $\nu_0=667.5$ cm^{-1}, when being emitted upwards from the surface of the Earth. Assume that [C]=400 ppm. The mean free path becomes 2.646m so that N=3024. The probability of returning to the Earth becomes $p(1)$=0.9997. A photon with frequency or wavenumber near the centre of the absorption band is virtually certain to make the return to Earth. If the CO_2 concentration is doubled, the probability doesn't change much; it becomes $p(1)$=0.9998. Any CO_2 increase has minor effect on the photons in the center of the absorption band. This part of the band is 'saturated'.

Suppose instead that the photon leaves Earth's surface away from the centre of the band, say at its wings at wavenumbers ν=585.2 or 749.8 cm^{-1} where $\sigma\nu$ has fallen off by several orders of magnitude. Now, the mean free path is 4,014m, the number of layers in the atmosphere is 3 (N=2) and the probability of returning to the surface is $p(1)$=1/2. The probability then for the photon to disappear into outer space is 1-$p(1)$=1/2.

No surprise, actually. It is a 50/50 chance to end at step 0 or step 2 when the photon starts at step 1. However, if the CO_2 concentration doubles, these numbers change considerably: $p(1)=3/4$ and $1-p(1)=1/4$. Hence, when the CO_2 concentration doubles, the probability of the photon at the two selected frequencies at the wings of the CO_2 cross-section coming back to Earth increases by 50%, and the probability to end in outer space is halved.

Clearly, because of the exponential decay of the CO_2 cross-section, the effect of a CO_2 increase is important mostly around the wings of the CO_2 cross-section. In addition, we observe that the mean free path of the photon in our simple model is halved by a doubling in CO_2 concentration. This implies that the number of layers in the atmosphere doubles, so that a large increase in the CO_2 concentration widens the range of photon frequencies that are blocked from reaching outer space.

Number of Photons Emitted from Earth's Surface

In 'Part VIII: How CO_2 Absorbs Earth's IR Radiation' (*GEO ExPro Vol. 19, No. 3*) we displayed the number of emitted photons from Earth's surface as a function of wavenumber for the surface temperature of 288K (15°C). How do we calculate the number of photons? We start with the Planck function:

$$B\nu = 2hc^2\nu^3 / \left(\exp\left(\frac{hc\nu}{k_BT}\right) - 1\right)$$

which tells the emitted power per unit area per steradian per wavenumber interval. Here, h and k_B are the Planck and Boltzmann constants and c is the speed of light. We now remind the reader that the energy flux (the Stefan–Boltzmann law) is given by the famous formula:

$$F = \pi \int_0^\infty d\nu \; B_\nu = \sigma_B T^4$$

It tells that a blackbody source of temperature T radiates a total power (per area per steradian) across the entire electromagnetic spectrum of $\sigma_B T^4/\pi$ where σ_B is the Stefan–Boltzmann constant.

The photon has energy $hc\nu$. Introducing the photon density $N_\nu = B_\nu / hc\nu$ the photon flux N_P is given by:

$$N_P = \pi \int_0^\infty d\nu \; N_\nu = \sigma_H T^3$$

where we name $\sigma_H = 4\pi k_B^3 \, \zeta(3)/(h^3c^2) = 1.5205{\cdot}10^{15}$ photons $m^{-2}\,s^{-1}\,K^{-3}$ the Haas constant, where ζ is the Riemann zeta function, which has $\zeta(3) \approx 1.202$.

The total number of photons emitted by a blackbody in thermodynamical equilibrium thus is close to $1.5{\cdot}10^{15}{\cdot}T^3$ photons per s per m^2. This number was first calculated by Haas (1938). For Earth's surface temperature of 288K (15°C) the total number of photons emitted is $3.63{\cdot}10^{22}$ photons per s per m^2.

Number of Photons Returning to Earth

The number of photons that return to the surface of the Earth can be estimated by use of the random walk probability formula. Earth's emitted photon flux depends only on the Earth's surface temperature. To get the flux of return we may multiply the emitted flux by the probability of return:

$$p_\nu(1) = 1 - \frac{1}{\eta\sigma_0 \; \exp(-r|\nu - \nu_0|) L[C]}$$

where the ν-subscript denotes that the probability depends on the wavenumber. This probability is plotted in Figure 4 for four different CO_2 concentrations. It is close to one near the centre of the CO_2 cross-section around ν_0 but drops towards zero at the wings of the cross-section. Due to the exponential decay of the cross-section the probability

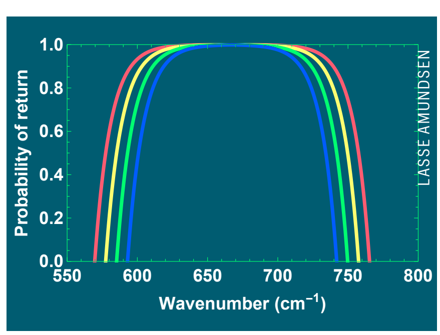


Figure 4: The photon's probability of return to Earth's surface as function of CO2 concentration [C]=100, 200, 400 and 800 ppm (the blue, green, yellow and red lines, respectively). With increasing CO2 concentration, the wavenumber probability spectrum of returning photons broadens.

p_ν will become negative at wavenumbers $\nu_\pm = \nu_0 \pm \ln(\eta\sigma_0 \, L[C])/r$ and we replace all negative probabilities by zero. The total number of photons returning then can be written:

$$N_P^{\text{in}} = \pi \int_{\nu_-}^{\nu_+} d\nu \; N_\nu \, p_\nu(1)$$

Numerical integration of the above equation gives the number of photons returning to Earth's surface: $4.9{\times}10^{21}$ photons per s per m^2. This is 13.5% of those that the Earth initially emitted.

Number of Photons Leaving for Outer Space

In Figure 5 (the white line) we display the number of photons that are departing for outer space per second per square metre per wavenumber interval. The total number of photons leaving the atmosphere is the total number of photons emitted by Earth minus those returning to Earth's surface. The percentage is 86.5%.

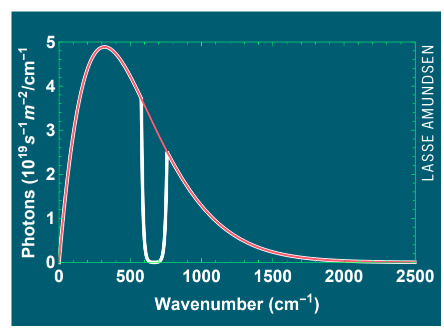


Figure 5: The number of photons (photon density) radiated by the surface of the Earth per s per m² per wavenumber interval (the red line) and the number of photons that travel to outer space per s per m² per wavenumber interval (the white line) in the random walk model. The absorption of photons is caused by CO2 at concentration 400 ppm. Numerical integration of this spectrum gives the total number of photons going out to space. See text for more details.

Warming Effect by CO2 Doubling

The Earth is considered a blackbody in the infrared spectrum. It radiates $F=\sigma_B T^4=390$ W/m^2. In the same way that we calculated the number of photons returning to Earth's surface we can calculate the inward flux to Earth for a given CO_2 concentration. First, multiply the blackbody radiation per wavenumber by the probability of photon return; second, integrate numerically over all wavenumbers.

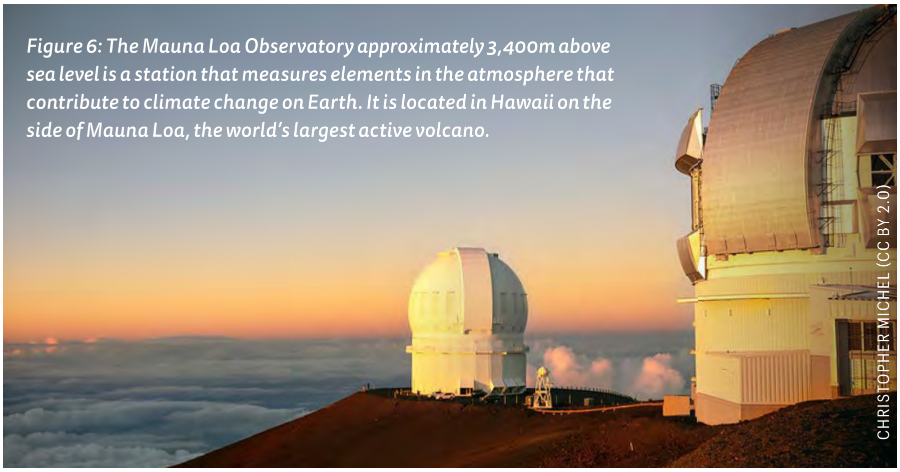


Figure 6: The Mauna Loa Observatory approximately 3,400m above sea level is a station that measures elements in the atmosphere that contribute to climate change on Earth. It is located in Hawaii on the side of Mauna Loa, the world's largest active volcano.

The monthly mean CO_2 content is measured at the Mauna Loa Observatory in Hawaii. At the end of November 2021 the concentration was measured as 415 ppm. By calculating the inward radiation fluxes from this time to the time a doubling is achieved, we find the fluxes 64.8 W/m^2 and 71.1 W/m^2, giving the change in flux ΔF = 6.3 W/m^2. This simple calculation assumes that the temperature profile of the Earth system does not change during the increase in CO_2.

Due to the simplicity of the model, the inward radiation flux numbers cannot be trusted. However, in the absence of processes other than the ones discussed so far, the model shows that the absorptive strength of CO_2 would be sufficient by itself, to cause an increase in the inward flux.

The Effect of CO_2 Radiation Efficiency on Warming

We speculate if the model can be made slightly more realistic by including the CO_2 photon radiation efficiency. The random walk model assumes that every CO_2 molecule that absorbs a photon also radiates the same photon, in a random direction. However, in 'Part IX: How CO_2 Emits IR Photons' (*GEO ExPro Vol. 17, No. 4*) we showed that only around 5% of the CO_2 molecules after having absorbed a photon radiate a photon. The rest of the CO_2 molecules relax by colliding with N_2 and O_2 molecules.

By including this effect, which we may call the CO_2 radiation efficiency, we redo the calculations and find that the inward fluxes are 37.4 W/m^2 and 43.8 W/m^2. Although the change in flux is the same, ΔF=6.3 W/m^2, the inward fluxes in Earth's energy budget are significantly reduced due to the low radiation efficiency (5%) of the CO_2 molecules in the atmosphere. The inward fluxes are reduced by around 40% by a 95% reduction in CO_2 radiation efficiency.

Conclusion

The model of random walk applied to the radiation of photons is simple but lacks obviously essential physics. Nevertheless, the mathematics of the model provides a simple picture to illustrate how absorption, followed by re-emission, result in a net stream or flux of photons back to Earth, at those frequencies where the atmosphere is strongly absorptive, that is, where the CO_2 cross-section is large, implying that the mean free path is short, so that the number of atmospheric layers is large. Absorption and re-emission of photons in random directions prevent some photons escaping out to space. They are returned to the surface of the planet where they heat Earth. At the wings of the CO_2 cross-section, the mean free path is much larger, giving the photons at those frequencies a higher probability of departing Earth into outer space.

Acknowledgement:

The authors have enjoyed many helpful discussions with Birgitte Reisæter Amundsen and Tore Karlsson.

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

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ARTIFICIAL INTELLIGENCE – ITS USE IN EXPLORATION AND PRODUCTION

PART I

What is it really and what are its limitations?

SHUTTERSTOCK

Dr Barrie Wells
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Artificial Intelligence (AI) has at least one feature in common with hydrocarbon exploration: a history of boom and bust. Other industries might complain about the unpredictability of demand for their products but generally do not have to contend with a market in which the price of their product fluctuates as wildly as that of crude oil. Oil exploration and production is notoriously boom and bust, for reasons that are too complex for most economists to understand. AI's boom and bust is probably much easier to explain: excessive optimism.

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Some Important History

AI is reckoned to have become a separate field of study in 1956, when the foremost USA researchers met at a summer school and gave the field its current name. As well as christening this new science, they made some predictions, broadly claiming that machines would be as intelligent as humans within a generation. This led to a huge influx of funding for research, notably from The Defense Advanced Research Projects Agency (DARPA) (i.e., the USA's military), and then an equally dramatic loss of funding a few years later when the predicted benefits failed to materialise. This withdrawal was later called the first AI winter, but only after a second wave of optimism in the late 20th century had led to history repeating.

We are now experiencing spring once again, with green shoots of AI springing up all over. This year's BBC Reith Lectures were on AI, specifically the dangers we will face when the machines eventually become more intelligent than us. So maybe we have learnt something: if not to dial-back on the optimism, then at least to look before we leap.

Is it really different this 'year'? Will our winter of discontent finally be made glorious summer? In considering this question, past performance may not be the best guide to the future, but it's not a bad starting point. So, some historical background should be useful; and understanding how AI works, at least at the heuristic level, should help us see where, in our industry and areas of specialism, we might expect to see the most change in the near future.

Benefits: The Internet and Search Engines

The first historical point to note is that AI has not actually been the failure implied by the periodic dramatic retreats made by the funders, although the successes have sometimes been of a different kind. DARPA's funding of purely conceptual research, with no strings attached, gave us the internet, and the internet gained widespread acceptance through search engines, and the main search engine gained its dominance through use of AI. Or, on a less pragmatic level, it is said that research into AI has taught us as much about human intelligence and the nature of intelligence in general as it has about machine intelligence. A statement on the state of AI at the end of the last century was that we have taught computers to beat the world chess champion but not to perform tasks mastered by three-year-olds, such as natural language processing. At the outset, playing (and winning at) chess was seen as the pinnacle of achievement.

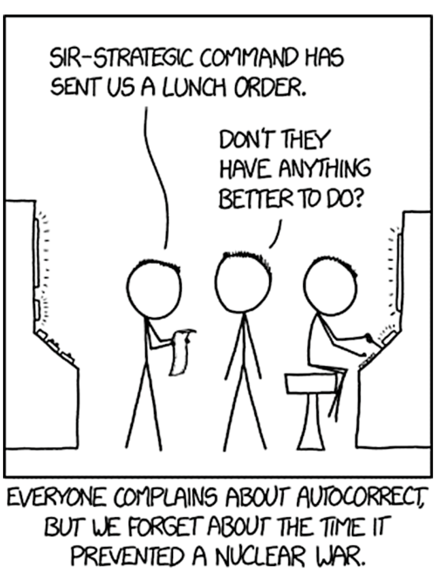
This is formalised in Moravec's paradox, which notes that proving theorems and solving geometry problems (deductive logic) is comparatively easy for computers, but a supposedly simple task

like recognising a face or crossing a room without bumping into anything (inductive logic) is extremely difficult. Mastering natural language processing is another example of a stumbling block for AI. The following pair of statements illustrates some of the potential difficulties: ***Time flies like an arrow.***
Fruit flies like a banana.

How could a computer be taught to distinguish the different uses of 'flies' and of 'like'? Simple rule-based systems find this (almost) impossible. But in conjunction with access to the entire corpus of literature in the English language for comparative testing, AI can use 'the wisdom of the crowds' to distinguish intention from context, and hence deduce, at least probabilistically, intended meaning.

AI has achieved its major successes by taking advantage of breakthroughs unavailable to those researchers attending that summer school in 1956:

- access to data: the internet makes available vast quantities of data (although not all would agree on describing it as 'information');
- computing power: Deep Blue, the IBM computer that defeated then-reigning world chess champion Gary Kasparov in 1997, was at least 10 million times faster than the fastest 1956 computer;



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- evolution and development of the mathematical basis for AI, including new tools and borrowing tools from other disciplines, notably mathematical statistics;
- commercial drive, e.g., from makers of phones (wanting to improve typing speeds by utilising predictive texting or auto-correct) and voice-controlled devices, creating measurable goals and provable outcomes which result in huge profit if successful.

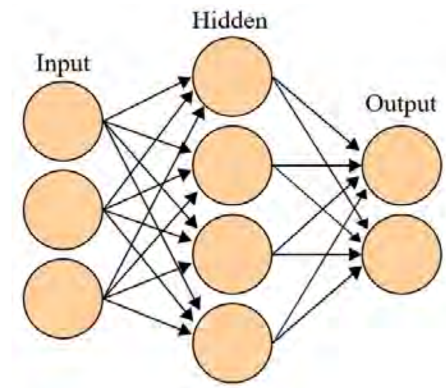
Expert Systems to Machine Learning

Expert systems had a rule-base or knowledge base: rules such as 'If the temperature drops below zero then water is likely to freeze'. Adding rules for the dependence on pressure and presence of impurities in the water, together with temperature sensors and pressure sensors and possibly even impurity composition detectors, or at least inputs of concentrations, and an expert system could easily handle tasks previously allocated to humans, with the benefits of more efficiency, less mistakes and greater speed of decision-making. In fact, the period of 'failure' in the last quarter of the last century left us with many embedded AI systems, quietly doing their jobs and making rigs and platforms, for example, safer places to work. There is only so far that an Expert System can go, however. Rules can cover some closed systems which seem quite complicated, but they have no hope of success at, for example, driving a car. The number of rules is just too great. A different paradigm was needed.

Neural Networks

Neural Networks were so called because they were intended to mimic the way human brains work, although the shared name is probably the greatest similarity between the two. Artificial Neural Networks (which we shall call NN for short, technically we should perhaps use ANN) are more of a concept or idea than a specific mathematical procedure.

The diagram used to illustrate NN is nearly always akin to this:



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which may perhaps be summarised as: 'There are inputs, there are outputs, and between, there be dragons'. To be useful, a diagram should help explain: what is this diagram intending to explain?

To take a step back, before NN we could perform similar procedures, of taking an input and finding a way to use data to make a prediction. The simplest would be linear regression, still the mainstay of prediction from data. This replaces ***'here be dragons'*** with ***'find the linear prediction that minimises the (squared) errors in the output'***.

This was, however, inadequate in all but the simplest situations. Archie, for example, relied on a two-step process to come up with a formula ('best prediction' or, in NN terms, 'output') for predicting an empirical quantitative relationship between porosity, electrical conductivity, and fluid saturation of rocks from inputs.

$$S = \left(\frac{R_o}{R}\right)^{\frac{1}{n}}$$

Where R_o = resistivity of the sand when all the pores were filled with brine, Rw = resistivity of the brine, $\emptyset$ is the porosity fraction of the sand and m is the slope of the line representing the relationship under discussion.

For Archie, the dragons would be replaced by finding a 'best' transformation, to get the formula's form, and then the best linear prediction, having transformed, to find the factors (cementation exponent, saturation exponent) in any specific situation. For us, this is now a simple two-step process, one step followed by another and then the result, but for Archie it was a partly trial-and-error process. He would, of course, have been guided by his knowledge of the physical process involved. That would have made him try inverse relationships and non-linearity (raising to the power $\frac{1}{n}$), so it wasn't simply trial-and-error, but partly so.

A computer, on the other hand, would have no knowledge of the process, so would have to rely entirely on trial and error. In return, it more than compensates by being able to conduct many more trials and quickly compute the errors. Each trial would involve trying a transformation, or formula form, and finding out how well it makes a prediction using the best possible factors or exponents. If the computer kept trying each combination, of formula form and best exponents in that formula, independently, it would be ignoring an important source of information: if one is worse than the previous, then it's going in the wrong direction. So, the two steps should communicate. If they do, we have a simple two-layer back-propagation Artificial Neural Network.

Linear regression is readily extensible to non-linear and multiple regression but, ultimately, there are only so many ways of picking trends or conclusions from data, and critically, the principle of correlation or coincidence lies at the heart of all those we currently know; it minimises the errors, and that is what we want to achieve: the least error. Machine Learning and Deep Learning are therefore, at heart, generalisations of the familiar processes of correlation and regression.

Problems: Conceptual Rather than Mathematical

When Archie was performing his non-AI investigation, he knew which formula form and which combination of parameters performed the best: it was the form and combination that gave the best prediction of water saturation for the resistivity data he had available. In other words, he knew the answer he wanted and so had a way to measure 'error' and had a meaning for 'best'. This was because he had sufficient data, from wireline logs.

In other situations, data may not be necessary. Due to its wide exposure in the popular press, one of the best-known examples of deep learning is AlphaGo, a program that taught itself to improve at playing Go and then defeated the reigning world Go champion. In terms of complexity, this was a greater achievement than Deep Blue's success at chess. And yet in some ways, the developers of AlphaGo had a comparatively simple task, because 'best' is so easily described: the best result is a win at the game. There are no points for 'how you played the game', it is all or nothing. Thus, it is, conceptually at least, easy to set up a computer to play a very large number of games of Go and have the software remember, or 'learn' in the current jargon, that moves that lead to a win are better than moves that lead to a loss.

Objective Function

However it is obtained, whether from theory or from a combination of data and experience, any learning algorithm requires a definition of what is good and what is bad: it needs an 'objective function' that can quantify the value of an output and hence tell it whether it is on the right lines or barking up the wrong tree. We have seen two possible sources of an objective function (AlphaGo's win/lose and Archie's data), a judgement of what constitutes 'best'. This judgement is necessary; without it, there can be no learning, and in the absence of an 'Ask Solomon' command in computer software, we have to rely on either rules (theory) or a combination of data and experience.

It is in the potential pitfalls of the choice of an arbiter of good versus bad that machine learning is most commonly criticised. Many of the commonly cited examples are, if investigated, often found to be apocryphal. An enduring urban legend is attributed to the US Department of Defence (DoD): during the Cold War it is said that the DoD tried to train an AI to differentiate friendly tanks and enemy tanks so that missiles could be fired automatically. Demonstrations were promising but trials were disastrous, as friendly tanks were targeted by the AI. Various versions of the story will say that this was because the AI was trained on photos in which all friendly tanks had been in fields and enemy tanks in forests, others that friendly tanks were photographed in the morning, enemy tanks in the afternoon. Thus, the AI was differentiating on the presence or absence of trees, or the direction of shadows. It is so enticing a story that it still gets repeated despite having no foundation. There are nevertheless sufficient real mistakes to indicate lessons have to be learned. One recent example of USA government facial recognition software was found to be 98% accurate with Caucasian males but barely better than guesswork with some other racial types. Whilst that error can be readily seen, how will we know, just by looking at the outputs

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DR BARRIE WELLS – AFTER TAKUYA HASEGAWA 2015.

Illustration of the challenge known in AI as the 'Buttons Problem'.

(results), whether the AI we have put in charge of exploration is, for example, using data from carbonate fields to make judgements about clastic reservoirs? The ability to interrogate an AI, to ask it why it made its choices, is currently missing, and with each increase in 'depth' of a Deep Learning system, it becomes more difficult to achieve. In the absence of any way to interrogate the AI, we, the experts, are still necessary, at least for the time being, to critically appraise the learning process.

So, we have a tool of great power for which there is strong pressure to put to good use, but we know it has limitations. How can we use our knowledge of the application domain (i.e., exploration geology and geophysics) to minimise the chances of targeting the 'wrong tanks'? The answer should lie in having a good understanding of the technology, but also in a little common sense. By way of example, in applications involving sequences, from lithostratigraphy to seismic interpretation, we know that a perfect fit in one sequence is not of use if it means the surrounding sequences cannot be reconciled. AI has also noted that this is a problem, and in AI this is sometimes known as the buttons problem.

In summary, we should be the best source of knowledge of the problems, from having worked in the field and seen the data. Handing over everything to the computer without also handing over this experience is a recipe for failure. We will explore this theme some more in part 2.

PALYNOLOGY REINVENTED

An old technique re-imagined and reducing uncertainty in CCS sites

Professor Mike Stephenson,
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Capturing carbon dioxide (CO_2) from industrial and power sources and storing it in subsurface geological formations is an option for reducing emissions into the atmosphere. Palynology (the study of fossil spores and pollen that are common in argillaceous rocks) would seem to be far away from the big engineering and reservoir research questions for carbon capture and storage (CCS) and the energy transition, but surprisingly may have purpose in the crucial area of reducing the uncertainty caused by geological heterogeneity. Its use in this area shows how science developed to understand oil and gas extraction can be reinvented to help improve confidence in the injection and underground management of CO_2.

Carbon Capture and Storage

At its most basic, CO_2 storage requires that supercritical CO_2 be injected into deep subsurface reservoir rocks over a long enough time period to make a difference to atmospheric CO_2 concentrations. Understanding the behaviour of CO_2 in advance of development of these reservoirs for long-term storage is therefore vital to provide confidence for investors and project developers and also for the governments and authorities that will regulate the process and eventually assume the long-term liability for a CO_2 store.

Geological models used so far have aimed at large-scale estimates of storage capacity to get a view of the overall feasibility of CCS as a technology, in comparison with other technologies that are on offer. In general, these large-scale estimates, for example the Energy Technologies Institute UK Storage Appraisal Project (UKSAP) in 2011, tell an encouraging story suggesting abundant storage space that could support a large-scale future European CCS industry. However, these models are necessarily broad-brush and incorporate very limited geological detail, particularly at the sub-seismic (metres to tens of metres) scale. One of the key uncertainties is heterogeneity along the migration path of an injected CO_2 plume. These heterogeneities can include those bestowed on the rock by primary sedimentological and palaeoenvironmental factors, those from diagenesis and those from tectonic and structural change. Detailed geological data on heterogeneities are often not available for the saline aquifers that are an important target for CCS because their depth falls between the relatively data-rich environments of shallow freshwater aquifers and hydrocarbon reservoirs. Biostratigraphy and palynology can of course help to identify and correlate suitable reservoirs for CO_2 storage, but recent research shows that palynology coupled with sedimentological analogue outcrop study can also offer insights and predictive tools to understand heterogeneity.

Analogue outcrop study combined with palynology is not a new thing for understanding reservoirs; oil and gas companies have consistently used outcrop models to better understand their subsurface assets. There are some crucial differences though: the practice of injection rather than extraction, that CO_2 is a reactive gas injected in supercritical form, and that CO_2 is being placed, as far as possible, in geological conditions that encourage slow migration, solubility trapping (where CO_2 dissolves) and/or stratigraphic trapping.

The famous Sleipner CO_2 storage facility is a case in point illustrating the balance that may be sought between injectivity and presence of sufficient heterogeneity to facilitate solubility trapping. Sleipner is the longest running facility for CO_2 storage, having injected around 1 million tonnes of CO_2 every year since 1996. A series of repeat (4D) seismic surveys has detected layers of rock with high CO_2 saturation which show the attenuation of CO_2 where it has accumulated below thin sub-seismic mudstone layers. The 4D seismic has also been able to track the rate at which buoyant supercritical CO_2 rises through the reservoir, how and when it reached the overlying seal, and how it moved under the seal as more CO_2 arrived. Perhaps the most interesting aspect for a stratigrapher is the role of the mudstone layers. Under other circumstances

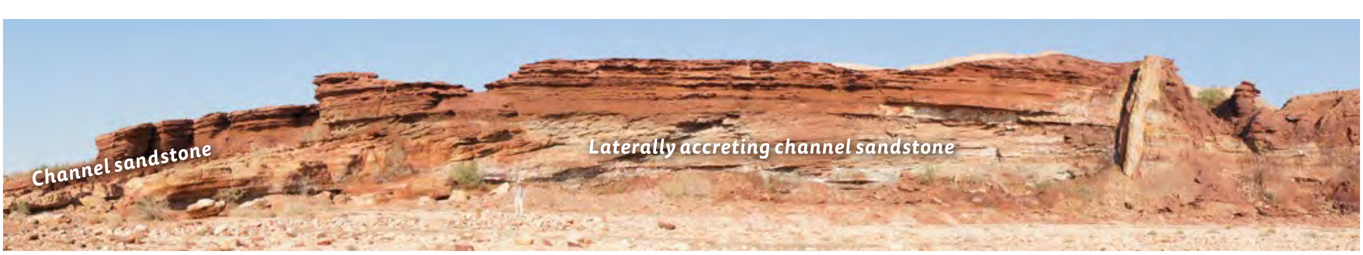

Figure 1: Laterally accreted channel sandstone (right) and channel sandstone (left) in the Umm Irna Formation. These are associated with laterally extensive mudstone units such as splays and flood plain inundations.

Figure 2: Stacked palaeosols and small channels in the Umm Irna Formation. These are often associated with laterally impersistent mudstone units such as oxbow and channel plugs.

these layers might have been seen as problems for injection – perhaps making less of the reservoir available to injection. But the presence of these baffles has also proved useful in slowing down upward migration, allowing more time for chemical reactions to take place dissolving CO_2 and leading to more long-term storage through carbonation. Thus, the low permeability mudstone layers promote 'solubility trapping' leaving the overlying seal (the physical trap) to do less of the work of confining the CO_2.

Understanding the Geometry of Mudstones

The importance of palynology in understanding the geometry of mudstones is a newer discovery. This came about through the study of mixed mudstone/sandstone successions during three field campaigns in Jordan. Palynology was being undertaken to support the description of some of the world-class fossil plant discoveries in the Upper Permian Umm Irna Formation, a succession similar to the more fluvial parts of the Sherwood Sandstone Group which is a major CCS target in the North Sea.

The Umm Irna Formation is 70m thick and outcrops for 40 km north to south along the Jordanian Dead Sea coast. Detailed field sedimentology allowed the reconstruction of a palaeoenvironmental model, and to support the model around 30 individual mudstone layers within the Umm Irna complex, both large and small, were sampled for their spores and pollen. Overall, the mudstone layers revealed pollen and spores that fell into two categories. The first group was found in laterally persistent argillaceous units (>50m wide) like migrating point bars or flood deposits associated with the main river channels (*Fig. 1*). This was high in diversity, containing a wide variety of Permian pollen and spores that probably represent a regional snapshot of the vegetation on the ancient floodplain and surrounding higher ground.

The second assemblage from smaller argillaceous units like oxbow and channel plugs (<5m wide) was of lower diversity with high proportions of one or two local palynomorphs, and also the spores of green algae (mainly zygospores) that usually indicate water bodies that are drying up (*Fig. 2*).

Taken as a whole, the palynology and sedimentological model (*Fig. 3*) envisage an alluvial plain with a wide hinterland feeding palynomorphs along the rivers. The palynology of the wider alluvial plain mudstones associated with active channels represents that big hinterland. The micro-environments around small, drying-up water bodies reflect a more local flora. Palynological study in the approximately contemporaneous alluvial pre-Khuff clastics and Gharif Formation of Oman tell a similar story. Laterally impersistent mudstones characteristic of these non-marine alluvial sediments outcropping in the Huqf area in central Oman contain low diversity assemblages with numerous zygospores. Similar characteristics have also been observed in comparable facies in Scottish Carboniferous successions.

The reason for this difference in the palynology between wide and narrow mudstone units is not completely clear, and more work needs to be done on other

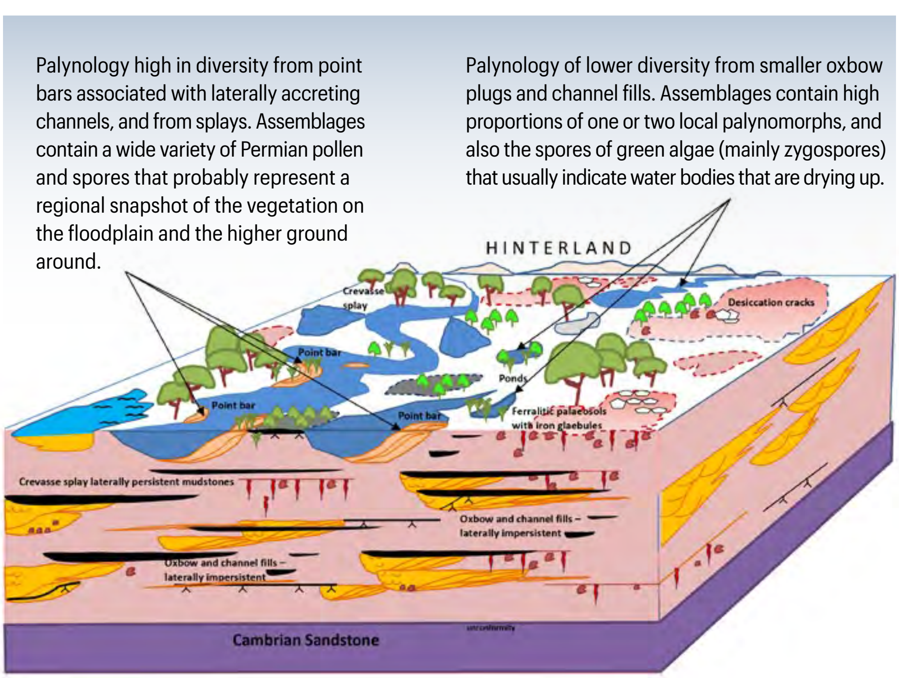

Figure 3: Palaeoenvironmental model showing laterally persistent and impersistent mudstone units.

similar fluvial and alluvial successions both ancient and modern, but it seems likely that the different assemblages relate to the way that palynomorphs are transported. Although 'winged' palynomorphs (with small air sacks) can be distributed by wind, their main transport is by flowing water (*Fig. 4*).

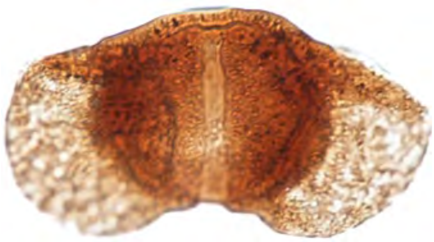

Figure 4: Falcisporites stabilis, a 'winged' palynomorph (with small air sacks) from the Umm Irna Formation – mostly transported by flowing water – is an indicator of plants growing in the hinterland. Specimen about 70 microns across.
CREDIT: M STEPHENSON

Thus, a depositional environment associated with an active river channel that drains a large hinterland through its network of tributaries is more likely to contain a diverse assemblage of palynomorphs. Those associated with abandoned channels, particularly where a water body is drying up, is more likely to contain palynomorphs like zygospores (where green algae start to dry up) and purely local palynomorphs from plants very close to the water body (*Fig. 5*) and possibly growing just around it.

Figure 5: Pretricolpipollenites bharadwajii, pollen from a cycad-like plant from the Umm Irna Formation – an indicator of smaller water bodies on the floodplain. Specimen about 35 microns across.
CREDIT: M STEPHENSON

From Outcrop to the Subsurface

The distribution and lateral continuity of mudstone baffles will be obvious in outcrop, but the key is transferring what has been learned from the outcrop to the subsurface. Here the geologist will try to recreate, using boreholes and seismic, the 3D awareness gained from the outcrop to reconstruct the reservoir that is a target for CCS, such as an offshore Sherwood Sandstone Group target in the UK. If detailed palynology work is done, preferably on core from fairly closely spaced boreholes, it should be possible to distinguish a horizontal baffle in a borehole from a narrower mudstone unit with less baffle potential (*Fig. 6*).

Palynological methods like these will not solve all the problems on their own but could contribute to the methods at the exploration geologist's disposal. At present there are plans to test the technique in representative outcrop formations of the Sherwood Sandstone Group in the UK, for example the beautifully exposed Otter Formation in Devon. Developing methods like these may help globally, not only with the Sherwood Sandstone Group in the UK and coeval formations in Europe, but also other continental successions which are the targets for geothermal exploration and carbon capture and storage. Both of these low-carbon energy techniques rely on an understanding of fluid flow for injectivity and extraction.

Acknowledgements:
Thanks to Dr J.H. Powell for his expert field sedimentological expertise.

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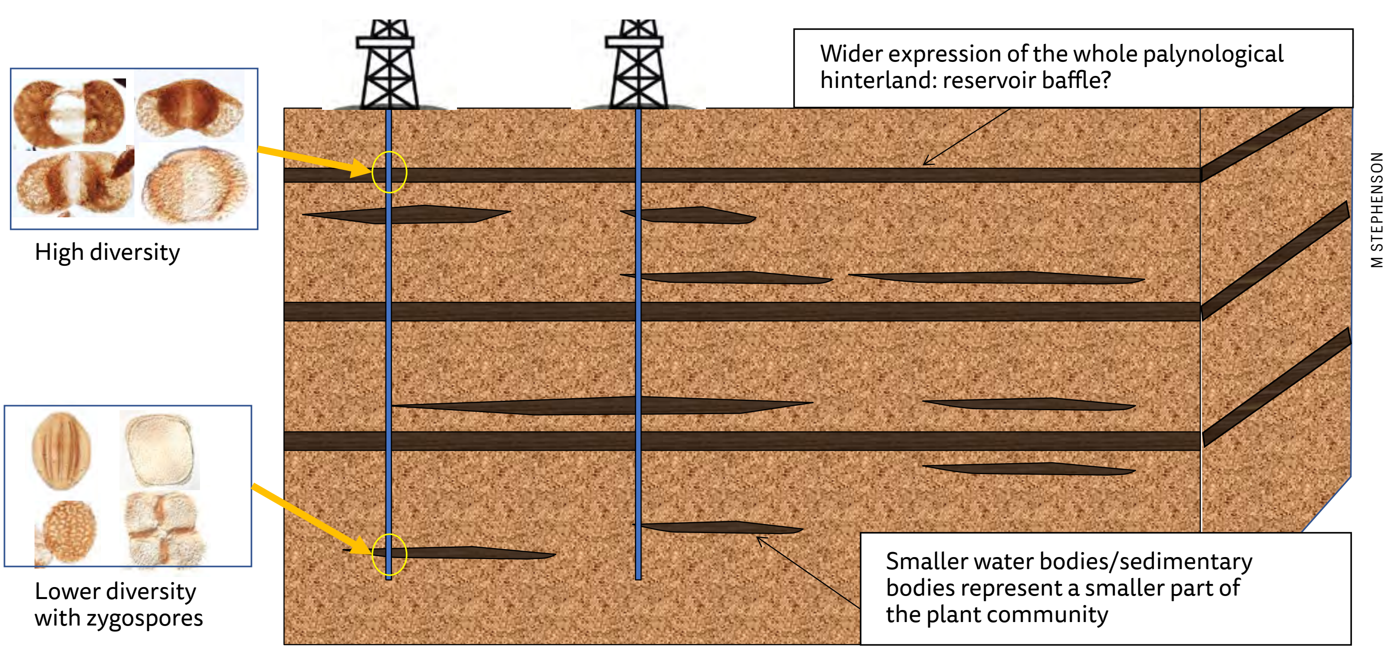


Figure 6: A predictive tool for distinguishing baffle potential.

OFFSHORE JAMAICA

The Walton Morant Licence: A Multi-Basin, Multi-Play, Billion-Barrel Exploration Opportunity

The Walton Morant Licence offers the opportunity to explore extensive but untested Cretaceous and Cenozoic plays in two highly prospective basins. Recent advances in understanding of the tectonic evolution of the Caribbean have unlocked Jamaica's untested source rock potential, and there is clear evidence for the presence of a working hydrocarbon system. 3D seismic acquisition in 2018 has provided geophysical support for the identified prospectivity in the Walton Basin, with 2016 2D seismic identifying previously unknown prospectivity in the Morant Basin. Across both basins, more than 2.4 billion barrels of mean prospective resources have been identified in 11 high-graded prospects and leads. The drill-ready Colibri Prospect alone holds mean prospective resources of more than 400 million barrels, with success-case economic assessment indicating the potential for highly attractive returns.

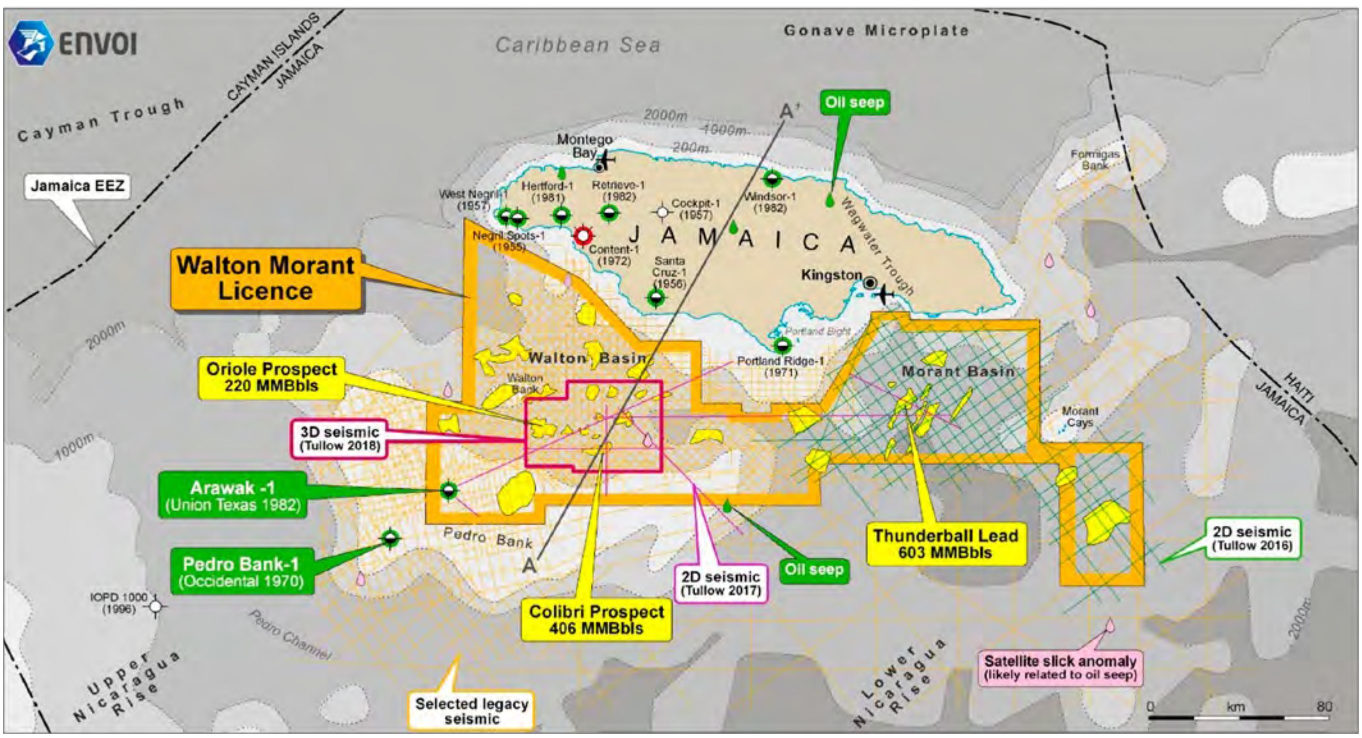


Figure 1: Generalised map showing the Walton Morant Licence area, the identified prospectivity, well locations and seismic coverage. Geoseismic cross-section A–A' is shown in Figure 7.

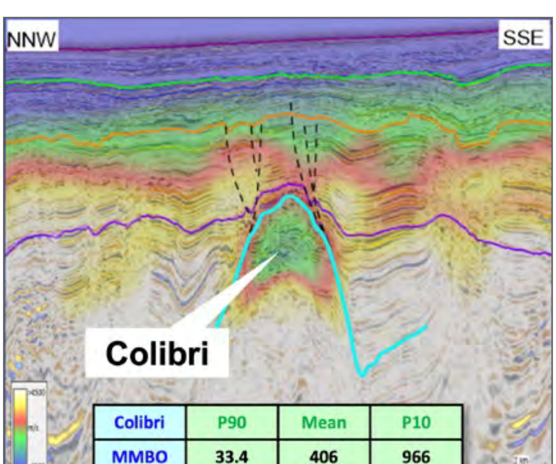


Figure 2: A prominent low velocity anomaly conforms to structure at the Colibri Prospect and is highly likely to indicate the presence of porosity/reservoir quality.

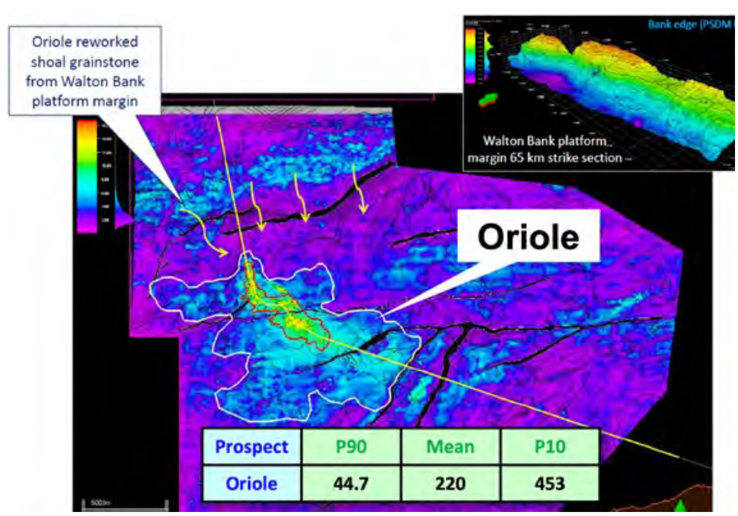


Figure 3: The Oriole Prospect is mapped out as an amplitude anomaly with a fan-like geometry. The main central channel axis is clearly evident as the area with highest amplitude response.

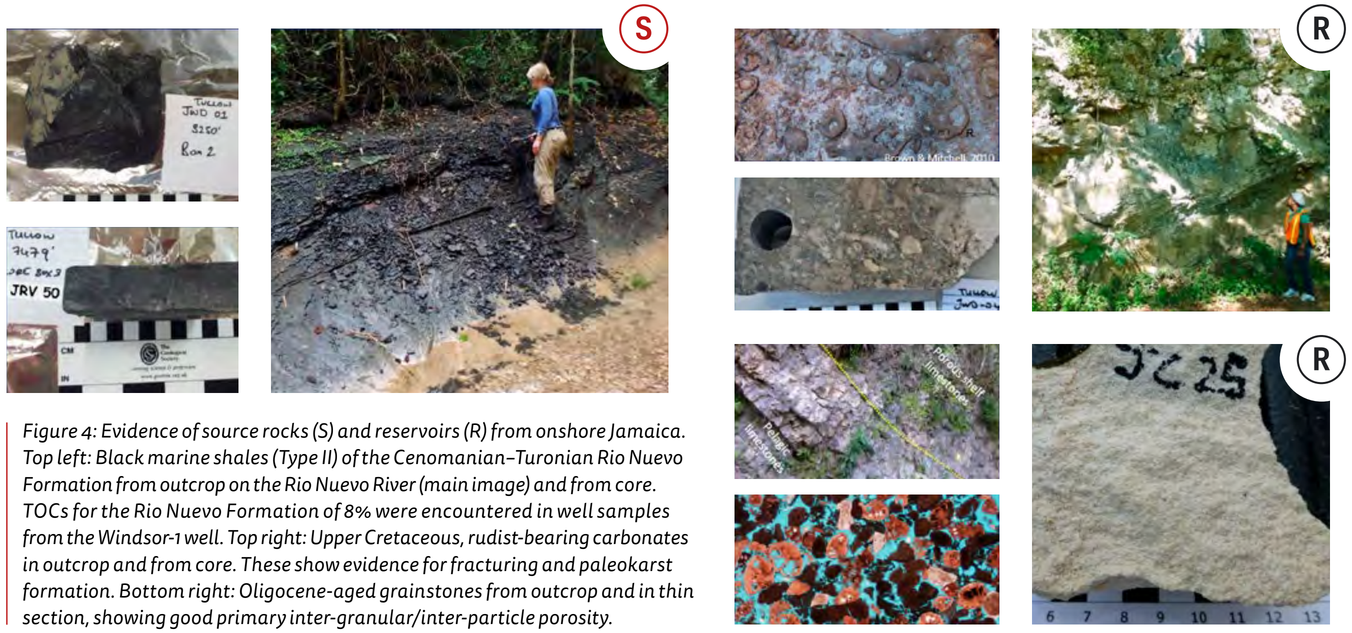
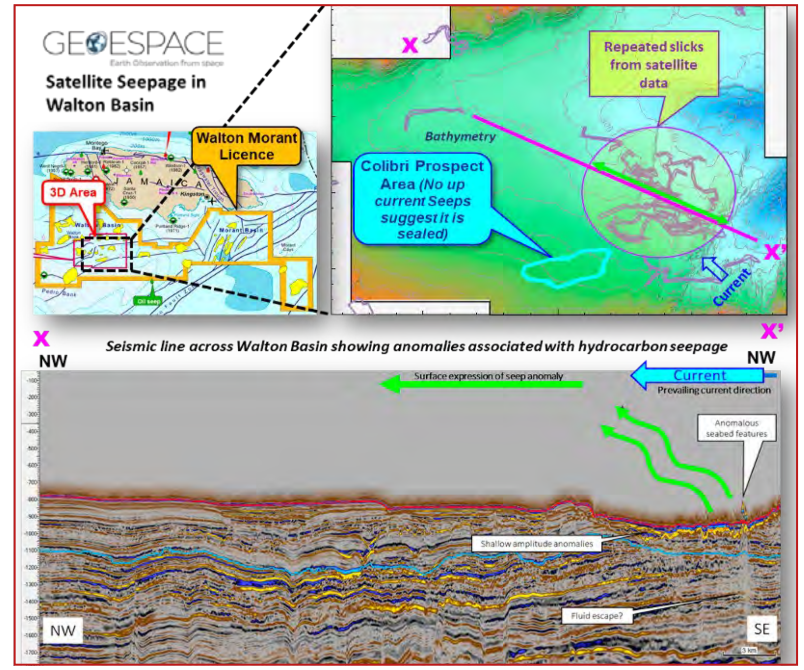


Figure 4: Evidence of source rocks (S) and reservoirs (R) from onshore Jamaica. Top left: Black marine shales (Type II) of the Cenomanian–Turonian Rio Nuevo Formation from outcrop on the Rio Nuevo River (main image) and from core. TOCs for the Rio Nuevo Formation of 8% were encountered in well samples from the Windsor-1 well. Top right: Upper Cretaceous, rudist-bearing carbonates in outcrop and from core. These show evidence for fracturing and paleokarst formation. Bottom right: Oligocene-aged grainstones from outcrop and in thin section, showing good primary inter-granular/inter-particle porosity.



UNITED OIL & GAS

Figure 6: Top right: Seabed map of the area of the Walton Basin covered by 3D, with seawater surface expressions of repeated satellite anomalies superimposed. Note the more rugose nature of the seabed in the E and SE of the 3D area. Crucially, the nature of the prevailing current direction suggests that the anomalies are not sourced form Colibri, some 10 km west of the likely source of these anomalies. Bottom: SE–NW arbitrary seismic line across the area with satellite anomalies showing some interesting features at the seabed and in the shallow seismic section which could be indicative of fluid movement.

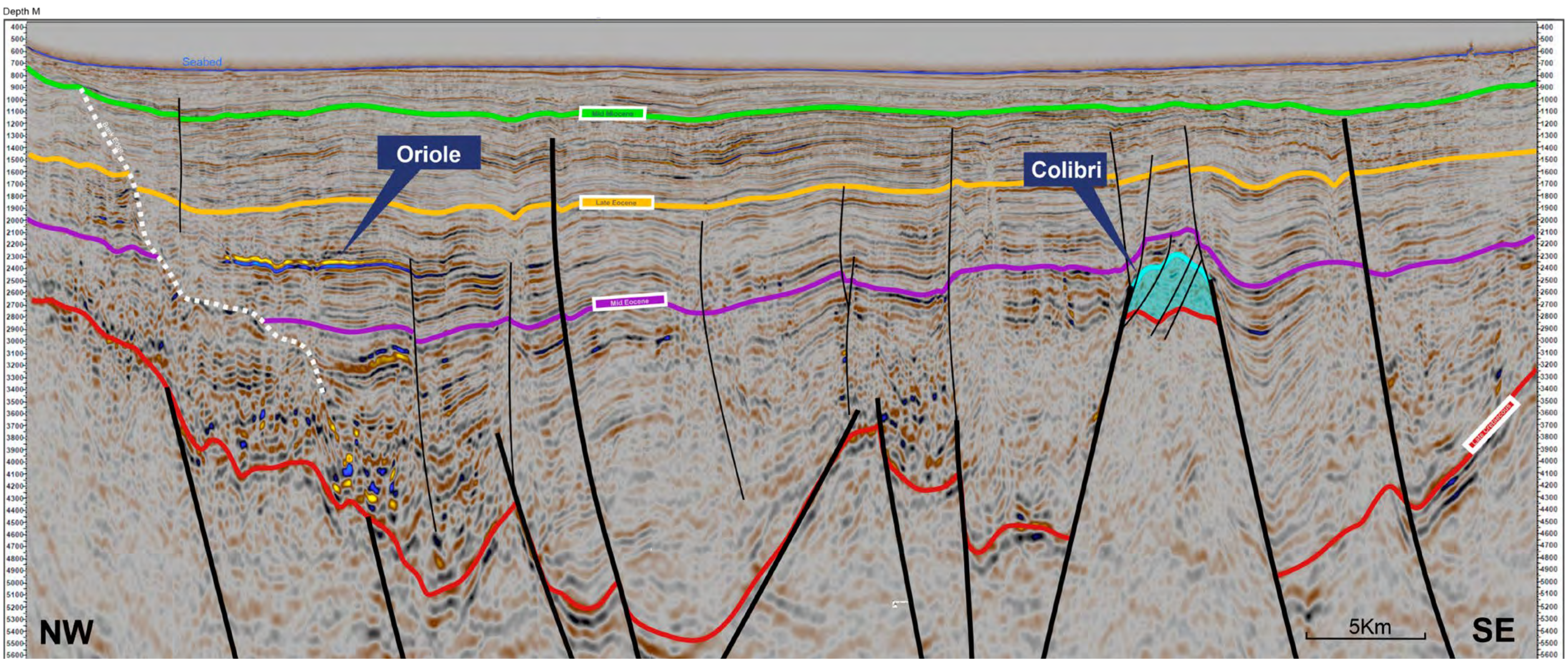


Figure 5: 3D PreSDM NW–SE arbitrary seismic line across the Colibri and Oriole Prospects in the Walton Basin. This line highlights the different plays that exist in the basin. Colibri represents an Upper Cretaceous syn-rift rudist-bearing, karstified and fractured carbonate platform. Oriole represents an amplitude-supported post-rift Cenozoic platform apron fan, consisting of high-energy platform margin carbonates which have been shed off the platform and redeposited in a basinal setting.

BRINGING EXPLORATION OPPORTUNITIES IN JAMAICA INTO FOCUS FOR AN ENERGY TRANSITION FUTURE

A new understanding of regional Caribbean tectonics and associated paleoenvironments unlocks world-class, multi-play potential in undrilled Jamaican basins.

Mike Lakin, Envoi Limited; Paul Ryan and Myles Watson, United Oil & Gas

Demand for New Exploration Projects is Anticipated to Increase

In the last 50 years, the upstream sector has experienced successive cycles of boom and bust at times of global economic or political change. Every cycle has been different, but one thing which has changed little is that exploration is usually the first thing to be cut in a downturn and the last thing to return when demand increases. While the world is rightly turning its attention to sustainable energy sources to power cultural and industrial advances into the future, there is an increasing understanding that traditional hydrocarbon-based energy sources will be part of the energy mix for the coming decades of transition. During this time there will be a sustained emphasis on efficiency and carbon offset and reduction. However, the need for new exploration is clear, to provide energy security while we move through this transition.

As news reports increasingly confirm, demand for energy has rapidly returned to pre-Covid-19 pandemic levels. However, unlike previous industry downturns, a lack of funding for exploration and production activities over the last seven years will have an impact on future supply. An emphasis on carbon neutrality and sustainability has led to less funding for exploration. However, with new technologies and increases in efficiency, future developments have the potential to be far less carbon intensive than previously, and in many instances could be carbon neutral or even carbon negative through their lifecycle.

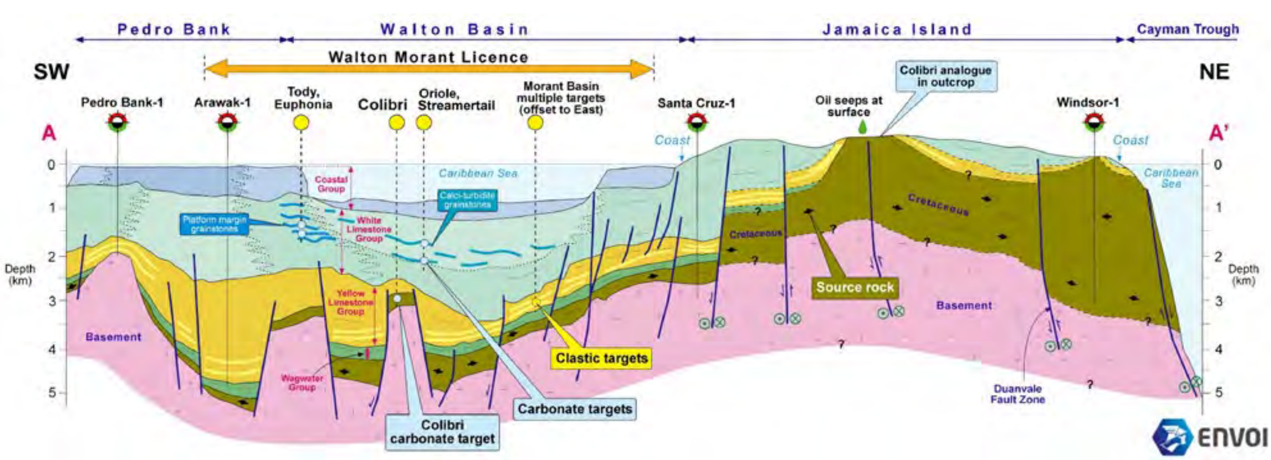
The reality is that new oil and gas reserves will be needed to meet demand. This will arguably lead to new exploration being necessary as recent successful play developments such as those offshore Ghana, Senegal, Mozambique, Suriname and Guyana mature, and incremental reserve replacement from these plays reduces. Couple this with the fact that unexplored areas with stable political and attractive fiscal regimes are becoming scarcer.

This is Where Jamaica Fits In

Jamaica is a country where traditional oil and gas exploration and renewable energy development could work hand-in-glove. Abundant solar, wind and sea-energy resources exist and await harnessing, while the offshore basins of Jamaica have had very little exploration to date. Only two wells have been drilled offshore, with the most recent one in 1982. However, both wells, along with all nine wells drilled onshore have shown evidence of an active hydrocarbon system, so the potential for discoveries in the large offshore area is huge.

United Oil & Gas plc, an AIM-listed, full-cycle E&P company, currently holds 100% interest in a low-cost, high-return, basin-opening exploration opportunity offshore southern Jamaica, namely the Walton Morant Licence. This covers a large area of 22,400 km² and includes two prospective basins: the Walton Basin in the west and the Morant Basin in the east. United farmed into the previously Tullow Oil-operated licence in 2017 for a 20% interest by funding the acquisition of a 3D seismic survey targeting some of the key plays and prospects in the Walton Basin. However, before they could validate this potential, Tullow exited the licence in 2020, as part of their corporate restructuring to refocus on development of their successful discoveries elsewhere. This gave United the opportunity to take 100% of the licence interest and to

Figure 7: A simplified geoseismic cross-section showing the relationship between onshore and offshore southern Jamaica. The petroleum geological features seen in outcrop and wells onshore are anticipated to be preserved at depth in the Walton and Morant Basins. See Figure 1 for location of the cross-section.



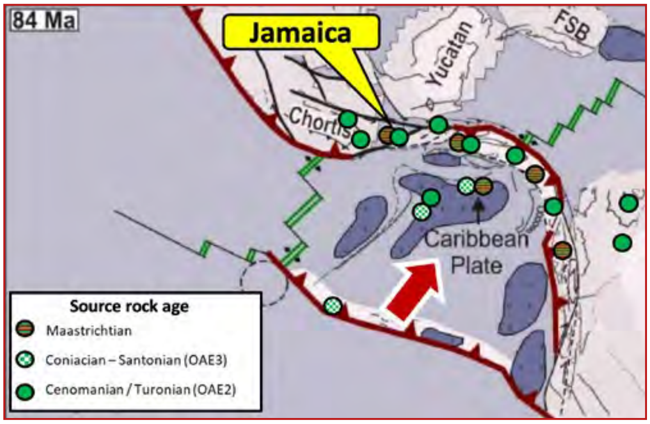


Figure 8: A Tectonic reconstruction of the Caribbean region in the early Upper Cretaceous period showing the distribution of known source rock being deposited at the time.

The present-day distribution of the same source rocks throughout the Caribbean.

continue to work towards realising the Walton and Morant Basins' exploration potential. United has been granted an extension of the licence until January 2024 in order to attract an industry partner and to unlock the offshore potential by drilling the first well in 40 years.

With one eye to the future, as part of United's work programme for 2022–2024, the company has committed to undertaking a carbon intensity study which will look at the options available to substantially reduce any future field developments' carbon impact through the implementation of best practice carbon-capture efficiencies and the development and use of renewable energies to provide power for any hydrocarbon production as well as for local communities.

World-class Frontier Exploration

United's work programme has established that although the Walton Morant Licence is in a frontier basin, all the elements of a working hydrocarbon system are present. The unique tectonic history of the Caribbean, resulting in the Miocene to recent uplift of the island of Jamaica, provides a window into the petroleum geology of the offshore through the onshore outcrops.

A detailed understanding of the region's tectonic and paleo-geographic history has also shed light on how the major, Cretaceous-sourced hydrocarbon provinces of the Caribbean region present today, originally lined up in a contiguous 'source rock fairway jigsaw' at the time of deposition. Since then, the 'jigsaw' has been redistributed through continued tectonic movement, with the pieces now found throughout the Caribbean region, including in areas such as Colombia, Honduras, Venezuela, Trinidad & Tobago and Jamaica.

The licence incorporates highly prospective stacked Cenozoic and Cretaceous multi-play potential in the Walton Basin and Cenozoic potential in the Morant Basin, all of which have analogues or lateral equivalents encountered onshore, either in outcrop or in cored well sections. Water depths range from less than 50m to over 1,000m and 2,000m, in the Walton and Morant Basins, respectively.

As well as the regional and local evidence for a working hydrocarbon system, live hydrocarbon seeps have been found in Jamaica, both onshore and offshore. Satellite imagery also shows evidence for an active oil seep anomaly which corelates with some interesting features on seismic, and shows evidence for migration near to, but crucially not associated with the primary prospectivity identified in the Walton Basin. Offshore southern Jamaica is therefore now considered as a preserved piece of the Cretaceous source jigsaw, containing substantial hydrocarbon play potential through different stratigraphic levels as seen in the uplifted onshore, and preserved in the offshore, with evidence for active hydrocarbon migration.

The Walton Morant Licence Opportunity – Multi-Basin, Multi-Play, Billion-Barrel Potential

United have high-graded 11 prospects and leads on 2D (3,650 km, shot in 2016–2017 across the Morant and Walton basins), and 3D (2,250 km² shot in 2018 in the Walton Basin) seismic. These have been independently estimated by Gaffney Cline & Associates to have a combined mean unrisked recoverable resource potential of over 2.4 billion bbls recoverable, with an upside of over 5 billion bbls recoverable. On its own, the primary 3D-defined 'drill-ready' Colibri Prospect in the Walton Basin is estimated to have 406 MMbbls mean unrisked recoverable resource potential, with an upside of >900 MMbbls.

The economics are very robust and confirm that the favourable fiscal terms in Jamaica would ensure that commerciality would be possible in any basin-opening discovery containing recoverable resources in excess of 100 MMboe (at US$60/bbl). Equally, a discovery of the mean 406 MMboe resources at Colibri would still be commercial with an oil price as low as US$30/bbl. At US$60/bbl, the mean Colibri resource potential is estimated to be capable of generating a >30% IRR and an NPV10 of US$2.5 billion.

United is offering a material interest and operatorship to suitably qualified parties in the licence in return for a commitment to fund a well to test the Colibri Prospect before January 2026, which would fulfil the obligations for the second exploration period of the Licence. A 2021 study by OPC estimates this well is likely to cost around US$30 million based on current rig rates.

Envoi Limited has been engaged by United to assist in their search for partners to accelerate exploration drilling on the Walton Morant Licence. For more information: www.envoi.co.uk/projects/active-projects/americas/caribbean/

Note: All prospect and lead volumes quoted in this article are as per a prospective resources audit carried out for United Oil & Gas by Gaffney Cline & Associates, December 2020.

AAPG
EUROPE REGIONAL CONFERENCE 2022
3–4 May 2022 • Budapest

Revitalizing Old Fields and Energy Transition in Mature Basins

On behalf of the Organizing and Advisory Committees, it gives us great pleasure to invite you to join us in Budapest, Hungary, for the AAPG European Regional Conference and Exhibition to be held from 3-4 May, 2022.

The theme we have chosen for this conference, “Revitalizing old fields and energy transition in mature basins” refers to the challenge we face in our industry in many of the hydrocarbon basins and folded belts across the entire European region these days. Special focus is placed on the topics revolving around the global energy transition such as advantaged hydrocarbons, enhanced oil recovery and carbon capture-utilization-storage. Topics getting more and more attention as oil companies are gradually transitioning into energy companies such as geothermal energy utilization, hydrogen exploration and storage, will also be highlighted by special sessions.

While Europe has many mature to super-mature basins, significant discoveries are still being made using either new exploration thinking and/or cutting-edge modern technology. A deeper understanding of the proven reservoirs, either siliciclastic, carbonate or fractured, combined with a systematic petroleum systems approach could result in unexpected breakthroughs in basins where exploration was already assumed to reach the point of diminishing returns. Some offshore basins, still in their emerging exploration phase, also saw some significant discoveries in their deepwater segments during the last few years.

With more than 140 papers submitted, our Technical and Advisory committees is working hard putting together an exceptional technical programme addressing various aspects of the energy transition and exploration in mature basins in Europe and beyond.

There will be two one-day field trips offered, the pre-conference focusing on the structural geology of Budapest and the post-conference one highlighting the Cenozoic basin fill of the Pannonian Basin. We are also putting an emphasis on having a healthy mix of professionals from both the industry and the academia.

We hope that all the explorers and geoscientists working on projects in the broader European region will not only enjoy this conference and but also find some extra time to visit Budapest and other parts of Hungary as well. This is the very first time for AAPG to have a conference in Budapest and we feel confident that it will be a nice and memorable one!

András Németh (MOL), *Conference Co-chair*
Gabor Tari (OMV), *Conference Co-chair*

Committee members

- **Raffaele di Cuia,** *Technical Director, Delta Energy Ltd*
- **Csaba Krézsek,** *Exploration Manager, OMV Petrom*
- **Piotr Krzywiec,** *Assoc. Prof, Polish Academy of Sciences*
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- **Zsuzsa Szabó,** *Senior Reservoir Geologist, MOL Plc*
- **Alan Vranjković,** *G&G Chief Expert, INA Plc*

Topics of the conference

1. Key discoveries in mature basins in the past decade
2. Remaining HC-potential in mature basins
3. New and emerging plays in mature petroleum provinces
4. Siliciclastic reservoirs – exploration and exploitation I: sequence stratigraphy
5. Siliciclastic reservoirs – exploration and exploitation II: stratigraphic forward modeling
6. Carbonates and fractured reservoirs
7. Advanced geophysical technologies and integrated G&G models to revitalize mature fields
8. The energy transition with global trends and regional solutions I: Geothermal energy utilization in mature basins, synergy with petroleum industry
9. The energy transition with global trends and regional solutions II: Hydrogen exploration and storage
10. Carbon capture, utilization, and storage (CCUS) and enhanced oil recovery (EOR)
11. Structural geology and its application in exploration, field development, energy storage and CCUS
12. Digital transformation: machine learning, artificial intelligence and innovative digital solutions

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GRAFF-1: ON THE CUSP OF HYDROCARBON SUCCESS IN NAMIBIA

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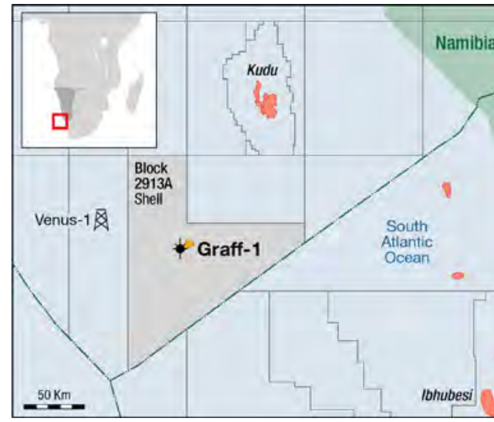

Shell has made a 'significant oil and gas discovery' at the **Graff-1** well offshore Namibia. It is unclear yet whether the discoveries are large enough for Shell to develop the country's first deepwater field.

The well results have so far shown at least two reservoirs in the **Upper Cretaceous**. Press reports suggest a **60m** net light oil column in the **Santonian**, in high quality channel sands. With reports of volumes of **250–300 MMbo**, the discovery may be economically viable, and Shell and partners **Qatar Energy** and **NAMCOR** are expected to announce more detail soon. The play is underpinned by a mature **Aptian** 'Kudu' shale. This is the 24th exploration well to be drilled offshore Namibia, and news of a commercial success will be welcomed by a number of operators in the **Orange Basin**, both in Namibia and adjacent in South Africa, as well as companies planning to drill in the **Luderitz** and **Walvis** Basins, which share a similar source rock history. To the west in deeper water, **TotalEnergies** (with **Impact** and **Qatar Energy**) continue to drill the **Venus-1X wildcat**.

KANCHAN-1: EXPLORATION RETURNS TO BANGLADESH

Exploration has returned to Bangladesh after a hiatus of several years, with **ONGC Videsh (OVL)** partnering **Bapex** and **Oil India** on the **SS-04 Block (formerly Block 16)** as part of the 2012 Licensing Round. **Sinopec** are believed to have the drilling contract. This is the first well on the block and would have been spud two years ago but for delays due to Covid-19. The Kanchan prospect, located on Moheshkhali (Maiskhali) Island, is ~30 km along strike from the **Magnama-1** exploration well, drilled by Cairn in 2007–2008, and plugged and abandoned with gas shows. There was abnormal high pressure in the deeper Mio-Pliocene targets of the well and these might be objectives in **Kanchan-1**. Shallower, normally pressured sands in Magnama-1 are also expected to be present at Kanchan-1. The prospect sits along the eastern edge of the fluvio-deltaic Mio-Pliocene Bengal Basin wedge against the Tripura fold belt, north of the Rakhine Basin. The prospect benefits from modern ocean bottom seismic data. Drilling is expected to be completed this month with the well at **3,199m** in mid-December.

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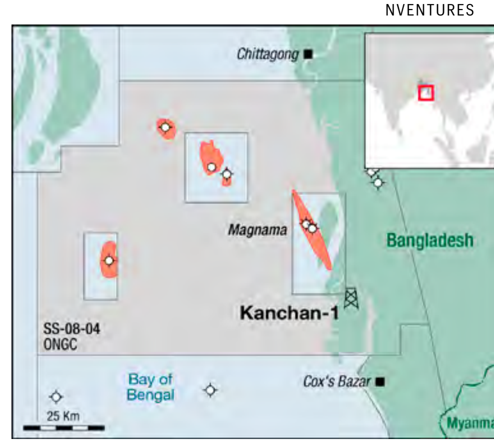

KARAU-1: ONSHORE SUCCESS REVIVES ACTIVITY IN TIMOR-LESTE

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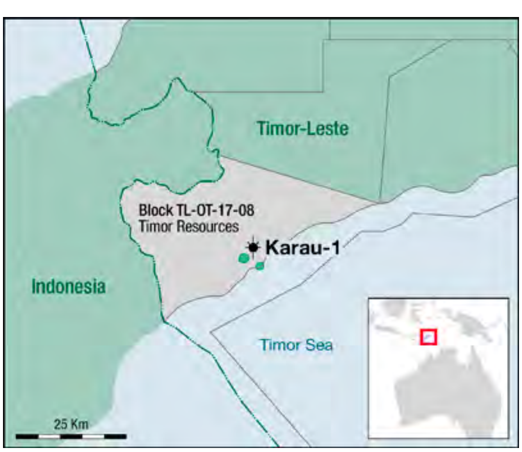

Good news from onshore Timor-Leste, where private Australian firm **Timor Resources**, in a 50:50 Joint Venture with **NOC Timor Gap**, has made an oil discovery. **Karau-1** (locally known as **Feto Kmaus**), which spudded late October 2021 in Block **TL-OT-17-08**, was reported in mid-December 2021 as discovering oil and gas, identified on wireline logging. A second well was spud in late December, **Kumbili-1**, locally known as **Liurai**, and was drilling ahead at the time of writing.

Part of a three-well campaign, the wells are located in the **Suai Basin** of Timor-Leste, where oil and gas has been tested in legacy wells drilled around 50 years ago, but there has been no subsequent drilling until the current programme. The Suai Basin is a **Late Miocene** to **Recent** synorogenic basin, perched on top of the Timor fold and thrust belt. The news will come as a timely boost to the appeal of the current Timor-Leste onshore and offshore licensing round, scheduled to close **4 March 2022**.

Ian Blakeley
NVentures
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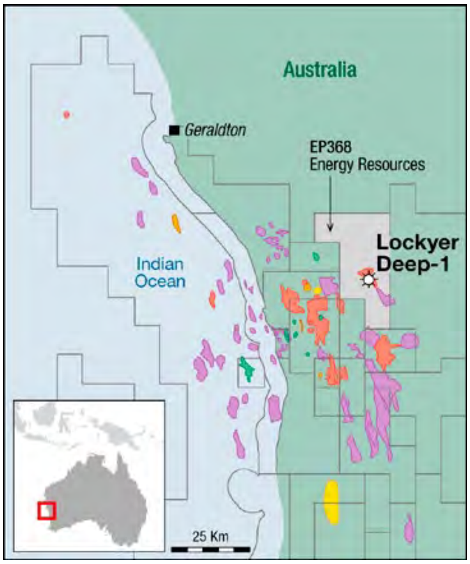
LOCKYER DEEP-1:
AUSTRALIAN FIRMS PROVE-UP FURTHER UPSIDE IN THE PERTH BASIN



Energy Resources and **Norwest Energy** have announced a gas discovery at **Lockyer Deep-1** in the **EP 368 Block** in the Perth Basin. Results indicate Lockyer Deep-1 is a significant gas discovery, with an estimated **600–800m** column. Logging confirmed **34m (TVD) gross pay** in the **Kingia Sandstone**, with around **20m net**. Porosity is reported between 16% and 28%, with an impressive 500 mD permeability. The **Dongara/Wagina** section contains a gross oil column of 66m (TVD), but with low (9%) porosity and permeability. The well has been completed as a future gas producer. The Perth Basin is a north–south trending, onshore and offshore basin extending about 1,300 km along the south-western margin of Australia. Fluvio-deltaic sands were deposited in syn-rift Permian grabens, representing a late **Palaeozoic play** beneath the proven shallower play. The play was opened with **Waitsia** in **2014** and more recently **Strike** and **Warrego** have had success at **West Erregulla**. Norwest Energy's pre-drill estimates were up to **1.1 tcf** gross recoverable gas-in-place. The operator, **Energy Resources** (a subsidiary of Mineral Resources Ltd and the largest holder of gas exploration permits in the Perth Basin) and Norwest now plan to acquire 3D seismic over the whole area, including the adjacent **North Erregulla Deep** structure. The Perth Basin represents an interesting growth area for domestic gas production in Western Australia, with early plans linked to urea and ammonia production along with other new energy and renewable energy solutions in this region.

ROCK DOCTOR

ADVENTURES OF A FIELD GEOLOGIST BEFORE 9/11

Jane Whaley

John Cater has led a fascinating and eventful life, wielding hammer and compass-clino in some of the most inaccessible corners of the globe and having the sorts of adventures many of us envisaged our geological careers might involve – before computers and security concerns transformed the world. Realising how much changed when, in his words, "those planes hit the Twin Towers and brought our simple, carefree world of tolerance crashing down", he has written this book to try to record for posterity the fun, freedom, excitement, boredom, exhilaration and at times sheer terror that came with being a field geologist in the days before satnavs, mobile phones and 24/7 communication.

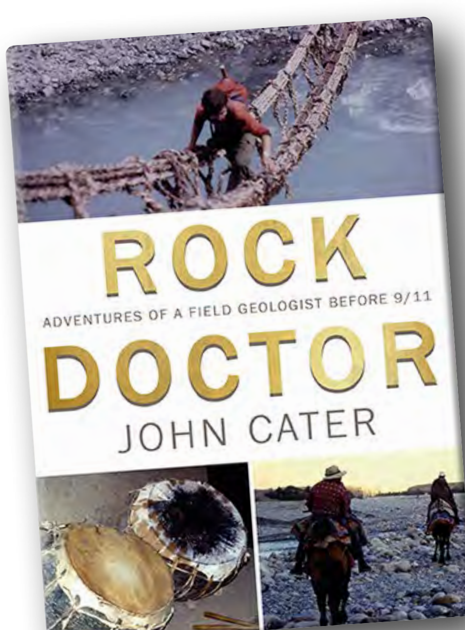
John graduated with a BSc in Geology with Astronomy from Leicester University in 1980 before moving to Birmingham to study Neogene carbonate gravity-flows, being awarded his PhD in 1984 – hence his titular joke about a 'rock doctor'. The earliest stories in his book stem from 1985, when, as a research assistant at Edinburgh University, he went to central Turkey as a consultant sedimentologist for the international fieldwork organisation ESRI and had his first introduction to the Middle East. For the next 14 eventful years, he travelled in India, Pakistan, Oman, Yemen, Syria, Turkey, Azerbaijan and Russia on behalf of ESRI, trying, as he says, "to identify areas where economic oil and gas resources were least likely to be found".

Lucky Escapes

The stories, which are entertainingly and amusingly recounted, include encounters with the local wildlife, varying from 4m-long snakes and deadly scorpions to slavering Anatolian Shepherd Dogs and flatulent horses. The various methods of transport required, and their associated dangers are also described, including recalcitrant camels, unreliable pickup trucks and wild helicopter rides, not forgetting many miles up and down steep rock faces on foot.

Many of the areas where John worked were almost war zones, so encounters with security forces and their opponents feature in some of the scariest anecdotes; in retrospect, John considers that he had some lucky escapes – not that he and his colleagues were necessarily aware of it at the time. He admits that: "field geologists could be blissfully ignorant of political reality, even when exploring the borders of Lebanon, Yemen or Pakistan. We got by with a few armed guards to keep any bandits at bay and a willingness to meet the locals on equal terms."

Important to John's story are his varied travelling companions, many of whom are locals. Some are highly knowledgeable geologists and some trainees just starting out, while his most interesting conversations tend to be with drivers, porters, security guards and local headmen, all of whom give him fascinating insights into the culture and traditions of life in their homeland. They also introduce him to some interesting culinary experiences: boiled goat's head soup (with eyes), anyone? His ESRI colleagues are an eclectic bunch, each with their geoscience specialities and personal traits; I was particularly interested in 'The Boss'; the feared and revered structural geologist Alison, who deserves her own book, if she hasn't already written it. (If you have Alison, let me know, as I would love to read it!)



CREDIT: JOHN CATER

Entertaining Insight

As this is a book involving fieldwork, John obviously must talk about his work and, assuming that not all his readers are geologists, he attempts to briefly explain the geological issues involved, which he does very well, helped by the inclusion of a number of photographs and maps. He also touches on some fascinating archaeological sites he came across, such as the 9,000-year-old ruins at Mehrgarh in Pakistan, the remains of Alexander the Great's cities in Turkey and the wonderful antiquities in Syria, many now sadly destroyed.

John is keen that a wide range of people read his book to learn about geologists' "pioneering but sometimes misguided journeys". I can recommend it as an entertaining insight into a life that in many ways is no longer possible. It is about the adventures of a 20- to 30-something young man, and at times seems a little 'blokey' – but to write it in any other way would not be true to the story. He comes across as a likeable, self-deprecating guide who describes well and with awe the stunning places he has seen, gives some interesting little geological and historical asides and who, above all, can tell a good tale.

***Rock Doctor: Adventures of a Field Geologist Before 9/11** is available as an e-book through amazon.com*

SOPHIE ZURQUIYAH – REPOSITIONING CGG FOR THE TRANSITION

After a successful international career with Schlumberger, Sophie joined CGG in 2013 and was appointed CEO in 2018. The collapse in oil price, Covid-19 pandemic and energy transition have created a tough business environment during her near four-year tenure in this role, but also created opportunities. In this interview, Sophie talks about CGG's path into the future.

Sophie Zurquiyah

Geoscience expertise is a core CGG strength. How will CGG capitalise on this resource in the race to net zero?

Yes, we have a lot of geoscientists at CGG! We currently have around 1,200 Masters and PhDs across our various disciplines within geoscience and we are very proud to be a geoscience technology leader.

Geoscience, together with our advanced technical capabilities, is central to the energy transition. This combination of technology and skills within the geosciences will provide the insights necessary to fully understand, navigate and optimise our approach across many of the energy transition challenges.

At CGG, along with our core businesses that support the efficient and responsible discovery and development of oil and gas, which will be required throughout the transition, we can see that our geoscience and technical expertise, along with our earth data library, are, and will continue to be, critical for many efforts around the 'race to net zero'. This includes: cloud-based high performance computing (HPC), environmental monitoring, growth of minerals and mining to access the critical minerals required to support the energy transition, the development of geothermal energy and the industrialisation of carbon capture, utilisation, and sequestration (CCUS) to reach the scale required.

As the first female CEO in CGG's 90-year history, what do you think is required to introduce more diversity into the energy industry?

It is a tough challenge, and I have spent a lot of time understanding the 'issue', because at the end of the day, it is not right, and we should have more females in senior management roles across our industry. I believe it starts with recruiting, where there is a gender imbalance at the university level in the disciplines that we require, and because of this, getting more than 30-40% female recruits is difficult. After that, women get promoted at a lower rate than men, unless companies make the effort to correct the selection biases. That is how an industry ends up with around 20% female in mid-management and less than 10% at senior management levels. One action that many companies have taken is to ensure candidates from both genders are considered for any promotion. At CGG we currently have 24% women in our most senior positions, which places us very well within our sector, and are taking actions to ensure we increase that number moving forward. Our ultimate ambition is to match the overall percentage of women in the company, which is closer to 30%.

As an industry, we must make it clear that we are committed to gender diversity and take all the actions needed to reduce biases and create an inclusive and equitable environment. In our industry, we have the added complexity of being very international, and considerations around diversity vary country by country and by culture.

I will finish by saying that the need to consider diversity goes beyond gender, as it also includes ethnicity, national origin, age, cultural identity, and sexual orientation. Being inclusive allows us to tap into the best talents to drive our success, as well as best support our diverse clients.

CGG is repurposing its business and has sold its seismic and multi-physics acquisition and geosoftware businesses in recent times. How do these divestments, particularly the software sale, fit into CGG's long-term strategy?

We engaged back in 2018 in our own transition, recognising that our markets were evolving, and that we needed to define our own path into the future. We have become asset-light after exiting the acquisition businesses (Land, Marine and Multi-Physics), and are focusing on our three core businesses of Geoscience, Multi-Client and Equipment where we are differentiated, have less HSE exposure, including greenhouse emissions, and have leading technology/market positions.

GeoSoftware is a specialised commercial software business with the brands of Jason and HampsonRussell. They enjoy a leading position in a particular part of the larger upstream subsurface software market. We realised that to become a significant player in the commercial software business and expand beyond seismic reservoir characterisation, we would need to make large investments in a commercial software platform and expand into other parts of the E&P workflow, and this is a very crowded market.

> *For an effective, well-managed and equitable energy transition, the responsible management of oil and gas will remain vital for decades to come.*

Instead, we decided to divest GeoSoftware and focus on our data, equipment and services businesses in geology and imaging, identifying opportunities to invest in the technology required, including HPC and advanced software that supports our services, so that we could further differentiate these and leverage our unique and leading capabilities to expand into adjacent and rapidly growing areas, such as digital or environmental sciences.

In line with most of the industry, CGG has had to significantly reduce its headcount. As the business environment improves post-pandemic, what challenges, if any, do you see in re-staffing?

It is always a difficult decision to reduce our personnel as we have strong professionals that give the company their best. We also invest heavily to train and develop our people. Recognising that it would take several years before the business recovered to the same level as 2019, we did make the decision to reduce staff. However, in our model, we never stopped recruiting entirely, as our skill sets are constantly evolving. This also helps as we start ramping up, as we already have the people and processes in place to bring new employees on board.

While we see increased competition from the large tech companies, we are generally able to attract talented profiles to CGG, because we are known for operating at the cutting edge of what is possible in computational science, including IT, software, and imaging algorithms. Today we have some of the largest HPC capabilities in the world. As a recent graduate and scientist, I remember being attracted by the technology challenges that a company could offer me, and I think this still holds true for those entering the industry.

The oil and gas industry faces significant challenges and opportunities. How do you see CCG adapting as integrated oil companies strive to become integrated energy companies?

It is clear that the energy transition is here, progressing rapidly, and that our industry is embracing the future. This is excellent to see. Capital is being heavily injected and reallocated by the E&P companies, into solar, wind and batteries, which are the new energies attracting most investments right now. Geothermal is also receiving more interest and it will be important to watch technology trends closely, especially for breakthroughs around geothermal energy from shallow sedimentary basins.

In parallel, it is equally critical to recognise that for an effective, well-managed and equitable energy transition, the responsible management of oil and gas will remain vital for decades to come. At CGG, along with our core businesses, which support the efficient and responsible discovery and development of oil and gas, we have decided to develop new businesses in rapidly growing sectors that are adjacent to our existing businesses, leverage our capabilities, and support our clients' challenges. These include digital sciences – to help our clients extract the most from their subsurface data and provide the cloud-based HPC needed for the most advanced algorithms; energy transition – which includes technologies and services for CCUS, geothermal and mining; environmental sciences – where we leverage our HPC and artificial intelligence lab capabilities along with our earth science expertise to provide data analytics-driven intelligence to monitor and mitigate environmental risks; structural and earthworks monitoring – solutions that utilise our sensor, acquisition and monitoring expertise and technology to deliver systems for the continuous monitoring of the physical integrity, and to extend the life of structures, such as rail tracks, buildings, or bridges; and finally, our earth data library, because data provides the foundation for good decisions.

These new business initiatives, where we currently employ around 150 people and are expanding, represent an increasing share of our total revenue and provide an avenue for the growth and development of our employees.

You were appointed a director of TechnipFMC earlier this year. Given the synergies with CGG, do you see benefits in future collaborations with Technip?

TechnipFMC is a great company, and I am very honoured to be a director. They are a leading technology provider both in the traditional and new energies industry, delivering fully integrated projects, products, and services. They operate in many of the same geographies that CGG does, and often with the same clients as ours, but the procurement for their products and services is fairly disconnected from the procurement of geoscience products and services and we do not work with the same groups within our clients' organisations. Of course, we could collaborate where it makes sense, on a case-by-case basis.

Where do you see CGG in 2031 on its 100th anniversary?

Wow! It is amazing to think that CGG has been celebrating its 90th anniversary this last year! During that timeframe we have seen oil production grow from virtually nothing to 100M barrels of oil/day, offering affordable energy around the world, playing a key role in global economic growth over the decades, and now a key concern in global warming that must be urgently addressed.

In a way, I find it even more remarkable that CGG has remained, all that time, in geoscience, which is very exposed to industry cycles. During this time, CGG expanded the range of its products and services from land acquisition to processing to equipment. We also moved offshore, developed the multi-client business model and expanded from a focus on the seismic market, to covering the full spectrum of geoscience technology and expertise.

Today, through our recent strategic journey, we are now an asset-light technology company, focused on our leading and differentiated businesses of Geoscience, Multi-Client and Equipment. Looking forward, I see our future continuing to be strong in geoscience, a lot more digital and expanding significantly into other areas and industries which I've already mentioned.

Last year we changed our branding and updated our tag line to 'See things differently'. This is because we believe we have a unique perspective on our planet, thanks to our people and technology. Along with the importance of our geoscientists, this change also recognises the importance of the rapidly evolving trends in IT and HPC, which push forward the limits of the problems we can solve.

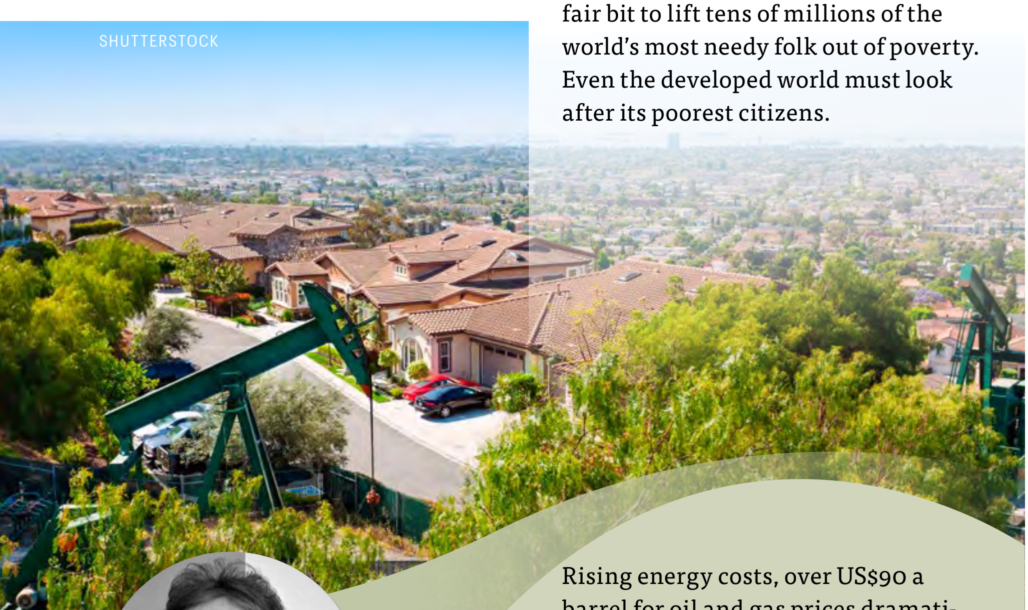
I am confident that we have the brains and the capability to create a positive future in these changing times, and in these rapidly growing new markets, while remaining true to our technology and geoscience history. I look forward to our 100th anniversary and seeing just how far CGG will have progressed along its continued journey.

OILING THE CULTURE WARS

Did you know that there are 5,200 oil and gas wells strung out below the busy streets of Los Angeles? Forget for a moment the glitzy Hollywood Hills or the J Paul Getty Museum, this is an oilman's urban nirvana – or was.

Nick Cottam

The news that the LA City Council has voted to phase out oil and gas drilling in and around the city is a reminder of how the culture wars – cancel culture, if you will – has embraced the flaring furnace of transition. On the one side we have an academic paper which berates drilling, not only because it will underpin future emissions and the health of the planet, but also because of the impact on human health and, notes a research paper from the University of Southern California, on the health of the poor. Yes, it's the poor who are most likely to live close to these active oil and gas projects.


SHUTTERSTOCK

On the other side of this transition argument is the jobs issue – 8,300 of them associated with extraction and development in LA. Shutting down domestic energy production not only puts people out of work and reduces taxes that pay for vital services, argues Rock Zierman, CEO of the California Independent Petroleum Association, but it makes the city more dependent on foreign imports from Saudi Arabia and Iraq. As the world in early 2022 looks down the barrel of a Russian gun and contemplates the fallout from another Middle Eastern rocket, this is an emotive argument. Clean energy or energy security: you take your choice.

The very complexity of transition – how fast, how expensive, how pervasive – makes it fair game for counterculture distortion. Living close to oil and gas sites is associated with reduced lung function says University of Southern California researcher Jill Johnston who is an assistant professor of preventative medicine. But what about the health impacts of losing your job? More broadly, you might add, fossil fuels have done a fair bit to lift tens of millions of the world's most needy folk out of poverty. Even the developed world must look after its poorest citizens.

Rising energy costs, over US$90 a barrel for oil and gas prices dramatically higher, are also an important short-term factor in transition. The world needs affordable, available fossil fuels to fund cleaner alternatives runs the argument. Environmental justice, yes, but perhaps keep just a few of those urban wells up and running.

Nick Cottam
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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 106
Billion = 1 x 109
Trillion = 1 x 1012

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
Crude Oil Prices Since 1861