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GEOSCIENCE & TECHNOLOGY EXPLAINED

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HISTORY OF OIL
The Land That Oil Forgot

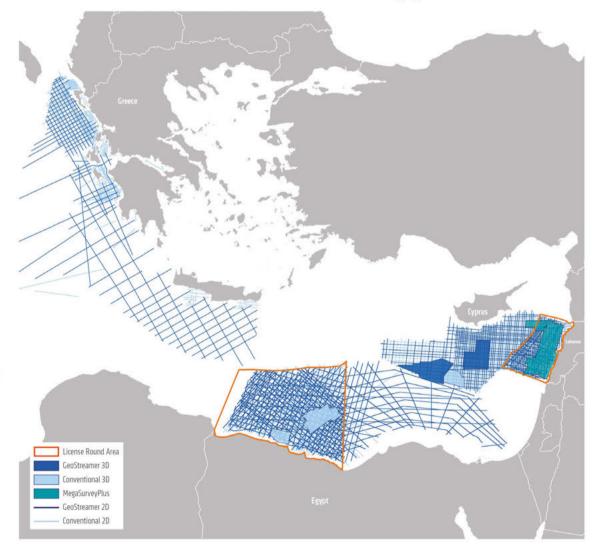TECHNOLOGY EXPLAINED
Pangea III:
At the Heart of E&P

GEOTOURISM
Oman's Musandam
Peninsula

**RESERVOIR
MANAGEMENT**
Salt Biostratigraphy

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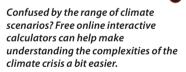GEOSCIENCE & TECHNOLOGY EXPLAINED

22

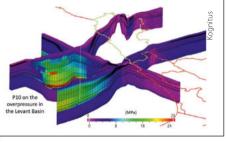*The Emirate of Ras Al Khaimah is relatively underexplored and offers plenty of potential.*

26

Machine learning combined with knowledge gleaned from experts can be used to rapidly assess hydrocarbon risks.

Kognitus

P10 on the overpressure in the Levant Basin   (MPa)

0   8   16   24

AAPG

32

Distinguished explorationist Bernard Duval advises young geoscientists to "study, read, attend technical society meetings, network – but also to get out in the field and have fun!"

46

David Mark/Pixabay

Confused by the range of climate scenarios? Free online interactive calculators can help make understanding the complexities of the climate crisis a bit easier.

66

Distinguished geologist Professor Ken Glennie's work on desert sedimentary systems was hugely influential in early North Sea exploration.

Contents

Vol. 17 No. 1

This edition of *GEO ExPro* focuses on the Middle East and Eastern Mediterranean; Digitalisation and Artificial Intelligence; and Reservoir Management.

A Hot Topic

Digitalisation, artificial intelligence and machine learning; it is a hot topic. Everyone across the world, including in the oil and gas industry, is talking about it, although it could be admitted that in some ways we were a little bit slow to join the party.

Leo Viktor Wolfert/123rf.com

Why is this so important? Money is, as ever, a prime mover; according to a 2018 Wood MacKenzie report, the adoption of digitisation and machine learning technologies could result in cost savings in the order of $75 billion in the upstream sector alone by 2023. These are likely to come from things like speedier drilling, fewer dry holes, more automation in production and the ability to undertake predictive maintenance. There are also benefits in health and safety, as fewer workers are required to work in dangerous wellsite situations.

The technologies involved have developed rapidly in the last couple of years, and their adoption by O&G is increasing at a very fast rate. At conferences and meetings, presentations on the subject of digitalisation and AI have moved in a very short space of time from simply explaining the concepts and how they could help the industry, to giving practical examples and case histories of the time- and cost-savings of applying these technologies. Ideas that barely a year or so ago were presented as new and innovative, such as using machine learning to rapidly update reservoir models in real-time, are becoming mainstream, as discussed in a couple of articles in this issue.

Interestingly, there are newcomers among the 'usual suspects' of oil and service company people giving talks at these conferences and seminars; the likes of Amazon, Google and Microsoft are now commonly sending delegates and speakers to address this industry, which they see as ripe for further digitisation and ready for the disruption – to use that popular buzzword – that this will inevitably bring.

As the use of digitalisation and artificial intelligence moves more mainstream it becomes accessible to a greater number of people and to a larger range of companies, possibly allowing small start-ups to leapfrog slower moving established organisations. In the always volatile oil industry, flexible, fast-moving companies that embrace this trend, using their data as an asset to be mined and learnt from, will ultimately be the successful ones.

Jane Whaley
Editor in Chief

PANGEA III: AT THE HEART OF E&P

Total's upgraded Pangea supercomputer delivers unprecedented computing power to help the company more reliably locate hydrocarbons, enhances mathematical modelling and visualisation and improves the management of uncertainties, to provide a better vision and understanding of the subsurface.

Inset: "The one spot in the Middle East that has no oil": a look at the history of exploration in Palestine from 1913 to 1948.
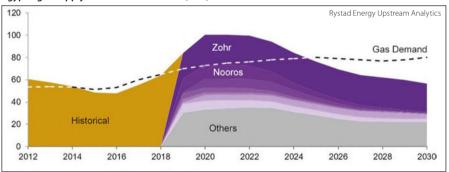
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Egypt: A New Regional Hub?

Egypt is in the middle of a supply turnaround. The gas-rich country became a net importer of LNG in 2015 after domestic production failed to keep up with LNG supply commitments; however, the country announced its intention to cease imports and begin exporting LNG through its main LNG terminal at Damietta in 2020.

The volumes to support this restart will come from the surplus gas production of about 550 MMcfpd at the giant Zohr field, where production reached 2.7 Bcfpd at the end of 2019. Supply to the three LNG trains in Egypt – Shell-operated Idku T1 and T2 and Eni-Damietta T1 – will produce 1.42 million tons a year in 2020. The uptick occurred after Shell and the Egyptian General Petroleum Corporation (EGPC) renegotiated the contracts for the Burullus and Rosetta fields. In addition to these volumes, West Nile Delta, Nooros, Atoll and Baltim South West will all be major contributors to this ramp up.

Earlier, Cyprus received permission from the EU to construct a subsea pipeline to Idku in Egypt to target growing demand in international gas markets. In Israel, Noble Energy signed a long-term contract in September 2018 with Dolphinus Holdings, an Egyptian consortium, to sell 64 Bm^3 of gas over a 10-year period from Tamar and Leviathan into the Egyptian domestic market through the existing East Mediterranean Gas pipeline. With in-place export infrastructure and growing domestic demand, Egypt is well positioned to serve as a gas export hub for the region.

Egypt's gas supply and demand balance (Bm^3)

Egypt's hydrocarbon production is set to rise to about 2.2 MMboepd in 2020, thanks to supply additions from Baltim South West and Zohr. With this, Egypt will have brought most of the resources discovered to date online. Further ramping up and maintaining production levels will be contingent upon future discoveries. In the recent past, Egypt has awarded relatively unexplored blocks to majors, so success or otherwise on these has potential to change the production outlook.

Top Discoveries

The Zohr gas field was discovered by Petrobel in 2015 in the Shorouk block, with the gas found in a Miocene Carbonate reef reservoir. Petrobel is a 50/50 joint venture between Eni and EGPC. The field was brought online in 2017 and currently produces over 2.5 Bcfpd. Rystad Energy estimates that the field holds a total of 3.55 Bboe of recoverable gas.

The Nooros gas field was discovered by Petrobel through drilling a directional well to a depth of 3,600m. The well struck a 60m-thick gas-bearing sandstone reservoir of Messinian age. The field was brought online in July 2015 and it is currently producing about 1.2 Bcfpd of gas. Rystad Energy estimates that the field holds over 650 MMboe of recoverable gas reserves.

Pharonic Petroleum Company, a 50/50 joint venture between BP and EGPC, discovered the Atoll gas field in the North Damietta offshore concession in 2015. The exploration well encountered 50m of gas pay in an Oligocene sandstone reservoir and the field was brought online in 2016. Rystad Energy estimates the field to hold about 250 MMboe of recoverable gas reserves.

Aditya Saraswat, Senior Analyst, Rystad Energy

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Timor-Leste:
Long Awaited 2nd Round
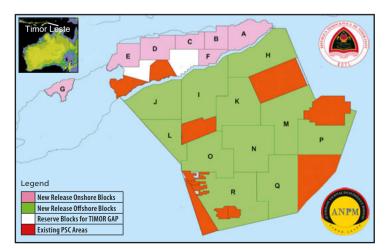
In October 2019 the Democratic Republic of Timor-Leste (East Timor) launched the county's second licensing round, releasing a total of 18 new blocks for public tender for Production Sharing Contracts (PSC), covering a large percentage of the total on and offshore area of the country.
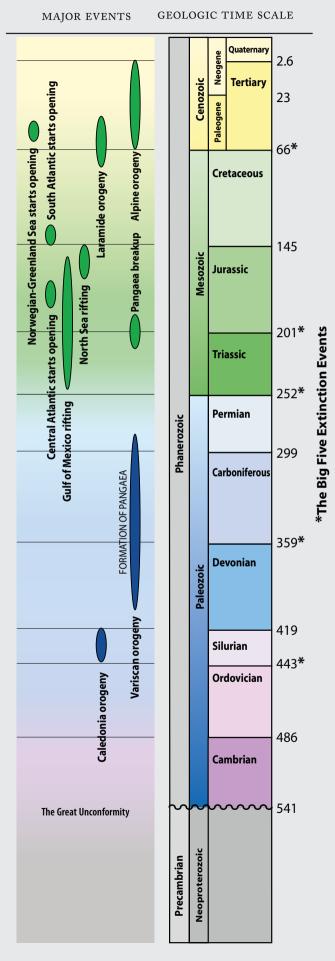
Seven of the offered blocks are onshore. They cover all the northern and eastern halves of the country, a total of nearly 10,000 km², with the largest covering the whole eastern end of the country. Of the remaining four onshore blocks in the country, two have been reserved for Timor Gap, the National Oil Company of Timor-Leste, and two are already the subject of PSCs. The whole onshore area has been covered by both gravity and magnetic surveys and data is available on 20 wells.

The remaining 11 new blocks are in the offshore area to the south of the country, in the Timor Sea. They lie in waters that increase rapidly to depths of nearly 3,000m in the narrow Timor Trench, about 50 km from the south coast, before shallowing towards the Timor Shelf where the water depths are about 200m. The blocks encompass over 50,000 km² in total, the largest being Block R in the south-west, which covers 6,522 km². Offshore data includes details of 80 wells and the whole offshore area is covered by 2D seismic of varying densities, as well as a number of 3D surveys.

Timor-Leste was recognised as an independent country in 2002 after decades of fighting against Indonesian occupation. The first licensing round was held in 2005/2006, but further rounds were delayed due to a territorial dispute with Australia, which was finally resolved in August 2019. Several fields, including Bayu Undan (350–400 MMbc and 3.4 Tcfg) and Buffalo (31 MMbo) were transferred to Timor Leste's exclusive jurisdiction as a result of this agreement, while the Greater Sunrise fields, which contain about 5 Tcfg, will be jointly developed by the two countries.

Roadshows will be held in Houston, London, Singapore and Perth and bids must be submitted by 9 October 2020, with the successful bids due to be announced on 4 December 2020. No signature bonus is expected and general terms call for full cost recovery, 5% royalty, 60:40 profit split in favour of operators and 30% income tax. ◾

Legend
- New Release Onshore Blocks
- New Release Offshore Blocks
- Reserve Blocks for TIMOR GAP
- Existing PSC Areas

MAJOR EVENTS   GEOLOGIC TIME SCALE

Insights into Africa's Fast-Changing E&P Horizon

The **Africa E&P Summit** provides a platform for upstream collaboration and deal-making, showcasing Africa's hydrocarbon hotspots and the most current licence rounds active in the region. Viewed by the industry as the 'go-to' event in Europe on Africa's upstream, the third Africa E&P Summit will take place in **London, UK**, on **20–21 May**. The Africa Licensing Promotion and NOC showcase this year will focus on presentations by Angola, Liberia, Senegal, Nigeria and Namibia and for the first time will include an in-depth Q&A with the audience on the geological and geopolitical attractiveness of these trending areas. In addition to the governments present from these focus countries, there will be 50 high-level speakers from leading companies active in Africa's oil and gas game.

Delegates who attend refer to the event as offering valuable technical and market insight into investment opportunities, superb networking and a great opportunity to meet with decision makers. ■

Seismic in the Energy Mix

Seismic 2020 will take place on **29–30 April** in **Aberdeen**. Conference Chair, Chrysanthe Munn, BP North Sea Exploration Manager, has set the vision for the conference and, together with an expert technical committee, has developed a strong programme featuring a range of operator and service company case histories, examples of collaboration, new projects and new technology examples.

As well as focusing on the 'here and now', the conference will look ahead to the future and how seismic feeds into the MER strategy in the North Sea and its role in the diversification of the energy mix. A speaker from the Oil and Gas Authority will set the scene and the keynote will be given by John Etgen, Distinguished Advisor for Seismic Imaging at BP. By highlighting the role seismic plays in the energy mix, this conference is not only relevant to geoscientists and geophysicists, but also to those in non-geo-related roles, such as petroleum engineers and senior decision makers in both operators and service companies. For more information contact the **Society of Petroleum Engineers Aberdeen (SPE)** website. ■

Exciting Senegal Licensing Round

The **2020 Senegal Licensing Round** is the first international competitive bidding round in **Senegal** arranged by the **Ministry of Petroleum and Energy** together with **PETROSEN**. It will be an open competitive tender, with applications evaluated on the basis of a set of standard criteria. Twelve blocks in the MSGBC Basin in a range of water depths will be available for licensing.

The Senegal offshore area is one of the most prolific hydrocarbon provinces in the world. Intensive exploration efforts over recent years has led to a succession of significant discoveries, notably **FAN, Sangomar** (formerly SNE), **Tortue, Teranga** and **Yakaar**. However, the full potential of the basin and the continental slope is still to be realised. Modern seismic data and improved geological models indicate a prospective zone located in the MSGBC deep offshore. Extensive regional 2D and 3D multi-client seismic data provides a high quality dataset that enables an unprecedented understanding of the evolution of the basin and especially the deep offshore.

A summary of the regional geology and petroleum prospectivity of the blocks on offer is provided on the dedicated website. This summary is based on the technical studies undertaken by PETROSEN and its partners, **TGS, GeoPartners** and **PGS**, utilising the variety of regional multi-client seismic data available. ■

Asia Pacific E&P Conference

The **2nd joint PESGB–SEAPEX** conference on **Asia Pacific E&P** will take place **on 24–25 June, 2020**, following the successful inaugural event in 2018.

The full technical programme features 32 talks across two days, extending geographically from India and Sri Lanka eastwards to Papua New Guinea, and from Australia northwards to Japan, Mongolia and North Korea, covering most prospective regions in between. As you would expect from these two organisations, the programme is focused on technical case studies of recent discoveries and new opportunities. Broad industry representation comes from key regional E&P players large and small, including BP, Equinor, ExxonMobil, Mubadala, Oil Search and Woodside, through focused contracting companies, plus academic and consulting expertise. Not to be missed is the talk by South East Asian veteran Geoff Bennett, a repeat of his famed talk on Kuala Langsar which won the prize at the SEAPEX 2018 Christmas 'My Favourite Screw Up' event. There'll also be a vibrant exhibition of booths and posters, including a screening area for Euro 2020 football matches. Networking will of course be a major part of the event, with plenty of coffee and lunch breaks, the celebrated quiz evening and the traditional SEAPEX pub crawl. ■

Largest Earth Science Programme

With the largest earth science technical programme in our history, **GeoConvention 2020** will feature a fully integrated programme representing a diverse collection of earth science disciplines, including geology, geophysics, petrophysics, minerals, mining, water, earth, environment and the energy world. From panel discussions to targeted technical content, workshops and field trips, GeoConvention provides the ultimate opportunity to expand your knowledge and push your capabilities to the next level. In addition to featuring over 110 exhibitors, showcasing their leading-edge technologies, solutions and workflows, GeoConvention 2020 will provide you with the opportunity to enhance your skills and further your expertise while you share and network with Canada's largest integrated geoscience conference.

With over 5,000 attendees expected and 100 sessions identified, GeoConvention 2020 is a once-in-a-decade opportunity to learn and knowledge-share with the brightest minds in academics and energy industry professionals, as well as thought-leaders from throughout Canada and the world.

Registration is now open. You are invited to attend, exhibit and sponsor GeoConvention 2020 on **11–13 May** at the **Telus Convention Centre** in **Calgary, Alberta**. ■

A Conference and Exhibition Catered for Everyone

A place where you can see the familiar faces of the industry, but also meet the most forward thinking and inspirational people in the field, the **82nd European Association of Geoscientists and Engineers (EAGE) Annual Conference and Exhibition** is the networking place to be this year!

The programme has over 1,300 technical presentations covering a wide variety of disciplines including geophysics, geology, mining and civil engineering, computer science, HSE and sustainability. There are also five forum sessions, gathering leaders of the industry to discuss the most pressing issues in the wider geoscience and engineering field. For those interested in looking for

more focused educational sessions, a variety of workshops, short courses, and field trips will be available. Additionally, the EAGE Annual will bring together around 350 exhibitors in the ground-breaking exhibition. Companies will showcase their emerging technologies, state-of-the-art innovations, new product launches and valuable industry services. Attendees can also maximise networking opportunities at all the social events.

The EAGE Annual 2020, to be held **8–11 June** in **Amsterdam**, will provide something of value to everyone! If you register before 15 March, you can take advantage of the early registration fee. Please visit the EAGE website for more details. ■

Africa – New Ideas, Plays and Innovation

The **HGS/PESGB** annual **Africa Conference** will take place **15–16 September 2020** at the **Norris Conference Centre** in **Houston, Texas**.

Exploration in Africa has undergone several exploration cycles throughout its history. In many places where giant discoveries have been made, production is in decline and investment has not sustained the growth of the industry. The theme for the 2020 conference is focused therefore on what can be and what has been done differently. What ideas should be tested? What has industry learned that should guide us toward new ways of thinking about exploration and development in Africa? What are the possible new areas with hydrocarbon potential? What technology(s) can help unlock additional reserves in existing basins and help find new reserves in unexplored areas? How can government attract and promote investment in new and existing areas? The call for abstracts ends 1 April 2020. Please submit all papers to the Africa2020 website. ■

First Gas for Leviathan

Leviathan, the giant **Israeli** gas field discovered by **Noble Energy** in 2010, delivered its first gas to the Israeli domestic market in December 2019, with the first exports, to Egypt and Jordan, following in January 2020. The field, which holds 33 Tcfg in place and 22 Tcfg recoverable, lies 125 km west of Haifa in water depth of 86m and is one of the largest gas discoveries of the decade. With a total production capacity of 1.2 Bcfgpd, Leviathan will more than double the quantity of natural gas flowing to the Israeli economy today.
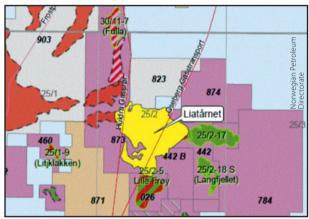
Noble Energy made the first gas discovery offshore Israel in 1999. It delivered the country's first domestic natural gas in 2004 from Mari-B, to be followed by the 10 Tcfg Tamar field, which came on production in 2013 and currently fuels 70% of Israel's electricity generation. The additional energy supplied by gas from Leviathan will allow Israel to phase out imported coal in electricity generation. Two smaller fields, Karish and Tanin, are set to start production in 2021. ■

The Leviathan field.

High Value Barrels

At least ten of the 17 discoveries made on the **Norwegian Continental Shelf (NCS)** last year will be presented at the **NCS Exploration – Recent Discoveries** conference in **Oslo, Norway**, on **12–13 May**. Roughly 600 MMboe were found on the NCS in 2019, the best year for value creation since the discovery of Johan Sverdrup in 2010. The programme committee is particularly proud to announce that there will be presentations on the three biggest discoveries: Liatårnet, Ørn and Echino South. The largest, Liatårnet (200 MMboe), was made in Neogene sandstones and represented a new play model.

Aker BP suggest that the discovery wells 25/2-10S (1986) and 25/2-21 (2019) belong to the same accumulation.

Last year's discoveries on the NCS prove that small but high value discoveries are becoming increasingly more important because NCS exploration has reached a stage where large, giant discoveries are less likely, although obviously sought after. The industry therefore now recognises the high value of smaller discoveries near existing fields that can rapidly be put into production at low cost. The success rate for drilling these prospects is also generally high: around 60% for drilling in established licences vs. 20% in frontier exploration and APA licences. ■

China Opens Up

Early in January **China** announced that for the first time **foreign companies** will be allowed to explore for and produce oil and gas in the country, opening up the industry to firms other than state-run organisations. Previously, international companies could only enter the industry in joint ventures with Chinese firms, mainly state-owned majors such as CNPC and Sinopec. Interested companies will need to be registered in China with assets of 300 million yuan (US$43 million) and any permits obtained will be valid for five years, with the possibility of extending for a further five.

This move is designed to increase domestic production in China, which currently imports 70% of the crude oil it refines and nearly half its natural gas consumption. It also hopes that opening up the sector to competition will encourage technological innovation and reduce production costs. ■

Leading Subsurface Conference

DEVEX 2020, the leading subsurface conference of its kind, will take place on **5–6 May** in **Aberdeen**. This is the only conference of its size which is focused on the full cycle of reservoir discovery, evaluation, development and recovery in the UK.

The committee driving the conference is represented by most major operators and as a result there are some excellent operator and service company collaboration case histories which will be showcased at the conference, along with some excellent technology development stories. The technical presentations will run in parallel and the conference will also feature some specialised masterclasses, an excellent learning opportunity. Subjects include how cores integrate with the wider reservoir; artificial intelligence; temperature modelling; and imaging.

New Aberdour Bay.

Andrew Buchan/Pixabay

The **DEVEX Field Trip** will take place on **4 May**. It will visit Gamrie Bay and New Aberdour Bay and will be led by Jim Ritchie of Forvie Geoscience Ltd. We are also delighted that the Young Professionals represented on the committee are driving forward their own YP Event, which will take place on the first day of DEVEX. ∎

New Permian Programme

CGG and **Fairfield Geotechnologies** have signed a second cooperation agreement to acquire a series of large-scale, high-density, multi-client surveys in the **Central Basin Platform (CBP)** of the **Permian Basin** in **West Texas**.

The CBP is a tectonically uplifted geological structure that separates the deep Delaware Basin and the shallower Midland Basin, which together make up the greater Permian Basin of West Texas. The cooperation agreement covers an area of approximately 17,000 km^2 across several counties, close to the New Mexico border.

The new wide-azimuth datasets will deliver high quality data in order to provide a better understanding of the structural complexity of the transition between the CBP and surrounding basins to provide unprecedented insight into the potential of this very prospective area within the Permian Basin, one of the most prolific regions in North America. ∎

Pangea III: At the Heart of E&P

Total's new supercomputer has a cumulative computing power of 31.7 petaflops – equivalent to 170,000 laptops – and storage capacity of 76 petabytes. It is one of the most powerful supercomputers in the industry – but what does this mean for oil and gas exploration?

PIERRE-OLIVIER LYS and PAUL ROBIN, Total

Alfred Wegener is certainly accepted as being foremost among the scientists whose work has promoted the development of modern geology and therefore the petroleum geosciences: his famous theory of continental drift is still today the backbone of oil and gas exploration, as illustrated by the recent interest in the conjugate Brazilian and Angolan margins.

In his theory, Wegener proposed in 1915 that the continents once formed a contiguous, single land mass which he called 'Pangea', a word formed after the Ancient Greek *pan* ('entire, whole') and *Gaia* ('Mother Earth, land'). Carrying both the ideas of uniqueness and entirety, the name was the perfect match for the High Performance Computer (HPC) that Total decided to install in Pau, France, back in 2013: Pangea was born.

Pangea has dramatically evolved in order to keep abreast of competition for processing capacity. Less than ten years after its conception, in mid-2019, the newest version of the supercomputer was brought online. Pangea III can deliver an amazing computing power of 25 petaflops, bringing the overall computational capability of the Total Group to 31.7 petaflops – the equivalent of 170,000 laptops combined together! It also brings the cumulative storage capacity to 76 petabytes (i.e. equivalent to about 50 million HD movies), and in June 2019 Pangea III was ranked the number 1 most powerful HPC in the industry, and the 11th most powerful computer globally. While this new supercomputer multiplied the processing power of the previous version by almost five, IBM – who developed and installed Pangea III

Alfred Wegener (1880–1930), the German meteorologist and geophysicist who formulated the first complete statement of the continental drift hypothesis, including the concept of the major land mass, Pangea.
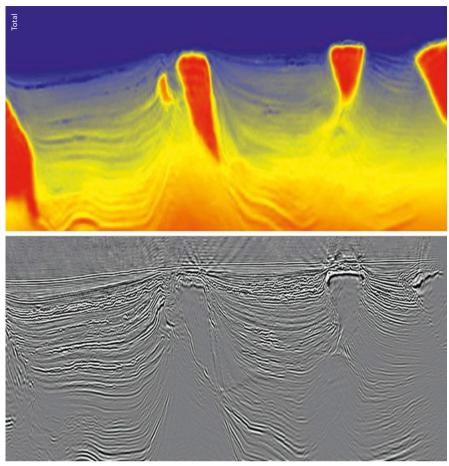
– managed to bring down its power consumption per petaflop by a factor of more than ten!

More Petaflops Equals More Oil!

Seismic reflection has been at the foundation of oil and gas exploration for decades, and is widely used by the industry to image the subsurface and therefore to increase the chance of drilling successful exploration and development wells. Seismic waves sent into the ground by a seismic source spread in the subsurface, reflect at geological interfaces and propagate back to the surface where tens of thousands of sensors record them. The process, which is repeated thousands of times, allows us to image what lies beneath our feet down to 10 km or more, after the reflected waves have undergone a complicated processing sequence, which we call 'seismic imaging'. Complex equations mimicking the propagation

Laurent Pascal

Velocity model (top) and migrated seismic image (bottom) in a complex geological setting. Red areas correspond to high velocity salt bodies.

of waves in the subsurface are used to relocate the seismic events recorded to their actual location in a 3D image called a 'cube', a process that is called 'migration' by geophysicists.

Whilst the principles of migration have been understood since the very beginning of seismic exploration, migration algorithms have only been used in the past 20 years because they are so greedy with regards to computing power. In fact, the first migration algorithms were based on simplified equations or assumptions in order to cope with the limited computational capabilities available back then, but this resulted in images whose quality could still be improved, especially in complex areas. Nowadays, High Performance Computers allow us to process huge amounts of data, using algorithms able to model the physics of seismic waves propagation more and more accurately, which in turn generates more precise, higher resolution images, and therefore reduced uncertainties for prospect evaluation, well positioning or reservoir monitoring.

So, having more petaflops leads to more oil, produced for less in a safer environment.

Leveraging E&P

Pangea III is part of Total's overall strategy to develop a unique know-how in seismic imaging, so as to be able to tackle the ever more complex problems arising from the company's wide-ranging portfolio. These requirements include subsalt imaging in Brazil, the Gulf of Mexico or deep offshore Angola;

higher resolution velocity models in order to better predict pore pressure and design well architecture accordingly; or precise time-lapse imaging for reservoir monitoring and the subsequent optimisation of development or infill wells.

The ability to perform such imaging studies internally is definitely seen to be a competitive advantage. Strong interaction between imaging geophysicists and geologists, such as specialists in structural geology, means it is possible to integrate several disciplines in velocity model building – a crucial step in the seismic imaging process. These models can then be used to test several scenarios in just a few days, thanks to the extra computing power available, allowing the geoscientists to easily refine the velocity model and obtain a better, more focused image.

This internal expertise also gives the company a priceless flexibility and reactivity when short-term problems requiring a quick but precise answer arise. For instance, as soon as a well has been drilled the velocity model and associated migrated image can be updated, thanks to the well information provided in a very short timeframe; typically, just a couple of weeks. A decision on, for example, drilling or updating a sidetrack wellbore could then be made rapidly, based on a better local image.

Last, but not least, having an HPC available is also advantageous to Total's internal R&D when they need to test and put in production the new imaging algorithms they deliver on a regular basis. Thanks to the close collaboration between the imaging and research teams, these more complex and/or efficient algorithms can quickly meet the needs of operational geophysicists, allowing them to tackle specific problems in a short timeframe. R&D can be compared to the fuel that is needed to power the competition engine – the supercomputer – so as to win the race for oil and gas!
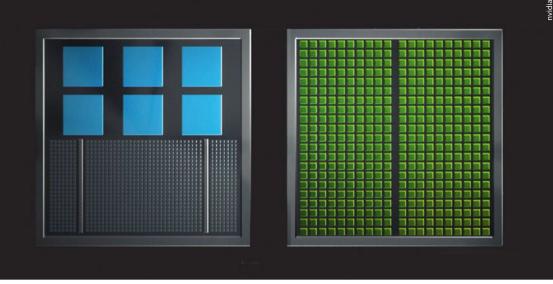
More Power, Smaller Footprint

Shifting from Pangea II, which had been installed in 2016, to Pangea III basically multiplied the processing capacity by a factor of five, which required a major shift in the HPC architecture: indeed, it was quickly realised that a GPU (Graphic Processing Unit) was the only technology capable of delivering the desired computing power while ensuring an optimal energy consumption, and as a result the CPU (Central Processing Unit)-based architecture of Pangea II had to be completely revised.

While CPUs and GPUs are both silicon-based processors, they process tasks in fundamentally different ways (see *GEO ExPro* Vol. 13, No. 1). A CPU is much more versatile and can work on a variety of tasks thanks to an architecture adapted

to working in a sequential mode, and made of a few cores (up to 24). A GPU, on the contrary, is designed to handle multiple tasks at the same time in a very effective manner, and is therefore made up of thousands of smaller and more efficient cores, an architecture aimed at parallel computing. Nowadays, GPUs deliver a much higher computing power than CPUs, and can be up to 100 times faster for tasks requiring massive parallel computations like machine learning or the handling of huge datasets – which is what we are actually doing in seismic imaging.

Pangea III could therefore be described as a bespoke configuration that gives more power but with a smaller environmental footprint.

Changing the HPC architecture for Pangea III was a sensible choice, since it paves the way for new algorithms based on artificial intelligence, but at the same time this choice involved a complete overhaul of the production

The difference between a CPU (left) and GPU (right).

algorithms used by Total in order to make them compatible with this new architecture. As a matter of fact, the geophysicists and IT engineers spent a full year adapting most of the codes to this new configuration, an extraordinary effort which eventually delivered unmatched and unprecedented performance in the applications used for imaging.

A Versatile Tool

Although Pangea III is – as of today – mainly used for seismic imaging purposes, its versatility and computing power will also be beneficial for many

disciplines across the Total Group. For example, the machine will allow reservoir engineers to run many more simulations, in order to better capture and manage uncertainties, or to quickly match actual production data to the reservoir model. New disruptive methods like enHM (ensemble History Matching) will produce better field-history matching and more reliable production forecasts, while reducing the research time required. In addition, other branches of the Total Group will benefit from the vast power of the HPC, since, for instance, chemical and molecular modelling and analysis will be made available to researchers from the Refining and Chemicals branch of the company.

In fact, the only stakeholders who complained when Pangea III was launched were the employees who cycle to work in Pau: the water feeding their changing rooms had been heated by Pangea II's cooling system, but since the new supercomputer is much less energy intensive, it was no longer able to heat the water to an acceptable temperature. Fortunately, a new heating boiler was installed for them, making everyone happy – and Pangea III a completely shared success! ◾

Overview of a few racks from Pangea III.

Teaching the Machines

Machine learning in oil and gas exploration and production has successfully begun to scale up from pilots to specific and bespoke industrial solutions – but must remain grounded in the real world.

JAKE BOUMA, Cognite

If the rapid pace of technological development over the last 30 years has taught us anything, it is that Utopia is not coming. The flying car and teleportation are still a long way off, and if they do ever arrive, we all know better than to imagine that they will magically transform society. Genuine technological progress is always grounded in the real world, with all the missteps, wrong turns and imperfections that go along with it.

And so it is with the latest buzzword zipping back and forth across the oil and gas industry: machine learning. Despite the hard lessons we have learned about the application of technology to the real world, some machine learning evangelists are still enthusiastically selling a vision of sentient robots that will solve all the industry's problems in a single stroke.

Machine learning *will* change the way the industry runs. Not because it is going to learn how to replace humans, but because we can teach machines to enhance the skills, performance and cognitive power of the humans involved, in ways we never thought possible.

Real-World Problems

Let's take a very ordinary problem: paperwork.

Written processes, printed forms and manual documentation are not disappearing as slowly as you might think. The oil and gas industry's need for complex machinery, precise engineering, rigorous safety standards and responses to variable conditions mean it is paperwork-heavy; very heavy. Many companies and operators are still wedded to forms, checklists and filing in triplicate.

The issue is not that those processes do not work, but that they absorb huge amounts of time from skilled, operationally-critical staff who have better things to do. Using machine learning by teaching a piece of software to carry out that manual paperwork with minimal oversight does not need to replicate and replace the skills of scientists and engineers, but it can free them up to make the most of their specialist skillset.

Too Much Information

Another issue is the sheer volume of data now being generated and collected. We might be forgiven for thinking that any and every bit of data gathered is of value, but it is actually the opposite – many companies have spent millions on collecting, cleaning and storing data from vast numbers of sources, only to be left staring at a mountain of data that they do not really know what to do with. A recent survey by McKinsey estimates that 80–90% of the data budget of major companies is spent gathering and cleaning data, with only 10–20% being spent on building models based on that data that actually generate value.

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Machine learning can help by automating the rules of collection, connection and cross-reference necessary to refine that mountain of data into recognisable patterns. Those patterns can then provide insight for the same critical staff to make more informed decisions at crucial times; enhancement of skills, not a replacement of expertise. But too many data science companies are still selling the 'snake oil' of algorithmic magic – the idea that all you need to do is hand over the mountain of data and they will sort it into solutions. That is simply not the case.

Numbers are Passive

Oil and gas companies need to be careful about what data they collect, collate and press into action. Numbers without meaning, purpose or application are just that – numbers. They cannot do anything by themselves.

However, when data collection and machine learning are used in targeted, contextual and specific ways, they can make a significant difference.

Let's say, for instance, that your pump has a temperature sensor on the motor, so you can prevent it from exceeding its operating temperature. However, the sensor data does not reflect the broader operational context, so it has somewhat limited potential for monitoring and decision-making. It does not know that the pump has to work a bit harder when maintenance

Paperwork – a real-world problem.

is being performed on one of its neighbours that typically operates in parallel with it; or how long it is since the filters have been changed; or simply that it is a hot day outside. There are many factors that need to be considered. So machine learning models can watch for patterns, but the trick is to efficiently present all of this data to the engineer. That way, they can use their experience

The Valhall oil field.

system that could recognise the unique combination of factors that indicated the beginning of chalk influx in the wells, allowing engineers to intervene before any real damage was done. This system is estimated to be saving the operator up to $15 million a year.

People Still Matter

Many industry operators are seeing the value of this highly collaborative approach, not just in terms of involving experts from every stage of their operations in designing the models, but in encouraging separate software and data providers to work together. A rising tide lifts all boats, and the specialist solutions that collaborations can produce have developed into new products, services and business models for the industry as a whole.

In other words, it is much more about how leaders in the industry choose to behave than any mythical power machine learning may or may not have. Think less about finding machines to do the difficult jobs we no longer want to do, or to replace the skills and expense of the human beings that currently do them. Think more about finding ways in which machines can be taught to enhance and improve the power of those humans to make informed decisions. ◼

to diagnose the problem without needing to chase data from multiple systems.

Different Every Time

In oil and gas, no two locations are the same. Geography, weather, location, legislative environment and more can all vary wildly. This, in turn, requires a specific and bespoke industrial solution where existing equipment is adopted, or designed and manufactured to order, to solve unique challenges.

So when it comes to applying the power of data and machine learning to those varying environments, it follows that specific systems and software should also be adaptable, following along with a way of working that allows for unforeseen changes and can adapt to a changing system. They must be able to change as lessons are learned.

Despite the need for tailored solutions, oil and gas companies should not let perfection be the enemy of 'good enough'. The time and trouble required to design a system that can do everything you could ever want costs far more than developing an MVP – minimum viable product – that can be up and working quickly. You need to be able to build it fast, test it fast, and change it fast, in order to keep pace with the lessons you are learning on the ground.

Chalk at Valhall

On the Valhall gas field in the North Sea off the coast of Norway, engineers working for an independent oil and

gas operator faced a unique problem. Chalk silt in the seawater was gradually plugging the wells, and existing sensor data was only monitoring pressure and temperature. The huge amount of broad historical data, fed into an off-the-shelf model, was proving to be not nuanced or specific enough to detect when wells were about to clog or to predict future events, and it led to costly delays. A unique set of circumstances – the geography, the machinery and the physics of the problem – needed a unique machine learning response.

By combining physics-based modelling with specific and targeted sensor data, a development team consisting of subject-matter experts and data scientists created a live warning

Helping humans to make informed decisions.

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Ras Al Khaimah: Great Hydrocarbon Potential

GIACOMO FIRPO Ph.D., RAK Gas

There is rejuvenated interest in the Emirate of Ras Al Khaimah – an underexplored province surrounded by producing fields and on trend with major discoveries.

Ras Al Khaimah (RAK) is the northernmost Emirate of the UAE and borders the Musandam Peninsula (see GEO Tourism, page 50), the Omani exclave that protrudes into the strategic Strait of Hormuz. The Emirate is famous for its rich history, dating back seven millennia, and for its diverse natural beauty such as pristine beaches and desert landscapes, set against the background of the Hajar Mountains.

RAK is also becoming an important international business centre and hosts a large number of companies from across the globe. These represent various sectors and industries such as oil and gas, banking, tourism, pharmaceuticals and minerals. Centrally positioned at the crossroads between Europe and Asia, the emirate is an ideal base from which to expand into the Middle East and Africa. For the past decade, Ras Al Khaimah has been consistently rated 'A' by Fitch and Standard & Poor's rating agencies and already the Emirate is home to more than 38,000 businesses from 100 countries representing over 50 industries (from RAK Media Office).

The Emirate is led by His Highness Sheikh Saud Bin Saqr Al Qasimi, UAE Supreme Council Member and Ruler of Ras Al Khaimah, and His Highness Sheikh Mohamed Bin Saud Al Qasimi Crown Prince of Ras Al Khaimah.

The Oil and Gas Sector

The oil and gas sector of the Emirate is regulated by the RAK Petroleum Authority (RAKPA), the entity which oversees the management of the petroleum resources (upstream and downstream).

The national energy company of Ras Al Khaimah is RAK Gas, which is 100% owned by the Government of RAK. RAK Gas manages a portfolio of operated and non-operated participation in upstream exploration properties in the Middle East and Africa. The company also owns processing facilities at the Khor Khwair gas plant, comprising two separate gas treatment trains that have been involved in the processing of gas from Oman's Bukha and West Bukha fields and the neighbouring emirate of Umm Al Quwain.

The domestic assets were the subject of a successful licensing round in 2018, which attracted the interest of major and supermajor oil companies. At present the entire offshore domain (Block A) is operated by ENI (90% interest), while Block 5, onshore and transition zone, is operated by PGNiG (90% interest). The two remaining

Figure 1: View of Ras Al Khaimah City with the Hajar Mountains in the background.

Figure 2: Map of the current RAK concessions and existing oil and gas fields.

onshore concessions (Blocks 6 and 7) are still open for investment (Figure 2).

Ras Al Khaimah is surrounded by multi-Tcf operated fields and discoveries, with over ten producing oil and gas fields within a 70 km radius. The closest examples are the Bukha fields in Oman to the north-east and the Sharjah, Mubarek and Umm Al Quwain fields to the south-west.

To date, two historical discoveries have been made inside the emirate: the Saleh field (gas and condensate) and the RAK B undeveloped discovery (oil, gas and condensate), both located offshore Ras Al Khaimah approximately 45 km from the coast. Both Saleh and RAK B targeted the Cretaceous carbonates of the Arabian Platform (Wasia and Thamama groups), but did not specifically target shallower Cenozoic or deeper Permian to Jurassic potential.

The Saleh field, in production since 1984, has been operated by various companies (Gulf, Chevron, RAKOPET, RAK Petroleum, DNO) until the operatorship returned to RAK Gas in 2016. The estimated GIIP hosted by the Cretaceous reservoir intervals is in the order of 320 Bcf; 200 Bcf in Wasia and 120 Bcf in Thamama reservoirs. Further reserv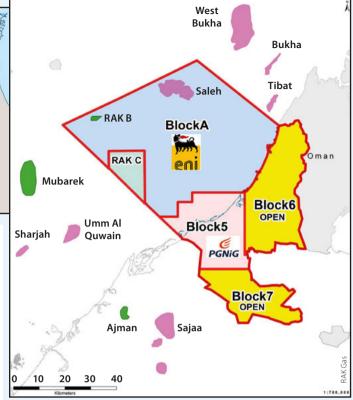es are expected to be present in the deeper and shallower sections with the possibility of multi-Tcf potential. The RAK B discovery, made in 1975, about 30 km south-west of Saleh, was initially considered likely to be too small for economic development. Recent work and revised volumetrics suggest that there may be sufficient recoverable liquid resources to enable development with an economic tie-back to Saleh. Further potential is again envisaged to be present in the deeper and shallower sections.

Geological Setting

The present day structural and stratigraphic setting of Ras Al Khaimah is strongly related to the compressional event associated with the obduction of the Oman-UAE ophiolite, which took place in the Upper Cretaceous (Turonian). This event, leading to the onset of the development of the Hajar Mountains, contributed to reconfiguring the topography of the area, with a fold and thrust belt dominating the onshore domain, the verge of which is approximately coincident with the current mountain front, and a foreland basin developing to the west of the uplifted area (Figure 3). The offshore domain is mainly characterised by extensional features,
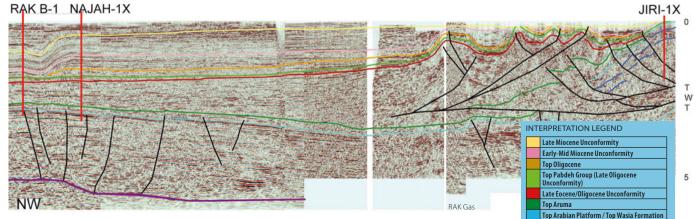
Figure 3: Vintage north-west to south-east seismic section showing the different structural provinces.

INTERPRETATION LEGEND
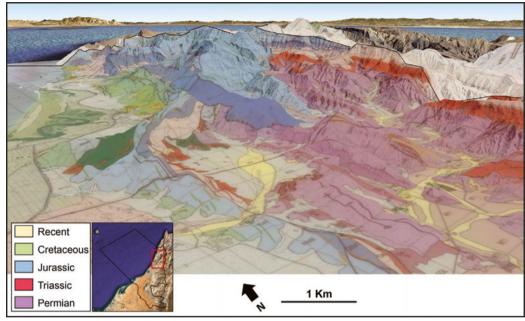
- Late Miocene Unconformity
- Early-Mid Miocene Unconformity
- Top Oligocene
- Top Pabdeh Group (Late Oligocene Unconformity)
- Late Eocene/Oligocene Unconformity
- Top Aruma
- Top Arabian Platform / Top Wasia Formation

Figure 4: Aerial view of RAK geology. (Modified after Ellison et al., 2006)

the consequent variation in the depositional setting from supratidal (sabkha) to shallow marine (platform) were responsible for the development of hard grounds and the process of dolomitisation, which was extensive between the Permian and the Triassic and occasional in the Jurassic and Cretaceous.

The Cenozoic is largely eroded or not deposited inland but is thickly developed in the offshore domain, filling the accommodation space created in response to the foreland basin evolution. From a lithological point of view, the succession presents thick sections of rhythmically bedded turbiditic sandstones and mudstones, alternated with evaporitic horizons and shallow water carbonate layers.

which appear to be geometrically reconfigured (often inverted) along the margin of the thrust front (foredeep), due to the influence of the compressional stress field.

The mechanism of the structural development heavily influenced the depositional history of the region, which can be subdivided into a pre-Cenozoic phase, dominated by carbonates, and a Cenozoic phase, characterised by the

deposition of clastics and, subordinately, carbonates and evaporates.

Spectacular exposures of the Late Palaeozoic (Permian) and Mesozoic stratigraphy are present in the onshore area (Figure 6). This section of the stratigraphy is principally represented by limestones and dolomites that were deposited in a stable platform setting on the Neotethys Ocean passive margin. Periodic fluctuations in sea level and

Treasure Yet to Be Discovered

Ras Al Khaimah's structural framework is characterised by a number of strongly zoned areas, with extensive thrusting observed onshore to the south-east and extensional fault blocks primarily
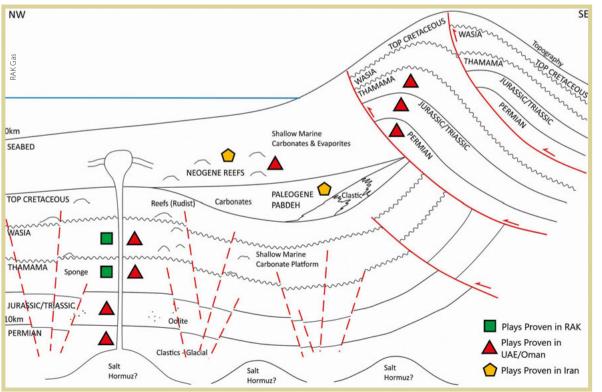

Figure 5: Play cartoon: a broad spectrum of exploration solutions.

related to local underlying salt tectonics offshore to the north and north-west. Despite the increased effort required and logistical concerns that this complexity brings to exploration, it also opens up the possibility of a variety of exciting and potentially very rewarding play types to be discovered in the area.

As mentioned, oil and gas exploration and production in RAK territory has been historically limited to the Cretaceous carbonates of the Arabian Platform. However, looking at the bigger picture, major UAE oil and gas accumulations are also encountered in Permian, Jurassic and Middle Cretaceous reservoir units, with minor production from Lower Cretaceous intervals (e.g. offshore Abu Dhabi, Dubai). This could imply the existence of further reserves yet to be discovered at deeper levels than are currently typically targeted.

Additionally, a variety of trap types are left to explore in the Cenozoic section, including reefal, salt onlap, diagenetic, and channel/turbidite traps.

Recent integrated petroleum basin studies, based on 2D and 3D seismic, potential field data (FTG and aeromagnetic) and geological field work, have identified a whole array of proven, potential and conceptual play concepts which could constitute the base for the future exploration of the territory (Table 1).

The number and diversity of the available play solutions (Figure 5) provide clear insights into the great potential still to be unlocked in the Emirate of Ras Al Khaimah.

References available online. ◼

Table 1: Proven and potential plays in Ras Al Khaimah.

PLAY	PROVEN?	RESERVOIR	SOURCE
CENOZOIC	Proven in Iran	• Marginal and non-marine coarse clastics and associated evaporites (Fars Group – Miocene); Reefs in shallow marine setting (Neogene); • Limestones, dolomites, claystones and cherts of the Asmari Fm (Pabdeh Group – Oligocene); • Limestones, packstones, claystones and mudstone of the Pabdeh Group. Potential also for deep water high energy deposits (calci-turbidites) (Paleogene).	• Calcareous claystones/marls of Aruma Group (Upper Cretaceous); • Bab intra-shelf basin shales (Aptian); • Shilaif intra-shelf basin shales (Cenomanian); • Arab Fm (Tithonian) and Diyab Fm (Oxfordian) mudstones.
CRETACEOUS	Proven in RAK	• Limestones of the Wasia Group (Mishrif and Mauddud Fm – Albian/Cenomanian); • Limestones of the Thamama Group (Shu'aiba, Kharaib, Lekhwair, Habshan Formations – Berriasian/Aptian).	• Bab intra-shelf basin shales (Aptian); • Shilaif intra-shelf basin shales (Cenomanian); • Arab Fm (Tithonian) and Diyab Fm (Oxfordian) mudstones.
JURASSIC	Proven in the UAE	• Limestones and dolomites of the Musandam Group (Sinemurian/Tithonian).	• Arab Fm (Tithonian) and Diyab Fm (Oxfordian) mudstones.
EARLY–MID TRIASSIC	Potential	• Dolomite of the Ghail/Hagil Formations (Triassic).	• Potential for the Gharif shale (Permian) and for the Silurian age Qusaiba Fm.
LATE PERMIAN–EARLY TRIASSIC KHUFF	Proven in the UAE	• Dolomites of the Khuff/Bih Formation (Late Permian–Early Triassic).	• The Silurian age Qusaiba Fm organic-rich graptolite shale is the source of Khuff gas in vast parts of the Arabian basin (Poppelreiter, 2013) but wells in RAK do not penetrate this interval.
PERMIAN PRE-KHUFF	Proven in the UAE	• Dolomites and clastics of the pre-Khuff/Bih (Gharif/Unayzah Fm?) (Permian).	• Potential for the Silurian age Qusaiba Fm

Figure 6: Wadi Bih: exposure of the Jurassic Musandam Group showing evidence of deformation due to compressional stress.

AI and Petroleum System Risk Assessment

A pragmatic use of machine learning can be applied to assess hydrocarbon charge risks.

MATHIEU DUCROS and FÉLIX GONÇALVES, Kognitus

At this turning point for the oil and gas industry, with escalating competitiveness and a need to optimise productivity, petroleum companies must pick their new exploration projects carefully, making sure the returns have the potential to be as high as possible, while keeping the costs and risks low. Numerical methods such as petroleum system modelling (PSM) or forward stratigraphic modelling have proved that they can play a key role in the assessment and mitigation of exploration risks in both mature and frontier areas (e.g. Chenet et al., 2014; Bryant et al., 2014). Formerly exclusively accessible to major oil and gas companies, these techniques are now part of the exploration workflows commonly used in most E&P teams.

However, in order to keep up with the evolution of geological knowledge through a prospect's life cycle, these powerful simulation methods can be very labour-intensive, which hampers the regular updating of the models with the most recent data and information. Additionally, as the present generation of exploration experts approaches

retirement, companies are facing the problem of retaining expertise while simultaneously reducing costs and increasing effectiveness.
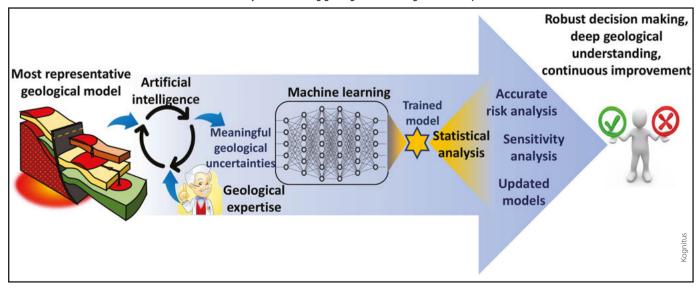
Taking these issues into consideration, a new solution that takes advantage of the investments made in numerical modelling has been developed by Kognitus, a technology company that specialises in the use of analytics and AI to help O&G companies gain insights from subsurface data. This system is based both on knowledge gleaned from experts, which enhances and guides the determination of the uncertainties, and on machine learning (ML) techniques, which provide maps of risks at exploration scale and in timeframes compatible with operational studies. Essentially, the solution takes the explorationist's petroleum systems model as an input from which to infer geologically meaningful uncertainties.
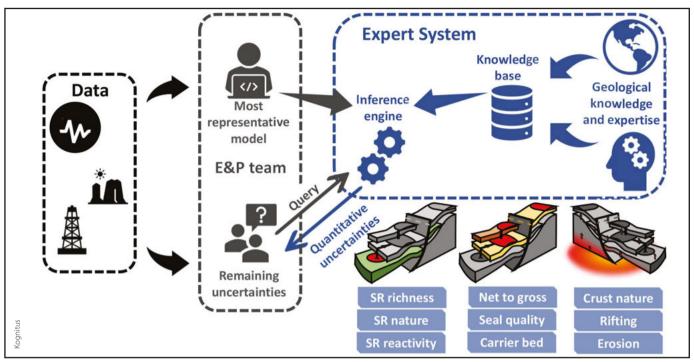
The process starts with the generation of a learning base from the results of physics-based simulations, which will support the training of an ML algorithm. Once the trained

algorithm achieves a good prediction capability, assessed through a set of simulations kept for testing it, the solution develops a set of statistical tools that will automatically or interactively produce risk and sensitivity analyses. This solution is a first step in making basin modelling useful throughout the full life cycle of E&P assets by continuously updating the geological model as new data is acquired.

Geological Expertise Remains Key

Risk assessment workflows in exploration still predominantly rely on subjective and qualitative expert-based evaluations which, in striving for consistency, follow standardised procedures and refer to tabulated values (Milkov, 2015). As geology must remain at the core of the process, this new solution provides a systematic way to estimate quantitative and geologically meaningful uncertainties to be used in PSM, based on its embedded geological expertise. The petroleum system, with all its elements and processes, is the cornerstone of the approach. Expert systems are designed to help the

Global workflow for an accurate and efficient risk analysis embedding geological knowledge and concepts.

Expert systems are embedded in the solution to provide geologically meaningful uncertainties on key elements and aspects of petroleum systems.

explorationist quantify uncertainty on key parameters through the consideration of geological concepts, with all the information integrated in the numerical model (Hacquard, 2018; Ducros et al., 2018).

The approach also offers the first effective tools to include complex uncertainties, such as source rock reactivity, which are usually discarded not due to their low impact on petroleum systems but because we lack the tools or knowledge to account for them. It strengthens the role of PSM as an integration tool by creating a consistent link between information coming from different exploration facets; for example, palaeobathymetry, source-rock thickness and horizon ages – all generic input data for PSM – can be used together to provide quantitative estimates of uncertainty on source rock richness in a consistent first guess.

Robust Risk Assessment

After defining quantitative uncertainties, the Kognitus approach uses the best physics-based simulation and ML techniques to provide quantitative risk analysis in an adapted format for petroleum system assessment (output risks provided on maps, 2D sections, well logs, etc.), in a time frame which remains consistent with

operational projects yet preserves accuracy.

The software relies on an extension of the 'proxy models' approach (also called surface responses), initially used in meteorological modelling, which is well suited to the study of spatial outputs (Gervais et al., 2018). It combines several ML techniques, such as regression and clustering, to learn the main aspects of the petroleum system. After the learning phase has been undertaken using a small (usually less than 100) set of simulations, it is possible to perform an interactive, rigorous and accurate statistical analysis which is required for the quantitative risk assessment and sensitivity analysis (see figure overleaf). This technique leads to a significant reduction in the time required to undertake risk analysis compared to the brute force of techniques such as direct Monte Carlo sampling, or derived Markov Chain Monte Carlo approaches, which require thousands of simulations.
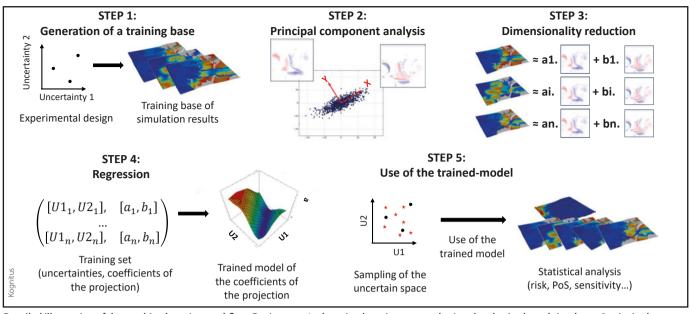
Lastly, these results, when used in a Bayesian framework, can assist in updating the petroleum system model during the whole exploration life cycle. This is set to be a major game changer, as it would speed up the process of re-evaluating risks and resources and help identify satellite fields while acquiring new data.

Applying the Methodology

The results of this new method can be provided in any format used by explorationists. It is therefore possible to get access to maps of risk (P10, P50 and P90) on every simulated property, such as source-rock thermal maturity, overpressure or volume of generated petroleum. Since the method also uses statistical techniques to compute sensitivity analysis, it gives a better understanding of the key controlling factors of the petroleum systems that contribute uncertainty to the risk. It is also possible to use the approach for pore pressure prediction through logs using P10/P90 estimates of pressure at the planned position of a well.

The complete methodology was applied to assess the deep petroleum system of the frontier Levantine Basin in the Eastern Mediterranean (Ducros, 2019). Significant gas discoveries have been made there since 2006 in the Oligo-Miocene section, where there is a proven biogenic system. While Cretaceous source rocks are known to outcrop in Lebanon, their presence in the deep basin is still speculative, so the objective was to study the potential for a deeper thermogenic system and to look at where hydrocarbons could have possibly migrated towards the Oligo-Miocene reservoirs. Uncertainty

STEP 1:
Generation of a training base

Uncertainty 2 / Uncertainty 1

Experimental design

Training base of simulation results

STEP 2:
Principal component analysis

STEP 3:
Dimensionality reduction

$\approx a1. \quad + b1.$
$\approx ai. \quad + bi.$
$\approx an. \quad + bn.$

STEP 4:
Regression

$$\begin{pmatrix} [U1_1, U2_1], & [a_1, b_1] \\ \cdots & \\ [U1_n, U2_n], & [a_n, b_n] \end{pmatrix}$$

Training set (uncertainties, coefficients of the projection)

Trained model of the coefficients of the projection

STEP 5:
Use of the trained-model

U2 / U1

Sampling of the uncertain space

Use of the trained model

Statistical analysis (risk, PoS, sensitivity…)

Detailed illustration of the machine learning workflow. During step 1 a learning base is generated using the physics-based simulator. A principal component analysis (PCA) then provides a set of uncorrelated maps (components of the PCA), with decreasing variance, on which to project the simulation results. A reduction of the dimension is obtained by keeping the first components of the PCA (explaining more than 95% of the variance of the simulations for instance). The machine learning takes place in the 4th step to learn the relationship between uncertain parameters and coefficients of the projection. Once the relationships are determined they can be used to perform rigorous statistical analyses on the results of interest (step 5).

on ten elements was taken into account: three on source rock characteristics (reactivity, depth and petroleum potential); two on the thermal system (nature and thickness of the crust); three on the hydrodynamic system (permeability of the regional Eocene seal, extension of the Oligo-Miocene turbiditic system and time-to-depth conversion); and two on the Messinian Salinity Crisis (timing and duration).

The results showed that there is no doubt on the maturity level of the Cretaceous source rocks in the deep offshore basin and onshore Lebanon,

which were found to be over-mature and immature respectively, but that there is a high risk along the margins (Cyprus, Lebanon and Israel) and in the basin offshore Israel. Sensitivity analysis demonstrated that the nature and reactivity of the source rocks would be the key elements to be studied in order to de-risk this aspect of the Levantine Basin petroleum system.

Potential for Changes and Continuity
The Kognitus system for assessing risk has proved to be both time-effective and robust. It provided highly

valuable results for the exploration of the still poorly known but promising Levantine Basin by giving access to the identification of sweet spots and presenting clues on how to further reduce risks. The approach can therefore be used in early basin exploration to evaluate the source rock maturity, or to assess the whole petroleum system, providing maps of risks compatible with common risk segment mapping methods, or for continuous model update.

This methodology could pave the way to a standardisation of quantitative risk analysis within a portfolio, as it provides a framework in which risks can be reviewed using quantitative and standardised uncertainties. It could also be used to enhance the role of PSM by re-evaluating risks and resources as new data is acquired. Thus, this technique could lead to a major increase in the use of PSM during all phases of basin exploration and production.

New approaches like this showcase the importance of human geological expertise, which remains at the heart of any successful AI approach.

Risk analysis results are computed on different classical formats used by explorationists.

P10 on the overpressure in the Levant Basin

(MPa)

0   8   16   24   25

Empires of Gas in the Eastern Mediterranean

The Eastern Mediterranean is a simmering crucible of gas and geopolitics.

PETER ELLIOTT and JON FORD, NVentures Ltd

The Eastern Mediterranean theatre has become a pressure point for high stakes energy politics between Europe and the Levant, and by proxy Russia and the West. The stage is set, with mega-gas basins and hungry markets. Gas is the hydrocarbon of choice for many policy makers aiming to hit tough carbon targets. The protagonists are warming up: Israel and Egypt are developing recent large gas discoveries; Lebanon is jostling for the drill bit, with Total planning to drill soon; Cyprus is sparring from the centre ground with undeveloped gas at Aphrodite and Calypso; Turkey is impressing a strong independent footprint over the northern area, bringing Libya in as a strategic partner; whilst Greece will play a pivotal role in keeping a lid on, and letting the gas out, of this simmering crucible.
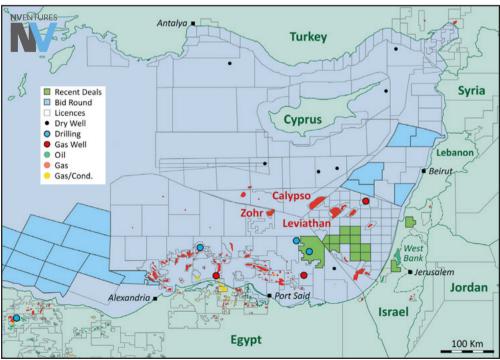
The Scramble for Gas

Licensing and wildcat activity is currently focused on the offshore basins of Egypt, Lebanon and Israel. Total, Eni and Novatek have committed to drill the first offshore well in Lebanon this year in Block 4, with a second licence round underway in the country. Pharos, Cairn, Energean and Ratio took acreage offshore Israel in the 2019 bid round, and Energean, a rapidly growing energy presence, found substantial new gas reserves at Karish North in 2019. Mixed results off Cyprus have deflated the search for the Zohr lookalikes bubble, at least for now, but Egypt has come back to the fore, with Shell, Eni, Energean (as the purchaser of Edison)

and soon ExxonMobil looking to reveal multi-Tcf fields in deepwater Nile Delta acreage.

Meanwhile, Turkey is conducting its own seismic and drilling campaigns including over acreage claimed by both Cyprus and Turkey: three wells are believed to have been drilled to date, results unpublished. Turkey has also allied itself with Libya, which may result in seeing further acreage awarded over contested areas, including some currently being promoted by Greece.

The Race for Exports

This exploration activity may well discover further significant volumes of gas ready to stir up the energy politics of these major and minor littoral countries. Israel has announced its first gas exports to Egypt and Jordan, with Leviathan now onstream. Reversing gas through the Ashkelon-El Arish line (from Israel to Egypt) is the first step to larger gas sales through new pipelines in the future. Energean wish to see gas sales to Greece over time. Israel, Greece and Cyprus are agreed on a new EastMed 1,900-km gas line from Israel to Greece, picking up Cypriot gas along the way. Turkey and the EU are exchanging diplomatic warnings in response to the EastMed pipeline as vested interests surface, with the Turkey-Libya axis challenging the dominance of Israel-Egypt-Cyprus for long-term gas and LNG exports, and Greece likely to be the common gas recipient. Egypt in the meantime plays a fascinating role like a pressure regulator, importing and exporting gas as the country and its gas supply, demand and infrastructure all develop. Egypt went from exporter to importer during the Arab Spring, but now with gas from Zohr and Leviathan, the Idku and Damietta terminals are once again sending LNG cargoes abroad.

The corporate potential winner from this fast moving energy saga is Energean, who in a few years has gone from a small independent with a field in Greece to a regional energy force, in the process of buying Edison, and now positioned to supply gas from three jurisdictions with stakes at either end of the gas value chain – and exposure to political outcomes. ■

Bernard Duval: Vive L'Aventure!

JANE WHALEY

According to Bernard Duval, geologists are the happiest people around because "we have fun!" He tells us about his long and illustrious career in exploration, for which he was awarded the AAPG Distinguished Achievement Award in 1995.

Despite retiring over 20 years ago from French supermajor Total, Bernard Duval is still a significant figure in the exploration business; in fact, in 2019 he was the recipient of the AAPG's Michel T. Halbouty Outstanding Leadership Award, given in recognition of outstanding and exceptional leadership in the petroleum geosciences. But like so many geologists, he found himself following this profession because he wanted to work outdoors.

"I like mountains – they have been good to me," he says. "I was born in Nice, in the south of France, close to the magnificent scenery of the 'arrière-pays Niçois'. I went to an elite military polytechnic school where I studied mathematics and engineering, but after a summer holiday in Morocco working for a small company in the oil industry I realised that a profession in petroleum would give me the chance to live and work outside. I had found geologists to be the happiest people in any company; they always seemed to have fun, so I decided that that was what I wanted to do!"

After a year of national service as a tank officer in the army, Bernard went to Grenoble University to study geology. Because of his engineering experience he did an accelerated programme in geology in a single year, which involved a lot of field work and a dedicated instructor for his small group. "It was intense – but we also managed to spend quite a lot of time skiing and mountaineering while looking at rocks!" he says with a laugh. "This was in the Alps, so I learnt a lot, as not many places have this kind of complicated geology. If you can become familiar with such complex rocks, you can understand anything in petroleum geology. A geologist can never have enough field work."

Gaining Experience

Bernard completed his studies with a master's degree in petroleum geosciences at the École Nationale Supérieure du Pétrole et des Moteurs (IFP) in Paris and on graduating in 1958 he joined Total as a geologist. His first assignment was in Libya, as a field surveyor, wellsite geologist and log analyst; an excellent opportunity to quickly acquire geological and operational experience. He also met his wife, Francine – "my finest discovery" – during his time there.

He spent most of his career with Total, except for a period in the late 1960s, when he was seconded to help the Venezuelan national company CVP create a 'master plan' for the exploration of that country, including a re-evaluation of the remaining hydrocarbon potential. "We spent a terrific three years in Maracaibo, preparing this plan and helping to train young Venezuelan geologists," he says.

After Venezuela, Bernard returned to Total in Paris to join the New Ventures team, with various assignments and postings around the globe, including working on the opening of the Mahakam delta of East Kalimantan and initiating Total's North Sea programme, before becoming E&P vice president of North America, based in Calgary.

"Strangely for a petroleum geologist, I also spent nine years in the mining business," he adds. "I was working in Paris as the assistant to the E&P VP for Total, and I was asked to transfer to a subsidiary company that specialised in looking for uranium. I didn't really know anything about mining and, of course, it involves very different geology – metamorphics, volcanics and the like – but I enjoyed it. This mining experience helped me a lot; it gave me a wider global perspective and an insight

Bernard Duval

into a different work culture, as well as a chance to get to know new people and places, such as Australia, Brazil, Niger and Argentina. I found the experience of managing full-cycle activities in these countries enriching. I would advise anyone reading this to take any opportunity offered and to 'get out of the box'!"

Using Experience

Bernard, who speaks fluent English and Spanish as well as his native French, obviously took his own advice and revelled in the opportunities that he was offered in his career, wherever in the world they were.

"In this profession you need a lot of creativity; you have to learn to interact with a range of people from a variety of backgrounds and different countries", he says. "I have been lucky enough to work in many wonderful places, including some, like Libya and Venezuela, that are no longer so easy to visit. We loved Canada, especially living in Calgary with the Rocky Mountains as a backdrop, so our two daughters, who were quite young then, could ski – although I did find the winters a bit long. And Libya was wonderful; the desert was magnificent and we also spent a lot of time visiting the beautiful Roman ruins.

"However, I think my wife and I left part of our hearts in Venezuela; we loved the country. It was the best time ever, in all senses. Technically I learnt a huge amount; we had access to so much material and documentation on petroleum geology, so that for me it was an academic exercise akin to a doctorate. We were able to spend a lot of time in the field, looking at myriads of rocks. And we were successful! After working on the project for a year we suggested that, instead of searching for stratigraphic traps on the edge of the Barinas Basin, our colleagues should drill in the deepest part of the basin to investigate the oil that we suspected had been trapped before the synclinal basin formed. They were dubious, but did as we advised and the first well in our programme found oil, the Caipe field.

"One of the most important things I learnt from my Venezuelan experience was the value of team work, especially

Bernard at the Cusiana discovery well in Colombia, with the French Ambassador, who was also a childhood friend.

multi-disciplinary teams, and I have tried to bring that to the rest of my career," he adds. "Experience has also taught me that it is important to get to know all the people in your team, especially if you are the boss. It's not just about how you build your team, it's how you understand those people and then how you use them within the team that matters. I always spent a lot of time talking to people in my team individually, to find out what they liked and discovering where they would fit in best. A lot of these decisions are now done on paper or computer, but I think they should be done personally wherever possible."

In 1985 Bernard was asked to return to the main Total E&P organisation as Senior Vice President – Exploration, responsible for the worldwide exploration strategy for the company, a position he

Bernard receiving the 2019 Michel T. Halbouty Outstanding Leadership Award from 2019 AAPG President Denise Cox.

held until his retirement in 1995. During this time he worked on upgrading the upstream portfolio of the company, resulting in some notable successes, such as the Cusiana and Cupiagua fields in Colombia and Peciko in Indonesia.

"An important aspect of this job was that I was responsible not only for the technical parts of the business but also for New Ventures negotiations relative to the acquisition of assets, where with my teams I was able to use my worldwide experience to be creative in the art of making deals," Bernard explains. "For example, when we were looking to acquire acreage in the Bongkot area offshore Thailand we decided that the classic profit-sharing model would not work satisfactorily. Instead, we proposed a deal that included technology transfer and training and offered the eventual transfer of ownership of the asset to the NOC. This proved a successful approach, which we subsequently used elsewhere as well, and which demonstrates that one should not always 'go by the book', but be prepared to be flexible and to build constructive partnerships."

Mentoring and Teaching

"Since my retirement in 1995 I have acted as advisor to various companies – I prefer to say mentoring them rather than consulting – which has allowed me to further enrich my experience. Companies have thanked me for my contributions, but of course such an experience also brings something new for me. It is interesting work, but also challenging, because I have to work alone and to do everything myself and rely on my own resources, without any staff to assist me like in the past; it can be very intense!

"I liked doing this work but the travelling can get very tiring, so I have reduced it a bit in the last few years," he continues. " This means I can spend more time in our 200-year-old house in a village just outside Paris, where I can see the fields all around me but from where we can easily get into Paris for concerts and theatre and the like.

"I have also been involved in training and teaching petroleum-related courses in a number of countries for different organisations," he continues. "I try to instil in my students a sense of adventure by using real life cases of petroleum systems and encouraging them step by step until they can make the 'discovery' themselves. I have realised that I love teaching, especially

Cowboys – a lesson in successful deal making: show your strength but keep smiling all the time!

in my old IFP School, where I still teach topics like petroleum systems, risk analysis, E&P decision-making, asset and portfolio management and upstream economics."

Be an Explorer

What advice would Bernard give to young geoscientists entering the industry now?

"Well, I wouldn't give too much advice of a technical nature – I think that will look after itself as there is plenty of excellent training available. My advice is more on the human aspects.

"I would tell them to gain as much experience as possible, to go out into the world and open their minds. If you want to be an explorer, then like me, you must be an optimist and persevere. You must go to the rocks and do field geology; we don't do enough field work these days – just looking at a computer doesn't tell you what a sand or a carbonate is really like, or what irregularities it may have. A lot of our young people are not trained or mentored enough and can become too reliant on the computer.

"Try to get into operations somewhere, if possible overseas, because you will have to interact with new people and try new things," Bernard adds. "And when you go back home, don't get too stuck in the office, make sure you get out and about; and also get some level of authority, maybe leading a small team, and build on that gradually, learning what command is.

"Continue studying, read a lot, attend technical society meetings and create a good network, but get outdoors too; and most importantly – have fun!" ∎

Bernard (left) boarding a helicopter en route to an oil field platform in the Austral Basin, Patagonia, Argentina.

Mexico:

Maximus Survey: Opportunities in Deepwater Gulf of Mexico

MCG acquired 23,612 km of long-offset high resolution 2D seismic data over the Campeche Basin and the Yucatan Platform within the Gulf of Mexico. Potential field data were acquired jointly with the seismic.

The hydrocarbon potential of the Campeche Basin continues to be the subject of interest to international oil and gas companies. The Maximus survey aims to develop and improve the current understanding of the spatial distribution of salt structures and sedimentary packages from shallow water to deepwater Gulf of Mexico. The data has been reworked to improve the velocity model, based on a better understanding of the expression of the salt in the area and the underlying deeper trends. The data has been migrated with RTM, Gaussian Beam as well as KPSDM, as each algorithm has unique qualities.

The seismic line shown in Figure 1 is located in the middle of the Bay of Campeche, running from the Yucatan Platform towards Cordilleras Mexicanas. The main trapping mechanisms shown in this line are salt-related fold belts (Figure 2), and flank structures to the salt domes (Figure 5).

Figure 1: Regional Gaussian Beam PSDM seismic. Line from the Yucatan Platform towards deepwater Gulf of Mexico.
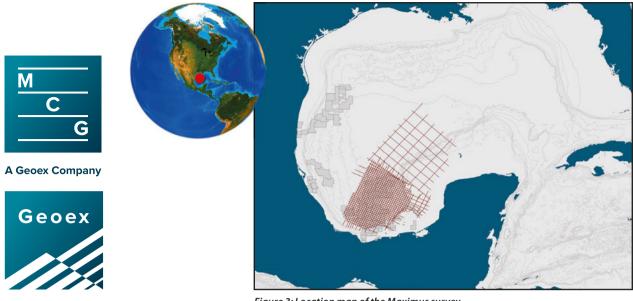
MCG
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Geoex

Figure 3: Location map of the Maximus survey.

Figure 2: Improved imaging of the fold belt complex due to Gaussian beam migration.

The Importance of Depth Imaging

Depth modelling using several algorithms has significantly improved salt imaging in the deepwater Bay of Campeche.

JEROEN HOOGEVEEN and JENIFFER MASY; MultiClient Geophysical AS (MCG)

The Bay of Campeche lies along the western border of the Yucatan Peninsula. The shelf contains a system of horst and grabens that are affected by salt intrusions, creating very complex structures, which involve severe folding, faulting and fracturing due to salt movement, mobilised by sediment loading. Mobilisation of the salt was initiated around the Late Cretaceous, possibly by a combination of the sediment overburden and Laramide-style compressive stresses from the south-west. Salt uplift continued during Palaeocene, Eocene and Oligocene depositional sequences in the coastal plain and persisted until the Miocene. Within the Bay of Campeche many structures are influenced by thick allochthonous middle Jurassic salts, while in the Yucatan Peninsula, salt bodies are thinner and considered to be more autochthonous. Primary exploration targets within the Bay of Campeche include conventional pre- and post-salt depositional structural and stratigraphic traps, both in the shelf margin and in deep waters.

Since 2013, when Mexico changed its policy allowing foreign exploration companies to invest and explore for oil and gas onshore and offshore Mexico, there has been an increased interest in the hydrocarbon potential of the southern Gulf of Mexico. MultiClient Geophysical (MCG) acquired the Maximus survey in 2015–16 over the Bay of Campeche and the Yucatan Platform. The Maximus survey is a high-resolution 2D seismic survey with very long offsets (12 km) and deep recording (14 seconds) with the objective of providing a clear image of all the play elements of the petroleum systems offshore Mexico. The processing sequence used state-of-the-art broadband solutions. High quality pre-stack time, pre-stack depth, gravity and magnetic data are available, and this survey is in a position to support future licence bid rounds offshore Mexico.

Velocity Model

Imaging complex structures, such as fold belts and salt-related structures, is challenging. These challenges were addressed though new pre-stack depth migration sequences. However, the success of seismic imaging methods not only depends on data quality, but also on accuracy of the background velocity model. When lateral velocity variations are significant, the generation of an accurate velocity model using a standard velocity analysis is difficult. For this project, a thorough interpretation of salt bodies and a local velocity model was created in order to support high quality imaging techniques.

The original processing was done by iterations of sediment model-building, picking top salt, flooding with salt velocities, picking bottom salt and revising the salt picks where needed. These 2D velocities were used to build a pseudo 3D velocity model which avoided depth-velocity mis-ties at line intersections. The initial model was generated using time RMS velocity models, followed by at least three iterations of sediment velocity tomography and inclusion of salt geometries for each line, which were then incorporated into the final 3D model. The resulting imaging from Kirchhoff Pre-Stack Depth Migration (KPSDM) was of good quality, especially in the sediment package. However, it did leave some room for improvement in more complex areas, where a refined salt interpretation may lead to enhanced imaging, especially with more advanced migration algorithms. In such complex areas, more work needs to be done to help define the salt geometries.
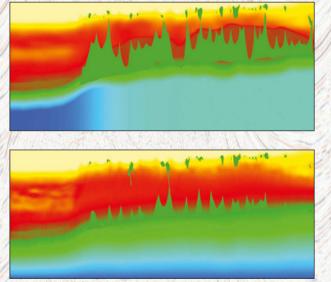

Figure 4: (top) Original velocity model; (bottom) new velocity model.

The process of enhancing the product was aided significantly by involving interpreters with extensive local experience. Changes to the shallow salt involved re-picking the base of many of the salt geometries and removing significant salt stalks. The deeper salt was modified to remove significant volumes of salt, which relied on the interpreters' experience and knowledge of the expression of the salt and its movements in the local geological setting. The salt modelling followed standard methods of picking a top salt on a Kirchhoff stack image, but several migration algorithms were used to test base salt scenarios after 'salt-flooding' the model.
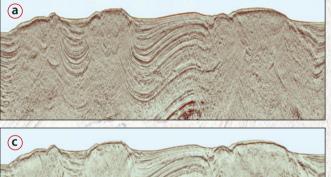
During this and further model building KPSDM was the main tool for assessing the sediment modelling. Gaussian Beam Migration (GBM) was effective in areas with complex ray-paths such as those found near salt flanks and areas with overhanging salt and salt feeders or stalks. Lastly, Reverse Time Migration (RTM) was used, mainly to evaluate the model below the allochthonous salt and for the modelling of the autochthonous salt. The interpreters used all migrations to adjust the salt interpretation. The process was iterated at least five times until no further improvement was seen. Some regional complexity was added to the model, including a new transition from the base of the autochthonous salt to the base of the model (Figure 4).

Care was taken to adjust for some unreasonably high velocities at or near tips of salt structures that were suggested by the tomography.

The final, individual 2D velocity models of the selected lines are structurally consistent and highly resolved, tying at the intersections and producing better pre-stack migrated images.

Enhanced Imaging

The final images were built from each of the three different algorithms, KPSDM, GBM and RTM. Careful consideration and testing of key parameters for each migration was undertaken. At this phase of the project there were no surprises in parameterising each of these migrations, as they had all been used and the parameters optimised along the way. Key parameters such as aperture, aperture taper and anti-alias filters had been tested and optimised. For each of the migrations the maximum aperture was set to 12,000m radius.

GBM has the advantage of being better at imaging steep dips such as seen at salt flanks and salt stalks (Figure 5). The 45 Hz mid-frequency RTM final product gave the best pre-salt images (Figure 6).

All these modifications to the original models and inclusion of additional migration algorithms resulted in significant improvements in the sediment and deeper pre-salt imaging within the Bay of Campeche and Yucatan Peninsula. With this improved new dataset, exploration companies will be able to generate new exploration prospects in preparation for future bid rounds. ∎

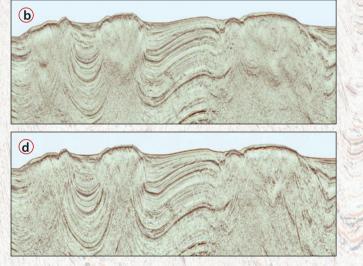*Figure 5. Image of salt flanks. (a) Original KPSDM; (b) New KPSDM; (c) New GBM; (d) New RTM Mid Frequency.*

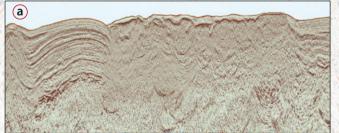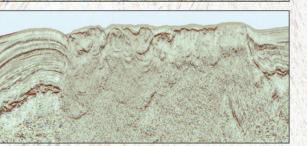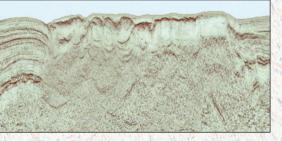*Figure 6: Image of pre-salt section. (a) Original KPSDM; (b) New KPSDM; (c) New GBM; (d) New RTM Mid Frequency.*

From Arrhenius to CO$_2$ Storage

Part VI: More on the Simple Greenhouse Model

"Order and simplification are the first steps toward the mastery of a subject."

Thomas Mann (1875–1955), 1929 Nobel Prize in Literature laureate

We continue the discussion of the simple greenhouse model introduced in Part III (*GEO ExPro* Vol. 16, No. 4).
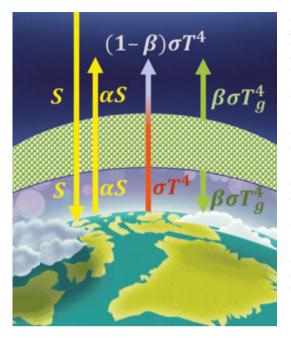
LASSE AMUNDSEN and MARTIN LANDRØ, NTNU/Bivrost Geo

The model discussed in Part III, which is widely used to explain the greenhouse effect in a conceptual way, succeeds in its main purpose: to demonstrate that an atmosphere which absorbs and re-emits some of the radiation from the Earth's surface results in a surface that is warmer than if there were no atmosphere. The Earth's surface temperature was determined as a function of the atmosphere's absorptivity of the terrestrial longwave infrared (IR) radiation by energy balancing the incoming and outgoing shortwave and longwave radiation. Here, using the same model, we derive the temperature of the atmosphere from Kirchhoff's law of thermal radiation.

The energy emitted from the Earth and its atmosphere is commonly referred to as thermal infrared radiation or terrestrial radiation. Trapping of this radiation by atmospheric gases is called the atmospheric effect – commonly known as the greenhouse effect because it is similar to the way the glass that covers a greenhouse transmits shortwave solar radiation and absorbs longwave thermal infrared radiation.

In Part III we introduced an educational model of the greenhouse effect, a short summary of which is: the Earth's system is driven and maintained by the radiation exchange between the system and space. The Earth absorbs shortwave solar radiation energy – in the form of visible light and ultraviolet radiation – after reflecting about a third of the incident solar radiation back to space. The shortwave radiation is converted to heat at the Earth's surface, and then re-radiated as terrestrial (i.e. longwave or infrared) radiation

Image of sunset on the Indian Ocean taken by astronauts aboard the International Space Station. Above the darkened surface of the Earth, the sequence of colours roughly denotes several layers of the atmosphere. Deep oranges and yellows appear in the troposphere, which extends from the Earth's surface to a height of 6 km at the poles and up to 20 km at the equator. Several dark cloud layers are visible at this level. Variations in the colours are due mainly to fluctuating concentrations of either clouds or aerosols (airborne particles or droplets). The pink to white region above the clouds is the stratosphere, which extends up to approximately 50 km above the Earth's surface. Above the stratosphere, blue layers mark the upper atmosphere (including the mesosphere, thermosphere, ionosphere and exosphere) as it gradually fades into the blackness of outer space. The troposphere contains over 80% of the mass of the atmosphere and almost all of the water vapour, clouds, and precipitation. Its global average temperature range decreases from 289K (16°C) on the surface to 222K (-51°C) at the top of the troposphere. Nitrogen forms 78% of the troposphere's chemical composition, oxygen 21%, argon 0.9%, water vapour 0.3–4% and carbon dioxide 0.04%. Weather, as we see it on Earth, happens in the troposphere. The stratosphere holds 85–90% of atmospheric ozone created by the photolysis – the decomposition by solar radiation – of oxygen. Ozone absorbs ultraviolet light from solar radiation and causes temperature to increase rather than decrease with height, from about 222K (-51°C) at the bottom to 258K (-15°C) at the top. (Image is provided by the ISS Crew Earth Observations experiment and Image Science & Analysis Laboratory, Johnson Space Center.)

Popular educational model of the greenhouse effect: a global mean one-layer atmosphere above the surface of the Earth. The atmosphere absorbs β of the Earth's IR radiation. The atmosphere heats and re-radiates energy to space and back to the surface. Kirchhoff's law from 1860 states that the emissivity of the atmosphere is equal to its absorptivity; if this equality were not true, there would be a violation of the laws of thermodynamics. The Earth is in energetic equilibrium between the radiation it receives from the Sun and the radiation it emits to outer space. From this equilibrium we can calculate the Earth's surface temperature and the atmospheric temperature. For diagrammatic clarity, a gap has been introduced between the atmosphere and the ground.

back to space. However, some of the terrestrial radiation is trapped by greenhouse gases and re-radiated to the Earth, resulting in the warming of its surface – known as the greenhouse effect. Under a steady state, the absorbed shortwave radiation energy is balanced with the emitted longwave radiation energy.

A greenhouse gas is any gas that has the property of absorbing infrared radiation (in the wavelength range 4–50 micrometres) emitted from the Earth's surface and re-radiating it back to the surface. The important greenhouse gases are those present at concentrations sufficiently high to absorb a significant fraction of the Earth's IR radiation. They include H_2O, CO_2, CH_4, N_2O, O_3 and chlorofluorocarbons (CFCs). By far the most important greenhouse gas is water vapour because of its abundance and its extensive IR absorption capacity. Although greenhouse gases make up only a fraction of all atmospheric gases they have a profound effect on the energy budget of the Earth's system.

Energetic Equilibrium

In Part III, we viewed the atmosphere as an isothermal layer (see figure above). The layer is transparent to shortwave solar radiation and absorbs a fraction β of the terrestrial IR radiation. The temperature of the Earth's surface is T and the temperature of the atmospheric

layer is T_g. We obtained the surface temperature:

$$T = \left(\frac{2}{2-\beta}\right)^{1/4} T_0 \; ; \; T_0 = \left(\frac{S(1-a)}{\sigma}\right)^{1/4} \quad (1)$$

where S = 1,365 W/m² is the average annual solar radiation arriving at the top of the Earth's atmosphere, $\sigma = 5.67 \cdot 10^{-8}$ Wm⁻²K⁻⁴ is Stefan-Boltzmann's constant, and a = 0.3 is Earth's average albedo. The clouds, aerosols, snow and ice reflect a lot of solar radiation; even water reflects a small percentage. On average, about 30% of the solar radiation is reflected to outer space.

T_0 = 255K (-18°C) is the frigid temperature of a non-absorptive atmosphere, as was the case in the early history of the Earth, 4 billion years ago. In fact, it was even lower during the solar evolution, when solar radiation was only around 1,000 W/m²; the temperature at the time was 236K (-37°C).

To reproduce today's observed global mean surface temperature of 16°C, the atmospheric layer must absorb 80% of terrestrial radiation (β = 0.8); then $T(\beta = 0.8)$ = 289K (16°C). β = 0.8 implies that 20% of the terrestrial radiation escapes directly to outer space.

As a result of the greenhouse process, the Earth's surface is 34°C warmer than it would be without it; for this we must be grateful. However, increasing concentrations of greenhouse gases

increases the absorption efficiency β of the atmosphere. Equation (1) reveals that an increase in β results in an increase in the surface temperature T.

Equation (1) follows from the radiative balance of the Earth. The Earth must be in energetic equilibrium between the radiation it receives from the Sun and the radiation it emits out to space. If Earth were not in radiative balance, the climate on the planet would not be stable. The simple model in the figure succeeds in its main purpose: to demonstrate how an atmosphere that absorbs and re-emits some of the radiation from the Earth's surface results in a surface that is warmer than if there were no atmosphere.

In Part I of this series, we introduced the concept of the blackbody – a perfect absorber of energy – and stated that this idea is useful in the study of radiation phenomena. In this respect it is worth observing that the Earth is not a blackbody at visible wavelengths since the absorption efficiency of solar radiation by the Earth is only $1 - a$ = 0.7. However, Earth radiates almost exclusively in the infrared, where the Earth's absorption efficiency is in fact near unity. For example, clouds and snow reflect visible radiation but absorb IR radiation. Therefore, in the infrared range the Earth can be considered a blackbody – a result of Kirchhoff's law of thermal radiation – and we approximated the emission heat flux from the Earth as that of a blackbody of temperature T.

A Correction

Order is a first step towards the mastery of a subject. In Part III, the energy balance equations (4)–(5) had a misprint, where the factor ½ should be replaced by the factor β. The same misprint appeared in the figure describing the simple model of the greenhouse effect, so that figure is redrawn above in its correct form. These misprints did not influence the surface temperature equation (1).

In this article we go on to derive the atmospheric temperature directly by invoking Kirchhoff's law of thermal radiation. In 1860, Gustav Robert Kirchhoff (1824–1887) stated that "at thermal equilibrium, the power radiated

by an object must be equal to the power absorbed." This leads to the observation that if an object absorbs 100% of the radiation incident upon it, it must re-radiate 100%. Kirchhoff termed a body that absorbed all incident heat radiation a blackbody. Thus, the Earth is a blackbody in the IR. For the atmosphere, the absorptivity is β since 1- β of the terrestrial radiation, called transmittance, goes to outer space. Following Kirchhoff's law, as absorptivity is β then the emissivity of the atmosphere must also be β. The atmosphere is often termed a 'greybody' since part of the incident terrestrial radiation is being transmitted through the body. When articles describe the atmosphere as 'grey', it means that its absorptivity, and equivalently its emissivity, are constant as a function of radiation frequency.

Temperature of the Atmospheric Layer

Stefan-Boltzmann's law (1879, 1884), discussed in Part II (*GEO ExPro* Vol. 16, No. 3), states that the total radiant heat power emitted from a surface is $B = \sigma T^4$ where T is the surface temperature of the body. This total emissive power is the sum of the radiation emitted over all wavelengths. The law applies only to blackbodies, perfect absorbers with unit absorptivity. From Kirchhoff's law, a blackbody in thermal equilibrium also has unit emissivity.

Assume that the atmospheric layer of temperature T_g is a greybody with emissivity equal to absorptivity equal to β. Since the layer obviously has both upward- and downward-facing surfaces, each emitting a radiation flux $\beta \sigma T_g^4$, its total radiant heat power is $E_{out} = 2 \beta \sigma T_g^4$. The energy balance principle applied to the atmosphere – energy in ($E_{in} = \beta \sigma T^4$) equals energy out – yields the ratio of the two temperatures,
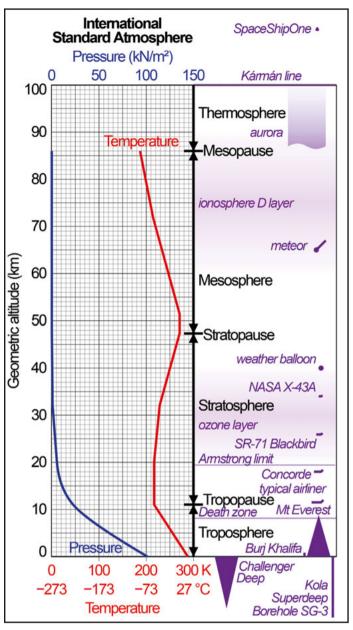
$$T_g = \left(\frac{1}{2}\right)^{1/4} T(\beta) = \left(\frac{1}{2-\beta}\right)^{1/4} T_0 \qquad (2)$$

This equation tells us that the atmosphere is always cooler than the ground. Specifically, $T_g(\beta = 0.8) = 243K (-30°C)$, which is roughly the observed temperature at the height 9 km of the atmosphere (see figure right).

This simple greenhouse model assumes a constant atmospheric temperature. In a later part of this series, we will extend the model by viewing the atmosphere as vertically layered. The energy balance equation can then be applied to the elemental slabs of atmosphere and expressions for the temperature of each layer can be derived analytically. The result is a decrease of temperature with altitude. When the number of layers gets large, the absorption β in each layer becomes small. Equation (2) is valid for the last layer; the temperature at the top of atmosphere (TOA) will approach:

$$T_g^{TOA} = \left(\frac{1}{2}\right)^{1/4} T_0 = 214K = -59°C$$

a temperature which is fairly consistent with typical tropopause observations. This modelled temperature is the coldest
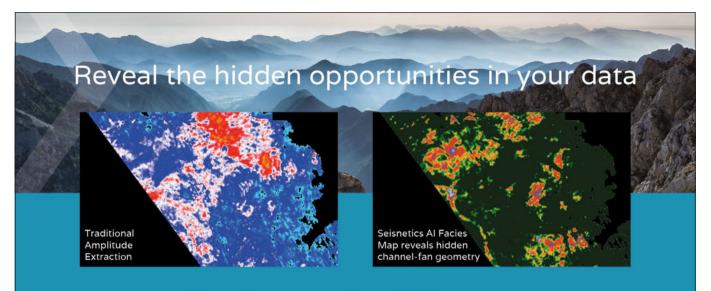

Comparison of an International Standard Atmosphere graph of geometric altitude against temperature and pressure with approximate altitudes of various objects. The Kármán line at altitude 100 km represents the border between the Earth's atmosphere and outer space.

temperature achievable in the atmosphere in the absence of absorption of solar radiation by gas molecules. The figure above shows that by the time you reach the top of the troposphere the temperature has fallen to a chilly 216K (-57°C).

The temperature of the first layer of a layered atmosphere is

$$T_g^{layer\,1} \approx \left[1 - \frac{1}{2}\left(\frac{T_0}{T}\right)^4\right]^{\frac{1}{4}} T = 264K = -9°C$$

In the real atmosphere, there is no discontinuity in the temperature between the ground and the lowest part of the atmosphere; heat will be transferred by convection. ■

Comprehending Climate Complexities

The Global and European Calculators are tools that can be used for both exploring the future of our climate and working out what can be done about it.

JEREMY WOODS and VICTORIA HOARE, Centre for Environmental Policy, Imperial College London

The Global Calculator is an open access, publicly available decision support tool that was developed to assist decision makers, particularly the national negotiators, in the lead-up to the Paris Climate Conference that was held in December 2015. The Global Calculator was based on an existing UK 2050 Climate Calculator. This calculator, developed by the UK government (DECC, Department for Energy and Climate Change) was designed to provide policy makers with the chance to explore the full range of pathways available for the UK to transition to a low carbon economy; pathways that were compatible with achieving EU and global temperature targets for 2100.

A unique aspect of the Calculators is that they are not designed to provide optimised outcomes; instead, they put the user in control of exploring a broad range of options, varying from minimal adjustment through to extremely ambitious climate change mitigation. The user directly and immediately sees the impacts of choices made when selecting specific technological and behavioural options that span across lifestyles, technology and fuels, land and food choices and population sectors.

Key Principles for Development

The calculators are targeted at decision support and enabling the building of transition pathways to 2050. They must, therefore, encompass a very broad range of technological and behavioural innovation options. In addition, immediacy of response is also important if the Calculators are to be relevant to policy makers, particularly when entering negotiations. The user must also trust that the impacts calculated from the choices made are a robust representation of the real-world outcomes projected into the future.

In order to achieve this level of robustness and trust the development of the Calculators is guided by three primary principles. These are **Openness**: the calculators are built on an Excel-based tool which is fully published and available free online; **Collaboration**: they have been designed by a global team using input from hundreds of experts; and **Simplicity**, with the aim of modelling the world in the simplest form possible, whilst including all energy sources and uses, emissions and a full range of future scenarios. A fourth principle of **co-design** has also been adopted to ensure

The Global Calculator summary interface. The lower half shows the selectable options such as lifestyle, technology, fuel, foods and demographics while the panel above shows the impacts of the selected scenario on energy supply and demand (top left); greenhouse gas emissions per year (centre) and cumulative CO$_2$ emissions and global mean temperature ranges (top right).
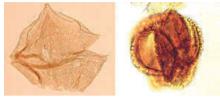
that the Calculators remain relevant to the users and meet their needs.

Forty 'levers' enable the user to vary the way we might live in the future, including the amount and types of energy we might use, how we travel and even our diet, including calories consumed, and quantity and type of meat. Each lever can be set to one of four levels of ambition for climate mitigation which relate to the full range of what is possible to achieve for that specific sector, technology and/or behaviour.

The user is also able to select a pre-defined pathway from a list of example pathways, including scenarios such as 'distributed effort', 'consumer reluctance' and 'low action on forests'.

Exploring the Global Calculator

The main goal of the Global Calculator was to answer the question: is it physically possible to meet our climate targets and ensure everyone has good living standards by 2050? The calculator demonstrates that there are very many different pathways available that allow us to achieve no more than a 2°C rise in global mean temperatures by 2100, and the team have published four plausible exemplar pathways which would ensure good lifestyles as well as explore the main uncertainties surrounding technology, fuels and land use. The key points these pathways show are:

1. It is possible for 10 billion people (the estimated global population by 2050) to eat well, travel more and live comfortably whilst reducing emissions by 50%.
2. To do this, technology and the fuels we use need to be transformed. CO_2 emitted per unit of electricity

The user of the Global Calculator can adjust predicted outcomes by selecting the level of change applied for various behavioural and technical factors.

http://tool.globalcalculator.org

globally needs to fall by at least 90% by 2050, while electric or zero-carbon sources for heating homes needs to increase from 5 to 25–50%.

3. Land resources; we need to be smarter about land use. Specifically, forest protection and expansion globally needs to increase by 5–15% due to the ecosystem service of being a carbon sink.
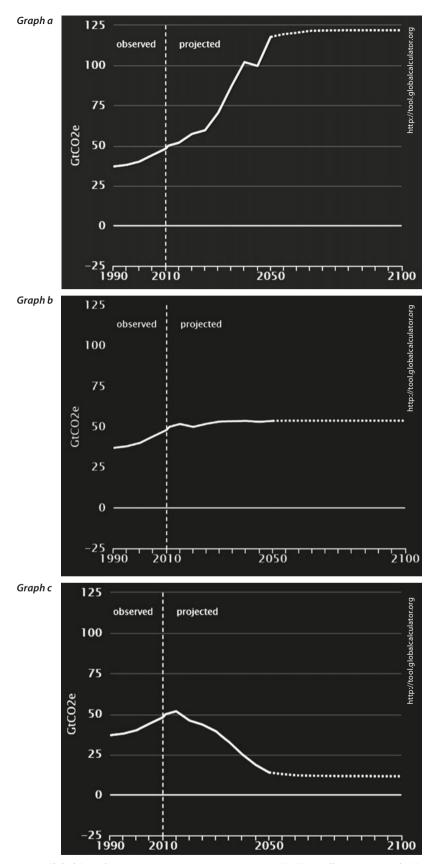
Perhaps the most controversial and important novel outcome from the Global Calculator is that we can no longer focus exclusively on emissions reduction in the energy sector. Without achieving a significant expansion of carbon sinks on the land and reductions in emissions from the food sector, and in spite of any significant reductions we might see in energy sector emissions, the Calculator found that meeting even the 2°C, never mind the 1.5°C target, will not be possible. To demonstrate this, the sensitivity of global climate mitigation pathways to the food production and dietary levers is shown in the graphs to the right.

An Invaluable Open Source Tool

With no silver-bullet solution to the climate crisis, the Global Calculator has been a predecessor for more regionally specific 2050 calculators, including the EU 2050 calculator (EUCalc). The EUCalc is an interdisciplinary, collaborative model of intermediate complexity. Unlike the Global Calculator, which represents a closed system, the EUCalc considers transboundary relationships within the EU and Switzerland and between the EU and the rest of the world.

Tools such as the Global Calculator and the EUCalc project provide policy makers, decision makers and students with *in silico* models to assess the impacts, trade-offs and applications of the potential choices available in real-time. In a climate where it is becoming even more urgent to make the right decisions now and to act on them as quickly as possible, having an open source tool which makes comprehending the complexities of the climate crisis a little bit easier is invaluable.

You can experiment with the Global Calculator yourself by going to www.2050calculator.net ■

Graph a

Graph b

Graph c

Global Greenhouse gas emissions trajectory per year (GtCO2e), all using an initial 4°C global emissions pathway (IEA 4DS) (a) with dietary levers set to 'level 1' – i.e. minimal mitigation ambition, equivalent to a global average diet in 2050 that is equivalent to the current European average diet; (b) with dietary levers set to 'level 2', in which the global average calorie consumption increases to a level similar to projections by the UN's Food and Agricultural Organisation (Alexandratos and Bruinsma, 2012, adjusted to exclude food losses) of 2,330 kcal per person per day; and (c) with dietary levers set to 'level 4' – an extreme mitigation ambition, equivalent to a global average diet similar to the current Indian diet.

Oman's Musandam Peninsula:
Geodynamic and Geopolitical Nexus

Admire soaring, fjord-like walls of Mesozoic limestone as you glide through the Strait of Hormuz by dhow, the type of traditional wooden ships that today share this strategic waterway with supertankers and flotillas of Iranian smugglers' speedboats.

LON ABBOTT and TERRI COOK

On a visit to Dubai, United Arab Emirates (UAE) we, like the city's tens of thousands of other daily tourists, were wowed by the towering skyscrapers, glittering shopping malls, and dancing, choreographed fountain and light shows. But we soon yearned to experience the wilder side of Arabia. Fortunately, this exists a mere 2.5-hour drive north-east, on Oman's Musandam Peninsula.

This isolated finger of land, which is little more than 20 km wide at its southern base, separates the Gulf of Oman to the east from the Persian (or Arabian) Gulf to the west. Every day 22.5 MMbo – 24% of the world's global daily production, according to Vortexa energy analytics – pass through the adjacent Strait of Hormuz, the narrow waterway between these gulfs, making it one of the most strategic spots on Earth. In addition to being a geopolitical nexus, the Musandam marks the boundary between the modern Makran subduction zone on the east and the Zagros continental collision zone to the west, making it a geodynamic nexus that has received considerable attention from tectonicists.

From Dubai Glitz to Wild Arabia
As we barrelled north-east along a motorway from Dubai paralleling the UAE's flat coast, the first hint of wilderness came after we passed through the city of Ras Al Khaimah, capital of the north-easternmost of the seven emirates that comprise the UAE. The city's suburbs sprawl eastward to the foot of the Musandam mountains, which rise 1,600m above the coastal plain.

The Musandam mountains are the northernmost extension of the Hajar range, which hugs the Arabian

The walls of Khor Ash Sham, which rise 800m directly from the water, consist of Triassic Elphinstone Group overlain by more resistant Musandam Group limestone.

The Musandam Peninsula, the northernmost point of Oman, separates the Indian Ocean from the Arabian Gulf.

Peninsula's south-eastern coast from the Musandam to south of Muscat, Oman's capital. The Hajar was raised by thrust faulting that began in the Oligocene and ended by the middle Miocene; the Hagab Thrust, which lies at the foot of the Musandam range, has accommodated about 15 km of east–west shortening, making it the master fault in this region.

We crossed the Hagab Thrust at the UAE–Oman border. Rugged, desert mountains rose directly from the water as we wound our way around one inlet after another on the remainder of the scenic drive to Khasab, the Musandam's main town. Khasab lies just 20 km south of the Strait of Hormuz.

Cruising Through the Norway of Arabia

The Musandam's tourist tagline touts it as 'the Norway of Arabia'. The validity of that comparison becomes evident on a day-long dhow cruise through Khor Ash Sham, the largest of the many 'fjords' that grace the region. Because no glaciers have covered the Arabian Peninsula since the Permian, these aren't actually glacial valleys. Rather, they are rias, drowned river valleys that strongly resemble fjords. The Musandam's rias, which are among the most impressive on Earth, have formed because the Arabian continental lithosphere is being flexed down to the north, causing subsidence at a rate of

about 6 mm/yr as the Eurasian plate overrides the Arabian plate.

The north-eastern Arabian Peninsula became a rifted margin in the Permian during the opening of the Neotethys Ocean. The area remained a stable continental platform from the Permian through the Early Cretaceous, accumulating a 4 km-thick section dominated by platform carbonates that host some of the world's biggest oil fields. The platform's tectonic serenity was disrupted during the Late Cretaceous, when the famous Samail Ophiolite and the associated deep-marine sedimentary rocks of the Hawasina Complex were thrust south-westward over the Arabian passive margin. Vast expanses of the Hajar mountains consist exclusively of that ophiolite, the world's biggest and best-preserved such exposure, although it crops out only at the extreme southern reaches of the Musandam, in what is

known as the Dibba Zone. The rest of the peninsula displays spectacular exposures of the most continuous section of Mesozoic sedimentary rocks on the Arabian Peninsula, making the Musandam a playground for field geologists seeking close examination of the reservoir rocks that host the region's giant oil fields.

We got to examine this sequence on a dhow cruise of the 16 km-long Khor Ash Sham, the longest of Musandam's rias. Cretaceous platform carbonates belonging to the Thamama and Wasia Groups comprise the mountains encircling Khasab and surround the mouth of Khor Ash Sham, which lies just a few kilometres to the north-east. As our dhow chugged deeper into this 'fjord', the peaks rose higher and higher, the tallest soaring 800m above the water. Several major east-dipping thrust faults cut the tightly folded sedimentary layers, so the farther east we ventured into the ria, the older the rocks became.

These faults all piggyback atop the Hagab Thrust; together, their Oligocene through Early Miocene motion built the Musandam mountains.

First we passed from the Cretaceous carbonates to an overlying thrust sheet composed of the 1,500m-thick Jurassic Musandam Group carbonates. The ria widens to about 3.5 km where it crosses onto the next, structurally higher, thrust sheet. That widening is likely due to the exposure at sea level of more easily eroded orange, ferruginous sandstones interbedded with oolitic limestones that belong to the Upper Triassic Ghalilah Formation of the Elphinstone Group (Khor Ash Sham used to be called Elphinstone Inlet). Cliffs of Musandam Group limestone tower above the less-resistant Elphinstone rocks.

Dolphins played in the dhow's bow wave as we headed to Telegraph Island, the most famous of several small islands located in this comparatively wide portion of Khor Ash Sham. We anchored just offshore for the first of two sessions of snorkelling and swimming in the clear water. Telegraph Island was the site of a repeater station, the ruins of which remain visible, on the London-to-Karachi telegraph line built by the British in 1864.

The line was abandoned less than 10 years later, but while it operated Telegraph Island was infamous as a hardship post. The summer heat is fierce and, although the British maintained extremely close relations with the Sultanate of Oman, some of the local tribes were sufficiently hostile that a gunboat had to be available at all times. The Oxford English Dictionary asserts that the idiom 'go round the bend' is an old naval term for someone who goes mad. Some claim it derives from the long procession of British naval officers who were slowly driven mad by the hardships and isolation of Telegraph Island and were recalled to India, rounding the bend in the Strait of Hormuz as they left.

The Strait of Hormuz

Being so close to the Strait of Hormuz, there was no way we could pass up a chance to explore it. Although such trips are not on the standard tourist itinerary, we had no trouble hiring a dhow to make the full-day journey around the Musandam's northern tip from Khasab to the village of Kumzar, Oman's northernmost settlement. Throughout the voyage we were treated to spectacular scenery, with the craggy coastline and rugged mountains all comprised of Jurassic and Cretaceous shelf limestones. As we neared the Strait, we glimpsed several supertankers and cargo ships through the marine haze.

We then passed west of Jazirat Al Ghanem Island, home to an Omani naval base perfectly positioned to monitor the strait's voluminous ship traffic. As we neared the island, we suddenly heard a cacophonous, high-pitched whine that turned out to be the vanguard of a flotilla of dozens of speedboats outfitted with multiple, oversized motors racing in formation southward toward Khasab. We reached for our cameras to record this unusual site, but the speedboats were so fast they were mere specks in the distance by the time we had our lenses trained on them. Our dhow pilot smiled and told us they were Iranian smugglers, who regularly come to Khasab to buy cigarettes and alcohol before returning to Iran at night. His prophecy was correct: that evening, as we sailed back to Khasab, the flotilla, whose pilots all stood at the tiller carefully surveying the scene around them, raced passed us again. What an unusual, exhilarating, and dangerous career that must be!

A Glimpse of Old Oman

As our dhow rounded the northernmost tip of the Musandam Peninsula we eagerly scanned the horizon for our first glimpse of Iran, expecting to spy Qishn Island, the southernmost anticline in the Zagros fold and thrust belt and the closest Iranian land, 56 km north-west of Kumzar. But the island never emerged from the marine

Folded Elphinstone Group rocks, with Musandam Group Limestones forming the mountains behind.

Lon Abbot and Terri Cook

PETROSEN/SENEGAL 2020 LICENSING ROUND

The 2020 Senegal Licensing Round will be an open competitive tender with applications evaluated on the basis of standard criteria. The Licensing Round is the first international competitive bidding round arranged by the Ministry of Petroleum and Energy in Senegal.

The 2020 Licensing Round officially commenced on Friday 31st January 2020 and will remain open for a period of six months. Applications are to be submitted to the Ministry of Petroleum and Energy no later than 17:00 (GMT) on Friday 31st July 2020.

Twelve (12) blocks will be available for licensing in the MSGBC Basin.

www.senegallicensinground2020.com

For more information on the Licensing Round and the opportunities available, please contact Joseph Medou jmedou@petrosen.sn or Bintou Wone Aidara bwone@petrosen.sn

République du Sénégal
Un Peuple – Un But – Une Foi

MINISTÈRE DU PÉTROLE
ET DES ENERGIES

PETROSEN
SOCIÉTÉ DES PÉTROLES
DU SÉNÉGAL

The authors stroll through isolated Kumzar.

haze. Instead, we looked south-east, across the Gulf of Oman, to glimpse mainland Iran. There, a mountain range with peaks up to 1,900m has been built by transpression along the north-west-trending Zendan fault, the structure that transfers plate boundary slip from the northward subduction of Arabian oceanic lithosphere beneath the Makran region of eastern Iran to the Zagros continent–continent collision zone. The imbrication of underthrust Arabian continental lithosphere has raised the Zagros Mountains, complete

Sunset in Khor Ash Sham, the longest 'fjord' in the Musandam peninsula.

with their famous salt diapirs sourced from Neoproterozoic Hormuz salt deposits, which are so voluminous that they produce salt glaciers.

When we reached Kumzar, we got a glimpse of how dramatic Oman's recent modernisation has been. Khasab, with its modern port facilities and plenty of new buildings, embodies this modernisation. Kumzar, by contrast, was a glimpse of the old Oman, with goats roaming its rough gravel streets and threadbare couches perched on makeshift balconies from which residents survey the scene during warm Musandam evenings.

Sultan Qaboos bin Said al Said ruled Oman from 1970, when he staged a coup d'état against his father, until his recent death on 10 January 2020. When he ascended to the throne, Oman was poor and isolated, but he used the country's growing oil revenues to fund an ambitious modernisation programme that has resulted, among other things, in gleaming buildings,

airports, and a road network ranked among the world's best. The pace of change is so rapid it is reaching even this most remote Omani outpost; we found crews hard at work building a road that climbs up and over the rugged Musandam mountains to link the very different worlds of Khasab and Kumzar.

Birth of a Nexus

While geographers and historians have pondered the geographic significance of the Strait of Hormuz, geologists have worked to explain how this narrow pinchpoint formed. Studies have shown that prior to 5 million years ago, the Makran and Zagros fold and thrust belts both involved thin-skinned deformation and were part of the same subduction zone. A sharp, north-trending geophysical boundary that coincides with the Musandam mountains and extends northward to Bandar Abbas, Iran, is thought to be a relict transform fault formed during the opening of the Neotethys.

Arabian continental lithosphere is offset to the north along that transform fault from the Musandam westward. That offset destined the continental lithosphere west of the Musandam to enter the trench first, which it did about 5 million years ago, initiating continent–continent collision and slowing the convergence rate there, which today is 9±2 mm/yr. Oceanic subduction continued east of the Musandam, as it does today at a rate of 19±2 mm/yr. This difference in convergence rate produced the northward step in the Iranian coast that forms the Strait of Hormuz and gave birth to the transpressional Zendan Fault.

Perched on the edge of one of the world's most important seaways, the Musandam offers glimpses into several very different worlds. We witnessed not only a subduction zone transitioning to a collision zone and the commercial realities of modern-day Iran, but also an Oman from a different time, one that will not last much longer. Lastly, we saw for ourselves the incessant ship traffic that makes the region so commercially important and glimpsed the unique geography that makes the Strait of Hormuz a location of almost unparalleled strategic importance. ■

Revolutionising the Prediction of Reservoir Performance

SINA MOHAJERI and MATTHIAS HARTUNG, Target Energy Solutions

Coupling deep learning methods with dynamic reservoir models can result in tremendous time saving and more reliable production forecasts.

Reservoir models are vitally important in the oil and gas industry, for example for estimating remaining oil and gas reserves and providing production forecasts. Managing the operational and financial performance of an E&P asset is also heavily dependent upon having access to a current and reliable prediction of the dynamic reservoir behaviour. All this information is crucial for creating development and operational plans and providing an auditable cash flow to shareholders. It is therefore important to have an up-to-date and accurate reservoir model.
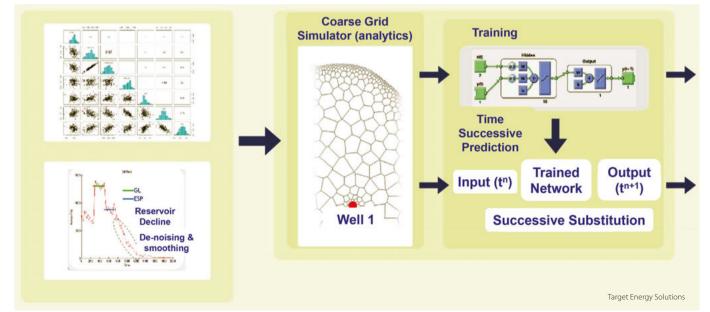
However, E&P asset operators have an issue, in that their optimum history matched dynamic reservoir models are becoming quickly out-of-date and 'dormant', due to the length of time it takes to update models. This means that frequent model updates are simply unaffordable. Engineers therefore often resort to using simpler approximation models to forecast production and remaining reserves, as these methods are faster and cheaper to use, although at the price of losing prediction accuracy.

This industry dilemma led engineers and scientists of the international technology and services company Target Energy Solutions to develop a new hybrid modelling method that couples conventional simulation with modern machine learning, thereby combining engineering knowledge of subsurface data with machine learning acquired through the stream of 'big data' coming from production.

A Revolutionary Breakthrough

This hybrid AI/physics-based system uses a conventional 3D, 3-phase numerical reservoir simulator coupled with a complex deep learning engine. The first step is to simply integrate an asset's optimum dynamic reservoir model into Target's platform MEERA™, and its AI-Simulation framework therein. This is done by re-assembling the components of the original conventional model, so it meshes into the machine learning framework. Various parameters are extracted from the original reservoir model, some of which, based on a comprehensive correlation analysis, are selected as key reservoir elements to be used for machine learning training and prediction. New production data is then incorporated, creating a rapidly self-updating live dynamic reservoir model that can be used as a reliable production forecasting and scenario-testing tool for operational planning and budgeting. It takes just minutes to train the AI using historic production data, while successive prediction simulations take merely milliseconds.

The lack of time constraints means that it is possible to optimise a development strategy by running numerous

Graphic describing the high-level workflow.

Target Energy Solutions

scenarios in minutes, all based on the experience of the asset's petroleum engineers. A reservoir model that is constantly being updated has the major advantage of allowing reliable maps of remaining hydrocarbons to be made, which can then be used to select optimum infill drilling locations. It also helps to provide stable and auditable cash-flow predictions to shareholders.

In comparison to purely data-driven processes, which mainly capture near-well behaviours, the system, known as MEERA Simulation, considers the whole reservoir's interconnected behaviour and therefore all inter-well effects. This makes it ideal for studying the effects of processes like well injection, as well as for looking at how major structures like fractures and faults in the reservoir may impact the production rates.
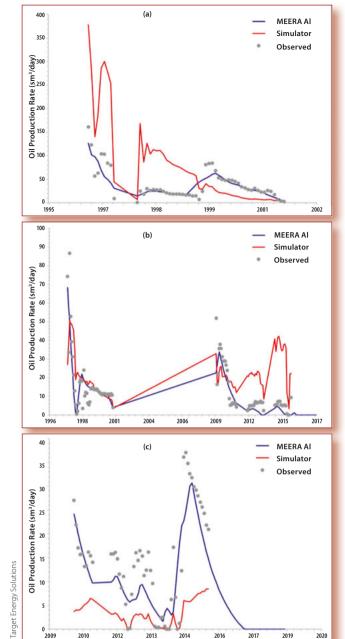
Case Study 1: History Matching
The benefits of the utilisation of a system like this can be seen by looking at some completed projects. One example comes from a field that had started producing in 1985 and now has more than 80 production wells, with strong aquifer support. In this case study, production data was matched up to 2010 and the period 2010–2018 was used for blind test prediction. Each full field simulation run took 7 to 8 hours using commercial simulators, but when using MEERA Simulation, each history simulation took 12 minutes, while prediction simulations took 50–70 milliseconds, all on the same IT infrastructure.

These faster results meant the engineers could run multiple simulations in minutes to generate lots of different potential scenarios, thereby allowing for better optimisation of development strategies. In this case study, the field history proved to be matched better using this system than with the traditional commercial simulators, and in particular the blind test prediction was more accurate than the traditional simulation historical-matching of the same wells. The better the history matching quality, the better the understanding of the reservoir, which in turn leads to a better production optimisation and re-development decisions.

Case Study 2: Lack of Data
Lack of available data is often another issue that asset operators face. Confronted with this problem, a company that had been using a model built on a reservoir modelling tool suite widely used in the industry decided to test using MEERA Simulation to build their models. As a result of the machine learning built into the software, the lack of data was not such an issue and the client found that not only was it quicker to build models through this system, but that the history matching was more reliable than before. However, it must be emphasised that although machine learning can fill in data gaps, the more data that is available, the more accurate the outcome will be.

A key feature seen across both these case studies is that a tool like this, that includes machine learning, has the ability to integrate with other industry reservoir modelling applications, allowing it to read and write from these applications using data-exchange industry standards such as RESCUE. In addition, the tool also possesses a wide range of professional and easy-to-use data-handling utilities and visualisers, including 3D and 2D models, a chart visualiser and a histogram visualiser.

Case study 1: Comparison of MEERA vs. conventional simulator in predicting oil production rates per well : (a) example in history match mode only, i.e. prior to 2010; (b) in both history match and prediction mode; and (c) well example in prediction mode only.

Evergreen Model Predictions
Field development decision making needs reliable predictive calculations, so a hybrid approach to reservoir modelling, using a fully coupled simulator with an AI/machine learning engine, is an obvious way forward. The result benefits from the history matching capabilities of artificial intelligence combined with the proven forecasting capabilities of a conventional reservoir simulator, while preserving local and global physical consistency.

With their evergreen model predictions and machine learning abilities, tools like MEERA Simulation have the potential to revolutionise the way that reservoir models are built and producing fields are developed. ■

The Land That Oil Forgot: Palestine, 1913–1948

Israeli premier Golda Meir once said, "Moses took us 40 years through the desert in order to bring us to the one spot in the Middle East that has no oil". We look at the history of exploration in this region.

Michael Quentin Morton

While the modern state of Israel has some reserves, and looks to the offshore for its gas supplies, it relies on foreign imports to meet its full demand for oil, a task complicated by its geopolitical situation. That might have been made easier if the hunches of the past had proved correct, since, before the declaration of the State of Israel in 1948, the territory then known as Palestine seemed full of petroleum promise.

Welcome to Kurnub

When my father, Mike Morton, first headed out for the Middle East in November 1945, he embarked from Liverpool on an empty troop ship, bound for Haifa in Palestine. Having gained a degree in geology from Leeds University, Mike was destined to join the Iraq Petroleum Company (IPC) at the start of a career that would span the next 25 years and take him across the region in search of oil; and it was in Palestine that he first experienced the trials and tribulations of life as a field geologist.

At that time, the territory of Palestine was controlled by the British under a mandate that had been approved by the League of Nations in July 1922. IPC operations were centred on Kurnub, to the south-east of Beersheba. Shortly after arriving,

Mike was taken on a tour of the area by IPC chief geologist, Norval Baker, who had been seconded from Standard Oil of New Jersey, and F. E. Wellings, his deputy. Both men were experts in the regional geology and highly respected for their work in the field.

Having collected Mike from his lodgings, they headed for Kurnub and took in the geology along the way. At one point they stopped for a group picture, which included another geologist, Sami Nasr. The photograph shows Mike wearing a new hat, which he struggled to keep on his head in a stiff breeze. Later, when they stopped for lunch and examined an exposed

The Israeli desert at sunset.

Palestine under the British Mandate, 1922–1948.

cliff above a small lake, a gust of wind snatched Mike's hat away and deposited it with a 'plonk in the middle of the pond', where it capsized and sank. With the aid of a shovel, Wellings and Baker retrieved and presented the hat to Mike – a miserable, dripping object returned to a rookie geologist with a sagging sense of self-esteem.

Perhaps that was an omen. As they approached the company's tented camp in the Negev Desert, they might have reflected on the history of the place. For Kurnub, the site of the ancient Nabataean city of Mampsis, holds a singular place in the annals of oil exploration.

Socony Steals a March
Back in 1913 much of the Middle East, including Palestine, was under the control of the Ottoman Empire. As the region's oil potential began to emerge, it became a theatre for competing petroleum interests. On one side were the Europeans, who had combined as the Turkish Petroleum Company (TPC),

the forerunner of IPC. On the other side were the Americans, including the Standard Oil of New York (Socony), a predecessor of Mobil. The Anglo-Persian Oil Company – today's British Petroleum – had just started pumping oil from its Persian oilfield, while Socony had an extensive distribution network in the Ottoman Empire, but lacked sources of crude oil.

TPC representatives were in Constantinople, locked in negotiations with the Ottoman government for an oil concession for Mesopotamia (today's Iraq). As those talks swayed between hope and despair, Socony was quietly working on the sidelines to obtain its own oil concessions. Having established an office in Constantinople, the company obtained exploration options from a group of Jewish businessmen in Palestine. By November 1913 its geologists and mining engineers had explored part of Anatolia, and were carrying out survey work in Palestine, which was considered the best prospect – from earliest times there had been reports of gas and oil seepages, and lumps of bitumen along the shores of the Dead Sea, known as *Lacus Asphaltitis* to the Romans.

Spearheading these efforts was William Yale, who was appointed to Socony's office in Constantinople. He set about drafting a new mining law for the Ottoman territories, which was necessary if his company

was to progress. He was a fluent Arabic speaker, and built a local network of contacts which would later prove useful in his work for the US government.

One day, while exploring the Judean Hills, his attention was drawn to the Kurnub massif some 50 km to the south; through his binoculars, he could see at its base strange, shining pools that looked like oil seepages. His appetite thus whetted, Yale returned to his office and wired Socony executives with the news. They agreed that he should return to Kurnub and take a closer look.
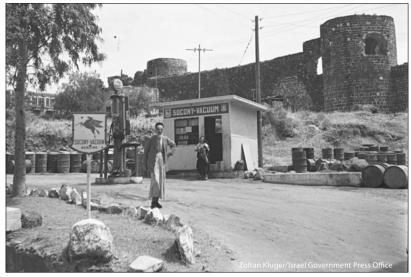
Enter Lawrence of Arabia
In January 1914, while travelling to Kurnub, Yale had a curious encounter in the desert. His small party had pitched its tents on a patch of meagre scrubland between low-lying hills to the east of Beersheba. After a night of storms, Captain Stewart Newcombe of the British Army – nicknamed 'Skinface' because of his sun-burnt features – and two civilians rode into their camp on horseback. The youngest of the group was T. E. Lawrence, who would later find fame as Lawrence of Arabia. What followed was a game of bluff, with the Americans pretending to be innocent tourists, the British inquisitive passers-by, and neither admitting their true designs, although Yale later noted that Lawrence's chatter

Kurnub camp, December 1945. Left to right: Sami Nasr, F. E. Wellings, Norval Baker and Mike Morton, hanging onto his hat.

A Socony-Vacuum petrol station in Tiberias, 1946.

was 'sprinkled with a stream of questions [that] pumped us dry'.

As it happened, Yale was disappointed by Kurnub: the shiny pools he had seen from a distance turned out to be water with iron deposits glistening in the sun. Nevertheless, he concluded from rock samples and borings that oil might be discovered there, though not in commercial quantities. In the minds of Socony executives, driven by a desire to gain a foothold in the region, that was good enough reason to proceed.

They purchased a 25-year concession and extended their interests in Palestine. The company went on to invest considerable resources in the Kurnub project, spending some $250,000 (about $6 million today) in buying and shipping equipment, building a 30-km road and setting up a camp in the desert as a prelude to drilling for oil. Meanwhile, the British authorities looked on with mounting alarm. Lawrence had confirmed Socony's interest in Kurnub, causing his superiors to redouble their efforts to block the American effort. When World War I intervened, the Ottoman authorities requisitioned Socony's shipment of trucks and the British diverted the company's pipes and drilling equipment to Egypt, where they were promptly impounded.

The chaotic Kurnub project would probably have failed anyway but, in the longer run, Socony could at least claim to have established a presence in the Middle East. On paper, its credentials were compelling – when the war broke out, the company had obtained concessions for seven plots in Palestine and another 60 were in various stages of negotiation. However, by the end of the conflict, the Ottomans had departed, the area was under British military occupation and the company was back to square one.

An Open-and-Shut Case

Great Britain now controlled the most promising petroleum lands and American attempts to access the Middle East soon met the brick wall of imperial officialdom. In August 1918, the British military forced the Socony agent in Jerusalem to show them the company's maps of their concessions in Palestine. This prompted Socony to make an official complaint to Washington, which in turn triggered a protest to London.

For the Americans, the last straw was the Treaty of San Remo in April 1920. This represented a carve-up of oil interests in the Middle East between the British and French, resulting in the French joining TPC and effectively excluding the Americans from Iraq. At the urging of US Secretary of Commerce, Herbert Hoover, seven US oil companies mounted a challenge to the Europeans, and Socony's earlier strategy now began to bear fruit. In April 1922, the British dropped their objections to a Socony survey in Palestine as a first move towards accepting a wider American participation in the Middle East.

This was the start of the 'Open Door' policy that eventually admitted American oil interests to the Middle East. In July 1928, five US oil firms, including Socony, joined TPC, renamed the Iraq Petroleum Company the following year.

The End of an Era

Socony thus dropped its claims in Palestine and threw in its lot with IPC, which went on to obtain exploration licences through its subsidiary, Petroleum Development (Palestine) Ltd. By the time my father arrived at Kurnub, operations had just restarted after the end of World War II. Once geophysical surveys had been carried out, a drilling site was selected at Huleiqat Ridge, in the coastal area 13 km north-east of Gaza. However, amid rising concerns about security, work was abandoned in February 1948 at a depth of about 1,000m without any

T. E. Lawrence (middle) walks behind Winston Churchill in a Jerusalem garden, 1921.

The IPC pipeline at Afulah on fire, April 1938.

significant flows of crude oil being found. The company surveyed the Kurnub area and completed preliminary work for spudding a well there; but it was not to be.

For many years, growing tensions between Arabs and Jews had threatened the company's activities in Palestine. The oil pipeline running between Kirkuk and Haifa was a frequent target, and the oil tanks at the Haifa terminal were sabotaged. A second pipeline was being built and when it reached the River Jordan the engineers saw British customs officials hurriedly evacuating their post on the opposite bank. That was in the spring of 1948, when the British mandate ended, the state of Israel was declared – and the Arab armies invaded.

As a result, IPC operations were shelved. After the Iraqi government banned the company from pumping oil to Haifa, it abandoned construction of the new pipeline and never resumed pumping oil through the old one. IPC's presence was at an end, though by then my father had long since moved on from Kurnub and was to be found riding a camel in the Dhofar, a province in the far-off land of Oman, in search of the elusive black gold.

Postscript

Rumours of vast oil reserves beneath the Negev Desert persisted and other oil companies entered the arena. The next well, Mazal-1, which was drilled in the Southern Dead Sea area in 1953, was a dry hole. The following year, oil was discovered at Heletz by deepening the well that IPC had abandoned at Huleiqat Ridge, with a producing zone consisting of sandstones and dolomites within the Cretaceous Kurnub group.

Despite extensive exploration drilling, Israel has remained a modest producer with proved oil reserves (2016) of only 14 MMbo. Nevertheless, the recent discovery of vast gas deposits in the Mediterranean has brought the so-called 'gas revolution' and made Israel an exporter of hydrocarbons for the first time in its history.

Quentin Morton's latest book, Empires and Anarchies: The History of Oil in the Middle East, *is available from Reaktion Books (UK), The University of Chicago Press (USA) and all good booksellers.* ■

Salt Biostratigraphy: An Untapped Source of Data?

Salt and evaporites in general are often regarded as both an excellent seal for hydrocarbons and an operational challenge to drill through – but they can also be turned into a valuable source of information.

GIL MACHADO, Chronosurveys Lda

Biostratigraphy in O&G

Biostratigraphy is a key discipline in hydrocarbon exploration and production as it allows a cost-effective, quick and logistically simple way to determine sedimentation ages and to provide insights into sedimentary environments. From real-time analyses at the rig site to long-term regional-scale studies, biostratigraphy provides vital information to geoscientists in their quest for hydrocarbons. There are now biozonation schemes for most of the Phanerozoic with a resolution close to or under one million years, depending on the stratigraphic interval, fossil group and area of the globe.

Although many fossil groups and biostratigraphic disciplines have stratigraphic relevance, by far the most

commonly used in the industry are micropalaeontology (usually referring to foraminifera and to a lesser extent ostracods and other calcitic fossils), palynology (spores/pollen, chitinozoans, dinoflagellates, etc.) and calcareous nannofossils.

These disciplines have been used successfully in the industry for decades. The main reasons for their success is, firstly, the small size of the fossils used in all these techniques – mandatory when the samples are commonly cuttings; secondly, their general abundance, although that is variable depending on lithology and sedimentation environment; and lastly, their rapid speciation and extinction rates, resulting in different fossil assemblages in each stratigraphic interval.

In recent decades high-resolution biostratigraphy with close-spaced sampling has been used as a sequence stratigraphic tool, for example for interpreting shallowing/deepening trends, by typing the characteristic assemblages of each system tract and for the identification of maximum flooding surfaces, hiatuses and sequence boundaries.

In operational geology there are many well-known examples of bio-steering, in which one or more biostratigraphic disciplines are used to guide horizontal drilling in order to keep the borehole within a specific bed (usually the reservoir) that has a characteristic fossil assemblage.

Palynology in particular allows for very detailed palaeoenvironmental interpretations, due to the fact that

Syn-depositional centimetre-scale fold-and-thrust structures of salt and salt-rich shale layers of the stratified member in the Wieliczka salt mine, southern Poland.

Gil Machado

Bas-relief in the Wieliczka salt mine, southern Poland. The magnificent statues and other artistic wonders were carved by salt miners over the centuries in hundred metre-scale hard salt boulders.

it studies organic particles derived from terrestrial and marine settings. This is particularly relevant for characterising potential source rocks, as the proportions and characteristics of the various organic particle types are used as indicators of source rock types and potential – a valuable add-on to geochemical analyses. In addition, the sensitivity of organic matter to temperature – it becomes darker with increasing temperature – allows us to estimate palaeo-peak temperatures attained by the rocks that contained the organic particles. Phytoclasts, the small plant remains that palynologists observe, is just another name for vitrinite, the standard material used to determine palaeo-temperatures in sedimentary rocks by measuring its reflectance under reflected light microscopes.

Salt: Friend or Foe?

Salt in the form of evaporites plays a key role in petroleum systems, as it acts as an effective seal, greatly influences thermal fluxes and frequently provides effective trapping mechanisms.
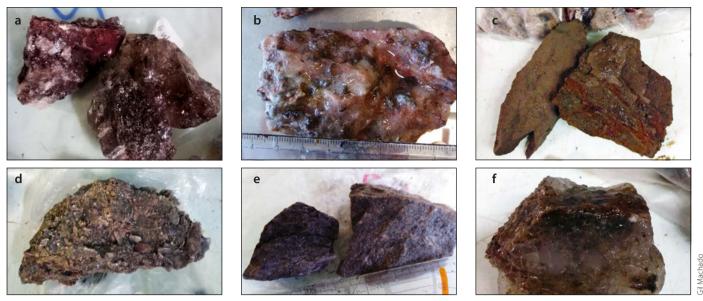
In petroleum system analysis, knowing the sedimentation age of the salt layer is critical in order to properly understand basin evolution, timing of fluid flow and trap formation, and the onset of salt movement, among other processes. Similarly, for basin analysis, forward modelling and structural reconstructions, knowledge of the age of the salt layer is extremely important. The sedimentation age of salt is commonly estimated based on the age of the underlying and overlying strata, as seen on seismic and/or from well data. This allows a crude estimation of the age, but is often biased, especially when salt is mobile and the bounding strata mark the stages of salt movement, rather than its sedimentation age. These methods also fail to determine the time span of salt deposition.

What About Salt Biostratigraphy?

There are several ways of dating salt deposits. Geochemical methods have been used recently, but the simplest and most effective way is to use biostratigraphy, specifically palynology.

Although typically palynology uses shales and siltstones, many other lithologies are suitable, including evaporites. Along with different salt mineralogies, such as halite, sylvite and gypsum, evaporite sequences usually include impure salts, containing clays and organic matter, as well as shales and carbonates. Palynology sample sizes vary, but usually 100g or less are more than sufficient to obtain significant results, thus well samples are suitable. There are some examples of this usage in salt deposits in the literature, but its use in the oil and gas industry is surprisingly scarce.

Chronosurveys, a Portuguese-based consultancy which specialises in stratigraphy, has refined a method of extracting palynomorphs from evaporites and interbedded sediments. Contrary to usual palynological techniques – which involve aggressive acid attacks, using hydrochloric acid for carbonates and hydrofluoric acid for silicates – organic matter in evaporites is extracted through the dissolution of halite and gypsum with hot water, with

Examples of lithologies with positive palynological results. (a) impure red halite (Souss-Massa mine); (b) impure halite (Loulé mine); (c) green salty shales (Wieliczka mine); (d) granular grey gypsum (Santana quarry); (e) Coaly mudstone (Loulé mine); (f) blackish halite (Wieliczka mine). (Images not to scale).

alkaline solutions applied for other, more resistant evaporitic minerals. Heavy liquid separation greatly helps to improve the quality of the final organic residues to be observed.

This salt biostratigraphy methodology has been tested at five locations using more than 30 samples. The rocks tested included early Jurassic, Miocene and Permian evaporites and associated sediments, with samples taken from outcrops, wells and mines. The sampled locations were:
• Loulé salt mine in southern Portugal,

which is in Early Jurassic mobile salt. Impure halite, coaly shales and dolomitised/silicified gypsum were sampled from the mine.
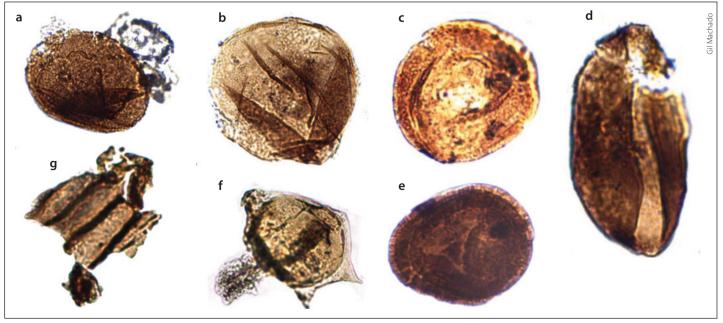• Souss-Massa salt mine in Morocco – an Early Jurassic non-mobile salt, where core samples from red, pinkish, grey and brown impure halite, grey and red shales were obtained.
• Wieliczka salt mine in southern Poland, which comprises Miocene mobile salt. Several types of salt and interbedded grey to brown shales were sampled. Don't worry,

the beautiful salt-carved statues of the tourist route, as shown in the photo on the previous page, were not tested, although samples were taken from equivalent lithologies.
• Zechstein salt in northern Poland, where red and grey shales, impure black halite, dolomites and black shales were sampled from a mine.
• Santana gypsum quarry in central Portugal, where outcrop samples of recrystallised and re-precipitated white-pink gypsum and primary grey gypsum were obtained.

Examples of palynomorphs extracted from evaporites and associated sediments. Images a – e are spores and pollen; (f) is a dinoflagellate cyst; and (g) is phytoclast (vitrinite). (Images not to scale).

Promising Results

Not all samples were successful, indicating that some lithologies and specific evaporite basin settings do not favour organic matter preservation. It is particularly difficult to obtain stratigraphically relevant organic particles from dolomite – a fact known to palynologists for a long time. Heavily recrystallised or re-precipitated halite and gypsum are also difficult samples because, while they can contain organic matter, most particles will be unrecognisable. Crystal size, however, does not seem to have a direct impact on organic matter preservation and samples: evaporite crystals from a centimetre down to sub-millimetre-size produce well-preserved assemblages.

As with other lithologies, the best results can be obtained from rocks with dark grey and black colours – a well-known indication of the presence of organic matter. Nevertheless, good assemblages were also recovered from pink-red impure halite samples.

The success rate using the refined extraction method is comparable to 'normal' non-evaporite routine biostratigraphy. Overall, assemblages are dominated by spores and pollen and other terrestrially-derived organic particles. This suggests that the salt was being deposited or formed in a terrestrial environment or that sea water was only sporadically present. Normal sea water conditions – notably salinity – were probably not the norm as dinoflagellates and other marine organisms are either very rare or totally absent in all the studied samples. Naturally, the palaeoenvironmental interpretation will vary from one locality to the next.

The thermal maturity of samples varied greatly, from very pale-yellow organic particles in the Wieliczka mine samples to dark brown-black in the northern Poland Zechstein samples. All observed samples also contained phytoclasts, or vitrinite, so the palaeo-peak temperatures the rocks were exposed to can be quantitatively determined.

New Perspectives

Salt basins are present in all continents and the vast majority of them contain proven petroleum systems. Salt is often regarded merely as the seal for hydrocarbon traps and a nuisance for drilling operations – but what if it there was a way to obtain valuable information from it? For example, is it possible to know the age of the salt seen on seismic or that of salt that has been drilled through? How long did it take to deposit? What about the stringers within it? Is it possible to calibrate the petroleum systems model with data from within the salt bodies and can the palaeoenvironment where salt formed be understood? Finally, can wellsite geologists know when the base of salt is about to be penetrated?

The tests performed show that samples from quite varied lithologies, ages, thermal maturation degrees and salt deformation stages and from non-mobile to allochthonous evaporites, can produce positive results, as long as the correct extraction method is used. Salt basins around the world, from the stratified salt of the Santos Basin in Brazil to the complex diapirs of the Gulf of Mexico, all have potential to provide valuable data for geoscientists.

Salt biostratigraphy opens a new highway of information, waiting to be untapped! ∎

Ken Glennie – The Passing of a Legend

In late November 2019 the UK lost one of the giants of the oil industry. Professor Ken Glennie was a legend in a number of fields, from the petroleum geology of the North Sea to turbidites and desert environments, particularly in the Middle East.
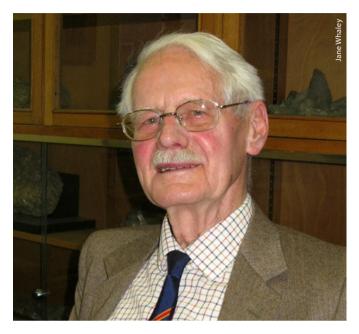
Ken joined Shell in 1954 – and so began his worldwide travels. The principles of petroleum geology had only just began to be formulated in the industry – as he said "we had no idea where oil came from. Oil was where you found it; it just happened" – and he was instrumental in refining these principles as he looked for potential source rocks in Europe, depositional environments in the deserts of northern Africa and turbidites – a totally new concept in the 1950s when he first wrote about them – in New Zealand. Ken was an exploration geologist in the days when mapping was done exclusively in the field, where the only tools were a hammer, a compass, a notebook and some paper maps, plus a lot of knowledge stored in the head. As a result, he had a wonderful fund of stories about his exciting adventures, near misses and interesting encounters.

In 1984 Ken published his book *Introduction to the Petroleum Geology of the North Sea*, which gave many an aspiring North Sea geologist a great grounding in the area, and he was also heavily involved in the series of conferences on the petroleum geology of north-west Europe known as 'The Barbican Conferences'.

For many, however, Ken's name will be forever linked to deserts, and in particular to Oman, a country he loved

Ken Glennie (left) in the field in Oman in 2003.

and which he first visited in the late 1960s. His work on deserts culminated in his seminal work *Desert Sedimentary Environments* (1970), followed by *The Desert of Southeast Arabia* in 2005. His long association with Oman, including the publication of *Geology of the Oman Mountains* in 1995, resulted by him being known as the 'Father of Oman's geology'. He kept up his interest in the country, and his visits there, well into retirement; in fact, at the age of 85 he returned to Oman to star in a documentary on the country's geological heritage produced by the Geological Society of Oman.

Ken Glennie was also an enthusiastic teacher and mentor, both during his career with Shell and after his retirement in 1985. He became an Honorary Professor at the University of Aberdeen in 1995, where he lectured on the petroleum geology of the North Sea and supervised PhD students working on desert and glaciogenic sediments until well into his 80s. He was also a keen member of his local branch of the University of the Third Age and was frequently involved with running courses and field trips on local geology around his home outside Aberdeen.

Professor Glennie was the recipient of many awards, including the Geological Society of London's William Smith Medal and the AAPG's Sidney Powers Memorial Award, but despite his undoubted intelligence, expertise and reputation he was a very modest, unassuming man who is fondly remembered by many as a wonderful teacher and a true inspiration.

Rest in peace, Ken Glennie (1926–2019); you will be sadly missed.

Read a profile of Ken Glennie in GEO ExPro Vol. 6, No. 1. ∎
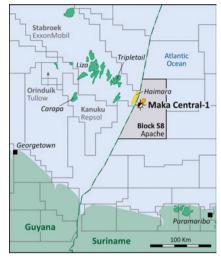
Jane Whaley

Success in Suriname

Apache Corporation announced a successful wildcat, **Maka Central-1 (Block 58)**, offshore **Suriname** in January, surprising for its proximity to 12 deepwater dry wells in that country, and also from a company more associated with low risk core basins in Egypt, the North Sea and the Permian play. The discovery is set to drive exploration and deal making in Suriname, proving as it does the southward extension of the 8 Bbo (to date) 'Liza play' across the border from Guyana into Suriname – the largest new offshore oil play in the world.
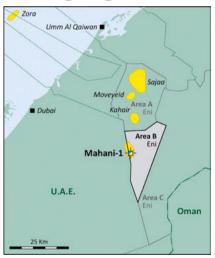
Maka Central-1 was drilled in 1,400m of water to a TD of 6.3 km, finding 50m light oil and gas condensate in Campanian sands and 73m oil in Upper Cretaceous Santonian clastics. Having reached the initial target, Apache promptly farmed down 50% to **Total**, who paid $100m cash plus longer term bonuses.

The discovery should improve the chances for other players in the basin – Petronas, Cepsa, Kosmos, Chevron and Hess – and perhaps NOC Staatsolie, which is planning to launch a licence round immediately to the south of Block 58 later this year. However, the geology changes quickly at the Lower Cretaceous and Jurassic Demerara platform high to the east, host to many a failed wildcat campaign so far, and all firms will be mapping just how far this Liza-style incursion will go. The discovery may also illustrate the potential of the Cretaceous in the southern MSGBC Basin across the Atlantic. ◼
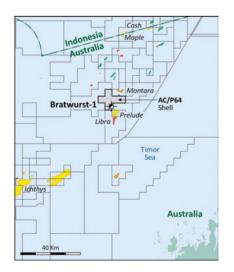
Charging Ahead in Sharjah

Italian giant **Eni** reported a significant gas condensate discovery, **Mahani-1**, in **Sharjah** recently. Eni, now well associated with successful campaigns in the eastern Mediterranean, has extended its strategic positioning to the Middle East over the last 18 months, presumably in a bid to take a commanding position in the gas production, infrastructure and LNG/GTP industry, as gas starts to take precedence over oil for some export routes.

In January Sharjah National Oil Company and Eni announced their 50/50 venture on **Area B** onshore. Mahani-1 was drilled to 4,562m and reportedly encountered thick gas-bearing pay in the carbonate Thamama Formation (Lower Cretaceous). The well tested 50 MMcfpd gas and condensate. The joint venture is now targeting difficult sub-thrust geological plays in the carbonate platform of the inner thrust zone of the Oman Foldbelt, requiring advanced 3D imaging and processing. Eni now have a Middle Eastern exploration portfolio stretching from Bahrain through the UAE to Oman; expect a very active exploration drilling campaign over the next two years from Eni and their partners in this region. ◼

North by North West

A number of drilling campaigns continue to expand on the oil and gas plays on the **North West Shelf** of **Australia**. After the excitement around the Dorado oil discovery in late 2018 in the Canning Basin, focus has returned to the deeper water Carnarvon, Browse and Bonaparte Basins, where the majors need to prove up large gas reserves to support the burgeoning LNG export industry.

Shell announced in December the successful drilling of **Bratwurst-1** in **Block AC/P64**. The well is understood to have targeted Lower Jurassic play (Plover) and Upper Triassic (Nome) clastics in the **Browse Basin**. Although it took 78 days to drill, Shell completed the work within 12 months of the award, testament to their demand for gas, which is now a core component of the supermajor's new energy mix and low carbon credentials. This campaign reflects a global shift to enriching the gas mix, with Bratwurst and other targets nearby lined up for tie-back to Prelude. This floating LNG project, which started exporting in 2019, is the largest of its kind and very much in the vanguard for the next generation of global offshore gas development projects for the industry. ◼

SUMMER NAPE: REFOCUSED

Summer NAPE is introducing a new format for 2020. Highlights include:

STREAMLINED SCHEDULE

The Business Conference will now be held on the trade show floor in conjuction with the Summer NAPE Expo, making education more accessible and convenient.

ALL-INCLUSIVE REGISTRATION

For the same low rate, the Business Conference and luncheon is now included with all Summer NAPE attendee registrations.

HIGH-PROFILE KEYNOTE SPEAKER

Summer NAPE will now open with a luncheon featuring a high-profile speaker. The 2020 keynote is political strategist and pundit **KARL ROVE.**

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The Saudi Aramco IPO: What Does it Mean?

The Saudi Arabian economy is almost entirely dependent on oil exports, and diversifying it has become crucial. As part of its plan to reduce this dependence, Saudi Arabia's leadership recently floated part of its giant state oil company, Saudi Aramco, on the Saudi stock exchange, selling shares in what was the biggest IPO (Initial Public Offering) in history. We talk to **Dr Ellen Wald**, author of *Saudi Inc.: The Arabian Kingdom's Pursuit of Profit and Power*, about the importance of this move to the oil and gas industry.

Can you tell us a bit about the background to the IPO?
Prince Mohammad announced the idea for the IPO in a seemingly offhand remark in 2016 during an interview with *The Economist*, but it was delayed for several years because the company was not in a position to list publicly. Saudi Aramco first needed to create a new fiscal regime so it could present accounting that met a modicum of international standards.

Why is it so significant?
The Aramco IPO is not immediately significant to the oil market. It is an offering of a very small portion of the company and will not impact the production of oil right now. However, it is a sign of the Saudi government's increasing involvement in its country's oil strategy. This could have long-term impacts.

Who can buy shares?
At the moment, shares are mostly limited to Saudi and GCC nationals, as well as regional institutions and foreign investment funds and banks. Global investors can best access Aramco shares by purchasing into a fund that invests in the company.

How was the initial sale received by the markets?
The IPO was made on the Saudi stock exchange, Tadawul, and the company quickly rose above a $2 trillion market cap. Since then, the stock has fallen significantly. There is very low-volume trading and the initial success must be viewed in line with the influence and manipulation of the Saudi government.

How will the money raised through the IPO be used?
We don't know how the money raised through the IPO will be used; however, we do know that Aramco will not see the proceeds of the IPO. Originally, Prince Mohammad wanted to transfer ownership of Aramco to the Saudi sovereign wealth fund before the IPO and give the proceeds to that fund. However, the transfer never occurred and no one knows where the money from the IPO went.

What does this tell us about the future of the oil industry?
The biggest concern for the future of the oil industry is that the new-found influence of the Saudi government on Aramco will mean decreased capex spending for the company. Saudi Aramco has been the leader in capex over the last few years, and a cut in spending could mean that the industry will see problems in long-term development.

What difference will the IPO make to the day-to-day business of Saudi Aramco?
The biggest difference is that Aramco cannot provide as much in the form of free services and goods to the Saudi government and people as it once did. The other difference is that the Saudi energy ministry may now be incentivised to promote higher revenue for the company, which generally would result from encouraging higher production rates. ∎

Ellen R. Wald, Ph.D. is the president of Transversal Consulting, an energy and geopolitics advisory firm. Dr Wald is the author of Saudi, Inc.: **The Arabian Kingdom's Pursuit of Profit and Power,** *which tells the history of Saudi Arabia through the central figure of Aramco. She is a Senior Fellow at the Atlantic Council's Global Energy Center. Her weekly column about oil markets in* Investing.com *is read by tens of thousands and translated into a half dozen languages. She also writes about energy issues for a general audience in* Forbes *online and has contributed to the opinion sections of* The New York Times, The Hill, Bloomberg *and others. Dr Wald is a graduate of Princeton University. She earned her doctorate from Boston University.*

Ellen Wald

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The Africa Factor

America sneezes and the rest of the world catches a cold. An old saying but what about this for a new one: China coughs and the world gets a virus. For the moment at least – certainly at the time of writing – coronavirus looks like it could have a significant impact on global trade and at the same time put more downward pressure on the oil price. OPEC is due to meet and even Russia is prepared to join talks with a view to curtailing production.

China consumes about 14 MMb of crude a day; getting close to US consumption in a global market predicted to top 100 MMbopd in 2020. This figure could dip sharply if coronavirus keeps China in shutdown mode – and in the meantime fewer container ship voyages, less air travel and a manufacturing hiatus in China might well be seen as good news by the green lobby.

But is it? The global economy arguably needs growth like never before. The latest Africa Outlook report by the International Energy Agency shows population growth in Africa dramatically outstripping other parts of the world. It notes: "Rapid economic and population growth in Africa, particularly in the continent's burgeoning cities, will have profound implications for the energy sector, both regionally and globally." In other words the developing world needs energy, the cleaner the better, from all sources.

Africa we know is rich in potential for solar power but development is piecemeal. In South Africa, for example, Eskom, the government-owned national power utility, gives consumers no incentive to install domestic solar while continuing with regular power outages. While oil will continue to have a role in Africa for the foreseeable future – both in production and consumption – natural gas can and should have a bright future as part of the region's cleaner energy mix, according to Dr Fatih Birol, Executive Director of the International Energy Agency.

"Africa has a unique opportunity to pursue a much less carbon-intensive development path than many other parts of the world," notes Dr Birol, adding that natural gas and greater energy efficiency have to be part of the mix, alongside the growth in renewable energy. Poor maintenance over a long period has undoubtedly contributed to what Eskom terms 'load shedding' and it is the consumer who suffers, not only with power cuts but also higher bills. When China stops coughing Africa will continue to be a prime target across the spectrum of energy investment.

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 = 1×10^6
Billion = 1×10^9
Trillion = 1×10^{12}

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

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

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

Historic oil price

Crude Oil Prices Since 1861
Nominal — Real (2014 dollar)

Senegal 2020 License Round

Data insights to support your block evaluation.

Legend:
- Senegal 2020 License Round (12 Blocks)
- Senegal South Ultra Deep Offshore 2019 3D
- Senegal North Ultra Deep Offshore 2019 3D
- Jaan 3D Seismic
- Multibeam & Seafloor Sampling
- Existing 2D Seismic

Map labels: OUP-Nord 1, OUP-Nord 2, OUP-Nord 3, OUP-Nord 4, OUP-Nord 5, OUP-Nord 6, SLOP 2, COP 2, OUP-Sud 1, OUP-Sud 2, SOSP, SOSS

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