VOL. 14, NO. 5 – 2017

GEOExPro

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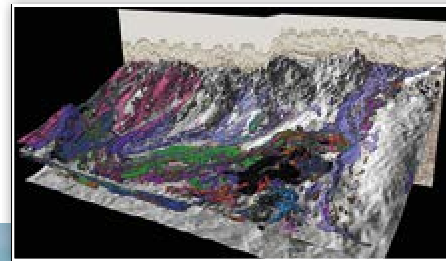

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GEOPHYSICS:
Liberia: A Fresh Approach

EXPLORATION

Benin: Low Cost, High Impact Frontier

INDUSTRY ISSUES
Being Green – Great For Business

RECENT ADVANCES IN TECHNOLOGY
An Introduction to Deep Learning

Q & A
BP's Big Data Plans

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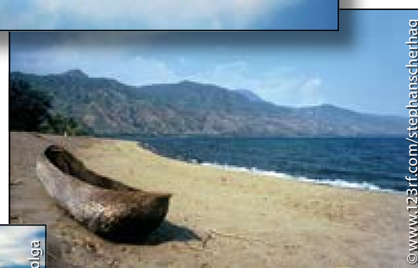
GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

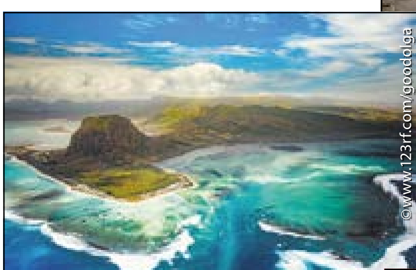
16

Technology and processes are changing rapidly, but data remains at the heart of everything we do.



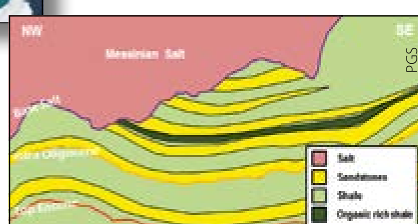
34

Beautiful Lake Malawi could be hiding hydrocarbon riches.



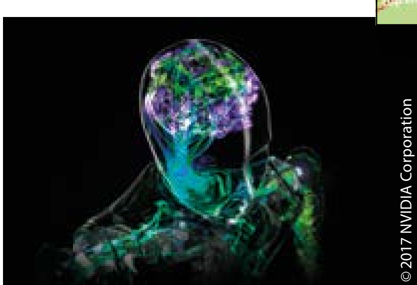
50

"Mauritius was made first and then Heaven; and Heaven copied Mauritius."



54

Several promising play types can be identified on new pre-stack depth migrated seismic.



62

Once, artificial intelligence was science fiction – today, it is part of our everyday lives.

Contents

Vol. 14 No. 5

This edition of *GEO ExPro* magazine focuses on Africa; Data and Analytics; and Protecting our Resources.

5 Editorial

6 Regional Update

8 Licensing Update

10 A Minute to Read

12 Cover Story Exploration: Benin – The Low Cost, High Impact Frontier

16 Industry Issues: Digitally Transforming Data Management for Geoscience

20 Seismic Foldout: Côte d'Ivoire – Completing the Jigsaw

26 Industry Issues: When Being Green is Great for Business

30 GEO Physics: Liberia – A Fresh Approach

32 Technology Explained: A Cleaner Future for Drilling

34 Country Profile: Unexplored Malawi

38 GEO Profile: Cath Norman – New Technologies Lead to Amazing Career

42 Seismic Foldout: Olympus Rising: North Carnarvon Basin Imaging

50 GEO Tourism: Mauritius – and Beneath

54 Exploration: Frontier Exploration in Egypt's Mediterranean Sea

56 History of Oil: A Brief History of Booms and Busts II

62 Recent Advances in Technology: An Introduction to Deep Learning I

66 Seismic Foldout: Exploration Opportunities in the Mediterranean

74 GEO Media: Anomalies

76 Exploration Update

78 Q&A: Big Data in the O&G Industry

80 Global Resource Management

Just Having Fun!

While reading Robbie Gries' excellent book about pioneering female petroleum geologists in the AAPG, reviewed on page 74, I was struck by the sense of fun running through so many of the anecdotes. These women had struggled hard to get into the profession and were frequently subjected to prejudice, disparagement and lack of recognition for their often ground-breaking work. Yet their fondest memories were of the excitement and good times they had, predominantly in the field but also in more mundane settings.

I am privileged to meet and interview a lot of people in the industry in the course of my work. Some have been in the business for decades and recall their early careers, when computers were in their infancy and they spent a lot of time in the field and had some pretty hairy adventures; many are younger, and although they tend to be in the office more than their predecessors, they still say what an exciting industry it is to be in. Yes, there are lows as well as highs, not just in oil prices and employment, but in the search for oil – bearing in mind that, despite all our high-tech capability, still less than 25% of wildcat wells are successful – the risk element seems to add to the excitement for many.

It has often been noted that geologists are a strange bunch, delighting in being outside whatever the weather in the search for that elusive outcrop and roughing it in some of the wilder corners of the earth. It was the same even in those early days, when the AAPG pioneers can be seen in photos clambering over rocks, geological hammer in one hand, long skirts gathered in the other – and broad grins on their faces. And I suppose it is the smile that sums it up – they're having fun with like-minded people. As Cath Norman, profiled in this edition, puts it: "I get to use the most advanced technologies outside the space race; to travel the world and hang out with very intelligent – and also wacky – people. What's not to like?"

It is good to sometimes remember that, despite the inevitable trials and tribulations of working life, we are all very lucky. We have rewarding careers in an exciting industry – and get to have fun! ■

Jane Whaley
Editor in Chief

BENIN: LOW COST, HIGH IMPACT FRONTIER

Exploration for oil and gas still has a long road to travel in much of Africa, including Benin, where there is overlooked potential in the shallow offshore, and Malawi, virtually unexplored.

Inset: New thinking inspired by innovative modelling could open new plays in West Africa.

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GEO ExPro is published bimonthly for a base subscription rate of GBP 60 a year (6 issues).
We encourage readers to alert us to news for possible publication and to submit articles for publication.

Cover Photograph:
Main: peeterv/istock
Inset: TGS

Layout: Winslade Graphics
Print: Stephens & George, UK

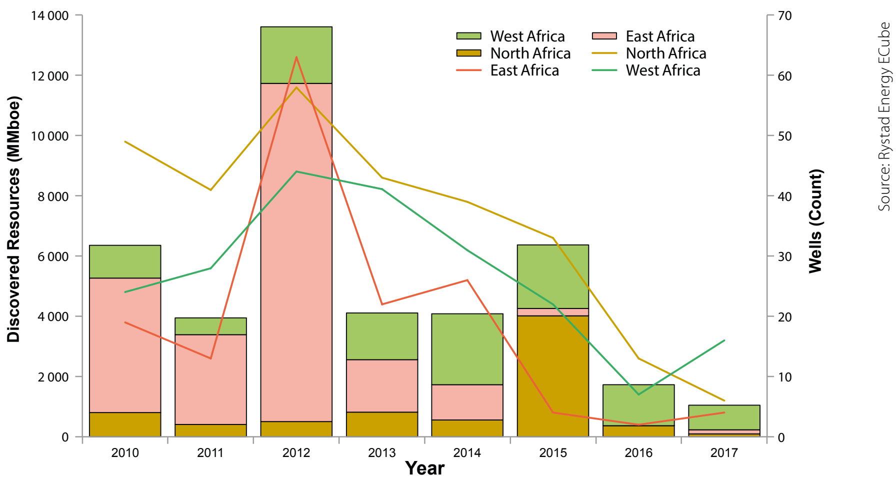
issn 1744-8743

North West Africa Leads Exploration

Over the last two years companies exploring North West Africa have seen a high value of return.

Conventionally, African exploration has been focused in Nigeria, Egypt and Libya; most other frontiers were either underexplored or not explored at all. However, in recent times Africa has been the hot spot for exploration activity, mostly concentrated in West Africa, offshore Mozambique and Tanzania, and the East African rift system in Kenya and Uganda, as well as the opening of new carbonate plays in the Nile Delta. The slump in oil markets has had a huge impact on exploration activity, with a decline of about 60% in the African continent since 2015.

The drop in activity since 2015, however, is not indicative of exploration efficiency. The success ratio (i.e. the percentage of wells encountering hydrocarbons) has been almost 60% since 2015 for both East and West Africa, but fell from 70% to 50% for North Africa. In the same period, the average discovered volumes per well dropped from 106 to 7 MMboe in North Africa and remained constant at around 50 MMboe and 70 MMboe for East and West Africa respectively. Exploration efficiency clearly highlights that overall exploration was a success in both East and West Africa.



Discovered resources (left axis) in the African continent per year by regions and the number of exploration wells (right axis, line graph) by region.

The discovered volumes from 2010 to 2012 came from East Africa, with giant gas discoveries like Prosperidade, Mamba South and Golfinho. From 2013 to 2014 most of the discovered volumes in Africa were uniformly distributed between East, West and North Africa. Following the drop in the oil price, there was Eni's Zohr discovery in 2015, which revitalised interest in the Mediterranean. However, over the last two years average discovered volumes have plunged significantly in both East and North Africa. All the major discoveries, like Ahmeyim and Yakaar, come from Senegal and Mauritania in North West Africa with operators including Kosmos Energy and BP.

After analysis of companies involved in exploration since 2015, we observe that BP has reserves of around 2.5 Bboe, followed by Eni at around 2.4 Bboe and Kosmos Energy with about 1 Bboe. The exploration cost after tax is approximately US$822, $1,233 and $315 million respectively for these companies and the value of discoveries for them is around nine, four and three billion US$ each. This clearly indicates that since 2015, BP, Eni and Kosmos Energy have created substantial value in their respective regions by discovering assets that are worth more than their investments after tax. Thus, we can conclude that in the last couple of years, considerable value has been added through exploration in North West Africa as compared to the rest of Africa. ■

Aatisha Mahajan, Exploration Analyst, Rystad Energy

ABBREVIATIONS

Numbers
(US and scientific community)

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

Liquids

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

Gas

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

Ma: Million years ago

LNG

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

NGL

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

Reserves and resources

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

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

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

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

BGP Multi-Client New Acquisition in Offshore Cuba

~25,000 km multi-client seismic lines are to be acquired around offshore Cuba. The whole project will consist of lines in the economic zone of the GOM, lines in the south of the Bahamas Border, and lines in the southern sea of Cuba.

In-filled well-tie 2D seismic lines have been designed by BGP with the assistance of CUPET. These lines will help to improve seismic imaging in deep targets in offshore Cuba. The high density of seismic lines are designed in prospective GOM-CEEZ, where excellent levels of source rocks, reservoirs and leads have been identified in recent years.

The project will commence with three phases:

Phase I: ~20,000 km – Red lines

Phase II: ~2,500 km – Yellow lines

Phase III: ~2,800 km – Blue lines

BGP is one of the world's leading geophysical service companies, delivering a wide range of technologies, services and equipment to the oil and gas industry worldwide.

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Interesting Upcoming Rounds

Two rounds due shortly should catch the industry's attention.

Guinea: Large Offshore Area to be Offered

Only two blocks offshore Guinea are taken at the moment, leaving another 20 available in this West African transform margin region, which should attract interest when the country launches its first ever licensing round in October during Africa Oil Week. The round will last six months and companies can submit bids on all the open blocks, with awards announcements expected before the end of 2018. In December 2014, the National Assembly in Guinea adopted a new petroleum law in which cost recovery terms and profit split arrangements have been revised.

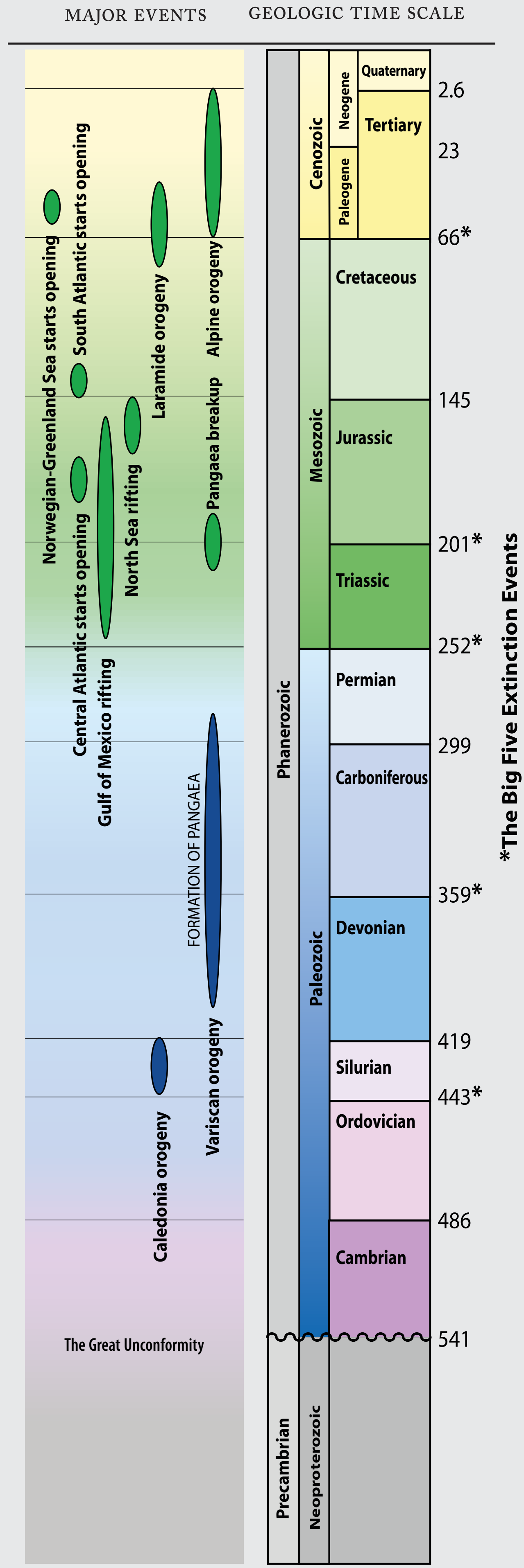
The round is organised by the National Office of Petroleum (Onap) and, working in partnership with Schlumberger and TGS, it is planning to hold roadshows in Houston and London. TGS undertook a 14,000 km 2D survey in 2016, leading to the re-designation of the blocks, which now include ultradeep water. TGS has set up a data room in Conakry and is also training local geophysicists.

The two blocks already taken are operated by Hyperdynamics, who recently drilled their first well on the acreage, as reported on page 76. ■

Argentina: First Offshore Round

Although exploration offshore Argentina first commenced in 1976, there has been little successful drilling and the area is seriously underexplored. In 1992, the country opened 560,000 km^2 of offshore acreage to international bidders, but it has never held an official offshore licensing round, a situation which is about to change, as Argentina's first bid round offering offshore acreage is due to open later this year. The plan is to offer acreage in stages, with shallow water areas available first, starting with the Austral Basin in the south, to be followed by deepwater rounds in 2018 and 2019. Argentina hopes to emulate some of the discoveries made further north in deepwater Brazil, and there are possibilities of analogue plays to those across the Atlantic in Africa.

With this proposed round in its sights, Spectrum has acquired 35,000 km of multi-client 2D seismic data covering 435,000 km^2 in the offshore deepwater, working in cooperation with BGP, YPF and the Ministry of Energy and Minerals. Searcher Seismic has also recently started working offshore Argentina with four new multi-client projects, the first being an Offshore Basin Analysis Report, which will provide a regional framework to help understanding of the offshore basins. ■

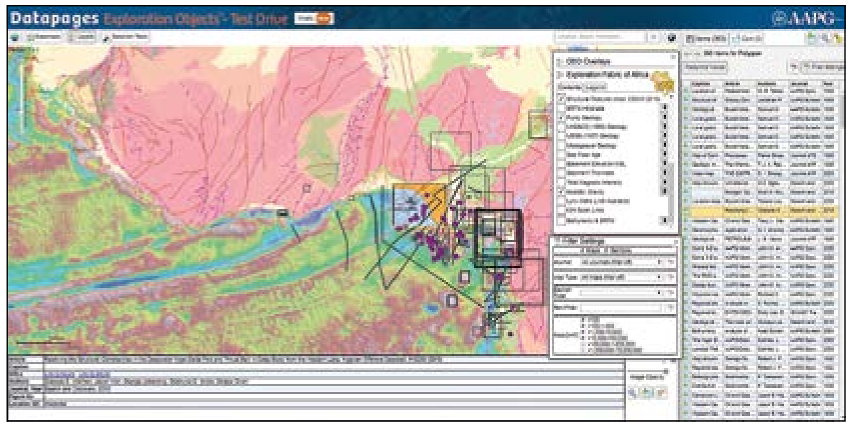


A Century of Geoscience Publishing

This year the **American Association of Petroleum Geologists** celebrated 100 years as a respected independent publisher of geoscience articles, all of which are now held digitally in the archives of **Datapages**, a company wholly owned by AAPG. In addition to the Bulletin, Memoirs, Special Publications and the Search and Discovery online journal, this archive currently contains articles from more than 60 other organisations; in total there are over 150,000 articles. Datapages started digitising AAPG publications in the early 1990s. The first digital products were CD-ROMs which innovatively featured full text searching; ten years later articles were migrated to the internet.

In recent years Datapages has been delving deeper into the archives to generate value-added products. The first of these was GIS-UDRIL, which used derived material to produce geographically and thematically focused maps, atlases and databases. More recently, 60,000 map figures have been georeferenced and over 15,000 sections geo-located, all of which are now incorporated into the **Datapages Exploration Objects** (DEO) product, an online service which allows users to graphically search areas of interest for maps and sections which can be viewed and downloaded. The project's long-term objective is to offer its services via a geoportal, allowing users to integrate data from a number of different vendors.

Datapages has been a digital publisher for 25 years and continues to provide innovative services in a constantly evolving marketplace. ■



FairfieldNodal Acquire WGP

FairfieldNodal, known as an industry leader in **marine seismic nodal technology**, continues to seek opportunities to strengthen and expand its technology portfolio, and transform itself into a world-class provider of integrated life of field seismic services, data and data analytics over the next three to five years through a combination of strategic partnerships and acquisitions. With this goal in mind, it recently announced that it is in advanced discussions with Thalassa Holdings to acquire **WGP Group Ltd.**, a premier provider of marine geophysical services headquartered in the UK. FairfieldNodal believes that WGP provides a unique set of products to complement its existing technology and services, specifically its proprietary ZLoF semi-permanent reservoir monitoring technology, meaning that WGP's proven operational capabilities around active reservoirs make them a natural fit into the FairfieldNodal suite of services. ■

From Institute to Global Seismic Business

The need to create a favourable infrastructure for natural resource exploration and development by national governments is undisputed. However, an aspect occasionally overlooked is the development of exploration service companies by governments.

In 1957, the fledgling state of **Israel** foresaw the need for geophysical services in its budding onshore oil and gas, copper and potash industries. As a result, it founded the **Geophysical Institute of Israel (GII)**, geophysical equipment was obtained and services and expertise developed. For 40 years the GII provided acquisition, processing, interpretation and R&D services to different executive bodies of the government. In the 1980s and '90s the natural resource sector was privatised; since then the GII has become a business-oriented company, providing geophysical acquisition and processing services outside Israel using advanced technologies. The GII's seismic explosive and vibroseis crews have specialised in complex terrain and challenging geo-political situations such as in Ethiopia, Tanzania, the DRC and Angola, on top of numerous projects in Europe and India.

This year, despite the industry downturn, the GII celebrates 60 years of operations, with over 30 international acquisition projects in the oil and gas sector alone. This shows that with the correct vision, developing countries can create catalysts and enabling factors for unlocking the potential in their natural resources. ■

A GII crew operating in Georgia.

Statoil Meets Emissions Target

In 2008 the Norwegian petroleum industry set a collective **energy efficiency goal** equivalent to 1 million tonnes of CO_2 per year between 2008 and 2020. **Statoil's** share of this was 800,000 tonnes. In 2015, four years ahead of schedule, Statoil achieved this goal, and therefore the company raised its target to 1.2 million tonnes by 2020. It has now announced that it has already achieved that target, a reduction which equates to the emissions from some 600,000 private cars annually – or almost every fourth car on Norwegian roads.

The Kristin Platform

Since 2008 Statoil has implemented 228 energy improvement measures, covering everything from better operation of gas turbines and compressors to reduction of flared gas, as well as smarter fuel consumption for mobile rigs offshore. For example, on the Statfjord A platform Statoil changed the way it produces drinking water, while on Oseberg South two main power turbines have been upgraded, reducing CO_2 emissions by around 4,800 tonnes and 10,000 tonnes per year respectively. By using gravity pressure from the sea instead of a water injection pump, emissions at the Kristin field have been reduced by over 7,000 tonnes per year. Norway now produces oil and gas with half of the CO_2 emissions per produced unit compared with the global industry average. ■

Game-Changing Seabed Seismic System

The Norwegian seismic equipment supplier **inApril** AS announced that in August it successfully carried out a full-scale sea trial of its fully integrated node-based seabed seismic acquisition system, **Venator**, which confirmed that Venator is the first seabed-based exploration tool to provide data far superior to conventional towed streamer solutions at competitive terms.

Retrieving the nodes.

The system, which features hands-free handling and flexible node spacing at unprecedented speeds, was tested in 110m water depth over a part of the Edvard Grieg field operated by Lundin Petroleum, in the Norwegian North Sea. The node used was inApril's A3000 node, suitable for both deep and shallow water operations. The trial repeatedly demonstrated 'node-on-a-rope' deployment speeds of 5–6 knots and retrieval at 3–4 knots, enabling up to 20 km^2 full-azimuth data acquisition per day in exploration mode.

Preliminary results confirm the excellent data quality also shown by previous sea trials, which is only achievable by seabed data acquisition. Data processing will be carried out in the coming weeks.

According to numerous industry executives and analysts, more efficient node-based ocean-bottom seismic will provide the optimal solution for oil companies looking to increase reserves at reasonable costs via targeted exploration and reservoir characterisation data acquisition. ■

PROSPEX 2017 – Come and Network!

The **Petroleum Exploration Society of Great Britain** and the **Oil and Gas Authority** are holding **PROSPEX 2017**, the 15th show in their highly successful series of Prospect Fairs – the UK's leading networking event for exploration and development.

The show has gone from strength to strength, with in 2016 over 60 exhibitors and 600 attendees, in addition to a full two-day programme of 'prospects to go', overviews from government and presentations by explorers and consultants. Comments from attendees and exhibitors include:

"PROSPEX is the industry bencmark conference, where you meet all the right people."

"This show always has a buoyant and optimistic mood."

"The exhibition was a constant hum of activity!"

"A yardstick for activity within a region."

If you want to see what all the talk is about, registration is now open and includes admission to the exhibition and conference, all-day refreshments, luncheon and a networking wine reception.

PROSPEX 2017 runs on 13–14 December 2017 at **Business Design Centre**, Islington, **London**. ■

Unexplored Malawi

Plenty of hydrocarbons have been found in the East African Rift system, but Malawi, lying at its southern end, is virtually unexplored.

JANE WHALEY

The hydrocarbon potential of the East African Rift System (EARS) has been known for years, with discoveries dating back to the early 1920s. Countries like Sudan, Uganda, Tanzania and Kenya have been proved to contain considerable quantities of oil and gas, but further south, where the rift passes through Malawi, exploration has barely started. Much of the country, and the Lake Malawi Basin in particular, is believed to possess promising geology and has indications of petroleum systems.

Rifting Dominates

As with much of East Africa, the geology of Malawi is dominated by the ongoing splitting of the African plate, which has resulted in the East African Rift System (EARS). This stretches more than 4,000 km from Eritrea and Ethiopia in the north, where rifting initiated about 40–50 million years ago (Ma), southwards to Malawi where rifting may have commenced as recently as 8 Ma, and on into Mozambique. The system comprises two arms; the older eastern branch through Kenya is more volcanically active than the younger western branch, which contains some of the world's oldest and deepest lakes, including Lakes Tanganyika and Malawi.

The majority of the country is dominated by crystalline metamorphic and igneous basement rocks which have been subjected to several periods of deformation, primarily during the Precambrian. In the Permo-Triassic, the continental extension splitting the supercontinent Gondwana apart led to extensive faulting, resulting in the formation of long narrow north-east to south-west trending troughs in which sandstones, limestones and mudstones of the Karoo Supergroup were deposited. These sediments were subjected to repeated periods of uplift, erosion and faulting from the Jurassic to the present, producing graben structures in which Tertiary and younger sediments were deposited. Quaternary lacustrine sands and gravels are common in the Lake Malawi area, indicating the retreat of the lake to its present position.

There are some Jurassic-aged basalts in the far north and south of the country and several carbonatite intrusions in southern and south-central Malawi. Unlike the older rift system, however, there is little evidence of magmatic activity and volcanism associated with rift formation, with the exception of some Pleistocene volcanics found near the northern end of Lake Malawi. There are also hot springs in the western and southern lake area.

Lake Malawi has a surface area of nearly 30,000 km^2, making it the ninth-largest freshwater body of water in the world.

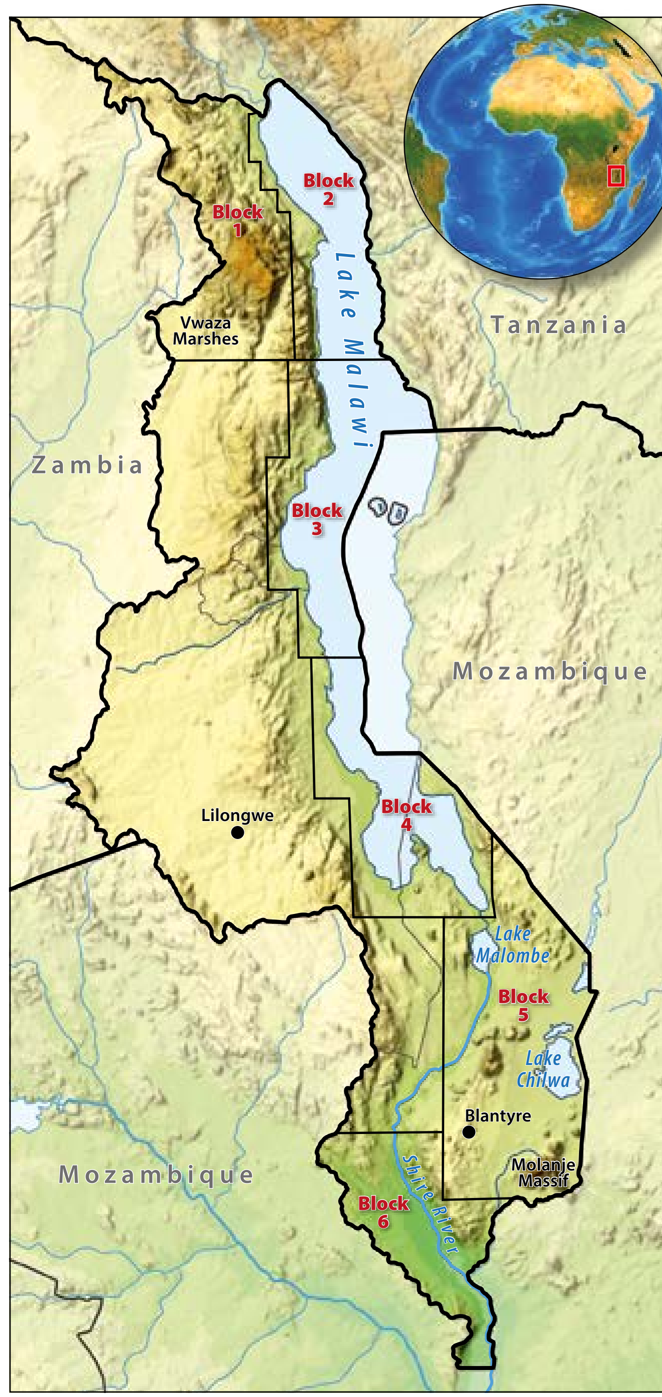
About 75% of Malawi's land surface is a gently undulating plateau lying between 750m and 1,350m, with mountains over 2,500m in the north and south. Lake Malawi comprises 20% of the county's total surface area.

Evidence of Hydrocarbons

Unlike much of East Africa, oil exploration did not commence in Malawi until the 1980s, when ten international oil companies sponsored Duke University to conduct a seismic survey over Lake Malawi. Lying as it does in the EARS, bounded on either side by major faults, and the recipient of deltaic sediment input from a number of rivers over millennia, the lake has long been considered the most likely place to find hydrocarbons in Malawi. Although a very broad-brush approach, this survey did indicate that there were thick sedimentary units, in places exceeding 4,000m, and also identified large structural features, suggesting the potential for Tertiary hydrocarbon systems similar to those found in the Albertine Graben, where ten discoveries have been made since 2006. The water depths where the greatest thicknesses of sediments were located made exploration uneconomical at the time. Further UN-funded airborne geophysical surveys noted the presence of thick sedimentary rock formations under Lake Malawi, in the Lower Shire Valley in the south and the northern Vwaza Marshes area.

Oil seeps have been observed in Lake Malawi and its vicinity for years, indicating the possibility of mature source rock deposition at depth. The seeps may be the result of the anoxic conditions which have been part of the development of the lake since the Tertiary, but could also be linked to the older Karoo sediments common in the southern part of the EARS, which are coal-bearing elsewhere in southern Africa. Studies by Kagya et al. (1991) suggest that kerogens found in Early Permian Karoo coals and carbonaceous shales in the Lake Malawi area could be good sources for gas/condensate or light oils. The source rock kitchen is expected to be in the deeper part of the half graben. Through sequence stratigraphy (Saunders), it has been shown that there have been many oscillations in the lake level linked to climate variations, and that peak source rock deposition may be linked to lake highstands and reservoir formation to lake lowstands.

The evolution of the rift basin itself provides a trapping mechanism for migrating hydrocarbons, not just in the Lake Malawi area but also further south in the valley of the Shire River, the only outlet of the lake.



State of Exploration

In 2011 the government offered six blocks for hydrocarbon exploration. Block 1, covering the Vwaza Marshes/Chitipa area in the north-west, is considered to have potential, as it contains a number of fault-bounded basins filled with Karoo sediments, overlain by Tertiary sediments. South African independent Sac Holdings have held the area since 2012 and have undertaken regional geological, geophysical and satellite screening studies, as well as environmental and social risk screening. After positive results from these, they are now planning a geochemical study and passive seismic tomography. The block encompasses environmentally sensitive areas both inside and outside national parks.

Lake Malawi is divided into three blocks roughly coincident with the basin structure. Block 2, Lake Malawi North, encompasses the North Basin, which is a single half-graben with the primary border-fault margin running along the eastern side of the lake. A zone of north–south trending faults downthrown to the west lies in the centre of the lake here. The Central Basin, covered by Block 3, extends about 150 km and is bound on the west by a border fault system downthrown to the east. In the middle of the block a north-west dipping fault zone striking south-west to north-east cuts through the southern edge of the basin, displacing the water bottom by about 75m. Blocks 2 and 3 were awarded to Surestream Petroleum in 2011, who undertook environmental and social

Elephants in the Vwaza Marsh National Park.

impact studies before selling the acreage to UAE-based Hamra Oil in 2013. It undertook airborne gravity, magnetic and full tensor gravity surveys and claims that the results indicate potential hydrocarbon accumulations, particularly in the deepest areas of the lake. The company is reportedly planning further investigations, possibly including 2D seismic and onshore drilling using environmentally friendly techniques.

Block 4, Lake Malawi South, encompasses the largest and shallowest part of Lake Malawi, the South Basin, where water depths of about 400m are found near the primary border-fault on the eastern edge of the lake. Another UAE company, RAK Gas, holds this acreage and the adjacent onshore Block 5 in the Lake Chilwa/Lake Malombe area to the south and has completed full tensor gravity surveys as well as environmental impact assessments over the two blocks. There are plans for more detailed geological mapping in parts of the acreage. Block 5 is believed to hold good thicknesses of sedimentary rocks.

Ghana-based Pacific Oil and Gas has also conducted airborne geophysical surveys across its Block 6 Lower Shire rift acreage in the very south of the country.

The Malawi government recently launched a project to geologically map the whole country, last done in the 1960s. Funded by France, Finland and South Africa, the project will commence with a countrywide aeromagnetic survey and will have a particular emphasis on mineral potential.

Issues to Solve

Although still in its infancy, hydrocarbon exploration in Malawi is already controversial. Licence allocation and alleged secrecy surrounding the process raised concerns that the original contracts had serious shortcomings. Exploration by RAK Gas and Hamra was briefly suspended in 2014 while legal investigations were ongoing and there have been some renegotiations, with moves to increase government take. The government is also undertaking a review of the Petroleum Act to tighten licences and regulations.

The greatest chance of hydrocarbon discoveries is in and around Lake Malawi, which is bordered to the north and north-east by Tanzania. There is a decades-long dispute over this area, as Tanzania claims half the lake – which it calls Lake Nyasa – while Malawi draws the boundary at the east coast. In May, Malawi threatened to take Tanzania to the International Court of Justice over the issue and negotiations are ongoing. Neither Mozambique, which owns the east-central part of the lake, nor Tanzania are encouraging exploration in the area at the moment, because exploration and discoveries elsewhere in their countries are taking priority. Heritage Oil has undertaken gravity and geochemical surveys on its Tanzanian Kyela block at the northern end of the lake and reported the presence of tilted fault blocks and structural features, reinforcing the prospectivity of the area.

Environmental Concerns

The prospect of drilling in Lake Malawi raises a number of environmental and ecological concerns which must also be taken into consideration. The third largest lake on the African continent, it is hugely important in the local economy; over a million Malawians rely on it for water, electricity, irrigation, and most importantly, fish. The lake is thought to be home to more tropical fish species than found in any other freshwater body on Earth, including over 1,000 species of colourful cichlids, of which at least 395 are endemic. Scholtz et al. (2001) found that water levels in Lake Malawi have ebbed and flowed many times over the past million years, sometimes by as much as 200m, which is thought to explain this diversity. The lake gives a unique record of climatic, evolutionary and tectonic change in tropical east Africa, and some believe it is as important in evolutionary studies as the Galapagos Islands. In recognition of the unique nature of this lake, the Lake Malawi National Park at its southern end was designated a UNESCO World Heritage site in 1984.

Fishing is a mainstay of life near Lake Malawi.

It is clear to see, therefore, that the prospect of drilling for, and producing hydrocarbons from such a unique and fragile ecosystem will be fraught with environmental concerns for many people. The government has countered these by pointing out that they have an overall structure in place to ensure sustainable development and also insist that only onshore drilling using modern technology will be allowed in the lake area.

Managing Expectations

Malawi is one of the world's most densely populated and least developed countries; more than three-quarters of the population depend on agriculture, which accounts for about one-third of GDP and 80% of export revenues, the majority being tobacco. Most of the population use wood as their domestic fuel, which, coupled with deforestation for tobacco plantations, is environmentally unsustainable.

It is understandable therefore, that Malawians are looking at the possible wealth in their rocks, and in particular at the definite potential for discovering oil and gas. Licences to explore for hydrocarbons include local content policies to ensure local opportunities and jobs, and discussions have been held with local stakeholders, increasing expectations in those regions. However, it is early days in the exploration process and these expectations should be tempered by the reality of the time scale and economics involved in exploring and developing a discovery; the many calls on oil companies' limited exploration budgets in the present price situation; and the issues involved in exporting from landlocked Malawi to markets a long way away.

Acknowledgement: Many thanks to Hilton Banda, Akatswiri Mineral Resources, for assistance with this article.

References available online. ■

Composite satellite image of the Mulanje Massif in south-east Malawi, an isolated predominantly granite mountain range which rises to 3,000m.

Digitally Transforming Data Management for Geoscience

JAMIE CRUISE
Target Energy Solutions

Technology and processes are changing rapidly, but data remains at the heart of everything we do.

lesleywang2015

As the oil and gas industry recovers from the downturn, the surge of new cloud technologies, analytics, the 'Internet of Things' and machine learning tools entering the business are promising to digitally transform old business processes and drive big improvements in efficiency. This article explores how data management services are evolving to play a vital role in this transformation of our working lives and the way we interact with complex information. How will traditional data silos evolve to support new analytical toolkits? Will data management departments progress to become more agile and efficient? How can we empower users to access relevant, high-quality data more effectively? And can we deliver lower-cost, open, integrated data-centric working environments, fit for the new generation of geoscientists, engineers, data scientists and data managers?

A Brief History of Geoscience Data Management

Data has always been at the heart of the oil and gas business. We conduct geophysical and geological surveys that allow us to construct pictures of the subsurface when we explore for reserves, we create and capture data when we plan, engineer and develop fields, and we continuously acquire data as we produce from these assets. The timeline of technology and services that data managers use to manage this hugely diverse collection of data charts the evolution of the tools used by geoscientists and engineers through our industry's historical journey.

In the analogue era, data management involved managing large physical libraries and warehouses of prints, films and analogue tapes. With the advent of digital technologies, we began to extend these libraries to include digitally formatted tapes for processing on mainframes and minicomputers.

In the workstation era, we started to work with large volumes of online data and developed disk-based formats for efficient interactive data access. We built highly structured databases, and we used advanced visualisation, modelling and simulation systems to accelerate interpretation and planning.

In the desktop application era that has dominated data management for the last 10 years, we saw a move away from proprietary workstation technology towards desktop platforms that took advantage of huge leaps in compute, memory and video capacity of consumer PCs, to deliver a wide range of functionality from seismic to economics. In parallel with the rise of the desktop application suite, our industry also started to build new, large-scale, centralised computing services for data management and processing. In the data management domain, 'big iron' systems were built to manage regional-scale and corporate datasets that held all the data for a particular discipline.

But unlike the transition between geological epochs, the evolution from one data management era to another does not typically involve a convenient mass-extinction event. In the world of data management, old species of data live on rather than joining the fossil record. It is only the data managers that become petrified.

The Digital Transformation Deluge

In the '80s and '90s, we might have reasonably claimed that oil and gas was pushing technical computing boundaries and was at the leading edge of visualisation, big data and large scale analytical processing. However, the developments in computing over the last 20 years have seen oil and gas data processing innovations reduced to a speck in comparison with those innovators that now dominate our highly connected and globalised digital society. New businesses are now creating a wave of 'Digital Transformation' that presents a powerful challenge to orthodox business models and stagnant enterprise IT platforms.

In the new digitally transformed economy, conventional wisdom does not provide much of a guide to what tomorrow's organisation will look like. The world's largest retailer owns no inventory, the world's largest taxi company owns no fleet, the largest accommodation provider owns no real-estate and the most popular media owner creates no content. Some might argue that these are transactional businesses, and are therefore poor analogies for the 'special' world of upstream data management, but digital transformation is less about the common ground between businesses that are transformed, and more about simplification or reduction in the use of intermediaries as a way of improving productivity.

The traditional oil and gas technologist is steeped in the culture of enterprise computing, and this new wave of unfamiliar technology has been resisted for some time. But the levee holding back the surge has finally broken, and we are faced with a deluge of innovation entering our industry, the origins of which lie in social media, online advertising and the gaming industries. Rather than being overwhelmed, can we embrace this change, rally together and deliver better data management products and digital services to our consumers?

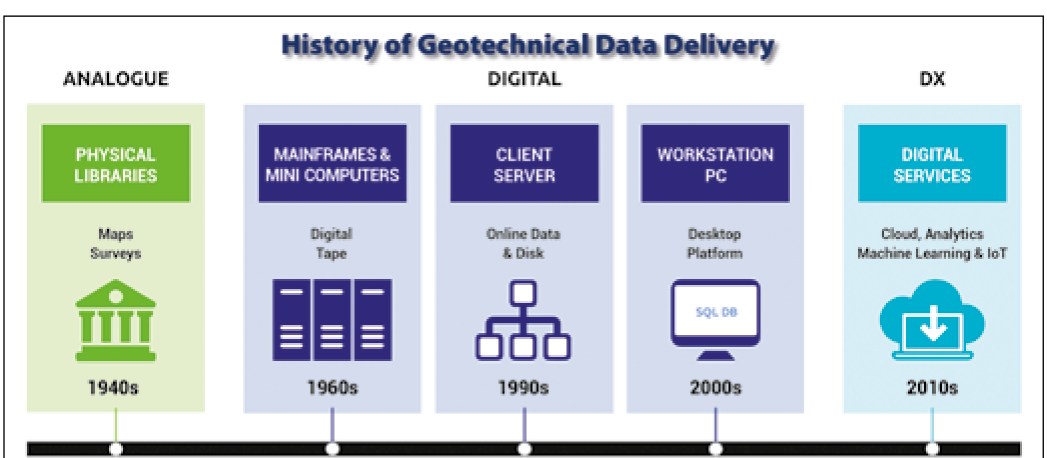
What can we do with this lot?

Accelerating Cloud Technology Adoption

The notion of using shared, public infrastructure has sat uncomfortably with organisations that are used to playing their cards very close to their chests, but in the current low-cost operating environment, the economic benefits of paying for IT infrastructure, data storage and applications 'as a service' are overwhelming. Companies have been steadily transitioning through internal and hybrid clouds, and now more are committing towards a Cloud First infrastructure policy for all of their IT needs.

The traditional arguments against using cloud services for petrotechnical data have included hidden and long-term costs, security concerns, volumes of data involved and loss of control of data and systems. These arguments have become weaker as more critical, non-technical enterprise IT systems are migrated to cloud. After all, if our most sensitive commercial data can be entrusted to the cloud (e.g. email, ERP, documents etc.), then maybe it is safe enough for bulk seismic trace storage. In general, the exploration and production departments in oil companies are starting to lose their 'special' status in IT terms, and are increasingly expected to adopt cost-effective systems.

There are still hard barriers to cloud adoption in certain business scenarios. Many countries have laws that prevent data from leaving their geographic borders. On the other hand, we also see data regulations evolving to become more aligned with modern digital infrastructure as regulators increasingly recognise that their primary challenge is not to protect their data, but to get as much of it in front of as many eyeballs as possible to stimulate inward investment.



Improving Data Services Delivery

Digitally transformed data management services delivery can both improve service quality and reduce costs. Shared online workspaces enable teams to collaborate remotely, across geographic, organisational and time-zone boundaries. Online 'data factories' can be created to extend the capabilities of a small core team. Online workflows and tools can dramatically improve the way teams control data quality, data loading and the governance of high-value datasets. Raw data placed on the cloud can be accessed by offshore or outsourced workers, with processed results distributed, reviewed and approved, interactively online.

This globally-distributed, collaborative working will become increasingly important given the demographic changes our industry has experienced in recent years – the 'big crew change' is well underway. Experienced staff permanently lost to the industry need to be replaced with less experienced staff in lower-cost locations, working with easy-to-use, automated data processing tools. The same environment can be used to re-engage experienced staff on a part-time or consultative basis.

The concept of a collaborative online workspace can be extended to full geoscience and engineering projects, from simple processing and interpretation through to field development planning. Using modern cloud infrastructure from major providers, it is now possible to deliver full interactive working environments as a cloud service, with legacy desktop applications hosted alongside cloud-native services. Creating virtual professional service teams in the cloud will improve the utilisation of global geoscience and engineering teams in the same way that a cloud-hosted data factory improves the utilisation of data management resources.

Rise of the Data Scientist

Traditional petrotechnical analysis revolves around the creation of physics-based predictive models. These are developed and executed by geoscience professionals with a deep understanding of geology, geophysics, engineering, reservoir dynamics, production technology and economics, among other things. They are supported by data managers who ensure the availability of high quality data that powers the decision-making process.

In regions where there is a high density of data from large-scale drilling and completion operations, significant money – and faith – is now being invested in advanced analytical techniques such as machine learning, to augment or replace decisions traditionally made exclusively by geoscientists and engineers. Some companies now use algorithms to define optimal drilling locations, using automated or semi-automated systems that deliver results on much shorter cycle times compared to traditional methods.

To be successful and meaningful these algorithms require vast volumes of data – much more than traditional human-driven workflows require. These new methodologies introduce a new role to the traditional decision-making process: the Data Scientist. The data scientist is a decision maker, in the same way that a geoscientist is a decision maker. However, he or she may not be a domain specialist. The data scientist who is helping you discover a pattern in your data to optimally place your next well, could be equally qualified to work for a client who wants to know the ideal number of ridges to place on the sole of their new running shoe.

That might sound far-fetched, but there can be no doubt that many companies believe that they can generate fresh insight, reduce decision cycle times and steal a march on their competition by automating the search for patterns and relationships in their data. In order for the data scientist to build effective models, they still need to collaborate with domain specialists to understand the features of the domain, as well as work closely with data managers to get access to high-quality, certified data.

The data manager has a critical role to play as a supplier of data for analytics projects. In the same way that they are a crucial part of the governance process for managing the traditional quality-controlled project and corporate data delivery to applications, they must also now track and manage petrotechnical data as they move into and out of analytical projects. If analytics projects are not connected with evergreen, validated data sources, the results of those analyses cannot be trusted by the business, and we will once again be burdened with the high cost and increased risk of managing and working with duplicated, untraceable and untrusted data.

Data Remains the Key

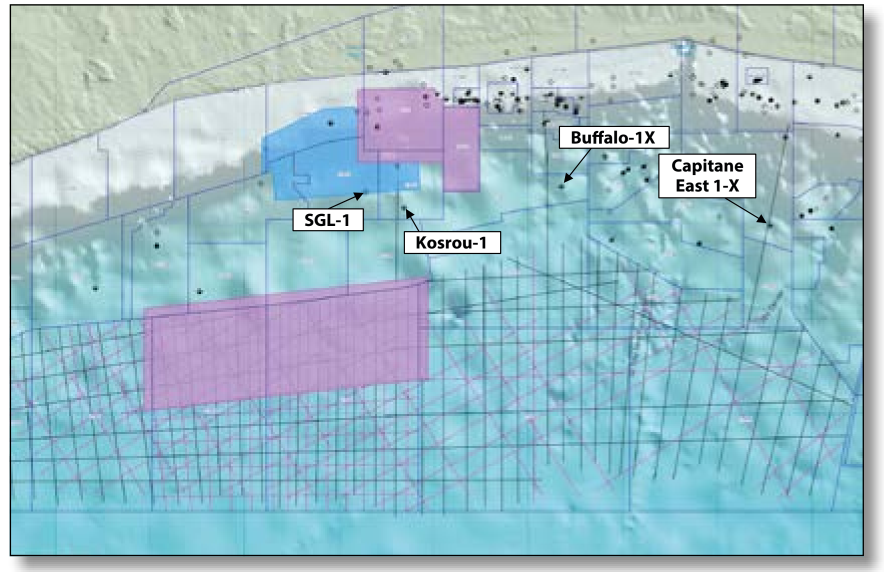
These technologies are digitally transforming the way we work and interact with our world at every level. Oil companies that ride this wave will significantly increase the current productivity of their knowledge workers, optimise business processes and reduce operational costs in a way that is not possible through incremental change. But whilst technology, people and processes are changing rapidly, we can take some comfort in the fact that data will still remain at the heart of everything we do. ■

Fully interactive and collaborative working environments can now be delivered as a cloud service.

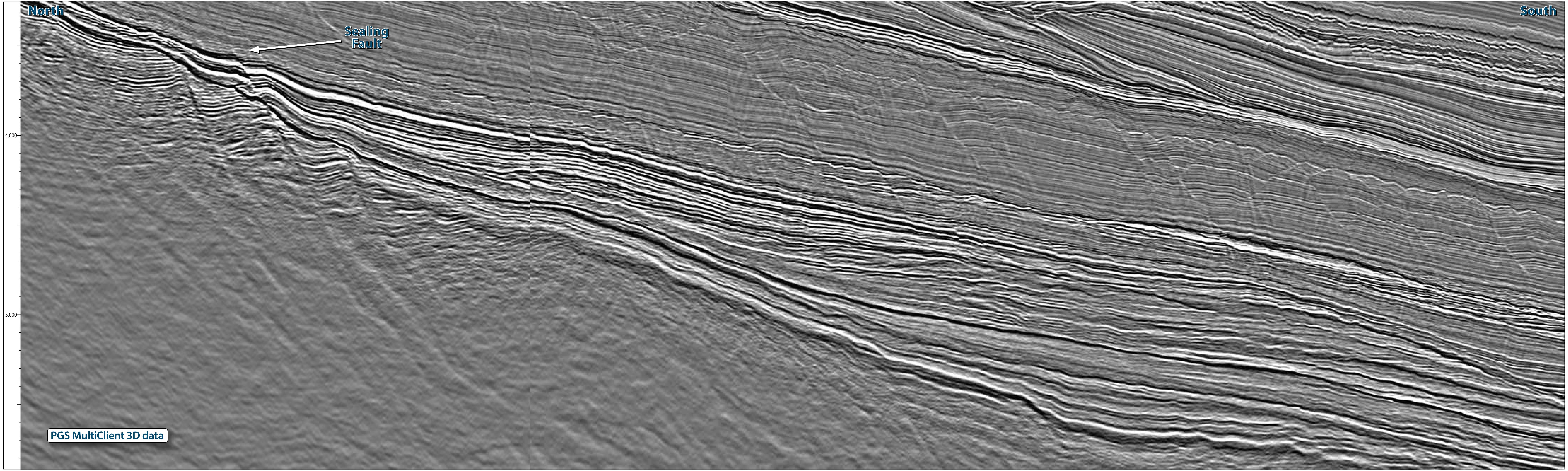
Côte d'Ivoire: Completing the Jigsaw

Distinct rift and transform tectonic phases are important in creating fault-seals and pinch-out traps to sandstone reservoir bodies in deepwater Côte d'Ivoire.

With every well drilled and seismic dataset acquired, understandings of the geological fundamentals of the Côte d'Ivoire Basin have improved. As the coverage of seismic datasets has extended from the shelf to the deepwater as well as from hydrocarbon fields to frontier areas, pieces of the tectonic jigsaw can be completed. Additionally, greater availability of modern, high quality seismic data over exploration wells, be they dry holes or hydrocarbon discoveries, will enable a thorough post-well analysis that is focused upon the influence of tectonism on the results of the well, thus further de-risking future prospects in the area.



Base map of central offshore Côte d'Ivoire showing the PGS multiclient seismic data library, together with the location of the four wells discussed in the text.



The lead shown is from Block CI501. The upper part of the post-transform sandstone body does not have a channelised character and appears to be offset and potentially sealed by a transform fault, demonstrating reactivated late tectonism.

Awaken Your Structural Geologist!

An understanding of tectonic phases will help regional exploration, facilitate modelling and de-risk leads.

MATTHEW TYRRELL, PGS
Dr. IBRAHIMA DIABY, Petroci

Offshore Côte d'Ivoire is a part of the wider West African Transform Margin, a structurally complex area bounded by major tectonic lineaments that formed during its separation from the Equatorial Margin of Brazil during the early Aptian. It exhibits syn-rift sub-basins that are bounded by later large right-lateral transform movements that drove the inversion of earlier basins and structures.

Tectonic Phases

In the sub-Saharan passive margins of Africa there is a distinct syn-rift phase with extensional basins providing new accommodate space, followed by a post-tectonic phase that sees sediments deposited during rising sea-levels in a period of tectonic quiescence. In contrast to this, the West African Transform Margin has a more complex tectonic evolution, with multiple extensional and compressional tectonic phases that exhibit interaction and remain active present day.

In order to constrain regional exploration and facilitate the modelling and de-risking of identified leads, these multiple tectonic phases are being interpreted and corroborated on regional datasets. Four controlling geological phases can be recognised, defined by tectonic events and constrained by plate tectonic reconstructions and gravity modelling.

The controlling phases, that may not be exhaustive, are:

a. Pre-rift: indeterminate Palaeozoic to Early Mesozoic sandstones and mudstones within intracratonic basins, undrilled in Côte d'Ivoire.
b. Syn-rift: pull-apart movement resulting in coastal and shallow marine sands of Aptian and lower Albian age. These sandstones provide the reservoir for most structural plays in Côte d'Ivoire.
c. Syn-transform: right lateral strike-slip transpressional movement of late Albian to Cenomanian age, resulting in the inversion of pre-rift and syn-rift basins and witnessing the deposition of shallow marine sands.
d. Post-transform: deeper water clastic deposits that remain influenced by transform related inversion and faulting.

These four tectonic phases can be interpreted on seismic and in well data across offshore Côte d'Ivoire and provide a tectonostratigraphic framework to constrain the interpretation of sea-level controlled depositional sequences. Furthermore, the influence that late tectonic movements have on reservoir distribution and hydrocarbon trapping in the post-transform is becoming increasingly apparent and the results of recent wells when integrated with regional seismic data suggest the recognition of two distinct plays.

Key Tectonically Influenced Plays

The two post-transform plays, influenced by late tectonic movements, are transform channel and fan sandstones that onlap against syn-depositional inversion structures that provide an up-dip sealed pinch-out; and post-transform channel and fan sandstones that are truncated up-dip by late-stage faults, which are either inversion-derived or late transform movement faults, providing a fault-seal.

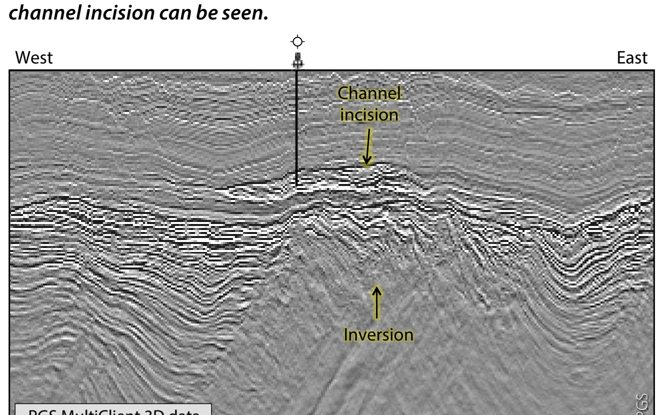
Many exploration wells have targeted viable channel or fan sandstone reservoirs and drilling results have shown the presence of good quality reservoir sandstones charged with hydrocarbons. Assessment of these successes suggests a strong indication that there are associated late-stage tectonic movements that have contributed to the success of the play, with syn-depositional inversion providing a trap and/or late-stage fault truncation providing an up-dip seal.

Whilst such late-stage tectonic activity can provide traps and fault-seals that contribute to the success of plays, the activity can also cause plays to fail. Inversion movements can reposition reservoirs, resulting in trap leakage, and can also cause channels to become more erosive, incising into underlying sandstones and breaching their top seals. Furthermore, late-stage faulting or fault reactivation after hydrocarbon charge can cause trapped hydrocarbons to leak through fault breach.

Role of Tectonism in Key Wells

The well-publicised Jubilee Field, discovered in 2007 by Kosmos Energy in offshore Ghana, is an example of a post-transform sandstone reservoir that is truncated up-dip

Figure 1: The South Grand Lahou-1 well (SGL-1), which was dry, targeted a post-transform sandstone body. Inversion of the syn-rift during the transform phase has uplifted the sandstone body and evidence of channel incision can be seen.



by late-stage faulting that provides the seal to hydrocarbon migration (Richmond Energy Partners, 2016). Similarly, in the nearby cluster of fields known as TEN (Tweneboa, Enyenra and Ntomme), hydrocarbons are understood to be trapped by lithological barriers within stacked sand channels, draped over an inversion structure, with additional sealing provided up-dip by late-stage faulting similar to that at Jubilee (Tullow, 2008).

In the deep waters offshore Benin, the Houmelan-1 well, drilled in 2013, tested a Senonian-age post-transform sandstone reservoir with good rock qualities. The well had oil shows, demonstrating a working petroleum system (Shell, 2013) but the hydrocarbons were believed to have migrated through the reservoir due to a lack of up-dip trap.

In Côte d'Ivoire, the South Grand Lahou-1 (SGL-1) well, drilled in 2009, targeted similar mid-Cretaceous age sandstones that onlap against an inverted syn-rift structure. Analysis of the reservoir target using multiclient 3D seismic data shows that although the sandstone body exhibits a pronounced onlap in dip direction, in strike direction the body is clearly uplifted over the top of an inversion structure and as such likely had its trapping potential disrupted (Figure 1).

The Kosrou-1 well, drilled in Block CI-116 in 2012, tested a sandstone channel system (*Offshore Energy Today*) that onlaps an inverted syn-rift structure, known as the East Grand Lahou High. This well encountered oil shows in sandstone channels with good reservoir qualities but are understood to have lacked top seal due to incision of younger channels, resulting in hydrocarbons migrating up dip. Further analysis is required on the available multiclient 3D data to understand the relationship of this incision with the timing of inversion events (Figure 2).

The Buffalo-1X and Capitane East 1-X wells, drilled in Côte d'Ivoire in 2011 and 2014 respectively, tested post-transform mid-Cretaceous channel and fan sandstone bodies. Both wells encountered hydrocarbon shows and sub-economic accumulations and the failure of the plays is interpreted as being attributable to the timing of late-stage tectonic events. At the Buffalo-1X well, the sand body appears to have depositional continuity over the inversion structure, suggesting that the inversion may not have been active enough to cut off the sand system and provide a trap. At the Capitane East 1-X well, although the pinch-out against the inversion structure appears trapping in dip direction, the upper part of the reservoir sandstone body is interpreted to have depositional continuity around the flank of the inversion structure (Figures 3 and 4).

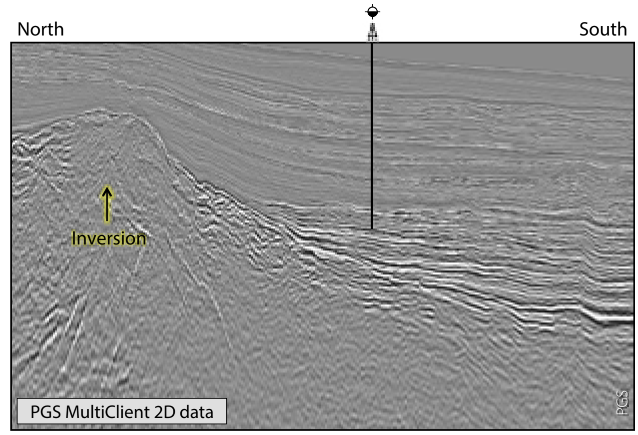


***Figure 2:** The Kosrou-1 well had oil shows in a post-transform channel system that onlaps an inverted syn-rift structure. Although the pinch-out appears trapping, channelisation of the youngest part of the body may have breached the top seal.*

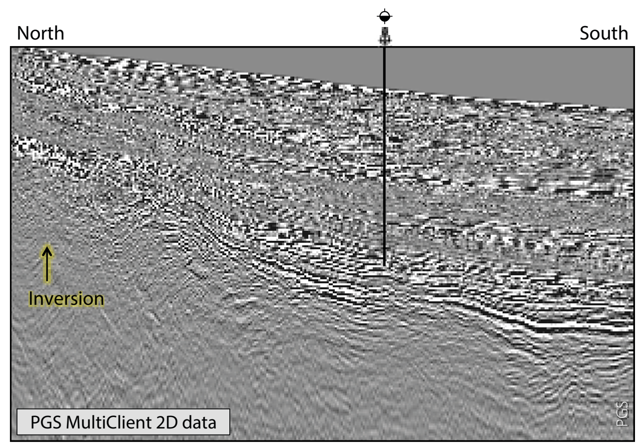


***Figure 3:** The Buffalo-1X well encountered oil shows in a post-transform channel system that onlaps an inverted syn-rift structure. The upper part of the system appears to have depositional continuity over the inversion structure, suggesting a lack of trap.*

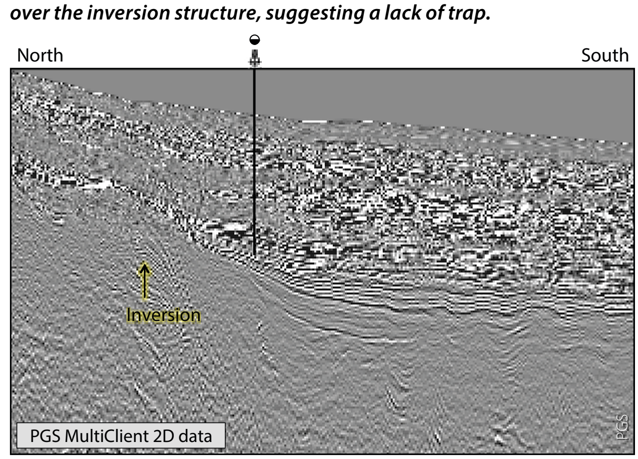


***Figure 4:** The Capitane East 1-X well encountered oil shows in a post-transform channel system that onlaps an inverted syn-rift structure in the dip direction but is interpreted to have depositional continuity around the flank of the structure.*

Robust Tectonic Framework

With a robust tectonic framework in place, corroborating the different observed rift and transform phases together with the timing of inversion, explorers can begin to model and de-risk the influence of late-stage tectonism on post-transform leads. The relationship of the timing of inversion to sand body deposition should help de-risk the trap integrity of pinch-outs against structural highs; where inversion is weak or late the risk of sand continuity up-dip is likely greater. Additionally, where inversion is syn-depositional and more pronounced, the risk of channel incision into the top of the reservoir resulting in top seal breach is greater. Finally, where late-stage faults are seen to cut through the reservoir body, either driven by inversion or simply the reactivation of earlier rift faults during transform movement, the timing of the faulting is critical. Where the fault cuts pre-date charge they can provide a critical seal for hydrocarbons but where faults post-date charge (Figure 4) they can rupture top seals, resulting in leakage.

References available online ■

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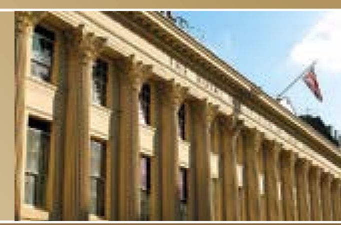

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When 'Being Green' is Great for Business

Many companies and industry commentators consider 'being green' a costly and unnecessary investment, but this need not be the case.

DUNCAN ELEY, CEO, Polarcus

Every organisation has the opportunity to make the right choices in order to contribute to a more sustainable future for us all. The compelling evidence provided by the Intergovernmental Panel on Climate Change (IPCC), in addition to the critical, time-bound United Nations Millennium Development Goals, should be incentive enough for the exploration industry, and society at large, to responsibly take action. Unfortunately, this is not yet the case.

The 3D seismic exploration sector is highly cyclical and correlates closely with the price of oil. The number of 3D vessels in the sector has more than halved during the current downturn. A corresponding environmental benefit of this natural selection is that a large number of old, inefficient tonnage has been scrapped. Unfortunately, in the resulting competitive environment, many companies and industry commentators consider 'being green' a costly and unnecessary investment, often quoting their challenges to comply with 'obligations to all stakeholders'. As a result, few companies implement thorough environmental measures in advance of international policy directives. A proactive approach, however, is critical when considering the inevitable time delay in aligning nearly 200 nations across the globe, all with vastly diverging priorities. Perhaps now, when compelling evidence proves that 'being green' can actually be great for business, more companies will adopt a proactive approach.

Multi-Source Revolution

Part of the challenge for the 3D seismic industry is that a seismic arms race took place over the past three decades, which led to the development of increasingly larger seismic vessels towing more and more streamers in the water. At face value, this evolution reduced the cost of 3D seismic for the oil companies through more efficient acquisition of seismic data (i.e. more square kilometres acquired per unit of time). However, this seismic arms race has inadvertently led to significant environmental, safety and geophysical inefficiencies. Larger vessels meant increased displacement (resistance through the water) and thus more energy consumption required to propel these ships through the water. Towing more streamers meant that the offshore seismic crews had to maintain more equipment, leading to significantly increased exposure to hazards for people working on the back deck of vessels, and in the small boats deployed to carry out equipment maintenance in the water. In addition, the increased number of streamers (corresponding to the width of the seismic array) reduced the geophysical integrity of data on the outer streamers when used in combination with traditional seismic sources in certain geological settings. A tipping point had been reached where bigger was no longer better.

Focusing on optimising the geophysical integrity of seismic data has led to the introduction of multiple array seismic sources to improve seismic data cross-line spatial sampling. A conventional towed streamer seismic source comprises only two arrays, whereas multi-source configuration provides three or more arrays. Developments in continuous recording systems and seismic data processing have allowed more arrays to be added and overlapping source records to be acquired, improving not only cross-line data sampling but also in-line data sampling. The energy from these overlapping source records can be de-blended during data processing, producing a discrete recording for each source. The result of this multi-source acquisition technique is that the increased number of arrays, in combination with fewer seismic streamers towed further apart, delivers a 3D seismic acquisition footprint that enables substantially higher

Polarcus, Adrien Baltardive

Banning the use of Heavy fuel Oil in the Arctic is a new IMO regulation.

productivity whilst maintaining data quality.

By simply adding one more array to a conventional seismic source, the same data quality and project efficiency can be achieved with 12 streamers towed 150m apart as that obtained with a conventional source configuration with 18 streamers towed 100m apart.

The benefits of a reduced number of streamers in the water are obvious: less drag on the seismic vessel, resulting in less fuel consumption and associated emissions to air; less capital investment associated with streamer equipment; lower costs resulting from the more efficient vessel; and reduced safety exposure for 3D seismic field crews. The multi-source revolution has therefore enabled seismic operators to realise significant operational efficiency gains and reduce the overall safety risks for onboard personnel, while delivering high quality 3D seismic data to clients.

This innovative seismic acquisition technique has now also proved its positive effect on the environment. During the second quarter of 2017, approximately 60% of Polarcus projects were acquired using a multi-source configuration called XArray™ and the quarterly reporting of the company's emissions showcased the positive environmental effects. As a direct result of acquiring more seismic data per sail line, a decrease of CO_2 emissions of about 10% per common mid-point was recorded.

Not All Emissions Are the Same

Discussions about gaseous emissions often revolve around carbon dioxide (CO_2) and the amount of carbon that is being emitted into our atmosphere. Carbon dioxide is an easy gas to quantify and compare against, and therefore acts as a useful reference point. However, according to the IPCC there are far bigger threats to our global environment than CO_2. The IPCC has established the Global Warming Potential (GWP) to allow comparisons of the global warming impact of different gases. The GWP is a measure of how much energy the emissions

Whales are crucial to ocean carbon absorption by pushing nutrients from the bottom of the ocean to the surface when they dive, and through fecal plumes, which provide nutrients for marine plants.

of 1 ton of gas will absorb over a given period, relative to the emissions of 1 ton of carbon dioxide. The larger the GWP, the more that gas warms the Earth when compared to CO_2.

Based on this research we now know that nitrous oxides (NO_x) have a GWP of almost 300 times that of CO_2, making them much more damaging gases than carbon dioxide in relation to global warming.

But the most toxic gas of them all is less well-known. Sulphur oxides (SO_x) contribute to the formation of acid rain and have approximately 400 times the environmental impact of CO_2. In recent years, the International Maritime Organisation (IMO) has implemented stringent regulations to limit sulphur emissions from vessel-operating companies in Emission Controlled Areas (ECA) to 0.1%. However, global limits are still at 3.5%, which encourages vessel-operating companies to continue to operate using the dirtier energy sources such as Heavy Fuel Oil (HFO) instead of the more efficient and environmentally-friendly alternative, Marine Gas Oil (MGO).

As the oil price has deteriorated along with E&P companies' exploration budgets, reducing operational cost has become a key focal point. At face value, HFO is significantly cheaper than low-sulphur MGO so it is challenging for vessel operators to accept responsibility and choose an alternative, responsible fuel option that causes significantly less damage to the environment than HFO. However, the actual financial benefit of cheaper HFO needs to be offset against realities such as the large and inefficient platforms that HFO is typically used to fuel, or the real cost of transporting and transferring HFO offshore and of heating and treating HFO onboard vessels.

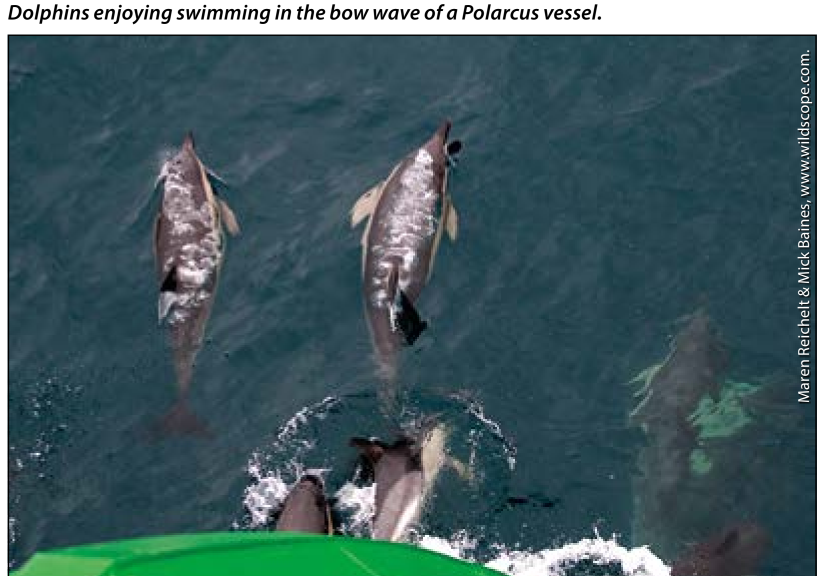
Key Initiatives

While maintaining the lowest operating cost in the 3D seismic industry, Polarcus's gaseous emissions continue to fall significantly below regulatory requirements and international averages of other companies. Enabling this superior combination of financial and environmental performance is a result of key initiatives that focus on geophysical and operational efficiency and the implementation of drag reduction across the entire fleet, in combination with Polarcus's commitment to low-sulphur MGO. By using MGO fuel, an average sulphur content of 0.1% was achieved across all operations in 2016, including fleet support vessels. This weighs in at 25 times lower than other companies in the industry and significantly below IMO regulations, even within ECAs.

The new regulations that the IMO is implementing, such as limiting the global fuel sulphur content levels to 0.5%, designating new ECAs with fuel sulphur content limits of 0.1% and banning the use of HFO in the Arctic, are a clear indication that environmental sustainability is gradually taking a front seat. We invite the rest of the industry to work towards a more sustainable future.

The author would like to thank Polarcus colleagues *Phil Fontana*, *Peter Zickerman* and *Erik Burlid* for assistance with this article. ■

Dolphins enjoying swimming in the bow wave of a Polarcus vessel.

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London, 17 Oct 2017
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Stavanger, 30 Nov 2017
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London, Dec 13
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London, 23 Jan 2018
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Liberia
A Fresh Approach

New thinking inspired by innovative modelling could open new plays in West Africa.

BEN SAYERS and **ALEX BIRCH-HAWKINS**, TGS;
RUFUS TARNUE, NOCAL;
GERRARD SPEAR, LAUREN MAYHEW, Lyme Bay Consulting

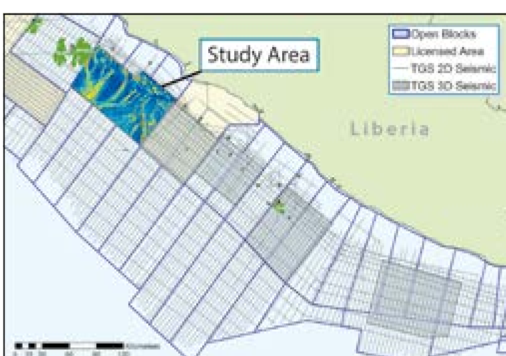
Recent exploration in Liberia has not provided the commercial success we all want, with the most recent well, Mesurado-1 (drilled by ExxonMobil in Block 13 in approximately 2,500m water) coming up dry. TGS feel that history is repeating itself with stratigraphic traps with strong AVO support being drilled and not producing a success. There is a working petroleum system, proved by sub-commercial discoveries, and Mesurado-1 provided a much needed boost to the understanding of reservoir quality, as 118m of good quality Santonian were logged (COPL press release, 19 December 2016). With all the pieces of the play puzzle in place, TGS has decided a fresh approach is needed to prospectivity hunting and has therefore begun a new wave of interpretation of the seismic data to help solve the puzzle and unlock the treasures buried offshore.

TGS has partnered with NOCAL (National Oil Company of Liberia) for over 15 years and has built up a comprehensive seismic database with over 34,000 km 2D and 24,500 km^2 3D seismic. The company is committed to working with the excellent exploration team in Monrovia to help deliver the hydrocarbon response so eagerly anticipated. The first step of the reinvigoration of geological and geophysical analysis is to work with Lyme Bay Consulting, taking a data driven approach to leads and prospect identification.

Detailed Reconnaissance Study

There are two known distinct hydrocarbon systems (Early and Late Cretaceous) within offshore Liberia (Bennett et al., 2002). Initial exploration demonstrated the potential for an Early Cretaceous petroleum system consisting of Apto-Albian marine and lacustrine shales, although the Late Cretaceous system has received more attention in recent years. This consists of Late Cenomanian to Turonian marine shales deposited throughout the central and southern Atlantic during a global anoxic event. Although missing in shelf wells, this sequence is characteristically organic-rich throughout offshore west Africa.

Trap types within this system are confined to stratigraphic channels and fan systems, a few of which have been delineated by the work undertaken by Lyme Bay Consulting, who applied their Detailed Reconnaissance Study (DRS) workflow to the pre-stack time migrated 3D volume and associated angle stack volumes from Blocks 15, 16 and 17 in northern Liberia, as shown in the inset to Figure 1. The DRS builds a 'GeoModel' based on the underlying seismic data, and calculates and correlates the relationship between 3D seismic events according to the similarity of the wavelets and their distance from each other. The DRS produces a horizon-consistent map



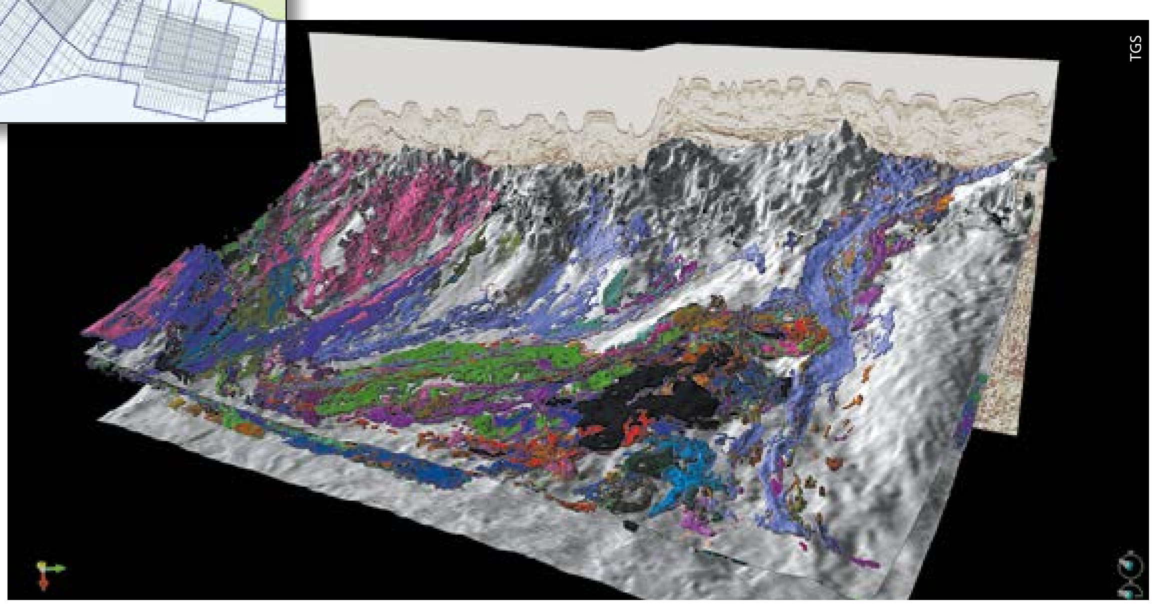


Figure 1: A geobody extraction highlighting extensive channel complexes overlain on the Top Cretaceous surface.

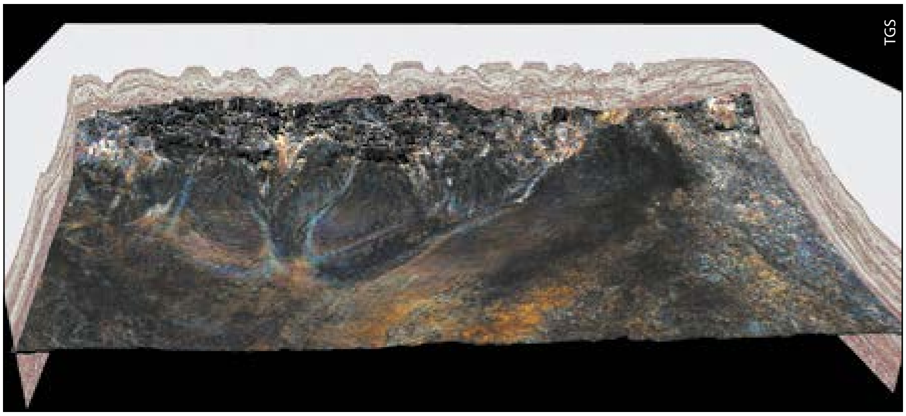


Figure 2: A spectral decompositon surface showing Late Cretaceous canyons feeding a basin floor fan.

for each and every reflector within the dataset. Attributes are then calculated from the original seismic and overlain on the horizons to deliver a high-resolution reconnaissance tool to enable identification of structural and stratigraphic features within the data. Two hundred horizons were generated for this initial pilot study, which TGS will be using to seed the next wave of interpretation and exploration in Liberia.

Geobody Examples

During the DRS work, geobodies were extracted from the data to highlight submarine clastic channel complexes and turbidite systems shedding into the basin from the shelf margin (Figure 1). Attribute volumes were created and analysed including Structurally Oriented Semblance/Coherency, Frequency Decomposition (Figure 2) and Reflectivity Data Amplitudes for the full and partial-angle stack data. The quality of the TGS input data was highlighted in the initial results, with excellent frequency content proving very valuable even at depths of greater than seven seconds.

Figure 2 shows a spectral decomposition indicating an example of an Upper Cretaceous stacked fan system being fed from channels on the shelf through canyons downslope to palaeo-basin floor. In total, the DRS has identified over 96 separate channel features from Early Cretaceous syn-rift to Tertiary post-rift. These regional channel and fan complexes have been mapped across the entire 3D study area, with the seismic imaging allowing delineation of multiple stacked systems, all highlighting the excellent reservoirs waiting to be unlocked.

AVO analysis has a lot to answer for in the Liberian Basin, as brightening with offset does not consistently appear to indicate hydrocarbons in this basin. It is possible that a sequence stratigraphic approach would be more beneficial, allowing for traditional geological prediction of plays when searching for drill locations. Integrating this knowledge with the data-driven results provided by the DRS, which in this study highlighted an abundance of braided channels, fan splays and levee complexes, will allow a more intelligent way to discern which sands to drill and which to leave alone.

Gerrard Spear, Geoscience Director at Lyme Bay, said that this DRS analysis is one of the best his company have ever worked on, with the seismic data exhibiting "an embarrassment of riches, with an awful lot of sand in the system". One of the largest basin floor fans identified on the 3D data was from an Upper Cretaceous horizon that is almost 100 km across. The fan is shown in Figure 3, which is an amplitude drape over a spectral decomposition surface. The image shows multiple sediment input canyons, illustrating the fan is a huge amalgamation of clastic supply on the basinal floor.

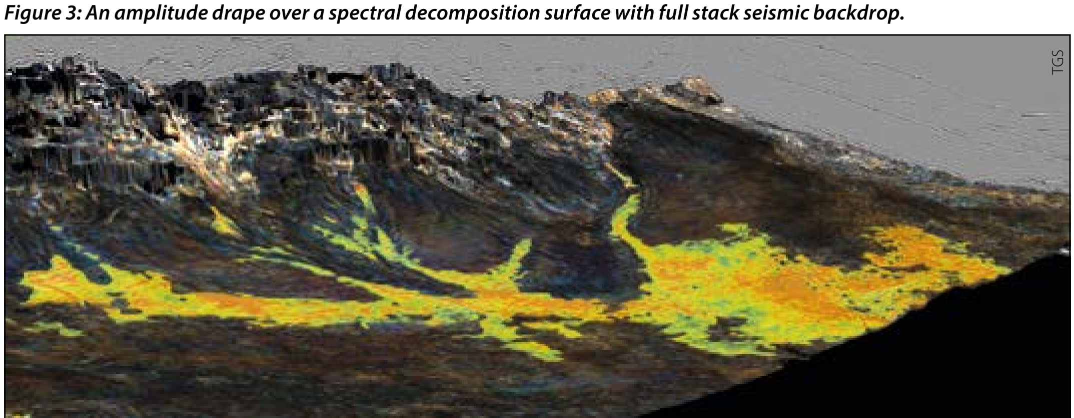
Moving Up and Downslope

It has been said by TGS before that the deepwater unrestricted basin floor fans are where the best reservoir sands could be found. BP and Kosmos are hunting large turbidite fans in the deepwater off the coast of Mauritania, further north on the West African Margin, and believe these deep fans to hold ten times the prize of their shelf and slope counterparts; perhaps this could be the next target for the Liberian explorer. With recent exploration a little further north in Guinea Conakry opening the margin for deepwater drilling, and water depths of over 2,900m now on the operational agenda, the deepwater turbidite plays are no longer out of technological reach.

It is not just in the deepwater that there is potential for Liberia; the next stage of the TGS and NOCAL exploration effort will be to revaluate and update the interpretation of geophysical data in the basin, including up-dip on to the shelf, which first tempted the industry into the offshore realm. The initial Lyme Bay DRS will be used to extract and extrapolate new thinking, opening new plays throughout the region. An update to this work will be published early in 2018.

References available online. ■

Figure 3: An amplitude drape over a spectral decomposition surface with full stack seismic backdrop.



A Cleaner Future for Drilling

Is it possible to drill with environmentally friendly fluids?

KATHRYN SHEPHERD, Clear Solutions International Ltd.

Over the last 30 years, Oil Based Mud (OBM) and Synthetic Based Mud (SBM) have become the fluids of choice for the majority of complicated oil and gas projects, particularly where troublesome shale formations are expected or are known to create unstable borehole conditions. Whilst the effectiveness of OBM and SBM in these environments is not in question, they are expensive and are potentially an environmentally damaging solution. Furthermore, the costs associated with OBM drilling cuttings remediation and disposal are significant.

HPWBM Systems

As a result, in the early 2000s a new trend developed as several drilling fluid companies started to develop and actively promote new High Performance Water Based Mud (HPWBM) systems. The intention was to substitute OBMs for more environmentally friendly water-based drilling fluids. These would provide similar properties to those of OBMs such as shale inhibition (reducing the hydration, swelling and disintegration of clays and shales) and degree of lubrication. The approach to HPWBM varies with each mud company, but all use an aqueous base and a large number of different products to formulate their best possible mud properties, combined with high levels of inhibition to suit the formations to be encountered whilst drilling.

The primary drawback with most HPWBMs is that they do require the use of a significant number of different products, many of which have a negative influence on the rheological properties of the drilling fluid, such as elasticity and viscosity. Specifically, many of the required filtration control polymers and encapsulators (PHPA) are known to increase the plastic viscosity of the fluid and as a consequence, these additives do very little to build the low-end rheology, or low shear rate viscosity. The net result is a tendency for the development of higher equivalent circulating densities with less hole cleaning capability. Furthermore, the use of many HPWBM mud additives are controversial in reservoir sections where filtration control and PHPA polymers have been shown to significantly impair reservoir productivity. This complexity makes them notoriously difficult and challenging to operate and maintain effectively in the field.

Ecologically Friendly Drilling Fluid

In response to these drawbacks, Clear Solutions, an industry leader in drilling fluid technologies, has developed Pure-Bore®, which is manufactured from natural material, using advanced nanochemistry and surface-active encapsulation technology. In contrast to standard HPWBMs, which typically use long chain screen blinding polymers with high molecular weights, Pure-Bore creates a highly sheered drilling fluid able to create superior encapsulation without the screen blinding tendency of a PHPA polymer because the nanochemistry interreacts to create a membrane on the side of the borehole. This effectively seals it and stops fluid entering the membrane, whatever the porosity. As a consequence, the operator benefits from the option to use finer screens, resulting in better cut points, dryer cuttings discharge, less overall fluid consumption and lower dilution rates. This system has been field proven to protect the reservoir whilst drilling and help optimise reservoir productivity; for example, cuttings are taken out of the well very quickly, meaning that wells can be drilled up to 30% faster, reducing risk and minimising downtime.

In addition, almost every HPWBM in the market contains components which in most cases do not readily biodegrade, unlike Pure-Bore, which is environmentally benign and easy to dispose of. The system has undergone many environmental tests in independent laboratories, which have certified it as being non-hazardous to soil and ground water and classed as both harmless and not dangerous to health. Following a successful test for environmental safety in Germany, the following comment was made: "The chemical and physical analysis of Pure-Bore shows that this product, based on current scientific knowledge, has no negative environmental effects on the soil and water it comes in contact with during its use as drilling suspension."

It is now possible to drill faster *and* cleaner. ■

This revolutionary drilling fluid was successfully tested in a case study in Alberta, where the mud properties were proved to be easy to maintain.

Benin

The Low Cost, High Impact Frontier

The overlooked potential of Devonian, Jurassic, Cretaceous and Tertiary plays within the onshore and shelfal Dahomey Embayment.

EMMA TYRRELL, PetroVannin; **PETER ELLIOTT**, PVE Consulting;
MATT LOFGRAN, Elephant Oil; and **BLANDINE BIAOU**, Societe Beninoise des Hydrocarbures

The Gulf of Guinea is characterised by a number of Mesozoic sedimentary wedges, where Cretaceous to Tertiary sequences extend through the shelf to the onshore: the Côte d'Ivoire and Tano Basins, the Dahomey Embayment (Ghana, Togo, Benin and Nigeria) and the Niger Delta. These onshore and shelfal Mesozoic wedges are additionally underpinned in part by Devonian and Jurassic failed-rift basin sediments associated with earlier intracontinental extensional tectonic phases active while Africa still formed a part of Gondwana (Kaki et al).

Onshore geological map showing the location of the Dahomey Embayment.

Palaeozoic and Mesozoic Plays

The Dahomey Embayment, the focus of this article, is the least explored of these sedimentary wedges. In the onshore setting, just 11 exploration wells have been drilled to date, all targeting Mesozoic reservoirs: three in Ghana and eight in Nigeria. Five of these encountered hydrocarbons, whilst an onshore aquifer well drilled at Sazue in south-west Benin in 1932 reported gas that was analysed as C1, C2 and C3, strongly indicating a thermogenic source.

In the shelfal setting, the 24 wells drilled have witnessed considerable exploration success within both Mesozoic and Palaeozoic intervals. The Lomé field, offshore Togo, has some 80 MMbo in place within Lower Cretaceous and Devonian clastics, charged from Devonian brackish marine source rocks, whilst the Seme and Dahomey Fields in Benin contain recoverable reserves of about 100 MMbo within Turonian and Albian clastics, charged from both Lower and Upper Cretaceous source rocks.

Immediately across the maritime frontier in Nigerian waters lie the Aje and Ogo Fields, reportedly with 200 MMbo and multi-TCF gas reserves recoverable from Albian and Turonian sandstones, again charged from Cretaceous source rocks but with unconfirmed reports of a secondary Devonian source

Wikipedia/Jbdodane

rock charge (Brownfield and Charpentier, 2006).

Across the Atlantic Ocean, onshore exploration success has been prolific in the conjugate Potiguar Basin of Brazil. With approximately 1,200 wells drilled and over 100 oil fields discovered, this success suggests that the remaining potential within the onshore Dahomey Embayment may be considerable.

Recent geological and exploration work, conducted to assess the exploitable petroleum resources of the onshore and shelfal acreage of the Dahomey Embayment, has sought to apply knowledge and insight from exploration efforts across the region. Vintage seismic, exploration well data and modern airborne gravity gradiometer and magnetic survey results have been integrated to build a valid geological interpretation; when combined with new regional play concepts this has resulted in the reassessment of the stratigraphy, petroleum systems and hydrocarbon prospectivity of the Palaeozoic and Mesozoic basins.

Proven Palaeozoic Failed Rift Plays

The Devonian to earliest Carboniferous sedimentary basins that underpin the Dahomey Embayment receive fleeting mention in technical publications (Kaki et al), despite being the target of exploration drilling in the shelfal waters of Togo in the 1970s and '80s. Where they have been penetrated, such as in the Lome-2 and Haho-1 wells, marginal marine sandstones with good potential qualities have been encountered, bearing liquid hydrocarbons expelled from a similar age source rock.

Over the Benin shelf and onshore areas, large half-graben structures, with an approximately east-west orientation, can be interpreted in seismic data and extrapolated in airborne gravity gradiometry data. The gravity data also permits the half-graben sedimentary fills to be calibrated to the structures and first-pass depth to basement calculations to be made. Geological modelling suggests that the Devonian-Carboniferous sedimentary basins are extensive throughout the Dahomey Embayment and are probably unconformably overlain by a thin Middle Jurassic sedimentary cover. The boundary between the earliest Carboniferous and Middle Jurassic successions is subtle within seismic data and thus structural interpretations tied to the available airborne gravity data have been made to help map this boundary.

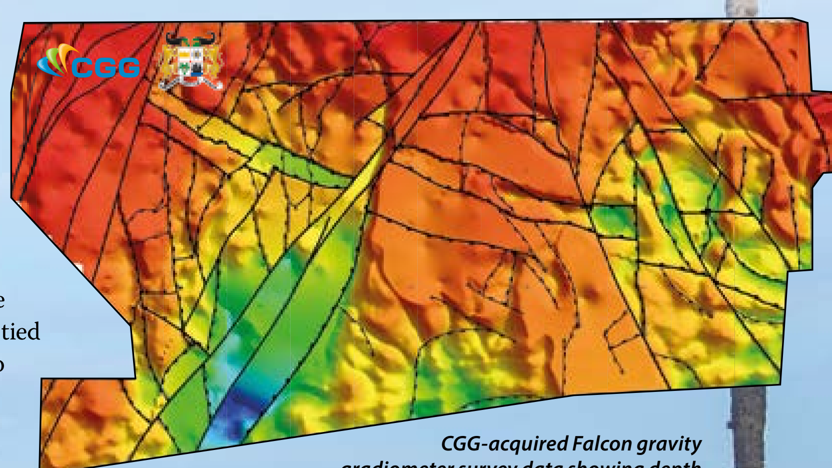
The extent to which these sedimentary basins seen deep within the Dahomey Embayment are connected to the better understood Devonian-Carboniferous basins of the margin is unclear. Encouragement can be taken, however, from the number of gas discoveries made within the Parnaiba Basin, onshore Brazil and the commercial quantities of oil discovered within the Saltpond Basin on the present-day shelf offshore Ghana, both in reservoirs of comparable age.

Enigmatic Middle Jurassic Plays

The controls of the presence of a Middle Jurassic depositional succession, interpreted throughout the shelf and onshore and constrained by penetration by the Lome-1 well on the offshore shelf of Togo, are poorly understood. This enigmatic succession represents a brief episode of pre break-up sedimentation and possibly failed rifting before the onset of the break-up of Gondwana. The Middle Jurassic succession is interpreted to contain deposits of continental clastic sands, possibly equivalent to the Sekondi Sandstone Formation seen on the Ghana Shelf.

In onshore and shelfal seismic, the Middle Jurassic sands are interpreted as being present within a succession of horst blocks with an east-north-east to west-south-west orientation. These provide numerous exploration drilling targets, with multiple blocks exhibiting areal extents of over 140 km^2. Due to the enigmatic nature of this succession, the depositional setting is unknown and thus the likely reservoir qualities need further de-risking. Initial basin modelling studies suggest that even with a small amount of uplift, preserved reservoir qualities of these sands should be good.

The boundary between the pre break-up Middle Jurassic and



CGG-acquired Falcon gravity gradiometer survey data showing depth to basement and fault hierarchy.

Mid-Cretaceous to Tertiary successions is seen in seismic data as a strong reflector, typical of a boundary representing a period of non-deposition and possibly undergoing uplift and erosion.

Devonian Source Rock Modelling

Basin modelling studies have been conducted on the Devonian section with pseudowell locations in both offshore-shelf and onshore settings. These studies have sought to model the potential maturity of the mid-Devonian Takoradi Formation equivalent source rock, although an earlier Lower Devonian Elmina Formation equivalent and a later Lower Carboniferous Efia Formation equivalent source rock may also be present.

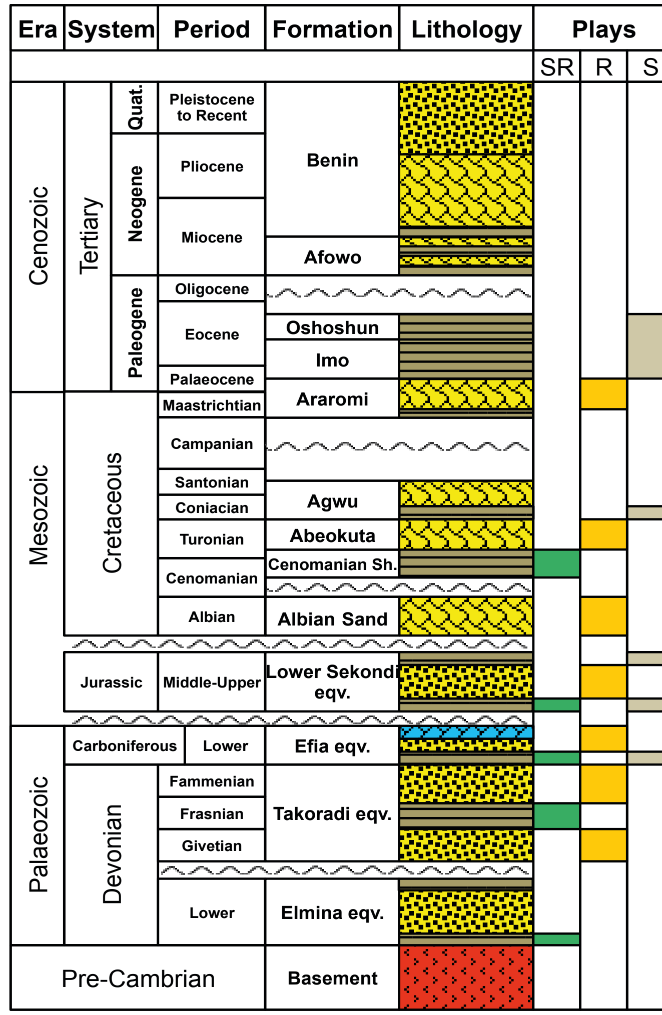
The extent of burial and subsequent uplift and erosion that took place after the deposition of the Devonian-Carboniferous succession and prior to the deposition of the Upper Jurassic-Lower Cretaceous succession is poorly understood. Consequently, basin model parameters have been considered that take account of this variation. Using regional heat flows from the results of wells drilled on the shelf in Ghana, particularly the Dzita-1 well (Brownfield and Charpentier, 2006), initial results are encouraging, showing a likelihood of the mid-Devonian source rock interval reaching expulsion maturity during the early Tertiary. The timing of this expulsion would be suitable to charge both Devonian marginal marine reservoirs within half-graben structures as well as Middle Jurassic-age continental to marginal marine reservoirs within horst and graben structures.

Source rock geothermal modelling, conducted on pseudowell #1, shows the Devonian Takoradi equivalent source rocks reaching maturity for oil in the Late Cretaceous.

Prolific Mesozoic Post Break-Up

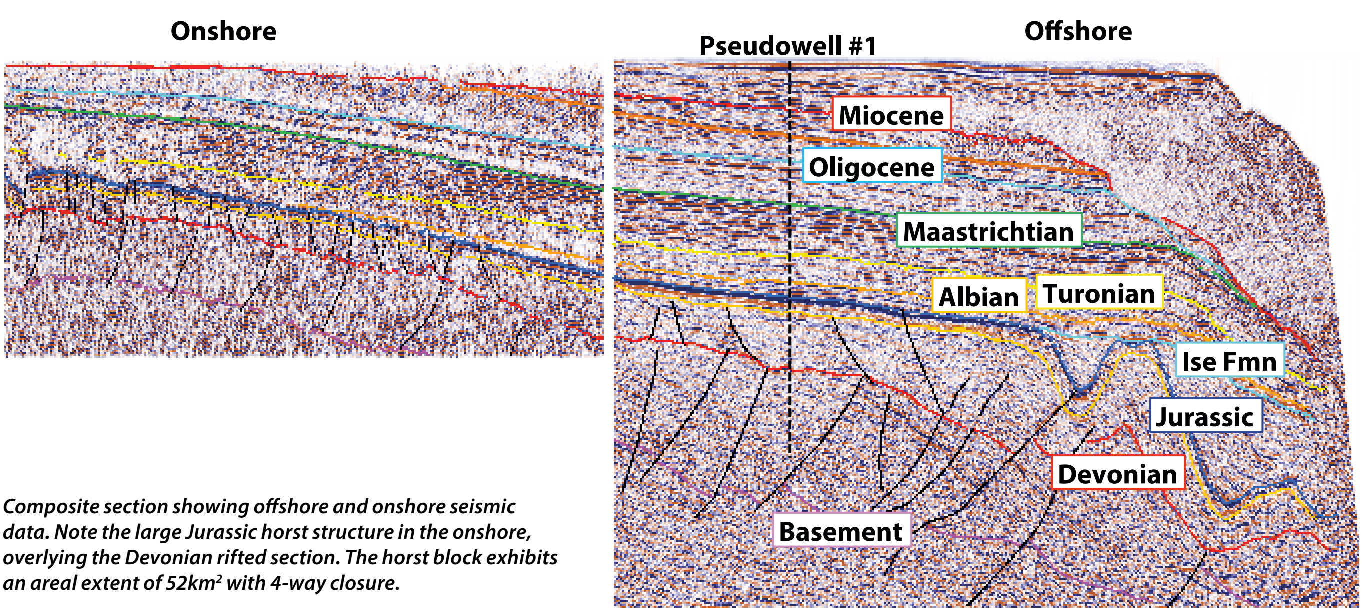
The Mesozoic sedimentary wedge that extends from the offshore to throughout the shelfal and onshore setting of the Dahomey Embayment was deposited subsequent to the break-up of the Gondwana supercontinent as the South Atlantic Ocean formed.

The onset of break-up in the Dahomey Embayment is understood to have occurred in the latest Jurassic to earliest Cretaceous, resulting in the clastic continental sediments



Stratigraphic column for onshore and shelfal Dahomey Embayment in Benin.

of the Ise Formation, deposited within a rift-valley habitat (Kaki et al). The Ise Formation sands are understood to only be present outboard of the present-day shelf edge as well as to the east of the Benin shelf, where they form the lower reservoir of the Seme North and Seme South oilfields. This is corroborated by seismic data, suggesting an up-dip limit of



Composite section showing offshore and onshore seismic data. Note the large Jurassic horst structure in the onshore, overlying the Devonian rifted section. The horst block exhibits an areal extent of 52km² with 4-way closure.

the break-up unconformity and associated sedimentation.

In the onshore setting, gravity gradiometer data allows the interpretation of two large post break-up transform fault complexes that likely influence the deposition and distribution of Mesozoic sediments. Present-day Lake Aheme lies within the western set of the transform fault complexes, and depth-to-basement calculations made on the gravity gradiometer data, calibrated to seismic, suggest that there may be up to 2,700m of sediment fill. The timing of the onset of these transform faults requires further investigation but they have probably influenced the distribution of depositional facies throughout the Mesozoic.

The earliest Mesozoic post break-up deposits in the shelfal and onshore settings are Albian continental to marginal marine sandstones (Kaki et al) that unconformably overstep the underlying enigmatic Middle Jurassic horst-block and Devonian failed-rift half-graben successions. These Albian sands, which are seen in seismic data to progressively onlap the underlying Middle Jurassic horst blocks, represent the basal unit of a thick succession of continental to fluvial-deltaic to shallow marine sands and form the main reservoir of the Seme North oilfield as well as the Aje gas-condensate field across the border in Nigeria.

Unconformably overlying the Albian sands are the regionally transgressive Cenomanian-Turonian marine shales that form both a regional seal to the Albian reservoirs and are a prolific source rock in the deeper waters throughout the South Atlantic margins. Evidence from wells drilled throughout the Gulf of Guinea suggest that this source rock has generated the hydrocarbons that have charged numerous successful Mesozoic plays and furthermore allow us to conclude that the C1, C2 and C3 gas encountered at the Sazue well, mentioned previously, is likely derived from this source rock.

A shallowing of depositional environments, subsequent to the deposition of the Cenomanian-Turonian shales, resulted in the deposition of tidal-dominated deltaic and shallow marine sands of the Turonian Abeokuta Formation and continental sands of the Coniacian-Santonian Agwu Formation. These Turonian Sands form the main reservoir in the Aje and Ogo Fields on the neighbouring Nigerian Shelf and also contained oil shows when encountered by the onshore Bodashe-1 exploration well, drilled close to the border with Benin. Additionally, the sands are seen to outcrop some 100 km north of the coastline. In-country fieldwork, undertaken to sample and photograph out-crops of the Mesozoic wedge, permitted the analysis of Turonian sandstones, which are interpreted as having been deposited in a fluvial environment.

The uppermost Cretaceous reservoirs are formed by the Maastrichtian to Danian Araromi Formation sands, again deposited in a fluvial-deltaic to shallow marine environment. The seal to these reservoir sands is provided by thick Paleocene and Eocene marine shales emplaced by a regional Danian transgressive event.

Within the Tertiary succession, the only sands sufficiently deeply buried to form reservoir rocks are the Lower Miocene Afowo Formation sandstones, deposited within a shallow marine environment and again sealed by intraformational transgressive mudstones.

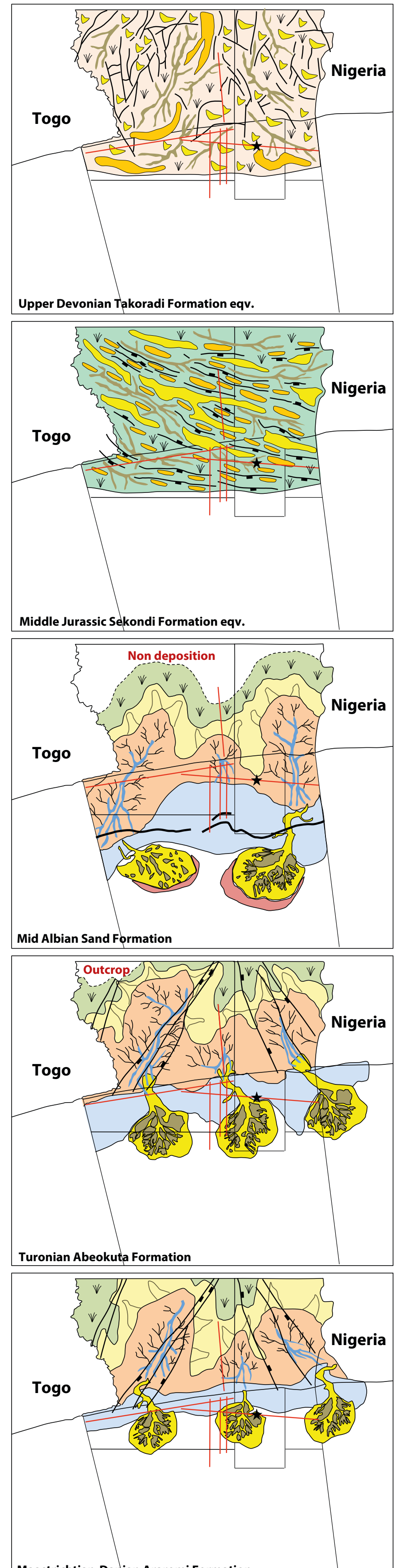
A Bright Future

With deepwater exploration in West Africa inherently risky and incurring unpalatable capital costs, exploration of the shallow water shelfal and onshore plays of the Gulf of Guinea has been reinvigorated. The Dahomey Embayment presents explorers with the opportunity to drill a number of Mesozoic structural plays with clastic reservoirs deposited in marine environments, as well as large Palaeozoic structural plays with marginal marine reservoir sands and proven source rocks, both within shallow water and onshore acreage and with a domestic market and rapidly increasing demand for energy.

The operators of these blocks are now progressing to drill the first exploration wells in the area since 1993, either located on structures derived from interpretation of the existing high resolution gravity gradiometer data or more accurately positioned with the acquisition of new 2D seismic data focused to reveal the interpreted structures.

References available online. ■

Palaeo-depositional maps showing the major fault orientations, distribution of facies and locations of project seismic lines.



New Technologies Lead to Amazing Career

JANE WHALEY

Cath Norman's belief in the application of new airborne technologies led her to become Managing Director of the Australian exploration company which went on to make the biggest offshore oil discovery in 2014.

"There is nothing like looking at the first data acquired in a new area for the first time: it is just so exciting!", says Cath Norman. Having worked in the industry for 30 years, it is obvious that she still finds it thrilling, particularly in the frontier arena: "Looking at a new play – that's what captures my imagination," she explains. "I love explaining geophysics to others. I find people are very interested and curious about how it's done, but as an industry we are very bad at de-mystifying our subject."

FAR Ltd

Specialist in Airborne Geophysics

Born in Perth in Western Australia, Cath was a high achiever from a young age – as well as being Head Girl at her school, she represented Western Australia in netball and Australia in volleyball and beach volleyball. But although she was good at maths and physics, she could not work out what she wanted to do until she was inspired by a school careers talk. "A lady came and told us all about her life in geophysics. I was bowled over – here was an older woman travelling the world having a great time doing something that many people considered a 'man's job'; it sounded amazing. I've never known her name, but I have always felt so grateful to her for inspiring me to study geophysics."

Cath went to Curtin University in Perth, graduating in 1985, when the oil industry was in the doldrums, and the Australian resource industry also in a bad state, so there were not many jobs around. "I considered doing a Masters, but I really wanted to get into the world of work, so I joined EPS, a small company which specialised in developing software to interpret airborne geophysical data and integrate it with other data," she explains. "EPS was bought by Western Geophysical in 1990, and I moved to Houston to assist in integrating this software with other products. It was such fun – Houston was a great place to be young and single!

"I slowly got more involved in the acquisition of airborne data, which was something I'd been interested in at university, eventually moving back to Perth to join World Geoscience, Australia's biggest airborne geophysical contractor. Airborne techniques were only just beginning to be used in oil exploration. I was part of a team which was revolutionising exploration by using high resolution data with tight line spacing to identify intra-sedimentary structures; until then, people had only used airborne data to look at basement or large structures. I also co-authored several papers on this very new topic."

Innovate or Die

In the early 1990s BP was selling off its in-house technologies, which presented an interesting opportunity for World Geosciences, and Cath in particular. One of the products BP had developed was an airborne-mounted laser, which fires into water and excites the molecules, making any hydrocarbons fluoresce: a good way to identify oil slicks and an excellent tool for frontier exploration. World Geosciences bought this tool from BP to integrate into its own airborne systems such as magnetometers, gravimeter and natural

Cath and the FAR team in Senegal

radiation monitors, so all the equipment could be used from a single plane.

"I moved to the UK in 1992 to supervise the technology transfer of this product, setting up an office and trying to build up business for the company," Cath continues. "It got off to a flying start! We had a joint venture with Robertson Research, creating big basin-wide packages of data. We were flying huge projects, and my two-year UK project turned into ten! We expanded our projects base from north-west Europe to Africa and the Middle East, opening offices in places like Dubai and Johannesburg, and started manufacturing in Prague. It was very exciting, partly because I was involved in everything, from interpretation to selling and marketing. It was my first experience of the business side of things; I had a ball!

"We also continued to research and develop products, widening the applications into areas like bathymetric mapping and onshore radiometrics, used for detecting nuclear leaks. With the state of the oil and gas industry in the late '90s we had to diversify; it was a case of 'innovate or die'!"

Fugro bought the company in 2000, and Cath continued working for them in the UK for another couple of years, with responsibility for the Fugro airborne group in Europe and the Middle East. This included running big mining projects and the largest ever airborne survey, in Saudi Arabia, which took three years and acquired ten million line-kilometres. "We were involved in areas where seismic is tricky, like the Empty Quarter and the newly opening Angola basins. I had some exciting times – fun but stressful!"

Technologies to Find Oil

In 2002, Cath returned to Perth with her British husband, a database engineer ("I'd done ten years in his country, I reckoned it was his turn!"), shortly before her son was born. "I'd planned on having a bit of a rest, but within weeks of arriving I was working at a variety of things, from consulting with Fugro to doing charity work and helping a friend set up a company – just because these things sounded interesting. I was also playing semi-professional volleyball and I had a young baby, so life was busy.

"I was having a great time, but knew I couldn't do it forever, and realised that what I really wanted to do was set up my own oil company, leveraging non-seismic technologies to find oil," she continues. "Looking at the problems that big oil companies had never solved with standard exploration techniques, I felt there was a role to use these technologies to identify and pick up acreage which had been discarded, especially in Africa. A friend recommended that I go and see some investors he knew next time I was in Melbourne. A couple of weeks later I was there for a volleyball competition, so I threw a suit in my bag and went along to their office. At the time, I had been doing some work with gravity-gradiometry with BHP, using their proprietary system, but realised that this high-resolution technique had much more applicability for the oil industry. I explained this to the investors, who really liked the concept and in 2005 we started Gippsland Offshore Petroleum, with me as Managing Director, having moved to Melbourne. We soon raised (Aus)$12 million and farmed into a project in the Gippsland Basin.

"However, my plan was always to look abroad for projects, and very soon we partnered with another company considering Jamaica – we ended up getting all the blocks.

We had an agreement to use BHP's gravity-gradiometry technology, which we employed primarily to look at structure and also to investigate beneath carbonates and other geological features which mask conventional seismic. The data from Jamaica proved to be of excellent quality, especially when combined with standard 2D seismic and it looked very promising, but unfortunately this coincided with the global financial crisis of 2007. We couldn't find a partner, so we had to hand it back at the end of the lease.

"We had also picked up a project in France, and had acreage in Gippsland and the North West Shelf in Australia, and one block in Kenya; Africa was the area which I thought had most applicability for this technology and where I had originally wanted to explore," she explains.


FAR

FAR's exploration success in Senegal was recognised with the company awarded 'Breakthrough Company of the Year', at the Oil and Gas Council's annual Africa Assembly in London.

Major Discovery

In 2008, Gippsland Offshore Petroleum reverted to private ownership, intending to list again at a later date. Meanwhile, Australian company FAR had bought into acreage in Senegal, Guinea Bissau and the jointly held AGC zone – but the three-man company had no geotechnical staff. The two companies decided to merge and create an Africa-focused company, centred for the moment on Senegal.

"FAR had been waiting for some time to complete the agreement of its PSC with the government of Senegal, so shortly after becoming MD of the merged company I headed off to Dakar and got it signed – and the PSC required drilling a well," Cath says. "At the time, I wasn't convinced it was worth pursuing, but after taking a good look at the data we realised it was really interesting. We opened a data room and very quickly got Cairn and Conoco Phillips signed up, a fantastic deal for a small company. Within a year Cairn, as operator, were drilling the first ever deepwater well off Senegal, and the first oil exploration well in the country for 40 years; it was incredibly exciting. The rest is history, really. We found a 500m oil interval in that first well, FAN-1, which told us we had a prolific working petroleum system. A couple of months later we announced the SNE discovery, which with 330 MMbo (2P) was the world's largest oil discovery in 2014. Senegal was the first well we had drilled and it came in – amazing luck! We're now on our 10th well and hope for first oil production in 2020 or 2021. And we're also back to my first love, frontier exploration, looking at new deepwater plays.

"Senegal is a gorgeous, beautiful country, with lovely people – I love working there," Cath adds.

Best Industry

"My life now is very different to how it was when I started in this industry, when I was young and everything was new and I was much more 'hands-on'," Cath explains. "I'm at a more corporate level now, dealing with governments and investors and the challenges that come with a growing company, like shareholder value and public relations. I can't be quite as adventurous about where I go, but I look forward to a point after FAR when I'll be able to travel more widely. I've never been to South America, for example. I'd love to go there, to see it, but also for business because it's still a frontier continent and there are lots of places to look at. New airborne technologies could open up different areas there, as well as in Africa and South East Asia. The world is not fully explored yet, and fresh concepts about play types and technologies can open up new basins all the time.

When I first came to Europe in the mid '90s, in the North Sea we were still looking at fairly shallow horst and graben type features, but with technologies like 3D seismic we started exploring deeper and discovered a whole lot of new plays. In a similar way, there are many areas which could be opened up through the use of new technologies. There is still plenty to do and a lot of innovative technology to bring to bear in our business – but there's always a role for the intrepid person who loves going to data rooms and old map rooms to dust off and wade through old sepia records – like I do!

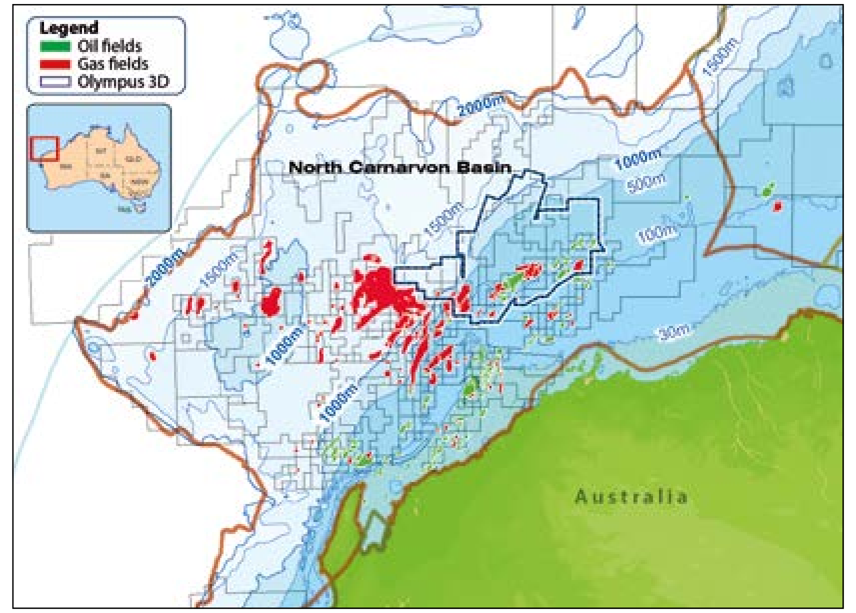
"I don't look back very often – I'm too busy looking forward because there's lots to do," she says. "But I know I've had a fantastic career and if it ended tomorrow I wouldn't be sorry about anything I've done, it's all been such fun. This is the best industry in the world to be involved in, as there are so many opportunities. A small company like FAR with access to the same technology as the bigger competitors can still make discoveries."

And Cath concludes: "What an amazing career; I get to use the most advanced technologies outside the space race; to travel the world and hang out with very intelligent – and also wacky – people. What's not to like?" ■

Olympus Rising

A Step Change in North Carnarvon Basin Imaging

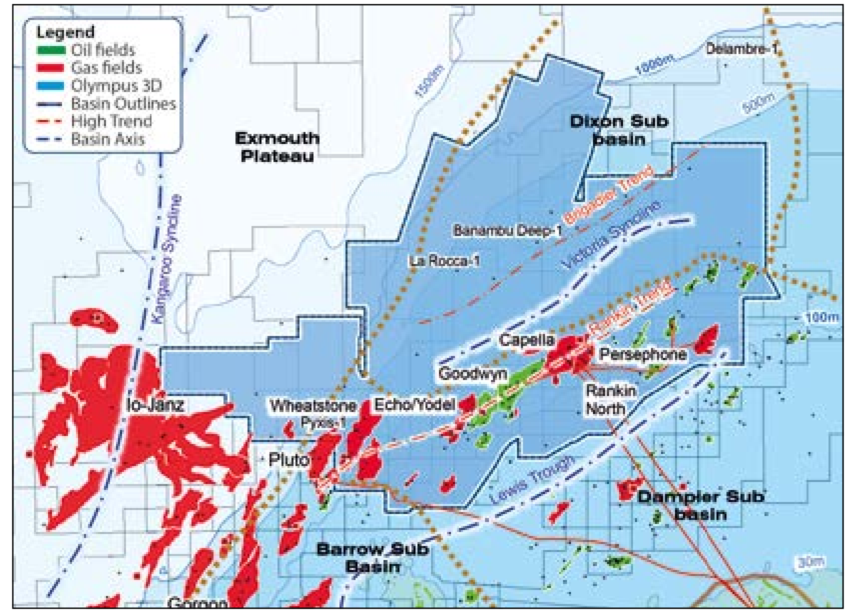
PSTM dip line through seven legacy surveys showing the seamless results and high quality that can be obtained with comprehensive broadband reprocessing of vintage 3D data.



Spectrum has completed comprehensive broadband reprocessing of 19 contiguous legacy 3D surveys in the North Carnarvon Basin, offshore the North West Shelf of Australia, one of the most prospective hydrocarbon provinces in the world (Figure 1). All surveys were processed as one volume from field tapes and the result is a fully conformable and seamless dataset, named 'Olympus'. This follows the theme of Greek mythology and is the place where the throne of Zeus was located and where Olympians such as Athena, Artemis, Demeter and Hermes resided – all of which happen to be the names of wells and/or 3D surveys within the area.

Figure 1: Location of the North Carnarvon Basin on the Australian North West Shelf and the 20,000 km² Olympus MC3D.

The reprocessed dataset covers nearly 20,000 km² and encompasses 180 km of the Rankin Trend along the south-eastern margin of the shelf, where over 30 oil and gas fields have been discovered. The data is complete to PSTM (Pre-Stack Time Migration) and as the PSDM (Pre-Stack Depth Migration) nears completion the astounding fidelity of the data is bringing new insights to rejuvenate exploration in this prolific basin (Figures 4 and 5).



The early results of the Olympus comprehensive broadband PSTM dataset, the first of its kind in the North Carnarvon Basin, have not only shown the significant uplifts that can be obtained from modern reprocessing of legacy data but have also revealed the potential of the ability to embark on fully integrated 3D basin studies tied to hundreds of wells. Even now, as the PSDM version of this data is being generated, the possibility of unearthing nearby exploration opportunities along the Rankin Trend looks very promising.

Further afield across the Victoria Syncline the Olympus data will rejuvenate exploration by allowing accurate basin modelling and reservoir mapping to unravel the details of complex but potentially prolific charge migration and trapping systems that have been barely touched to date.

The fortunes of Olympus and the underlying Mesozoic basin are truly rising!

Figure 2: The location of the Olympus 3D relative to the structural elements and main fields in its vicinity.

Untapped Riches to be Unlocked

Broadband reprocessing gives new life to legacy datasets.

JULIAN MATHER and **NICOLAS HAND**, Spectrum

The Rankin Trend is arguably the sweet spot on the Australian North West Shelf, with the initial North Rankin-1 discovery well having been drilled in 1971. Since then there have been a number of giant gas/condensate field discoveries along trend, including Goodwyn, Dockerel, Echo-Yodel-Sculptor, Perseus-Capella, Gorgon and Wheatstone-Pluto-Iago (Figure 2). Forty years later exploration drilling continues and oil and gas pools are still being found in a wider variety of hydrocarbon traps with more complex migration-charge histories.

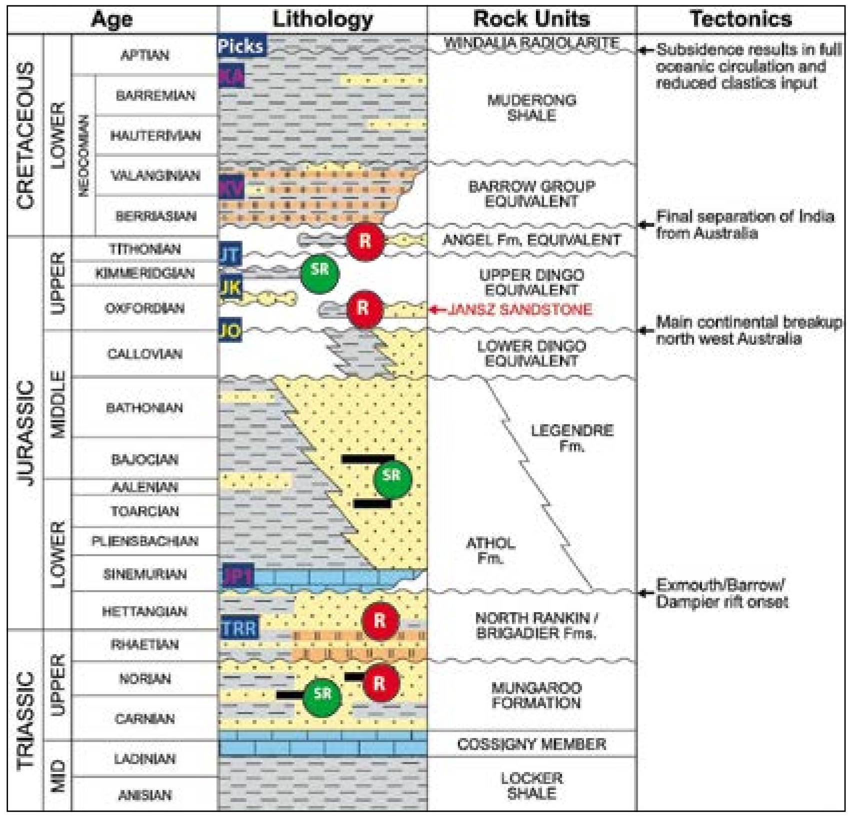


Figure 3: Stratigraphic column showing the main plays and tectonic events.

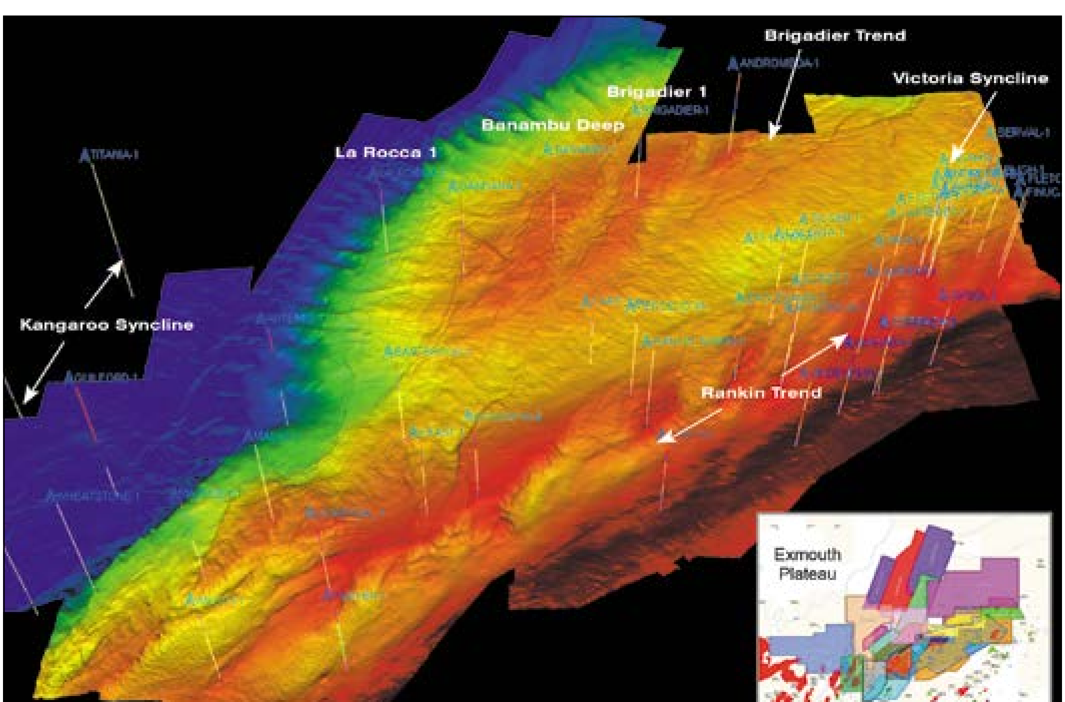


Figure 4: Preliminary Near Base Cretaceous (KV) on the PSTM volume. Note the strong effect in time of the platform break and canyons and the near north–south underlying structural grain overprinted by the Late Jurassic north-east to south-west continental breakup trend.

The Olympus 3D dataset, completed in association with Searcher Seismic, extends northward over the Dixon Sub-basin, which includes the better-known Victoria Syncline and Brigadier Trend. A large part of the survey is on the platform where water depths are between 50 and 250m but along the western margin towards the Exmouth Plateau the sea floor descends to 1,500m. The largely unexplored Victoria Syncline to the north of the Rankin Trend, which lies at the centre of the Olympus 3D dataset, is thought to be the Late Triassic to Early Jurassic source kitchen area for the Rankin Trend accumulations. In particular, the Goodwyn and Persephone fields have been mapped to have direct unobstructed migration pathways to the structural highs (Jablonski et al., WABS 2013).

Exploration success is ongoing to the south where quantitative inversion techniques have been used to target stacked pay within the Mungaroo Formation. To the east in the Bedout Sub-basin, the Phoenix discovery is also in the Early Triassic and this success is now re-invigorating exploration on the Brigadier Trend to the north.

The Olympus PSTM and PSDM dataset allows for seamless structural and attribute analysis from the proven hydrocarbon province into the under-explored northern area, not previ usly possible. This removes uncertainty in calibration between surveys and allows matched results across large areas.

Broadband Reprocessing

The application of modern deghosting is perhaps the most significant addition to the processing tool box for conventionally shot data. Properly applied deghosting improves the zero-phase wavelet by reducing the side lobes, cleaning up the data and subsequently broadening the resultant bandwidth. As a result, the demultiple sequence has a cleaner dataset to work with and is more effective, allowing a more adapted pre-migration Radon transform and an improved velocity model. This is of particular relevance along the platform margin, where canyon walls and thin beds distort and cause constructive interference, particularly on the far offsets.

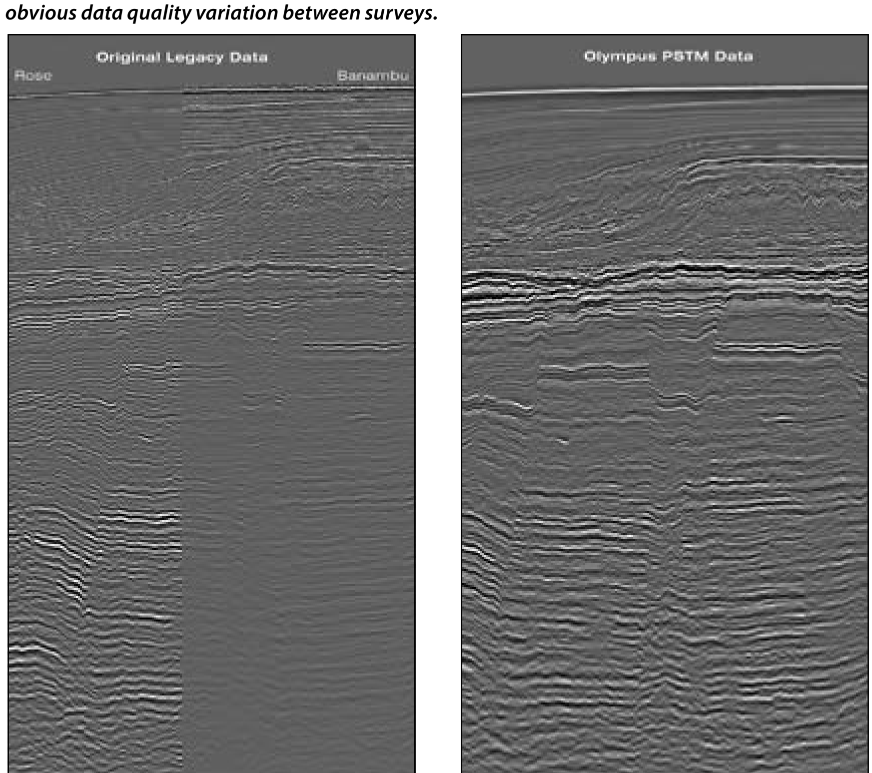
By combining multiclient and open file 3D data, a near contiguous dataset was reprocessed and this represents the first 'fully processed from field tapes' dataset incorporating so many surveys in this region, with a consistent inline direction roughly orthogonal to the regional grain (north-west to south-east). The major improvement in the data quality coupled with the massively increased computing power available means that a full-flow depth migration approach was also feasible at a reasonable cost and the results obtained by Down Under Geosolutions (DUG) confirms this improvement, as can be seen in Figure 5. Furthermore, for a fraction of the cost of new acquisition, such older datasets give better coverage in areas where there is more recent infrastructure installed and where stricter environmental and safety buffer zones are being required along with source power reductions, as is increasingly the case on the North West Shelf.

More options from PSTM and PSDM datasets for calibrating wells and tying to existing legacy time data mean that a wider basin synthesis – or, indeed, semi-regional analysis in depth covering large structural trends and major discoveries, with hundreds of wells calibrated in – is possible. Regional trends can then be overlaid on more local evaluations to ensure consistency and similarly detailed evaluations; for example, QI work over fields can be more easily broadened into neighbouring areas as a more regional exploration tool.

Regional Trends Obvious

Initial work on the Olympus PSTM dataset has been very positive, with the shallower events such as KA and KV in the Cretaceous (Figures 4 and 6) easily propagated over large areas. Attribute analysis shows little or no indications of variations in data quality across 3D survey joins (seams) or between areas. The regional and more

Figure 5: Comparison between legacy data (Rose and Banambu) and the new broadband PSTM showing a much cleaner-looking dataset with improved character, sharper faults and no obvious data quality variation between surveys.



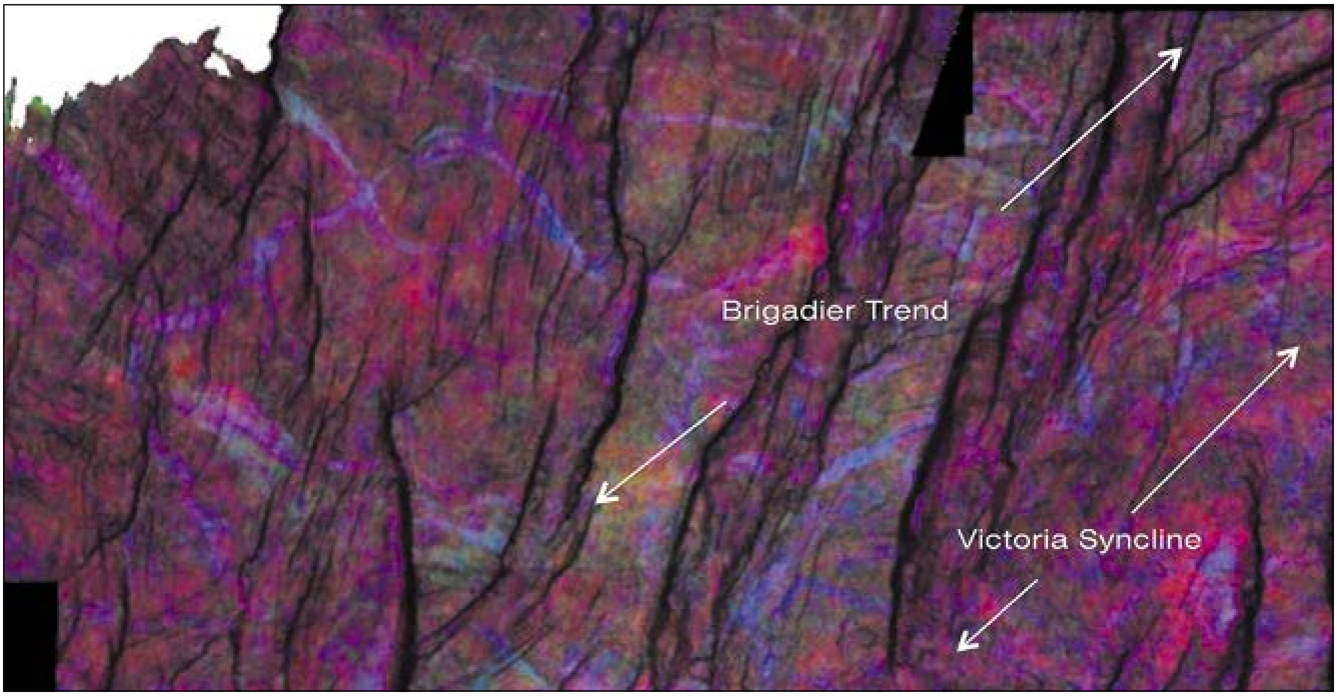


Figure 6: An example of a spectral decomposition slice within the Mungaroo Formation created by stepping down from the JP1 (Near Base Jurassic) preliminary pick. Even though this is a very early poorly-constrained slice a number of channels can be followed over great distances and suggest a dominance of an east–west sediment flow across the region.

local structural trends are now obvious as are the seafloor and the imprint of the seafloor canyons along the platform break (Figure 5). Early results from the PSDM are also very encouraging with further improvement in the data quality and sharpness of faults.

However, what will be really interesting is to see how the basin maps out in depth with all the water column and shallow sediments velocity effects that plague time datasets removed. Ultimately this means a far more accurate and integrated burial history across the region can be constructed and the petroleum system better understood. Sedimentary depositional environments and architecture can now move from being prospect or block specific to being seamlessly tracked over a 100 km range.

The main prospective intervals lie beneath the Cretaceous and now that nearly all the obvious highs have been drilled recent work has focused more towards partial angle stack data inverted to elastic rock properties and most likely facies models. Generally, the Jurassic to Late Triassic is difficult to separate due to the lack of character variation and contrast, with the exception of the near base Jurassic (JP1) just above the North Rankin/Brigadier Formation (Sinemurian in age). The JP1 is an excellent quality peak which marks the transition into a calcarenite horizon by a major marine transgression over much of the area and is a good proxy for tracking potential reservoirs above and below it.

Complex Charging Paths

Moving northward of the Rankin trend, the Victoria Syncline and Brigadier Trend has been far less explored since the early Brigadier-1 (1978) and Gandara-1 (1979) wells were drilled. In this area, wells had until recently only tagged the Jurassic and sometimes the uppermost part of the Mungaroo. The Mungaroo Formation is an extensive Triassic fluvio-deltaic to marginal marine sequence of interbedded sands and shales which further to the south has in the last ten years proven very successful deeper down into the Norian. Only recently have wells started to test this interval on the Brigadier Trend. Recently La Rocca-1 (2011) and Banambu Deep-1 (2012) have specifically targeted channel sands supported by quantitative analysis. Post-well studies indicate deeper good quality sands may be locally charged by hydrocarbons, with the upper channels charged down-dip in the Victoria Syncline against sealing faults. For the Upper Mungaroo sands to be charged on the highs, hydrocarbons will need to follow more complex paths than previously envisaged, indicating that there is still genuine opportunity to find trapped hydrocarbons north of the Rankin Trend.

Figure 6 is an example of a spectral decomposition slice stepped down from the JP1 mapped surface through the Mungaroo Formation. It shows how quickly an image of the depositional system can be obtained, even if poorly constrained. What is clear is that charging from the Victoria Syncline is not going to be via a simple drainage pathway on a depth map. Migration is going to be in a more east–west direction along the channels and strongly affected by the northerly-orientated fault grain. Interplay of the meandering channels will also need to be taken into account, plus the effectiveness of the cross-cutting fault seals. Whilst this has been extremely difficult in the past, with only small, disconnected pockets of variable quality 3D seismic available, the Olympus dataset is ideally suited to this type of evaluation and our first forays into this suggest untapped riches are ready to be unlocked.

References available online. ■

Mauritius – and Beneath

After the American adventurer and author Mark Twain visited Mauritius in 1896 he quoted an islander as saying: "Mauritius was made first and then Heaven; and Heaven copied Mauritius."

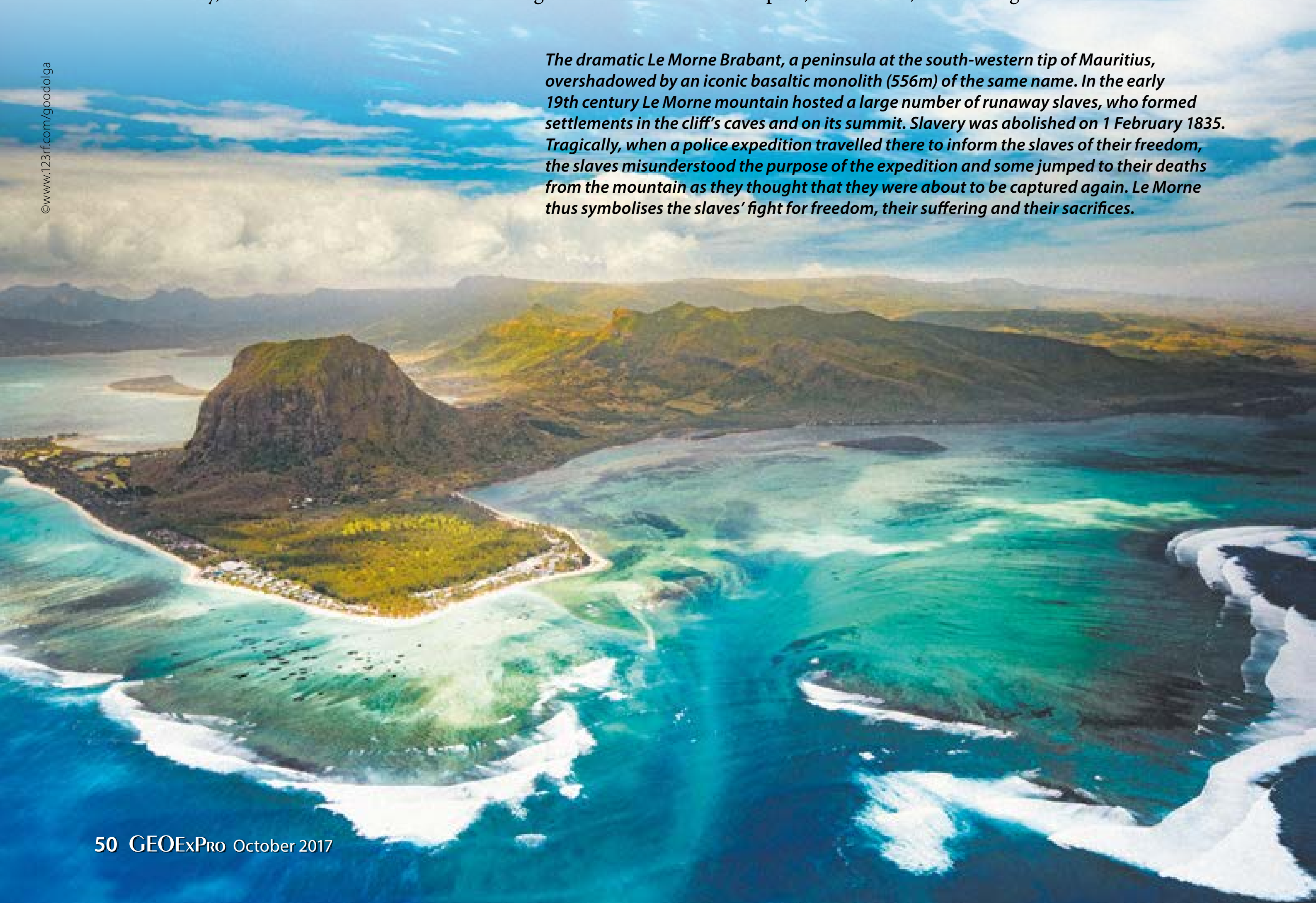
BIRGITTE and CHRISTINE REISÆTER AMUNDSEN, ELI REISÆTER and LASSE AMUNDSEN

Dotted with emerald sugar cane fields and surrounded by silver sands, azure waters and beautiful coral reefs, this tiny tropical paradise island, located 890 km east of Madagascar in the middle of the Indian Ocean, has the most competitive and booming economy on the African continent. Mauritius spans 2,000 km^2 and is home to over 1.3 million people, an ethnically and religiously diverse mix of Indian, African and French heritage. English is the official language; however, Creole, derived from French, is the most widely spoken. A former Dutch, French and British colony, Mauritius achieved its independence in 1968 and became a Republic in 1992. The country attracts nearly a million tourists annually.

Another World

On our trip to Mauritius we learnt that Norwegian compatriots recently identified remnants from another world right beneath our feet – a now submerged continent billions of years old. Mauritia, once a tiny part of the Rodinia 'supercontinent' prior to the formation of the Indian Ocean (Torsvik et al., 2013) is believed to have detached about 60 million years ago as Madagascar and India drifted apart, and is hidden under huge masses of lava. Continental drift, responsible for Mauritia's downfall, also gave birth to Mauritius, as geological processes surrounded the paradise island with white sandy beaches and transparent lagoons, protected from the open sea by one of the world's largest coral reefs.

But Mauritius' birth was more about violence and burning hell than the heaven suggested by Twain. The island rose from the depths of the Earth between nine and ten million years ago when a huge volcano built by fluid magma flows created a large, low-lying land, resembling a warrior's shield



The dramatic Le Morne Brabant, a peninsula at the south-western tip of Mauritius, overshadowed by an iconic basaltic monolith (556m) of the same name. In the early 19th century Le Morne mountain hosted a large number of runaway slaves, who formed settlements in the cliff's caves and on its summit. Slavery was abolished on 1 February 1835. Tragically, when a police expedition travelled there to inform the slaves of their freedom, the slaves misunderstood the purpose of the expedition and some jumped to their deaths from the mountain as they thought that they were about to be captured again. Le Morne thus symbolises the slaves' fight for freedom, their suffering and their sacrifices.

lying on the ground. At the time, the region was a volcanic hotspot. Gigantic underwater eruptions originating in the Earth's mantle were not uncommon, forcing magma to gush into and out of the ocean before solidifying into islands. Later, two more series of volcanic eruptions gave rise to the numerous mountains, gorges and valleys that can be seen all over the island. The youngest volcanic activity occurred 30,000 years ago.

Since the days of Plato, who wrote the story of Atlantis in a Socratic dialogue about 360 BC, tales of a sunken land have been told. These have met with a sceptical response, but some have proved to be true, and scientists have long suspected that volcanic islands may contain evidence of lost continents. Could there be a microcontinent lurking beneath our feet, under Mauritius?

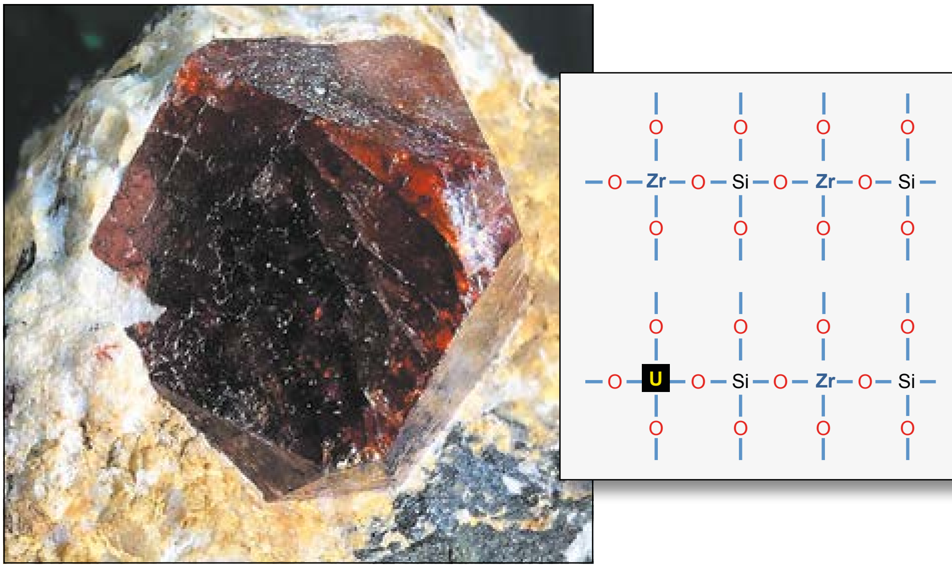
The highest waterfall on Mauritius – the spectacular Chamarel Falls fed by the Viande Salée and St. Denis rivers in Black River Gorges National Park – plunges 100m down against a scenic backdrop of forests and cliff-forming basalt lava flows of different ages. The first flow, 8-10 million years old, is a 70m-thick basaltic rock which was exposed to air and weather over millions of years before being covered by the second flow, 30m thick, between 1.7 and 3.5 million years ago.

Sunken Lemuria

Lemuria was a hypothesised sunken continent under the Indian Ocean. In the 1860s the English ornithologist Philip Sclater found it puzzling that similar primate fossils had recently been found in the geographically-isolated Madagascar and India, but not in Africa. Would these primates, which he called lemurs, have swum across the 6,000 kms of Indian Ocean from Madagascar to India, yet never attempted to swim across the shorter Mozambique Channel into Africa? Implausible; Sclater concluded that the lemurs had never swum across any ocean at all. But, he hypothesised, since they are found in both Madagascar and India, they must have walked across on a land bridge, long swallowed by the Indian Ocean. He called the sunken land Lemuria. Lemuria captured the imagination of generations of people. At Belle Mare Plage, in the north-east of Mauritius, the hotel director and islander Yash very confidently likened the story of Mauritius to the phoenix dying in a show of flames and then obtaining new life by arising from the ashes of its predecessor.

However, geological knowledge eventually disproved Sclater's hypothesis of ancient Lemuria through the theory of continental drift, proposed in 1915 by the German geologist and meteorologist Alfred Wegener, who suggested that parts of the Earth's crust slowly drift on top a liquid core. The fossil record supports and gives credence to the theories of continental drift and plate tectonics: continents are not static but in motion. This acceptance led to the realisation that Madagascar and India were once part of the same landmass. Lemuria might never have existed but it became history's precursor to Mauritia: a Madagascar-India land link, now hidden beneath the Indian Ocean.

The name Lemuria comes from the charming primates called lemurs, found only on the island of Madagascar and some tiny neighbouring islands. The silky sifaka, a large lemur with long, white fur, is one of the rarest mammals on Earth, and is listed by the International Union for Conservation of Nature as one of the world's 25 most critically endangered primates.

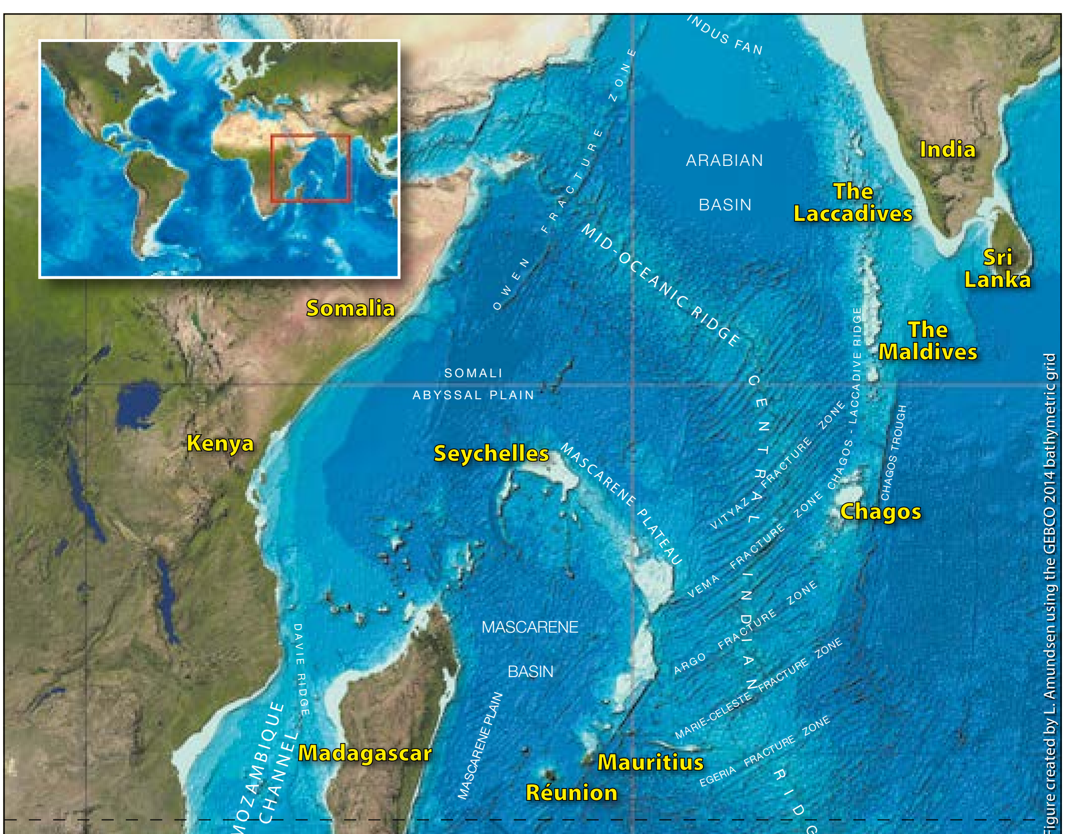


Zircons – tiny crystals of zirconium silicate (chemical formula $ZrSiO_4$) – are very resistant to erosion or chemical change, and are associated with continental crust. Zircons contain 'clocks' by adding small traces of radioactive uranium, because uranium atoms are similar enough to zirconium that they occasionally can slip into the crystal's lattice in zirconium's place when the mineral is forming. The unstable uranium atoms eventually decay into lead (Pb) atoms. The age of a zircon is calculated from the ratio of radioactive uranium to lead atoms; the more lead that you find in a zircon crystal, the older it is. For example, zircons from Jack Hills in Western Australia have yielded U-Pb ages up to 4.404 billion years, interpreted to be the age of crystallisation. These are the oldest minerals so far dated on Earth.

Mauritia Proved

In 1999, an American scientific drilling ship discovered evidence of a submerged continent, the Kerguelen Plateau, at the intersection of the Indian and Southern Oceans. Drilling samples contained traces of 90 million-year-old pollen and wood trapped in sediments. Areas of strong gravitational fields were identified from south of the Northern Mascarene Plateau down to Mauritius, an indication of hidden submerged crusts – but were those crusts merely oceanic or were they continental? If the latter, they could be indicative of a lost continent.

A group of geoscientists from Norway, South Africa, Britain and Germany, led by Norwegian geophysicist Trond Torsvik at the University of Oslo, were interested in the findings. To investigate further, they made a tectonic plate movement model to reconstruct the past history of the Earth, including the geography of continents and oceans, and the processes controlling the creation and destruction of landforms. Until around 750 million years ago, all of the land on Earth was collected into a single continent called Rodinia. This supercontinent was driven apart by tectonic forces, slowly fragmenting and drifting apart. In this continental ballet, the team found that in the Indian subcontinent there was one microcontinent that about 60 million years ago disappeared beneath the waves,



In Nature Geoscience *in 2013, Torsvik and co-workers published their findings on Mauritia, a submerged continent in the Indian Ocean, between Madagascar and India. At some time in the last 2 billion to 600 million years, Mauritia was an archipelago that separated from Madagascar and the Indian sub-continent. Slivers of Mauritia may today be preserved in two chains of sub-sea mountains, one extending from Réunion through Mauritius and up to the Seychelles in the western Indian Ocean, and a second one from Chagos through the Maldives and the Laccadives up to the Indian coast in the northern Indian Ocean.*

leaving a fractured mass of continental crust lying kilometres beneath the Indian Ocean. They dubbed it Mauritia.

To gather more proof about the existence of Mauritia, the geoscientists set course to Mauritius, located above some of the fragments of the lost continent, hoping to find pieces of the missing land. The team hypothesised that as magma flowed up from the Earth's interior to form Mauritius, it would drag up to the surface a few rocks containing zircon minerals from the continental crust of the sunken Mauritia. Hopefully, some super-tough grains of zircon would survive the high temperatures of the lavas and during the eruption be 'frozen' into them. If they did, this would leave behind some clues in the lava-made basalt land of Mauritius.

They collected samples of sand on remote beaches and brought these back to Oslo, where they found 20 grains of zircon (wow!). Furthermore, they dated the zircons to be much older than Mauritius; the oldest grain was nearly 2 billion years old while the youngest roughly 600 million years old. There is no obvious local source for zircons on Mauritius, so Torsvik and his colleagues suggested that the zircons originated in the fragments of Mauritia's ancient continental crust located beneath Mauritius. Volcanic eruptions brought shards of the crust to the surface, where the zircons eroded from their parent rocks to pepper the island's white sands, but further research is needed to fully investigate what remains of this lost region. The ultimate proof of Mauritia and the key to new knowledge would be new seismic data that can image the structure.

The authors admiring the vibrant colours playing out across the "Seven Coloured Earth" dunes in Chamarel, which contain traces of ancient activity of geoclimatic events. The basalt from the intermediate periodic lava flow (3-1.7 million years) has been leached by the hot and humid climate, leading to gullied clay. This profound and ultimate decomposition has left behind iron and aluminium oxides. Iron and aluminium repel each other and gather spontaneously in colourful stripes. The ferric oxide gives the land shades ranging from red to brown, while aluminium gives the blue to violet-blue colours. The leaching of the basalt has resulted in depletion of the the nutrients from the soil that are necessary for vegetation to grow. This is why no plants will ever grow on the dunes. A similar landscape also occurs in Papua New Guinea, and may be common in tropical, high-rainfall regions with volcanic bedrock.

The Phoenix Rises

Maybe our friend Yash is right? Perhaps Mauritius was reborn from Mauritia. Only one beautiful phoenix exists at any one time, and it is long-lived; the same could be said for Mauritius. As the end of its life approaches, the phoenix builds a nest of wood and spices and climbs on to it. There it faces the sun, the fire ignites, and it is consumed in the flames – but after a time, the phoenix rises again from the ashes. In the same way, if Mauritius was reborn from Mauritia, then at some time will Mauritius itself die and be reborn?

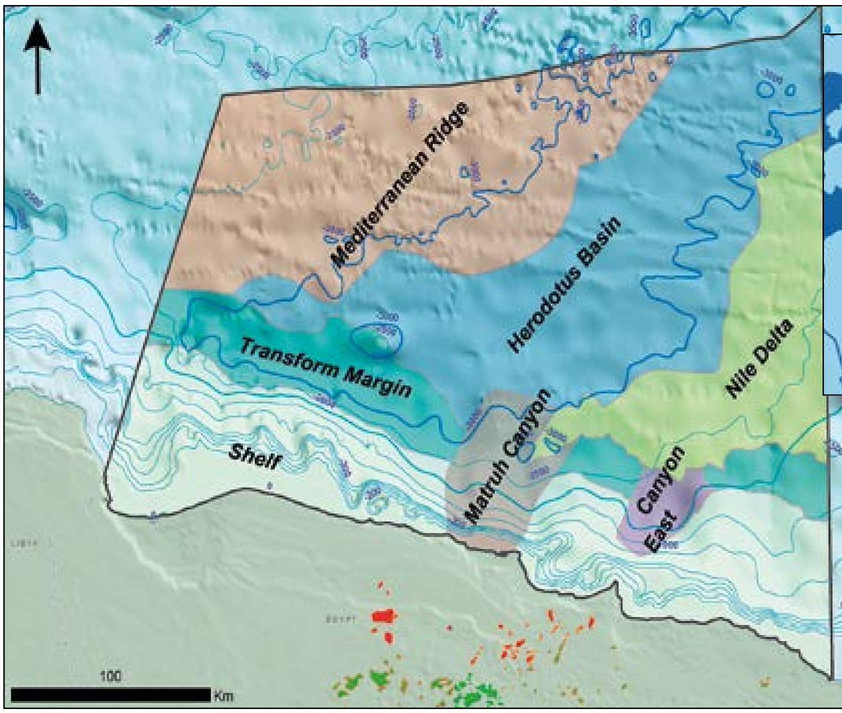
References available online ■

Off the south-west coast of Mauritius, about 200m from the shore, sits the famous Crystal Rock. It is an exposed section of a fossilised coral reef, an example of a biochemical sedimentary rock. Whether you are on your way to the coral sand island Ile aux Bénitiers or going snorkelling or swimming with dolphins, every boat stops at Crystal Rock.

Frontier Exploration in Egypt's Mediterranean Sea

Several promising play types can be identified on new pre-stack depth migrated seismic.

SIMON BAER, ØYSTEIN LIE, MATTHEW PYETT, CHRIS DAVIES, RUNE SAKARIASSEN; PGS
AYMAN EL MORSHEDY, EGAS (Egyptian Natural Gas Holding Company)



The frontier area offshore west Egypt comprises (from south to north) a comparatively narrow shelf zone, including south-west to north-east trending canyons, a transform margin and a section of the Herodotus Basin, with the Mediterranean Ridge to the north-west and the Nile Delta to the east.

Offshore west Egypt is a frontier region that offers significant and diverse potential plays. There are proven onshore Jurassic/Cretaceous oil and gas plays, Nile-sourced Pliocene sandstones, and Oligocene to Miocene deep marine fans as well as Jurassic to Miocene carbonate structures. A geological overview of this area, west of the Nile Delta Basin, was published in 2016 (New Opportunities Offshore West Egypt, *GEO ExPro,* Vol.13, No.1). Since then, the existing 2D seismic database has been reprocessed using the latest processing and imaging techniques. In addition, new 2D GeoStreamer® data has been acquired that complements the rejuvenated seismic database whilst expanding the seismic footprint across the region. This has allowed new structural insights and helped to further understand the offshore area and the anticipated play types. In this article we look at some examples of various identified leads, which are presented on pre-stack depth migrated images.

Attractive Carbonate Leads

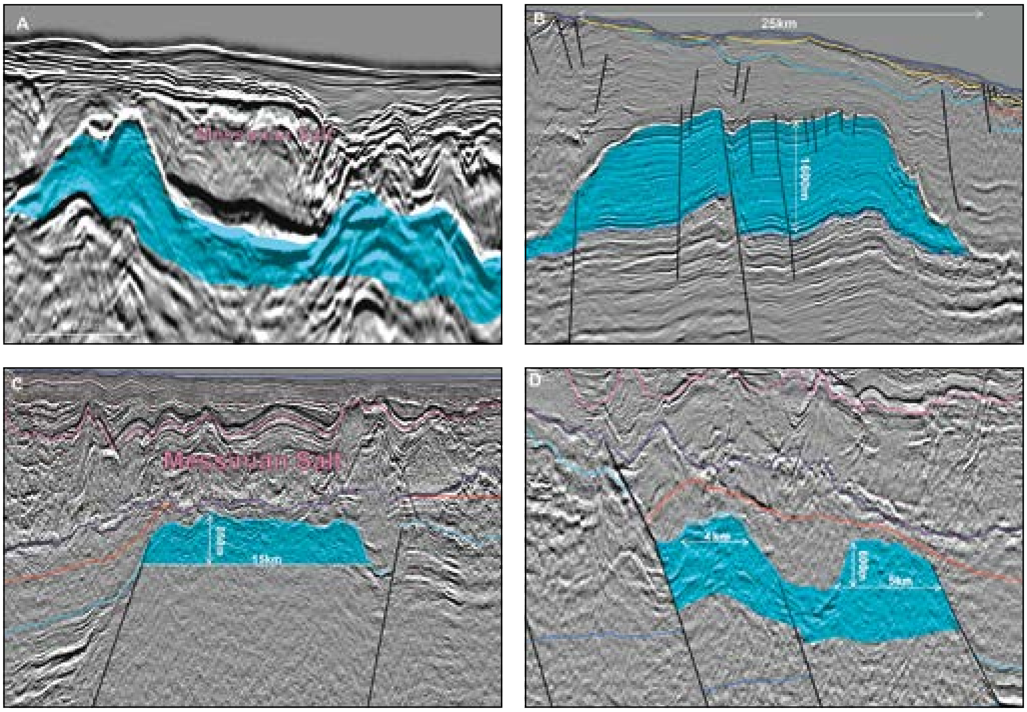
Numerous Cretaceous and Miocene carbonate leads have been identified on the shelf and on the transform margin. These structures have been identified on continental crust, as suggested by the acquired gravity and magnetic data. The setting is proximal to a proven thermogenic system in the onshore Western Desert region. In-house basin modelling suggests that there is potential for both biogenic and thermogenic sources of hydrocarbons. In terms of a seal, the Messinian salt pinches out towards the transform margin and does not overlie all the carbonate structures across the shelf. However, overlying intra-formational shales are expected to act as a sufficient seal.

Large Deep Marine Fan Systems

The Oligocene/Miocene deep marine fan play is proven east of the study area within the Nile Delta/Cone area, where it can be defined as a lowstand incised valley/submarine canyon play. This play is believed to exist further basinward as a distal part and is therefore considered to be a deep marine fan system/turbidite play in the Herodotus Basin. Several potential areas of sediment provenance may have sourced coarse-grained siliciclastic material into the deep Herodotus Basin, including the Nile Delta/Cone (proven from the east), mainland Egypt (from the south) and the Cyprus Margin (from the north-east). The extension of the Nile provenance is probably the most influential source of sediment input into the deep basin.

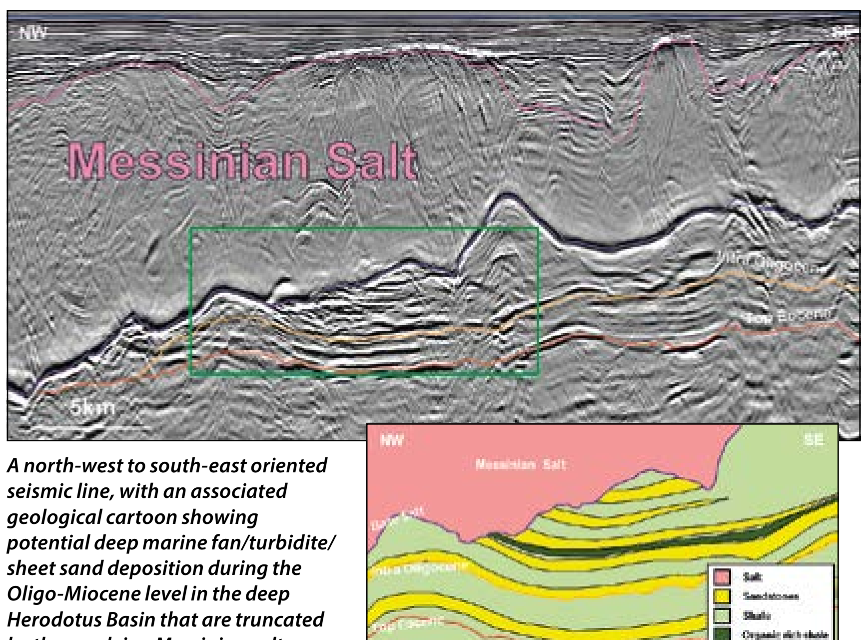
Oil-Prone Shelf

The narrow shelf is near to the proven onshore oil and gas discovery trend. Both siliciclastic and carbonate reservoir units



The platform-slope architecture has provided several Jurassic, Cretaceous (Near Top Cretaceous – turquoise horizon) (B, C, D) and Miocene (A) carbonate structures. Some of these extend to more than 150 km² and are clearly indicated by an impedance increase on top of the structures, which is also seen as a lateral polarity-change in A where the base salt reflector changes polarity from a peak (soft kick) to a trough (hard kick) due to the lateral change from clastics to carbonates beneath the salt.

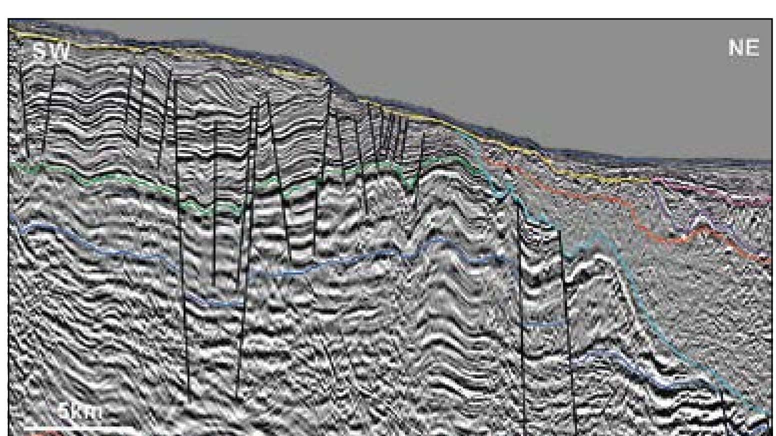
are likely to extend offshore, where several leads have been identified. The Matruh Canyon and the Canyon East are situated downdip from numerous oil and gas fields in the Western Desert and form a potential offshore extension of that onshore discovery trend. Both canyons may contain several potential reservoir and source intervals. Syn-rift Jurassic highs and post-rift rollovers on a shale detachment are considered to be the main play types.



A north-west to south-east oriented seismic line, with an associated geological cartoon showing potential deep marine fan/turbidite/ sheet sand deposition during the Oligo-Miocene level in the deep Herodotus Basin that are truncated by the overlying Messinian salt.

Promising Frontier Area

A comprehensive study supported by new geophysical PGS data identifies numerous leads and play types throughout offshore west Egypt, which makes the area a promising frontier region for exploration. Attractive Cretaceous and Miocene carbonate leads of significant sizes are situated on the shelf and on the transform margin. Large deep marine fan systems as well as numerous sub-salt inversion structures have been identified in the Herodotus Basin. The oil-prone shelf contains both carbonate and sandstone reservoir potential, in addition to play types within the canyons. ■



This south-west to north-east oriented line highlights several lead opportunities within the Cretaceous and Jurassic carbonate platform on the shelf and on the transform margin. These leads are indicated to be four-way closures, sealed by Lower Cretaceous shales and sourced by Jurassic source rocks, which are proven in the working petroleum system onshore Western Desert. (Top Salt – pink; Base Salt – violet; Messinian Unconformity – yellow; Intra Oligocene – orange; Base Oligocene – salmon red; Near Top Cretaceous – turquoise; Top Alamein Dolomite – green; Top Jurassic – blue; Top Basement – red).

Riding the Switchback

In this second part we review the history of oil booms and busts during the 1960s–2010s, which witnessed the turbulent rise of OPEC.

RASOUL SORKHABI, Ph.D.

A Brief History of Booms and Busts: Part II

At the end of WWII in 1945, the USA held a prominent position in the world in terms of oil reserves and production, but over the following two decades power shifted to the Middle East. Between 1948 and 1972 (just before the First Oil Shock), the world's proven reserves grew from 62 Bbo to 534 Bbo, the Middle East accounting for 70% of this increase. During the same period, the western world's production grew from 8.7 to 42 MMbopd while that of the Middle East grew from 1.1 to 18.2 MMbopd. This growth in production was in response to a rapidly rising market, especially in America, Europe and Japan where the manufacturing and use of cars were rapidly increasing. Throughout the 1950s and '60s, oil prices remained relatively low and stable at US$ 1.70–2.1, thanks partly to the production of cheap oil from the Middle East which was controlled by the 'Seven Sisters'.
This control of oil in the Middle East and North Africa by major Western enterprises in conjunction with the spread of anticolonial sentiments in the region heralded major changes in the relationships between the Seven Sisters and the oil-producing countries, climaxing in the formation of OPEC in 1960 (see *GEO Expro*, Vol. 7, No. 6).

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Two Oil Shocks

The rapid increase in oil prices from $2.48 per barrel in 1972 to $11.65 at the end of 1973 was associated for months with public panic, oil shortage and gasoline lines in the USA and most industrial nations. It was the First Oil Shock on a global scale (see *GEO Expro*, Vol. 12, No. 3) and occurred against a backdrop of latent factors that surfaced during 1972–73. OPEC, largely ignored by the major Western oil companies throughout the 1960s, was like a fire under the ashes and blazed up in the early '70s, asserting its powerful presence in the international oil market against the Seven Sisters. The cheap oil of the 1950s and '60s had addicted the USA and Europe to oil and the industrial countries dependent on oil imports were thus vulnerable. Domestic oil production in the USA indeed peaked in 1970 as M. King Hubbert had predicted in 1956; from 1970 onward, the US significantly increased its imports of foreign oil. Finally, the Israel-Palestinian conflict was revived in October 1973, when Egypt and Syria invaded Israel to expel it from the land it had taken in 1967. The oil-rich Arab countries imposed an oil embargo against the US and other countries for their support of Israel. This did not achieve its objectives against Israel, but the OPEC countries as a whole came out in financially a much better position than ever before.

These factors triggering the 1973 oil shock are well known, but what is perhaps less discussed is that the US administration actually favoured oil price increases for a number of reasons. For one thing, high prices would decrease oil consumption in Western countries and would also make the development of the recently discovered oil fields in Alaska and the North Sea financially feasible. On the foreign policy side, it would strengthen Iran and Saudi Arabia, the main US allies in the region, against the Soviet Union during those years of the Cold War. This aspect of the 1973 oil shock has been articulated by several OPEC insiders including Francisco Parra in *Oil Politics* (2004) and Fadhil Chalabi in *Oil Politics, Oil Myths* (2010).

The Second Oil Shock in 1979–80 was also due to political unrest in the Middle East. In 1978, a popular revolution began against the Shah's regime in Iran and a consequent strike in Iran's oil industry decreased its oil exports from 4.5 MMbopd to less than 1.0 MMbopd. A year later, the Shah's pro-US government was replaced by Khomeini's less US-friendly Islamic Republic. Oil prices rose from $12.80 in October 1978 to nearly $40 in November 1979, the year in which the USSR invaded Afghanistan, further disrupting the geopolitics of the Middle East. In September 1980, Iraq invaded revolutionary Iran – a futile war that lasted eight years and weakened both nations' economies. Other oil-producing countries seized these opportunities and raised oil prices drastically. Overall, oil prices increased from $14.00 in 1978 to $36.83 in 1980. Gasoline lines again hit American consumers and cost President Jimmy Carter his re-election in 1981. The Second Oil Shock further strengthened OPEC's position internationally.

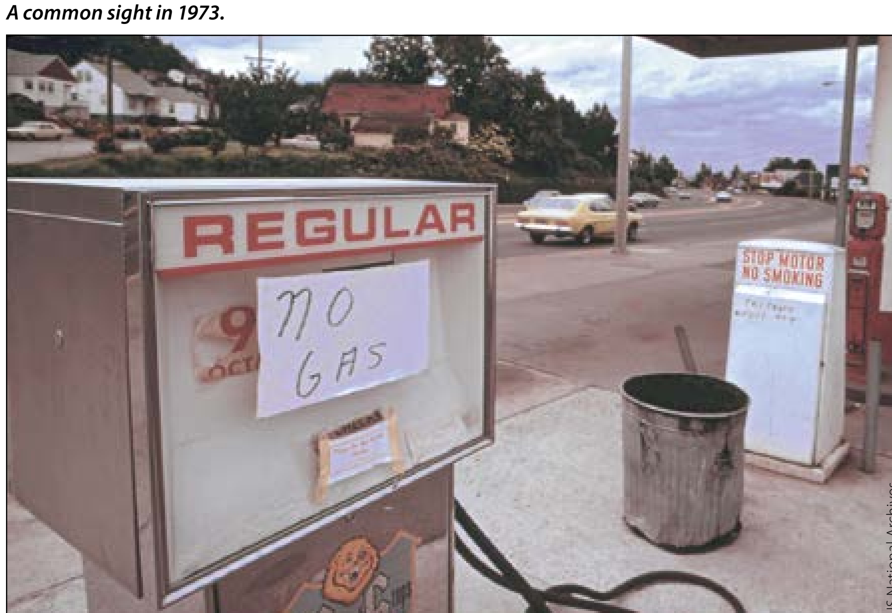
OPEC

The Iranian delegation at the inaugural OPEC meeting in 1960.

The 1986 Oil Glut

The 1980 price increase motivated rapid increases in oil production by both OPEC countries and non-OPEC producers, especially the Soviet Union,

A common sight in 1973.



US National Archives

the USA and Mexico. This increase in production, however, went in parallel with decreasing demand as a response to high prices; consumption in the US, Europe and Japan fell by 15% between 1979 and 1984.

With the prominent position of non-OPEC producers, OPEC members were weakened. Although they decided to cut production several times from 1980–85 to maintain high oil prices, they were not united and cheating on production quota or selling oil below official prices tore them apart. Moreover, in the first half of the 1980s, non-OPEC oil producers had become far more important players. Saudi Arabia produced over 10 MMbopd in October 1980 but had cut back to only 2.3 MMbopd by August 1985. In 1986, Saudi Arabia, tired of OPEC members' non-compliance with their production quota, increased its own oil production to 6.2 MMbopd, flooding the world market with cheap oil; it did not want to be a swing producer any longer. Rumour also has it that Saudi Arabia's push for oil production was encouraged by President Reagan's administration in order to hurt the Soviet economy, which was increasingly dependent on oil revenues. True or not, the oil price plunge indeed contributed to the decline of the Soviet economy.

The oil glut of 1986 brought about the most severe market crash in oil history (matched only by the 2014 bust). Oil prices in 1986 were $14.43 on average, but at times fell below $10. Oil companies shut down exploration projects and laid off hundreds of thousands of workers. The independent oil producers in the US were hit hardest; more than half went out of business. It took ten years for prices to rise to the level of $20 a barrel. From 1985 to 1995, US oil production steadily declined from 10.6 to 8.3 MMbopd.

Kuwait War to Asian Financial Crisis

In August 1990, Saddam Hussein invaded neighbouring Kuwait and the following January the US and allied forces launched a massive military assault on Iraq in order to drive them out of Kuwait. By March Operation Desert Storm had liberated Kuwait, although it took the rest of 1991 to put out fires in more than 700 oil wells that the retreating Iraqi soldiers had started. Oil prices increased from $17 to $36 in September 1990, but Saudi Arabia increased its production from 5.4 MMbodp to about 8 MMbopd in October 1990 to make up for the market loss of Kuwaiti oil. Moreover, the US released 17.2 MMb of its strategic petroleum reserves to the market. These efforts helped ease the temporary oil shortage; nevertheless, average oil prices in 1990 and 1991 stood at slightly higher than $20 a barrel, partly because of the collapse of the Soviet Union in 1991 and consequent disruption of their oil industry.

By 1996, oil from both Kuwait and Iraq were back on the market. Late in 1997, however, financial crisis hit the South East Asian 'tiger' economies, reducing demand, which coupled with increased OPEC production resulted in the oil market crash of 1998 with prices below $10 a barrel. This bust was short-lived; by the end of the 1990s, the oil market was set for a dramatic return.

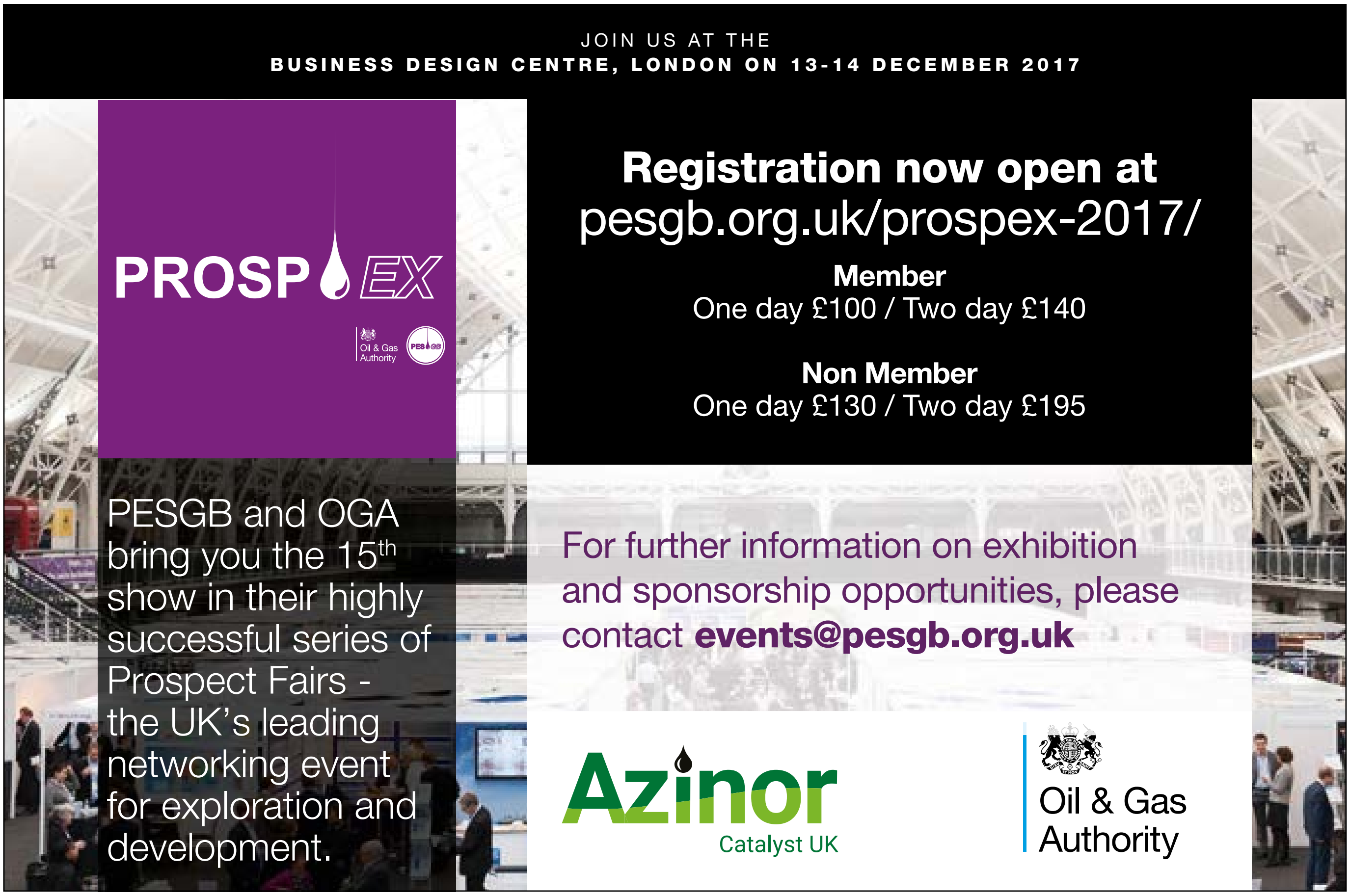
A New Century for Oil?

As the 21st century began, economic growth, especially in populous China and India, together with the resurging Asian tigers, enormously increased global demand for oil. Indeed, from 1999 to 2008, oil prices increased from $18 to $97 a barrel. During the same period consumption rose from 76.3 to 86.6 MMbopd, with China and India accounting for nearly half this increase. This rapid demand reduced spare capacity in oil-producing countries to less than 1 MMbopd in the mid-2000s. From 1999 to 2008, domestic oil production in the US fell from 7.7 to 6.8 MMbopd and the US dollar was weakened against European and Asian currencies.

The US invasions of Afghanistan in 2001 and Iraq in 2003 and the long-term 'war on terror' in the Middle East

Oil wells burning after Iraqi troops retreated from Kuwait in 1991.


Jonas Jordan, USACE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created uncertainty over oil supplies throughout the 2000s. Unrest in the Niger Delta disrupted oil operations. President Putin's policy of restraining foreign oil companies sent alarming signals about Russian oil. In August 2005, Hurricane Katrina disrupted oil operations in the Gulf of Mexico and southern US coastal states, further adding to uncertainties and price increases.

The rapid rise of oil prices between 2003 and 2008 can be regarded as the Third Oil Shock. Peak oil fears were widespread in the 2000s, with many articles, websites, and conferences promoting the idea that global oil reserves and production had reached a peak and oil was on the verge of a rapid decline. Disciples of M. King Hubbert's peak oil scenario revived the idea in the late 1990s, suggesting various years of peak oil throughout the 2000s. Politicians were alarmed too; President George Bush, Jr. openly called for a cure for America's "addiction to oil."

Did the 21st century bring peak oil – or a new century for oil? The following years provide some clues to unravelling this question.

2008 Recession and 2014 Bust

The price of oil increased sharply from $50 in early 2007 to $140 in the summer of 2008. Just as some experts were suggesting $200 a barrel by the end of 2009, economic recession hit in late 2008 and oil dropped as low as $32 a barrel. This recession began in the USA as a result of real-estate mortgage crises, tight credit lines and the bankruptcy of large financial institutions, but it rapidly translated into a global economic crisis, the largest since the Great Depression of the 1930s. With slowing economies, consumption dwindled, thus lowering oil prices considerably. Nevertheless, with improving economic conditions, in August 2009 prices rose to $70 a barrel and remained at $90–120 until mid-2014.

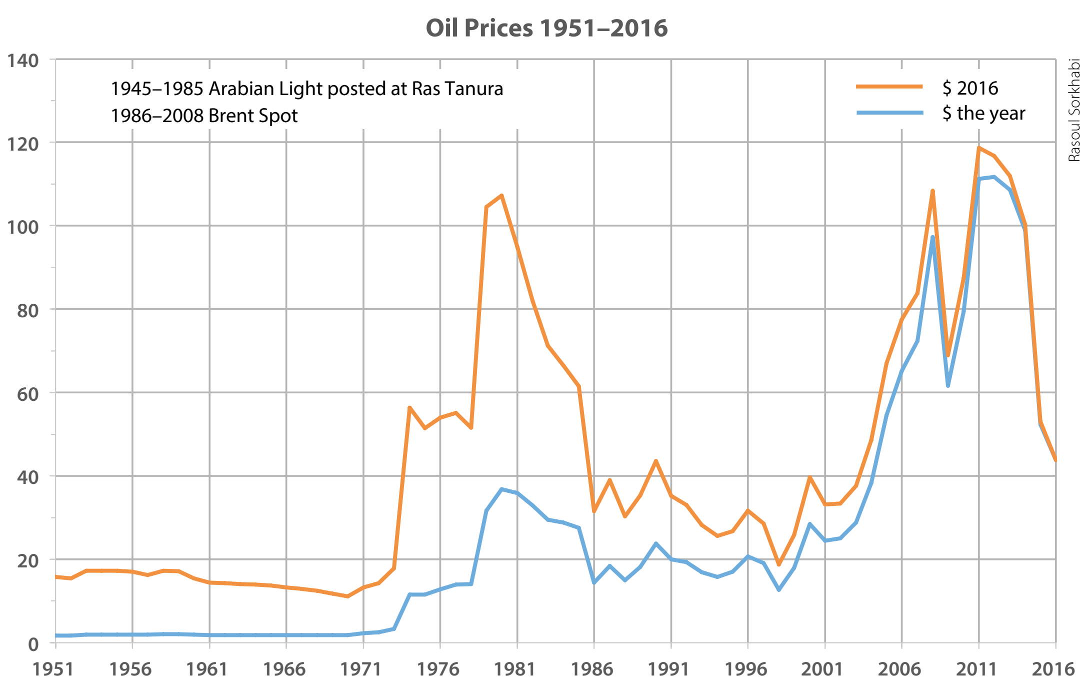
The recent oil bust is comparable to the market crash of 1986. It is usually thought that the 2014 bust began when Saudi Arabia again refused to act as a swing producer to stabilise the market and began flooding the world market with oil. Initially, it was argued that they wanted to punish Russia or Iran by weakening their oil-dependent economies. Later, however, it was revealed that the real target was North American shale oil producers; the Saudis wanted to secure their oil market share in the US and other parts of the world by driving shale producers out of business through lower prices. The partial lifting of sanctions against Iran and the return of Libyan oil added to the glut.

The increase in US shale production as well as the strengthening of the US dollar contributed to the oil bust of 2014. In that year, USA became one of the top oil producers alongside Saudi Arabia and Russia, and oil prices fell below $30 a barrel in January 2016. Despite this, current technological developments in shale oil production have made this new oil supply resilient and profitable, making this oil bust different from that of 1986. Only the future will tell where this new oil player will take prices.

A Sum-Up

Oil prices are basically controlled by supply and demand. This simple relationship, however, is complicated by other factors. For one thing, supply is not solely controlled by geology and technology; political conflicts and violence in the Middle East and North Africa obviously played critical roles in the first and second oil shocks, and natural hazards like hurricanes also influence oil supplies, albeit perhaps briefly and locally. Consumption is closely related to economic growth. During the mid-2000s rapid economic growth in China and India increased global demand for oil and thus put restraints on oil supplies and spare capacity. Geology, therefore, is not an ideal indicator for forecasting oil prices and production, despite what the proponents of peak oil say. In fact, technological advances in the oil industry have historically been made in response to market demands. Because of the non-geological uncertainties in oil supply and demand, speculation over future oil sales in stock exchange markets also factor in oil prices. Since much of the world's oil has historically been traded in US dollars, the strengthening or weakening of the dollar against other currencies also directly affects oil prices. ■

Chronology of oil prices 1951–2016 (source: BP Statistical Review of World Energy 2017).



Introduction to Deep Learning: Part I

HONGBO ZHOU, Statoil, **LASSE AMUNDSEN** and **MARTIN LANDRØ**

Once, artificial intelligence (AI) was science fiction. Today, it is part of our everyday lives. Tomorrow, AI is speculated to make computers smarter than people, and perhaps threaten the survival of humankind. In the future, can computers begin to think for themselves? What are the trends in AI? What is to come?

"We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run."
Roy Amara (1925-2007)
American scientist, futurist and president of the Institute for the Future.

Encyclopaedia Britannica defines Artificial Intelligence, or AI as it is commonly called, as the ability of a computer or computer-controlled robot to perform tasks that normally require human intelligence, such as the ability to reason, discover meaning, generalise, or learn from past experiences.

We have seen AI robots in movies or read about them in science fiction novels. C-3PO is a robot character from the Star Wars universe whose main function is to assist etiquette, customs, and translation, so that meetings of different cultures run smoothly. On the evil side, recall the 'Terminator' series. Before becoming self-aware, Skynet is a powerful AI system for the US military to coordinate national defence; after becoming self-aware, Skynet decides to coordinate the destruction of the human species instead, with the Terminator robots serving as its agents, disguised as humans.

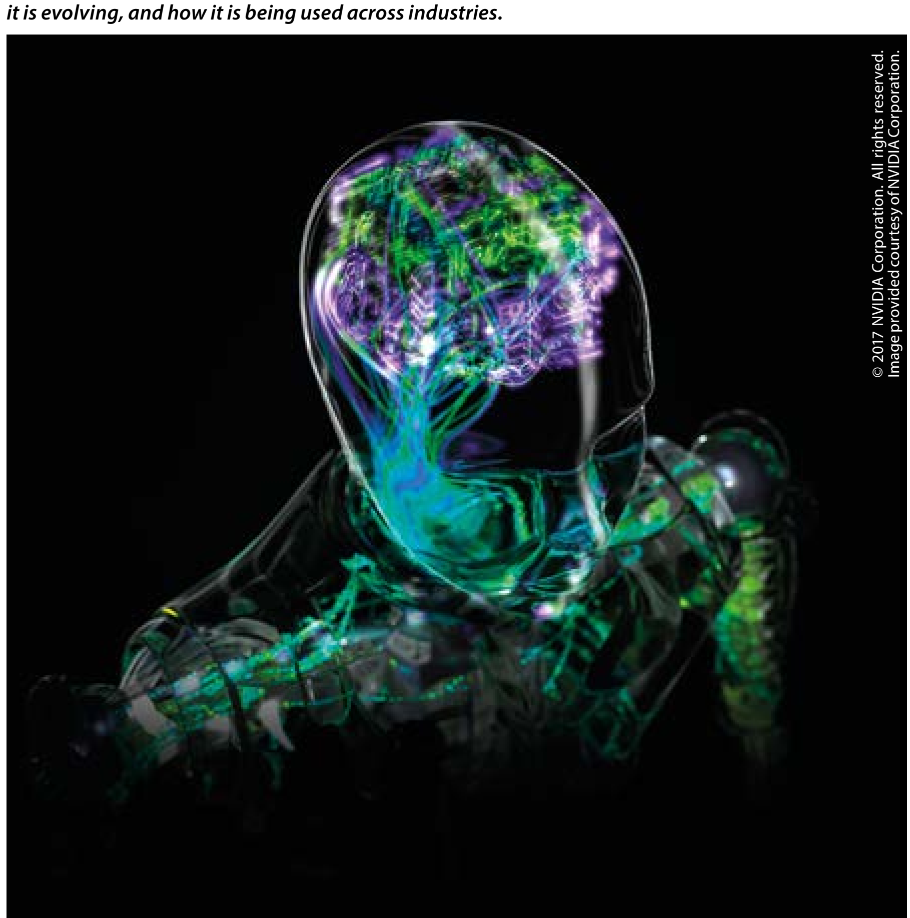
Whilst the idea of AI can be terrifying, there are interesting 'passive' forms of real AI. First, however, we will look briefly into the history of AI.

Early AI Milestones

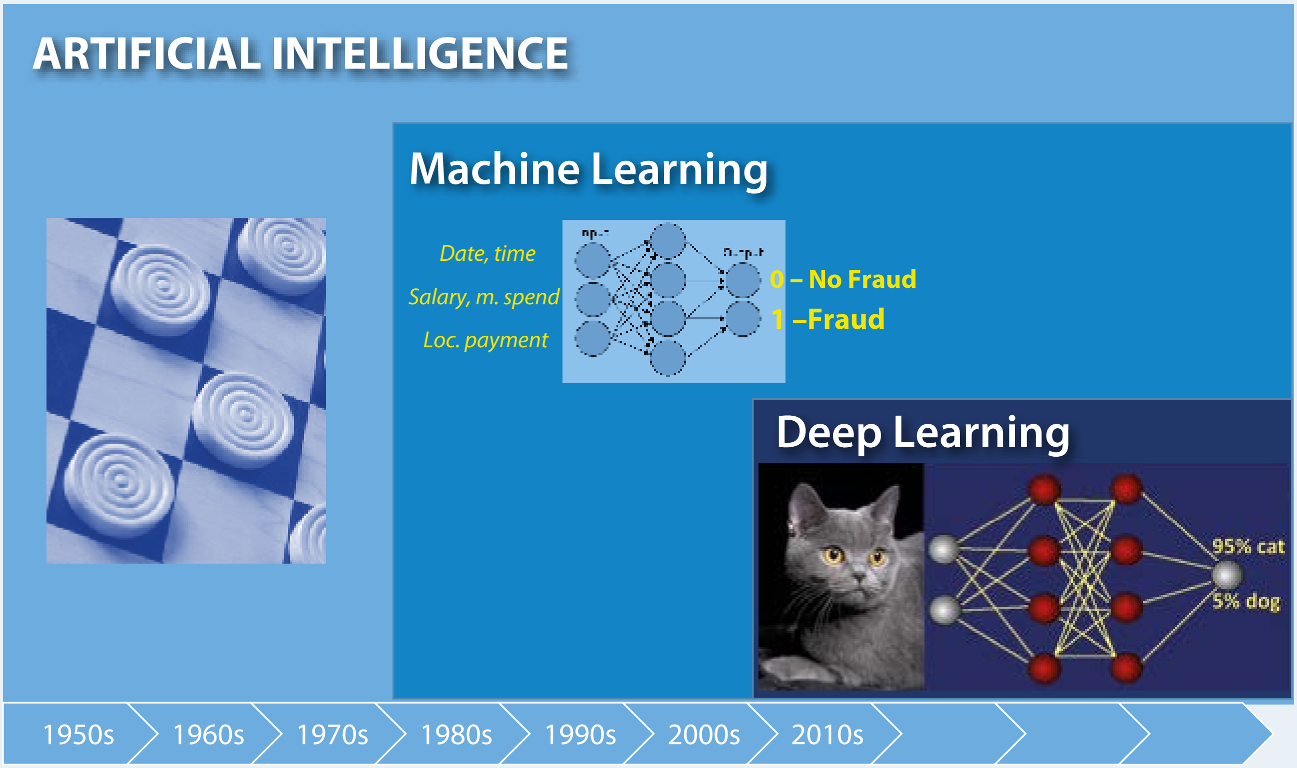
The earliest work in the field of AI was done in the mid-20th century by the British mathematician and computer pioneer Alan Turing. In 1947, he discussed computer intelligence in a lecture, saying, "What we want is a machine that can learn from experience," and that the "possibility of letting the machine alter its own instructions provides the mechanism for this." In 1950, he wrote a paper, 'Computing machinery and intelligence,' addressing the issue of AI.

One of the earliest successful demonstrations of the ability of AI

Artificial intelligence is the use of computers to simulate human intelligence. Deep learning – driven by ever more powerful GPUs – grows more useful as the amount of data in the world grows. This image is NVIDIA's brand representation of their AI podcast, where experts discuss how AI works, how it is evolving, and how it is being used across industries.



AI Progression



Machine learning and deep learning are subsets of AI. One of the first AI programs was a checkers (or draughts) program, written by Arthur Samuel, which won a game against a former checkers champion in 1962. Machine learning is applied to automatically discover patterns in data, which can be used to make predictions. For instance, a machine learning system can learn patterns in credit card transactions in a bank's database that are predictive of fraud. The more data (e.g. date, time, salary, average monthly spend, location, merchant, price and whether the transaction was legitimate or not) the system processes, the better its predictions become.

Deep learning is driving today's AI. It is widely used for tasks like face-tagging of photos, voice recognition, and language translation. There is now hope that deep learning will be able to diagnose deadly diseases and do countless other things to transform whole industries, including the oil and gas industry.

programs to incorporate learning was published in 1952. Anthony Oettinger at the University of Cambridge, influenced by the views of Alan Turing, developed the response learning program 'Shopper', in which the universe was a mall of eight shops. When sent out to purchase an item, Shopper would visit these shops at random until the item was found, but while searching it would memorise a few of the items stocked in each shop visited. The next time Shopper was instructed to get the same item, or some other item that it had already located, it would go to the right shop straight away. This simple form of learning is called rote learning, a memorisation technique based on repetition without proper understanding or reflection. Today, we note that AI in online shopping is big business. AI technology allows businesses to analyse the customer's behaviour, predict consumer needs and offer tailored customer experiences. AI is designed to make online experiences altogether more personal.

The 1956 Dartmouth Artificial Intelligence Conference marked the birth of the field of AI as a vibrant area of interdisciplinary research; many of the attendees later became leaders in AI research. These pioneers were optimistic about the future and believed that within two decades machines would be capable of doing any work a person can do. Their attitude was shown in their proposal: "a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer". Their dream was to construct complex machines – enabled by emerging computers – that possessed the characteristics of human intelligence.

After expressing the bold goal of simulating human intelligence, researchers developed a range of demonstration algorithms that showed that computers could perform tasks once thought to be solely the domain of human capability. However, lack of computer power soon stopped progress, and by the mid-1970s AI was considered overhyped and tossed into technology's trash heap. Technological work on AI had to continue with a lower profile.

Machine Learning – An Approach to Achieve AI

In the 1990s, machine learning, a subset of AI, started to gain popularity. The machine learning field changed its goal from achieving AI to tackling solvable problems of a practical nature. Machine learning adapted methods and models borrowed from statistics and probability theory. Among the most common methods are artificial neural networks or ANNs (weighted decision paths), which are electronic networks of 'neurons' loosely analogous to the neural structure of the brain, and genetic algorithms, which aim to evolve solutions to problems by iteratively generating candidate solutions, culling the weakest, and introducing new solution variants by introducing random mutations.

Machine learning thus has links to optimisation. Many learning problems can be formulated as minimisation of some objective or loss function on a training set of examples. Loss functions express the misfit between the predictions of the model being trained and the actual problem instances; for example, in classification, one wants to assign a label to instances, so models are trained to correctly predict the pre-assigned labels of a set of examples. The difference between optimisation and machine learning lies in their goals: while the goal of optimisation algorithms is to minimise the loss on a given training set, the goal of machine learning is the prediction of unseen samples. In this way, the machine learning discipline is concerned with the implementation of computer software that can learn autonomously.

Machine learning is mainly about feature extraction, i.e., the extraction of representations or abstractions that are pieces of information or characteristics that might be useful for prediction. Historically, there exist two major arenas of machine learning: the traditional computationalism concept that mental activity is computational and symbolic or logic-based; and the connectionism view, in which mental activity can be described by interconnected networks of simple units and is neural-based. Neural networks, as we will discuss below, are by far the most commonly used connectionist model today. These two scenarios, however, have duelled each other since their birth.

Computation or Neural Networks

Traditional symbolic-based machine learning models depend heavily on feature engineering, a process of using domain knowledge to manually extract features that make machine learning algorithms work. Specifically, the programmer needs to tell the computer the kinds of things it should be looking for that will be informative in decision-making. The algorithm's effectiveness relies on how insightful the programmer is. For complex problems like object recognition, this proves to be both difficult and time-consuming, meaning that feeding the algorithm with raw data rarely ever works for traditional symbolic-based machine learning. But, unlike its rival, the ANNs system, people have full control of obtaining what they want to achieve.

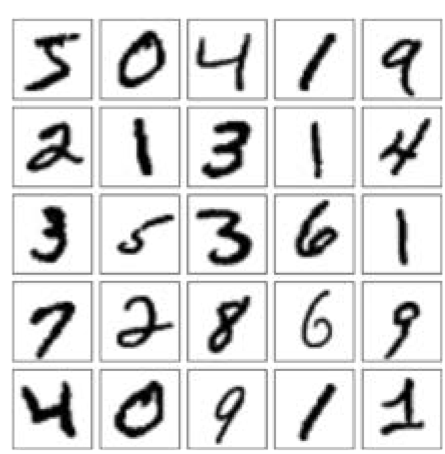
Consider this example: a human driver uses his eyes and brain to see and visually sense the traffic around him. When he sees a red rectangular-shaped plate with a white border and large white letters saying WRONG WAY, he knows that if he drives pass the sign, he is in trouble. For many years experts tried to use machine learning to teach computers to recognise signs in the same way. The solution, however, required hand-coding. Programmers would write classifiers such as edge detection filters so the program could identify where an object started and stopped; shape detection routines to determine if the object had four sides; and a routine to recognise the letters 'Wrong Way'. From all those hand-coded classifiers they would develop a theoretical and algorithmic basis to achieve automatic visual understanding. But would you trust the computer if a tree obscures part of the sign?

The other arena for machine

learning is ANNs. Neural networks, based on learning multiple levels of representation or abstraction, have traditionally been viewed as simplified models of neural processing in the brain, even though the relation between this model and the biological architecture of the brain is debated as it is not clear to what degree ANNs mirror brain function. Over the past few decades computer scientists have developed various algorithms that try to allow computers to learn to solve problems automatically through Big Data. ANNs have been successful in various applications in recent years but the criticism remains about its opaqueness. People have some clues on how to make it work, but do not actually know why it works so well.

In the next issue of GEO ExPro we will extend our discussion on deep learning. ■

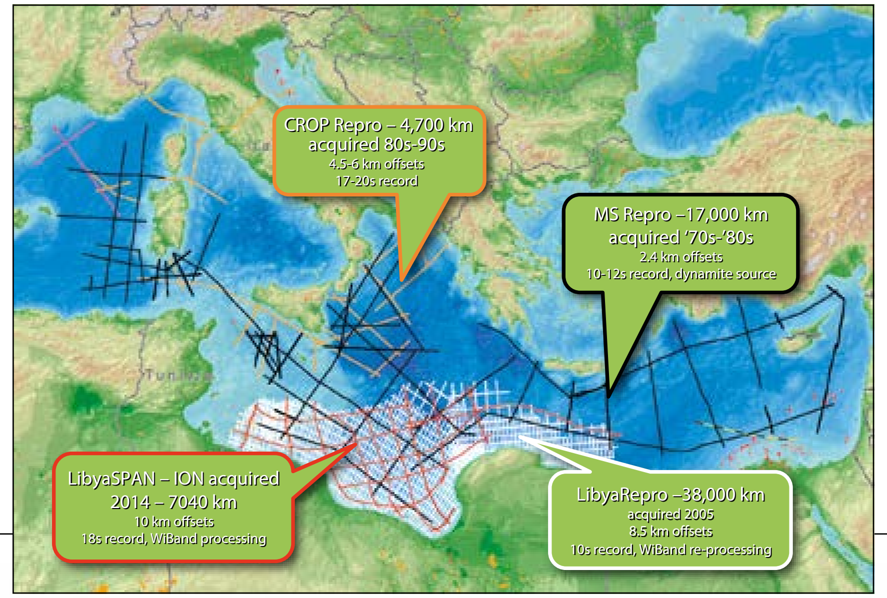
The MNIST dataset is a standard benchmark dataset for machine learning. It is a modified subset of two datasets collected by National Institute of Standards and Technology (NIST). It contains 70,000 scanned images of handwritten digits from 250 people, half of whom were US Census Bureau employees, the rest being high school students. There have been numerous attempts to achieve the lowest error rate in solving the handwritten digit recognition problem; one attempt, using a hierarchical system of convolutional neural networks, manages to get an error rate on the MNIST database of 0.23 %.



Exploration Opportunities in the Mediterranean

The value of a regionally calibrated seismic dataset

Exploration in the Mediterranean Sea has experienced significant renewed interest over the last decade, with exciting, play-opening discoveries in Israel, Egypt and Libya. ION has taken an innovative approach in order to rapidly and cost-effectively develop an integrated dataset to aid understanding of the whole Mediterranean, which can be used as the framework for future exploration programmes and to challenge existing basin models. The dataset consists of newly acquired BasinSPAN data and reprocessed data from both industry and academic sources. These surveys have been processed concurrently to provide a consistent velocity model across the Mediterranean and generate a fully integrated geological and geophysical interpretation using seismic, well, gravity and magnetic data. ION has created a unique dataset in the region to support the next phase of exploration, with licence rounds expected in the near future.



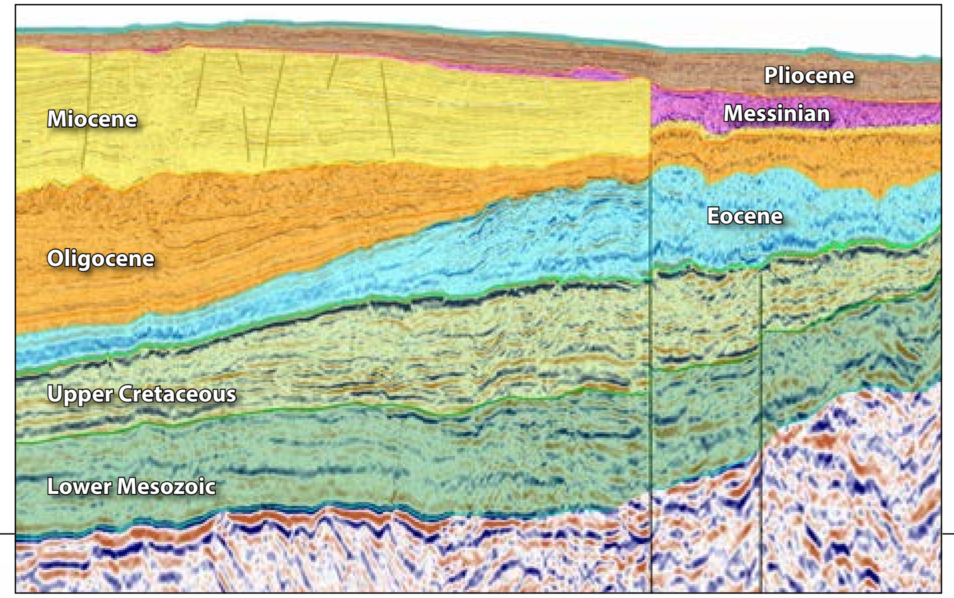


Figure 1: Interpreted section of seismic outlined in black on foldout line.

Integrated Seismic Datasets

VERITY AGAR, PAUL BELLINGHAM, NICOLA CLARKE, ELISABETH GILLBARD and KEN McDERMOTT; ION

The offshore Mediterranean basins are the focus of renewed interest since the 2008 discovery in Libya, the Tamar and Leviathan discoveries in Israel, and the recent Zohr discovery in Egyptian waters. ION's regional Mediterranean programme demonstrates the utility and exploration value of a fully integrated seismic dataset and velocity model across the entire basin. Interpretation of these data provides the context to correlate known discoveries into those new and complex underexplored areas.

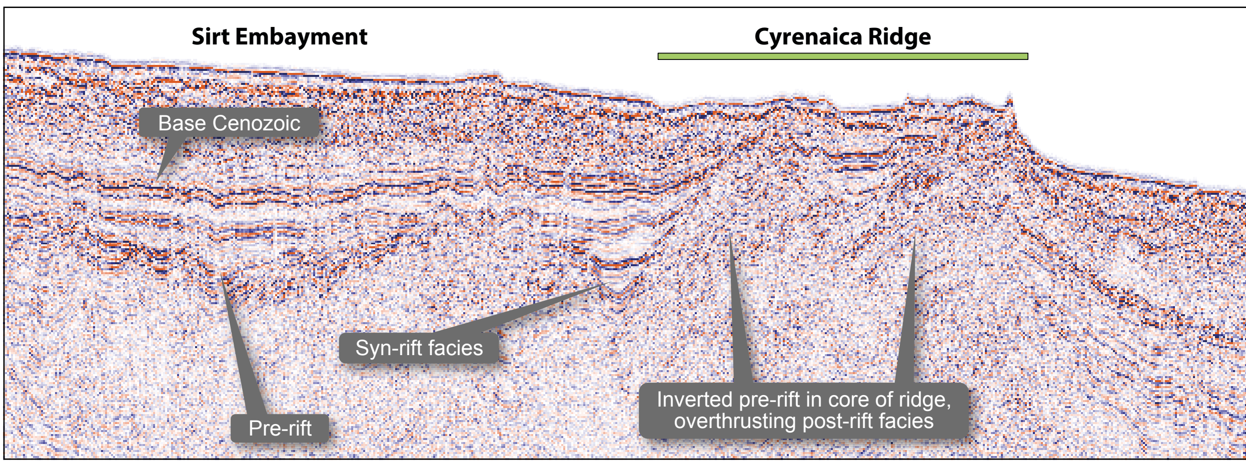


Figure 2: Example line in Cyrenaica area from reprocessed Libya dataset highlighting areas of improved imaging and features of interest.

Regional Geology

The present-day configuration of the Mediterranean Basin is dominated by the Cenozoic collision of Africa and Eurasia, creating compressional and back-arc extensional tectonic settings. The current tectonic elements and basins have overprinted pre-existing Tethyan margins that stretch from Algeria to the Eastern Mediterranean and extend to the Arabian Peninsula. The variability in basin types and ages provide significant hydrocarbon potential for a wide variety of play types, with source rocks of Palaeozoic to Cenozoic age.

The Mediterranean contains several well-known plays: biogenic Pliocene gas offshore Nile Delta; salt-generated structural plays of the Sabratha Basin; and the Po Valley/Adriatic Sea gas play. There are also areas where commercial discoveries have been elusive and areas which have yet to be explored with the potential for new play types.

Offshore Libya

Offshore Libya has attracted exploration interest for some time. The prolific petroleum systems of Libya have generated proven oil discoveries of about 130 Bbo, the majority of this onshore. The offshore extensions of these petroleum systems are largely unexplored. The success of the 2005 EPSA IV licence round highlighted industry interest in the area and the subsequent play-opening Arous Al-Bahar gas discovery in the offshore Sirt Basin in 2008 confirmed the continuity of the onshore Cretaceous carbonate play into the Sirt Basin. The potential of Eocene marls and limestone reservoirs lying unconformably on the Cenomanian and Turonian carbonate blocks remains poorly understood. Discoveries continue to be made in the more developed Sabratha Basin, but several structures and deeper targets remain undrilled.

Given the proven offshore extension of the enormous reserves onshore Libya, creating an integrated depth-migrated seismic dataset and basin framework interpretation provides the basis for future exploration. The regional framework LibyaSPAN™ data are infilled with 39,000 km of modern reprocessed 2D data. The processing and imaging of these datasets are fully integrated and calibrated using gravity, magnetic, and well control data. The improved imaging provides a database to identify new prospects and plays in the Sirt and Cyrenaica Ridge areas as well as the eastern margin of the basin. These data create the framework to develop a new understanding of the entire offshore system from crust to sediment in a basin-scale context and are vital to understanding the petroleum potential of the offshore Libyan margin. (See Figures 2 and 3.)

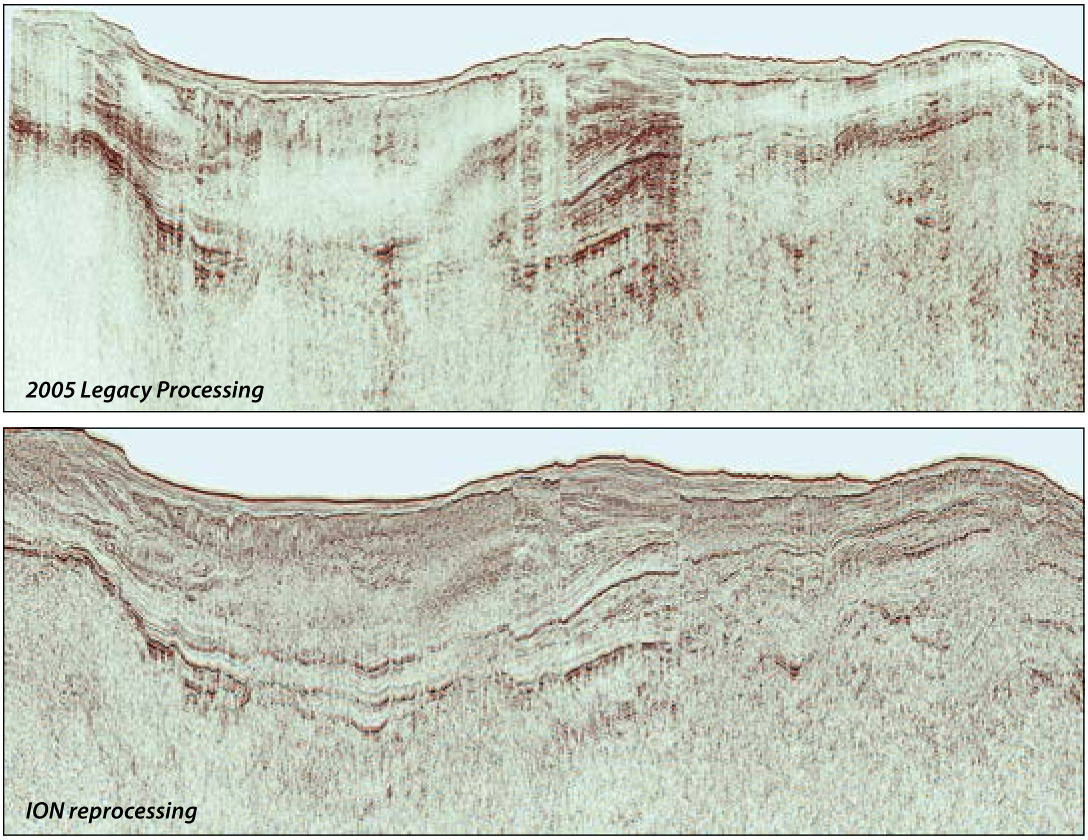


Figure 3: Example of improvement in imaging with modern processing offshore Libya.

Nile Delta

The Nile Delta region has undergone several phases of exploration, but is dominated by Plio-Pleistocene gas discoveries in stratigraphic and structural traps. Exploration of deeper Miocene and Oligocene strata has had varying success and has been slower to develop. However, even with the extensive dataset across the area, fundamental questions regarding deeper stratigraphy and structure still remain. Development of new exploration plays in deeper water and older stratigraphy requires a better understanding of the underlying basement architecture and stratigraphy. ION, in collaboration with the Egyptian Natural Gas Holding Company (EGAS), acquired a deep, long-offset line across the central and western parts of the Nile Delta, imaged to 40 km depth. One of the critical observations from these new data is the >12 km thickness of sediment to the west of the Delta.

The Nile Delta 2D line was processed using ION's WiBand™ broadband processing solution, which provides deghosting that enhances the bandwidth of the data by recovering low-frequency components of the data and performing multiple suppression prior to waveform inversion. High resolution non-parametric inversion (GMO Tomography) incorporating anisotropy combined with the use of full waveform inversion created the detailed velocity model in the complex strata below the Messinian salt (Figure 4). Interpretation of crustal events (basement and Moho) using the new migration velocities calibrated with potential field data were combined to create high quality depth imaging. The integration of these data (potential field, refraction and PSDM) support the interpretation, addressing questions of crustal structure and the nature of the basin development. Recent discoveries and the presence of thick sediment

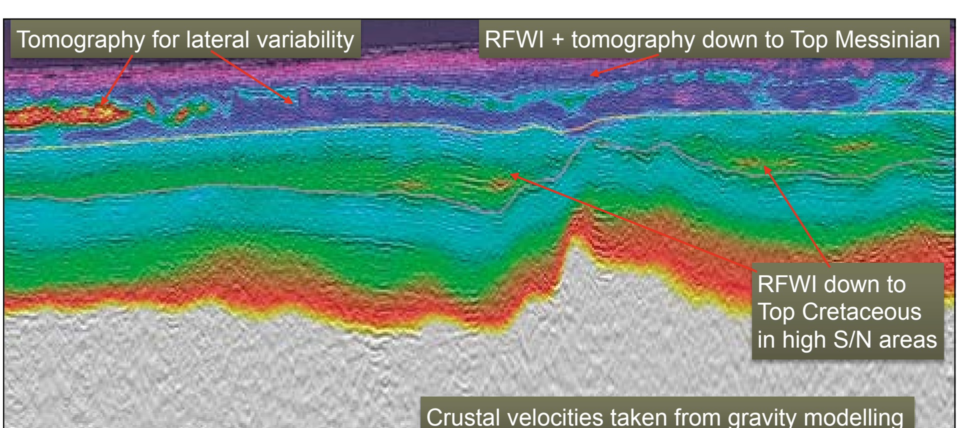


Figure 4: Nile DeltaSPAN velocity model highlighting the modern techniques used to maximise the accuracy of the velocity model and improve the quality of the deeper imaging.

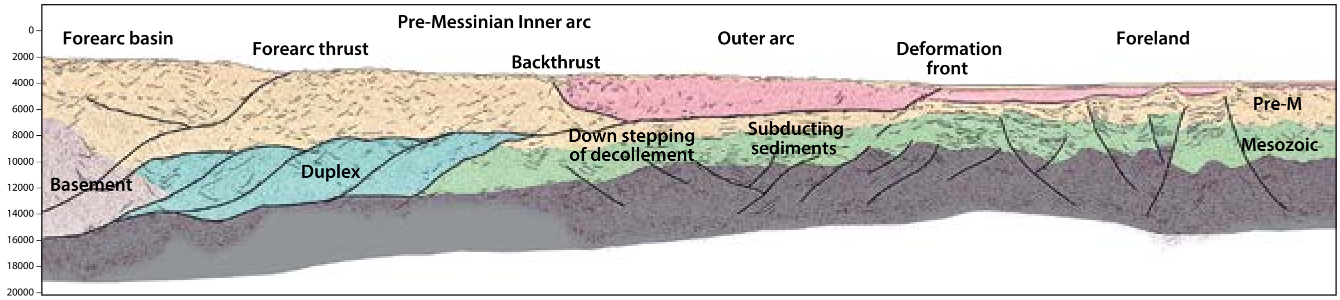


Figure 5: Geoseismic section (PSDM) of the Calabrian Arc from Sicily to the Ionian Abyssal Plain demonstrating the complex structure of the Arc with deformation younging towards the south-east. Thick deformed and undeformed Messinian evaporites dominate the Outer Arc and foreland. Improved sub-salt imaging provides uplift of the sediments and structures below.

lend support to source rock maturity continuing beyond the areas previously predicted.

Central and Western Mediterranean Exploration

Exploration successes in the offshore Ionian, southern Adriatic, and Sicilian Channel occurred predominantly from the 1970s to the 1980s. Oil discoveries within the Apulian platform were made in the 1990s and gas discoveries were made in the Gela foredeep of the Pelagian Basin beginning in the early 2000s. Despite intensive onshore and shallow water exploration, there remains significant underexplored offshore potential, including searching for known plays along strike and new play types.

Both the North African and Southern Eurasian margins developed as carbonate-dominated platforms on the margins of the Tethyan Ocean. The complex Mesozoic palaeogeographies (shallow water platforms and intervening deep water euxinic basins) were controlled by extensional phases and later inversion. Proven hydrocarbon plays in structural traps in the up-dip platform carbonates are thought to be sourced from basinal organic-rich mudstones.

Middle Eocene Alpine orogenic events across the margin resulted in the Apennine fold belt having an eastward migrating subduction system and the development of foreland and back-arc basins. The east–west trending Maghrebian thrust belt of North Africa, the Calabrian Arc and connected north–south trending Italian Apennines show significant variability in the width and deformation style along its strike. Progressively younger foreland fold-thrust belt settings characterise the compressional system and are important to hydrocarbon generation and accumulations sourced from either terrigenous flysch or mature pre-Alpine Mesozoic strata.

A New Look

Reprocessing of two legacy datasets, MS (acquired 1970–82) and CROP (acquired 1988–95), using ION's BasinSPAN™ processing workflow, has been integrated into the interpretation and regional velocity model. These data span the complex and varied domains of the central and western Mediterranean basins, providing a new look at the petroleum systems and multiple play types.

Identified analogue plays on the Apulian Platform include karsted carbonate reservoirs and shelf-edge carbonate deposits. Fractured carbonate reservoirs in sub-thrust plays sealed by flysch are another attractive candidate.

The Calabrian Arc remains virtually untested with only nearshore fields in the Cretone Basin and academic wells which only penetrated the top of the Messinian evaporitic section in the deep basin. Inverted extensional structures in the thick Mesozoic and Cenozoic strata underlying relatively undeformed Messinian evaporites are compelling, but are located in ultra-deep water (Figure 5).

More mature and shallow water areas, such as the Pelagian Basin offshore Sicily, Malta and Tunisia, contain multiple play types and multiple source rock intervals that are working in Sicily and Libya/Tunisia. These plays are likely to be present in the Maltese offshore, but exploration efforts are hampered by boundary disputes and paucity of data. A younger Oligocene rift basin with a thick post-rift section in offshore West Sardinia may also contain an active petroleum system. Multiple plays in the pre-, syn- and post-rift sections are possible, with several source and reservoir intervals that could be sealed by Messinian evaporites or Pliocene shales. Interpretation of this contiguous dataset across the complex inverted margin of the Maghrebian in the Sicily Channel to the Balearic creates a new correlation framework between these diverse basins.

Cost-Effective Exploration

Exploration teams constantly strive to understand the basin framework in order to high-grade areas that align with company strategy and identify proven and future successful hydrocarbon plays. The complexities of the Mediterranean Basin architecture and the variety of play types highlight the importance of understanding the regional tectonic and stratigraphic framework to fully assess the remaining potential in the region. Using a fully integrated Mediterranean seismic dataset that crosses multiple country boundaries, tying mature areas (Sabratha Basin) with less explored areas in Libya, Malta and Italy, makes this interpretation and model refinement possible.

Given the current low price environment, it is critical for companies to acquire high quality information in a cost-effective manner. Combining new acquisition with reprocessed legacy data and modern integration techniques, ION has created a dataset that can be used to understand the future hydrocarbon potential in the Mediterranean.

Reference:

Hallet, D., and Clark-Lowes, D., Petroleum Geology of Libya, Elsevier, Amsterdam, Netherlands, 2016. ■

100 Years of Amazing Women

Anomalies – Pioneering Women in Petroleum Geology: 1917–2017

Robbie Rice Gries

Jewel Publishing, 2017

JANE WHALEY

An anomaly is 'a departure from the expected or normal'. The anomalies Robbie Gries is talking about in this fascinating book are female petroleum geologists – still a minority today.

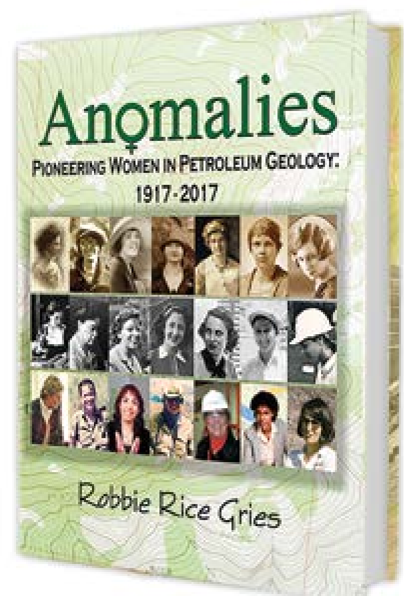
This account of women in the oil and gas industry is a fantastic achievement, requiring detailed research which highlights how they have been both celebrated and side-lined. The life stories of over a hundred pioneering women in petroleum geology are told, from those born in the late 19th century, to people now in their 40s. We meet them in roughly chronological order, linked through chapters tracing the trajectory of women's progress through the industry, from the first female geologists employed during WWI, through the Depression and WWII, and on to ongoing struggles for equality, culminating in the anecdotes of some present-day 'rock stars'.

Prejudice and Persistence

As a woman reading this book, I frequently felt furious at the prejudice and arrogance which consigned women to bit parts in this exciting history, whatever their abilities. As men left to fight in WWI, highly qualified women took over, only to be pushed to one side when the men came back, their contribution forgotten – and the same thing happened 20 years later after WWII. Women were forced to choose between a career and love, most companies refusing to employ married women. From even just an economic standpoint, what a waste of training, knowledge and experience.

But then you get into the stories of these resilient, courageous and tenacious pioneers who had to battle just to study geology, and you are overcome with admiration. They were tough, intelligent ladies who loved geoscience and wanted to take part in the exciting journey of oil exploration. Physically brave as well as mentally resilient, their tales of early car travel, with breakdowns in deserted locations commonplace, are fascinating, and not a little scary. Stories of "hard work, persistence and patient fortitude" eventually rewarded are found on every page.

It is also encouraging to read of the (male) managers who defied the conventions of the times and insisted on both employing and promoting women, recognising ability when they saw it (even if they still paid them less). They even accepted a woman's right to 'sit' a well in the field – although there are some interesting anecdotes about the men's reactions when the first woman joined their team!



Affirmative Action Needed

One would expect that these stories of the struggles of women to become petroleum geologists came from the early years of the industry, but the number of women joining the profession between 1947 and 1972 was as low as it had been in the 1920s–30s. Robbie believes that popular culture sought to propagate the idea that 'a woman's place is in the home'; they often had to work their way up from menial roles, accept lower pay, running errands and making coffee.

The 1973 increase in AAPG female membership was down to Affirmative Action, as the US Equal Employment Opportunities Commission enforced hiring goals for minorities and women, as well as equal pay. Even then, as Robbie herself confirms (as a geologist of note and the first female President of the AAPG, she is rightly included in this collection) there was subtle discrimination; when she was at university in the 1960s only boys were offered industry internships, for example. Having levelled the playing field in many ways, there was still the "lack of appropriate accommodation" issue on ships and rigs, preventing women from gaining wider experience, as Denise Stone found in the 1980s.

Many stories centre around the unchanging problem of child care, with a variety of solutions – although few would now adopt that of single mum Fanny Carter Edson in the 1920s. With no one to mind her daughter while she 'sat' a well, Fanny checked the seven-year-old into a hotel room, gave her some cash and told her it had to last a week!

Strong and Determined Women

Using diaries, recordings, company archives, interviews with families and friends and chats with the pioneers themselves, Robbie has built up a fascinating view of the life of these women. She has included many photographs, really bringing them to life, superbly illustrating the changing times – from long skirts to hard hats – and has also included insights into social and political changes covering more than a century.

This is a book to dip into and learn from – including the lesson of how easy it was to nearly forget the contribution that these individuals have made to their industry. Without this book and the hours of work that Robbie and her helpers in the AAPG have put into researching and compiling it, "the life and times of these strong and determined women" were almost lost. As Robbie says: "I took so much pleasure in getting to know these amazing women". The same pleasure awaits anyone who picks up this book. ■

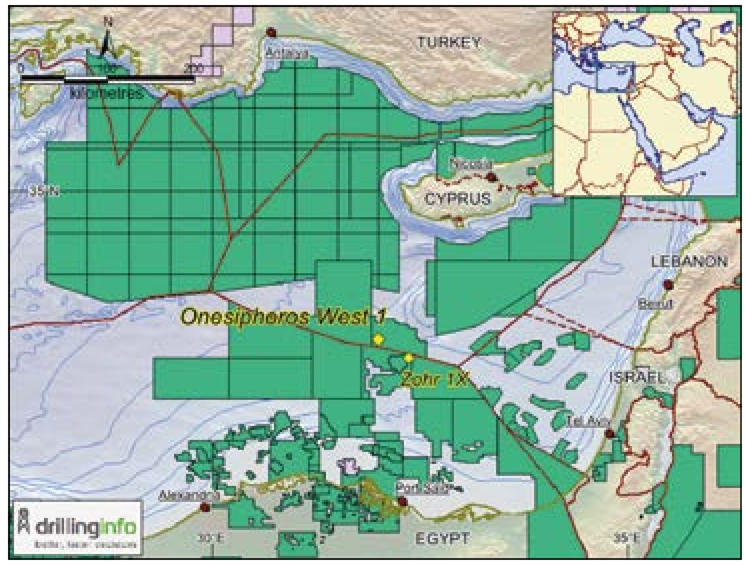
Cyprus: Non-Commercial but Encouraging Discovery

On 12 September 2017, Cypriot Energy Minister Yiorgos Lakkotrypis announced **Total's Onesiphoros West 1** new field wildcat on **Block 11** had discovered less than 500 Bcfg and as such is not commercially viable on its own. However, while the volumes of discovered gas are disappointing, the results are also encouraging, as the well proved the existence of Zohr-like reservoirs and a working petroleum system in the Cypriot EEZ.

Onesiphoros West 1, which is located offshore to the south of **Cyprus**, was spudded by Total in mid-July 2017 and is the company's first exploration well on the block. Drilled in a water depth of 1,698m, it had a PTD of around 4,000m and was designed to test the southern edge of the Eratosthenes Continental Block (ECB). The targets were Zohr-like carbonates on a north-south elongated four-way closure, which may have a stratigraphic element due to possible facies changes.

In December 2015, the Cypriot Cabinet gave approval for the first two-year renewal of Block 11, with Total making a statutory 25% part-relinquishment. The company had been fast-tracking its efforts to secure the necessary approvals ahead of the licence expiring in February 2016, motivated by Eni's super-giant Zohr gas discovery, which is located 5 km to the south of Block 11 in Egyptian waters. Zohr encountered over 400m of net pay in Miocene/Cretaceous carbonates in the Nile Delta Basin and an appraisal programme has confirmed over 30 Tcf gas in place. The carbonate reef is perceived to be a satellite structure to the ECB, with several analogues/lookalikes wrapping around the high and enhancing the prospectivity of Cypriot Blocks 6, 7, 8, 10, 11 and 12.

Block 11 had been awarded exclusively to Total on 6 February 2013, and following the finalisation of a farm-in agreement between Total and Eni in March 2017, Total operates Block 11 with a 50% interest, with Eni holding the remaining 50%. ■

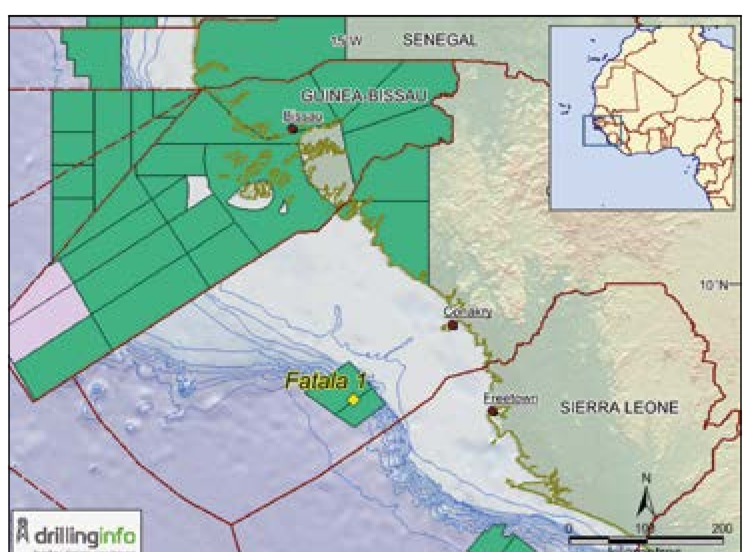


Guinea: Hopeful Signs

Hyperdynamics initially reported that its **Fatala 1** new field wildcat on **Block E3**, 200 km offshore Guinea, had failed to discover hydrocarbons. The well, which was targeting stacked Cenomanian turbidites in a transform margin play, with a Pmean recoverable resource estimated at 647 MMbo, was spudded in August 2017 in a water depth of 2,897m. It reached a TD of 5,117m in early September, intersecting a 75m Cenomanian channel sequence largely containing siltstone and clay lithologies. However, further detailed study of the well logs and oil saturation has identified 5m of calculated hydrocarbons with average porosity of 17% and a hydrocarbon saturation of 61% in the Upper Cenomanian channel located above the primary target formation. Fatala 1 was drilled on the edge of this channel, and the well result will be integrated with the seismic data to determine the commercial potential of this zone.

Hyperdynamics believes that whilst the well is not commercially viable these are encouraging signs for Guinea's hydrocarbon potential and has requested a two-year appraisal period. The company was considering three additional drill targets for future exploration on its Offshore PSC acreage (blocks E3 and F3), particularly the Bamboo prospect north-west of Fatala.

Fatala 1 had initially been slated for drilling in 2014, but faced numerous delays. Following a 77% part-relinquishment of the Offshore PSC, the current exploration phase was extended by a year to September 2017, to allow the well to be drilled. In April 2017, Hyperdynamics completed its farm-out of 50% equity in the Offshore PSC to SAPetro, in a deal that saw SAPetro pay 50% of the cost of the well, in addition to reimbursement for past costs. SAPetro has now said it will assign its 50% interest to Hyperdynamics, who will be seeking new partners. ■



Big Data in the O&G Industry

Ahmed Hashmi, Global Head of Upstream Technology, BP, talks about the big data future.

What do you understand by big data?
Big data is the challenge that many industries, including oil and gas, face in handling large volumes of data and information, much of it diverse, unstructured, and increasingly real-time. When harnessed properly, big data is a big opportunity, offering enormous value through improved knowledge and decision-making.

Why is it so important to E&P?
E&P is an intensely data driven, high technology business; it always has been, particularly in the subsurface. The data and knowledge we have about the fields we operate today, and from others in our past, inform our future developments, as well as providing analogues to other fields for new access.

In operations, control of big data offers improvement in safety, efficiency and reliability: today our operational environments are enabled with hundreds of thousands of sensors, each transmitting performance data against a defined operational envelope, enabling us to adjust, optimise and increasingly to predict anomalies before they arise.

What are BP's big data plans?
At BP, we have publicly stated our ambition to be the leading digital upstream company. Harnessing the power of data is key to this ambition. Over the past decade we have invested in subsea fibre to connect our operations to our centres of expertise, in high performance computing to crunch through massive volumes of subsurface data and in a proprietary data lake. Every day, twice as many data records enter the BP data lake than daily tweets on Twitter – and we plan a six-fold increase by 2020. We are building the Connected Upstream – connecting up our equipment, systems and people. It is BP's Industrial Internet of Things.

What is driving these plans?
The E&P sector faces many challenges today, not least the lower oil price. There is still short- and long-term demand for oil and gas: the world needs our products, but it wants lower carbon energy, and renewables are now presenting a real alternative. The economics of our industry have changed – we need to adapt to succeed.

Building the Connected Upstream and becoming the digital leader in our sector is part of our strategy to transform, and become more efficient, more resilient and create more value for our shareholders.

Is the industry technologically at the forefront of big data?
As a sector, we can often appear to be digital laggards. But there are pockets where we have moved further and faster than almost every other sector, including high performance computing. We have continuously invested in compute power over the past two decades to underpin our seismic processing capability. BP's Centre for High Performance Computing is equipped with six petaflops compute capacity, and growing. Today, we run complex seismic algorithms in a week that would have taken us 2,000 years about 20 years ago.

But while high performance computing is an acknowledged leadership area, in other areas we are building capability. For a long time our sensors were transmitting more data than we could handle; that is changing, with platforms like Plant Operations Advisor, a collaboration with GE using its world-class Predix systems – the first application for our industry. We have built a proprietary capability, using Distributed Acoustic Sensing with downhole fibre, to record sounds within our wells two miles below the seafloor to listen for sand which can constrain our ability to produce oil. Each hour we record a terabyte of data: the equivalent of downloading 1,000 Netflix films simultaneously. Today, not only can we record those data, but we can extract what's valuable, visualise them, and make decisions from them.

So the answer is, yes, we're at the forefront in some areas, and catching up fast in others.

Will big data and cloud computing change the industry?
Big data – when coupled with the cloud, machine learning, AI, automation and even higher performance computing – is a big opportunity, but we need to be realistic. Right now, there is a lot of hype around digital, with claims of exponential value; 10x rather than 10% improvements. Delivering anything close to this magnitude of improvement will require the industry to throw out the rule book. It will need novel technology collaborations, fresh thinking around some of our established ways of working across the industry, skilling up our people in advanced analytics and getting our mindset to one of balancing physics-based approaches with data-driven solutions.

Digital is already changing our industry; those who seize the opportunities it presents are likely to adapt best, become more resilient and create more value. ■

A Watershed Moment?

We cannot give up oil and gas exploration if we are to meet energy demand 20–25 years from now.

According to ExxonMobil's *The Outlook for Energy: A View to 2040*, over the next 20 years we will see a dramatic expansion in the world's population: approaching nine billion, up from today's seven billion. Global GDP will more than double as the size of the worldwide middle class increases.

This is the backdrop to the discussion about future energy demand and CO_2 emissions.

ExxonMobil forecasts growth in energy demand of about 25% from 2014 to 2040. The company admits that this is a significant increase, but adds that it would have been far higher (exceeding 110%) if they did not also foresee steep improvements in energy efficiency across all demand sectors. This strong demand will not be met by solar and wind energy alone, as claimed by environmentalists. In fact, ExxonMobil believes that oil, natural gas and coal will continue to meet about 80% of global demand until 2040. The fossil fuel share today is about 86%.

ExxonMobil concludes that the world will need to pursue all economic energy sources in order to keep pace with demand. In 2040, oil and natural gas will likely constitute nearly 60% of global supplies, while nuclear and renewables will be approaching 25%, in contradiction to many other predictions that see a much brighter future for renewables.

DNV-GL, in its inaugural *Energy Transition Outlook 2017*, has a different view of the energy future, forecasting energy demand to flatten at a level 7% higher than in 2015, mainly due to increased efficiencies in the use of energy and an increased share of renewables after 2030. The company calls this "a watershed moment in human history, where collectively we will need less energy to satisfy our energy demand".

As for fossil fuels, their prediction is that coal has already peaked, oil will peak within the next 10 years and gas in 20 years, but gas will remain the biggest single source of energy for the world through to 2050. This is different from the ExxonMobil forecast, which predicts that oil will be the largest energy carrier from 2033.

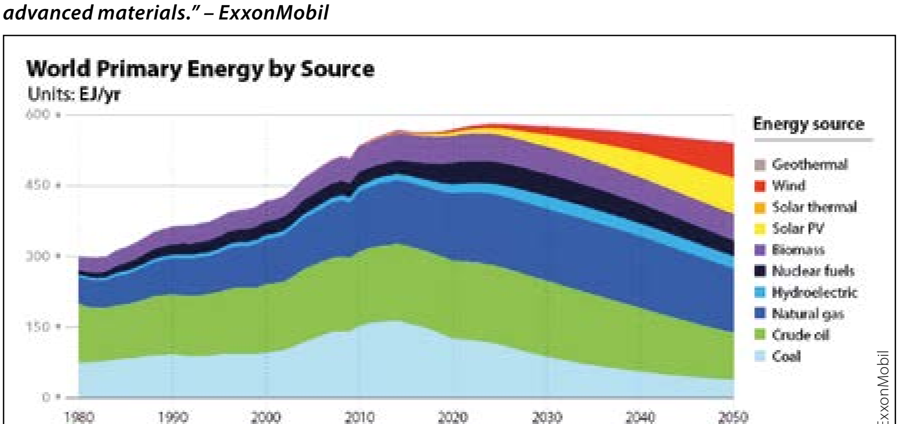
The oil and gas industry will therefore continue to be key, with hydrocarbons accounting for 44% of the total energy mix in 2050, down from 53% today. Key areas of demand for fossil fuels will be within heavy transportation, air and shipping, according to DNV-GL.

And, for those who are concerned about the environment, DNV-GL believes that total energy-related CO_2 emissions will be around half of today's level in 2050.

ExxonMobil and DNV-GL represent contrasting views, but both agree that oil and gas will play an important role as energy carriers for the next 20–30 years.

Halfdan Carstens

"We expect oil to continue to be the world's leading fuel, driven by demand for transportation fuels and by the chemical industry, where oil provides the feedstock to make plastics and other advanced materials." – ExxonMobil



Conversion Factors

Crude oil

1 m^3 = 6.29 barrels

1 barrel = 0.159 m^3

1 tonne = 7.49 barrels

Natural gas

1 m^3 = 35.3 ft^3

1 ft^3 = 0.028 m^3

Energy

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

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

Numbers

Million = 1 x 10^6

Billion = 1 x 10^9

Trillion = 1 x 10^{12}

Supergiant field

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

Giant field

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

Major field

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

Historic oil price