VOL. 9, NO. 4 – 2012

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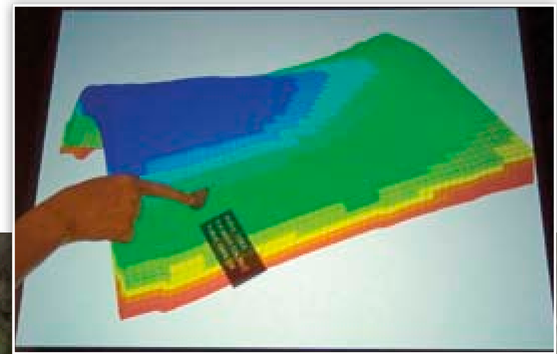

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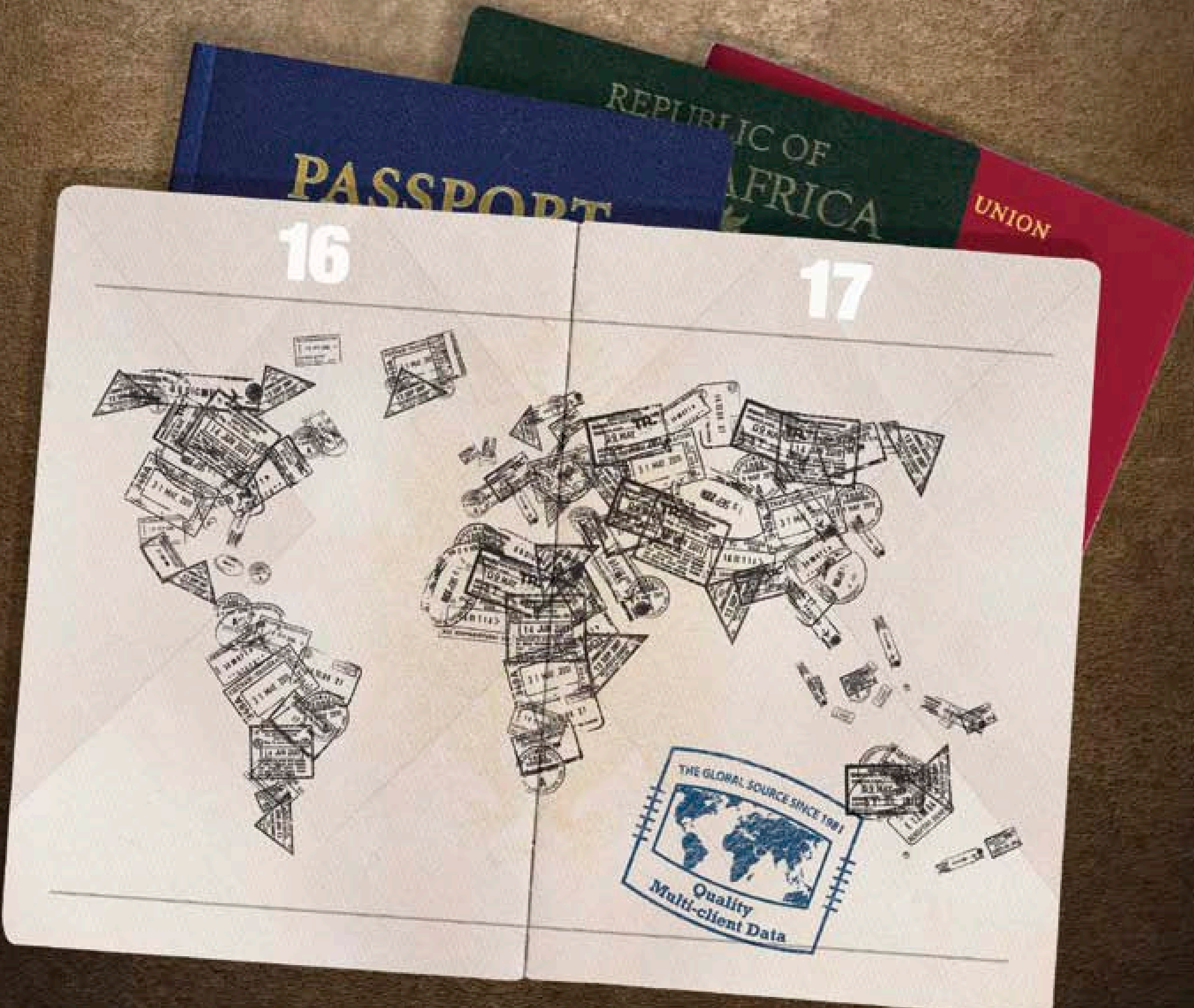

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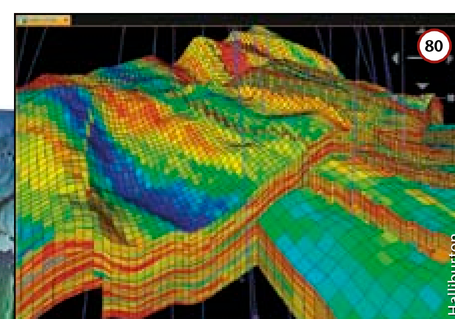
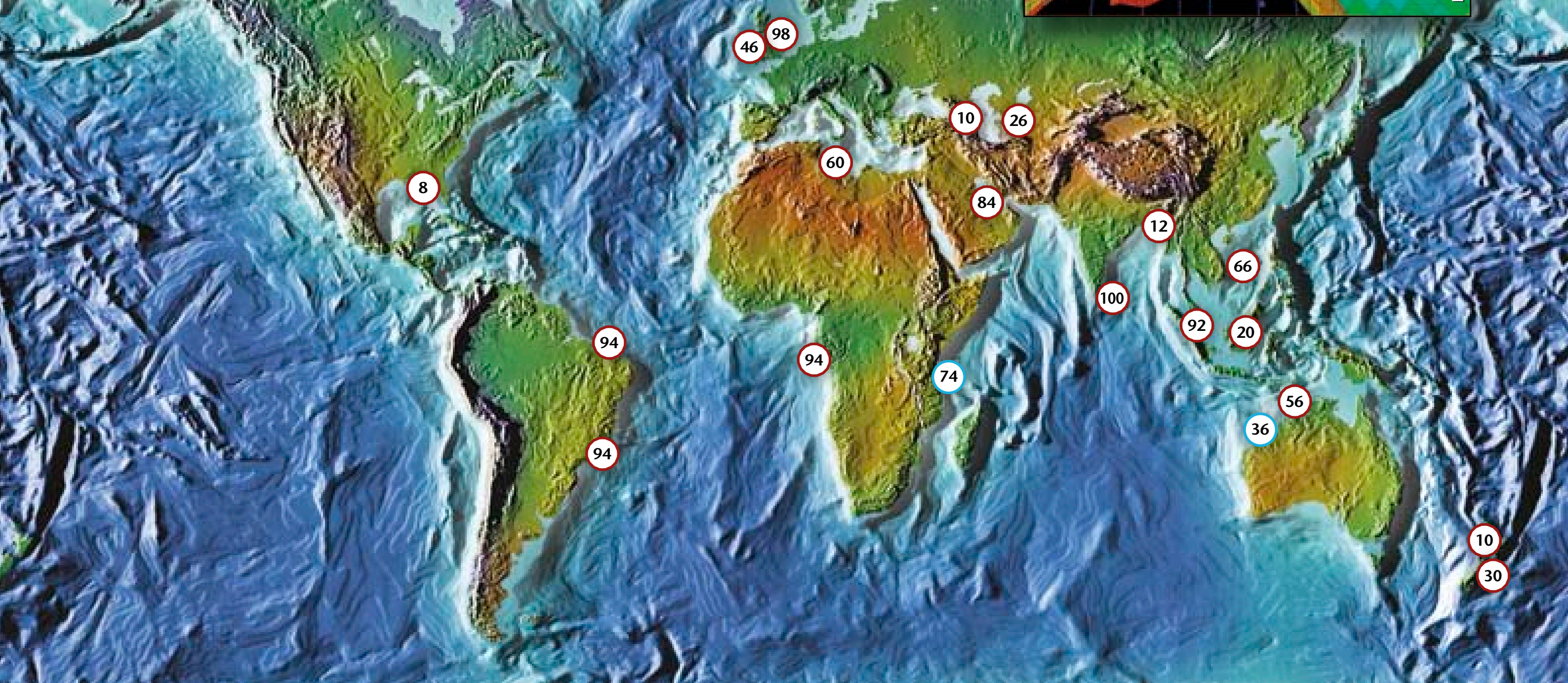




The Search Must Continue

The energy-hungry population of India has now topped 1.22 billion

So the amazing, record-breaking, exhausting sports-fest that is the Olympics is over for another four years, to a loud chorus of cheers, tears, recriminations and yawns, depending on your opinion of the event – and your country's position on the medal table. And slowly the holiday season draws to a close, vacations turn into memories and working life takes over once more.

But for those of us in the oil industry, should we ever be allowing our concentration to waver? Estimates suggest that by 2030, there will be a 30% increase in global energy demand when compared to 2010 levels *(Exxonmobil Energy Outlook 2012).* The increase in demand from non-OECD countries will actually move close to 60% as their economic growth and prosperity levels race to catch up with the countries of North America and Europe. While many efforts are being made throughout the world to make energy use more efficient and sustainable, this increase in demand will have to be matched at least in part by an increase in supply – and the hydrocarbon industry will have to keep searching and developing technologies to help achieve that growth.

This is particularly relevant for South East Asia, the geographical focus of this edition of *GEO ExPro* Magazine. Sandwiched as it is between two of the fastest economically developing countries in the wold, India and China, who between them hold over a third of the world's total population, the region is ideally positioned to supply these rapidly growing markets. At the moment, however, South East Asia only contributes 3% to oil and 6.5% to gas production globally. Few giants have been found and many of the known fields are nearing depletion. The region has lots of untapped potential however, but to bring it into the supply chain will need technological innovations, not only to squeeze each drop out of the existing fields, but to move into frontier deep water and other challenging areas.

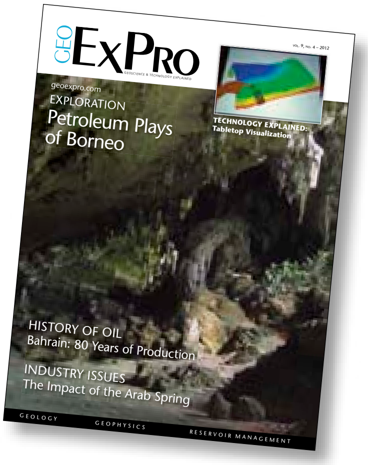
Luckily for all of us, technological innovation is something the oil and gas industry is good at, even if we do occasionally get distracted by worldwide celebrations and personal holidays.

JANE WHALEY
Editor in Chief

BORNEO'S PETROLEUM PLAYS

Niah National Park, about 109 km south-west of Miri, Sarawak, is home to the famous Niah Caves carved into a cliff of Miocene-age Subis Limestone. Stalactite and columnar structures in the caves are fascinating geological features. The Niah caves also contains prehistoric tools and remains including a 38,000-year-old human skull. The photo shows the view from Traders' Cave.

Inset: Digital tabletops provide a true collaborative environment for reservoir analysis and visualization



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Shell to Drill Arctic This Summer

In the first exploratory drilling program in US Arctic waters in two decades, Shell is to start drilling prospects in the Beaufort and Chukchi Seas off northern Alaska this August

Two massive Shell Oil Company drilling rigs left the Seattle docks on June 27 for the long trek to reach Alaska's Arctic waters. "The *Kulluk*, a conical Arctic rig that spent more than a decade mothballed in Canada, was the first to leave," says Curtis Smith, Shell Alaska spokesman. "The *Noble Discoverer*, a 60s log carrier that was converted for drilling, was close behind." Shell had been planning up to three exploratory wells on the Burger prospect in the Chukchi Sea, where they discovered oil and gas in 1990. The US Minerals Management Service estimated about 14 Tcf for the structure and the possibility of undiscovered oil below the gas. In addition to the Burger drilling, up to two wells on the Sivilliq prospect in the Beaufort Sea were programmed for this year. Shell paid US$12.2 million for the block over the prospect in the 2005 US Outer Continental Shelf Lease Sale 195.

Obstacles beyond Shell's control have added more delays to its drilling plans, which have been scaled back to just two total depth wells this season. The drilling rigs and most of the support vessels have made it to Dutch Harbor, located on Unalaska Island in Alaska's Aleutian Chain, still five to seven days from their Arctic Ocean destinations. A slow sea-ice melt forced a reduction of the drilling program and now the certification of Shell's containment barge is holding up the final permits to drill. This barge, the *Arctic Challenger*, is a containment vessel that would be the fourth backstop in a string of contingencies to assist in a major blowout. It will float between the Beaufort and Chukchi Seas and if a spill cannot be contained, the barge is designed to submerge a large dome to capture spilled oil. The oil could then be brought to the surface and pumped into a tanker for removal.

Shell is hoping to start drilling operations by early September, which would give it two months working time before having to vacate for the fall whaling season guaranteed to the native Alaskan Inupiats. "The data from the two wells and having all the necessary permits and support vessels in place will put the company in a very strong position for 2013," says Smith. "Our goal of drilling ten offshore wells in the Arctic over two years is still intact."

Investing Years in the Arctic

Shell is not a newcomer to the Alaskan exploration scene dating back nearly 60 years. The company was one of the original Arctic explorers including the North Slope where Prudhoe Bay would be discovered. Shell has long specialized in the offshore, developing fields in Alaska's Cook Inlet in the 1960s despite the very harsh conditions encountered there. Shell sold its platforms in 1998 – they are still producing today. It has also drilled the majority of the wells in the Beaufort Sea and undertaken four of the five wells drilled in the Chukchi Sea.

Shell re-entered Alaska by purchasing OCS leases in the Beaufort Sea in 2005 and has netted more acreage in subsequent lease sales. It now holds position in 137 Beaufort Sea lease blocks. In the February 2008 Chukchi Sea Lease Sale 193, it bid US$2.1 billion for 275 lease blocks. Since those lease sales, the company has spent over US$4.5 billion on permitting, research, outreach, spill prevention and an exploration plan that exceeds all regulatory requirements.

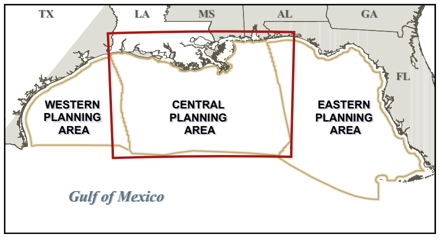
THOMAS SMITH

The Kulluk drilling rig leaving Seattle, Washington, towed by Shell's icebreaking and anchor-handling tug supply vessel Aiviq.

Photo courtesy of Shell Alaska

Back in the Gulf

Two years after the Deepwater Horizon blow-out, companies are back in the central Gulf



On June 20, 2012, Sale 222 became the fourth largest sale in the prolific central Gulf of Mexico with 56 companies participating. This was the second lease sale in the Gulf since the Deepwater Horizon disaster. The first was held in December, 2011 in the western Gulf and received $337.7 million in high bids. The active bidding was in spite of new safety measures and requirements the federal government imposed after BP's catastrophic blow-out and oil spill in 2010. Acreage was snapped up in the Mississippi Canyon in the vicinity of the explosion. This area had the most bids per block at seven and received the single highest bid for the sale from Statoil for $157 million.

Apache Corporation won the most (61 blocks) with BP second, winning 43. Shell spent the most money at $406.5 million, gaining 24 blocks, with Statoil coming in second, with 26 blocks for over $333 million.

While the shallow water (0 to 200m) Gulf leases had the most blocks receiving bids at 193, it was clear that companies are looking for the huge rewards the deep Gulf waters have produced. Blocks in waters greater than 800m received 90% of the winning high bid total spent by companies. In water depths of 800 to 1,600m, 75 blocks with a seven-year lease term received winning bids totaling $633.5 million. In water depths greater than 1,600m, which carry a 10-year lease term, 146 blocks received winning bids totaling over $906 million. The deepest block receiving a bid was located in 3,062m of water. The royalty rate for all blocks is 18.75% and the lease term for blocks shallower than 800m is five years.

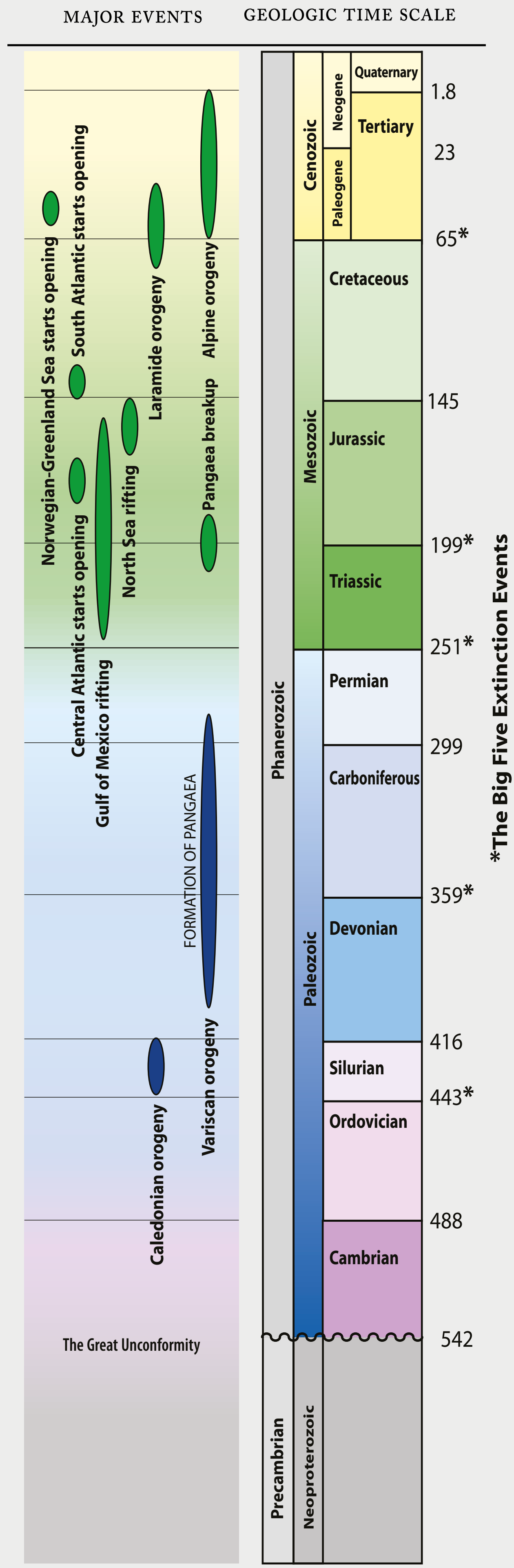
Government resource assessments published in 2011 put the undiscovered technically recoverable oil and gas resources for the total US outer continental shelf at 159.5 Bboe, with the central Gulf comprising a third of that at 54.7 Bboe. The EIA puts 84% of those resources in deep water and about 80% of the production from Federal waters. The Gulf of Mexico area currently produces about 1.6 MMbopd which constitutes 29% of US crude production. Twenty-three new deepwater projects due to come on stream over the next two years are projected to push the Gulf's production higher.

Active Drilling and Record Depths

Shell's 1987 gas discovery in the Mississippi Canyon was the Gulf of Mexico's first in deep water exceeding 5,000 feet (1,524m). Since then there have been at least 64 confirmed ultra-deep discoveries in the Gulf, with over 100 deepwater production projects brought on line since 1995. One of these, the Perdido development located 354 km offshore Galveston, Texas, started pumping oil from the Tabago Field (the second field brought on line in the area) in November, 2011. At a water depth of 2,934m, it is currently the deepest production in the world. As this is about as deep as the Gulf gets, the entire Gulf is now well within reach.

It seems that the drilling moratorium imposed after the BP spill did little to dampen the industry's enthusiasm for deepwater Gulf prospects. By early 2012, there were more rigs in the Gulf designed to drill its deep water than before the spill. Drilling activity is slowly picking up and is expected to reach pre-Macondo drilling levels by the end of this year.

THOMAS SMITH



Integrated Approach Showcased

Azerbaijan has played a major role in the hydrocarbon industry for centuries, as it was the first place where people learnt how to obtain and use oil for domestic use. By the beginning of the 17th century, there were about 500 wells drilled around Baku, the capital of Azerbaijan, and by the end of the 19th century, the town's fame as the 'Black Gold Capital' had spread throughout the world. It is therefore fitting that Baku is now going to host a major conference concentrating on the petroleum geology and hydrocarbon potential of the Caspian and Black Sea regions, where geoscientists from different countries will be able to meet, review the latest technological advances and share their experience.

The theme of the conference, which will be held on 3–5 October, 2012, is 'An Integrated Approach For Unlocking Hydrocarbon Resources'. In addition to a range of talks and seminars, the conference will offer field trips to look at the sequence stratigraphy of the Late Miocene/Pliocene Productive Series outcrops on the floor and walls of the Kirmaky Valley, and to the famous mud volcanoes in the Perikishkul area, which discharge gas, turbidity water, and mud with varying intensity.

This exciting conference is organized jointly by the Azerbaijan Society of Petroleum Geologists and the Azerbaijan National Committee of Geophysics, in association with AAPG Europe, the local chapters of SEG and EAGE and the Russian Association, AIS.

New Zealand Bidding Round Opens

The government of New Zealand recently opened its annual bidding round for oil and gas exploration permits; between June 8 and October 15, 2012, bids from petroleum exploration and production companies are invited for competitive assessment. A total of 23 areas are available, encompassing about 40,000 km^2 offshore in a variety of basins and 3,300 km^2 onshore in Waikato, Taranaki, Tasman, the West Coast and Southland. The blocks cover a number of petroleum basins and a variety of environmental settings, and resource types and work programs may target conventional hydrocarbons, including 'tight' resources, or unconventional (shale gas, shale oil, and coal seam gas) hydrocarbon systems. A data pack is available with free data relating to the block offer, containing new Kingdom projects, satellite seep studies, reports, 2D and 3D, SEG-Y and well data.

There are multiple sedimentary basins with known or potential hydrocarbons onshore and underlying the extensive continental shelf of New Zealand, as well as several deepwater basins within its Exclusive Economic Zone, although the Taranaki Basin off the east coast of North Island is the only producing basin in the country. Over 400 onshore and offshore exploration and production wells have been drilled to date in the basin, although none beyond the shelf edge, and it remains underexplored compared to many comparable rift complex basins of its size. The rest of New Zealand is seriously underexplored, although many frontier basins yielded discoveries which confirm viable petroleum systems, and it is considered that there is considerable potential for commercial hydrocarbon discoveries under New Zealand's largely untouched seabed (see *GEO ExPro* Vol. 8, No. 2 for further information about the petroleum geology of New Zealand).

View south along the north Taranaki coast, showing the 120,000 year highstand wave-cut platform and overlying terrace deposits. White cliffs are Late Miocene slope-fan deposits, age equivalents of producing petroleum reservoirs in the subsurface Taranaki Peninsula.

Lloyd Homer/GNS

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

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  - Tractor
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Myanmar Opens Up to the West

With Western sanctions suspended or removed, Myanmar's lucrative oil and gas sector could soon see a rush of bids from Western companies.

According to senior government officials, Myanmar will offer up to 18 onshore blocks in the 2012 international bidding round, scheduled to be launched in September, opening the prospect of a flood of new investment to the poverty-stricken nation. Further opportunities are promised, as the Energy Ministry indicated at a similar conference in Rangoon in June 2012, namely that 23 offshore blocks would be made available for bidding at an unspecified date. But as the Ministry prepares for a second promotional drive for potential foreign investment in this resource-rich country, opposition leader and Nobel Peace Prize winner Aung San Suu Kyi, while calling for greater Western investment in the country, has urged foreign oil and gas companies not to deal with the state oil agency MOGE (Myanmar Oil and Gas Enterprise), suggesting it was a "shadowy business and had so far failed to account for its activities".

Myanmar's hydrocarbon reserves are estimated at over 88 Tcfg and 3.2 Bbo – significant volumes in the regional context. Foreign investment in the oil and gas sector reached US$13.8 billion as of the end of November 2011. Natural gas accounts for 90% of hydrocarbon production, over 80% of which is exported to Thailand. Gas production is expected to increase to 2,000 MMcfpd by 2016, following the start-up of the offshore Shwe and Zawtika projects in 2013 and 2014 respectively, according to estimates by Wood Mackenzie.

In recent years investment has come largely from Asia, though Chevron and Total have stakes that pre-date sanctions in the country's largest project, the offshore Yadana gas project. With political reforms gaining international recognition, competition for Myanmar's oil and gas reserves is expected to intensify as foreign companies move in on a sector long closed-off due to Western governments imposing economic restrictions in response to alleged human rights abuses. A new foreign investment bill, one of numerous key reforms needed to spur economic growth and attract foreign investment, is expected to be passed into law before autumn, part of President Thein Sein's 'second wave' of reforms which he says will be enacted over the coming year and which the government hopes will triple the size of the country's economy by 2016.

Offshore Potential

Offshore exploration opportunities took a boost in March 2012 when Myanmar and Bangladesh announced that they had resolved their long-running maritime boundary dispute, at the center of which was an area covering 150,000 km^2 in the hydrocarbon-rich Bay of Bengal. MOGE has indicated it will invite foreign companies to explore and develop 17 deepwater blocks and six shallow-water blocks in three offshore areas in the Bay of Bengal and Andaman Sea. The offshore blocks, none of which have been explored by multinational oil companies before, will be awarded through 'direct negotiations', with the state holding a stake of between 15% and 25% in each project. It is believed that successful bidders will be granted an exploration period of up to six years, followed by a three-year tax holiday upon the start of production. The contractor will pay 30% income tax, while a 12.5% royalty will apply.

Nobel Peace Prize winner Aung San Suu Kyi is keen on Western involvement in oil exploration, but has reservations about the Myanmar state oil agency, MOGE

The geological settings of the three offshore zones differ considerably, with knowledge of the petroleum systems and reserves in Moattama and Tanintharyi better established. The Rakhine Offshore Area has an extremely thick sequence of sedimentary rocks, varying from 18 km in the north to 1 km in the southern part of the Bay. Preliminary test drillings in this Offshore Area indicate natural gas reserves of up to 14 Tcf. Water depths over the delta-shelf are less than 200m and deep objective depths are thought to lie between 2,000m and 5,000m. The Tanintharyi Offshore Area lies between the Mergui platform off the south-west coast and the east central Andaman Sea, where the seabed steeply slopes in a westward direction, with water depths up to 1,000m. It is expected that a significant sediment thickness should be affected both by folding and faulting. As in the Mergui platform, prospects may include both Miocene reefs and argillaceous sequences, thus both reservoirs and source rocks are expected to be developed.

India and China have been competing in many places in their quest for natural resources and Myanmar is the latest arena, with China already ahead. However, analysts suggest that Myanmar may not be too comfortable depending heavily on one country, predicting the country is set to become Asia's latest tiger economy. It is all down to the pace of reform and whether this can be sustained. ■

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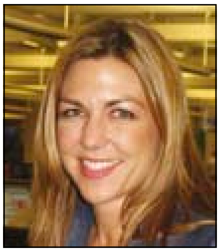
Lower Oil Prices – Good or Bad?

The strong oil price growth plus environmental issues has triggered demand-side changes that may challenge the industry



THINA MARGARETHE SALTVELT, PH.D

The sharp oil price rise since 2003 has revived interest in oil, and companies are jostling to secure access to new reserves in Africa, Asia and Latin America.

Protectionism and political unrest have curbed investment activity in many areas with cheap, producible, conventional oil reserves. This, coupled with high oil prices, has triggered the innovation of new technology, turning unconventional reserves previously seen as unprofitable into financially viable fields. So far the oil companies have concentrated on shale oil production in the US, oil sands in Canada, pre-salt oil from Brazil and heavy oil from Venezuela.

Based on a field-to-field survey by Maugeri, the world's overall oil production capacity may rise by as much as 17.6 MMbo from today's level in the period to 2020, with the major part expected to come on stream from 2015. The study is based on a long-term oil price of US$70/barrel, implying a significant drop from today's level of around US$110/barrel. It is now widely feared that this sharp increase in new production capacity worldwide may outmatch new, more expensive, conventional oil production projects in countries such as Norway, Russia and the Arctic region, curb activity levels in the offshore oil industry and reduce revenues to the oil sector and oil exporters.

But is intensified competition on the supply side really what oil producers should be most worried about in the long run? Should the changes in consumers' choice of energy source that have been triggered by the high oil prices not be seen as at least equally challenging?

The oil companies are used to competing under demanding market conditions, and technological advances will make new, more expensive, oil production in areas such as Norway, Russia and the Arctic region more competitive going forward. In addition, we do not consider it very likely that the entire production capacity expansion will be carried out, as the risk of political unrest, new regulation as well as lack of infrastructure and investments could lead to delays or cancellation of projects. This will also curb the oil price decline.

Energy Challenges

The strong oil price growth combined with an increased focus on the environment has triggered a process of changes on the demand side that may pose major challenges for the oil industry in the long run.

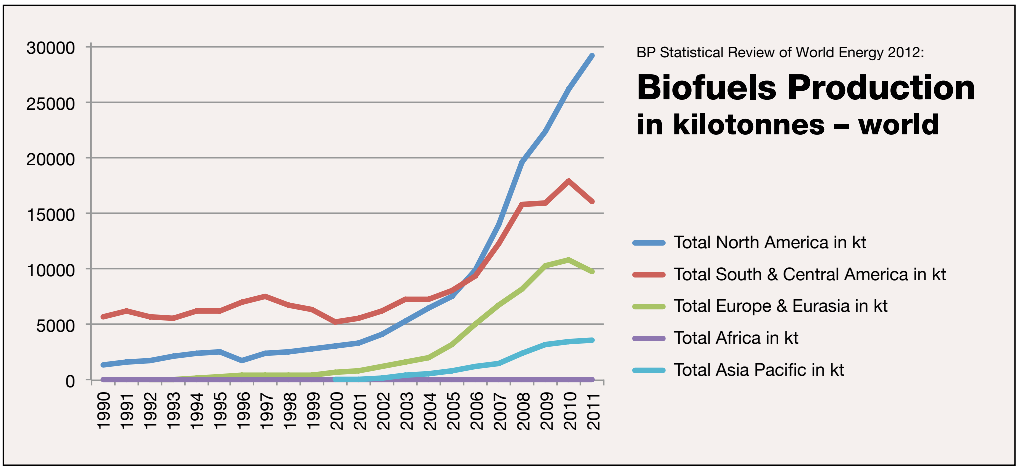
Development of new technology that makes it possible to use other types of energy in areas that have previously been dominated by oil, the focus on energy efficiency optimization, price trends for competing products and environmental concerns all contribute to changing consumers' preferred energy sources. This is particularly important in the transport sector, which accounts for more than half of global oil consumption and where oil-based fuels have been used almost without competition. But the oil market's last bulwark may soon fall. The strong oil price growth and growing focus on the environment over recent years have also forced the transport sector to develop more efficient fuel types and fuel solutions. Once a new competitive technology that uses other energy sources than oil has been developed, the sheltered position of oil in the transport market will be threatened. Technological advances cannot be reserved and this will affect the outlook for oil demand in the long term.

Of course, it will take time for the production and availability of new fuel types to make any major impact on the fuel market. The more that prices of oil-based fuel are compared to other energy types, the more the innovation of new fuel types and engines will accelerate.

Globally, biofuel production has tripled since 2005, and airlines are researching the possibility of using algae fuel, while competitive prices of natural gas, rising production of unconventional gas and an expansion of LNG capacity have boosted interest in gas on the transport side. How soon non-oil based products will get a widespread breakthrough in the international fuel market will depend on the prices of oil, environmental and transport policies, infrastructure construction and economic trends.

New advances on the transport side may be a more serious challenge in future for the oil sector and for oil prices than harsher competition caused by an expansion of global production capacity. Increased production capacity and slightly lower oil prices will probably slow the pace and innovation of new fuel types on the transport side. Maybe lower oil prices will be more of a good thing than a bad thing? ■

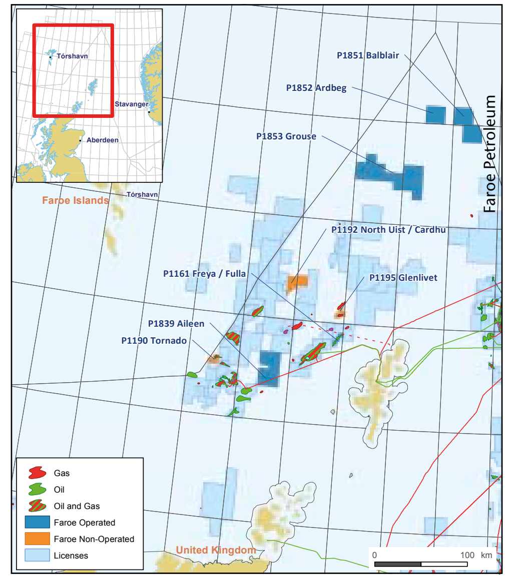
Biofuel production has increased hugely in recent years.



EM Survey North of Shetlands

PetroMarker AS, a marine EM specialist oil and gas exploration service company based in Stavanger, Norway, has been awarded a contract for an EM survey in the frontier West of Shetland area by **Faroe Petroleum** (UK) Ltd. Following a competitive invitation to tender, PetroMarker has been selected to carry out the survey on the Grouse prospect, which is located in UK License P1853, about 200 km north of the Shetland Islands, a promising area for future developments. **Grouse** is a large structural and stratigraphic post-basalt prospect of Upper Eocene age, on the southern flank of the Pilot Whale Anticline, part of a new exciting exploration play in this remote area. The survey will be executed with the newly mobilized 'Normand Baltic'.

PetroMarker's EM technology is based on the unique, fully-patented, vertical electric method, TEMP-VEL, which offers better accuracy, high sensitivity and deeper penetration, depending on local geology. The company's activities range from feasibility studies prior to offshore investigation, preparation of the offshore surveys in terms of survey configuration and planning, acquisition and processing of the data, to finally interpretation and recommendation to oil companies. ■



Faroe Petroleum

Challenges and Opportunities

Challenges for today, opportunities for tomorrow: the tantalizing theme for the second **Arctic Technology Conference** (ATC) due to be held in Houston, Texas, on December 3–5 this year. This highly focused international conference addresses the cutting-edge technologies and innovative practices needed for exploration and production in the Arctic. Part of the Offshore Technology Conference portfolio of events and managed by the AAPG, ATC brings together a dozen professional societies and associations to create a comprehensive technical program which features hundreds of technical presentations and posters. There are also a number of topical panel discussions covering subjects ranging from Arctic production to oil spill preparedness and specialist technology. And new for 2012: the Spotlight on Arctic Technology awards, with exhibitors competing for top honors.

The inaugural event last year attracted 1,300 attendees from 23 countries and was deemed a great success and this year's conference is expected to be even bigger. From pipelines to flow assurance, environmental regulations to vessels – you will see it or hear it at ATC. ■

Onshore Canning Basin Reprocessing

Searcher Seismic Pty Ltd has recently commenced a major onshore multi-client reprocessing project in the **Canning Basin**, Australia, which will tie-in over 60 wells and deliver approximately 40,000 km of high-quality reprocessed seismic data. The magnitude of the Onshore Canning Super-Tie™ Reprocessing Project means that a multi-phased approach has been implemented, and phase 1 has now commenced, with priority lines expected to be delivered to participating companies in Q4 2012.

The Onshore Canning Basin has been generating increasing levels of interest recently due to a combination of conventional exploration success and recognition of huge unconventional resource potential in the basin. Recent bid rounds and acreage uptake reflect this trend and have been highly contested with increasingly aggressive work program commitments required to secure acreage.

Searcher Seismic

Searcher, which designs, manages and markets 2D and 3D non-exclusive seismic, is uniquely placed to tackle such a large project, having recently completed reprocessing over 80,000 km of similar data offshore Australia. ■

1,000 Fugro Surveying Courses

At the end of June 2012, the **Fugro Academy** delivered its 1,000th surveying course. The Academy is an internal organization which was created to support corporate and divisional initiatives relating to training of Fugro staff at all levels. Courses range from induction modules to technical and professional training and management development, and in addition to surveying they cover everything from health and safety and office software applications to leadership and interpersonal skills. Courses are delivered by either Fugro trainers or external providers and can be traditional instructor-led training, online e-learning or virtual classroom sessions.

Fugro Academy, created in 2006, has been delivering survey training since then and the 1,000 survey courses were undertaken by over 7,600 staff, representing about 35,000 days of training. Survey courses are developed to support the training and development of Fugro's surveyors, engineers, geophysicists and data processors. Training starts with basic induction to and familiarization with the company and offshore survey operations, leading to technical courses in systems and processes used by Fugro, plus supervisory and management training for senior staff as they take on relevant positions in offshore operations. Almost 50 different courses are available to Fugro staff to help them develop the experience and competence required to perform their roles. A dedicated team of experienced survey professionals with many years of experience design, develop and deliver these courses. ■

Offshore Survey Training Team

Third European Shale Gas Conference

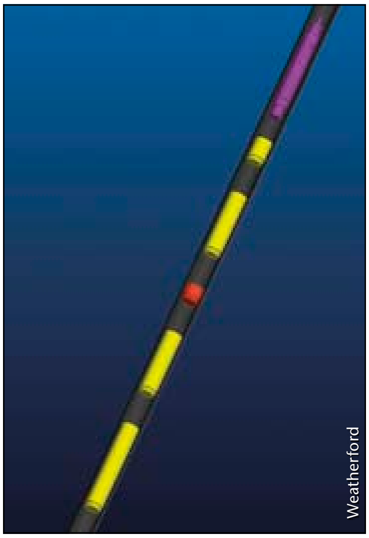
European shale gas exploration could be said to still be in its infancy, but interest in the resource continues to increase and to date, shale gas exploration is underway in Poland, Sweden, Austria, the UK and Germany, among other countries.

Poland is considered Europe's hot spot, although some estimates suggest that shale resources in France may be as big as Poland's – if they choose to develop them. Romania is also considered to hold significant potential. It is appropriate therefore that Warsaw in Poland is due to host the 3rd annual Shale Gas World Europe conference at the end of November, 2012. Over 80 speakers from across Europe and beyond will be presenting their ideas, covering a range of related but diverse issues, such as regulatory frameworks, drilling technology, water management and geophysical advances. ■

Improving Reservoir Evaluation

To more accurately pinpoint the extent and location of hydrocarbons in a reservoir, operators have relied on pulsed-neutron measurements for more than 40 years. The industry's increasing interest in gas production from both conventional and unconventional reservoirs over the past decade has prompted the need for such tools to provide a heightened level of sensitivity and accuracy to formation evaluation behind casing.

Weatherford's pulsed-neutron, cased-hole evaluation system known as the Raptor™ Pulsed-Neutron Tool was designed specifically to fulfill this need. With the industry's first five-detector array that incorporates unique lanthanum bromide detectors and a fast-neutron detector, the technology yields a more sensitive measurement of the neutron-gamma transport field in gas-filled formations. These features, combined with the tool's calibration system, enhance accuracy, spectral processing, signal-to-noise ratios and logging speeds, ultimately providing operators a higher degree of confidence in the data in a shorter period of time.



Interpretation software includes algorithms for determining shale and mineralogy effects in carbon-oxygen and formation gas saturation measurements, which replace operator intuition with quantitative petrophysical processes. In addition, new computer-based characterization techniques can distinguish previously indistinguishable wellbore and reservoir conditions in all-gas formations, in formations and boreholes with varying oil and water properties and in multi-tubing strings.

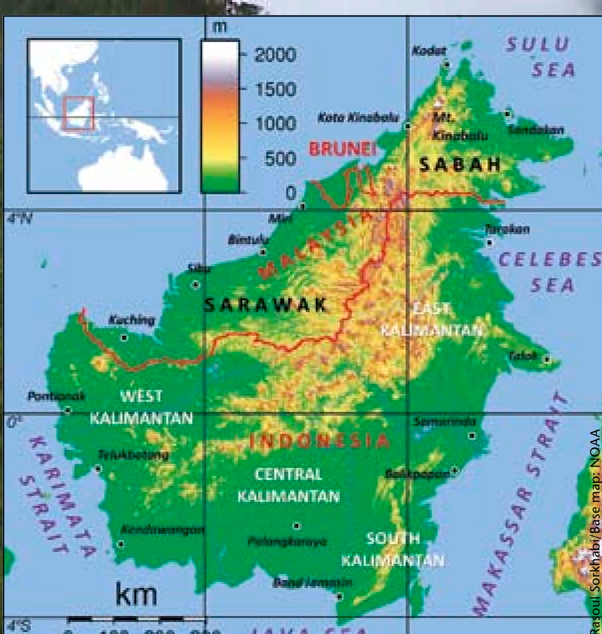
The new technology has been successfully field-tested in more than 40 wells in the United States, Middle East, Europe and the Caribbean in both unconventional and conventional gas reservoirs. ■

Borneo's Petroleum Plays

RASOUL SORKHABI, PhD

Mt. Kinabalu (4,101 m), located in Sabah, is the highest summit on Borneo and a very young granite pluton of late Miocene age.

Layla Sousou



Located in equatorial South East Asia, Borneo is home to ecologically rich rainforests. It is administered by three countries: Kalimantan (72.9% of Borneo) belongs to Indonesia; Sarawak (16.8%) and Sabah, also called North West Borneo (9.8%), are parts of the Malaysian Federation (Eastern Malaysia); and Brunei (0.8%) is an independent kingdom, its Sultanate having ruled over much of Sarawak and Sabah during the 16th to mid-19th centuries before it gradually lost these territories to Great Britain. Brunei itself was a British protectorate from 1888 to 1984.

Borneo, the world's third largest island, has lush tropical forests, rich wildlife, coral reefs, and fascinating tribal cultures. It also has classical petroleum basins characterized by vast deltaic sediments and carbonate platforms which continue to make this region an attractive source of energy for the populous Asian markets.

Oil seeps and anticline structures in the near-shore sedimentary rocks of Borneo drew the attention of British and Dutch oilmen in the late 19th century. In 1897, an 84m-deep well in the Mahakam delta (Kutei Basin) hit 32° API oil in the Sanga Sanga oil field, and consequently a small refinery was built in Balikpapan, then a fishing village and today a large port town in East Kalimantan. The second oil discovery in this basin was the Samboja field (with heavier oil of 21° API at a depth of 110m) in 1909. Dutch oilmen went on to discover the Pamusian field in 1901 on Tarakan Island, which amazingly remains to this day the largest oil field in the Tarakan Basin, having already delivered 193 MMbo, or 60% of the total volume of oil produced from the entire basin. The second discovery in Tarakan was the Bunyu field in 1929, which has produced 83 MMbo.

On the western side of Borneo, the first oil discovery was Shell's Miri field in Sarawak in 1910, which produced about 80 MMbo before it was abandoned in 1972 (see *Geo Expro* Vol. 8, No. 2). Three years prior to this, Shell and Royal Dutch oil companies had merged into one company, which established local subsidiaries, Sarawak Oil Field (now called Sarawak Shell) in 1910 and British Malayan Petroleum Co. (today's Brunei Shell Petroleum) in 1922. The latter discovered the Seria oil field onshore Brunei in 1929, which in 1991 passed its billionth barrel, and continues producing oil. These early discoveries put Borneo on the world's petroleum map.

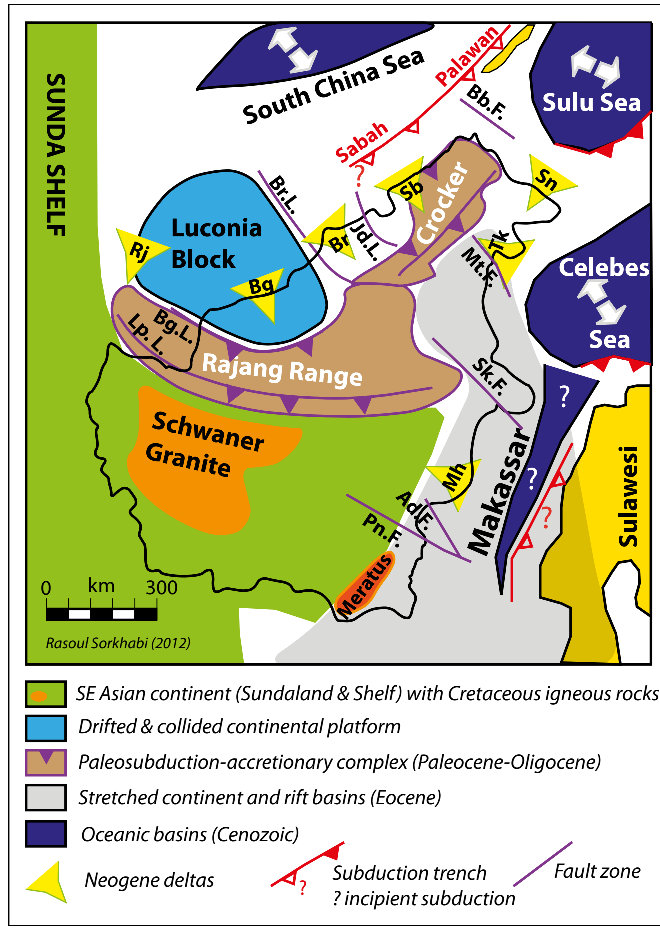
Tectonics and Basin Evolution

To better understand the hydrocarbon riches of Borneo, we need to consider the formation of its sedimentary basins within the tectonic framework of South East Asia.

Present-day Borneo is under remote tectonic stresses from nearby plates. On the south, the Australian oceanic plate is subducting beneath Sumatra-Java islands, and on the east, the Philippine Sea plate is subducting beneath the Philippines. The region between the Philippines and Borneo is occupied by three relatively smaller ocean plates: Celebes Sea, Sulu Sea, and South China Sea, all of which opened in Cenozoic times, and are presently subducting beneath the Philippine islands.

Although Borneo is not an earthquake-volcanic country today, it has experienced a violent tectonic history in the past. The south-eastern part is a continental block made up of Paleozoic rocks intruded by Cretaceous igneous rocks, and is actually part of Sundaland, the continental core of South East Asia that spans the region from Vietnam all the way to Sumatra. During the Paleocene, a continental fragment, the Luconia block, drifted away from China and toward Borneo. The intervening oceanic floor between Borneo and Luconia was subducted beneath Borneo, and in the Late Eocene Luconia collided with Borneo. This subduction, accretion and collision created the Rajang Mountains that form a topographic high between Kalimantan and Sarawak.

In the Eocene, the eastern margin of Borneo underwent different tectonic changes. Coeval with the opening of the Celebes Sea, the continental crust under the Mahakam-Makassar region was stretched forming rift basins filled with sandstone and shale. In the Miocene, Borneo experienced



A sketch map showing the main tectonic features of Borneo. Tectonic lineaments and faults shown on the map are: Balabac Fault (Bb. F.); Jerudong Line (Jd. L.), Baram Line (Br. L.), Balingian Line (Bg. L.), Lupar Line (Lp. L.), Paternoser Fault (Pn. F.), Adang Fault (Ad. F.), Sangkulirang Fault (Sn. F.), and Maratua Fault (Mt. F.). Major deltas are: Sabah (Sb), Baram (Br), Balingian (Bg), Rajang (Rj, paleodelta), Mahakam (Mh), Tarakan (Tk), and Sandakan (Sn).

regional uplift, terminating carbonate sedimentation (which is now mainly restricted to platforms offshore Borneo), and large deltaic systems-dominated sedimentation around Borneo. Growth faults, turbidity currents, shale diapirs, and deepwater toe-thrusts thus characterize the Neogene structures off the west and east coasts of Borneo. During the Pliocene, tectonic compression further uplifted Borneo's coasts.

Shell geologist Harry Doust has suggested a generalized sedimentary facies model for the Cenozoic rift basins in South East Asia in which four different phases are recognized: (1) syn-rift phase (Eocene-Oligocene) associated with development of grabens and deposition of fluvial and lacustrine sediments; (2) late syn-rift phase (Late Oligocene-Early Miocene) characterized by waning graben subsidence and transgression (backstepping) of deltaic deposits; (3) early post-rift (Early to Middle Miocene) marked by tectonic quiescence and shallow marine sediments covering the rift basins; and (4) late post-rift phase (Middle Miocene-Pleistocene) which corresponds to tectonic inversion and folding and the transgression of deltaic systems. Of these, the first phase has mainly oil-prone source rocks (with kerogen types I and II), while the other phases contain both oil and gas sources (kerogen types II and III).

Exploration Goes Offshore

After the discovery of the Miri and Seria fields, Shell continued exploring onshore Sarawak and Brunei, but despite drilling more than 90 wells in over forty years no new onshore field was discovered. In 1955, Shell started exploring the Sarawak shelf and in 1962 it discovered the Temana oil and gas field in the offshore Balingian Basin with 41° API light crude, thus adding a new petroleum basin to Borneo's portfolio, although production from Temana only started in 1979. The offshore Baram delta and nearby Brunei still remained Shell's focus areas. By the end of the 1960s, six fields (Baram, Lutong West, Bakau, Baronia, Betty, and Beryl) offshore Baram and three fields (Ampa, SW Ampa, and Fairley) offshore Brunei had been discovered.

In the 70s and early 80s exploration efforts on the western margin of Borneo ensued partly because of high oil prices caused by the 1973 and 1979 oil crises. Malaysia's national oil company Petronas, founded in 1974, joined these oil ventures and a number of new offshore discoveries were made not only in the Baram and Balingian Basins but also offshore Sabah (notably, Tembungo, Barton, Erb West, Furious South, Saint Joseph, Ketam, and Lokan). All these, like their predecessor onshore fields, were in deltaic sandstone reservoirs of Miocene-Pliocene age.

Another significant development was the discovery of major gas fields in the carbonate reservoirs of the Luconia platform offshore Sarawak. This play began with the discovery of F-6-1X, F-13-1X, and E-8-1x in 1969, continued through the 1970s and reached its climax in 1980 when five gas fields were discovered in that year alone.

The second wave of petroleum exploration on the eastern side of Borneo was most successful in the Kutei Basin where Unocal hit the first offshore oil field, Attaka, in 1970. Huffco, which initially operated small old fields in Kalimantan but discovered the onshore Badak gas field in 1971, and Total were other major players in that region. Unlike Sarawak, Brunei and Sabah, oil and gas discoveries in the Mahakam delta were both onshore and offshore, including Bekapai (1972), Handil, Nilam, Pamaguan, Semberah and Tamboram (1974), Tunu (1977), and Kerendan and Mutiara (1982).

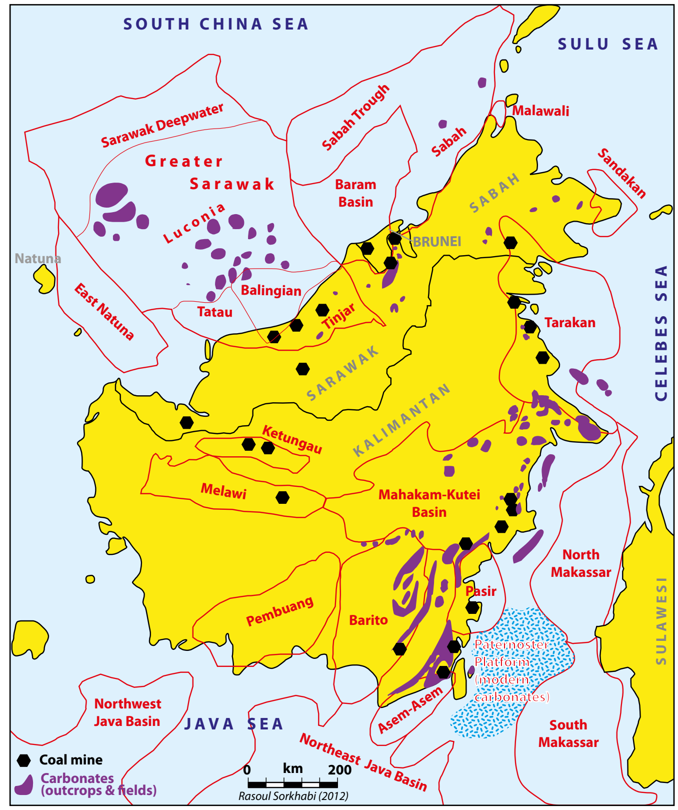
Deepwater Petroleum: The Third Wave

As in many other regions, since the late 1990s deepwater basins have become the most significant plays in Borneo, with Unocal (acquired by Chevron in 2005) performing a pioneering role. In 1999, it was operator in five deepwater blocks in Kutei under Indonesia's PSCs – East Kalimantan, Makassar Strait, Sesulu, Rapak and Ganal. What motivated Unocal to enter these plays was its discovery of oil and gas in Pliocene sands at West Seno (in 1996 and Merah Besar (1997), both located in the Makassar PSC. In 1999, Unocal began intensive exploration of the nearby Rapak and Ganal blocks. Janaka North-1, drilled to a depth of 2,934m in water depths of 1,316m in Rapak (then the deepest well drilled anywhere in Indonesia), encountered oil in high quality reservoirs and in thin-bedded sandstones. After this breakthrough, the Ranggas (oil and gas), Bangka and Gehem (gas) fields were discovered in Rapak.

In the Ganal PSC in 1998, Unocal initially focused on Pliocene targets, probably thinking that Miocene sands could not be deposited that far from the shore. After shooting 2D seismic over Ganal, three wells were drilled into Pliocene sands draped over structural highs, but all were dry. In late 1999, Unocal decided to drill deeper into the Upper Miocene sands in the same block and found Gandang, followed within three years by four other gas fields – Gendalo, Gada, Gula and Maha. With these successes, Unocal covered the entire 5,050 km² Ganal PSC, in water depths of 1,829m, with 3D imaging.

Unocal's deepwater successes drew other companies to the Makassar Strait, either teaming with Unocal, like Lasmo, or entering on their own. In 2002 Amerada Hess discovered the Halimun and Papandayan gas fields on the south-eastern edge of the Mahakam Delta. After acquiring Lasmo in 2001, Eni entered offshore Kalimantan and in 2010 announced the discovery of Jangkirk, with recoverable reserves of 1.4 Tcf, in the Muara Bakau deepwater block. In 2011, Eni was awarded the 2,432 km² North Ganal PSC offshore Kutei.

On the eastern side of Borneo, Shell's discoveries of Kebbangan (1994) and Kamunsu (2000) gas fields offshore Sabah were pioneering steps. What particularly gave momentum



A simplified map showing the distribution of major sedimentary basins onshore and offshore Borneo. (Sarawak-Sabah basins based on Shell and Petronas; Kalimantan on Unocal and Pertamina; carbonates from Wilson et al., 1999, Journal of Asian Earth Science, 17: 183–201; coal mines from Wilson and Moss, 1999, Paleo3, 145: 303–337.) In its 2010 assessment of the world's undiscovered petroleum resources, USGS estimated (95% probability) 2,116 MMbo for the Baram-Brunei-Sabah Basins, 80 MMbo for Balingian, 58 MMbo for Sandakan, 136 MMbo for Tarakan, 1,462 MMbo for Kutei, and 20 Mmbo for Barito. Of this total of 3,872 MMbo yet-to-find oil resources, 83% are in deepwater basins. Similarly, USGS estimates 134 Tcf of undiscovered gas resources (both associated and free gas) in Borneo's basins as follows: Kutei (46.0 Tcf), Greater Sarawak (38.1 Tcf), Baram-Brunei-Sabah (26.4 Tcf), Tarakan (12.7 Tcf), Sandakan (8.7 Tcf), and Barito (2.9 Tcf).

Typical Malaysian stilt houses in Borneo

to deepwater ventures in Sabah was Kikeh-1, drilled in 2002 by Murphy (Petronas 20%) in SB-K Block in 1,340m of water. Murphy entered Malaysia's offshore blocks in 1999, and drilled the field after doing methodic homework. Kikeh is estimated to contain 536 MMboe and came onstream in 2007. Other notable deepwater discoveries offshore Sabah include Gumust-Kakap (Shell, 2003-2005), Malikai (Shell, 2004), Jangas (Murphy, 2005), Ubah Crest (Shell, 2005), Pisangan (Shell, 2005), and Wakid (Petronas, 2011).

In 2009, Newfield discovered Paus (10 MMbo and 12 Bcfg) in deepwater Block 2C offshore Sarawak, and in 2011, Petronas found two major carbonate gas fields off the coast of Sarawak. NC8SW, with over 450 Bcfg recoverable in a 440m column, was drilled September 2011 to a TD of 3,853m, and Kasawari (estimated to hold up to 3 Tcfg recoverable, out of the total gas-in-place of 5 Tcf in a 1,000m continuous column) was drilled November 2011 some 17 km north of NC8SW.

News from Brunei is also encouraging, especially after resolving in 2009 its 20-year-old offshore border issues with neighboring Malaysia. In 2011, Brunei Shell found the Gernoggong oil field about 100 km offshore. This year, Total announced the discovery of two hydrocarbon fields in water depths of more than 1,000m in CA-1 block.

Future Prospects

Borneo's deepwater basins are an active playground for oil and gas exploration with promising plays. 3D geophysical imaging and geological understanding of these basins, especially in terms of the origin of hydrocarbon source rocks, distribution of sand channels and trap integrity of toe-thrust structures, will help increase the success of exploration.

Borneo's near-shore and shallow-water basins are often categorized as mature, but they still hold surprises. In 2007, Total's well ML-4 drilled offshore Brunei in 62m water depth to a total depth of 5,227m and hit gas, and in 2009 Anadarko discovered 40m of oil and gas in Badik-1 in only 70m of water offshore Tarakan. In 2011 in shallow waters off the west coast of Sabah, Petronas discovered a gas field estimated to contain 500 Bcfg in place. Interestingly, this discovery was made in the Samarang-Asam Paya block, in which Petronas also drilled an oil discovery well, Alab-1, in water depths of only 54m in 2000. A better assessment of Borneo's shallow-water Neogene clastic reservoirs compartmentalized by growth faults will add new marginal reserves to these 'mature' basins.

Miocene-Pliocene deltaic plays have so far accounted for the bulk of oil and gas discoveries in the region. Deeper pre-Middle Miocene plays of Borneo remain less explored, and these may contain gas resources in tight reservoir rocks such as shale gas. Being a densely forested region for tens of millions of years, Borneo is also noted for its coal-bed methane (CBM) resources. Indonesia's Ministry of Energy and Mineral Resources has estimated CBM resources of 101.6 Tcf for Barito, 80.4 Tcf for Kutei, 25.9 Tcf for Berau-Indonesian Tarakan, and 3.0 Tcf for Pasir and Asem Asem Basins. With more gas discoveries and production in Borneo, construction of LNG plants will become a necessity. ■

A view of Upper Miocene deltaic sandstone and interbedded shale (Miri Formation) cut by a normal fault. Neogene deltaic sediments predominate in the sedimentary record and petroleum reservoirs of Borneo.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Central Asia:

Cutting Edge Technology in Frontier Exploration

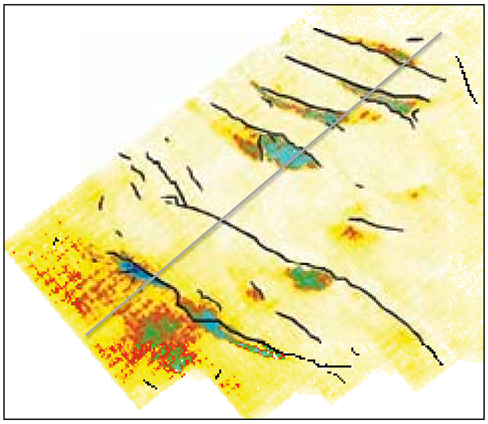
Central Asia represents an exciting frontier for oil exploration, from sub-salt to sub-thrust exploration. The region remains a hive of activity, boasting some of the largest oil and gas fields in the world, including Yolotan (Turkmenistan), Gazli (Uzbekistan) and Karachaganak (Kazakhstan). The implementation of new technology has revealed significant new potential in the Amu-Darya, Ustyurt and Afghan-Tajik Basins

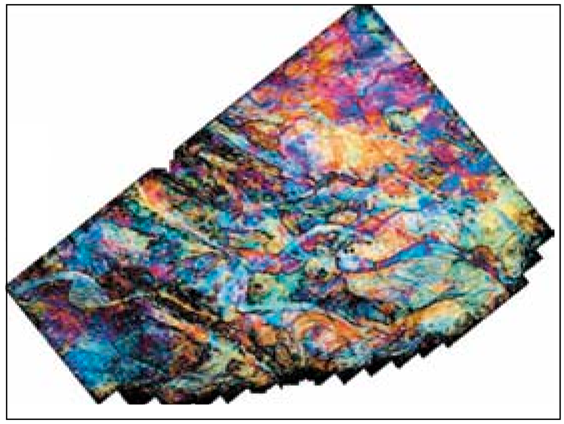
M. JAMESON, D. GOULD, G. WALL and R. JOHNSON SABINE, Tethys Petroleum

Central Asia has long been an area of interest for explorers, from ancient merchants to modern oil explorers. The region boasts some of the largest oil and gas fields in the world, including some major discoveries made within the last 20 years. In the 1960s significant investment in exploration was undertaken by the Union of Soviet Socialist Republics (USSR), which applied a rigorous exploration methodology across the region from extensive structural drilling to seismic and magnetotelluric acquisition. However, Soviet technology of the time had its limitations in computing power, seismic processing, acquisition and drilling technology. Following the fall of the USSR, many Western exploration companies have entered the Central Asian Republics in the hunt for hydrocarbons.

Central Asia lies in a fortunate location with energy-hungry markets such as Europe to the West and China, Pakistan and India to the East. Extensive pipeline infrastructure exists in many of the Central Asian republics with a range of new pipeline projects planned in the area. Tethys Petroleum is in the unique position of exploring three Central Asian Republics

A map of Tethys Petroleum's acreage in Central Asia, with acreage listed in Kazakhstan (Kul-Bas, Akkulka, Kyzyloi), Uzbekistan (North Urtabulak) and Tajikistan (Production Sharing Contract)

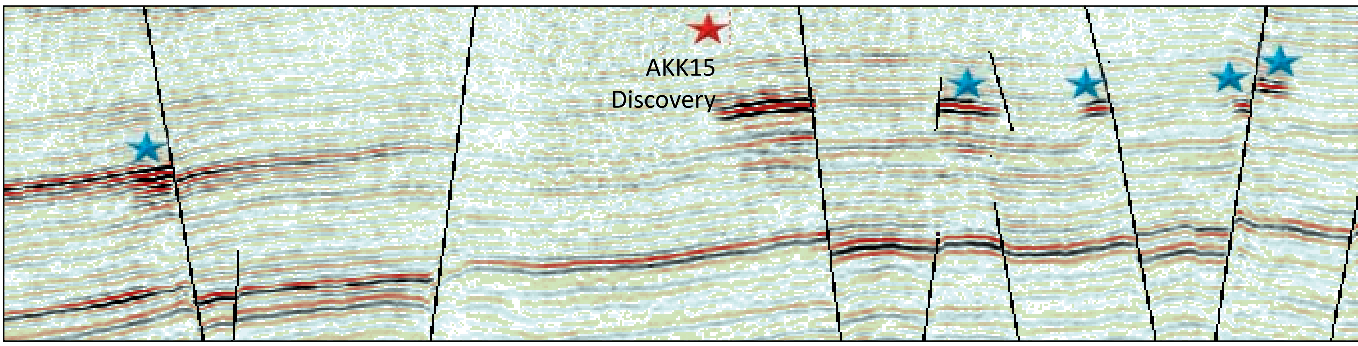




Left: *Seismic amplitude map of Eocene reservoir, displaying distinct areas of seismic brightening.*

Right: *Identification of multiple channels from seismic attributes, spectral decomposition by A. Stout, derived from 3D survey analysis.*

Below: *Seismic cross-section showing seismic brightening with discoveries alongside multiple prospects.*



– Kazakhstan, Uzbekistan and Tajikistan – holding producing oil and gas fields and exploration acreage in the prolific Amu Darya, Ustyurt and Afghan-Tajik Basins.

Tethys has implemented modern, cutting-edge technology to explore and de-risk its exploration and maximize production. Here we present three case studies of the application of new seismic, magnetic and gravity and drilling technologies.

North Ustyurt Basin, Kazakhstan

In Kazakhstan, Tethys Petroleum maintains a strong presence in hydrocarbon exploration, development and production within the Akkulka and Kul-Bas licenses of the North Ustyurt Basin with proven reserves of 52.5 Bcfg and 5.8 MMbo and prospective resources of 634 Bcfg and 1230 MMbo respectively.

The North Ustyurt Basin lies immediately to the west of the Aral Sea and historical exploration within the area discovered shallow gas reservoirs of Eocene age. Initial exploration undertaken by Tethys Petroleum has furthered the understanding of these gas reservoirs with multiple discoveries, characterized by a seismic brightening on 2D seismic. In 2009–10, Tethys Petroleum drilled AKD01, the first well within the license area to flow oil at commercial rates from two deeper reservoirs of Upper Jurassic and Lower Cretaceous age. As part of the ongoing appraisal program associated with these discoveries, Tethys Petroleum acquired two 3D surveys across the area. Interpretation of the new data has included AVO analysis and color inversion techniques, and this information allowed further identification of multiple prospects for both shallow and deep reservoirs.

Following detailed mapping, it was apparent that alongside the structural traps associated with the Upper Jurassic reservoir, the Lower Cretaceous reservoir incorporates an important stratigraphic element. The analysis of attributes extracted from the seismic volume recognized the Lower Cretaceous reservoir as part of an established channel system. The extensive lateral coverage of this channel system, along with additional prospective fan systems, has proved encouraging for significant reservoir continuity and greater hydrocarbon potential as part of the ongoing exploration and appraisal program.

Afghan-Tajik Basin, Tajikistan

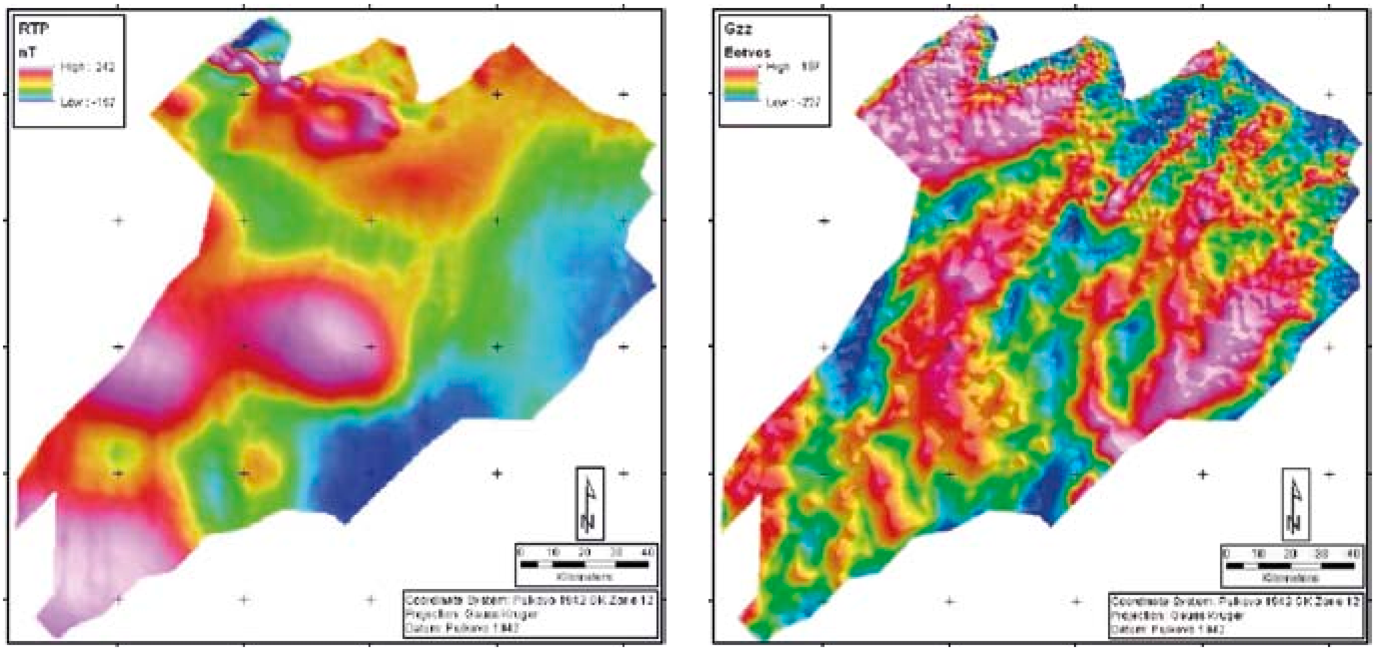
Tethys has been operating in Tajikistan for five years, holding a Production Sharing Contract (PSC) in the Afghan-Tajik Basin (34,785 km^2), with unrisked prospective resources in excess of 113 Tcfg which were independently assessed in 2012. Current production in heavy and light oil occurs from Paleogene carbonate reservoirs (Beshtentyak, Kichikbel and Akbash Adyr oil fields) with some historic production from heavily fractured Cretaceous and Jurassic reservoirs (Komsomol field). Significant potential in Jurassic and Cretaceous intervals has been revealed by modern seismic, magnetic and gravity and drilling campaigns, although to date these intervals are largely unexplored.

Owing to the size of Tethys' exploration acreage, a regional magnetics and gravity program was planned using ARKeX's BlueQube Full Tensor Gravity and Magnetic acquisition, processing and interpretation services. The aim was to uncover the deep structure of the Afghan-Tajik Basin as well as to better delineate the sub-regional to local structure and its influence on prospectivity. The data was then used in conjunction with modern and vintage seismic datasets to plan a new seismic acquisition programme, which is currently underway.

The 2012 Tethys acquisition campaign is also utilizing new technology. The selected contractor Prospectiuni will be employing the SERCEL Unite, cable-free acquisition system, which will enable quicker and easier acquisition in the varied arable and mountain terrain of Tajikistan.

Amu Darya Basin, Uzbekistan

In 2009, Tethys Petroleum acquired the contractor rights to the North

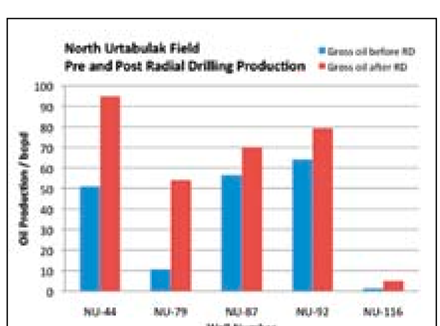


Left: Airborne magnetic dataset acquired by ARKeX for Tethys in 2011, highlighting deep basement structure in an East–West orientation.
Right: Full-tensor gravity dataset highlighting the N–S to NNE–SSW Neogene structure that has been typically used to target exploration.

Urtabulak Production Enhancement Contract (PEC), whereby the contractor was obligated to implement new technologies and techniques to enhance liquid hydrocarbon production from the North Urtabulak oil field, which is reservoired in Jurassic reefal limestones.

Tethys Petroleum and its predecessors to the PEC, together with the state-owned oil company Uzbekneftegaz, had previously implemented horizontal drilling and sidetracking technologies as a means of accessing additional oil reserves. However, these capital-intensive and relatively high-risk technologies are no longer cost-effective for the North Urtabulak reservoir in its current state of depletion. Similarly, acid stimulation of the reservoir had been attempted at North Urtabulak, although it was found that the stimulation fluid tended to follow the path of least resistance, which is invariably into the lower productivity zones of the reservoir. It was therefore hoped that radial drilling might allow Tethys to more efficiently and accurately access trapped and/or previously inaccessible hydrocarbons.

Radial drilling's principal application to date has been in marginal and mature fields with low productivity and shallow (<2,750m) wells. Radial drilling effectively applies modified coiled tubing technology to penetrate lateral holes of 50mm in diameter up to 100m from the original wellbore. The principal objective of this technique is to improve the production profile around the original wellbore by penetrating beyond the damaged skin zone and by accessing trapped pockets of hydrocarbons. At present this technology can only be applied in vertical (or near-vertical) wells, although research is ongoing to adapt this technique to deviated and horizontal wells. In total, five well candidates were selected for the radial drilling trial at North Urtabulak, with wells selected based on their production potential and mechanical condition. These were a combination of vertical and near vertical wells with cased-hole and open-hole completions located in different parts of the field. In four of the well candidates, one level of four laterals was attempted, and in well NU-116 two levels of four laterals were attempted. With the exception of well NU-44 (where only two laterals were achieved), in all the remaining wells four laterals of ~100m were successfully achieved at each level.



In conclusion, despite the pressure-depleted condition of the reservoir, the trial at North Urtabulak proved emphatically that radial drilling can be a cost-effective and time-efficient application to increase production and to access trapped hydrocarbons. It allows accurate placement of laterals and extended horizontal penetration over conventional perforating. It is a technology which Tethys Petroleum Limited fully intends to implement elsewhere, both in Uzbekistan and within the Tethys Petroleum Group's other assets in Central Asia.

New Technologies the Future

The application of cutting-edge, cost-effective technology has opened up a wealth of new opportunity in Central Asia, from enhancing recovery in declining fields to exploring old basins with new technology. Tethys Petroleum and the countries that it operates in have benefited from the application of new technologies that have increased production and recovery and lowered exploration risk and cost.

The scope of opportunity and acreage on offer in Central Asia, and its position at the doorstep of numerous energy-hungry markets, makes the area an exciting place for exploration and development. With continued investment in exploration and infrastructure, the region has a very bright future. ■

The Age of Uncertainty

Maximizing resolution from integrated seismic and quantitative biostratigraphy using CONOP

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Biostratigraphic correlation based on the geological succession of fossil species remains one of the fundamental workhorse approaches to geological correlation in the exploration industry. The method is only as good as its sampling, and even in the most thoroughly sampled sequence a plethora of problems conspire to confound the interpreter. For example, the lowest or highest observation of a particular fossil species in a well will never represent the true first or last occurrence in time – a problem that reflects sample spacing, stochastic effects related to limited sample sizes and examination effort, and the incomplete nature of the stratigraphic and fossil records. Furthermore, other potential sources of confusion include cavings, fossil reworking, post-depositional mixing and biogeographic and facies effects. For these reasons, the observed orders of lowest or highest occurrences of particular species vary from well to well.

Despite these problems, global geology has been extremely well served by biostratigraphy because scientists have tended to focus on a small subset of 'well behaved' fossil events that tend to show minimal variation in order. These key events are well behaved because they are relatively widely spaced in time and thus have less likelihood of showing event-order contradiction from well to well. They have also been selected because they

The Kaikoura Peninsula, South Island, New Zealand lies at the southern margin of the East Coast Basin – a region of active exploration interest. An extensive shore platform cuts into gently folded Late Cretaceous to Oligocene strata, the former containing potential source and reservoir facies. In the background the Seaward Kaikoura Range rises from the active Hope Fault at the base of the range.

Lloyd Homer, GNS Science

The submerged continent of New Zealand showing locations of basins discussed in the text.

are apparently relatively insensitive to facies effects and are geographically widely distributed.

Constrained Optimization

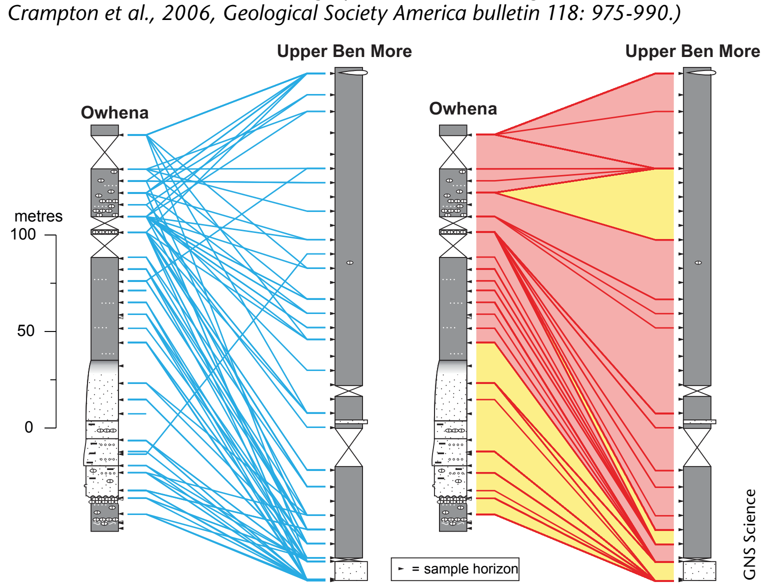
Although still an important part of the biostratigraphic toolbox, the use of key fossils ignores a very large amount of biostratigraphic data and inevitably limits the resolution of correlation that can be achieved. This issue is becoming increasingly important as explorationists and basin modelers seek to squeeze ever greater time and depth resolution from available data, with the ultimate aim of correlating to absolute (geochronological) age. Age is a key property in generation modeling and is commonly assigned to structural surfaces as a value selected arbitrarily from an age range or from age maps that better capture the diachronous nature of many geological surfaces. Increased geochronological resolution and improved lithological detail are critical to better identification of potential hydrocarbon carrier beds and seals.

In response to these issues, biostratigraphers have developed a suite of fully or semi-quantitative techniques that use many or most available events and determine 'best-fit' solutions to event-order contradictions. The task of identifying the best-fit event ordering is known as the 'correlation problem'. The oldest and simplest approach to this is graphic correlation, with events integrated graphically, well-by-well, into a best-fit composite sequence. Although graphic correlation is used widely, it is time-consuming and retains a subjective, operator-dependent element.

Newer techniques include Constrained Optimization (CONOP[1]), which is fully automated, handles large datasets, and has been shown to be a versatile, efficient and powerful tool in hydrocarbon exploration[2]. Importantly, recent developments have allowed for the incorporation of non-biostratigraphic data, such as seismic picks, chemostratigraphic and chronostratigraphic datums, with great flexibility in the assumptions attached to each particular data type. The CONOP method has been applied successfully in two of New Zealand's geologically complex basins containing thick, dominantly terrigenous clastic successions, which have undergone intense polyphase deformation resulting in highly complex stratigraphies.

The aim of CONOP is to produce a best-fit composite sequence of events, to age-calibrate this composite, and to achieve the most refined correlation possible by locating the likely 'true' position of each event in each well. Importantly, the approach also yields various measures of well- and event-reliability that can be used to guide future sampling and interpretation. Typically, CONOP analysis is iterative, with run-time settings and data being refined progressively in order to converge on the best solution.

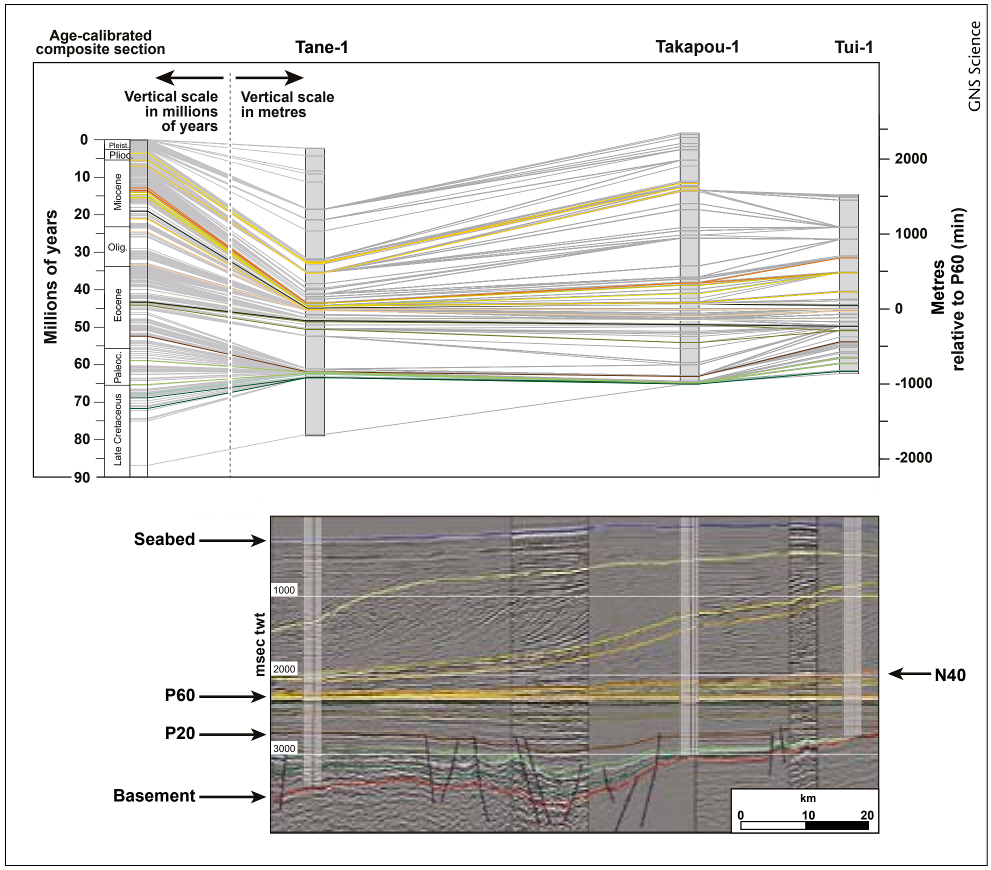
Before and after: correlations between two well-sampled, onshore sections based on marine dinoflagellate microfossils. These two sections are in the East Coast Basin and span all of the Campanian (Late Cretaceous, ~83.5–70.6 Ma). On the left, blue lines link the observed lowest or highest occurrences of species in each section. On the right, red lines are the inferred correlations based on the CONOP best-fit composite sequence of biostratigraphic events; red and yellow blocks indicate the limits of traditional biostratigraphic resolution using biozones. (Data from Crampton et al., 2006, Geological Society America bulletin 118: 975-990.)



Untangling the Correlation Knot

The utility of CONOP in solving the correlation problem is illustrated on page 31, based on 15 onshore sections from the East Coast and northern Canterbury basins. The East Coast Basin is located on the eastern North Island and occupies the accretionary prism of the present-day Pacific-Australian plate boundary, although it initiated on a mid-Cretaceous passive margin. The Canterbury Basin, on the east coast of the South Island, initiated in response to mid-Cretaceous rifting. Late Cretaceous formations in both basins are characterized by thick and commonly monotonous mudstone or very fine sandstone successions.

Even in the absence of caving and associated sampling issues, there is a dramatic contradiction in biostratigraphic correlations based on marine microfossils. Following CONOP analysis, these contradictions are eliminated and the most parsimonious, internally consistent correlation is identified. In this study, the composite sequence was age-calibrated using a subset of dated biostratigraphic events, to yield an average composite age resolution of 130,000 years for the interval between ~90 and ~65 Ma. In addition to the highly refined correlation and dating of sections, the CONOP analysis also helped to identify both basin-wide and local unconformities – a topic that is explored in more detail in the following section.



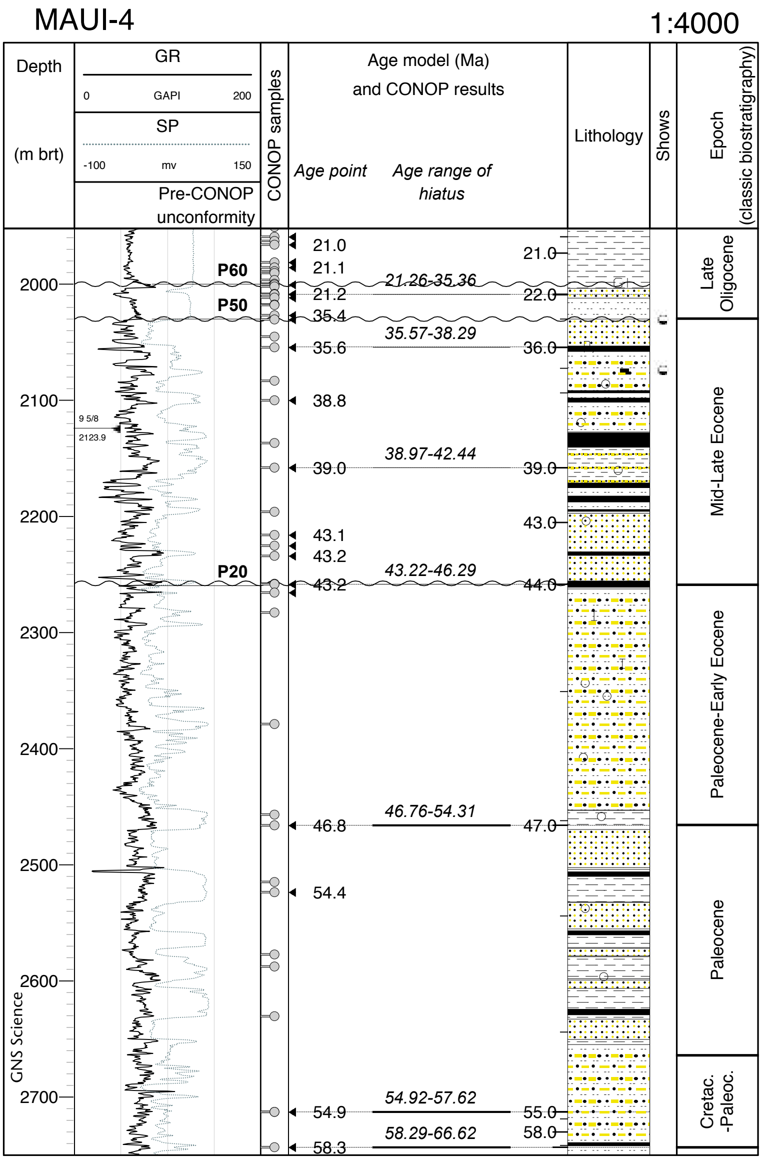
Comparison of CONOP and seismic correlations for three wells in the Taranaki Basin. Both panels are flattened on seismic pick P60. The CONOP correlation also shows the time-calibrated composite on the left. Some seismic picks are duplicated in the CONOP panel – this reflects the limits of uncertainty intervals, as explained in the text. A few discrepancies are visible between the panels – such as apparent stratigraphic condensation in the lower part of Tane-1 in the CONOP correlation, which relates mainly to presently unresolved questions regarding treatment in CONOP of a problematic seismic pick, P20, a regional unconformity that is probably strongly diachronous.

Quantitative Stratigraphy in the Taranaki Basin

The Taranaki Basin, New Zealand's only producing basin, is located along the west coast of the North Island. Taranaki initially formed as an Early Cretaceous to Paleogene intraplate rift basin during fragmentation of the Gondwana continental margin. The basin was structurally overprinted in the Neogene as a result of the development of the modern convergent Pacific-Australian plate boundary. Exploration targets include structural and stratigraphic traps formed by rift-related processes and compressional inversion structures.

Data derive from 20 offshore wells with the highest available quality biostratigraphic and seismic information. The initial dataset contained depths to biostratigraphic events for 1,376 species of foraminifera, dinoflagellates, and pollen, derived from 2,829 cuttings, sidewall core, and conventional core samples. Biostratigraphic events are mainly lowest- and highest-occurrences of species, but include some foraminiferal coiling-event boundaries and pollen assemblage-zone boundaries. The study also included 77 estimated depths to 18 seismic reflectors in 12 of the wells, and 106 depths to 34 lithostratigraphic unit tops in 18 of the wells. Depths to seismic reflectors were encoded conservatively as uncertainty intervals to take account of various sources of error: vertical resolution of seismic data, mis-picks, including those due to bulk shifts applied during phase-matching, and time-versus-depth relationship errors; the summed errors are typically on the order of ± 100–200m.

Importantly, these various event types were treated quite differently during analysis, and event treatments were tested repeatedly and modified during interative CONOP runs. Thus, different biostratigraphic event types were given varying weights in the analysis to reflect assumptions regarding their reliability and likelihood of misplacement. For example, observed lowest-occurrences were down-weighted and allowed to move freely in the solution, to account for the likelihood of caving and low confidence in these observations. In contrast and following testing, some observations of foraminiferal coiling events were treated as high-value time-planes, albeit with uncertainty in stratigraphic placement. Seismic reflectors were initially treated as independent events in different wells and allowed to 'float' in the composite. Those that converged in the resulting solution were subsequently encoded as time-planes that were constrained to lie within their uncertainty intervals, and these



Composite log of Maui-4 well, Taranaki Basin.

intervals were 'shrunk' according to biostratigraphic constraints. Lithostratigraphic tops, on the other hand, were regarded as precisely located in each well but were never treated as time-planes.

New Information Revealed

CONOP absolute age to depth data points can be plotted on a well composite log relative to the well depth. Plotting event ages along a proportional depth scale means that the age-calibrated time scale of the composite becomes non-linear, expanding in intervals with high sedimentation rate and shrinking in intervals of low or negative (erosion) sedimentation rate. Viewed in this way, the data allow the interpreter to identify unconformities or condensed sections, relate them to petrophysical log and sedimentological patterns, and – via seismic time to depth conversion and synthetics – to the seismic wiggle, as seen above. Interpretation of unconformities is subject to some caveats, of course: clustering of events at one horizon may indicate the position of a local unconformity, a regional (sample-wide) unconformity, times of elevated evolution or extinction rate, or simply wide sample spacing. Once an unconformity is identified, however, the amount of missing geological time can be determined from the composite age model.

In the high resolution dataset used in Taranaki, CONOP-inferred unconformities often correlate with changes in wireline log pattern at the resolution of sample spacing. Not all CONOP-inferred unconformities are expressed on the wireline logs for any particular well, however. This may indicate that these unconformities are missing locally or, alternatively, that they have no obvious lithological or petrophysical expression. For example, in the well Maui-4 (left) there is good correlation between the pre-CONOP unconformities P20, P50 and P60, and log breaks – the occasional slight offset between the two reflects the fact that CONOP sample horizons are discrete. The identification of these three unconformities was primarily based on seismic interpretation and classic biostratigraphy and they correlate well with lithology and petrophysical property changes in the well. Based on CONOP results, we can now quantify the absolute age and the time missing in each event (e.g., P60, age 35.36-21.26 Ma, 14.1 m.y. missing). Also, based on CONOP, several new unconformities have been revealed (i.e., at 2,713m, 2,465m and 2,158m) and their durations and log expressions identified. The lack of log-expression of a CONOP-inferred unconformity at 2,713m may indicate that it is associated with a fault or, alternatively, that this unconformity is locally missing in Maui-4. A comparison between ages based on traditional biostratigraphic analysis and the CONOP ages shows generally good agreement and greatly increased age resolution of the CONOP results. For example, in Maui-4 the Cretaceous-Tertiary boundary (65.5 Ma) is bracketed by a CONOP unconformity with age-span of 58.29–66.62 million years.

It is important to note that CONOP does not set out to duplicate existing traditional age assignments but, instead, aims to create an alternative, reproducible correlation model that integrates seismic and lithological observations with observations from traditional biostratigraphy. Only future stratigraphic work, crucially incorporating CONOP, will be able to resolve apparent contradictions and pave the way for a unified age model. ■

The authors acknowledge the work of Hugh Morgans, Ian Raine, and Poul Schiøler of GNS Science.

GNS Science is New Zealand's premier provider of natural resources research and consultancy services. Open-file data and reports are available from the Petroleum Basin Explorer website: http://data.gns.cri.nz/pbe.

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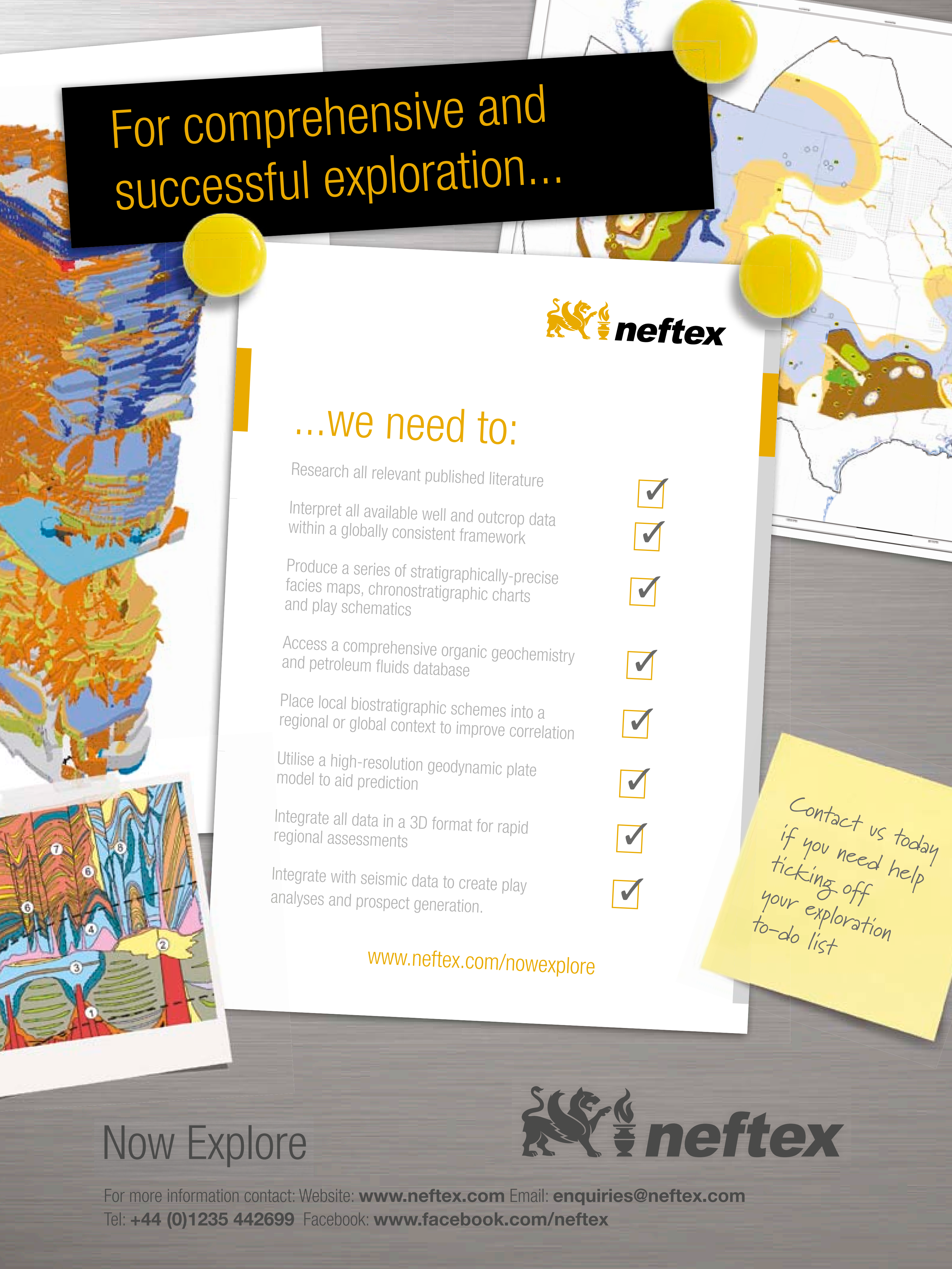
1. Developed by Professor Peter Sadler at the University of California.
2. Cooper, R.A., Crampton, J.A., Raine, J.I., Gradstein, F.M., Morgans, H.E.G., Sadler, P.M., Strong, C.P., Waghorn, D. and Wilson, G.J. (2000). Quantitative biostratigraphy of the Taranaki Basin, New Zealand: A deterministic and probabilistic approach. AAPG Bulletin V. 85 No 8. 1469-1498.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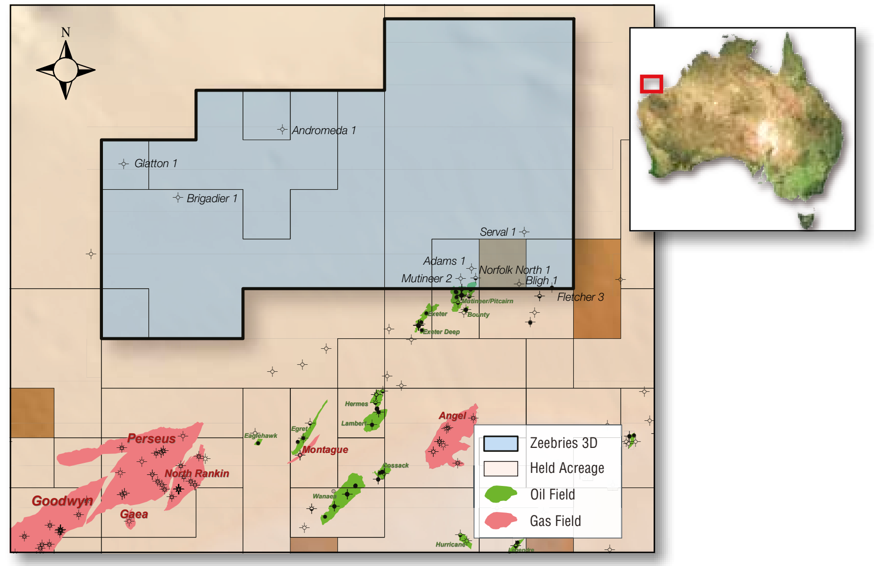
Zeebries:

New High Quality Data in Australia's Most Prospective Basin

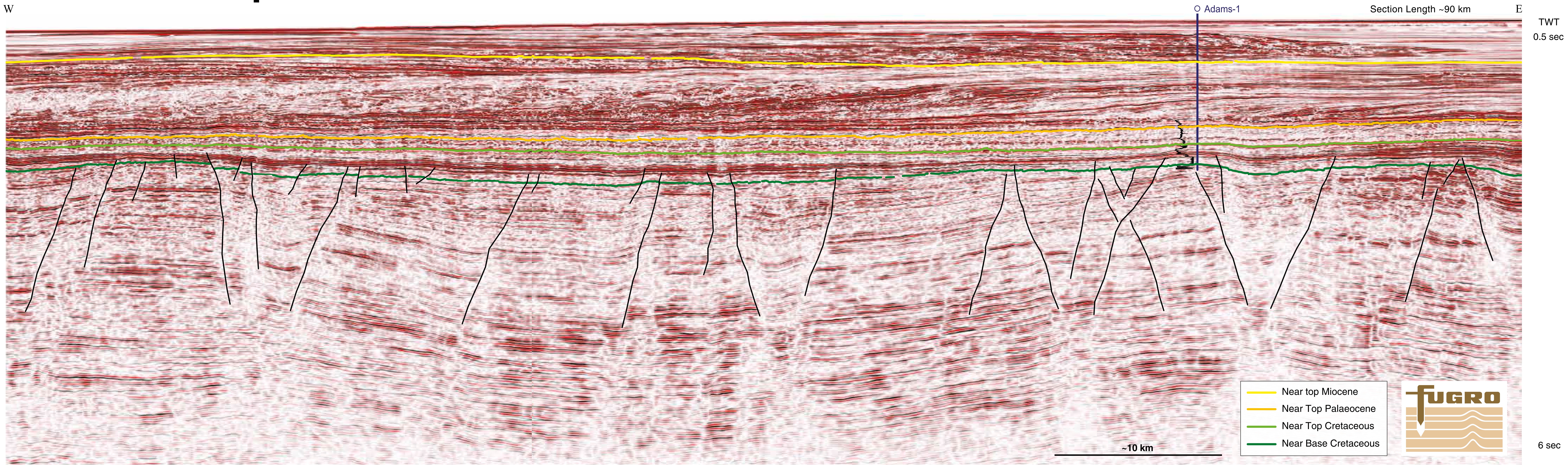
Fugro has commenced a full seismic inversion of the newly acquired Zeebries 3D non-exclusive seismic survey, including lithology probability volumes, which will aid in fast-tracking the interpretation process.

The Zeebries 3D covers an area of about 3,800 km² in the Northern Carnarvon Basin between the Dampier and Beagle Sub-Basins north of the large Goodwyn and Perseus gas fields. It was acquired by Fugro in 2011 and was designed to clearly define plays in the area, including reservoir rocks of Jurassic and Triassic age. Structural plays occur along north-east to south-west and north to south trending structures. Wells in the area penetrated Cretaceous regional sealing rocks, coarsening upward sediments of the mid-Jurassic Legendre Formation and the potential source rocks of the Middle – Early Jurassic Athol and Late Triassic – Early Jurassic Brigadier formations.



Map of the Zeebries 3D. The survey name Zeebries means sea breeze in Dutch, a homage to Fugro's Dutch origins

West-east oriented seismic line through the Zeebries 3D survey located in the Northern Carnarvon Basin, Australia. The main reservoir rocks are Jurassic deltaic sediments of the Legendre Formation. Regional seals occur in the Cretaceous fine-grained sediments and source rocks occur in the lower part of the Legendre Formation and in the Athol Formation. Main structures are horst and grabens.



Significant Insights from New Survey

by **PATRICIO SILVA GONZALEZ**, Fugro Multi Client Services

The offshore part of the Northern Carnarvon Basin is a depocenter, which covers an area of about 535,000 km². The basin is bounded to the north-east by the Roebuck and Canning Basins, to the south-east by the Pilbara block, to the south by the Southern Carnarvon Basin and to the north-west by the Gascoyne abyssal plain, which in turn is bounded in the north by the Java Trench/Timor Trough.

The basin is filled with thick Paleozoic, Mesozoic and Cenozoic sedimentary successions, which were deposited during multiple phases of extension and following break-up of Gondwana. A prominent north-east to south-west trend of significant structures and alignment of basins are a consequence of this rifting event, which occurred mainly during the Jurassic to Early Cretaceous. These polycyclic extensional events produced dominant structural elements, including the Beagle, Dampier, Barrow and Exmouth Sub-Basins and the Exmouth Plateau and Lambert and Peedamulla Shelves.

A second, nearly north-south oriented structural trend is prominent in the Beagle Sub-Basin and adjacent areas. It can be related to the transitional character of this Sub-Basin being located between the Northern Carnarvon and the adjacent offshore Canning and Roebuck Basins.

Pre- and Syn-Rift Stratigraphy

During the pre-rift (Silurian to Early Jurassic) extensional events caused by northward block-migration during Carboniferous times resulted in regional deposition of related sediments in the area of what is now the North Carnarvon Basin. During the Late Permian, shallow marine clastics and carbonate sediments were deposited in north-east to south-west trending depocenters (Longley *et al.* 2002). Regional marine transgressional events during the Triassic resulted in the deposition of shales, siltstones and minor paralic sandstones and shelfal limestones, grading into the fluvio-deltaic sandstones of the Mungaroo Formation. Fluvial and shoreline sandstones of the Mungaroo Formation are the reservoirs of some giant gas accumulations on the Rankin Platform, and the Mungaroo Formation is also a gas-prone source rock in the Dampier Sub-Basin. The shelfal sediments of the Brigadier Formation were deposited from the Late Triassic to Early Jurassic; they are also a significant gas source in the area.

The structural configuration developed in the Northern Carnarvon Basin during the Early Jurassic is still apparent today. Major bounding faults separate individual sub-basins, while a combination of pre-existing Paleozoic north-south structures combined with oblique extensional directions resulted in the en echelon trend of the sub-basins seen today.

The syn-rift period covered the Middle Jurassic to Early Cretaceous. The clay and siltstones of the Athol Formation were deposited in a restricted marine environment, while the overlying sandstones of the Legendre Formation are interpreted as deltaic sediments. Distal deltaic sediments are likely to provide the source of some important hydrocarbon accumulations in the area.

Continental break-up and related seafloor spreading occurred in the Oxfordian, with the break-up unconformity as one of the main events in the North West Shelf. Continuous break-up, related faulting and rapid tectonic subsidence resulted in thick marine successions, which filled the ensuing sub-basins during the Late Jurassic. High-quality, oil-prone, Oxfordian source rocks are the result of a maximum flooding phase, while at the sub-basin margins, shoreline and fluvial sandstones and related fans with potential reservoir quality have been deposited.

Upper Jurassic sandstones are the result of the erosion of Triassic rocks from uplifted blocks. They are significant as reservoir units, including shallow marine to turbiditic sandstones. These rocks are the main reservoirs in the Dampier Sub-Basin, and the Late Jurassic Jansz Sandstone is the main reservoir of the giant Io/Jansz gas field in the Exmouth Plateau.

The Barrow Delta, and deposition of the resulting Barrow Group sediments, occurred mainly during the late syn-rift phase. The delta prograded northwards over the Exmouth Sub-Basin and Exmouth Plateau and deposited a sediment thickness of about 2,500m. Two phases of delta progradation have been interpreted, with a diachronous boundary in between. The second delta lobe and related sediments were deposited in the Barrow and Dampier Sub-Basins; Barrow Group sediments show good reservoir qualities.

Post-Rift Stratigraphy

Post-rift subsidence (Early to Late Cretaceous) resulted in an overall transgression and consequently a deposition of a fining-upward marine sequence during Early Cretaceous times. Widespread deposition of shales, siltstones and radiolarites happened during that event. The Muderong Shale is a regional seal although it locally also contains reservoir quality sandstones. Uplift events during the Late Cretaceous caused erosion of earlier deposited rocks in the area.

During the post-rift phase (Late Cretaceous to present) widespread shelfal carbonate sediments were deposited on a passive continental margin, and uplift events resulted in a phase of inversion in areas like the Exmouth Plateau. Pre-existing rift-related structures have been reactivated with transpressional character.

The collisions between the Australia-India and Eurasia plates affected north-west Australia and the Northern Carnarvon Basin (Longley *et al.* 2002), resulting in tilting, inversion and fault-reactivation in the area. Many structural traps within Cretaceous and Cenozoic units were created during that time.

Northern Carnarvon Basin Petroleum Systems

As has been described, the generation, migration and entrapment of hydrocarbons in the Northern Carnarvon have been controlled by Jurassic to Early Cretaceous syn- and post-rift structures, syn- and post-rift deposition and Neogene reactivation. The basin contains thick successions of late Paleozoic to Cenozoic sediments with thicknesses of over 10 km. The most dominant successions are Triassic to Lower Cretaceous sedimentary units.

Gas-prone source rocks in the Barrow and Dampier Sub-Basins are in general located in the Triassic fluvio-deltaic units of the Mungaroo and Brigadier Formations and the Jurassic marine to deltaic Athol and Legendre Formations. Geochemical studies undertaken in the Rankin Platform area indicate that gas accumulations there were sourced by Triassic source rocks, and accumulations in the adjacent Barrow and Dampier Sub-Basins have Jurassic source rocks.

Reservoir rocks in the Northern Carnarvon Basin are dominated by fluvio-deltaic and marginal marine clastics of the Triassic Mungaroo and the Jurassic Legendre Formations in the Beagle and Dampier Sub-Basins, and by the Lower Cretaceous Barrow Group sediments in the Barrow and Exmouth Sub-Basins and Exmouth Plateau.

Most of the discoveries in the Northern Carnarvon Basin are sealed by the lower Cretaceous Muderong Shale, an effective regional seal in the Northern Carnarvon Basin. Additional significant intraformational seal units occur in the Cretaceous Barrow Group sediments and Forestier Claystones, the Jurassic Athol and Legendre Formations and the Triassic Mungaroo Formation.

The main structural trap styles in the area are horsts, tilted fault blocks, drapes and fault-over anticlines. Stratigraphic traps include basin-floor turbidites, pinch-outs and onlaps.

Significant Insights

Located along the same structural trend as producing fields, the Zeebries 3D survey adds significant insight into a highly prospective part of the Northern Carnarvon Basin. Complementary inversion by Fugro will aid in fast-tracking the interpretation process of potential reservoir intervals present in the area.

Several wells located within the survey area penetrated potential reservoir, seal and source units. Preliminary seismic interpretations confirm their distribution away from the well location within the survey area, while there is ample evidence of both stratigraphic and structural traps. ■

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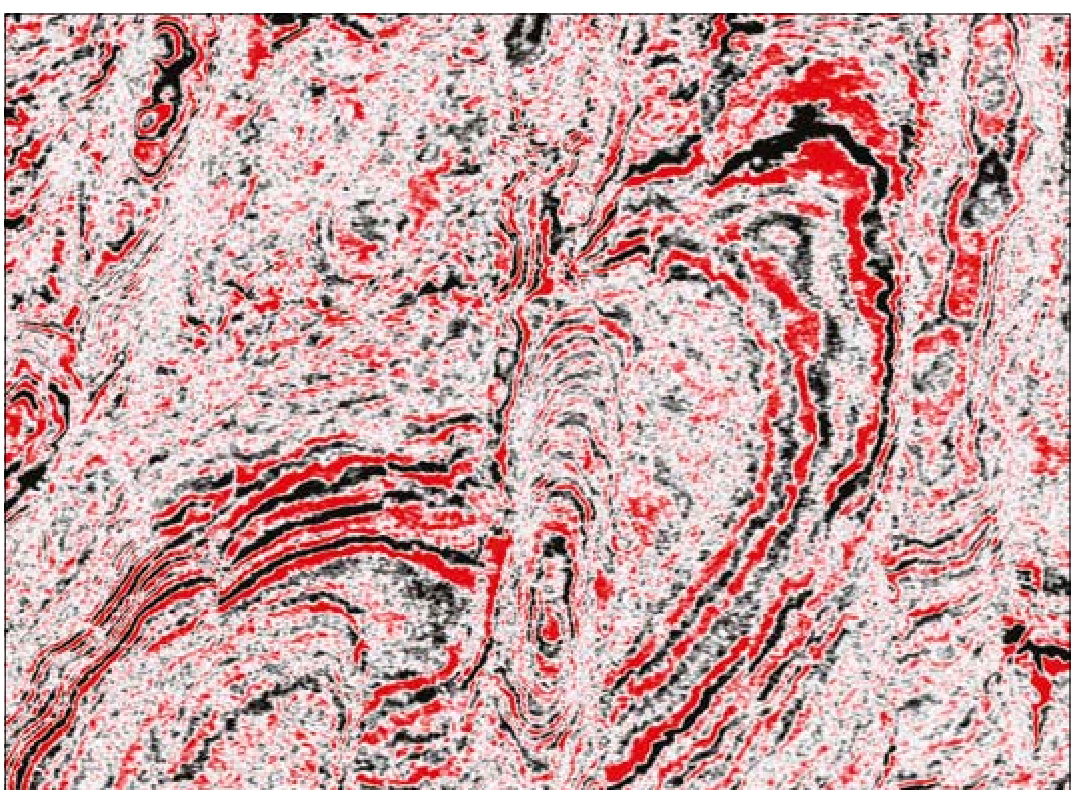
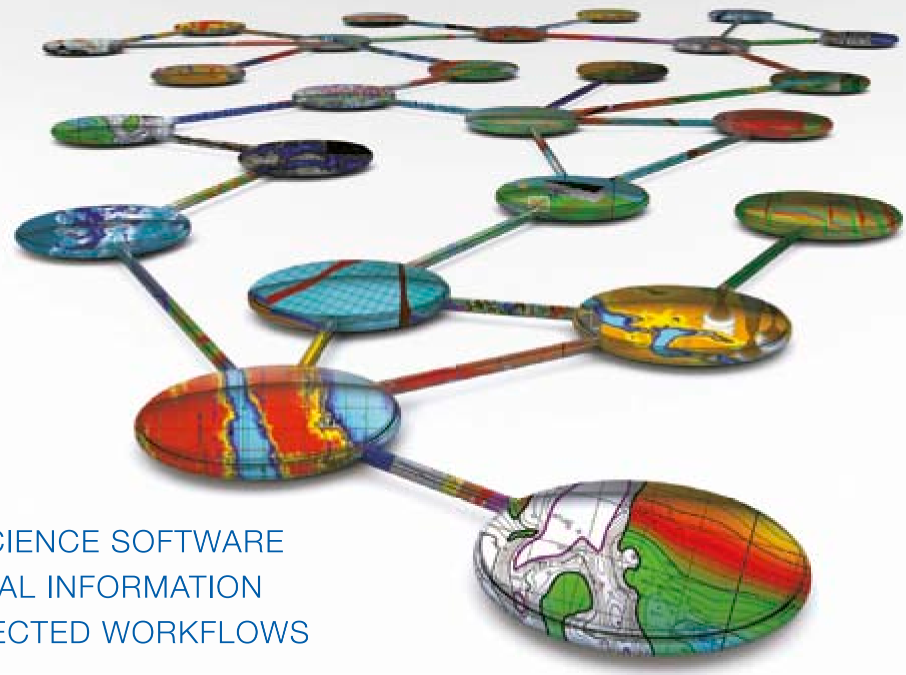
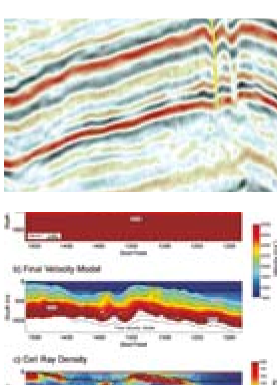
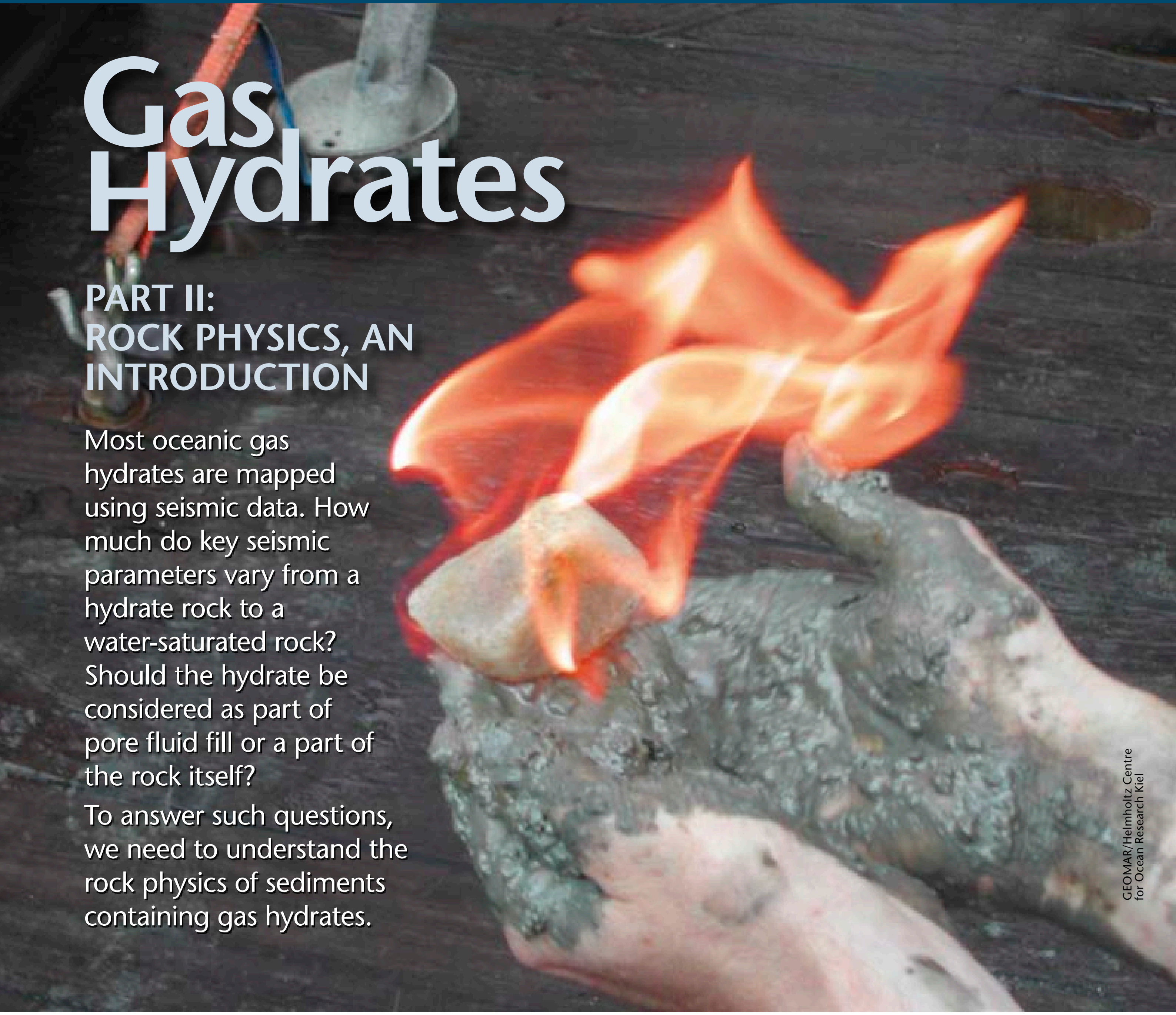


The time slice shows reflectors interpreted as Jurassic source rocks. These source rocks are disrupted by north-south trending structures which serve as migration paths for hydrocarbons. The hydrocarbons may be trapped in the overlying Jurassic reservoir units.







Gas Hydrates

PART II: ROCK PHYSICS, AN INTRODUCTION

Most oceanic gas hydrates are mapped using seismic data. How much do key seismic parameters vary from a hydrate rock to a water-saturated rock? Should the hydrate be considered as part of pore fluid fill or a part of the rock itself?

To answer such questions, we need to understand the rock physics of sediments containing gas hydrates.

GEOMAR/Helmholtz Centre for Ocean Research Kiel

LASSE AMUNDSEN and **MARTIN LANDRØ**

"The world is the geologist's great puzzle-box; he stands before it like the child to whom the separate pieces of his puzzle remain a mystery till he detects their relation and sees where they fit, and then his fragments grow at once into a connected picture beneath his hand."

Jean Louis Rodolphe Agassiz (1807–1873), Swiss paleontologist, glaciologist, geologist

A major and obvious difference between ice and hydrate is that the hydrate is highly flammable ('burning ice').

It is of course the methane content in hydrate that makes it of commercial interest. In fact the difference between ice and methane hydrate is not huge: one could consider hydrate as one dash of methane gas and six dashes of pure ice. Ice has a hexagonal crystalline structure, with a density of roughly 0.92 g/cm^3 at 0°C and increases to 0.93 for a temperature of -180°C. The density of methane hydrate is slightly less (0.90 g/cm^3), since there is only 1 mole of methane per 5.75 moles of ice. Another way to formulate this is to say that whereas ice has the formula H_2O, the empirical chemical formula for methane hydrate is $(CH_4)_8(H_2O)_{46}$.

So, if the density difference between ice and hydrate is negligible, what about other crucial seismic parameters, such as velocities?

Rock Physics Experiments

In 2001 Michael Helgerud presented a comprehensive PhD thesis at Stanford where he analyzed wave velocities in gas hydrates and sediments containing gas hydrates.

For pure gas hydrate samples made in the laboratory he measured P-wave (compressional) velocities around 3700 m/s and S-wave (shear) velocities around 1950 m/s. Only small variations with temperature and confining pressure were observed.

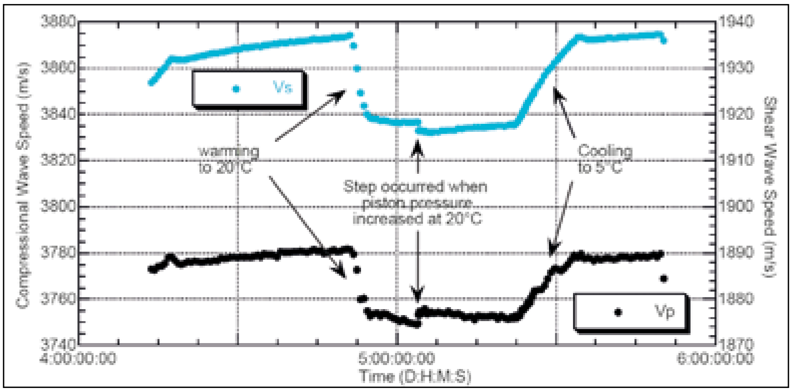
The ratio between P-wave velocity of pure hydrate versus ice is 0.98. For the S-wave velocity the corresponding ratio is close to 1.0. This means that, acoustically, pure ice and pure methane hydrate are very similar. This is maybe as expected since the dominant crystalline structures of the two are similar.

Fluid, Frame or Cement?

Is hydrate a part of the fluid, the frame or is it cement?

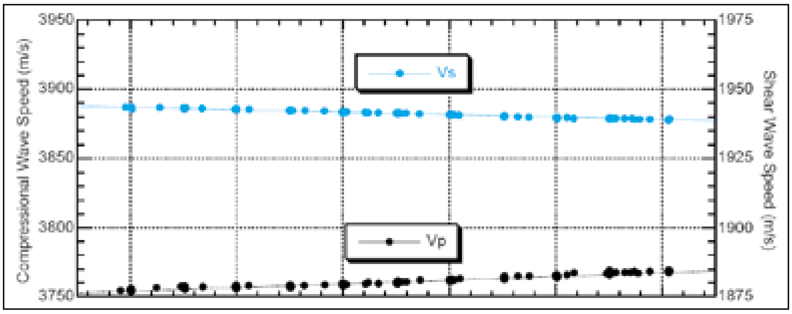
We have seen that pure hydrate and ice are very similar with respect to traditional seismic parameters, such as velocities and densities. However, in nature, the hydrate is found as a part of a rock, making the rock physics relations more complex. What happens when methane hydrate enters into a sedimentary rock? Hydrate is found both in clay rich sediments ▶

Compressional and shear velocity versus time. The figure shows the response to a warming of the sample from 5 to 20°C followed by a cooling back to 5°C again. Confining pressure: 9,000 psi.



Helgerud (2001)

Compressional and shear wave velocities versus confining pressure for methane hydrate. The horizontal scale is from 4,000 to 9,000 psi.



Helgerud (2001)

Rock Physics

Rock physics provides the connections between geophysical (elastic and electromagnetic) properties of the rock measured at the surface of the earth, within the borehole or in the laboratory, with the intrinsic properties of rocks, such as mineralogy, porosity, pore shapes, pore fluids, pore pressures, permeability, electrical resistivity, viscosity, stresses and overall architecture such as laminations and fractures. These parameters affect how seismic and electromagnetic waves/fields physically travel through the rocks. Establishing relationships between geophysical expression and physical rock properties therefore requires knowledge about the elastic/electromagnetic properties of the pore fluid and rock frame, and models for rock-fluid interactions.

Equations that attempt to describe the relationships between seismic velocities and lithology, porosity, pore fluid, etc. are either theoretical or empirical.

Zhijing Wang summarizes the tension between theoretical and empirical approaches this way: most direct measurements are carried out either in the laboratory or inside a borehole, whereas most theoretical calculations are based on the Gassmann equation (*Gassmann, 1951*) because of its simplicity and ease of use. Direct laboratory measurements are carried out in controlled, simulated reservoir environments and provide accurate effects of pore fluids on seismic properties. Direct borehole measurements, however, are often affected by uncontrollable factors such as stress concentration, hole washout, mud invasion/filtration, and saturation conditions. In both laboratory and borehole measurements, the wave frequencies are higher than seismic frequencies.

Jan Dewar summarizes that the crux of all this is that there are a great number of relationships between seismic velocities (and constituent elastic properties) and rock parameters, all valid to some degree but not always valid, and many that do not illuminate the physical principles involved. The trick is to try to gain a fundamental understanding so that, on a practical basis, the different relationships can be evaluated for their applicability to solving specific problems.

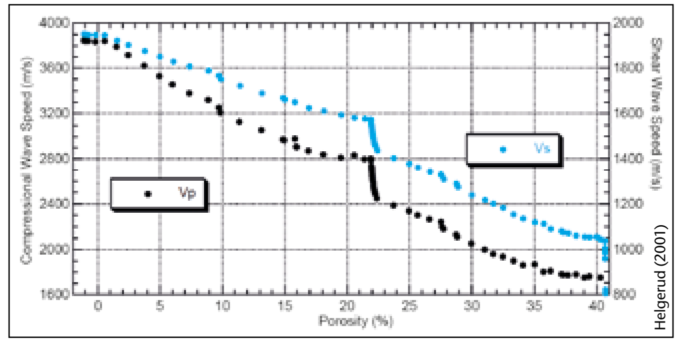
Theoretical rock physics modeling can also be applied to understand the physical properties of natural gas hydrate systems and accumulations. A major goal is to establish linkages between gas hydrate concentration/saturation in sediments and the measureable physical properties, like P- and S-wave velocities and electrical resistivity. Modeling the elastic properties of sediments as a function of gas hydrate content can be achieved in various ways, such as effective medium modeling or three-phase Biot theory. The effective medium theory can incorporate the effects of cement and grains. In the case of gas hydrate, the hydrate can form in various ways. The effective seismic velocities vary quite strongly depending on which formation scenario is used.

To model gas hydrate systems via rock physics one needs to define the elastic/electromagnetic properties of the system in terms of (i) elastic/electromagnetic properties of the (unconsolidated) sediments that host the hydrates, (ii) elastic/electromagnetic properties of the embedded gas hydrates, (iii) the concentration of hydrates in the sediments, and (iv) geometrical details of the distribution of hydrates within their host sediments. The inverse modeling problem is to infer hydrate concentration from geophysical measurements.

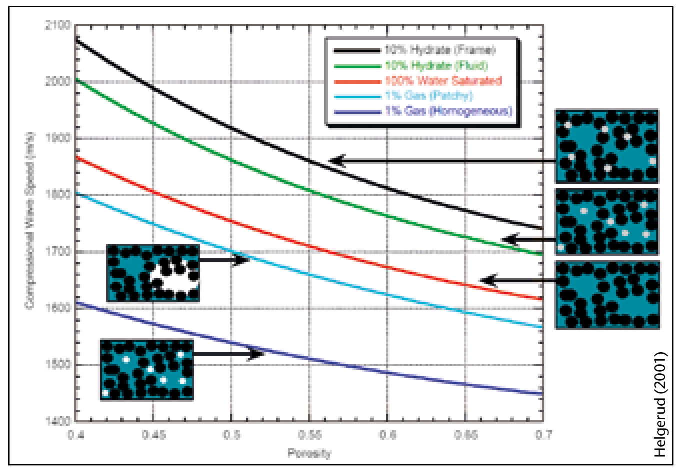
Acoustic well-logs with full waveform show a pronounced decrease of wave amplitude in hydrate-bearing zones.

and in sands. Several models have been proposed for this, varying from regarding the hydrate as a part of pore fluid fill, via being a part of the rock frame or acting as cement between sand grains. Helgerud found that the P-wave velocity is slightly higher when assuming that the hydrate is a part of the rock frame.

There are two ways of addressing this problem: either to perform measurements in wells drilled into hydrate-bearing rocks, or to inject hydrate in a controlled way into a rock in the laboratory. We will discuss both methods in the next issue of *GEO ExPro*. ■



Compressional and shear velocity versus porosity for ice.



P-wave velocity versus porosity assuming that the methane hydrate is a part of the rock frame (black line), of the pore fluid (green line). The red line shows a rock which is 100% water saturated (no hydrate), the blue solid line represents 1% patch gas saturation, and the dark blue line represents 1% homogenous gas saturation.

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Martin Landrø is professor in Applied Geophysics at NTNU, Trondheim, Norway.

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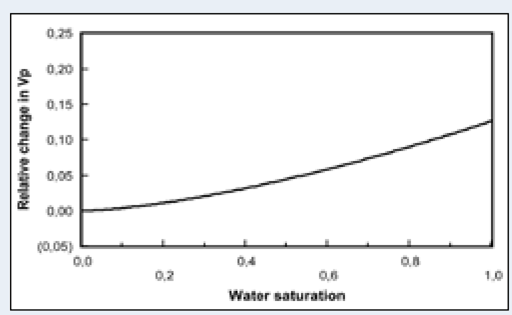
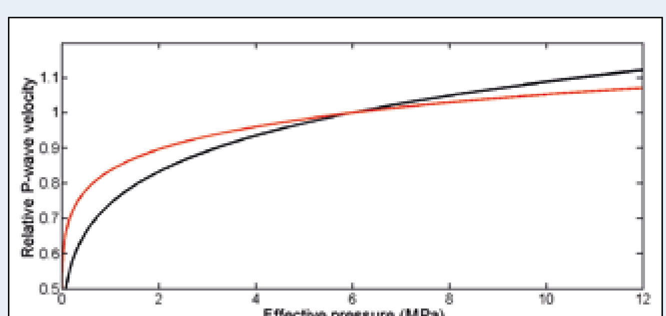
Examples of Rock Physics Relations

In this box we show two examples of some of the most frequently used rock physics relations.

The most famous model in rock physics is the Gassmann (1951) equation, which is used to describe the effect of gradually changing the pore fluid in, for instance, a sandstone. It needs calibration prior to use, for which we often use well logs. The figure on the right shows how the relative P-wave velocity varies as a function of water saturation, assuming that the pores are filled with either oil or water.

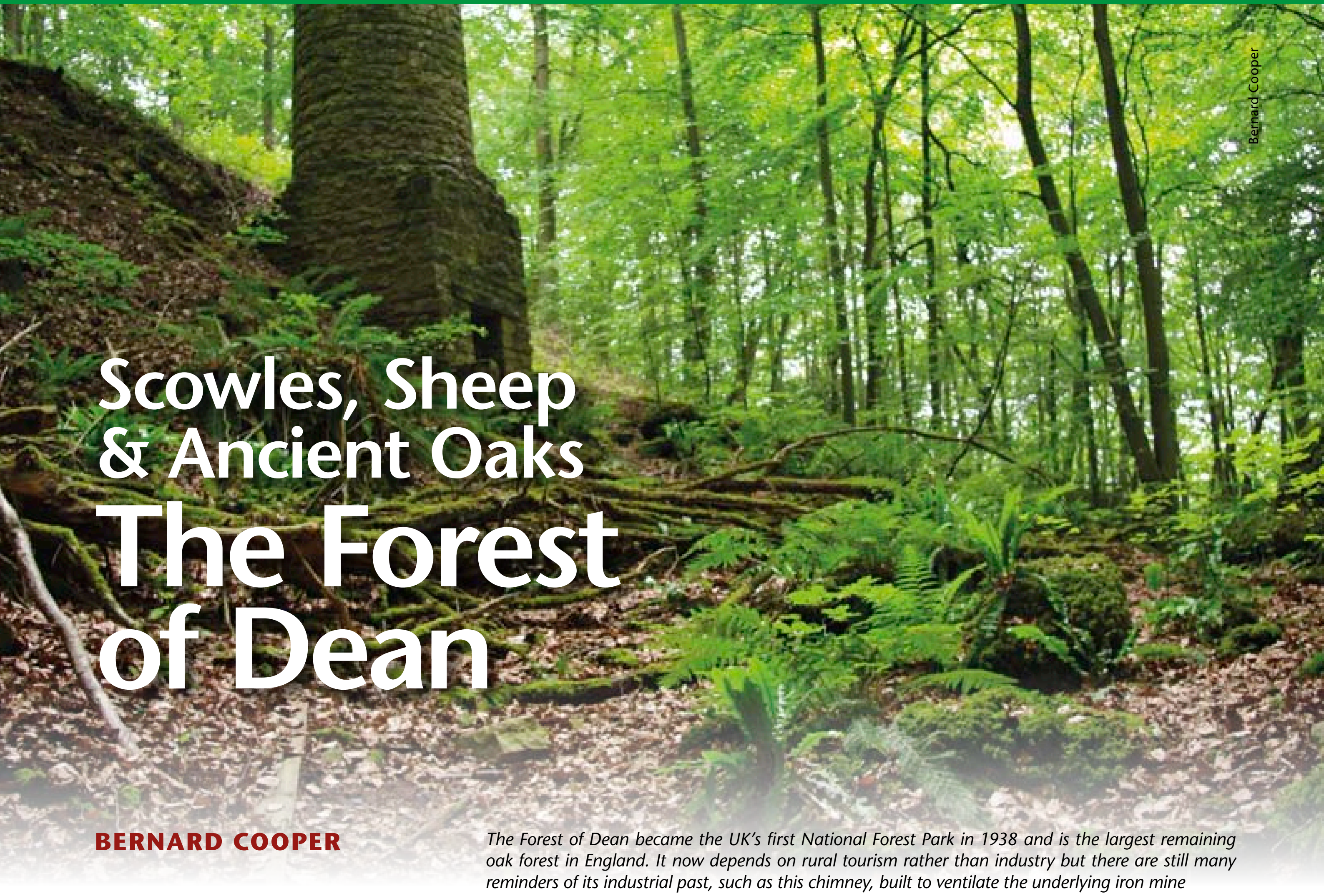


Another key reservoir parameter is the pore pressure. For wave velocities it turns out that it is the effective pressure (which is approximately equal to the overburden pressure minus the pore pressure) that controls the velocity. The simplest version for a theoretical model that includes changes in effective pressure is the Hertz-Mindlin model. This is a contact model, where it is assumed that the rock grains are identical spheres with a given contact area that increases with the effective pressure. As this contact area increases, the velocity increases, as shown below. The black line corresponds to a Mindlin-coefficient of 1/6 and the red line to 1/10, demonstrating that also in this case we need a calibration procedure prior to practical application of this simple model.



In most cases we assume that the density does not change as the pore pressure changes. However, in some cases the rock might compact or undergo stretching, and in such cases the porosity will change and hence also the density. Typical examples are chalk reservoirs that may compact by several meters, due to production.

Rock physics plays a crucial part both in exploration and production geophysics: advanced and quantitative use of, for example, pre-stack seismic data require rock physics input to link the seismic parameters to key reservoir parameters such as saturation, pressure and porosity.



Scowles, Sheep & Ancient Oaks
The Forest of Dean

BERNARD COOPER

The Forest of Dean became the UK's first National Forest Park in 1938 and is the largest remaining oak forest in England. It now depends on rural tourism rather than industry but there are still many reminders of its industrial past, such as this chimney, built to ventilate the underlying iron mine

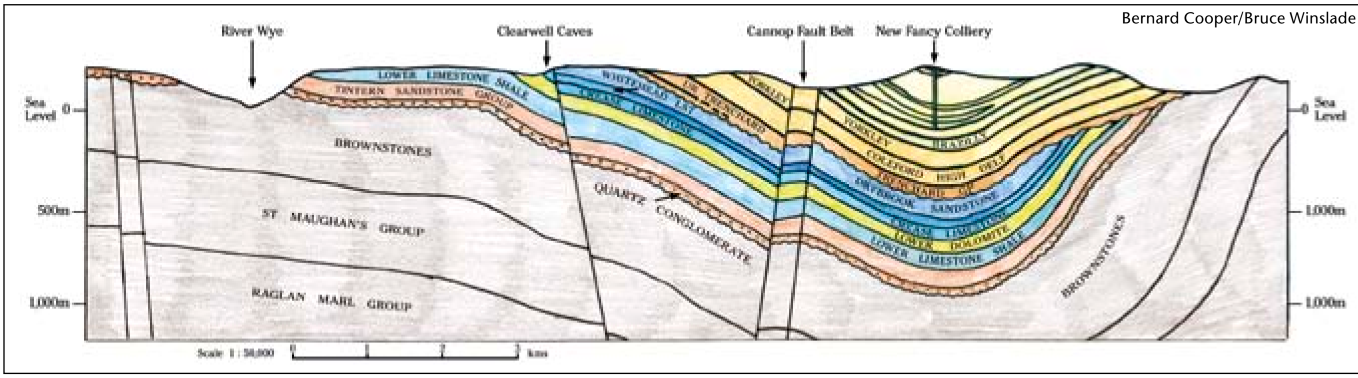
The Forest of Dean is an ancient royal forest, and is now a popular tourist destination. For much of its history, the people of the area have been dependent on the coal and iron found within its rocks

The Forest of Dean in Gloucestershire is an area of great natural beauty with a distinctive character and history, covering over 100 km^2 between the River Wye and the River Severn on the southern border of England and Wales. It was already reserved as a Hunting Forest for royalty before 1066, with a good supply of deer and wild boar, and was later a major source of oak timber for building warships.

Geologically it is an asymmetrical syncline, exposing the Old Red Sandstone and Carboniferous Limestone on its flanks and the Westphalian Coal Measures in its core. With a combination of outcropping ores from the Tournaisian Creace Limestone and coals from the Westphalian Coal Measures, this is probably the oldest area of iron and coal mining in Britain. The local people or 'foresters' have long combined the skills of mining, charcoal-making, forestry and iron-smelting with recreational poaching. They are very independently minded, with a strong sense of community.

Scowles and Iron Mining

The outcrop of the Crease Limestone around the flanks of the Forest of Dean syncline is marked by a wide variety of naturally formed pits and cavities locally known as scowles, which are thought to be unique to the Forest. These are probably paleo-karst features developed in the outcropping Crease Limestone during Permo-Triassic uplift and erosion and range from shallow pits to irregular hollows several meters deep. The cave walls within the scowles are covered with massive or stalactitic brown haematites. The remaining cavities are frequently filled with fibrous goethite, and yellow, red, brown and purple ochres, much valued by artists ever since the Stone Age, are often found. Replacement red haematite is also present in the Crease Limestone. The haematite and goethite is thought to have been derived from solutions of pyrite and siderite from the overlying Westphalian sediment during acid conditions.



West to east cross-section of the Forest of Dean syncline (line of section shown on map on page 48)

Some 14 named coal seams are present in the Westphalian, all of which outcrop. The thickest and most commercial seams were the basal (Westphalian C) Trenchard seam which is 1.3m thick. The Coleford High Delf seam is up to 1.5m thick and the Yorkley seam averages less than a meter. The latter are both Westphalian D of the Pennant Group, interbedded with thick sandstones.

The first use of Forest of Dean iron ore is thought to have been during the late Stone Age when ochre was used to dye cloth and glaze pottery. There was much more extensive iron mining during Roman times, although the mines remained relatively shallow.

The intensity of iron-mining appears to have increased after the Dark Ages. Medieval ironworks were relatively small and mobile, with charcoal for fuel and the use of foot-operated bellows. In 1217, during the reign of Henry III, so much of the King's deer forest was being felled to make charcoal that private forges were banned and only those which could afford a Royal Charter remained. Some coal was being mined in the 1240s and, during the reign of Edward I (1272–1307), at least 59 small iron mines were operating in the Forest.

The Forest of Dean miners were much appreciated by the Crown as sappers and archers. They were often conscripted for military service in Edward I's wars against the Scots and French and in 1296 were rewarded with 'free mining rights'. Broadly speaking, any man over the age of 21 who was born within the Forest of Dean and had worked down a mine for a year and a day was then entitled to mine for coal, iron or stone anywhere in that location 'without let or hindrance'. The individual mines were, and still are, called 'gales'. The coal seams are 'delfs' and the inclined roadways 'dipples'. The Free Miners had their own court where disputes between them were settled. By the later Middle Ages the Crown regulated mining and mines in the forest through the Office of Gaveller or 'keeper of the gale', an office which still exists.

During medieval times the Forest of Dean was a major center of the British iron industry but by the 18th century it was declining, with production dropping from 192,000 tons in 1860 to only 1,700 tons in 1921. Many iron mines closed between 1890 and 1900 although several re-opened during WWI and one in WWII. The last commercial iron mine closed in 1946.

Mining and Museums

Meanwhile the coal industry rapidly expanded and by 1787 the Forest had 90 working coal mines employing 662 Free Miners. The Industrial Revolution was a boom time when deeper coal mining predominated and probably more people were working underground in the forest than on the surface. There were disputes over the employment of 'foreigners' and over the boundaries of adjoining mines. The Miners' Court decreed that mining in any gale was to cease when 'mattocks clashed'!

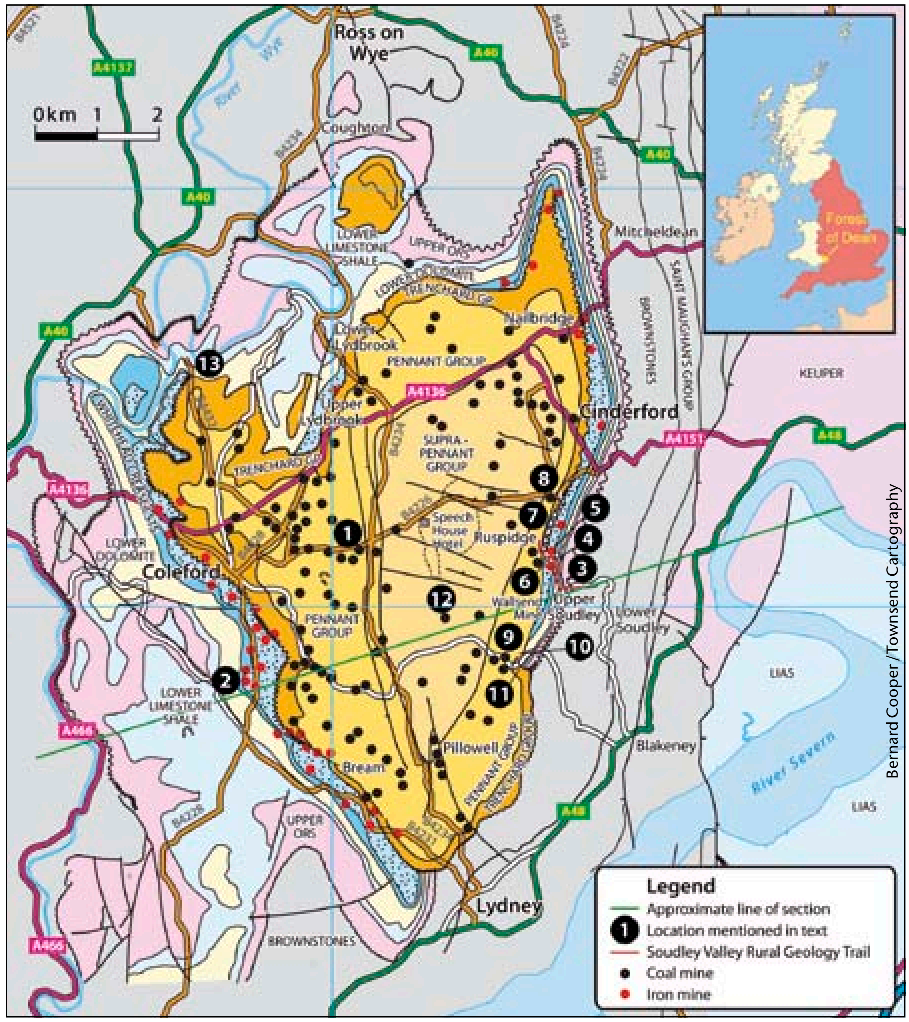
Coal output rose from 145,000 tons in 1841 to 1,176,000 tons in 1898, by which time three-quarters of the coal mined in the Forest came from six deep mines with the Free Miners supplying local needs from smaller drifts and shallow pits. The coal industry was nationalized in 1946 but the rights of the Free Miners were preserved. Coal production declined due to the high cost of draining water from the deeper mines. Production increased during WWI and II but the last deep mine finally closed in 1965.

Blue Rock Quarry: a source of lime and sand, this quarry in the Lower Carboniferous Lower Limestone shale was worked until the late 19th century

The long tradition of free mining continues in the Forest of Dean and there are thought to be about 150 Free Miners living today. In 2007 two small coal mines were still producing and two were in the course of development.

Hopewell Colliery (*site 1 on map*), near Cannop in the very center of the Forest, is a Mining Museum operated by its legendary Free Miner owner, Mr. Robin Morgan. Visitors, suitably equipped with hard hats and headlamps, are led down an adit to see the Yorkley seam and return to surface via a drainage adit cut in the 1800s. When no visitors are present Mr. Morgan continues to mine coal from the deeper Coleford High Delf.

Clearwell Caves, near Coleford (*site 2*), have been mined for iron ore for thousands of years and are now a system of show caves and a working iron mining museum. They have been owned since 1968 by Roy Wright and his son Jonathan, both Free Miners. The show caves, with the Crease Limestone, display a range of iron ores 'in situ' as well as an assortment of mining tools and displays. Visits to the more exciting and strenuous deeper cavity levels can be arranged. Ochre is still being mined on a small scale and can be purchased from the mine shop.



Geological map of the Forest of Dean, showing sites referred to in the text

Rural Geology Trail

The Soudley Valley Rural Geology Trail, maintained by the Gloucestershire Geoconservation Trust, is an excellent introduction to the geology and mining history of the Forest of Dean. The walk starts and finishes at an abandoned railway cutting in Upper Soudley and traverses the steeply dipping eastern limb of the Forest of Dean syncline.

In the railway cutting (*site 3*) a basal quartz agglomerate of the Upper Old Red Sandstone (Tintern Sandstone Group) unconformably overlies fluvial sandstones of the Lower Old Red Sandstone (Brownstones Group). The base of the Carboniferous Limestone Series, the massive transgressive shales, argillaceous limestones and calcareous sandstones of the Lower Limestone Shales are exposed in Blue Rock Quarry (*site 4*). Adjacent to this quarry is a memorial to the many Forest of Dean sheep culled in the 2001 Foot and Mouth epidemic.

The massive, finely crystalized and well-joined Lower Dolomite is dramatically exposed in Shakemantle Quarry (*site 5*). The footpath from this to Perseverance Quarry (*site 6*) passes the concrete-capped main shaft of Perseverance Iron Mine, the underground workings of which extended at least 1 km southward and supplied iron works in Lower Soudley, Parkend and Cinderford with iron ore from the Crease Limestone until 1899.

At Perseverance Road Cutting the red haematite-rich granular dolomite of the Crease Limestone is unconformably overlain by the pale grey calcite mudstones of the Visean Whitehead Limestone. These, in turn, are conformably overlain by a thick succession of Visean fluvio-deltaic sandstones of the Drybrook Sandstones, which are exposed in two old quarries (*site 7*) in the hill above the Perseverance Road Cutting.

Further up the hill the Westphalian D Pennant Sandstones are exposed in Staple Edge Sandstone Quarry (*site 8*), overlying the Coleford High Delf, the most productive coal seam in the Forest of Dean. An adjacent spoil heap from the Eastern United Colliery (1906–1959) yields plant fossils from this formation. The underlying (Westphalian C) Trenchard Group rests unconformably on the Carboniferous Limestone Series but is not exposed in this location.

A path south through the woods leads to a series of scowles in the Crease Limestone, the cave walls showing extensive iron staining. A stone chimney was built in the 18th century to ventilate the underlying Perseverance Iron Mine. A fire in the base of the chimney drew foul air up from below which, in turn, would draft clean air into the mine entrance.

The (Westphalian C) Trenchard Group can be examined in a more southerly traverse of the eastern line of the syncline on the northern side of the B4431. The road is narrow and twisting so it is best

Bernard Cooper

The view over the River Wye from Symonds Yat, one of the best-known viewpoints in the region.

to park and do the traverse on foot. The roadside Mosses Level Mine (*site 9*) is still open on a care and maintenance level, working the Coleford High Delf, which directly overlies the sediment of the Trenchard Group. In a roadside quarry (*site 10*) the grey-green mudstone and shales of the Trenchard Group can be seen unconformably overlying the Tournaisian Lower Dolomite. A roadside cutting (*site 11*) exposes cross-bedded sandstones of the Pennant Group.

A Geological Sculpture

To the west of the outcrops, on the site of the New Fancy Colliery, the Forest of Dean Local History Society have recently commissioned a geological sculpture, the Geomap Project (*site 12*). This sculpture, undertaken by David Yeates, is a large scale geological map, using stone from local quarries, showing the location of the 102 collieries, 35 iron mines and 49 stone quarries as well as the railway lines and tram roads which were so important in the past. An adjacent memorial sculpture honors those who died in the mining and quarrying industry (*see www.forestofdeanhistory.org.uk*).

Symonds Yat Rock (*site 13*) is well worth a visit for a dramatic view of the incised meanders of the River Wye and, hopefully, a sighting of the Peregrine Falcons which nest on the adjacent Colwell Rocks. A walk down into the wooded Wye Valley gorge gives excellent views of gently dipping Carboniferous Limestone, especially the Lower Dolomite and Crease Limestone.

Bernard Cooper will be leading a PESGB Field trip to the Forest of Dean in October – there are still spaces available.

Shakemantle Quarry exposes a large section through the Carboniferous Lower Dolomite

Bernard Cooper

Putting the Pieces Together

Interactive Tabletop Visualization

Digital tabletops provide a true collaborative environment for reservoir analysis that often requires a varied input from different fields of expertise.

THOMAS SMITH

Multiple users can manipulate a point-based data set through a camera-enabled tablet.

Remember dumping 1,000 varied shaped and colored pieces on a big table and then trying to put it all back together to match the picture on the box? One person could concentrate on the blue and white pieces that match the sky; another person could put together the greens and browns of the animals and the pasture; and yet a third could concentrate on the red and white shapes that make up the barn. By sorting the colors and fitting pieces together, a picture would gradually come to life on the tabletop.

Now, imagine having even better 3D capabilities with a complex reservoir 3,000m below the surface. This is the goal of a prototype tabletop interactive reservoir visualization program being developed at the University of Calgary.

> "Revolutionizing the way reservoir models are seen, understood and harnessed… bringing it closer to us, at our hands' reach."

Hands On

"We have attempted to harness the power of digital tabletops into a new interaction paradigm – bringing the reservoir to hand's reach," says **Nicole Sultanum**, a researcher at the IllustraRes – the University of Calgary's Interactive Reservoir Modeling and Visualization Group, affiliated with the Department of Computer Science. "The aim is to facilitate collaborative manipulation and analysis, and potentially contribute to the overall understanding of the reservoir."

Their prototype utilizes the new technology of digital tabletops to provide a suitable form factor for collaboration into the very complex and multi-faceted field of reservoir engineering. Any single project incorporates many threads of knowledge from geoscientists, engineers, and economists to achieve production goals while maximizing return. This all has to be accomplished while maintaining the integrity of the production installations and wells, and guaranteeing a safe operating environment.

Companies have commonly utilized teams of experts and immersive virtual reality environments for reservoir visualization. While this type of shared view of the reservoir does facilitate analysis, it does not allow for the easy multi-user interaction that the digital tabletop can provide.

How It Works

"The unique capabilities of the tabletop environment provide better ways to manipulate reservoir models, from basic activities such as spatial navigation and probing, to the ability to browse and inspect the reservoir through direct, intuitive manipulation," explains Nicole.

In evaluating reservoirs, geoscientists and engineers deal with rock and fluid properties like porosity, permeability, saturation values, and changing fluid properties as oil or gas is extracted. Wells and geologic features are also important to reservoir modeling. However, this important data can remain hidden without mechanisms to uncover, depict, and highlight.

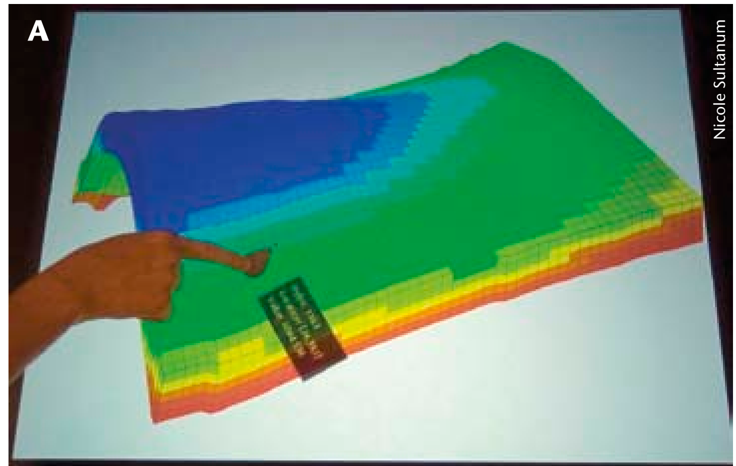
"We have developed a set of interactive tools on the tabletop that facilitate the unveiling of the reservoir's hidden attributes, at the same time allowing users direct access to essential reservoir information," says Nicole. "The tools include a cell probing device, the capability to split pieces of the reservoir and peel them out to reveal correlations between adjacent sections, and to highlight wells. Specialists using these tools are able to look at data that has been previously 'buried' in the reservoir model, which potentially contributes to more informed decisions concerning its production."

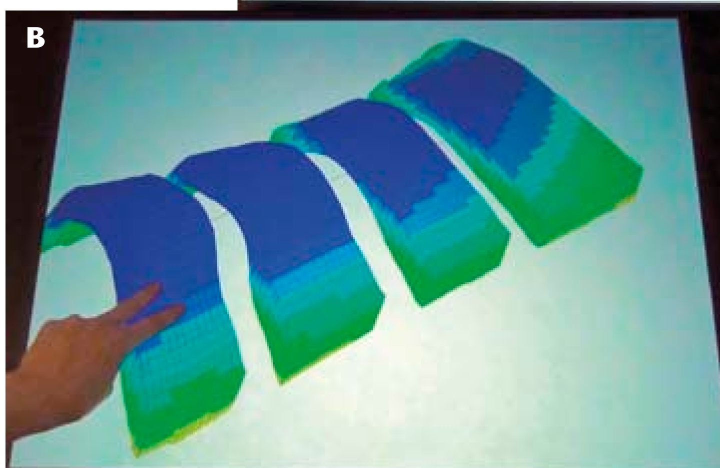
Besides the internal exploration techniques depicted across the pages, users have a reservoir model selection menu with physical reservoir property cards. These are activated when placed on the screen and can perform a variety of spatial navigation functions within the reservoir such as orbiting, zooming, rotating, and panning. Another goal is to create an

interactive and visual environment to probe deeper into different views of the reservoir model. Allowing multiple users to view and manipulate multiple perspectives of reservoir datasets, visualizations can be overlain above the tabletop reservoir through mixed reality, utilizing tablet devices as windows to the virtual view. The tablet's onboard camera is used to detect its orientation and position relative to the tabletop by tracking special image-based markers positioned around the device – the markers do not disrupt the tabletop interaction, allowing multiple users to collaborate while working on the same reservoir.

Testing and the Future

To see if this new tabletop environment will be of value to geoscientists and engineers, the researchers let them test it. Requests for improvement to the technique centered on two concepts: control and correlation. Participants needed more precision and control within multi-touch environments, which was a reflection of the meticulous nature of their work. The second recurring concept revolved around the ability to compare or correlate two or more properties and visualize several layers or models, among others.





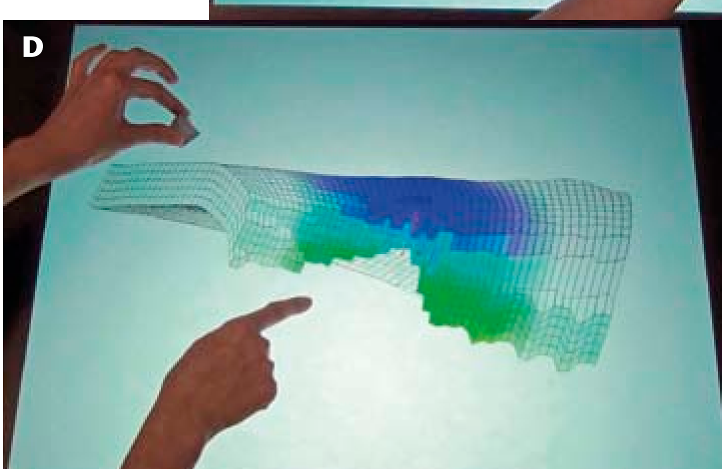
Some of the internal exploration techniques that have been developed for the tabletop:

(A) cell probe displaying cell-specific information

(B) splitting

(C) peeling

(D) focus and context for wells.



The list of changes and improvements is included with all the techniques they have introduced here and are important when designing future systems. "Participants in the tests were engaged by these tools and were eager to share their thoughts and insights regarding each," says Nicole. "Our impression was that such a creative environment can add and facilitate the thought and problem-solving process. As one of our testers put it, 'It actually brings some new ways of analysis… (and) creativity for sure'."

Current and future development involves further exploration of other techniques for the tabletop environment, such as the visualization of uncertainty, sketch-based interaction, and the integration with robotic tabletop assistants to support the users' work of analysis. As Nicole Sultanum points out, "We hope to bring the tabletop environment's many strengths to light, not only for reservoir engineering but beyond to demonstrate their potential to transform the ways humans explore scientific data." ■

Author's note: The work presented here is a collaborative effort between Nicole Sultanum, Sowmya Somanath, and Paul Lapides, guided by supervisors Ehud Sharlin and Mario Costa Sousa at the University of Calgary.

New Insights into the Browse Basin

Despite recent drilling success, the Browse Basin remains relatively underexplored, and imaging and mapping of the deeper horizons presents challenges to conventional seismic.

ANAND TRIPATHI and ROB McARDLE,
Petroleum Geo-Services

Location of the Browse Basin Aurora MC3D survey, offshore North West Shelf Australia.

The Browse Basin offshore North West Shelf Australia is currently one of the world's exploration hot spots in the quest for new oil and gas reserves. Despite recent drilling success, however, the basin remains relatively underexplored. It is a geologically challenging area, where imaging and mapping, especially of the deep Lower Cretaceous and Jurassic intervals, remain difficult using conventional seismic data.

PGS's proprietary GeoStreamer® technology has delivered outstanding results, available through the new Aurora MultiClient 3D. This survey, which lies within a proven oil and gas fairway along the south-eastern flank of the Browse Basin, comprises nearly 8,000 km^2 of high-quality broadband data, which was acquired by PGS *Ramform Explorer* in 2011/2012 and extends over both licensed and open acreage. Several proprietary GeoStreamer surveys were acquired on the North-west Shelf of Australia during the same period, showing the adoption of broadband seismic in this area. The Aurora survey is the first GeoStreamer MultiClient 3D project in Australia, and demonstrates a substantial improvement in resolution and penetration over existing data sets. Additionally, 200 km^2 of MultiClient 3D data were acquired over the Gwydion oil discovery located to the east of the Aurora survey.

Regional Geological Setting

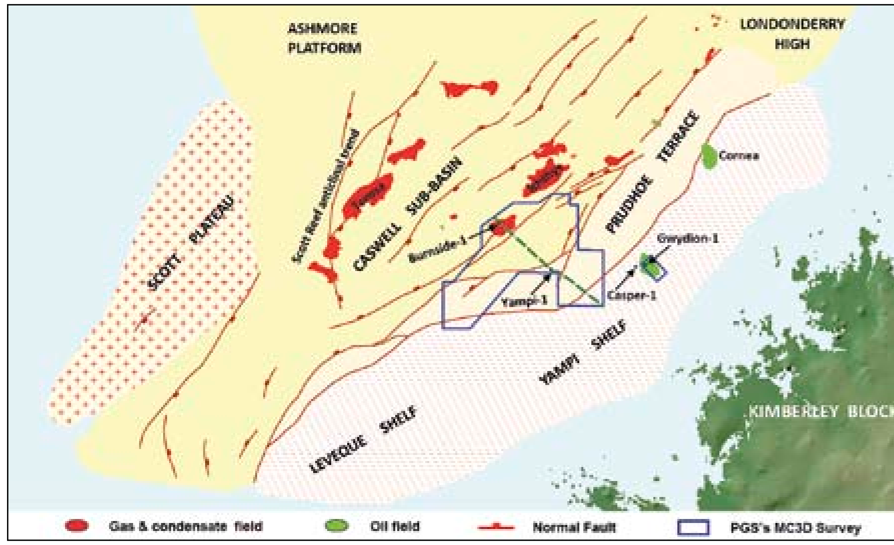
The Aurora and Gwydion 3D surveys are located on the Prudhoe Terrace and Yampi Shelf within the north-east-trending Browse Basin. The basin extends westwards to the Scott Plateau and is bounded to the east by the Precambrian Kimberley Block and its seaward expression, the Yampi and Leveque Shelves.

The Browse Basin covers approximately

The Ramform Explorer was used to acquire the new Aurora 3D dataset

PGS

140,000 km^2 of Australia's western continental shelf and slope, and is part of a series of rift/extensional basins that forms one contiguous Westralian Super-basin primarily filled with pre-rift Permo-Triassic intracratonic sediments, overlain by Jurassic to Cenozoic syn- and post-rift successions. The Yampi Shelf forms the south-eastern margin of the Browse Basin and is underlain by shallow basement with a distinct erosional paleo-topographic relief. The basinward boundary of the Yampi Shelf is characterized by a change in dip of basement from relatively flat-lying to gently basin-ward dipping. The Yampi Shelf passes westwards into the fault-bounded Prudhoe Terrace, beyond which lies the Caswell Sub-basin with up to 15,000m of sedimentary thickness. The Caswell Sub-basin is bounded to the west by the Scott Reef Anticlinal Trend, which itself passes westwards into the deepwater Scott Plateau.



Regional structural elements of the Browse Basin, showing location of composite seismic line shown on p58

The regional geology of the basin is shown by the north-west to south-east composite line that highlights the distinction between the highly-faulted, rift associated pre-Jurassic succession, and the overlying largely progradational

What is Geostreamer?

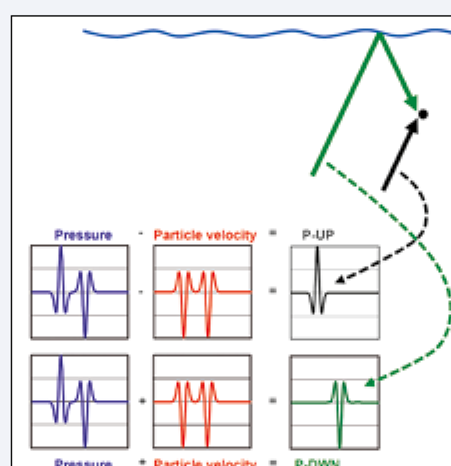
PGS is the exclusive provider of towed dual-sensor streamer technology, referred to as the GeoStreamer®. This uses co-located hydrophones and velocity sensors to explicitly measure both the total pressure wavefield and the vertical component of the particle velocity wavefield. It is consequently possible in processing to separate the up-going and down-going pressure and particle velocity wavefields.

These four datasets provide several unique opportunities for subsequent data processing and interpretation. The up-going pressure wavefield does not contain the receiver ghost that is present in all conventional (total pressure) seismic data. Thus, the reflection events are shorter, richer in both low and high frequency content, and have better resolution and event continuity. The removal of the receiver ghost through wavefield separation during the initial stages of data processing means that all stages of processing benefit from de-ghosted data. The up-going pressure and the down-going velocity wavefields can be used in the most accurate SRME implementation available, while the PGS dual-sensor SRME (surface related multiple elimination) predicts surface related multiples that automatically acknowledge non-flat sea surface and non-flat streamer, in contrast to 'conventional' SRME. Furthermore, the PGS dual-sensor SRME automatically incorporates an angle-dependent obliquity amplitude correction into the predicted multiple wavefield. Consequently, the primaries-only wavefield is more accurate after the adaptive subtraction of multiples.

Dual-sensor data can be processed to use any receiver datum, irrespective of the actual towing depth in acquisition. Thus, new GeoStreamer surveys can be precisely matched to existing legacy data, and can be used for 4D baseline or monitor surveys. Furthermore, several new and sophisticated data QC opportunities are created.

Operationally, the GeoStreamer is towed at a depth of at least 15m. Data acquisition is much less affected by operational and environmental noise, yielding higher signal-to-noise content at all depths in the seismic data. As wavefield separation in processing removes the effects of the receiver ghost, unwanted interference is reduced at all target levels. In contrast to conventional streamer data, the dual-sensor towed at 15m depth actually provides a double benefit: optimal data quality and resolution plus optimal operational performance.

Significant benefits of Geo-Streamer acquisition include extended bandwidth of high and low frequencies, enhanced resolution for improved imaging of stratigraphic traps, better penetration for imaging of deep targets, enhanced multiple attenuation, accurate determination of Q, and better signal-to-noise ratio. The extended bandwidth of GeoStreamer is essential for inversion and detailed reservoir characterization, with the additional low frequencies from GeoStreamer 'filling the gap' and providing a more data-driven inversion. GeoStreamer enables a more stable estimation of Vp/Vs ratios and subsequent fluid discrimination and litho-fluid analysis.



Schematic illustrating how the receiver ghost wavelet carries the unwanted sea surface reflection series in the down-going wavefield.

succession of Jurassic to Cenozoic age. The late Cretaceous to Cenozoic carbonate represents a major progradational cycle in which the shelf edge migrated northwestwards to the outboard limits of the Scott Plateau.

New Exploration Opportunities

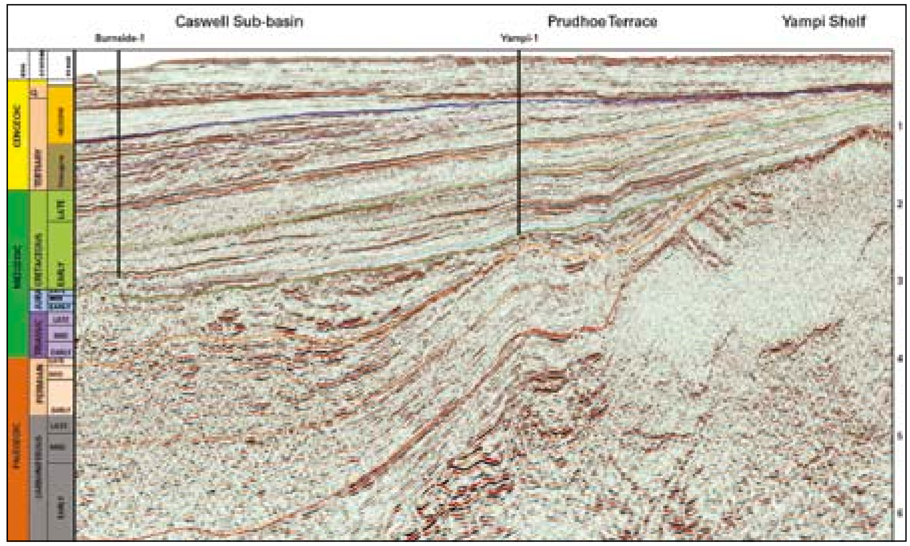
Exploration over the past forty years has established the Browse Basin as one of the most prospective basins in Australia, hosting significant multi-Tcf gas fields, condensates and, to a lesser extent, oil. The giant Ichthys Field (13.5 Tcf recoverable), under development by Inpex, is just 10 km to the north of the Aurora survey area. It also covers the Burnside discovery (65m gas column) which is currently being appraised by Santos, and lies on-trend with, and approximately 40 km southwest of, Ichthys. Other significant discoveries made during the mid-seventies include Yampi-1, which encountered numerous hydrocarbon shows and traces of residual oil. Evidence of the oil potential of the Yampi Shelf was demonstrated by the discoveries at Gwydion-1 (covered by the Gwydion MC3D survey) and Caspar-1 in the mid-nineties, which challenged the previous perception that the basin was a gas-prone province. These discoveries also proved evidence of long-distance migration from the mature kitchen areas in the Browse Basin depocentre.

The majority of the gas is sourced from Early to Middle Jurassic Plover Formation pro-delta shales and coastal plain shaly coals, whereas most of the oil-prone source potential is associated with Late Jurassic to Early Cretaceous transgressive marine shale sequences. Good quality reservoir sands are known to occur within the fluvio-deltaic Plover Formation as well as shallow marine sandstone reservoirs within the Late Jurassic to Early Cretaceous Vulcan and Echuca Shoals Formations. High quality Early Cretaceous stacked sandstone reservoirs were encountered in wells drilled on the basin's shallow eastern margin. The Prudhoe Terrace and Yampi Shelf are located on the migration pathway of known petroleum systems, as proven by the Ichthys, Burnside, Gwydion and Cornea discoveries.

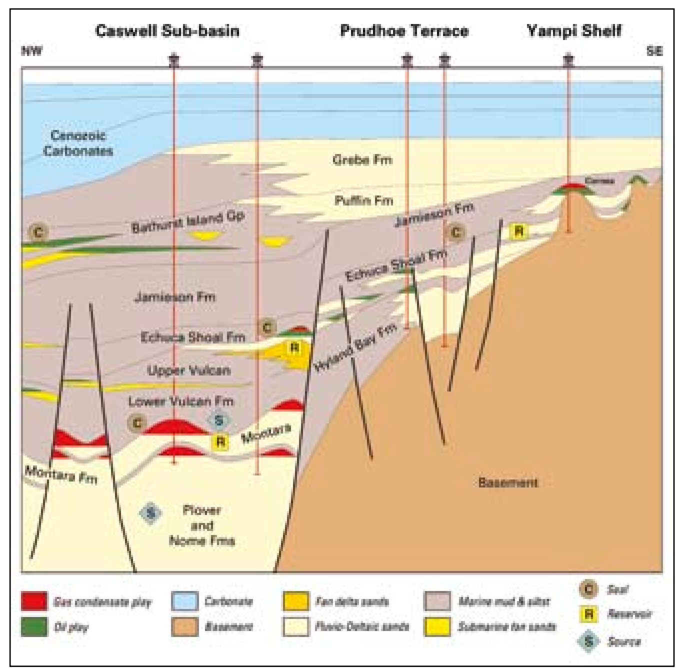
Hydrocarbon accumulations have been encountered in both structural and stratigraphic plays within Jurassic horsts/tilted fault blocks and associated drape features, and late Jurassic to early Cretaceous drape of erosional basement highs on the eastern margin of the Yampi Shelf. Other potential play types include shallow marine Tithonian to Berriasian sandstone onlap/pinchout plays on the Prudhoe Terrace and Yampi Shelf. Late Jurassic to early Cretaceous claystones within the Vulcan and Echuca Shoals Formations provide the regional seals throughout much of the basin.

Although a working petroleum system and migration have both been established on the Yampi Shelf and adjoining Prudhoe Terrace, the area remains thinly explored and offers good potential for new discoveries. High-quality 3D seismic surveys such as Aurora and Gwydion provide a key exploration tool for identification of additional valid structural and/or stratigraphic traps with access to charge. New broadband technology with increased resolution and deeper penetration has enabled detailed reconstructions of the migration pathways and recognition of more prospective play fairways.

Exploration of stratigraphic plays towards the basin margin benefit from GeoStreamer's higher bandwidth resolution. Improved penetration and high resolution imaging of the thick Paleozoic section underlying the main break-up unconformity, particularly the superior imaging of deeper Permo-Triassic fault blocks, will assist in evaluation of these untested plays. In addition, a consistent dataset calibrated to wells and suitable for quantitative attribute analysis can support a new phase of exploration around the Browse eastern margin. ■



Aurora MC3D composite line across the Caswell Sub-basin, Prudhoe Terrace and Yampi Shelf tying Burnside-1 and Yampi-1 wells.



NW-SE oriented cross-section across the eastern Browse Basin illustrating the main play types covered by Aurora and Gwydion MC3D surveys in the Caswell Sub-basin, Prudhoe Terrace and Yampi Shelf. (Modified from Martin, 2008.)

The Arab Spring and the Oil Industry

What has been the impact of recent political developments in North Africa on the oil and gas industry?

MOHAMED ZINE, IHS

The challenges facing the oil and gas industry in North Africa in the aftermath of the Arab Spring are many, ranging from the impact of the struggles on the relationships between international oil companies and the local NOCs to efforts to identify further much needed resources.

Egypt: Supply and Transport Issues

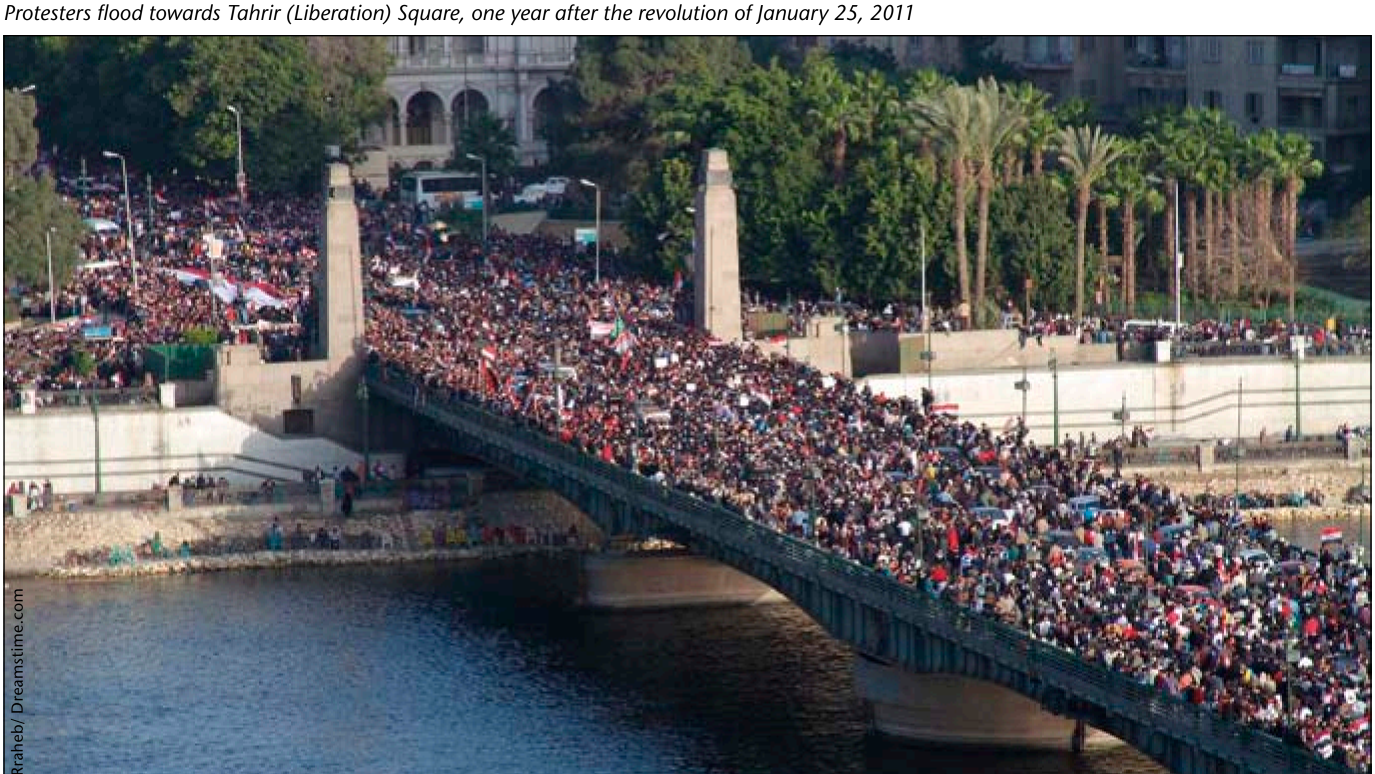
The power struggle that is smoldering in Egypt at the moment is clearly having knock-on effects on the oil and gas industry in that country.

Although gas production is expected to continue growing, a rise in domestic consumption (the country's population is already at 80 million) will result in a net decrease in the amount available for export. Oil and gas subsidies have increased ten-fold, from US$875 million in 1999 to US$8.7 billion in 2009, and are unlikely to be removed by any newly elected government clamoring for votes. Although in 2007, Mubarak's government increased the gas price from some Mediterranean Sea fields from US$2.6 to US$4.5 per MMBTU, around US$7 per MMBTU is the price needed to boost deepwater projects, so a number of projects were put on hold. With more discoveries needed to support the delayed projects, such as the Dammietta LNG Train 2 which was initially planned for 2009, Egypt's gas price and output is unlikely to change any time soon.

Egypt's appetite for oil may have increased; however, its production is declining. In 1993/94 the country exported 500,000 bopd, but with no major oil discoveries in 2009/10 (the average size of discoveries is around 20 MMbo) the country passed from being an exporter to an importer, and its slow decline in export is expected to continue.

There are also gas transport issues. The 1,200 kilometer-long, 35" Arab Gas Pipeline (AGP) exporting gas from Egypt to Jordan, Syria and Lebanon is planned to be extended the final 60 km from Homs, Syria to link up with the Syrian and Turkish pipeline network and ultimately on to Europe. However, the unrest in Syria is expected to delay the supply from reaching the European market in the immediate

Protesters flood towards Tahrir (Liberation) Square, one year after the revolution of January 25, 2011



future. Egypt has been selling its gas for US$2 per 1,000 cubic feet, less than half the market price, although negotiations to increase this to $6 have started with Jordan. And with recent major discoveries having been made in Israel and Cyprus, competition for gas markets in the region is likely to increase.

Egypt provides around 40% of Israel's gas imports through the Arish-Ashkelon pipeline. This has created a sensitive issue, with acts of sabotage halting exports for extended periods and general disapproval within the country. EMG and EGPC/EGAS have submitted a dispute for international arbitration whereby former Oil Minister, Sameh Fahmy, and five ex-officials are under investigation because of agreements to sell gas to Israel.

Although there has been no major impact on the international oil company's relationships with Egypt's NOCs, it is hoped that the departure of Sameh Fahmy and other long-serving managers at the top of the oil and gas sector within Egypt will create more transparency within the industry. For example, the new oil minister has proposed merging EGPC (Egypt General Petroleum Company) and EGAS (Egyptian Natural Gas Company) under one roof in the hope of decreasing bureaucracy for the IOCs. However, bid round processes and decision-making slowed down whilst the country awaited the election of a new government and the closing date has been extended to give IOCs more time for bidding. Ultimately, Egypt needs foreign investments, and efforts are being made to speed up the process.

There are still potential resources to be explored in Egypt. Onshore, there are the deep Jurassic and possibly Paleozoic resources in the Western Desert, while offshore exploration continues in the Ultra Deep Nile Delta. In addition, potential offshore resources exist in the Levant Basin and the Red Sea. No significant shale gas potential has been discovered so far, although more studies are needed.

The Arab Gas Pipeline from Egypt was due to be extended through Syria to Europe

Libya: Security Major Concern

Post-Gadhafi Libya is a small gas producer relative to its neighbors, Algeria and Egypt, despite its ambitions. Its only pipeline for export is 'Greenstream', jointly owned by Eni North Africa and the Libyan NOC, which goes from the Libyan coast to Sicily *(see map on page 64)*.

Unlike Egypt, Libya has suffered a full-scale war, so its issues are more logistical than political. Security is still a big concern – the Greenstream pipeline was stopped for eight months until operations resumed in November 2011 – and it continues to keep expatriate workers away. At the moment, there appears to be two possible scenarios that could play out within the country. The most likely (and favorable) scenario has fighters in the new army and police of Libya involved in the industry and the oil revenue fairly managed and distributed. A less likely (and worst case) scenario would be civil war breaking out in the country, with tribes fighting for power.

Before production can be resumed, the facilities need to be re-established. For example, the personnel camps need to be rebuilt, along with their telephone and Internet connections, and secure transport for expatriates to field locations also needs to be set up, as the old 4x4s, vital for moving around the desert, were all either confiscated by the rebels or destroyed by Gadhafi's army.

Previously, Libyan bid rounds were set essentially through competitive bidding for blocks every couple of years. Awards were based on getting the best financial deal for Libya whilst giving opportunities to worldwide IOCs, whose take was about 10%. It is unlikely that there will be changes in the terms of the agreements already signed by IOCs, because it will be against Libya's interest, which will upset the Libyan people. However, for the next round Libya may improve the terms, with lower bonuses and more stakes for IOCs in areas where drilling operations were unsuccessful, such as South Murzuq, Kufra, East Sirte, Gulf of Sirte and Cyrenaica.

Libya's shale gas potential resources are estimated at 1,145 Tcfg risked in place (290 Tcfg technically recoverable). There are potential onshore opportunities within the East Sirte Deep Gas Paleozoic play and offshore in the Pelagian Basin, the Gulf of Sirte and the Cyrenaica Basin.

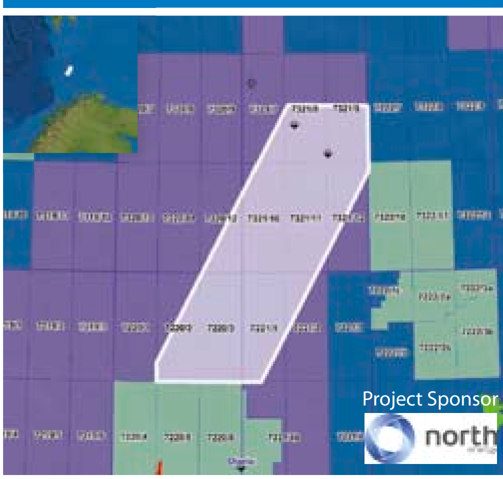
Tunisia: Little Impact on Oil Industry

Tunisia, the birthplace of the Arab Spring during December 2010, has suffered heavily from the unrest. Tourism, which employs more than a million people, has more than halved since the revolution. The country has also suffered from the unrest in Libya, which is a substantial market for and employer of Tunisians.

However, the oil and gas Industry has experienced little impact. Although protesters disrupted production at the Hasdrubal, Franig and Cercina fields, 2011 oil production

Gulspurv 3D Bjørnøyarenna Fault Complex

1,997KM^2 - Barents Sea - Norway



Dolphin geophysical Project Partner

The Gulspurv 3D Seismic Survey

- The Gulspurv 3D Seismic Survey overlies the highly prospective Bjørnøyarenna Fault Complex and is focussed for the 22nd Licensing Round in the Barents Sea.
- The key objective of the survey is to properly image the structure and stratigraphy within the shallow section. This will be achieved using a dense sampling interval and a high frequency air gun source (1300 cu. inch) that will produce high resolution data to facilitate a better understanding of the nature and geometry of the faulting and distribution of potential reservoirs, leading to more confident definition of potential hydrocarbon traps.
- The Fast Track Cube is ready for immediate delivery for evaluation of the 22nd Round Licensing blocks.

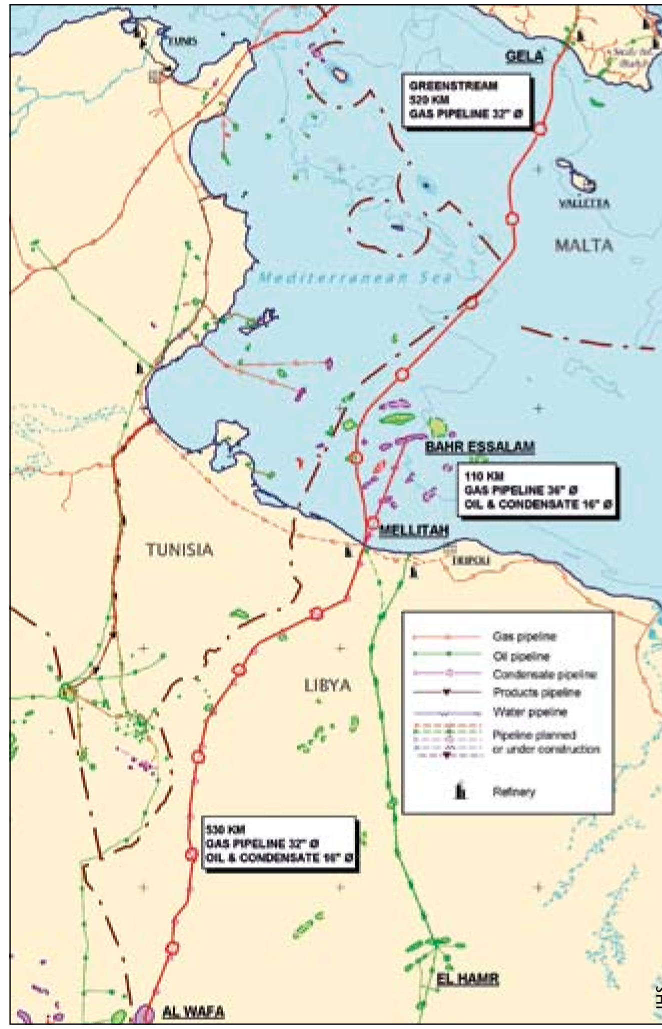
(70,000 bopd) was only down 10% compared to 2010 and the impact on the relationship with local NOCs is minimal. Fiscal terms that are among the best in Africa have also meant competitive profit margins, even though there are limited hydrocarbon resources in the country.

That being said, there are large unexplored areas in the offshore Pelagian Basin, with drilling expected to commence in 2013, and the complex Sud-Tellian zone has recently (re) attracted majors such as Shell and Repsol. Shale gas is also a possibility, with the Ghadames Basin resource estimated at 61 Tcfg in place, with technically recoverable resources estimated at 18 Tcfg.

Algeria and Morocco: No Significant Unrest

Hydrocarbons represent 60% of Algeria's income. Fearing an uprising similar to its neighbors', Algeria's government successfully initiated a number of reforms to avoid large protests. This meant that, apart from a few limited strikes, there was no significant unrest. The government plans to make changes that will bring more investors into the country and increase the role of the government-owned NOC, Sonatrach, in delayed projects. Correct incentives should attract investors, boosting the economy and hopefully avoiding more social unrest, although a recent corruption scandal involving Sonatrach's senior executives has added to the bureaucracy of this, delaying the decision-making process on some projects. This, combined with the domestic demand for gas increasing by 5–6% per year (from 988 Bcf in 2009 to an estimated 1.5 Tcf in 2019) may affect their ambitious projects for gas export. So, under pressure, Sonatrach are pushing for IOCs to complete projects.

Algeria needs to find more gas for its multiple export projects. At the moment there are potential resources in lower Paleozoic plays (Infra-Cambrian, Ordovician, Silurian, Devonian) in the Reggane/Tindouf Basin and Mediterranean Offshore. There are also potential resources for shale gas in the Silurian and Frasnian. Sonatrach estimate these resources to be 2,500 Tcfg (using Sonatrach geochemical modeling) although IHS estimates that less than 1,000 Tcfg is recoverable. These resources are located at the marginal zones of the Illizi, Ahnet-Mouydir and Reggane Basins, where the Hot Shale interval is more than 100m thick at a depth of between 1,000 and 3,000m, and displays TOCs over 10%. Potential prospective zones have been identified from preliminary regional mapping. Sonatrach is also drilling its first shale gas well in the Ahnet Basin.



The 'Greenstream' line from the Libyan coast to Sicily is the only gas export line from Libya.

Although there was some unrest in Morocco, it was something of a 'Quiet Revolution'. King Mohammed VI is still popular and little has changed since the Arab Spring.

Morocco has one of the most attractive petroleum legislations in the world and there has been a revival of exploration in the last five years, revealing resources both offshore (Miocene, Lower Cretaceous, Triassic and Jurasssic) and onshore (Triassic and Paleozoic). Shale gas resources are also estimated at 108 Tcf risked gas-in-place (18 Tcfg technically recoverable) with Repsol and Anadarko exploring for shale gas in the Paleozoic basins. However, the country still imports about 95% of its energy needs. ■

The narrow-gauge Red Lizard Railway, originally built to transport phosphate deposits, was a popular tourist attraction in Tunisia, but the tourist industry has been severely hit by the revolution

Tunisian National Tourist Office

South East Asia: Looking to the Future

Szefei/ Dreamstime.com

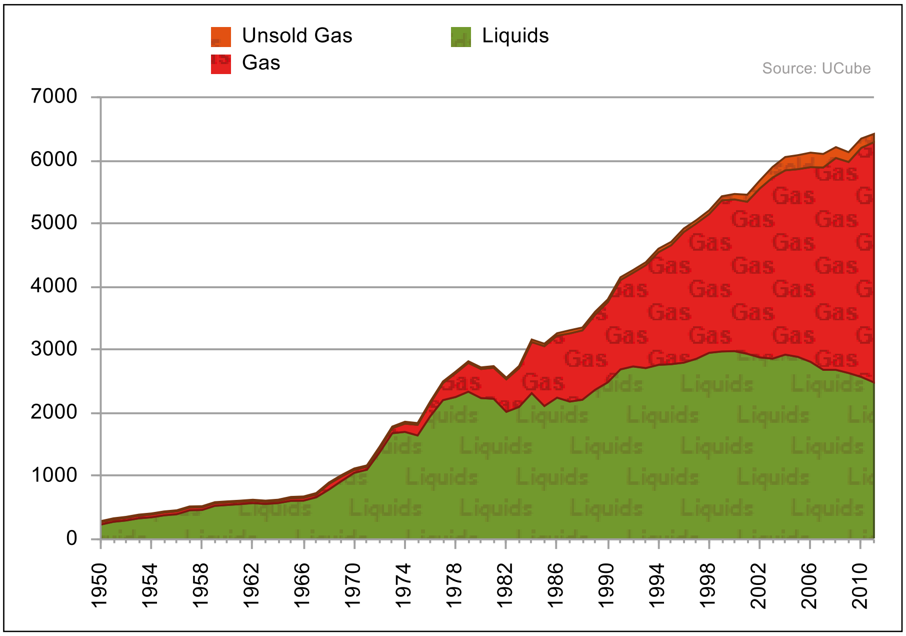
South East Asia, comprising the countries south of China, east of India, west of New Guinea and north of Australia, was an early starter in oil and gas exploration

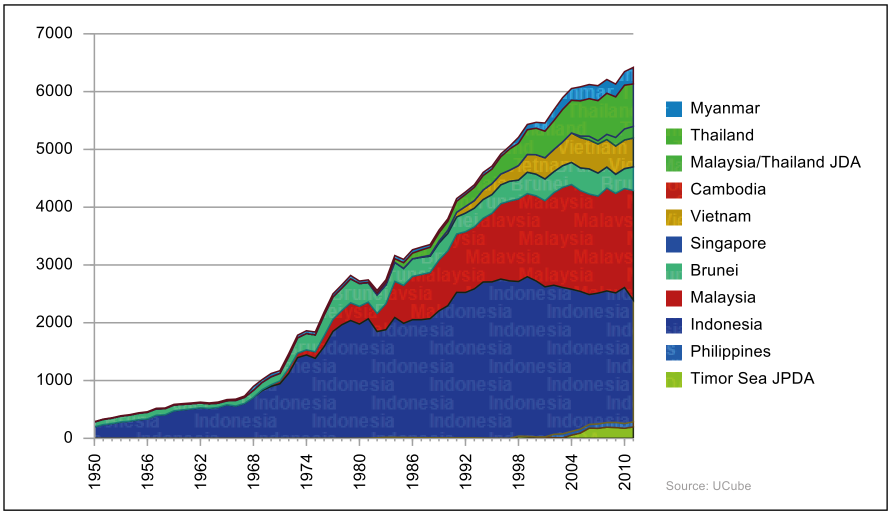
ARNE GULBRANDSEN
Rystad Energy

South East Asia is an important player in the hydrocarbon industry. It is very strategically positioned, with over half of the world's merchant fleet capacity passing through the Malacca Straits annually.

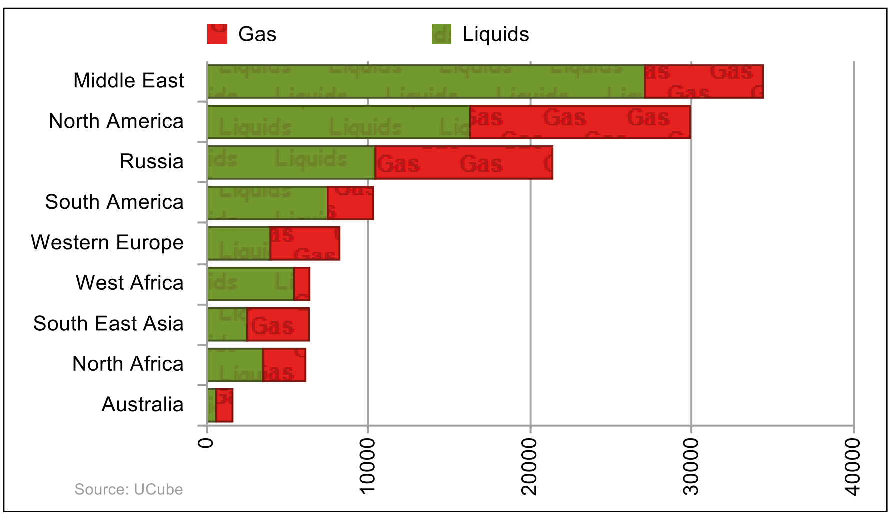
The region has been engaged in oil and gas production since the beginning of the last century, first and foremost in Indonesia and later also in Myanmar and Brunei. It was only when offshore exploration was fully introduced in the 60s that oil and gas production became notable in a significant country like Malaysia. And only during the recent decades has production started up in countries like Thailand, Vietnam and the Philippines. Traditionally, the focus of the region has been on oil production, but there has been a constant, strong growth in gas production since the beginning of the 70s. In 2011 South East Asia had an average oil production of just above 2.5 MMbopd and gas production of almost 3.7 MMboepd. Oil production has slowly been declining since its peak at the turn

Production history of South East Asia split by oil and gas (Mboepd)





Oil and gas production history of South East Asia split by countries (Mboed)



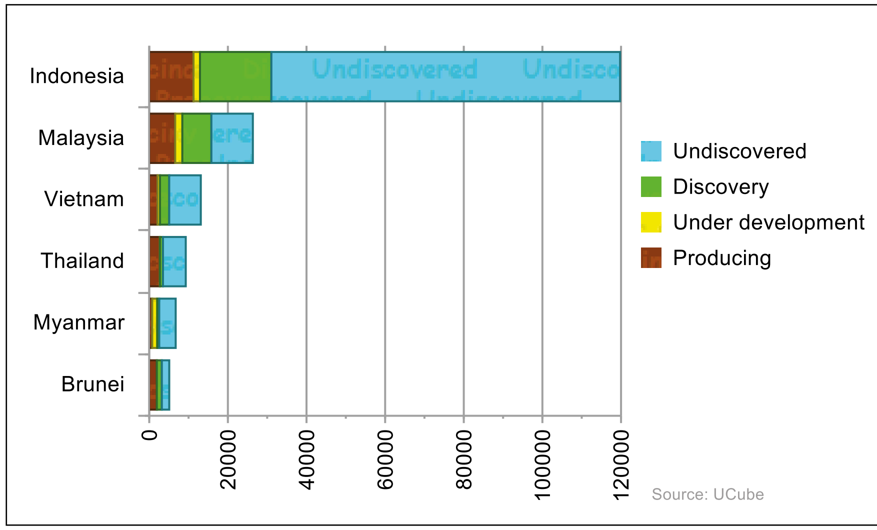
South East Asia 2011 oil and gas production compared with other regions of the world (Mboepd). Compared to global production, South East Asia is a relatively minor region. In 2011 oil production contributed to less than 3% of global production, whereas it is a more significant player when it comes to gas, with approximately 6.5% of global production. However, South East Asia plays an important role within LNG and the region is currently by far the largest LNG exporter in the world besides Qatar.

of the millennium, and gas production passed that of oil in 2005.

Moving Offshore

Since the introduction of offshore exploration and production in the 60s, South East Asia has gone through a remarkable transition from an onshore to an offshore-focused region. In 1965 the offshore represented just 2% of total production, rising to 50% by 1985, and by 2011 more than 80% of oil and gas production came from offshore fields, the highest offshore share in the world. With emerging new technologies South East Asia has also moved to deepwater production (>125m), and from the startup of the first main deepwater field in Malaysia in 1996, deepwater production now makes up more than 10% of the offshore production, with an increasing trend.

The number and size of companies operating in the region is quite different between the countries, reflecting when in history oil and gas exploration commenced. In Indonesia, where exploration started early, majors and other international companies have traditionally had a much higher share of production than Pertamina, the national oil company, and other domestic companies. At the same time the country has allowed a very large number of companies, more than 200, to operate in it. For Malaysia, however, where production commenced in the



South East Asia reserves and resources by country and production status (MMboe)

60s, the situation is quite the opposite, with Petronas, the national oil company, controlling about 50% of the working interest production. In total less than thirty companies are active in the country. However, Malaysia is now trying to motivate the creation of new domestic companies as well as inviting international companies to take over tail-end production of selected fields from Petronas, as well as explore for new resources in the country.

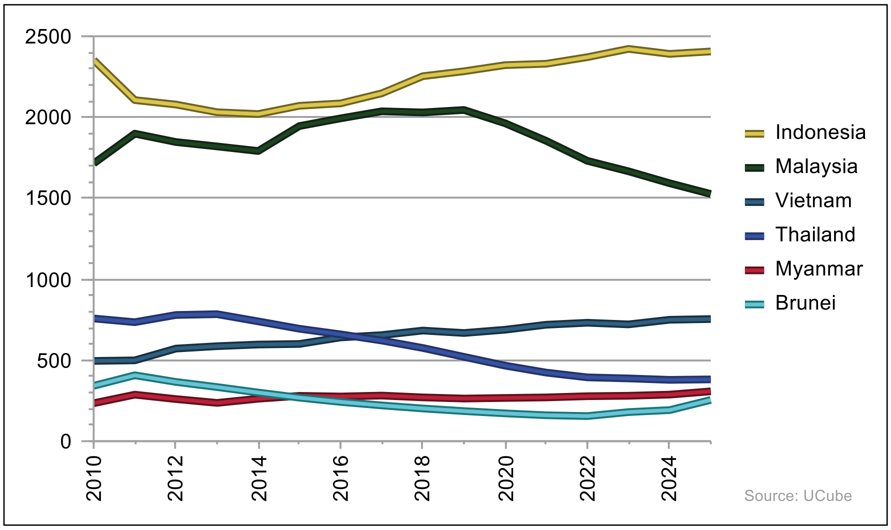
Looking at the entire South East Asian region, in 2011 international oil companies held a 60% share of production. The largest producer in the region in 2011 was Petronas, while the largest international players are Chevron and Shell, who have chosen different countries for their main focus. All seven supermajors are present in the region to a lesser or greater extent, which generally is regarded as a positive sign.

Looking Ahead

Looking forward, South East Asia is expected to have a relatively stable rate of total oil and gas production, staying above the 6 MMboepd mark for the coming years. The strong growth in gas production in the past has now flattened out and will instead show a small decline, whereas oil production is anticipated to remain stable. The main challenge for the region is that current producing fields will experience a steep decline from 2013, so maintaining current production levels will require the development of many new fields as well as future exploration success. In addition, the shift towards offshore and deepwater will continue, making future developments more technically and financially challenging. On the other hand, most hydrocarbons are probably conventional, reducing uncertainties and costs for future exploration and developments.

With regard to remaining reserves and resources, Indonesia offers by far the largest opportunities, holding an estimated 63% of total remaining volumes within the region. In fact, Indonesia is among the top ten countries of the world with undiscovered resources, the majority of which are located in still unawarded and rather remote areas. Even if one ignores the risked but more uncertain undiscovered volumes, Indonesia still accounts for 48% of the undeveloped resources of the region.

For the entire region it is positive that the portfolio of remaining reserves and resources consists of a mix of producing fields, new developments, a high number of discoveries and a very large exploration upside, all of which will be important in order to maintain oil and gas activities and to attract more international players in future. Bearing in mind that the development of undiscovered resources in Indonesia lies many years ahead, Malaysia is expected over the next seven to eight years to have almost as high oil and gas production as Indonesia. However, from approximately 2020 onwards Indonesia, building on its high growth potential,



South East Asia oil and gas production forecast by main countries (Mboepd)

will again become the clear number one country within the region.

Main Fields and Projects

In many regions of the world the era of relatively few but large fields is being replaced by a high number of small fields going forward. In South East Asia this is only partly true, since the region traditionally has always had a high number of relatively small fields, with only a handful of them reaching more than 50,000 boepd. Going forward, more than 100 new fields are expected to be developed during the remainder of the decade, but with average production of not more than 30,000 boepd. This may discourage large international companies from investing in the region, but on the other hand it may well attract a high number of smaller oil and gas companies as well as start-up firms to the region.

The largest producing fields for the coming period are Vorwata, Tunu and Duri in Indonesia and Bayu/Undan in the Timor Sea joint development area between East Timor and Australia. The largest new development projects are Gumusut-Kakap in Malaysia and Hai Thach (Sea Stone) in Vietnam, both starting production in 2013. Behind these follow a number of small to medium sized discoveries, primarily in Indonesia and Malaysia. As one can understand, in terms of discovered volumes, the two latter countries are the places to be, even though Vietnam, Thailand and Myanmar have a relatively interesting exploration upside.

The large number of existing and new fields in the coming years in the South East Asia region is good news for the oil service industry. The region will experience a very strong growth in E&P spending over the next four years, with the strongest growth taking place in offshore drilling and subsea installation, reflecting the increased offshore exploration and development in the region.

South East Asia will thus remain an attractive region going forward. In the immediate future we will probably see a growth in smaller companies attracted by the large number of small fields to be developed, as well as fields with tail-end production becoming available. In the longer view, Indonesia with its potential for a large volume of undiscovered resources should be particularly interesting for the super majors and other larger, international companies with offshore and deepwater competence. ■

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Reservoir Dynamics and the New Geophysics

DAVID BAMFORD

Why do time-lapse (4D) seismic surveys of producing reservoirs 'work' and why do we make observations from them that appear to be related to production?

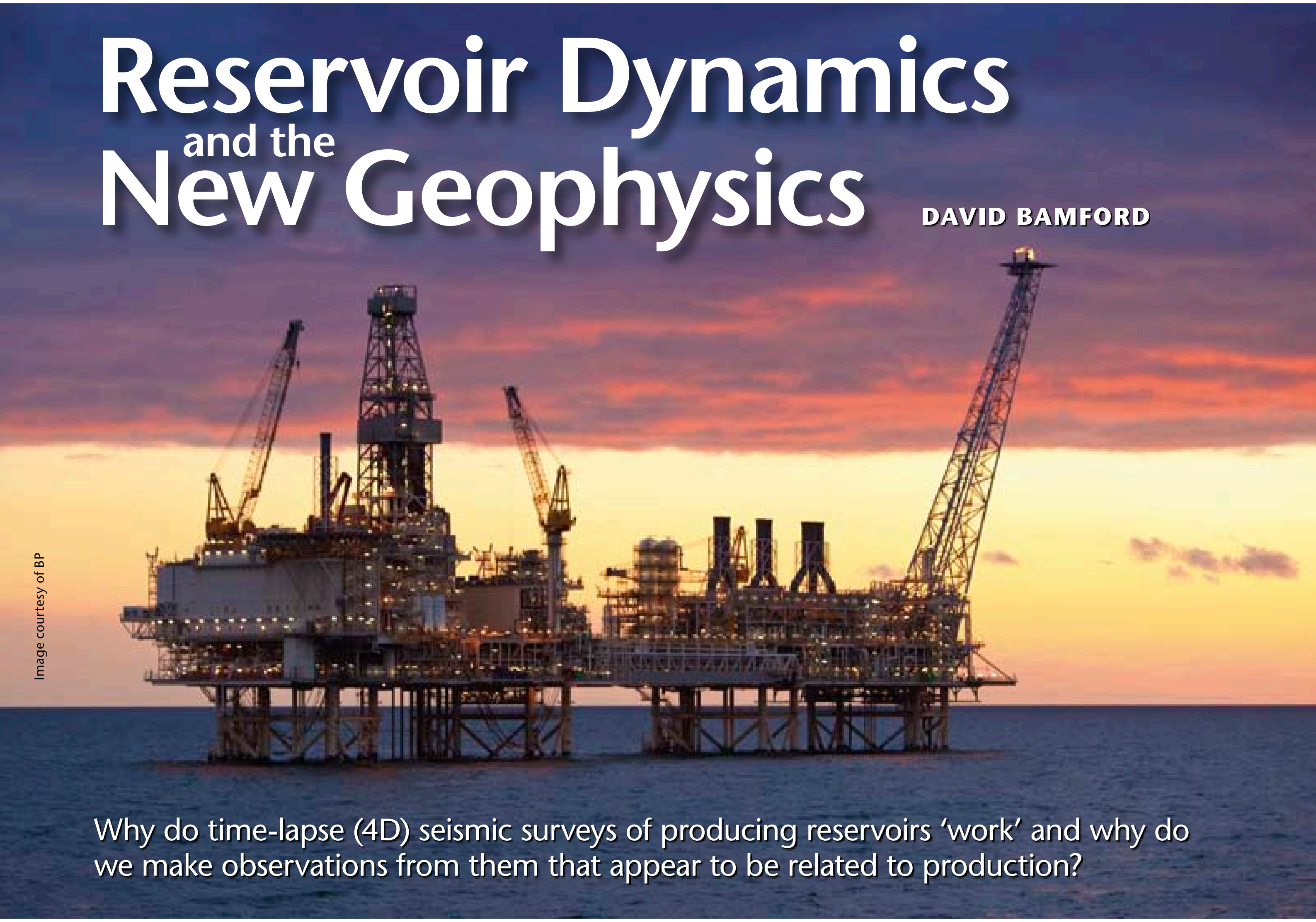


Image courtesy of BP

The Chirag Azeri Reservoir Surveillance Project (CARSP) involved the deployment of a semi-permanent seismic monitoring system over the Azeri Chirag Gunashli (ACG) Field, offshore Azerbaijan.

When a reservoir – any reservoir – is put under production, fluid compositions change; oil may be partially replaced by water or gas, gas may be expelled from oil, and so on. What is also significant is the fact that fluid pressures drop, changing the 'internal stresses' on the reservoir rock. Tempting as it may be, however, it is not possible to understand the (time-varying) geophysics of reservoir rocks by theorizing an isotropic pore space responding to fluid changes and changing 'internal stress'. So we need to step back, look at some simple models, and understand what we know about how reservoirs actually perform.

We can start with a relatively simple idea. Porosity and permeability in a granular rock can be understood simplistically using a 'billiard ball' model of grains and porosity: beginning with a hexagonal crack distribution, increasing differential horizontal (external) stress progressively results in aligned crack/fracture sets. Once established, these aligned micro-cracks are sensitive to changes in internal stress caused by production.

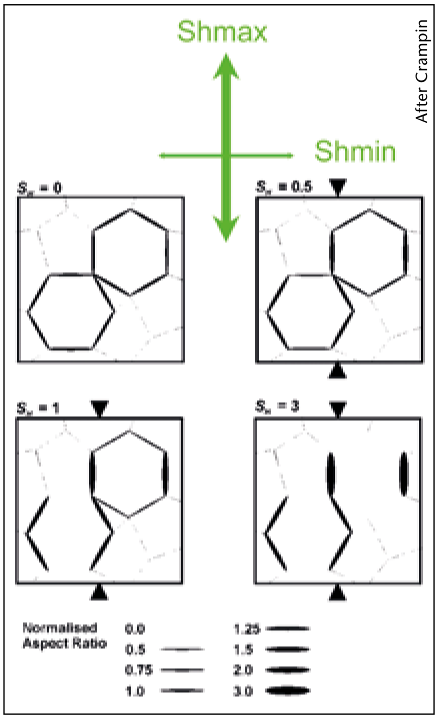
What evidence is there that such preferred orientation of micro-cracks exists in nature, in particular in reservoir rocks? In fact, there is significant evidence, from observations of producing reservoirs, from shallow (ground water) reservoirs, and from seismic observations.

Observations of Producing Fields

Several studies have shown that the hydraulic conductivities of faults and fractures in reservoirs can be influenced by geomechanical perturbations due to production operations and it is reasonable to anticipate that such dynamic permeabilities will be manifest as changes in flow-rates at production and injection wells. Heffer and co-workers (Edinburgh University) have shown that statistical correlations in flow-rate fluctuations between wells from fields in the North Sea appear to bear out this expectation. They are characterized by high correlations over very large separation distances between wells, and appear to be stress- and fault-related.

Note that typically, for a field with many injectors and producers, only a subset of wells are required in order to 'explain' the production at a subject well as required by the principle of parsimony; and that many of the correlated wells are at large distances from the subject well – not just nearest neighbors apparently influencing it.

Heffer has proposed that the most



Aligned cracks/fractures occur as differential horizontal stress increases

likely geomechanical mechanism to explain such orientational characteristics of correlations relative to stress state is dilatation or compaction of aligned compliant fractures in en echelon patterns and at critical densities, also previously proposed by others as active in the nucleation of shear failure.

Those characteristics are not consistent with the assumptions of most reservoir simulators; they are, however, characteristics to be expected in a system of coupled fluid flow and geomechanics near a critical point. Rather than just pure Darcy hydraulic flow between wells, there is probably a complex mixture of diffusive and wave propagation in a coupled system with long-range spatial and temporal correlations which incorporate the heterogeneities of pre-existing faults and fractures as well as being influenced by the modern day stress state.

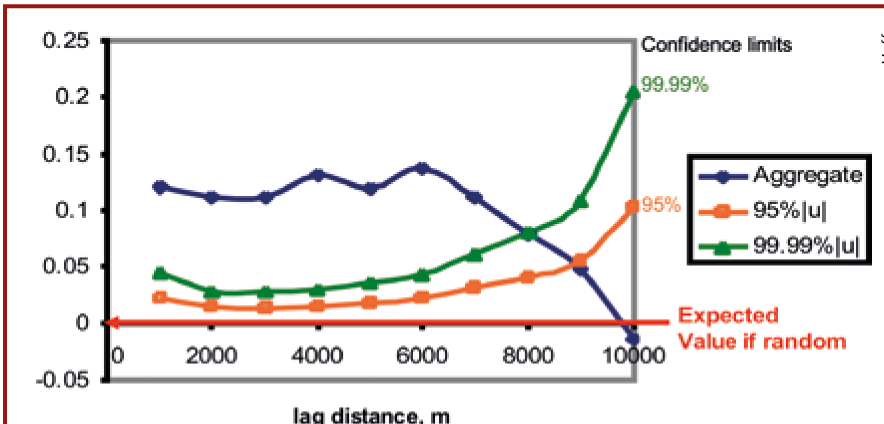
This mechanism is also consistent with an independent empirical feature of production data: the observed frequencies of directionalities in flooding schemes. Beginning with evidence from fields under secondary recovery, it has been known for some time that the directions that injected fluids prefer to take through a reservoir from an injector well to breakthrough at a producing well tend to align on average with the local orientation of the maximum horizontal stress axis. For 37 field cases, taken from reservoirs which would not be conventionally considered as naturally fractured, the orientational distribution of the preferred directions shows this pattern. The interpretation is that the stress perturbations due to the flooding operations, those from fluid pressure changes and from temperature contrasts of the injected fluid from the in situ reservoir temperature, change the conductivities of the faults or smaller scale structure, with greater conductivity being induced on those fractures at small angles to the max horizontal stress. Numerical modeling of the geomechanics, coupled with fluid flow simulation with this concept as a guide, results in a very similar pattern in the rock deformation around a single injector. In summary, the orientation of well pattern relative to permeability axes can change recovery factors by 10's of percentage points (Caudle *et al.*, 1960).

These behaviors – directionalities in flooding schemes and coupled fluid flow and geomechanics near a critical point – are commercially profound, capable of major impact on recovery factors, but ones that conventional reservoir simulators are not able to handle.

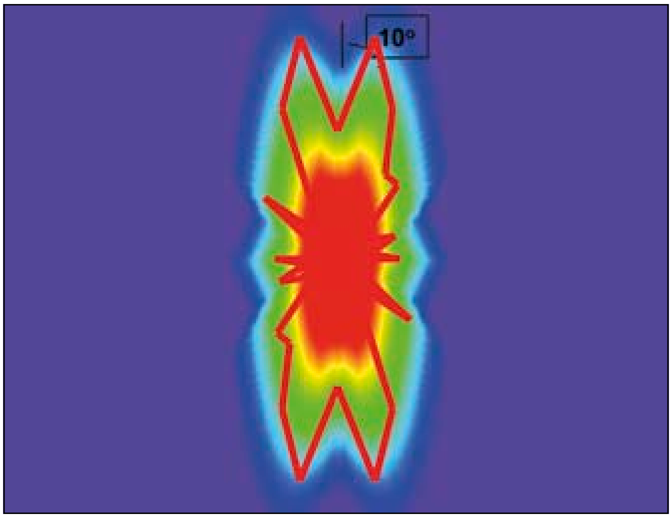
Observations of Shallow Reservoirs

Less well known to the oil and gas industry are studies of the effects of fractures and micro-pores on aquifers and possible directionally-varying contamination of ground water by salinity or pollutants. Cook (2003) provides a comprehensive review and Chen *et al.* (2011) provide a recent example.

Quite modest geophysical experiments reveal these effects. For example, Nunn *et al.* (1983) used the then recently developed modifications of conventional seismic refraction and electrical resistivity techniques to measure in situ P-wave velocity and electrical resistivity anisotropy of chalk at sites in north Lincolnshire (the chalk being overlain by a thin covering of drift). All sites showed significant anisotropy with the directions of the maximum observed velocity and resistivity



Aggregation of five North Sea fields – long-range correlations, zero lag time (detrended rate data). A remarkable feature of the correlations is their long-range nature. This characteristic is common and fairly robust. Large correlation coefficients have been observed between the rate histories of widely separated wells in ~10 fields. For Spearman rank correlation coefficients, the probability of true correlation can also be estimated (complementary to the probability that a particular value of correlation coefficient might have been obtained by chance with random data). This figure shows the average value of the probability of correlation between the flow rates at all of the well-pairs within five fields in the North Sea, binned according to the distances between each well pair. A constant expected value of 0.5 has been subtracted from all points such that the resultant average value would be close to zero for 2 random time-series. Also indicated are the 95% and 99.99% confidence limits for random data. It is seen that the null hypothesis of random data can be very confidently rejected for all lag-distances between well-pairs out to ~8 km, implying that the correlations are very significant to those large distances. Beyond that distance the data availability is insufficient to demonstrate any significance. The long-range correlations are found despite the fact that, in comparing the rates between any two wells, no lag-time is included (i.e. each month of production rate at one well is compared with the same month's production at the paired well). Only if permeabilities were consistently about 1,000 mD could the observation of significant correlations to a separation distance of 8 km be explained by Darcy flow alone. Even at such unlikely levels of consistent permeability one would expect more decay in correlations with distance than is observed.



A model of a flood progressing through dilatant rock of medium permeability (after Heffer). For more information please refer to Kes Heffer's papers on http://www.reservoir-dynamics.co.uk/publications

being consistent with direct fracture observations made at quarries in the study area; significantly, high fracture densities were implied. This work followed on earlier studies by Bamford and Nunn (1979) where similar P-wave anisotropy results had been obtained on the Carboniferous Limestone of north-west England, rooted in techniques developed by Bamford (1977) that demonstrated P_n velocity anisotropy in the continental upper mantle.

A New Geophysics

These observations of both deep and shallow reservoirs lead to the conclusion that time-lapse geophysics – any observations of any producing reservoirs over time – must be based on the understanding of the physics of fluid-filled, parallel, compliant, fractures/micro-cracks, dilating or compacting as the reservoir is produced. This 'new geophysics', documented over many years by Crampin, is based especially on understanding and observing the effects of closely-spaced stress-aligned fluid-saturated micro-cracks on seismic shear-wave splitting (SWS) in the crust and upper mantle. Whereas P-waves are in both theory and observation only weakly sensitive to such crack systems, SWS is wholly determined by parallel micro-cracks and can be measured with first-order accuracy. Thus SWS is a second-order quantity (small changes in shear-wave velocities) that can be read with first-order accuracy – leading to tremendous resolution.

Thus P-wave reflectivity, the basis of all our conventional reflection seismic technology, whether 2D, 3D or 4D, is not sensitive to rock anisotropy. P-wave velocity anisotropy and, most significantly, shear-wave splitting, are proffering a methodology for the new geophysical characterization of real rocks.

The Case for Permanent Reservoir Monitoring

The notion that reservoirs, having experienced a maximum horizontal stress over geological time scales, will contain micro-cracks that are both aligned and at a critical density – thus responding rapidly to quite small pressure changes induced by injection and production – has significant implications for geophysical, especially seismic, monitoring of reservoir dynamics.

Firstly, we can say that conventional 4D seismics only discern changes in P-wave reflectivity and thus offer at best an incomplete view of reservoir dynamics – one that is unquantifiable, allowing only empirical or 'phenomenological' comparisons. This answers my opening question but necessitates a follow-up statement.

And so, secondly, a complete, predictive, quantifiable, view of reservoir dynamics requires 3C seismic acquisition, with probable reservoir volatility strengthening the case for frequent measurement, i.e. permanent installations.

Finally, changes in stress can be monitored by changes in SWS so that stress-accumulation before fractures in reservoirs (and earthquakes and volcanic eruptions) can stress-forecast the time, magnitude, and estimated location of impending fractures (and earthquakes and eruptions). This is of course relevant to the practise of 'fraccing' and associated seismic activity. ■

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Stuart Crampin's website: http://www.geos.ed.ac.uk/homes/scrampin/opinion/

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Bamford, D. & Nunn, K., 1979: In situ measurements of crack anisotropy in the Carboniferous Limestone of Northwest England, Geophysical Prospecting, Volume 27, Issue 2, pp.322–338.

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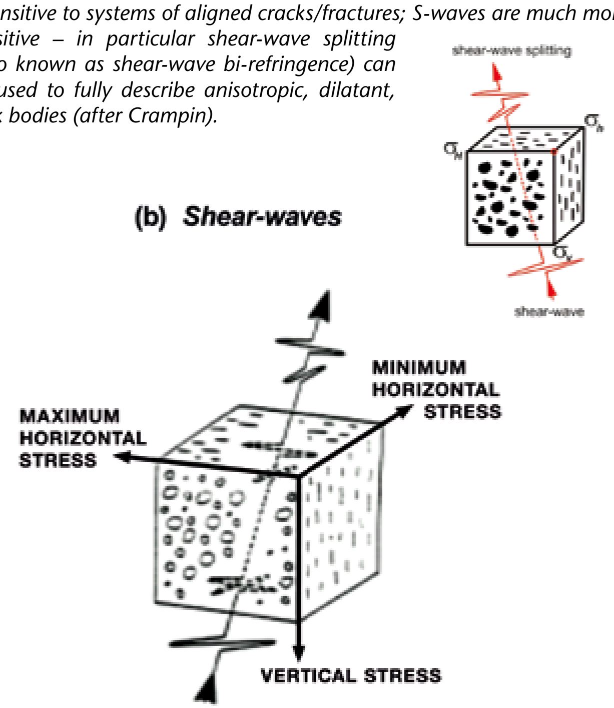
Chen, Z., Grasby, S.E., & Osadetz, K.G., 2011: Geological controls on regional transmissivity anisotropy, Geofluids, Volume 11, Issue 2, pp. 228–241.

Cook, P., 2003: A guide to regional groundwater flow in fractured rock aquifers, published by CSIRO, Australia, 115pp.

Nunn, K.R., Barker, R.D. & Bamford, D., 1983: In situ seismic and electrical measurements of fracture anisotropy in the Lincolnshire Chalk, Q.J.eng.Geol.London, Volume 16, pp.187–195.

Seismic consequences of dilatancy: P-wave reflectivity is relatively insensitive to systems of aligned cracks/fractures; S-waves are much more sensitive – in particular shear-wave splitting (also known as shear-wave bi-refringence) can be used to fully describe anisotropic, dilatant, rock bodies (after Crampin).

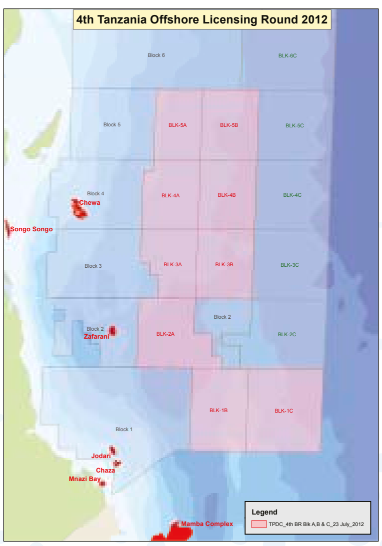


THE UNITED REPUBLIC OF TANZANIA

Announcement

4th Tanzania Offshore Licensing Round 2012

The Government of the United Republic of Tanzania, through Tanzania Petroleum Development Corporation, is pleased to announce the 4th Tanzania Offshore Licensing Round 2012 to be launched on the 13th of September, 2012, just after the HGS/PESGB Africa Conference to be held in Houston, Texas USA. The licensing round will include nine (9) offshore deepwater blocks in water depths of 2000m to 3000m. **ION GeoVentures will manage the logistics of the licensing round on behalf of TPDC.**



New deep offshore blocks

ROADSHOW SCHEDULE

13th to 14th September 2012, Houston, USA
After the 11th HGS-PESGB Conference on African E & P

20th to 21st September 2012, Singapore
After the AAPG ICE

22nd to 23rd October 2012, London, UK
Preceding the Geological Society East Africa Conference

6th to 8th February 2013, Arusha, Tanzania
After the East Africa Petroleum Conference

Bid Round Closes 15 May 2013

For additional information, please contact:

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F: +44 01293 556080
W: westerngeco.com

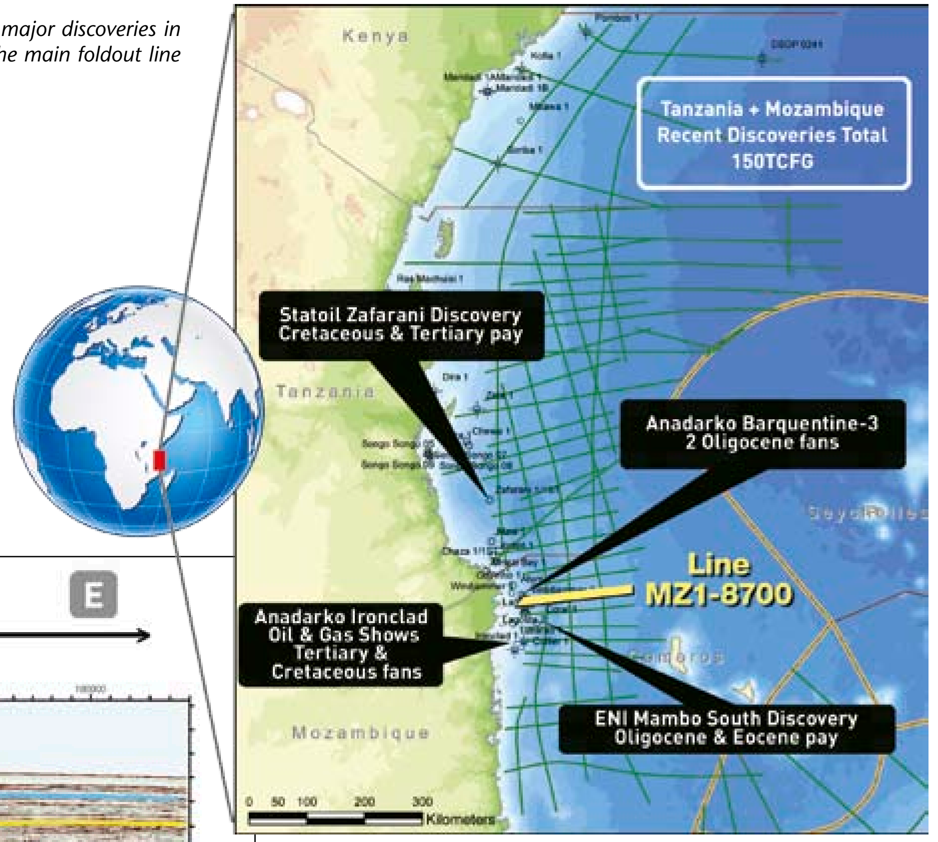
www.tz-licensing-round.com

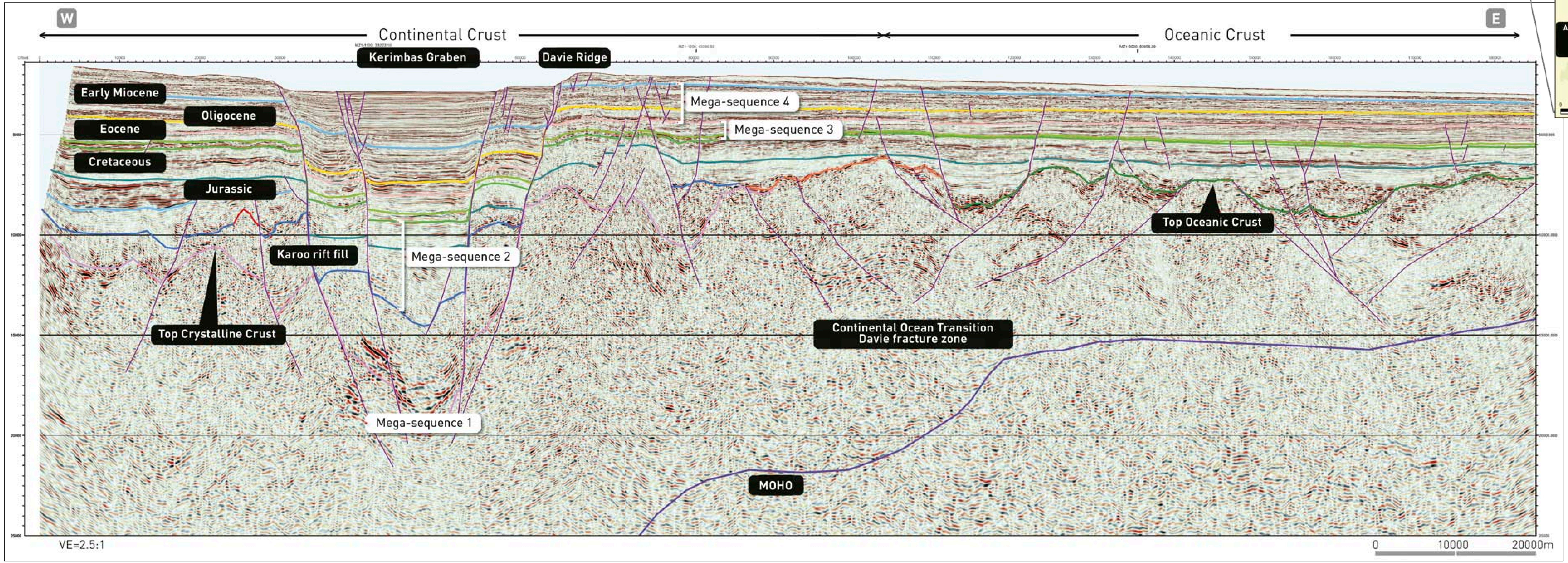
Deepwater Fans Across a Transform Margin, Offshore East Africa

The East AfricaSPAN™ surveys straddle the continent-ocean transition (COT) along the western and southern transform margin of the Somali Basin. Madagascar was rifted away from the Somali coast and translated southward relative to mainland Africa during the breakup of Gondwanaland. The eastern portions of the lines image oceanic crust and overlying Jurassic and younger sediments of the southern part of the Somali Basin. The inboard part of the survey captures Jurassic and younger sedimentary section where it overlaps continental basement and its Karoo cover. The lines reveal the prospective continent-derived sedimentary section, which built seaward to form the hydrocarbon habitat for the new offshore discoveries.

A new 8,620 line-km addition to ION's East AfricaSPAN long-offset seismic program infills previous Tanzanian datasets and extends the program into the area of prolific gas discoveries in northern Mozambique. This Phase III survey images the transition from a continental shelf to the open oceanic Somali Basin between East Africa and Madagascar. That ocean basin is filled with a thick Jurassic to Cretaceous sedimentary section derived from the surrounding landmasses.

Map showing location of recent major discoveries in East Africa and the location of the main foldout line shown here.





Line MZ1-8700 of the East AfricaSPAN seismic program reveals structural and stratigraphic details of an emerging deepwater fan play. Analysis reveals four phases of basin evolution and associated exploration play configurations:

Mega-sequence 1. *Syn-rift, Permo-Triassic to Early Jurassic extension with early rift fill; deposition localized in mini-graben; commonly topped with high-amplitude, laterally continuous seismic reflections (potential mature source rocks).*

Mega-sequence 2. *Transform margin, Late Jurassic to Mid-Cretaceous early drift sequences: restricted anoxic shales overlain by multiple, high-gradient regressive pulses comprising mounded, variable-amplitude reflection character (proximal slope channel/fan systems).*

Mega-sequence 3. *Passive margin, Late Cretaceous to Eocene late drift sequences: widespread transgressive shales encasing retro-gradational channel/fan reservoir systems.*

Mega-sequence 4. *East Africa uplift, Late Paleocene to Miocene multiple regressive successions: widespread, multi-phase submarine fan deposition – the current Paleocene, Oligocene and Eocene target reservoirs.*

A Developing Province

East Africa has undergone extension since the Neogene, as reflected in its spectacular and famous rift system. The eastern branch links to currently active structures in the coastal region, and thus is imaged in the SPAN surveys. Associated uplift of East Africa created an impressive plateau that furnished copious amounts of sediment to the coastal basins via several world-class rivers. The result was widespread deepwater fan complexes developing down slope from the major deltaic influx.

AL DANFORTH, JAMES W. GRANATH, JON S. GROSS, BRIAN W. HORN (ION Geophysical); **KATIE-JOE MCDONOUGH** (KJM Consulting, LLC); **EDWARD J. STERNE** (Independent Consultant)

The USGS assesses resources in the East African region at 27.6 Bbo, 441 Tcfg and 13.77 Bb of natural gas liquids (Brownfield *et al.*, 2012) including the Tanzania-Kenya and Mozambique Coastal provinces, West Madagascar and the Seychelles. At the time of writing, discoveries of approximately 150 Tcfg have been announced in Tanzania and adjacent Mozambique, making this an emerging world-class petroleum province. Exploration success rates have been remarkable, with 25 announced discoveries out of 27 offshore wells. Additional success, with the possibility of an oil-prone area, is anticipated. Leasing and drilling continues along the coast and into deeper water. The recently announced Tanzanian bid round will constitute the next exploration phase in this region.

Coastal Tanzania hosted hydrocarbon discoveries as early as 1974; the Songo Songo Field currently supplies gas to Dar es Salaam. The 1982 M'nazi Bay Field is slated for development via a second pipeline. In deepwater Tanzania there have been 7 gas discoveries (of 8 attempts) since 2010. The most recent announcements put gas reserves in Tanzania at 24 to 26 Tcfg, with more wells planned and in progress. In Mozambique, 17 of the 19 exploration wells have been completed as commercial gas discoveries by Anadarko and ENI.

Much of this emerging province remains unexplored and basin modeling suggests it may yet yield discoveries of liquids.

Structure of Survey Area

The East AfricaSPAN surveys are designed to image crustal architecture as well as structure and stratigraphy within the overlying sedimentary package. Thus, the deep parts of the lines capture classic seismic expressions of the Moho, fossil spreading centers, oceanic and continental crust transition (COT), faults bounding Karoo-age rifts and transform faults within oceanic crust (see foldout, previous page). The shallow portions of the lines show reactivated faults that cut into the overlying sedimentary package and in some cases to the ocean floor, major bounding faults along the margins of the Kerimbas Graben (see foldout), and a myriad of growth faults that cut the unstable delta lobes of the Ruvuma Basin. Any and all of these structures offer potential migration paths, as well as structural and stratigraphic trapping mechanisms.

The survey grid also allows regional-scale anticlines to be mapped. A spectacular example is the Davie Ridge, which straddles the international boundary between Tanzania and Mozambique. The structure consists of an east-plunging arch enhanced by the constructional lobes of the Ruvuma delta, which is cut to the west by the Kerimbas Graben. This immense and undrilled closure covers an area of approximately 400 by 200 km.

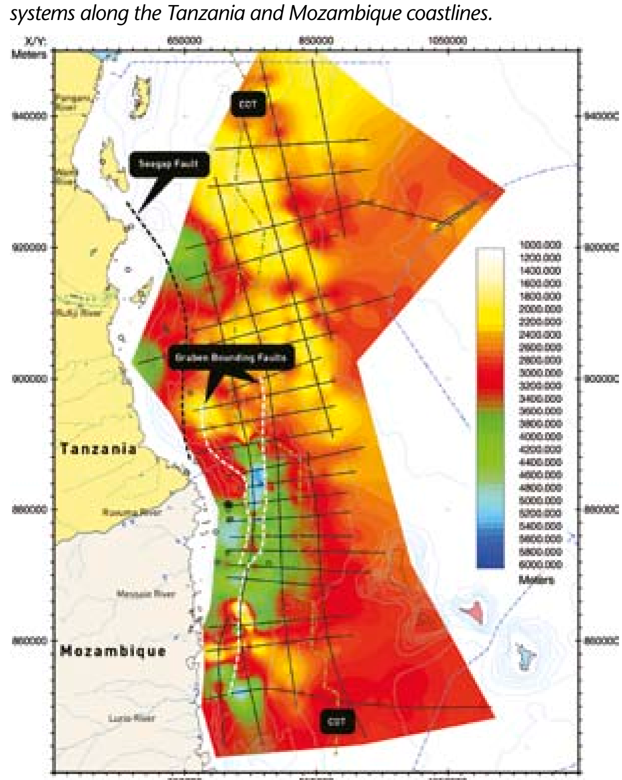
Prolific New Petroleum System

Large volumes of sediment were shed off the African craton from Late Jurassic through Miocene, punctuated by several major transgressions, leaving the critical components of a viable petroleum system present over the entire area. Multiple regressive pulses fed extensive deep sea fan complexes, which comprise current exploration targets. The resulting four tectonostratigraphic sequences reveal the basin margin evolution of offshore Mozambique and Tanzania (see foldout).

The four mega-sequences each comprise critical reservoir/source elements of a functioning hydrocarbon system. This configuration thus offers exploration potential at a minimum of four stratigraphic levels, only one of which has been tapped to date.

Play-opening deepwater reservoir systems have recently tapped into a prolific new petroleum system in offshore East

Early Eocene to Early Miocene regional isopach map, showing depositional loci for deepwater sediments related to deltaic input from the major river systems along the Tanzania and Mozambique coastlines.



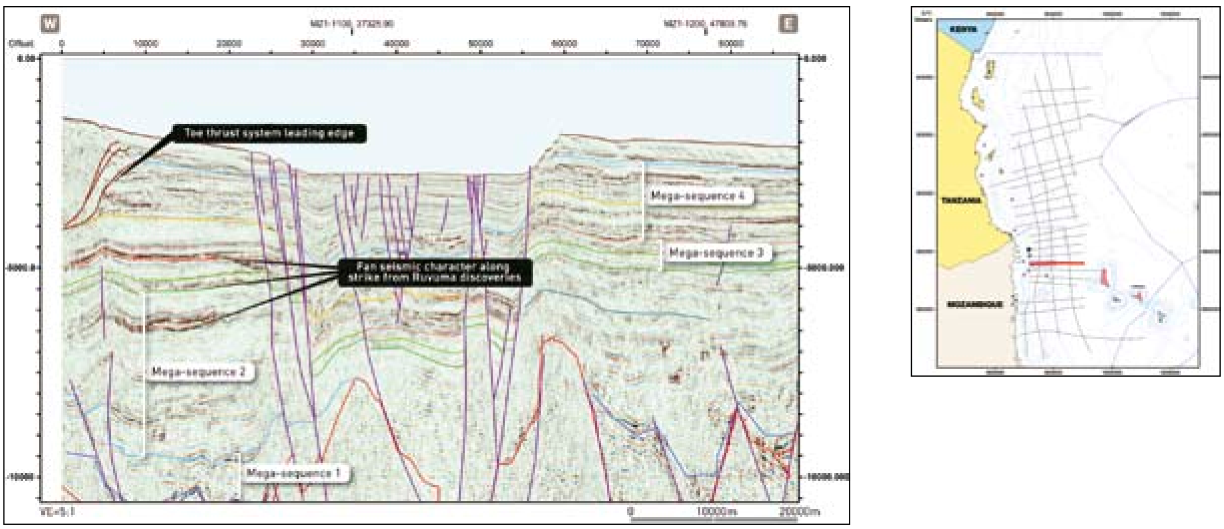
Africa. Drilling targets are Tertiary and Cretaceous deepwater channel/fan systems. ION Geophysical's East AfricaSPAN Phase III data not only highlight the regional structural and stratigraphic regime, but also discern Tertiary fan systems evolution at a remarkable level of detail.

Understanding the regional distribution of potential and proven reservoir systems, crustal type and thickness, basin evolution and heat flow across the region is essential to determining the ultimate potential of the area. Current basin models suggest that an oil play is likely in the deepwater areas, thus the next exploration phase in East Africa may prove to be even more successful. ■

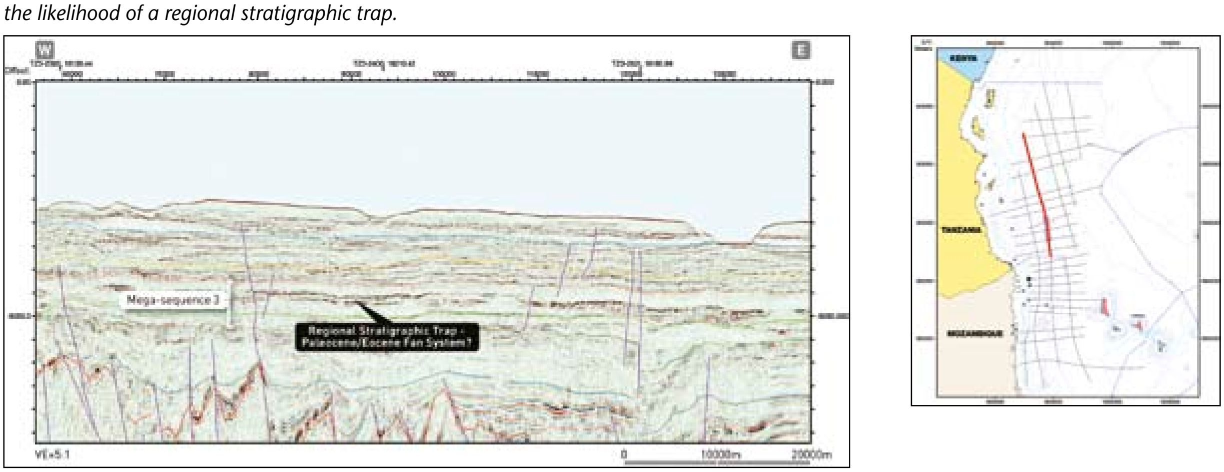
Reference:

Brownfield, M.E., Schenk, C.J., Charpentier, R.R., Klett, T.R., Cook, T.A., Pollastro, R.M., and Tennyson, M.E., 2012, Assessment of undiscovered oil and gas resources of four East Africa Geologic Provinces: U.S. Geological Survey Fact Sheet 2012–3039, 4 p. http://pubs.usgs.gov/fs/2012/3039/contents/FS12-3039.pdf.

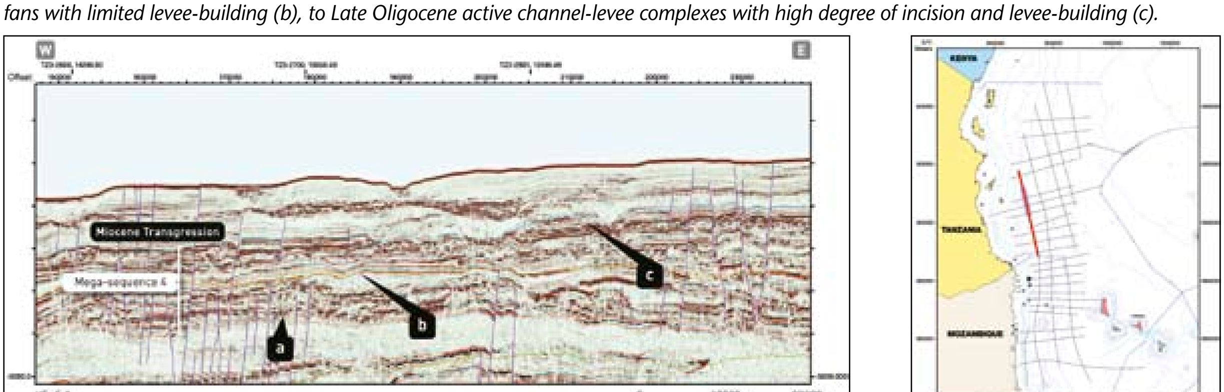
Dip Line. Late Cretaceous and Early Tertiary high-amplitude, mounded potential fan systems along strike and south of the recent Ruvuma Basin fan play discoveries.

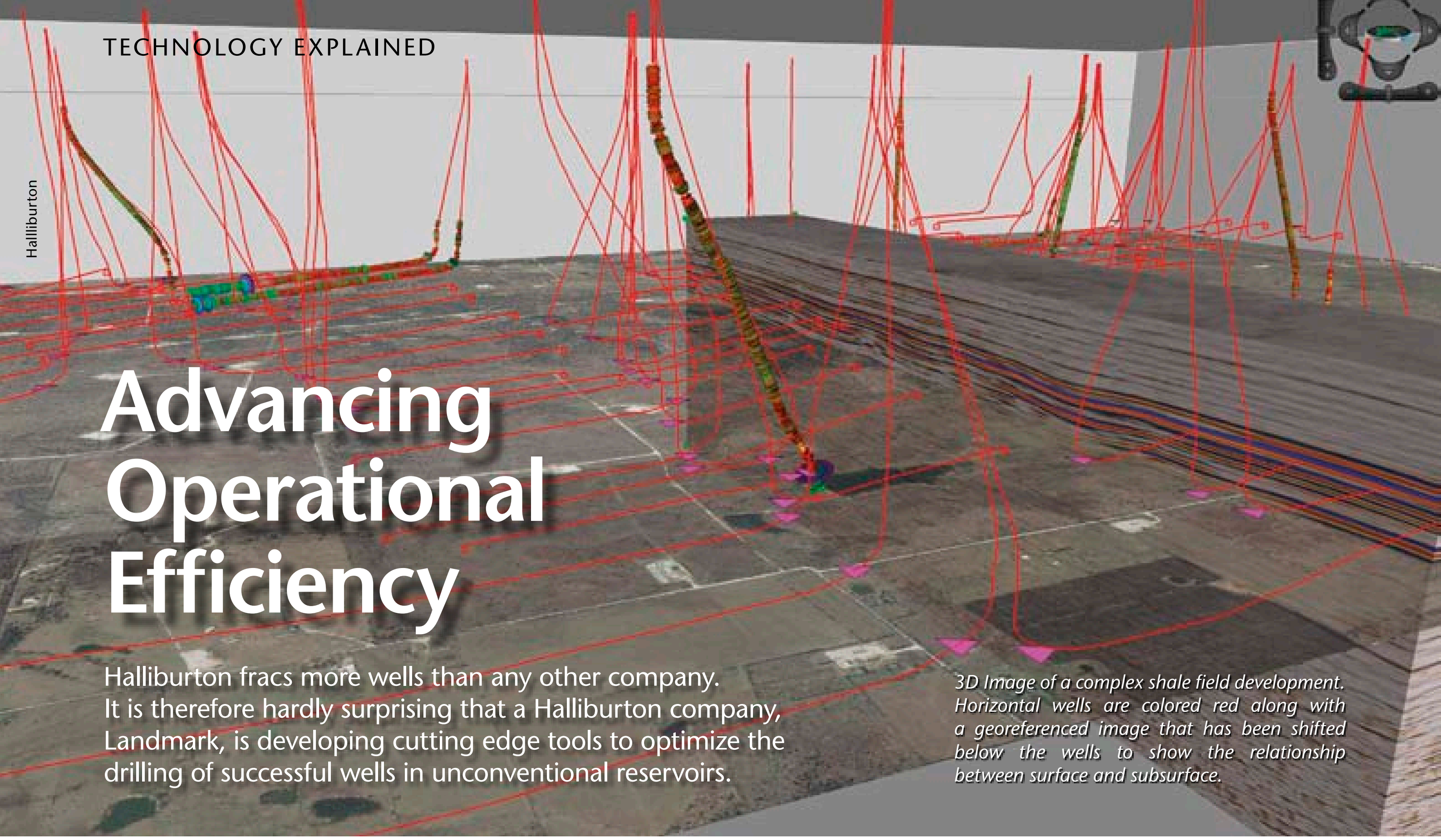


Strike line. Strike extent (> 50 km) of Early Tertiary high-amplitude, potential fan system. Note feature is encased in transparent (shaly) facies, enhancing the likelihood of a regional stratigraphic trap.



Strike line. Evolution of Tertiary fan architecture, from Early Eocene lobe-building confined channel systems (a), to Oligocene unconfined, muddy, aggradational fans with limited levee-building (b), to Late Oligocene active channel-levee complexes with high degree of incision and levee-building (c).





Halliburton

Advancing Operational Efficiency

Halliburton fracs more wells than any other company. It is therefore hardly surprising that a Halliburton company, Landmark, is developing cutting edge tools to optimize the drilling of successful wells in unconventional reservoirs.

3D Image of a complex shale field development. Horizontal wells are colored red along with a georeferenced image that has been shifted below the wells to show the relationship between surface and subsurface.

JANE WHALEY

For many years, geologists, geophysicists and reservoir engineers all used different interpretive tools in their quest to discover new hydrocarbons, making it very difficult for them to work together in the teams that are often the key to successful exploration. In the last few years, however, these disciplines have been moving closer together and one of the leading integrated products available to the whole team within a single platform is Halliburton's DecisionSpace® Desktop software.

"A key strength of our software is that it enables exploration at any scale," explains Nick Purday, Director for Geosciences and Reservoir Technologies with Landmark Software and Services, part of the Halliburton Group. "Everything in the database is cartographically referenced, so a team can move seamlessly from basin scale investigations to the implications derived from a single well. All of the interpretations are saved to the OpenWorks® database, so every user can see and access live updates. In addition, the software can use data from any source and medium, including historical paper cross sections, all of which can be integrated into the digital domain."

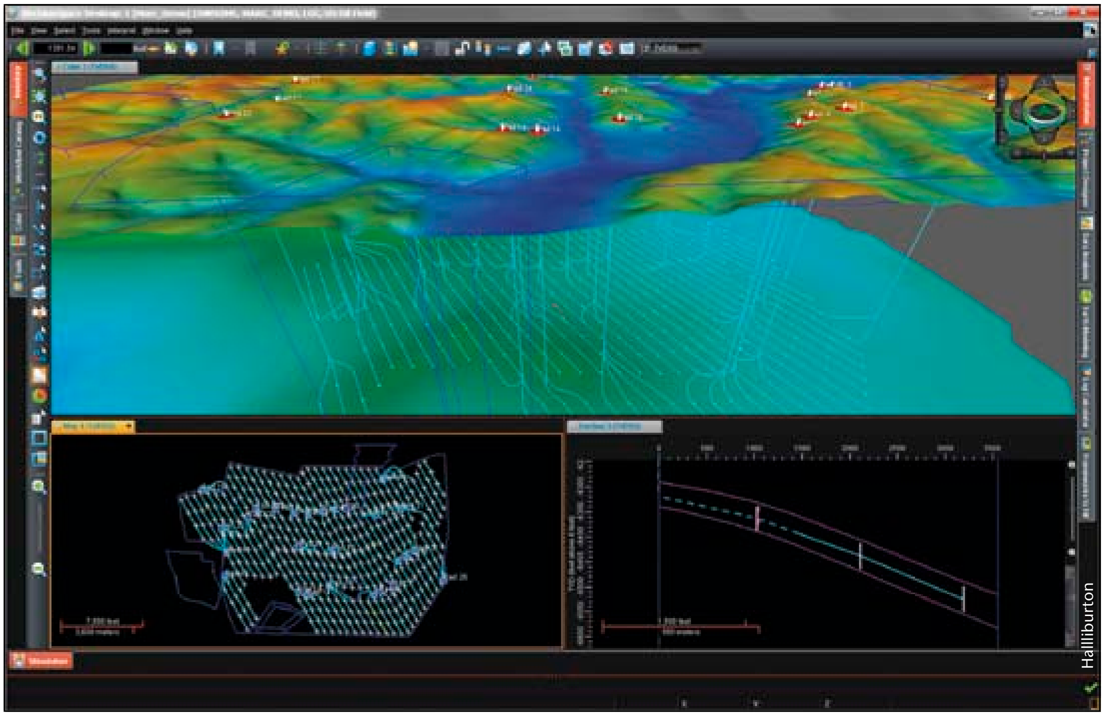
This software is continually in development, and recently added tools combine classic geologic concepts in sequence stratigraphy and structural geology with automated processes that enhance quality, efficiency and ease of use, in a technology known as Dynamic Frameworks to Fill™. "We believe this product is differentiated from similar tools because it operates through a sealed structural framework, built up continually as part of the interpretation rather than at the end of the process," Nick explains. "This saves interpretation time and also forces you to think in 3D throughout the operation, as you seamlessly integrate seismic and well data, rather than working sequentially through tasks. And since all data are integrated within a single 3D framework, any change made to one geological feature, such as a fault or horizon, or the addition of a new well, dynamically cascades throughout the model, automatically updating every associated surface and interval attribute."

Geosteering in Thin Reservoirs

"Updating the 3D framework in real time also leads to improved accuracy during drilling activities," Nick adds. "And this has resulted in the most recent exciting development in the DecisionSpace Desktop software: the addition of the ability to geosteer, which we believe will be of vital assistance in accurate drilling, particularly for horizontal wells in unconventional shale reserves."

Nick likens the shale gas development life cycle, from initial exploration through appraisal and into the final production phase, to a factory assembly line, where the owner is trying to increase profit by eliminating inefficiencies and boosting production. "Low margins, very large numbers of wells and the requirement to link multiple geosciences and engineering workflows means it is our job to find ways to optimize overall operational efficiency," he explains. "Drilling in real time with precise, intelligent geosteering enables the geoscientist to target the sweet spot and to react to the unexpected. We want to be able to predict the depth of a target reservoir ahead of the bit, and to revise both the geologic model and the well plan on the fly during geosteering operations.

"Using the DecisionSpace Desktop 3D view, the geoscientist is able to dive into the subsurface and see where each well lies within the formation. It is often easy to identify wells which have not been drilled using dynamic geosteering of the drill bit, *A planned shale field development in DecisionSpace. The planned wells have been optimally placed for orientation, Z position and spacing using the DecisionSpace Well Planning tools. The surface platforms have been optimized to avoid hazards and minimize the number of platforms.*



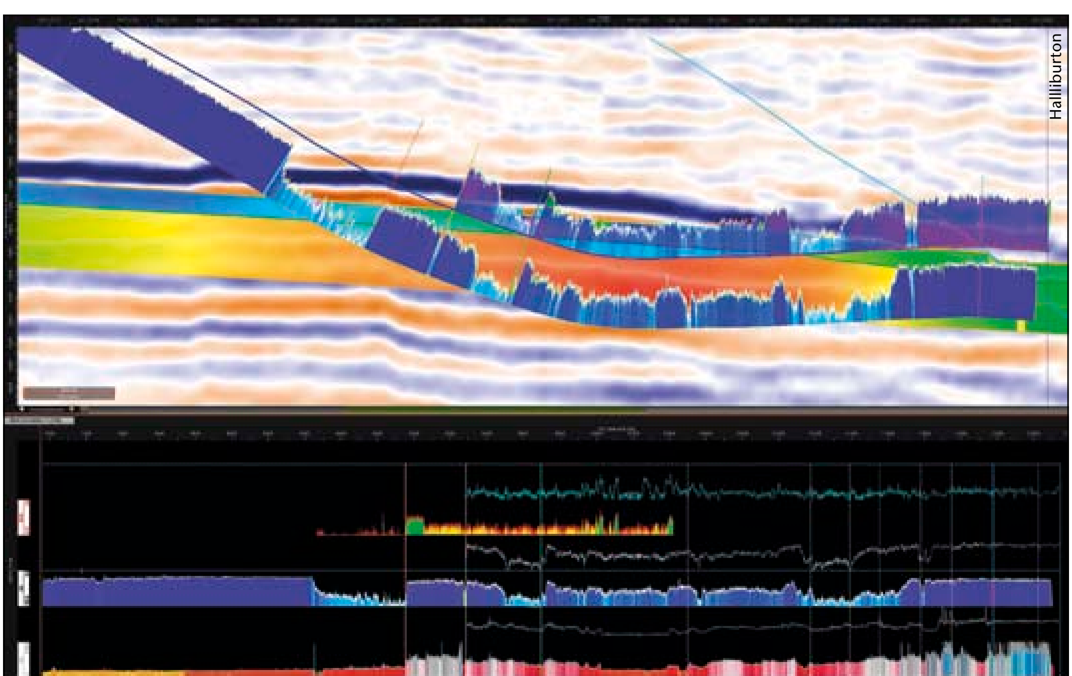
as they can be seen to have come out of the formation in places – sometimes drilled too shallow, sometimes breaking through the base of the formation. This is especially critical in the thin reservoirs so common in unconventional plays. As new wells are drilled, the information gleaned from them is added to the database, dynamically updating the information on screen in both 2D and 3D."

As a result, it is possible to compare planned and actual well positions and constantly adjust and optimize the field plan. Many such schemes, particularly in unconventional fields, are designed to cover the drilling of possibly hundreds of wells over a 10-year time period, and being able to identify where a well has deviated from the formation is critical. Comparing planned and actual well positions and adjusting in real time – "just grab and move," as Nick says – means that the geoscientists back in the office are effectively talking directly to the drillers on the rig.

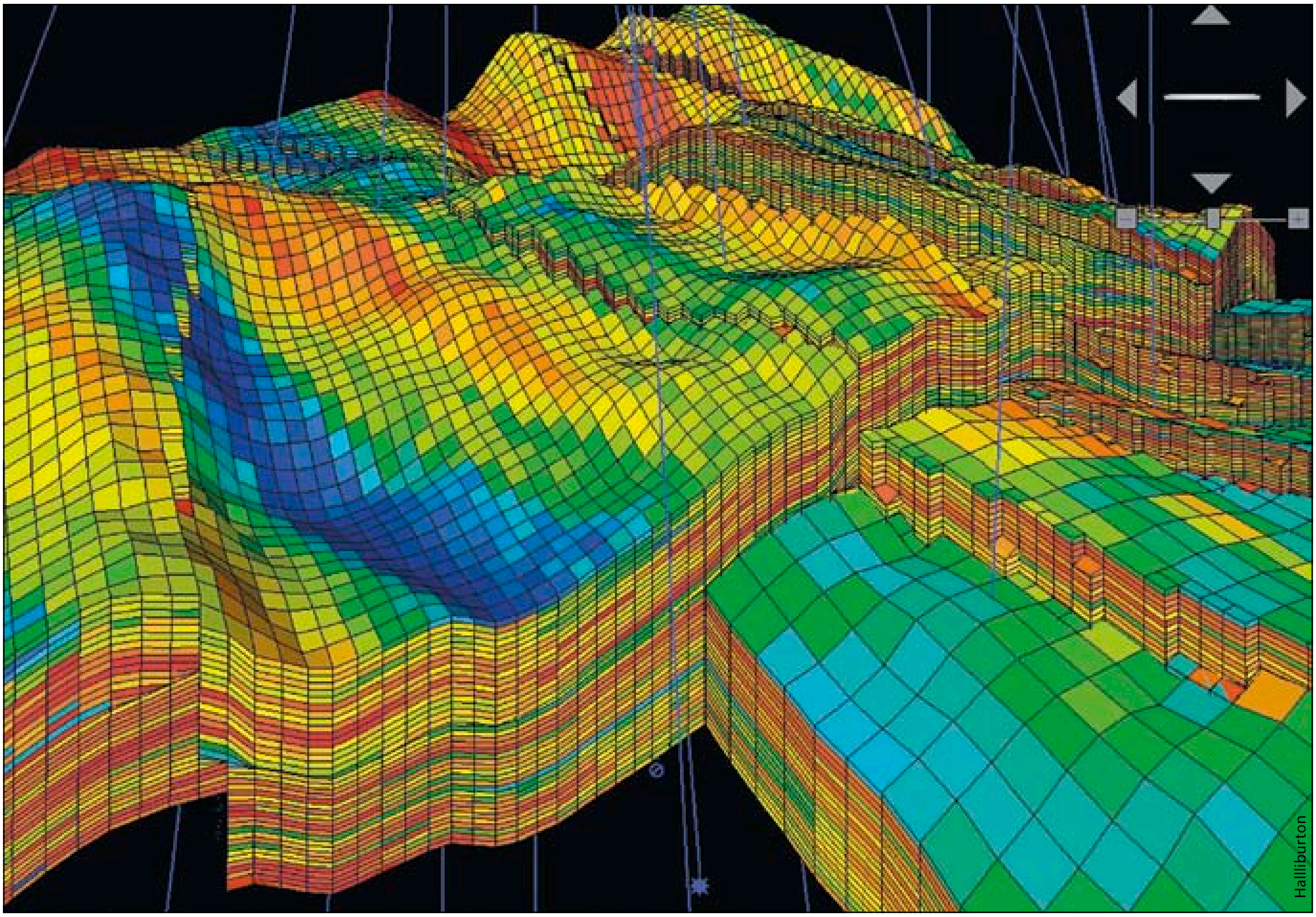
Interface for the New Generation

Landmark is continually working on upgrading and improving its DecisionSpace software – and not just with new modules such as Real-time Drilling and Geosteering. After listening to user feedback and advice from specialists in contemporary software, it has recently introduced an updated interface which uses contrasts in light and dark backgrounds similar to that found in modern tablet platforms and e-readers. Modern technologies such as touch screen and pinch and zoom are also being investigated. The software is available through the Windows operating system as well as Linux.

Nick says that the feedback which Landmark has received from users of these new tools has been incredible. "Basically, the 'Great Crew Change' means that we do not have enough experienced geoscientists to steer all the wells we need. Customers who have tried this technology have indicated that the efficiency gains could have a significant impact on shale field economics." ▶



Comparison of planned and actual well positions. The lower tab is the Horizontal Well Correlation/Geosteering Window. In this view the predicted and real time logs are correlated leading to a revised well trajectory and updated 3D model.



A screen shot from the DecisionSpace Earth Modeling module, which integrates all the subsurface data into a 3D shared earth model.

Collaborating Across Domains

Released in 2010, the DecisionSpace® Desktop software is a unified workspace where global teams can work simultaneously and consistently on E&P projects to establish more accurate subsurface interpretations. It is built on OpenWorks®, the most widely adopted data management system in the industry, which enables real time updates to project data, thus reducing risk, improving efficiency and allowing for more accurate and timely decision-making. It provides a common, flexible 1D, 2D or 3D workspace for the whole team, incorporating seismic, logs, maps, sections and cubes.

The new Real-time Drilling and Geosteering capabilities are examples of a specialized suite of components, which can be implemented together or independently as needed. These include a GIS module which allows spatial data to be incorporated as a base on which all information can be assimilated. The Geophysics module provides rapid interpretation and sharing of ideas, while the Geology module offers the ability to produce quick structure and lithology maps and a sealed, structural framework. Integrated with these is the Earth Modeling module, through which a 3D geocellular model can be created in order to estimate reservoir potential, and the Stimulation module, which enables visualization of fracture treatment and microseismic data in real time to optimize stimulation effectiveness. Having compiled the data and knowledge, collaborating across disciplines to build up the earth model, the Well Planning module is then used to plan a drilling program with the number of platforms and multilateral wells needed to minimize risks and costs.

Nick Purday is currently Director for Geosciences and Reservoir Technologies with Landmark Software and Services. His 19 years with Landmark have taken him from postings in London, the Middle East, Calgary, Denver and finally Houston. Nick is a strong advocate for volume interpretation and visualization, and he has pioneered the use of these techniques in a number of regions, as well as authoring numerous technical papers and articles on advanced interpretation techniques and workflows. He has a master's degree in petroleum geology from the Royal School of Mines at Imperial College.

Bahrain: 80 Years and Still Producing


Jane Whaley

The old and the new: the modern and ever-growing city of Manama looks over the archaeological site of the Qal'at al Bahrain, which goes back almost 4,500 years

For such a small country, Bahrain certainly knows how to make an impression on the world. It is currently celebrating the 80th anniversary of the first discovery of oil in the Arabian Gulf

SINEAD ARCHER

Strategically located in the busy Persian Gulf waterways, Bahrain has a rich and fascinating history. Once the seat of the eminent lost civilization of Dilmun, it is described in the ancient *Epic of Gilgamesh* as an island paradise – 'the land of Dilmun is holy, the land of Dilmun is pure' – and is often touted as the original Garden of Eden. Watered by once copious freshwater springs and situated at a central point between Mesopotamia and the Indus Valley trading routes, Bahrain was a verdant island cluster that flourished during the Dilmun Empire 4,000 years ago, largely aided by the Omani copper trade.

However, as the civilization faded following the decline of this trade, Bahrain became absorbed into the Babylonian empire and little was reported from this small Gulf archipelago until Bahrain's fabled pearls became a much prized commodity. It soon became a thriving centre of the pearling industry and this remained the staple economic income until the 19th century, when Bahrain's geographical location once more made it the trading centre of the Persian Gulf. As such, Bahrain became a cosmopolitan country, with large numbers of Persians, Omanis and Indians making up the population, alongside the British, as Bahrain during this period became a British protectorate.

The welcoming of foreign nationals has continued to the present day. Bahrain currently has a population of about 800,000, over half of whom are not actually Bahraini citizens. A huge number of expatriates now call Bahrain their home but it is no longer shipping or pearling that has lured them to the tiny Gulf state. It is, of course, the lure of the oil industry and its knock-on service and construction industries that has brought them, all hoping to make their fortunes and careers in the relentless Arabic sun.

Persistence Rewarded

The first oil discovery in Bahrain is largely credited to one man, Major Frank Holmes. As a quartermaster in the British Army, posted to the Middle East during World War I, Holmes had heard of seepages in and around the Persian Gulf and was convinced he would discover oil in Bahrain. He was faced with a certain amount of pessimism – one Dr George Lees, a geologist in the Anglo-Persian Oil company went as far as to promise to "drink every drop of oil produced south of Basra", although records do not show whether he went as far as to attempt his promise. But Holmes was a passionate and convincing man and he persuaded Bahrain's ruler at the time, Sheikh Hamad Bin Isa Al-Khalifa, to let him drill for oil. Sheikh Hamad stipulated that Holmes could search for oil, on the proviso that he drilled for freshwater first. After painstakingly mapping the whole country for over a year, Holmes found freshwater and was rewarded by the Sheikh with an oil concession in 1925.

Holmes was keen to attract the support of international oil companies. Although faced with rejection from the Anglo-Persian Oil Company and Standard Oil of NJ, the Bahrain concession finally came to the notice of Standard Oil of CA (SOCAL) and in 1929, SOCAL established BAPCO – the Bahrain Petroleum Company. However, progressing to the drilling stage of the project produced strong opposition from the British. Prior to WWI, they had made an agreement with a number of Sheikhs in the Gulf area, including Bahrain, deeming that all oil exploration in the area would be done by them. Eventually, the British rescinded their opposition and on October 19, 1931, the first log entry to commence drilling was made.

It was not long before everyone's efforts were rewarded – in 1932, the first discovery of oil was made and soon Well Number 1 had been established near Jebel Dukhan, Bahrain's highest point – although at just 134m above sea level, 'high' might seem somewhat of an exaggeration. By 1934 the first shipments of oil had been sent out, Sheikh Hamad had granted the first mining lease and Bahrain's oil industry was well underway.

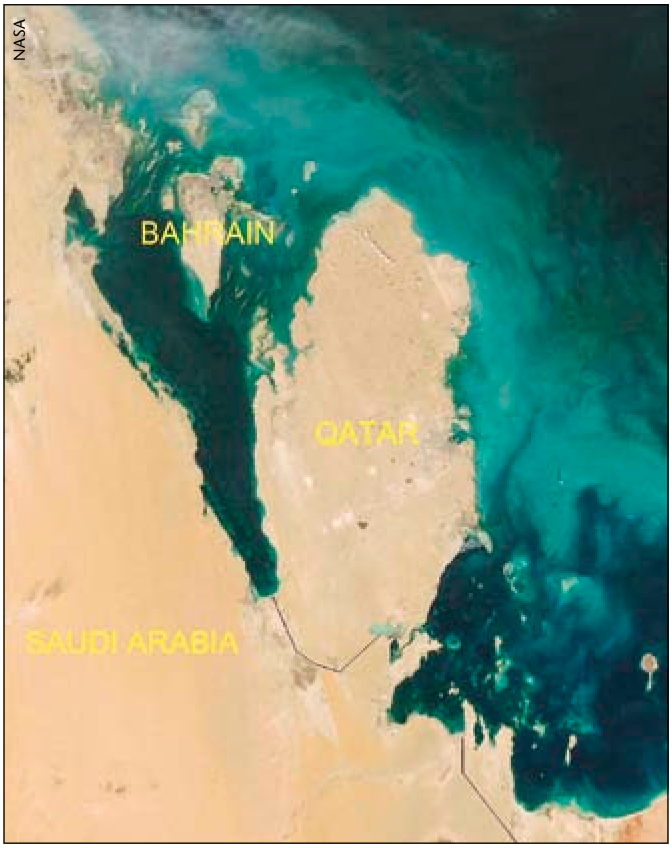
Well Number 1 at first produced 400 bopd, but by 1936 the first refinery had opened its doors, and this rose rapidly. Peaking at about 80,bopd in 1971 the field still produces about 35,000 bopd, and there are plans to increase production with additional drilling. The field, originally known as Awali but now called the Bahrain field, covers an area of about 400 km^2, approximately 80% of the main island. The oil reservoirs lie between 380 and 2,000m and gas is found as deep as nearly 4,000m.

An excellent collection of photographs housed at the BAPCO oil museum goes back to the 1930s and it is fascinating to see how methods of oil production have changed. The best example of this is seen in a delightful photo of a team of donkeys which were vital to the transporting of tools, team members and even barrels of oil. Just two years after the BAPCO refinery had been established, the first fuelling station opened in Bahrain's capital Manama and the first signs of the country's new revenue stream started to trickle through. The next few years saw great leaps in social and economic development, with hospitals, housing and roads built and a new national education system established, alongside the introduction of tankers and pipelines to the oil production process to help shoulder the donkeys' load.

Bahrain Declares War

But serious rumblings far away in Europe were starting to drift towards the little Gulf islands and threaten this exciting time of national growth – rumblings that would turn out to be a world war.

In the lead-up to World War II, Germany and its ally Italy had shown increasing interest in acquiring concessions in the Middle



Although most of the population reside on four islands, interlinked by roads and bridges, Bahrain is in fact an archipelago of 33 islands with a total area only a little larger than the Isle of Man.

Well Number 1, drilled in 1932 and the first discovery in the Arabian Gulf

Mounted camel guard at the refinery, 1938

East. Although oil by this point was certainly recognized as a lucrative area of development, the location of a German-controlled oil well close to the strategically important Red Sea coastal stretch smacked of more than just economic gain. Concerned, California Standard Oil Company held a meeting with the new German Minister for the region, Dr. Grobbe, to investigate further the rumors that the Germans stood to gain more than just oil with a Middle Eastern concession. In what is now a poignant reflection of the Nazi mind-set, Dr. Grobbe rubbished the rumors, claiming them to be merely Jewish propaganda. California Standard Oil Company and several key players in the Gulf, including Saudi's Ambassador to London, Sheikh Hafiz Whaba, were far from convinced and felt that the Germans had hoped to enlist the Arabs to their cause.

Instead, rather than bend to German persuasion, the day after Britain declared war on Germany, Bahrain too declared it was at war with the Axis Powers of Germany, Italy and Japan. The impact on oil production was felt immediately – security was tightened around the refinery and, as a precaution, the large waste gas flares were moved as it was felt they could have acted as a marker for the refinery when viewed from the air. The precaution proved judicious, as on October 19, 1940, the Italians attempted to bomb the oil plant in a move designed to make inroads into Middle Eastern control. However, because of the wisely moved flares, the attempt was less than successful – the bombs fell on a petroleum coke pile, killing no one and damaging very little.

Independence in 1971

As with most countries, the years through the war were tough, with tight rationing and rising unemployment. A result of this was the nation's growing dissatisfaction at its status as a British protectorate and the decades following the war saw considerable anti-British uprisings and riots, often brutally crushed by the British administration. However, the years after the war also saw some exciting developments for the BAPCO. Natural gas was detected in 1948 and the discovery of the offshore Abu Safah field in 1963 proved to be a core income generator for the Bahraini oil industry.

Finally, after over a century of treaty relationships with Persian Gulf states, in 1968 the British government made the decision to bring these treaties to a close. Whilst for a couple of years Bahrain remained under British protection as part of a failed attempt to create a union of all Gulf states, the Bahraini people finally got their wish and independence was declared on August 15, 1971.

Five years later the Bahraini government began to take control of BAPCO too, with 60% of the company's shares bought by the government from the key shareholders, SOCAL and Texaco. Soon the Bahrain National Oil Company (BANOCO) had been integrated and by 1980 the government had attained 100% ownership of BAPCO.

The years towards the end of the twentieth century were strong for the oil industry in Bahrain, with high production and the establishment of several additional companies, such as a petroleum marketing business and a gas liquefaction plant.

Moving Forwards

It is well known that the oil reserves in Bahrain are greatly depleted and certainly won't last forever. In order to secure the country's economic future, BAPCO have invested heavily in strategies that will enable them to move forward in years to come. Exploration and development has and will continue to play a key part and the company has completed several low sulphur diesel production projects which will enable this stream to become more of a focus in coming years.

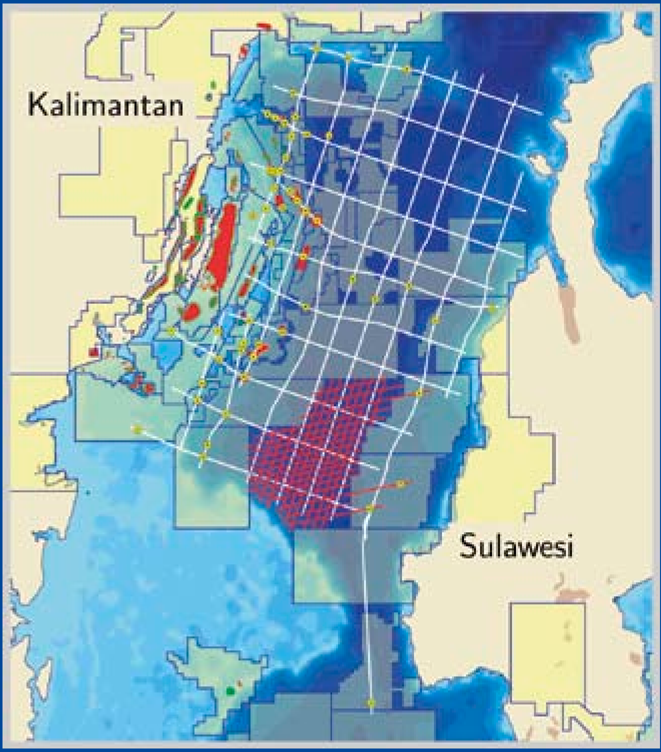
The Bahrain petroleum story is far from over and we can be assured that even when it is, this tiny country, which despite its size has managed to have a global presence over the centuries, will always have a bright new chapter ahead of it. ■

Acknowledgement: Many thanks to Yahya Al-Ansari, BAPCO Head of Exploration, for assistance with this article.

Basket-weaving is a traditional Bahraini handicraft

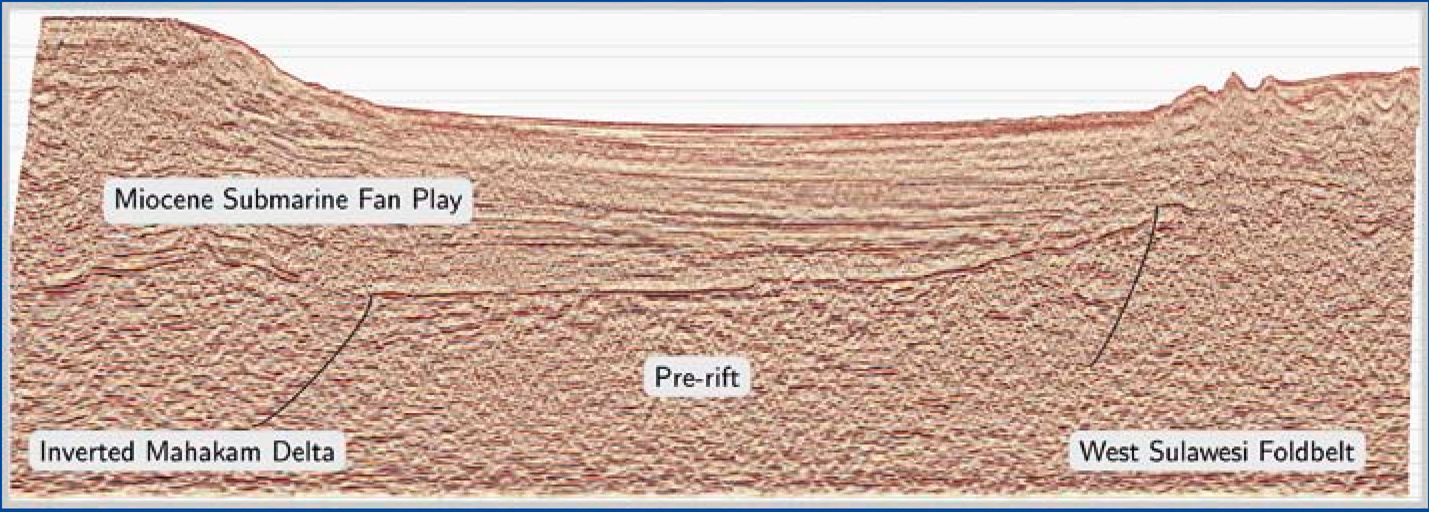
MultiClient Geophysical

Makassar Regional Super-Tie with Phase 1 Infill



- The superior quality Super-Tie broadly cover submarine fan, syn-rift and carbonate play fairways and provide the regional context for licensed and open areas, thereby optimizing exploration and obtaining more value from existing data.
- The Phase 1 Infill covers a high-graded area based on a regional study and AVO investigation of the Super-Tie dataset.
- Surveys optimally tie existing wells including recently drilled.
- Regional Super-Tie 4,769 km (white lines)
- Phase 1 Infill 2,294 km (red lines)
- Final data available now

Dip line across North Makassar Basin



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Communication Is Crucial

Safety training video being filmed in Egypt

If you have an interesting story to tell, how do you get your message across to colleagues, to the oil industry – and to the rest of the world?

JANE WHALEY

Your company has developed a new technology which you believe will revolutionize exploration; you want to tell people about the new promising acreage you have acquired; or maybe you want to inform colleagues throughout a worldwide organization about the success of the new health and safety strategy. How do you effectively communicate important messages across a diverse range of subjects and to people with varying levels of knowledge?

"You need to be able to get under the skin of the audience, to talk their language and understand the context in which the message will be received," explains John Simmons, founder and Agency Director of ON Communication, a multimedia agency which specializes in working in the energy sector. "I was originally trained as a geologist, and worked in mining for several years, before becoming a writer and producer of scientific films and documentaries, for the BBC and later for corporate clients, mainly in the energy sector, so I understand a lot of the technical issues involved.

"Our diverse range of clients comes with an array of issues they need to disseminate to a wide and varied audience. Designing the right campaign is crucial, so the first thing we do when we start talking to a client is to ask 'What do you want to achieve, what would success look like?' We challenge them to precisely define the message they want to communicate. Then we help them to define their audience, or audiences, and work out the best way to approach them. Where possible we like to talk directly to representatives of the audience by running research workshops or telephone surveys to shape the communications we produce and effective ways to deliver them. Only then do we start to define the methodologies to be used; film, print and digital media all have their place."

Wide Range of Projects

The range of communication projects undertaken by ON is broad and fascinating. For example, it is important that an oil company and the representatives of the country where they are exploring communicate effectively. The company may want to demonstrate their progress to the licensing authority, while the country needs to be reassured that the contract is being fulfilled. "To help get this message across we can make a film which shows how the exploration company is progressing, to demonstrate that they are operating in a responsible fashion and illustrating how the local energy professionals are benefiting from technology transfer and training," John explains. "The audience for this is not just the government authority, but also the locals. We undertook a project in Algeria where I spoke to several workers who were keen to be interviewed so that they could express how happy they were to be involved and undergoing training. It is important that this information is delivered in an easily understood manner to their colleagues, as well as to their bosses."

Sometimes ON is commissioned by large multinationals to help with corporate communication from concept

to implementation. For example, for one IOC it produced a complete four-year multilingual, multimedia campaign as part of a major safety awareness drive. "We first identify the story with the client – in this case, it was simply 'why are people getting hurt and what can we do to change this?' – and then design a campaign to deliver this message to a broad range of people throughout the company's worldwide operations. Not as simple as it sounds; safety covers everything from driving and lifting to energy isolation and integrity management, and the message needs to be appreciated equally by the PhD in the laboratory and by the laborer down a trench.

"Sometimes we are asked to help open up communication channels between politicians and oil companies, or between NOCs and ministers, and we are often involved in consultancy and production, where the challenge is to communicate effectively with people with a completely different level of knowledge and set of prejudices," John continues. " It can be very challenging. We have, for example, been involved on behalf of a partnership of several major energy companies in conceiving, writing and designing a poster-style brochure to explain the importance of depth in CO_2 capture and storage. This was aimed specifically at politicians and decision makers and necessarily had to be clearly expressed in layman's terms."

A recent contrasting challenge involved explaining the complex technical issues underpinning a breakthrough in marine seismic acquisition for a major contractor who needed its technology to be understood both by geoscientists and in the boardroom. ON believed the key to this relied on the oldest form of communication, storytelling. The result is a documentary that captures the enthusiasm of the man behind the breakthrough and the technology team who developed the new system, with 3D animations to explain the technological challenge and how this development overcomes it.

Communication is Important

Over the 27 years that ON Communication has been in business, it has undertaken projects in 64 different countries, in temperatures ranging from +55°C (the Sahara Desert) to -35°C (West Siberia) and in over 20 languages in both film and print. "As a result, when a client comes to us with a new project, we usually have some previous experience to bring to it, so we can hit the ground running," John says.


John Simmons

John Simmons (right) directing the making of a corporate film in Brazil


John Simmons

Geology being explained in the Gulf of Suez

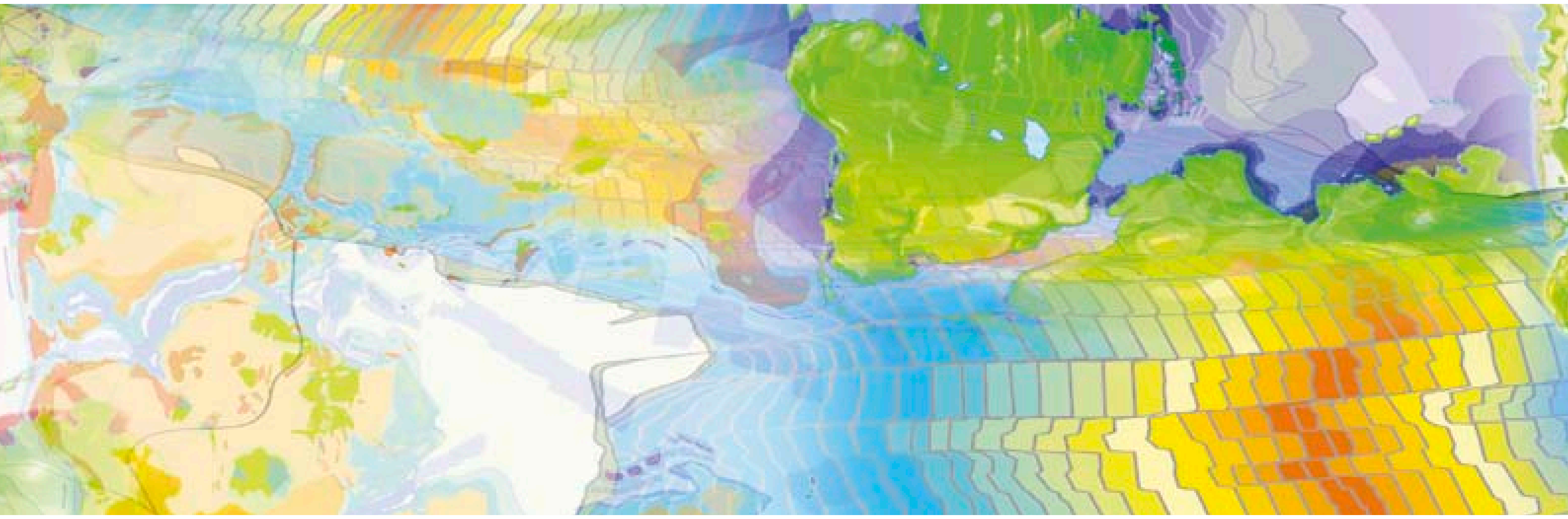
John is passionate about communication, and in particular helping the general public to understand and appreciate the oil and gas industry – something which he believes needs much more work.

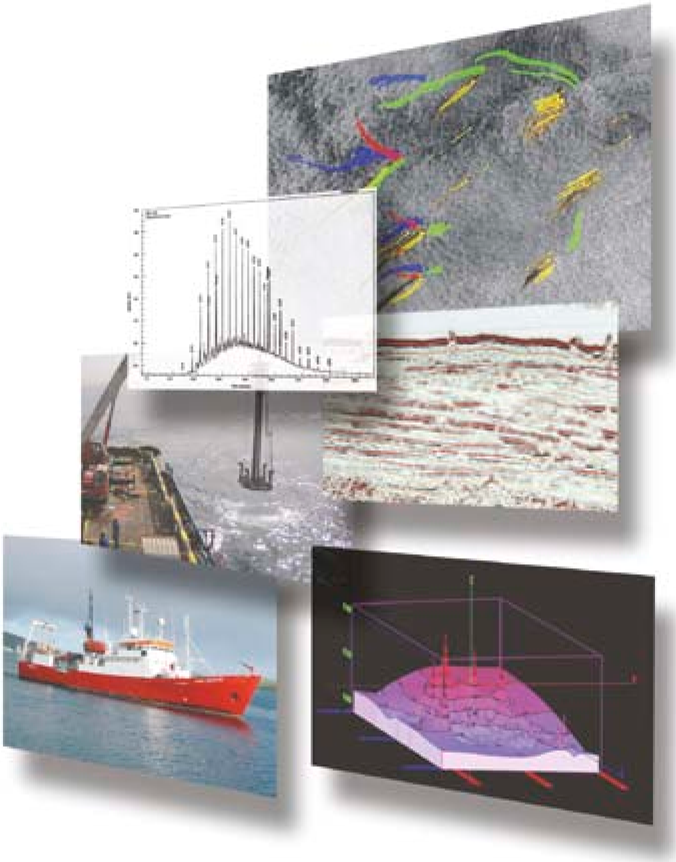
"The industry must overcome the disdain the public feels for it," he says. "It receives such bad press all the time. People complain about the price of petrol, but readily spend much more per litre on bottled water. How can the industry help them to understand the vital place of hydrocarbons for decades to come, or the costs involved in extracting them from the ground, and the work and care that goes into it – and the excitement? Or make them understand that most people involved in this industry genuinely care for the environment? We need to build a bridge of understanding, to overcome the idea that oil is nasty, dirty stuff. We must educate the public about the chain of events which ultimately allows them to turn on a light or start their cars, and the real cost involved in the process. Communication is important and I believe that it is vital to involve the technical community to deliver the messages needed to build those bridges to the public.

The Joy of the Craftsman

"Lots of people produce communication media for the oil and gas industry, but few are as interested in it or have the technical knowledge that we have. I have a great respect for this industry and for the chain of talented people working in it, stretching across the planet, and I want to tell everyone about it.

"What I particularly love about what we do at ON is the satisfaction of being able to say 'We made that'," John explains. "The joy of the craftsman – few people have the thrill of that. If on top, people are gaining from our productions, becoming technically more competent or working more safely, then we have achieved what ON stands for." ■





Slings, Storage… Singapore and Success

A small, crowded, vibrant island – where there are few barriers if there is money to be made.

PAUL ARCHER

As you sip an incredibly overpriced Singapore Sling in the famous Raffles Hotel, a quick survey of the crowded Long Bar summarizes this 'Asian Tiger'. Families with bored-looking kids getting the waitresses to take their holiday snaps; Chinese and Western businessmen enjoying a beer; a Malay couple in their finest gazing lovingly into each other's eyes over champagne; and even the odd gap year traveller in their only smart shirt, wrinkled from their backpack, spending three days' budget on one Sling. Although monkey nut shells still carpet the floor, noticeably absent are the literary icons (Ernest Hemingway was reportedly a keen patron of the Long Bar), down-and-out aristocracy and bustling merchants of the hotel's colonial heyday.

That is because Singapore is a very different place from the city it used to be in those days (for example, if you were Chinese, you weren't allowed to stay at Raffles until the 1940s). Huge skyscrapers, marked with the logos of banks and multinational corporations, tower over the small group of islands. The shopping malls selling the latest gadgets and fashion items are as full as its bustling port, marking the city as a major trade hub for Asia and the world.

Amalgamation of Cultures

Singapore had a population of less than 1,000 when the British East India company's representative, Thomas Raffles, arrived to build a port on this strategically positioned island off the coast of Malaysia. Within 50 years there were over 100,000 inhabitants. Immigrants from India, China and Malaysia mixed with British colonials and Arab traders, creating a diverse amalgamation of cultures. Independence was granted in 1959 and Singapore eventually emerged as a hodge-podged cultural tapestry of a nation.

I once had the misfortune of shipping a vehicle out of the monstrous port, a huge industrial machine that works like clockwork, and certainly not the place to be wandering around alone trying to ship a car. I was fortunate to have an agent to navigate the vast expanse of containers, docks, trucks, cranes and offices; otherwise I expect I would still be searching for the exit. He was a large Singaporean Indian, who barked into his phone in Hindi, showed me where I should sign paperwork in English and commanded a small army of Chinese workers in their own language, all in the same breath – whilst simultaneously playing a game on his iPad. He epitomized the diversity and functionality of the place, a country where language or race present few barriers if there is money to be made.

It is, however, a very small and crowded place. Although set to grow by 103 km^2, thanks to land reclamation projects, it crams over 5 million citizens into an area smaller than 710 km^2 – about the same area as the city of Austin in Texas.

Singapore is one of the more wealthy countries in the world and its wealth can be attributed to a few factors. Highly business-friendly, it is ranked number two in the Index of Economic Freedom and is rated favorably for competitiveness, freedom and innovation, as well as being one of the least corrupt countries in the world. Tourism is healthy and the country has tried to promote itself as a hub for medical tourism as well.

Regional Oil Hub

Singapore is the region's premier centerb for oil and gas, and the oil industry accounts for 6% of the country's economy,

even though Singapore itself doesn't have a drop of oil! As the undisputed oil hub in Asia, Sinagpore is one of the world's top three export refining centers. It also has a well-established petrochemical industry, and US$500 billion of oil stocks are traded through Singapore markets (beaten only by London and New York). Storage is set to become the next step, with a large project planned to turn the Jurong Rock Caverns into a super storage site, with a capacity to store 9.2 MMbo by 2013, and potentially another 8.3 MMbo after that.

Rochelle Hulst

Marina Bay

Wandering around Chinatown, low rise and run down (but only relative to the pristine towers of the city), is an almost welcome relief from Singapore's obsessive cleanliness, for which the country has a famous reputation. Down by the riverfront, fish restaurants and bars are busy with tourists and Western businessmen. Beer flows, and rugby and English Premier League football are shown on the big screens; you could be forgiven for thinking you were in London on a muggy summer's afternoon.

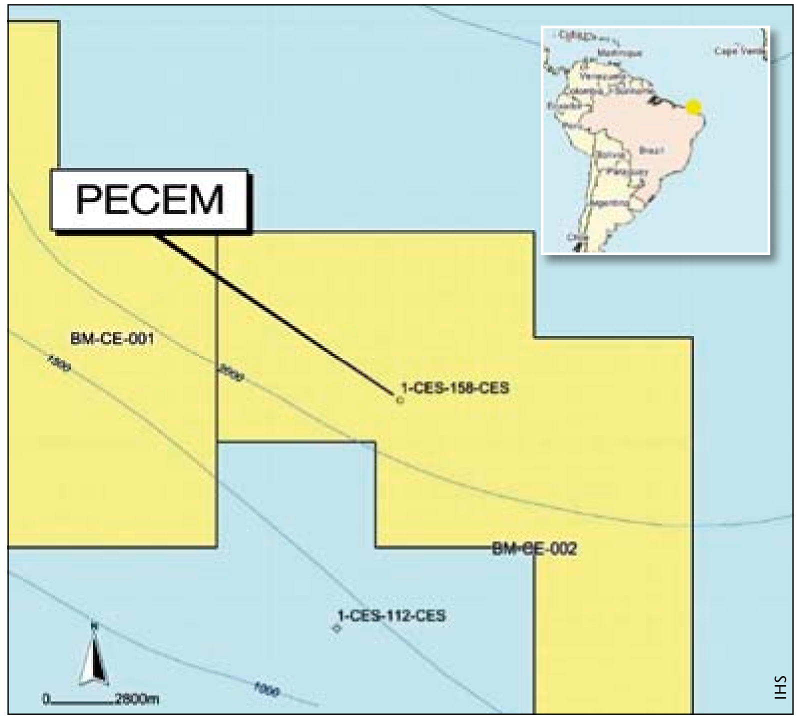
Muggy is key though; Singapore's weather ranges from hot and humid to hotter and more humid. Sometimes it is so hot, you would be forgiven for spending the day kicking back and sipping Slings – but you won't get much change from US$20! ■

Rochelle Hulst

Brazil: New Area Opens Up

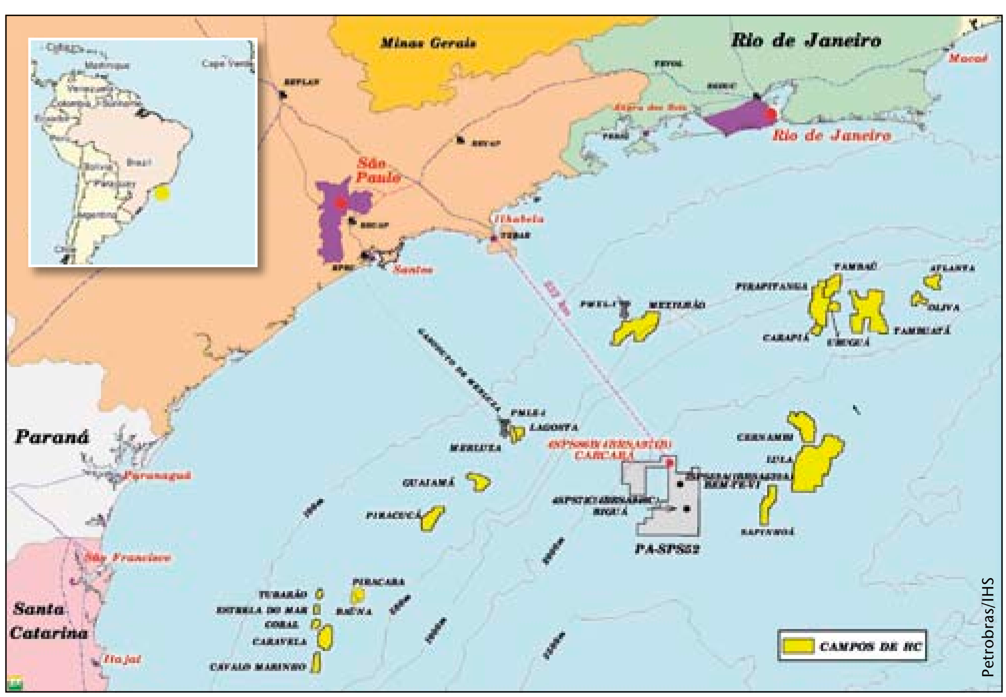
Petrobras (60%) and partner BP (40%) have found oil in a deepwater well in the BM-CE-2 concession in the offshore Ceara Basin, a new area for exploration off Brazil's north-east coast. The Pecem discovery is one of the first in a region where companies are testing theories that the same geological systems that created and trapped oil off the west coast of Africa are present in Brazil's north-east.

In a securities filing, Petrobras said it found a 290m hydrocarbon column in the well with 140m of net pay in structures in the Paracuru formation, 76km off the coast near Fortaleza. At last report the well, sited in 2,129m of water, had reached a depth of 4,410m and was being extended to 5,500m. The well is being drilled by Diamond Offshore's Ocean Courage S/S and these early results suggest the well appears to be a very significant discovery for new trend implications.



IHS

Further south in the already prolific Santos Basin, discoveries continue to be made. Initially reported as an oil discovery in March 2012, the Petrobras-led consortium drilling the Carcará wildcat in block BM-S-8 in the Santos Basin have reached a depth of 6,213m and are continuing to find oil. The company has confirmed a 31° API oil column of more than 400m with excellent porosity and permeability. The results so far have prompted one of the partners to claim that the well is "one of the most significant oil discoveries" in the country's offshore sub-salt area, a comment that has fuelled expectations that another giant find has been made. Located in 2,027m of water, the Carcará strike is the latest in a region that is home to several of the world's largest recent oil discoveries. The first discovery, announced in 2007, was in a nearby block owned by Petrobras, BG Group Plc and Galp Energia SGPS, and was the biggest discovery in the Americas in three decades. Now known as the Lula and Cernambi fields, that discovery holds an estimated 8.3 billion barrels of oil and natural gas. A discovery of similar size has been predicted for some time and with an oil column that looks to have exceeded 400m, the Carcará strike is already being touted as another Lula. However, IHS comments that to be that big, the structure will have to extend beyond the block outline into Federal controlled territory and will have to be unitized with acreage that will be put out for bid in a 'Pre-salt' Bid Round at some point in the future. The largest it could be within the confines of the current block appears to be 500 MMb to 2 billion barrels. Interests in the BM-S-8 license are held by Petrobras (66%), Galp Energia (14%), Queiroz Galvao Exploraçao e Produçao and Barra Energia do Brasil each with 10%. ■

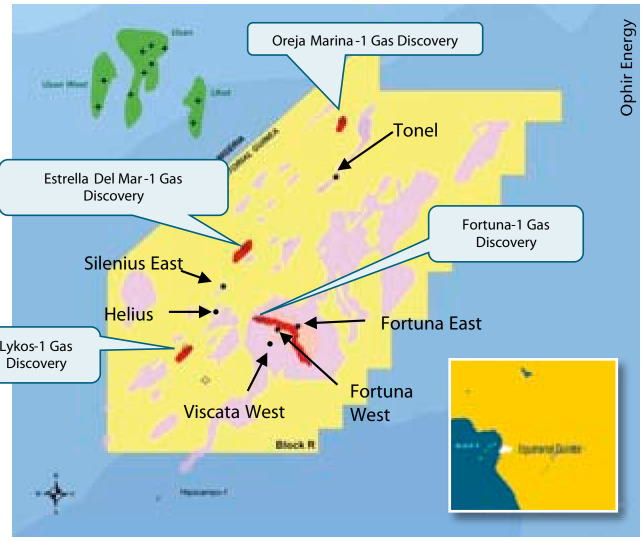


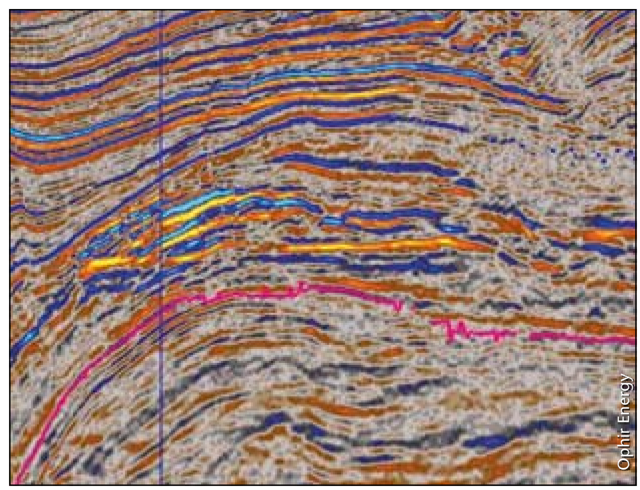
Petrobras/IHS

Equatorial Guinea: Gas Discovery

Ophir Energy has made a gas discovery with Tonel-1 (R-4), the first of three wells planned in deepwater Block R off Equatorial Guinea using the 'Eirik Raude' S/S. Targeting a thrust belt prospect with a mid-Miocene stacked objective in 1,599m of water, the well was drilled to a total depth of 3,072m and encountered a 182m gross gas column with 117m of net pay. The gas quality appears to be consistent with that observed in previous dry gas discoveries in Block R. Gross recoverable mean resources are estimated to be 800 Bcf (133 MMboe), exceeding pre-drill estimates of 708 Bcf (118 MMboe). The Tonel discovery is significant as it takes the total de-risked, recoverable gas resources in Block R to 2.2 Tcf (367 MMboe), just a fraction short of the minimum commercial threshold for a second LNG train on Bioko Island, which is estimated at 2.5 Tcfg.

This discovery comes just 10 months after Ophir secured an amendment to the Block R Production Sharing Contract that saw the permit area expand by 773 km^2 to 2,447 km^2; a move that incorporated the Estrella del Mar-1 and Oreja Marina-1 gas discoveries which had been drilled by ExxonMobil in February 2001 and June 2002 respectively. Continuing with its three to four well campaign, Ophir's Fortuna East-1 (R-5), some seven kilometres east-south-east of the Fortuna-1 discovery, has successfully found gas in the eastern lobe of the Fortuna Complex and has established gas in the deeper Viscata exploration target. The well also encountered the lateral stratigraphic equivalent interval of the Tranquilla and Iambe exploration prospects, confirming good quality reservoir and significantly de-risking the Forethrust play across the Block. The rig has now moved to the Fortuna West-1 (R-6) location testing the western lobe of the Fortuna Complex and the Felix exploration target. ■



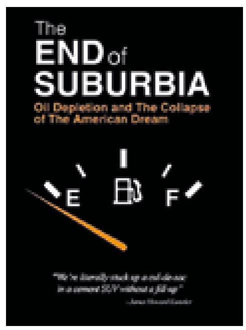


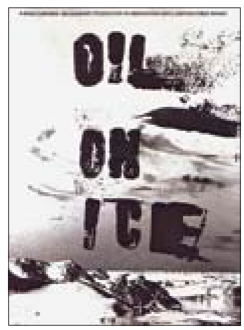
DHI over the Tonel discovery in Equatorial Guinea

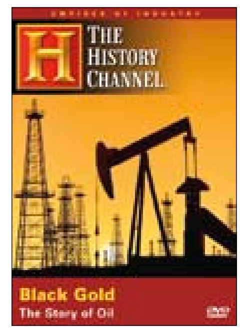
The Sight and Sound of Oil

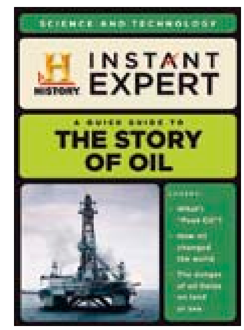
A brief tour of documentary films on the oil and gas industry

Given the myriad role that oil and gas play in our daily life, society and industries, the importance of public education about the science, technology, and history of petroleum should be obvious. Documentary films are an important medium that shape public perceptions and knowledge about the oil and gas industry. I have watched a large number of these oil-related documentaries produced in recent years; here is a brief report.

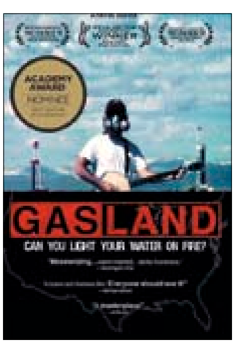


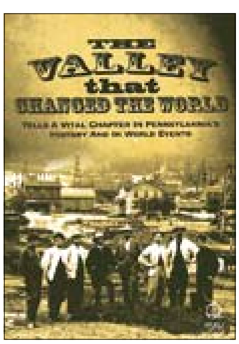


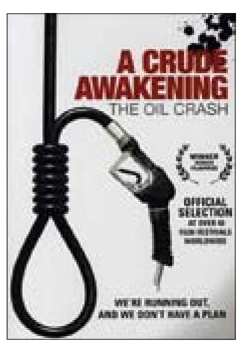


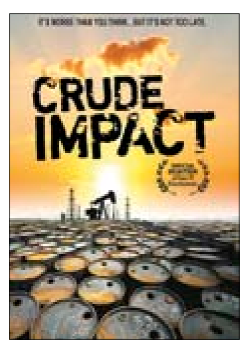


Shortly after Daniel Yergin published his Pulitzer-winning book *The Prize: The Epic Quest for Oil, Money and Power* (1991), it was made into an eight-part series which was aired on PBS in the USA. This documentary (available in 4 video tapes, running 480 minutes) still remains our major audiovisual source on the history of oil in the 20th century with a focus on international politics.









The History Channel has produced three outstanding documentaries. *Black Gold: The Story of Oil* (1998 and 2005, 50 min.) portrays a sweeping history of oil and its impact on our world; *Instant Expert: A Quick Guide to the Story of Oil* (2010, 94 min.) is more educational on the science of oil and comes with a quiz at the end; *Oil Rigs* (2011, 47 min.) focuses on the design and operation of offshore oil rigs and platforms in the Gulf of Mexico.

Of the Discovery Channel's *Extreme Engineering* series (hosted by Danny Forster), two episodes (50 min. each) are noteworthy here: *Offshore Oil Platforms* (2003) and *Sakhalin Oil and Ice* (2006).

Extreme Oil, produced in 2004 by Films for the Humanities and Science, comes in three parts (each 57 min.): 'The Wilderness' features the environmental impact and politics of oil production in Alaska's Arctic National Wildlife Refuge (ANWAR); 'The Oil Curse' contrasts Texaco's toxic environmental legacy in Ecuador with the prosperity that oil has brought to Angola; and 'The Pipeline' discusses the ambitious project of building a 1,100-mile pipeline from Baku on the Caspian Sea as far as Turkey's Mediterranean port of Ceyhan.

Most of the documentaries highlight the adverse international, 'peak-oil' (no 'cheap oil') 'oil addiction' and environmental impacts of the oil industry, and hence promote the development of alternative energy sources. Notable among these are: *The End of Suburbia: Oil Depletion and the Collapse of the American Dream* (2004, 78 min.), *Crude Impact* (2006, 97 min.), *Who Killed the Electric Car?* (2006, 92 min.), *A Crude Awakening: The Oil Crash* (2007, 85 min.), *Fuel* (2010, 112 min.), and *Gas Hole* (2011, 100 min.).

Some documentaries deal with more focused, hot topics. *The Oil Factor* (2004, 93 min.), comments on the recent wars in the Middle East, while *Blood and Oil: The Middle East in World War I* (2006, 112 min.) takes us back to the very beginning of this issue. The award-winning *Oil on Ice* (2005, 58 min.) discusses ANWAR's oil development; *Crude* (2009, 105 min.) is a look at the infamous Texaco case in Amazonian Ecuador; while *H2Oil* (2009, 76 min.) and the award-winning *Petropolis* (2010, 70 min.), both films by Canadian directors, explore the environmental hazards of developing the Athabasca oil sands (the size of England) in Alberta. *Gasland* (2010, 107 min.) discusses the environmental effects of hydraulic fracturing in the development of shale gas fields.

Last but not least, I should mention a documentary film that takes us back to the beginning of the oil industry in Pennsylvania in 1859. *The Valley That Changed the World* (produced by WQED, 2009, 57 min.) was released on the 150th anniversary of the Drake Well which changed the world. Here is a final point to contemplate: in 1859, when Edwin Drake drilled that successful well near Titusville, it was indeed a pioneer venture that proved timely, but no one in those days could imagine the industrial and digital technologies we now have access to – including the film industry.

The above documentaries are all available on DVD for purchase in online stores.

RASOUL SORKHABI

PETEX Spreads Its Wings

PETEX, the biennial London conference and exhibition organized by the Petroleum Society of Great Britain to celebrate the oil and gas industry, will be held between 20 and 22 November this year at Earls Court. We talk to **Dr. Oliver Quinn**, Conference Chair, about the conference and find out what special events are planned for this year.

Oliver Quinn is Team Leader for West African New Ventures with Hess, based in London. He was previously Exploration Planning Advisor with Hess and before that worked for Fairfield Energy and Shell. He has a degree in Geology from the University of Manchester and a PhD in Petroleum Geoscience from the University of Edinburgh. Oliver is currently Chairman of PETEX 2012.

What's changing in PETEX this year and why?
Lots! PETEX 2012 sees an expanded technical program covering projects and technology from across the globe and reflecting the increased international outlook of European companies. The ever popular Plenary Session debate will include, for the first time, leading figures from non-governmental organizations as well as industry speakers, addressing the oil industry's 'social license to operate'. Broadening this debate recognizes our growing need to further industry engagement with the wider public.

Have you new themes and ideas?
The North Sea still represents a key theme, but as well as being increasingly international, the main technical program has a large component of unconventional hydrocarbon and seismic technology. Emerging global exploration provinces are also a major area, reflecting some of the recent big discoveries in the Eastern Mediterranean and East Africa. For the popular social program, 2012 sees the addition of a final day 'Sundowner' event on our Exhibition floor to close out the show in style.

Why should people attend PETEX?
PETEX remains the largest geoscience-focused oil and gas meet in the UK, and the ideal place to catchup on the latest industry developments, as well as being a great networking opportunity. Along with the breadth of industry presentations, the Exhibition floor has companies from oil majors all the way through to university research departments.

Why did you get involved?
I first got involved as Technical Chair of PETEX 2010, which was a fantastic opportunity to influence the program to reflect a more international dimension, which continues into 2012. As part of the wider Organizing Committee it is a chance to give something back to our peers and the industry. One of the most pleasing aspects of involvement in PETEX is knowing that it is a key source of financial support to the PESGB and allows the funding of several MSc scholarships.

How does attending PETEX help young professionals?
PETEX 2012 sees a huge number of events for both young professionals who have already entered the industry and aspiring students who are looking at starting their careers, with dedicated exhibition areas for a University Forum, Graduate Careers Fair and Student-Industry Lunch. Following success in 2010 the Industry-Academia Collaboration Conference continues to be hosted by PETEX, where the latest petroleum geoscience research will be presented over two days.

What advice would you give to young geoscientists considering a career in the hydrocarbon industry?
It is key to focus on developing a really strong and broad geoscience skill base. Once you have that more and more opportunities will open up in front of you. We live in exciting and interesting times: rising global energy demand and the emergence of unconventional hydrocarbons for example, but balanced with considerable challenges for the industry in the form of environmental and social impact – our 'social license to operate,' which is the theme of the PETEX plenary discussion. So I would say that along with developing excellent geoscience skills, they need to understand the importance of our role in energy supply, but also be aware of our impact and take a personal responsibility for managing that as a geoscience professional. ■

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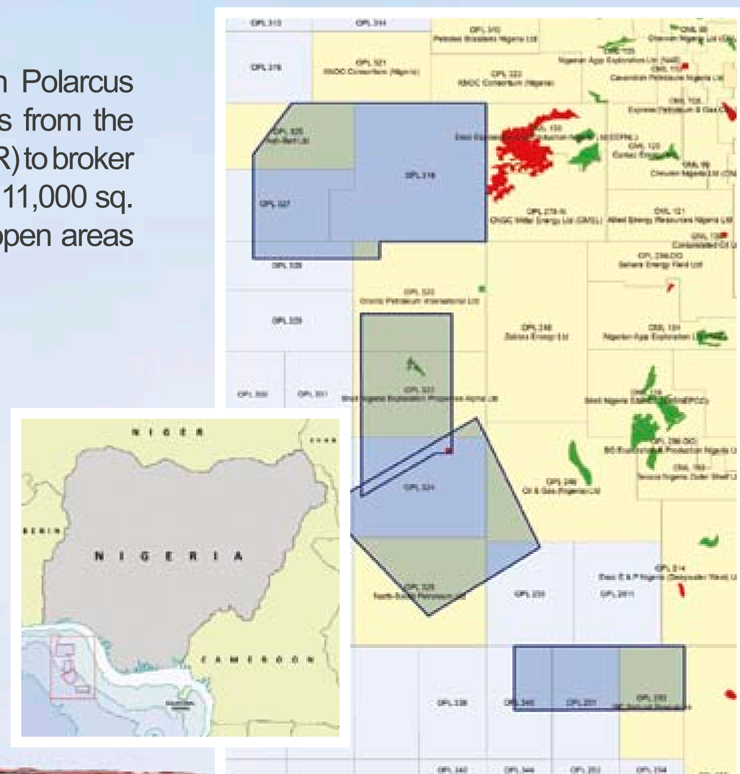

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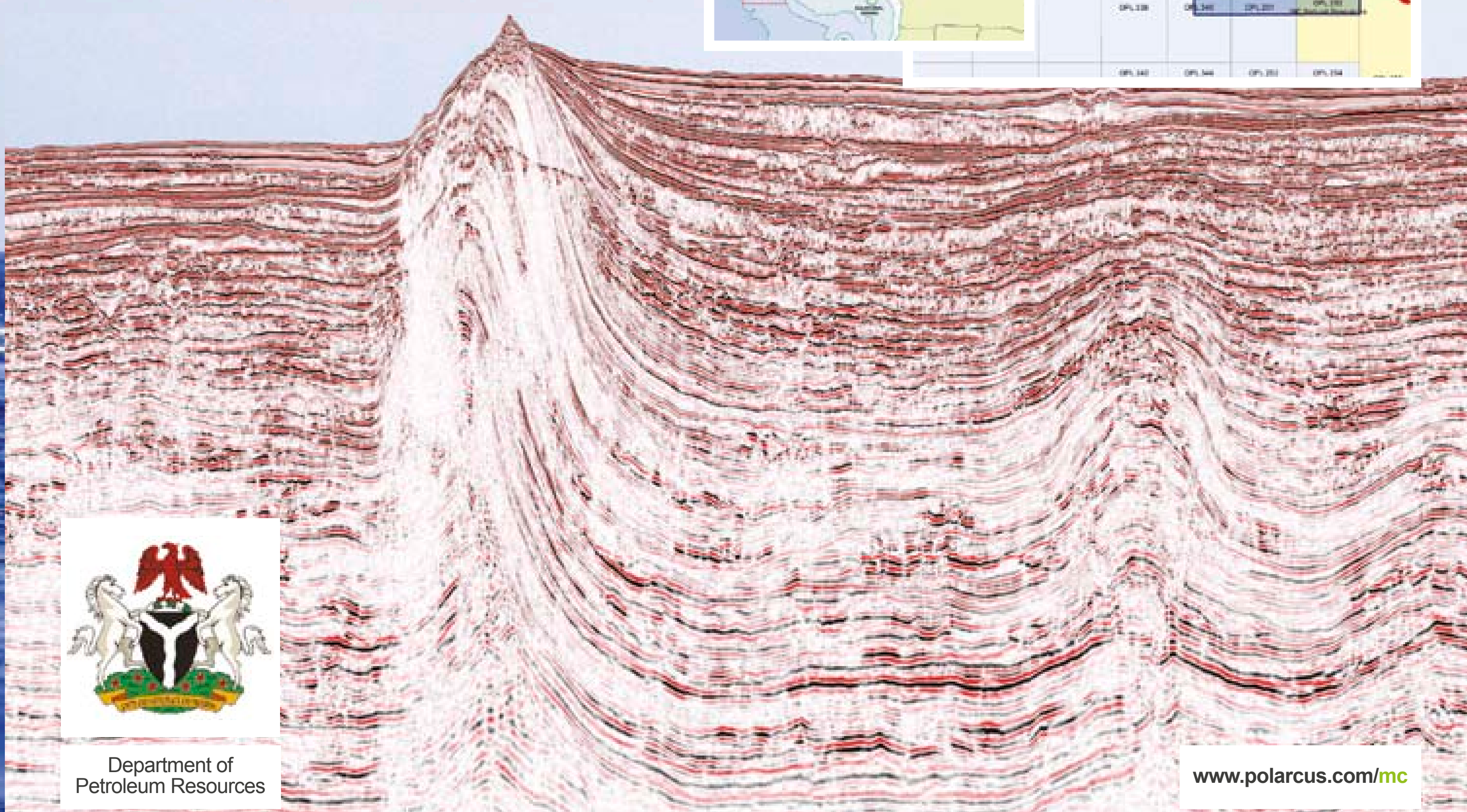

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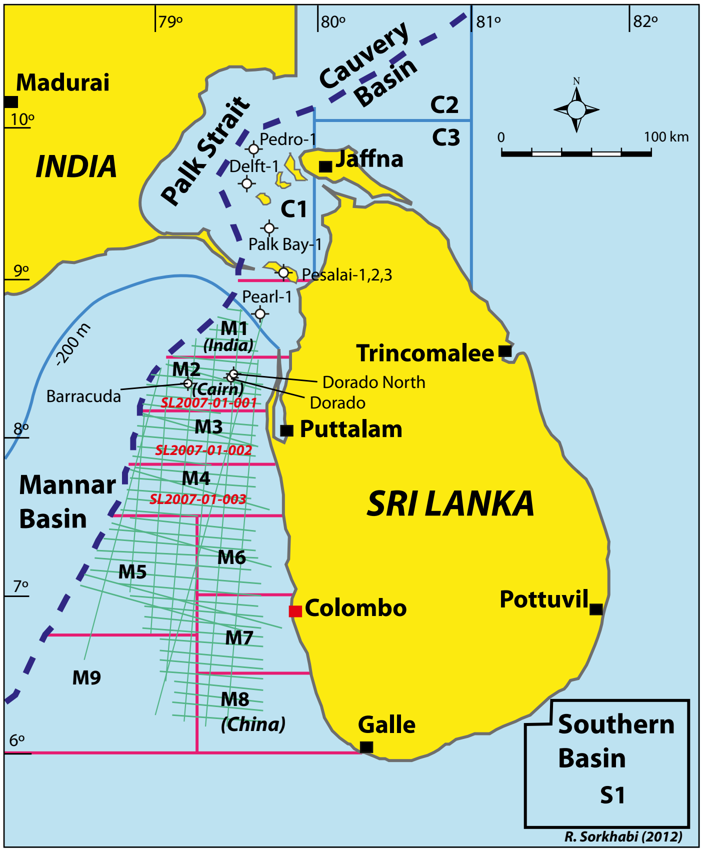
Cairn Discovers Gas Offshore Sri Lanka

After a successful track record of petroleum exploration in the Barmer Basin in the Indian state of Rajasthan (see *GEO ExPro*, Vol. 8, No. 6), Cairn India has expanded its activities to Sri Lanka. Cairn Lanka, a subsidiary of Cairn India, has struck gas in the offshore Gulf of Mannar Basin between Sri Lanka and the southern tip of peninsular India. As operator, Cairn Lanka holds 100% participating interest in the block.

Cairn's discovery comes after three decades of hiatus in the oil exploration of this small island country. Sri Lanka (previously called Ceylon) has a land area of 64,630 km^2 with a coastline of 1,340 km; the country is mainly made up of Precambrian granites and metamorphic rocks, and only 15% of the island, notably its northern corner close to India, is covered by sediments. This area, extending across the Palk Strait, is geologically part of the larger Cauvery Basin, which contains Cretaceous-Quaternary sedimentary rocks. Indeed, only these Cauvery Basin sediments had drawn the attention of petroleum explorers in the past, with wells that included Pesalai 1, 2 and 3 undertaken by Soviet oilmen in 1974, Palk Bay-1 and Delft-1 drilled by Marathon in 1976, and Pedro-1 and Pearl-1 drilled by Cities Services in 1981. None of these wells proved successful, although Pesalai-1 drilled on the island of Manar to a depth of 2,594m encountered some gas in Lower Cretaceous sandstone, and Pearl-1 drilled in the northern part of Sri Lanka's Gulf of Mannar to a total depth of 3,050m bottomed in a volcanic sill after penetrating an 850m-thick Upper Cretaceous sandstone.



Two Discoveries

In 2002 and 2005, Norwegian contractor TGS NOPEC acquired 2D seismic data in Sri Lanka's Mannar Basin, to the west of the island. Based on their encouraging report, in 2007 the government of Sri Lanka divided the basin into nine exploration blocks and offered three of them for bids from international oil companies. On 7 July 2008, Sri Lanka's Ministry of Petroleum and Petroleum Resources Development Secretariat awarded to Cairn Lanka Block SL2007-01-001, with an area of 3,340 km^2 in water depths from 400 to 1,900m. The period of licensing runs until October 2016. In December 2009, Cairn conducted a 3D survey in its exploration block, and went on to drill its first well in August 2011.

Cairn has reported two discoveries from its block. In October 2011, the company announced that its exploratory well CLPL-Dorado-91H/1z, drilled some 30 km from the Sri Lankan coast in a water depth of 1,354m, encountered 24m of gas-bearing sandstone. A month later, a second well, CLPL-Barracuda-1G/1, located 38 km west of the discovery well and drilled to a total depth of 4,741m in 1,509m of water, hit three similar gas-paying zones. While the pay zones are mainly natural gas, potential for some liquid hydrocarbons has also been indicated. A third well, CLPL-Dorado North 1-82K/1, was plugged and abandoned as a dry well in December 2011.

These deepwater wells were drilled by the Japanese drillship *Chikyu* ('Earth'), which was originally built for use in the Integrated Ocean Drilling Program.

After completing its first phase of exploration at a cost of US$150 million, Cairn has launched its second phase, with 3D seismic acquisition in 2012 (by Petroleum Geo-Services aboard the seismic vessel *Pacific Explorer*) and drilling expected in 2013. The company is reported to be looking for a drillship or semi-submersible rig capable of drilling to a total depth of 5,500m in water depths between 800 and 1,700m.

Window of Opportunity

How much hydrocarbon the Mannar Basin holds is unclear. But in March 2011, Dr. Neil De Silva, then Director-General of Sri Lanka's Petroleum Resources Development Secretariat, was reported as suggesting a billion barrels of oil equivalent in the basin, based on interpretations of the TGS seismic images.

Cairn's gas discovery in the Mannar Basin has opened an important window of opportunity for Sri Lanka, which imports all of its petroleum (costing US$3 billion in 2009), mostly from the Middle East. Moreover, these discoveries for Cairn came at a time of significant changes for the company. In 2011, Cairn India, which was largely owned by Edinburgh's Cairn Energy, sold its majority stake to a London-based Indian mining company, Vedanta, after a complicated series of negotiations with the Indian government. By paying $8.7 billion, Vedanta acquired 60% of Cairn India, while Cairn still retains about 22% of the company's share as well as the company's name.

RASOUL SORKHABI

CONVERSION FACTORS

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

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

Energy
1000 m³ gas = 1 m³ o.e
1 tonne NGL = 1.9 m³ o.e.

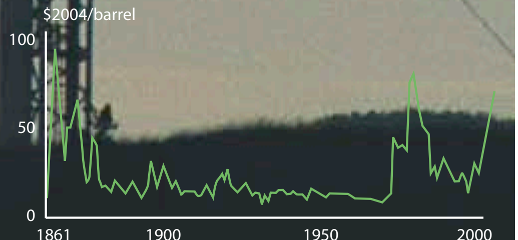
Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 10^{12}

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

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

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

Historic oil price



Coal Takes Charge

Fossil fuels continue to dominate the energy mix

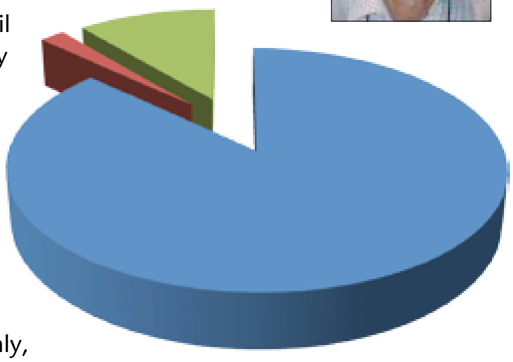
Their market share is 87%; fossil fuels therefore still dominate energy consumption. Renewable energy continues to gain markets, but still only accounts, however, for 2.1% of energy consumption globally. This is up from 0.7% in 2001, meaning there is still a long way to go before renewables will play an important role in the energy mix.

With respect to fossil fuels only, oil is still in the lead, although the black liquid is reducing its market share every year. Regrettably for carbon emissions, coal – accounting for an astonishing 30% of energy consumption – is the fastest growing fossil fuel, with China alone recording an increase of 9.7% last year. As a consequence, global CO_2 emissions from energy use continued to rise in 2011.

World primary energy consumption grew by 2.5% in 2011. All of the net growth took place in emerging economies, with China accounting for 71% of global energy consumption growth. OECD consumption declined, falling by 0.8% in OECD countries, while non-OECD consumption grew by 5.3%.

These figures are taken from BP's Statistical Review of World Energy 2012, released early this summer.

HALFDAN CARSTENS



Fossil fuels (blue) account for 87% of our energy consumption, while renewable energy (red) is only around 2%, with nuclear energy making up the remainder.

Biofuels

Biofuels are produced in over 25 countries. The two dominant producers in 2011 – by far – were Brazil and USA. Brazil was in the lead with about 115,000 bopd, while the US production was roughly 68,000 bopd. The third largest producer was France with only 6,500 bopd. World total production of biofuels amounted to 205,000 bopd in 2011, a mere 0.0023% of world oil production.

Halfdan Carstens

Coal is the fossil fuel that increases the most in production and consumption. The incremental increase last year was larger than the total production of renewables.

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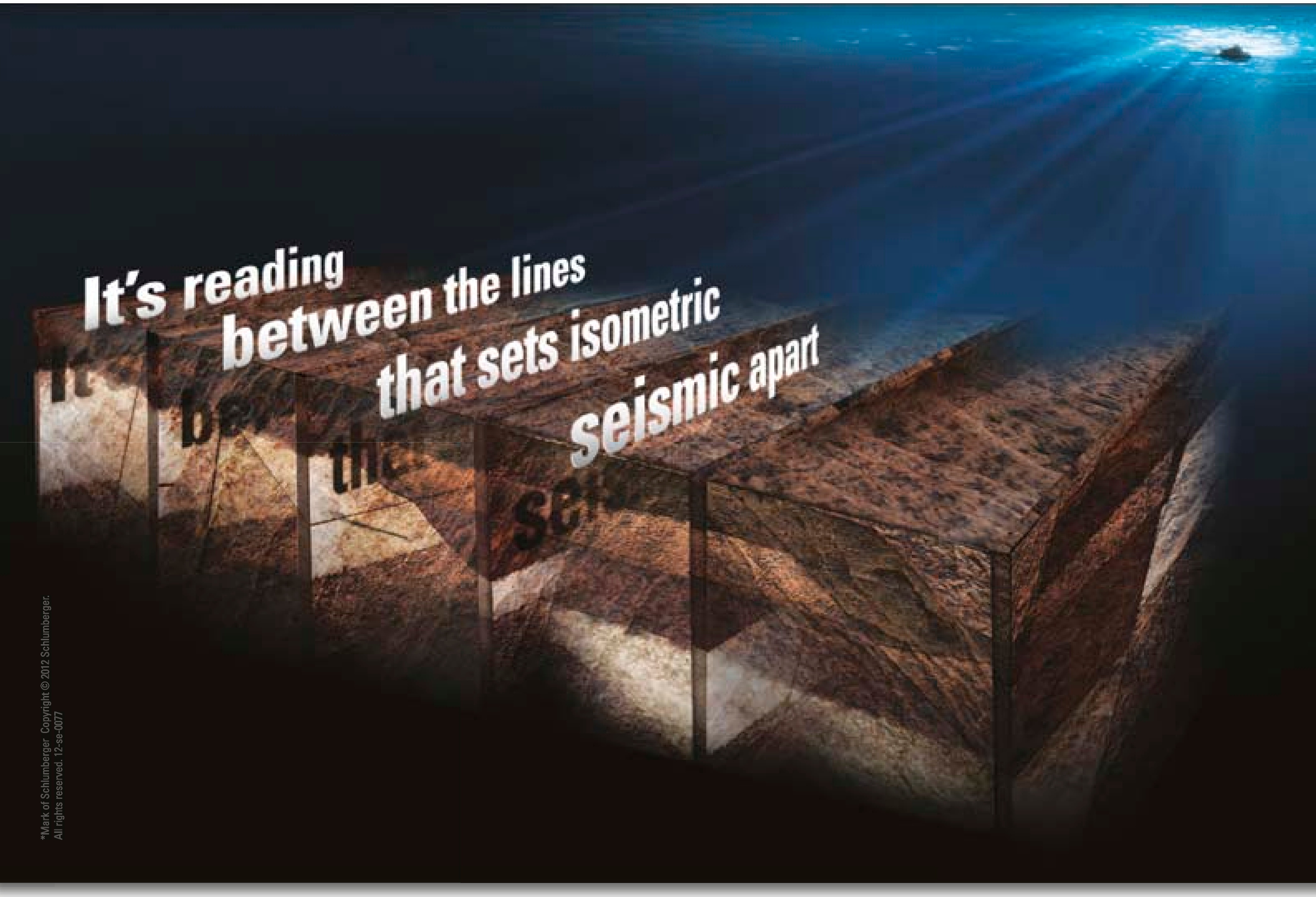

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