Vol. 1. no. 3 – 2004

GEO ExPro

GEOSCIENCE & TECHNOLOGY EXPLAINED

Geology

Richard Hardman

Billions of barrels to his credit

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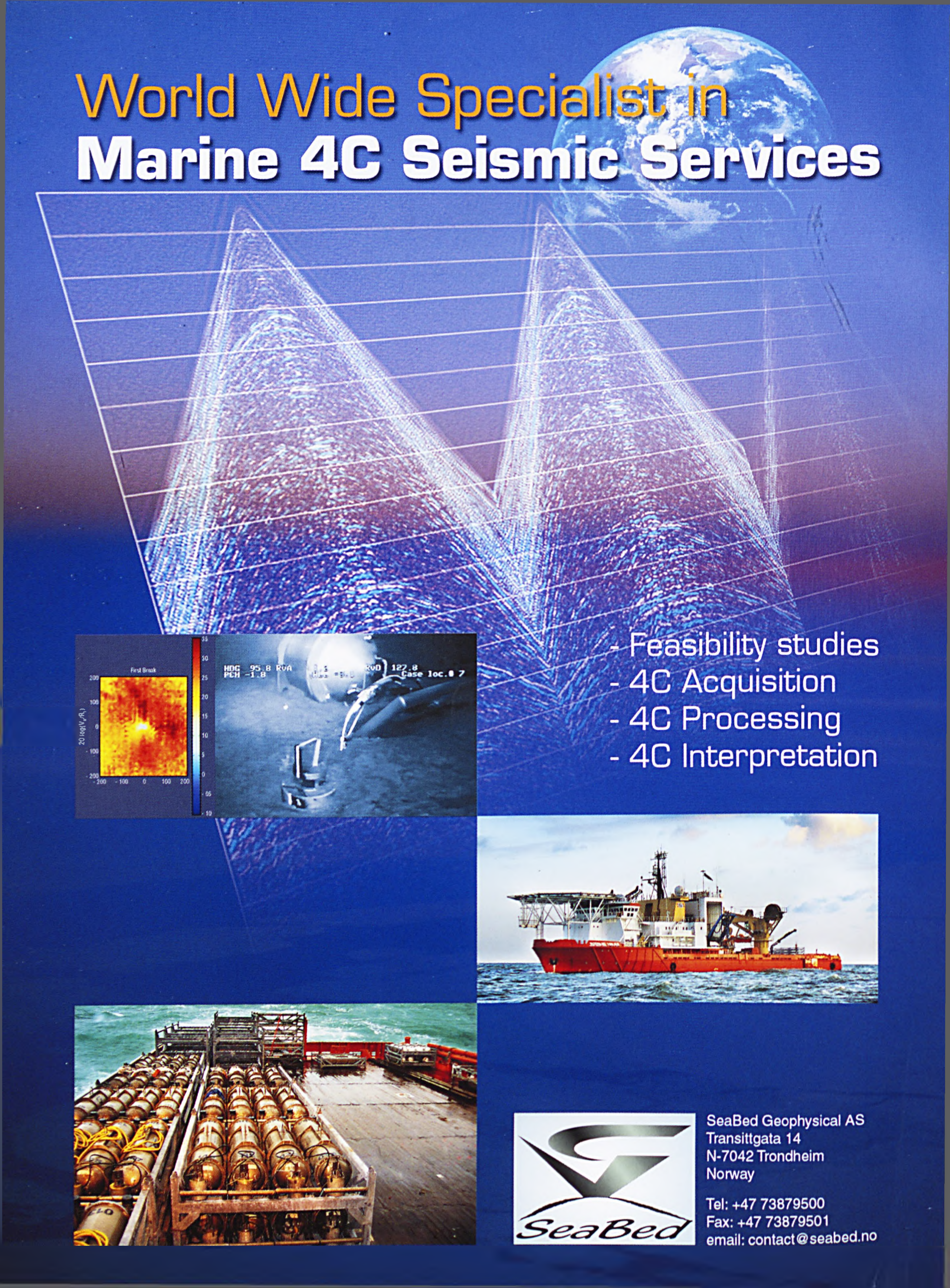
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GEOSCIENCE & TECHNOLOGY EXPLAINED

Yemen has small reserves compared to its oil-rich neighbours. For the independents not hunting for elephants, exploration and development may, however, be a profitable game.

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Every morning drilling and petroleum engineers gather in the Onshore Support Center to discuss the drilling operations on the Kristin field in the Norwegian Sea. The use of modern technology makes it very easy to communicate with the rig.


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Improved knowledge required

World petroleum resources are dwindling. The numbers clearly show that we are replacing oil and gas reserves at a slower pace than we are producing them. According *IHS Energy*, close to 14 billion barrels (2.2 billion Sm^3) discovered last year replaced only 50 per cent of the production.

The present situation is very different from the 1960s and the 1970s when the industry discovered substantially more resources than they brought on stream. In 1980, following a series of successful years, including the discovery of numerous North Sea giant oil and gas fields, the gap between discovered resources and developed resources had reached a peak of 860 billion barrels of oil (137 billion Sm^3).

It is important to remember that the above numbers concern only conventional oil. There are several other energy sources that interest geoscientists, including conventional gas, coal (the world's coal resources are far higher than the oil and gas resources measured in energy equivalents), coal bed methane, gas hydrates, gas shales, oil shales and tar sands (the latter presently representing 1.7 % of the world liquid production), that may all prove to be crucial to fulfilling the energy needs of the future.

GEO ExPro No 2 dealt with gas hydrates in the deep marine and arctic environments that may constitute a future source of energy. The resource estimates are very approximate for several reasons. However, there seems to be a general agreement that there are vast amounts of gas left underground, and it may not be long before we start production: "*Most probably we will produce from this source of energy in 10-20 years time in order to cover the increasing energy demand,*" according to E. Dandy Sloan Jr. of Colorado School of Mines, Centre for Hydrate Research.

In this issue of GEO ExPro, we focus on oil shales that have been in use before oil was discovered in Titusville, Pennsylvania, in 1859. Large-scale production of this resource only takes place in Estonia where millions of tonnes of shales are combusted annually for production of electricity. Oil shales are abundant; particularly in the Rocky Mountains, and calculations show that oil extracted from oil shales represents a volume that could surpass the remaining oil reserves of the world.

There are several inherent problems in getting the energy out of both gas hydrates and oil shales. This is why we need to improve our geoscientific knowledge of these resources as well as inventing new technology to recover them.

Halfdan Carstens
Editor in Chief

Photo: Halfdan Carstens

Petroleum geoscientists have a need to study the real thing: rocks. To fully appreciate the value of geophysical maps, seismic data, well logs and other geological and geophysical data imaging the subsurface, it is useful to know what the sedimentary rocks and sequences look like in the real world. This is why geoscientists, reservoir and drilling engineers take field trips outside the urban sprawl where thick stratigraphic sections can be studied without being hampered by vegetation.

Richard Hardman, experienced petroleum geoscientist with an excellent track record, believes in "mental models" (pages 36-38), and the only way to build them is through observation.

This is also why the Norwegian University of Science and Technology takes their students to the Ainsa Basin in northern Spain for one week of intense learning. Eight hours are spent in the field describing rock sequences and building mental models, the rest of the day they are working with the data on their computers building imaginary logs and seismic sections.

Cai Puigdefabregas has intimate knowledge of the fluvial and deep marine sedimentary facies of the Ainsa Basin following decades of fieldwork. His style and talent for simplifying the complex geological processes make him a popular teacher.

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Hunting for Giants

In the offshore basins oil leaking from the reservoirs reaches the surface, usually in the form of oil coated gas bubbles, and then form slicks identifiable from satellites. This is to the dampening effect of the oil on the wavelets, which produces an area of relative calm compared to the background waves. Satellite data extracted by INFOTERRA indicates that the onshore petroleum system continues offshore. The 3D seismic survey will be acquired within the seep area.

Tunisia, squeezed in between Libya and Algeria, dwarfs both neighbours in fossil fuel resources. The country's oil reserves are, according to BP Statistical Review of World Energy, in the order of 500 million barrels.

Extensive hydrocarbon investigations offshore Tunisia has principally been concentrated within the Gulf of Gabes and the Gulf of Hammamet. A recent geological evaluation of the northern offshore region of Tunisia by ETAP, the national oil company, has given fresh hope to the existence of 'giant' fields (that is fields with reserves in excess of 500 million barrels of oil equivalents).

"With production rates of 80,000-100,000 barrels per day of oil, Tunisia is looking into the future with the possibility of finding new fields equivalent to El Borma (operated by Agip), Ashtart (operated by OMV AG) and Bouri (Libya, operated by AGIP)," says Exploration Advisor, Mark Spencer Jones of PGS Geophysical AS.

With the assistance of a number of contractors the Tunisian government and ETAP are now attracting foreign firms to fund exploration of offshore areas in the Gulf of Hammamet and off the northern coast, as well as onshore in the northwest and other parts of the country.

Exploration frontiers

Northern Tunisia corresponds to a fold thrust belt linking the North African Atlas and the Sicily Apennine chains, all belonging to the Mediterranean arc that came into existence during the Tertiary following the collision between the African and European plates. This overthrust belt contains the giant Val d'Agri oil field in the southern Italy, the Gagliano gas condensate field in central Sicily and oil fields in Algeria where it is known as the Atlas thrust belt.

The Numidian petroleum system belonging to the thrust belt has a play concept, which has already been proven in Sicily. In Tunisia, this petroleum trend corresponds to the northern offshore area where, based on a recent interpretation by ETAP, many prospects and leads have been identified.

"The Numidian petroleum system provides turbiditic sand bodies, a petroleum charge system comprising thermally mature source rocks, a regional topseal provided by shales and traps which are both structural and stratigraphic," says Spencer Jones.

"Existing 2D seismic already suggests a series of undrilled leads on a NE – SW trend. It is also apparent that they can be sufficiently defined for drilling utilizing more modern reprocessing and new 2D/3D seismic," he adds.

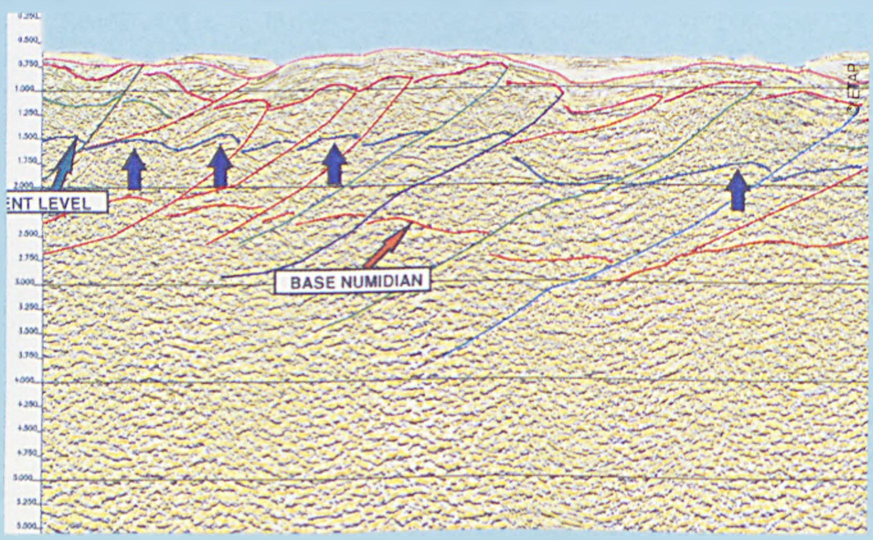
The geological groundwork, which has been carried out in collaboration with ETAP, has motivated PGS to acquire a 2D survey and 1000 sq km of 3D seismic. This data will form the basis for a future Tunisian license round during 2005/2006.

"We believe the overthrust belt offshore Tunisia has the potential for giant oil and gas fields. The assumption is based on geological correlations with the continuation of this belt into both Algeria in the west and Sicily in the east where several giants have already been discovered," says Spencer Jones.

Favourable Terms

"With the new hydrocarbon law effective since 2000, favourable fiscal regulations, flexibility of licensing procedures and a renewed emphasis to negotiate most terms Tunisia are attracting new entrants. Tunisia is also providing great opportunities for foreign direct investment due to its proximity to developed countries and its close ties with the European Union."

"The government sees the development of its natural gas reserves as a 'strategic objective' for the country as it is estimated to meet approximately 50% of the country's energy demand in the long term," says Mark Spencer Jones.



Seismic line through the overthrust belt.

Gas burn-off

National Geographic has published an updated version of their Lights of the World map, which is a composite of satellite images from cloud-free nights gathered over a one-year period. The most obvious feature is how developed nations are using substantially more energy than poor nations.

Another striking feature of this map is the burn-off of natural gas in places like West Africa (in particular the Niger Delta), North Africa (Algeria and Libya), the Middle East and western Siberia in Russia. The reason being that they are too far away from any market and is therefore considered a waster during oil production. According to National Geographic, more than 100 billion cubic metres of natural gas are burned off every year. This is roughly 5 percent of the total production of natural gas in the world. For comparison, the annual production of sales gas in the UK is slightly higher than 100 billion cubic metres.

"Nigeria alone emits up to 20 percent of the world's flares, which adds to atmospheric pollution," writes National Geographic. That's an understatement.

Selected by PETRONAS

Roxar has recently won a US$1.73m contract from PETRONAS Carigali Sdn Bhd for the supply of reservoir modelling software and related training and consultancy services over the next three years.

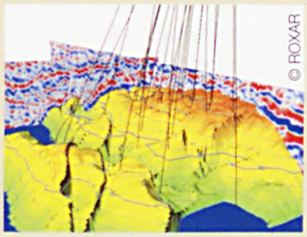
"This agreement represents a major milestone for us in the Middle East and Asia Pacific region," said Morten Tønnesen, Regional Manager of Roxar Software Solutions, Middle East & Asia Pacific. "It recognizes our expertise and commitment to working in partnership with our customers to help them to optimise reservoir performance and maximize the value of their assets," he added.

PETRONAS Carigali's domestic and global asset team of geoscientists and engineers will use Roxar's Irap RMS software to optimise reservoir performance and recovery in PETRONAS' operated assets in South East Asia, Middle East and North Africa.

Roxar's Irap RMS consists of a suite of easy-to-use software modules including mapping, modelling, flow simulation, well planning and workflow management tools. PETRONAS Carigali's asset team will be able to run the system on Windows, Linux and Unix – on both desktop and portable PCs.

PETRONAS Carigali Sdn Bhd, is the wholly owned exploration and production arm of PETRONAS (Petroliam Nasional Berhad), which is Malaysia's national petroleum corporation. Wholly-owned by the Government, the corporation is vested with the entire oil and gas resources in Malaysia. Since its incorporation in 1974 PETRONAS has grown to be an integrated international oil and gas company with business interests in 35 countries. PETRONAS Carigali has exploration and production interests in Malaysia as well as in more than 20 countries around the world.

Roxar provides software solutions and related services from Europe, Africa, the Americas, Middle East, Asia Pacific and CIS. Roxar recently announced expansion plans for its Middle East and Asia Pacific (MEAP) operations to service its growing client base. Customers in the region include Saudi Aramco, the ADNOC group of companies, Kuwait Oil Company, Dubai Petroleum Company, PETRONAS, PetroVietnam, and Santos as well as global accounts ConocoPhillips, Total and BP.



New vessel

Multiwave Geophysical has brought a new vessel into operation as the company gears up for a major seismic acquisition campaign in the Mediterranean which is due to start this fall. The vessel, C-Orion, has been rigged by Multiwave specifically for the project, which will include a large-scale 2D survey and 3D program.

Specifically designed for acquisition of deepwater seismic surveys, the C-Orion is a 6-streamer vessel and provides a high capacity 3D solution for the delivery of the highest quality data. As such, it is perfectly suited to the needs of Multiwave's clients worldwide.

Largest ever

WesternGeco has just recently started to acquire and process a 1520-square-kilometer 3D marine seismic survey over the Marlim complex, offshore Brazil, on behalf of Petrobras. The survey will be completed within five months.

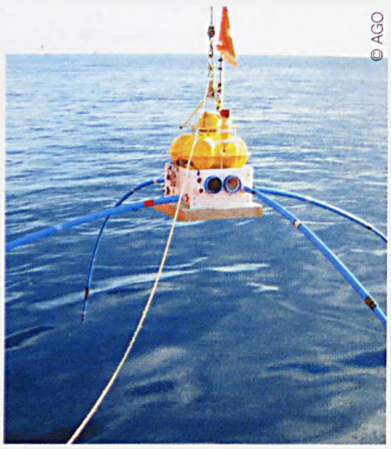
The Marlim complex, comprising the Marlim, Marlim East and Marlim South fields, is the largest deepwater producer of oil and gas in the world.

"The survey of the Marlim complex will be the largest 4D acquisition and processing project undertaken in the petroleum industry," said Paulo Johann, coordinator of reservoir characterization technology, Petrobras.

The Q-Technology vessel Western Pride will tow 10 x 6000-meter cables with 50-meter streamer separation, resulting in the same data density used by Petrobras in all of its current projects. The survey will comprise the baseline against which future surveys will be compared to monitor fluid movement for reservoir characterization and asset management.

Competition in sea bed logging

Arnold Orange (right) and David Peace represented the new provider of electromagnetic services at this year's SEG exhibition in Denver. "We believe that this technology has considerably more potential for enhanced applications with better economics than what has been demonstrated to date, " they say.



The new technology has been discussed in the 2 previous issues of GEO ExPro. It utilizes a ship that tows a dipole source just above the seafloor, with an array of electromagnetic receivers positioned (shown here) on the seabed. On-board processing of the deep resistivity data thus obtained can confirm the existence and extent of hydrocarbon bearing zones. This method has been coined "sea bed logging" by the Norwegian company Electromagnetic Geoservices (emgs).

With the recent acquisition by Schlumberger of the privately held AOA Geomarine Operations (AGO), the Norwegian company Electromagnetic Geoservices (emgs) has got a strong competitor (see articles in GEO ExPro Vol. 1, Nos.1 and 2). AGO says they are presently working with several clients in preparation to perform multiple sea bed logging surveys in 6 continents around the world.

AOA Geophysics was founded more than 25 years ago by Arnold Orange, one of the few world experts in the use of electromagnetics (EM) for oil exploration.

"Deep resistivity measurements are important in determining the presence of oil and gas accumulations, particularly when used in association with other data sources," said Dalton Boutte, executive vice president of Schlumberger and president of WesternGeco following the acquisition. AGO will continue normal operations as a Schlumberger Company under the ongoing leadership of Lionel Fray, AGO president and CEO.

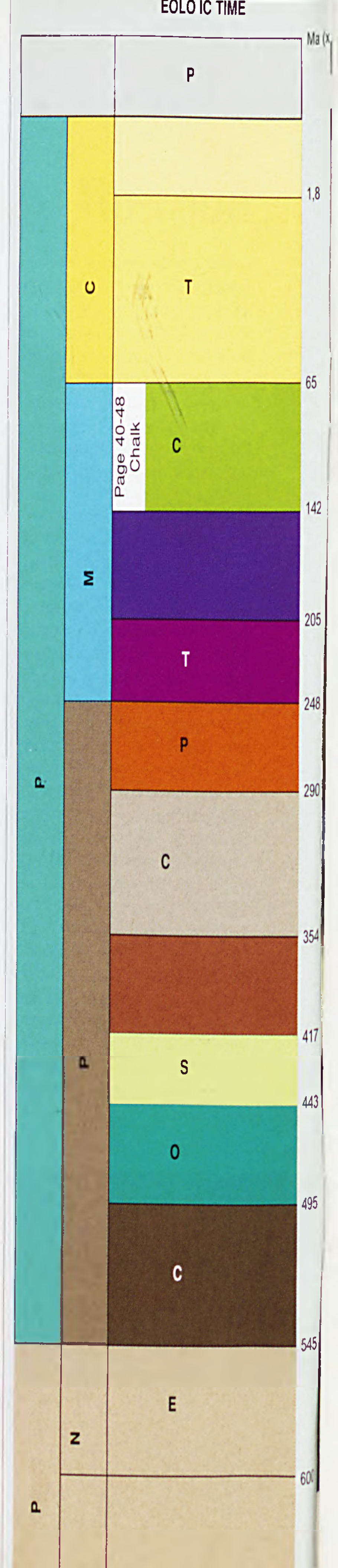
AGO believes that Marine Controlled Source Electromagnetic (MCSEM), which is their name for this new technology, can significantly reduce the risk during appraisal. "It permits a more accurate definition of the reservoir extent than previously possible from only seismic and AVO. This can reduce appraisal and development well costs and better indicate reservoir extent," according to Lionel Fray.

Once proven in an area, electromagnetic surveying, sea bed logging or MCSEM, according to what you prefer, has the potential of reducing risk in both near-discovery satellite structures and other exploration leads in the same geological setting. Reservoir management is thus likely to be a future application in which the technology would enhance and possibly compete with 4D surveys to determine what is left in the reservoir during production.

AOA played a key role in the early sea trial experiments that were done for Statoil and ExxonMobil in 2000 and 2001, and which later ended up in the founding of emgs. To commercialise the technology, AGO was formed as a separate company. AGO obtained a long-term charter of the Norwegian ship Polarbjorn to conduct sea bed logging operations for ExxonMobil.

The EM source used was designed and built by Southampton University, and data interpretation was performed by ExxonMobil. AGO ran more than a dozen surveys, placed hundreds of receivers on the seafloor, and towed the EM source over numerous survey lines.

Today, AGO is a full-service "Marine CSEM" company, offering 1D and 3D prospect modelling, survey planning, survey equipment and boat operations, onboard data processing, and integration of sea bed logging results with existing seismic and other tools to provide the exploration decision-maker with an optimised drilling target.



Unmanned surveying

Terence McConnell points towards the GEORANGER I model displayed at this year's SEG exhibition.

Following a two-year research and development programme, Fugro Airborne Geosurveys has introduced a new high-resolution unmanned aeromagnetic survey system to both the petroleum and mining industries. The purpose is to provide safe and efficient alternatives offshore and in remote locations.

The GEORANGER I has an endurance of over ten hours and cruises at 75 km per hour. Using a point location launch and recovery system, it can be operated from undeveloped sites in close proximity to survey areas.

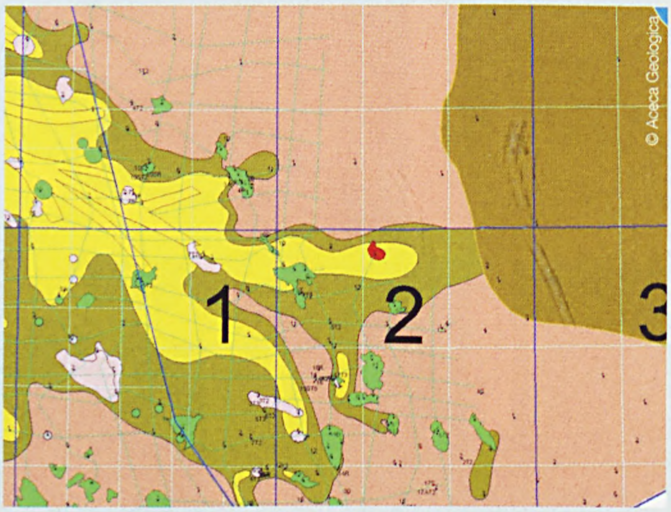
Fugro has conducted their initial airborne trials and test surveys, and is now being flown on sponsored non-exclusive surveys.

Modelling depositional systems

Models for depositional systems are the fundamental building blocks for hydrocarbon play fairway mapping. In turn, this is also the foundation for modelling of petroleum systems and hydrocarbon exploration in any given basin.

Aceca Geologica has developed an intranet solution for subsurface teams to share knowledge of depositional systems. Their Dynamic Facies Map Bowser (FMB), as it is called, is the flagship product for Aceca Geologica. "The FMB captures the mapped distribution of depositional systems and presents the borehole evidence for the model as each downhole section samples the model. A seismic facies investigation extrapolates the model into the "soft" geophysical data to provide control away from the "hard" borehole evidence," says director Ingvar Mikalsen of Aceca Geologica to GEO ExPro.

"All subsurface models remain contentious to a lesser or greater degree. An important aspect of any model is thus to have an understanding of the information upon which that model is based. The FMB provides that context, a very powerful aspect of the system," Mikalsen adds.



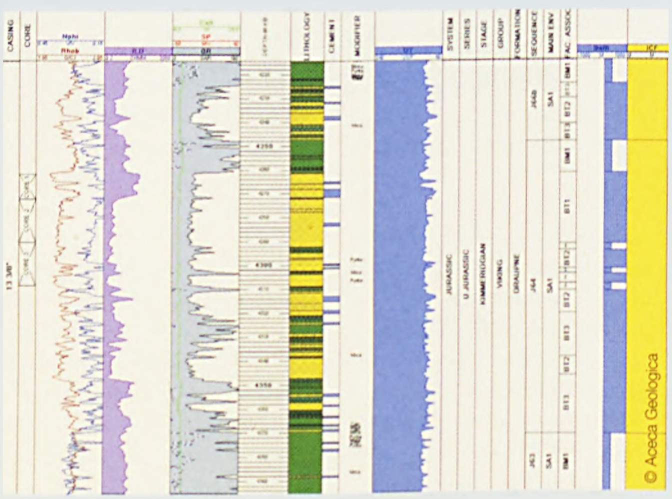
Sand fairway distribution of a Tertiary basin floor fan system of the Central North Sea.

Assessing models and pushing data around can be an arduous task. Enhanced workflow such as that adopted by the FMB has the potential to make this activity entirely transparent to the user.

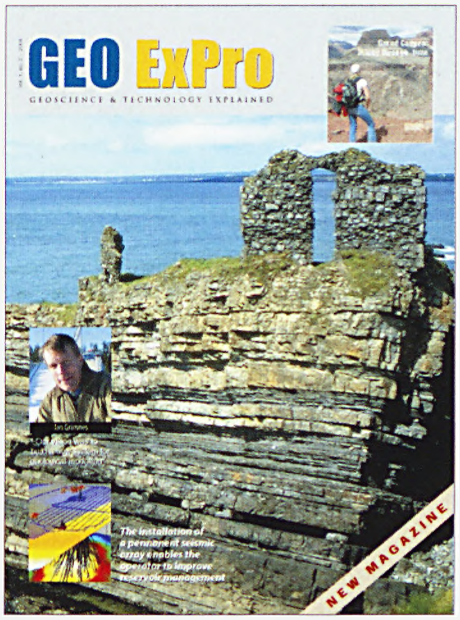
Building upon GIS, the FMB enables the review of depositional systems models as maps across the basin or in each well bore in the basin, and the extrapolation of these models through the soft seismic data. Raw data to corroborate the depositional systems interpretation is always close at hand.

"Knowledge management is a challenge for all companies, and even more so for explorers working in the subsurface realm. The capture and database of recorded and analytical data is relatively straightforward in comparison to the task of sharing subsurface knowledge and experience, and retaining this knowledge for the benefit of the company. In their field of expertise Aceca Geologica has probably achieved more than most in this respect," Mikalsen says.

Phillip Slater, Managing Director of Aceca Geologica comments: "The Dynamic FMB is currently drawing a lot of attention. This is in part due to the extensive geographic footprint we have obtained by offering our product over the larger part of the North Sea. Another reason may be that we are assisting both established players and new entrant companies to improve the efficiency of their workflow. Strategic alliances such as that with PGS for our use of well tie profiles extracted from the Mega Survey ensure that the FMB is unrivalled in all aspects."



WellPanel presents borehole data.

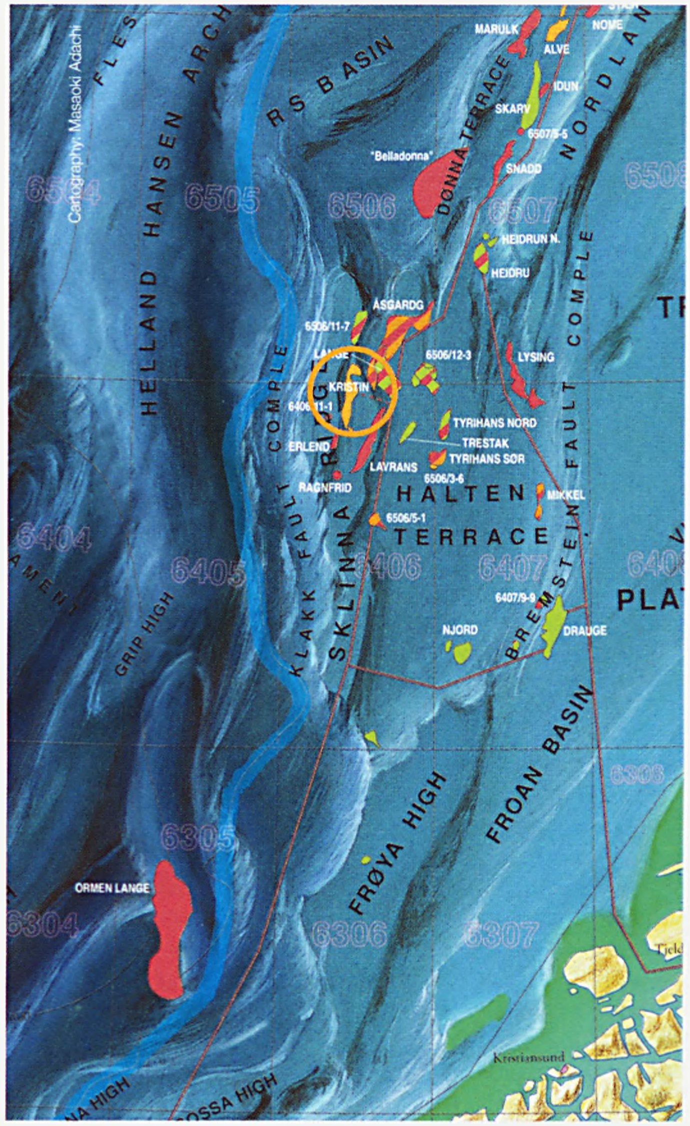


Did the Golden Zone theory surprise you?

'It's the temperature that counts'

Kristin – a tough lady

A deeply buried reservoir – characterised by ultrahigh pore pressures and temperatures – represent a major challenge for both petroleum and drilling engineers. To minimise risk and maximise the collaborative efforts within the project team the operator focuses strongly on integration.



Structural map of the Norwegian Sea shows the relief at the base Cretaceous level. The 500 m contour drawn on top of the geological features separates shallow water from deep water (blue curve). The Norwegian independent Saga Petroleum discovered Kristin in 1996. It is located next to a number of other Norwegian Sea oil and gas fields within the geological province named Halten Terrace.

The Kristin Onshore Support Centre (OSC) is the heart of the marine operations carried out several hundred kilometres away in the rough Norwegian Sea. Images and data from the drilling and logging operations are transferred directly – in real time – from rig to land using fiberoptic cables and then displayed on three large wall monitors.

A centre like this facilitates close cooperation between operator, rig contractor, suppliers and service companies, which is essential in such demanding drilling and completion jobs. Daily videoconferences between the land organisation and the rig strengthen coordination and communication. Access to data and visualisation of shared information are absolutely essential for analysis, the best possible location of wells and handling the challenging reservoir conditions.

In the support centre geologists, reservoir engineers, drilling engineers and specialists from other key disciplines follow the work on the two drilling rigs, Scarabeo 5 and West Alpha, that are currently drilling simultaneously.

Halfdan Carstens

Kristin is different. Very different from almost any other oil and gas field, not only in Northwest Europe, but also in the rest of the world. And this is why it represents an unrivalled challenge for the operator, the partners and a series of service companies that are intimately involved in development of the field.

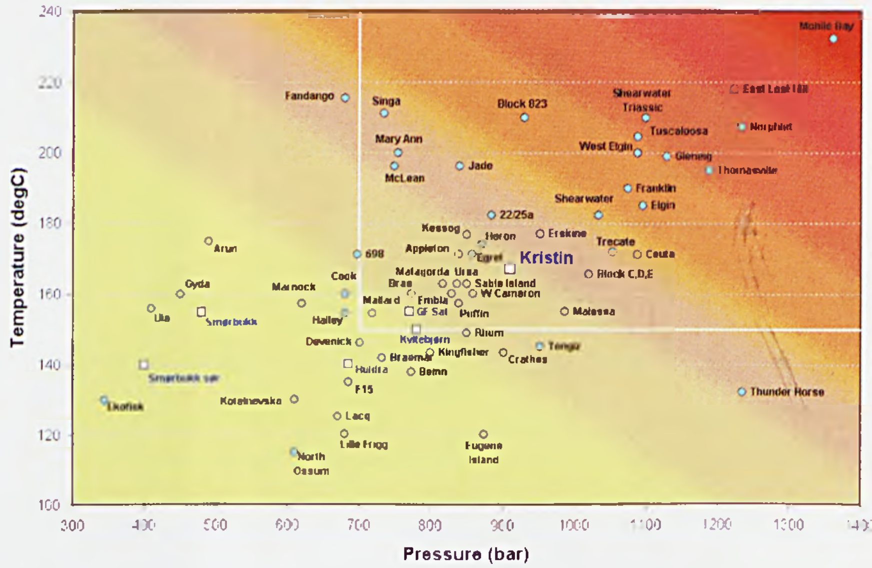
Production startup next year

Kristin is a huge gas field in the Norwegian Sea. It is situated just below the Arctic Circle and about 240 kilometres off the Norwegian coastline. The first strike was in 1996, when Saga Petroleum as operator drilled the discovery well based on a new exploration concept. Most experts believed that porosities and permeabilities would be too low at this reservoir depth, but the exploration team in Saga thought otherwise and set their target at 4500 m below sea level in 350-370 m of water depth. The well came in successfully, with gas in two separate formations and with high porosities down to almost 5000 m. A new field had been discovered and a new play concept had been defined.

Three appraisal wells were subsequently drilled, including one side-track, proving a substantial discovery. Statoil took over as operator on 1 January 2000, and the plan for development and operation (PDO) for the Kristin field was approved by the Ministry of Petroleum and Energy in Norway on 17 December 2001. Kristin is due to start producing gas as planned on 1 October 2005.

The original budget for the development of this field was approximately USD 2,5 billion. It has, however, lately been recognised that the field is probably more complex than previously thought. The Kristin Owners have consequently increased the budget by USD 250 million in order to implement a modified drainage strategy. A new drainage strategy is expected to boost both condensate recovery and revenues.

The partners in the field are ExxonMobil, Eni, Norsk Hydro, Petoro and Total.



An HPHT-field is defined as having reservoir pressure and temperature higher than 690 bar and 150 °C. Kristin is well within these limits, along with a few other North-West European fields like Embla, Kvitebjørn (both Norway), Franklin, West Elgin and Elgin (both UK). Thunder Horse in the Gulf of Mexico, is characterised by extremely high pressures (1240 bar), equivalent to a burial depth of 12,400 m in a normally pressured environment (hydrostatic pressure).

Classified as HPHT

The favourable reservoir properties had to do with an abnormally pressured reservoir, which means that the pore pressures in the formation fluids are higher than the hydrostatic pressure and lower than the overburden pressure.

In the case of Kristin, pore pressures are close to the overburden pressure. Measurements showed that the reservoir pressure is above 900 bar; that is, 900 times the atmospheric pressure and equivalent to a normally pressured reservoir buried at 9000 m.

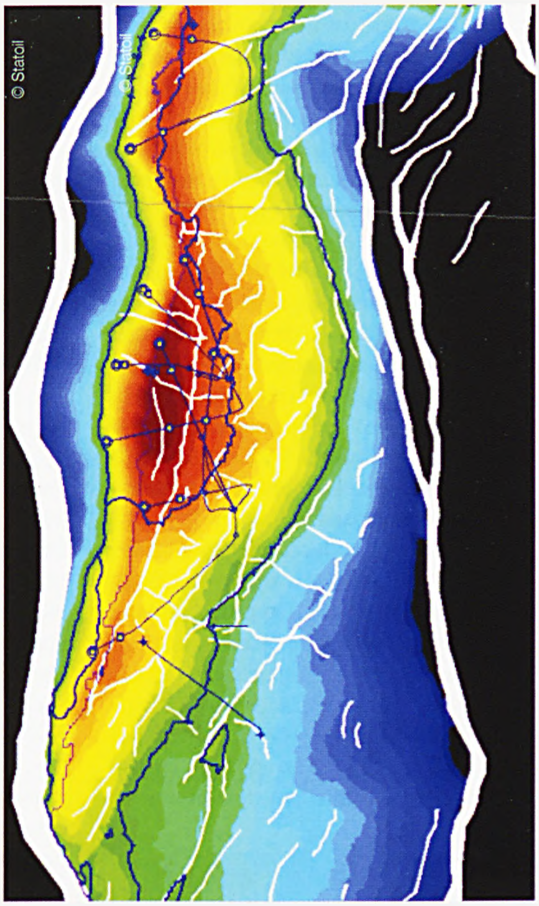
In itself, the high pressure is a challenge, but, in this case, the real challenge is the small difference between the pore pressure and the fracture pressure.

It also means that one cubic metre of gas in the reservoir becomes almost 1,000 cubic metres at the surface.

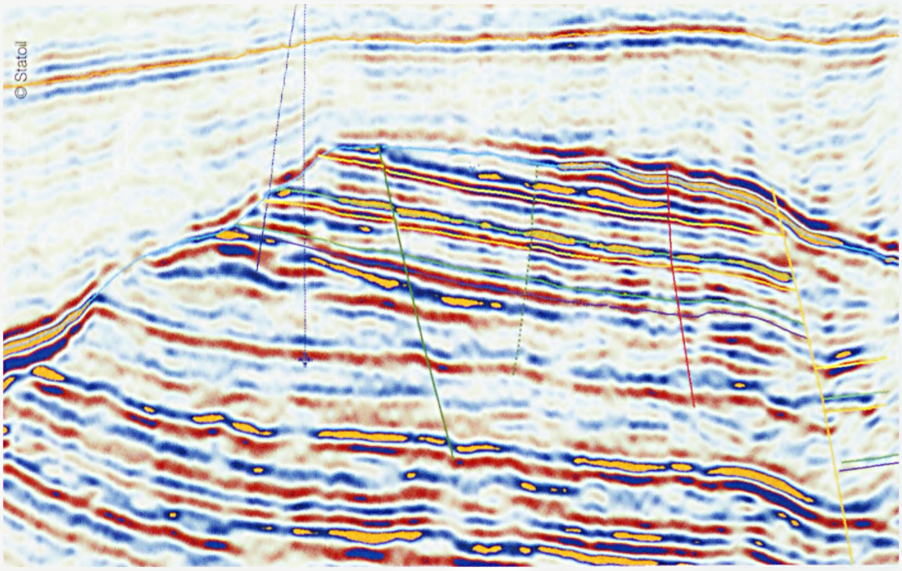
In addition to the extremely high pressures, the temperature in the reservoir is 170 °C, well above "normal" conditions that the oil companies are facing in neighbouring fields. With only one exception, both the reservoir pressure and temperature of Kristin were higher than in any other oil and gas field so far developed offshore Norway. The field was therefore a classified as a "HPHT" (High Pressure High Temperature) reservoir.

To qualify as an HPHT reservoir, one of two criteria need to be met: Wellhead equipment must handle a pressure of more than 690 bar, and/or the formation temperature has to exceed 150°C. Very few reservoirs belong to this class. In fact, as shown in the graph, there are only a few fields around the world with comparable reservoir conditions.

Torolf Christensen is petroleum technology manager on Kristin. He and his colleagues seek to use their familiarity with the reservoir to determine the best location for each well. He also heads work on the drainage strategy, after which an experienced team of drillers must ensure that the wells accord with the chosen approach.



Kristin is a four-way dip closure defined at the Base Cretaceous level. Four exploration and appraisal wells were drilled on the field before the plan for development and operation (PDO) for the Kristin field was approved in 2001. The map also shows the path for the production wells, which are drilled from four templates.



This east west seismic section through Kristin illustrates the structural closure defined by the prominent marker at the base of the Cretaceous shales (coloured in blue). Three reservoir levels (Garn, Ile and Tofte) are defined by east dipping reflectors transacted by normal faults. Two 3D seismic surveys have been acquired, the last one in 2003. It covered the central part of the field, and the lead-time from the idea of acquiring more seismic to processed data was, according to the operator, extremely short. The reason for this hurried work was to ensure that the data could be used to place the production wells, which were in the process of being drilled, in a best possible position. "The purpose was to get a better understanding of the fault pattern, and this goal was achieved as we moved some of the wells. In this way we were also able to reduce the risk, even if it is still an unresolved task to tell if the faults are sealing or not," says Torolf Christensen.

The Norwegian Sea

Following more than 20 years of exploration in the Norwegian Sea, it can be concluded that this vast geological province has proven to be a success story for many oil companies as well as for Norway.

Last year, the daily production averaged 780.000 BOPD and 33 million Sm^3 of gas per day, and according to estimates released by the Norwegian Petroleum Directorate (NPD), the original proven reserves are 3,9 billion bbls of oil (625 million Sm^3) and 500 billion Sm^3 of gas from fields that are already in production or under development.

The oil production offshore Mid-Norway is fairly similar to the output from countries like Angola, Argentina, Australia, India, Malaysia, Kazakhstan and Qatar, while the daily gas production equals that of the giant oil and gas field Ekofisk in the North Sea.

All but two discoveries are made in shallow water (< 500 m). This sector of the Norwegian Sea has now reached a mature stage in line with most of the North Sea.

In shallow water, the play concept is largely with Lower and Middle Jurassic reservoir rocks and Upper Jurassic source rocks.

Deep-water (> 500 m) exploration in the Norwegian Sea was initiated in 1995. This also meant that exploration moved further offshore, into deeper sedimentary basins and testing progressively younger reservoir rocks. To date, nine years after the campaign started, only seven prospects have been drilled. The exploration of the deep-water sedimentary basins has therefore been slow. Two gas discoveries, the giant Ormen Lange in the Møre Basin and Nyk in the Vøring Basin, of which Nyk is so far subcommercial, give a success rate for the combined basins of close to 30%.

Production concept

The reservoir is due to be drained through 12 subsea wells. Four subsea templates installed on Kristin will be tied back to a floating production platform moored on the field. The daily production capacity is 126,000 barrels of condensate and just over 18 million cubic metres of rich gas.

The development solution involves coordination with Statoil's nearby Åsgard field for condensate storage and gas export through the Åsgard Transport pipeline. This integration also involves use of the Kårstø complex north of Stavanger for further processing and the gas transport network from there to continental Europe. Stabilised condensate (light oil) will be exported by storage ship.

The challenge was then immediately transferred from the explorationists to the engineers who got the task of developing the field. Says Kristin project director Nina Udnes Tronstad: "This reservoir – located almost 5 000 metres beneath the seabed – calls for innovative technology."

Good reservoir conditions

"The field has three formations that are gas bearing – Garn, Ile and Tofte – which are all Jurassic sandstones deposited in shallow waters separated by impermeable shales. The hydrocarbons lie in a 300-metre thick zone at a depth of 4,500-4,850 metres," says petroleum technology manager Torolf Christensen of Statoil.

The field will produce a rich gas, which will be separated into methane (CH_4), natural gas liquids (NGL), primarily ethane and propane, and light condensate. Reserves in Garn and Ile are estimated to 35 billion Sm^3 of dry gas (1,225 billion cu ft), 9 million tonnes of NGL and 35 million m^3 (219 million barrels) of condensate. Hence, the Kristin field is also classified as a *giant field* (reserves higher than 500 million barrels of oil equivalents) in a world context. The recovery rate is estimated to close to 50%.

When put into production, the plateau level of approximately 17 million m^3 of gas per day (the capacity is 18.3) will last for approximately 2 years. Production will continue through 2016, and even longer if neighbouring fields are tied into the production unit.

Two-thirds of Kristin's reserves lie in the uppermost formation (Garn). This formation also poses the greatest uncertainties because the rocks are "tight", i.e. relatively impermeable to hydrocarbon flow. "Porosities in both Garn and Ile are close to 20%. There is, however, a considerable difference in permeability. While 100–1000 millyDarcy is typical of the lower Ile formation, and in some places also exceeding 1 Darcy, typical values for the upper Garn formation are 0.1-10 millyDarcy, with occasional zones having permeabilities up to 50 millyDarcy. The lower limit for producing gas is in the order of 1 millyDarcy, even if zones with even lower permeability are expected to contribute to the production," says Christensen.

The first production well drilled this year proved gas in the lowermost reservoir formation. "Although only one well has penetrated the deep Tofte formation, we believe that another 8-10 billion Sm^3 of dry gas may be present in this sandstone. With a recovery factor of close to 50%, we have discovered "a small field" that will eventually also be put into production," says Christensen.

The semi-submersible platform will be installed on the Kristin Field in March 2005.

Striking a balance

High-pressure wells like the ones that are drilled on Kristin present special challenges. With exceptionally high pore pressures, the difference between the pore fluid pressure and the fracture pressure is very small. Hence, the margins are narrower than with conventional producers, thereby substantially narrowing the driller's working window.

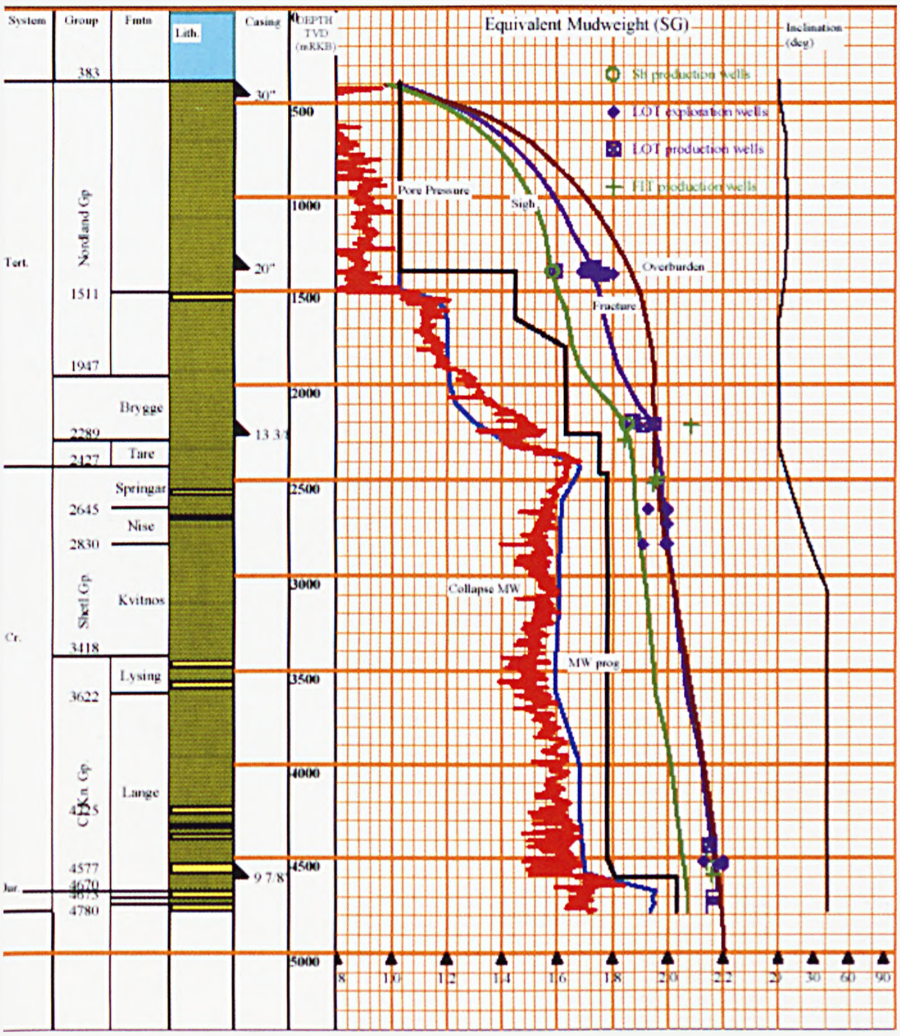
One highly significant factor for achieving a good result is the kind of drilling mud used to lubricate, cool and keep pressure under control. If the mud is too heavy, the subsurface rocks could fracture. But an excessively light mud might, in the worst case, allow a "well kick" or an uncontrollable blowout. Experience from other North Sea fields (compare HPHT-graph) has been useful in this context, and following some "trial and error" attempts an oil-based mud is now applied in the drilling at Kristin.

"The reservoir is characterised by pore pressures that are almost the same as the fracture pressure (the strength of the rock). As soon as the gas starts flowing and the reservoir is being depleted, the pore pressure in the reservoir will begin to fall. What will actually happen to the strength of the rock when this happens, however, is still uncertain," says Christensen. "It should therefore be obvious that what we are doing in developing Kristin is "breaking boundaries". We learn by doing," he adds

"The difference between the pore pressure and the fracture pressure is so small that we will not drill into the reservoir after the pressure has fallen more than 10 bar. This is why all 12 producers must be drilled and preferably completed before production startup. We simply can't take the risk of drilling wells when the margin between the reservoir pressure and the fracture pressure becomes so small," Christensen says. "However, we are working towards extending the 10 bar limit. This will require a lot of technical qualifications based on thorough studies and a good understanding of the pressure regimes in the reservoir. Our ultimate goal is to extend the 10 bar limit to 100 bar."

Nevertheless, Christensen can foresee that additional wells will be drilled in the future. It may be necessary in 3-4 years time to use mud weights that are lower than the pore pressure. "This is known as underbalanced drilling and is an even greater challenge for the drillers. Our motivation is that the reward may be high, as infill drilling is expected to be a major contributor to enhance gas recovery."

"Another uncertainty is whether the faults in the reservoir are tight and thereby block the movement of gas and condensate. The reservoir specialists are unsure



© Statoil

The pressure profile for a well on the Kristin Field clearly illustrates the small difference between estimated and measured pore pressures (blue curve) and fracture pressure (violet curve) in the reservoir section.

Thunder Horse

Located 190 km south of New Orleans in the Gulf of Mexico, the Thunder Horse field with recoverable reserves of one billion barrels (and possibly nearer three billion) is the largest discovery in the region to date. High pressures and high temperatures represent significant challenges.

The Thunder Horse reservoir lies beneath some 4000 m of mud, rock and salt and 1900 m of water. To reach the hydrocarbons requires some of the longest deviated wells in the world, which when they enter the reservoir are greeted by a combination of formation pressure and temperature rarely encountered in the Gulf of Mexico or anywhere else – more than 1200 bar and 135 °C. According to the operator BP, the Thunder Horse development represents one of the most ambitious offshore field developments ever undertaken.

The Thunder Horse discovery well was drilled in 1999 to a depth of almost 8000 m. It found 160 m net of pay in three intervals. Thunder Horse 2 was drilled in 2000 and reached its total depth of almost 9000 m.

Initial production is expected by 2005 from a floating production facility that will be capable of producing 250,000 bbls of oil per day, at peak rate.

whether the various sections of the reservoir are in communication with each other, or sealed into separate compartments, small or large. The properties of the largest reservoir, the Garn formation, do also represent an uncertainty as to how much each well will produce under low permeability. We will consequently be very curious when we start producing this reservoir next year."

"Good insurance against the uncertainties posed by this reservoir is to drill long "horizontal" wells, which give robustness for drainage and production," says Christensen. "In fact, our production wells are not horizontal because this may cause a problem when producing gas. Instead the wells are high angle, and we have coined the wells High Angle High Pressure High Temperature (HAHPHT) wells.

"HAHPHT-wells are a tremendous challenge and push the limits of what can be achieved in the drilling industry. Only a few months ago we completed a 6000 m well with an angle of 75° (90° is horizontal). This is definitely a major step forward for the drilling industry and probably qualifies as a world record," says Christensen.

Only after Kristin has been on stream for a while can the specialists in the relevant disciplines evaluate how the reservoir behaves in this phase.

Teamwork

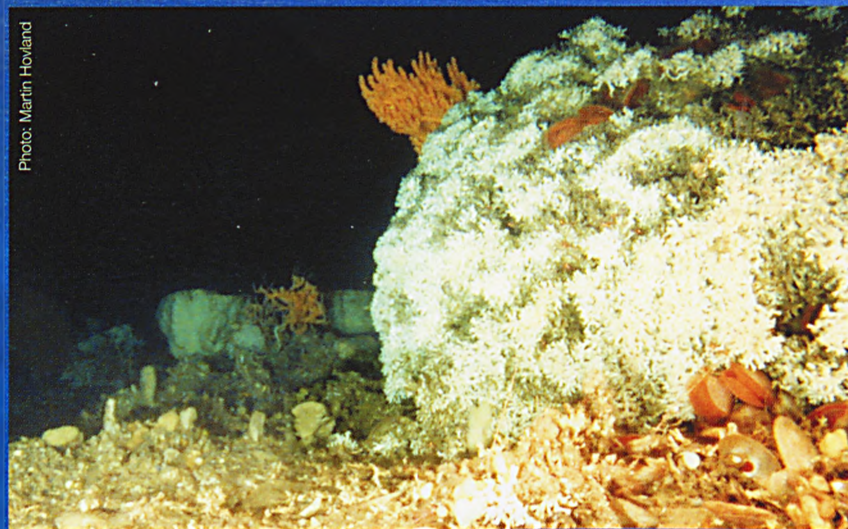
"In this project we focus on risk management. We believe it is critical to calculate the probability for certain events to happen and to determine how we can actually avoid problematic situations during drilling or production," Christensen says.

To solve the many challenges presented by this project, the various specialist groups in Statoil have collaborated closely from the start. Everything is closely interconnected – the development solution, the field drainage strategy and the choice of materials. In this way the project organisation has been able to break barriers, be they organisational or technological.

"This cooperative atmosphere goes beyond Statoil personnel. We also involve experts from the service companies (e.g. specialists in drilling or directional drilling) who all take part in our ambitious goal of being the "Best Integrated Team Ever", Christensen says.

This certainly explains why BITE is written on his teacup.

Coral reefs in the dark



Corals discovered in the area of Kristin.

Above the Kristin field on the Halten Bank, Martin Hovland in Statoil has found coral reefs in craters at a depth of 230 metres. These craters are thought to have been formed by seeping gas.

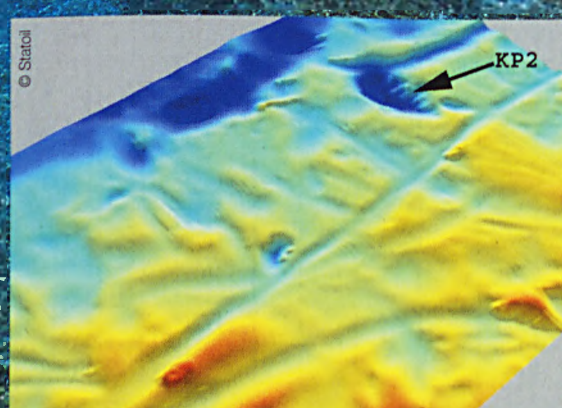
Oil and gas was discovered offshore Norway in the early 1970's. During detailed seafloor mapping for a gas pipeline in 1982, Statoil came across a 15 m high, 50 m diameter reef constructed by the frame-building coral *Lophelia pertusa*, the "Fugløy Reef", north of the Polar Circle. It was, however, not before the early 1990s that numerous large reefs were mapped and investigated. This time, they turned up during the mapping campaign for the 200 km long pipeline Haltenpipe, at 300 m water depth.

A cluster of 9 reefs was selected for future investigations and monitoring prior to the pipeline construction (completed in 1996). "This work has led to some interesting results, amongst which is the age of the reefs: the oldest piece of coral found in the sediments below this cluster is 8,600 years before present," explains Hovland. For comparison, the last ice age ended approximately 10,000 years ago.

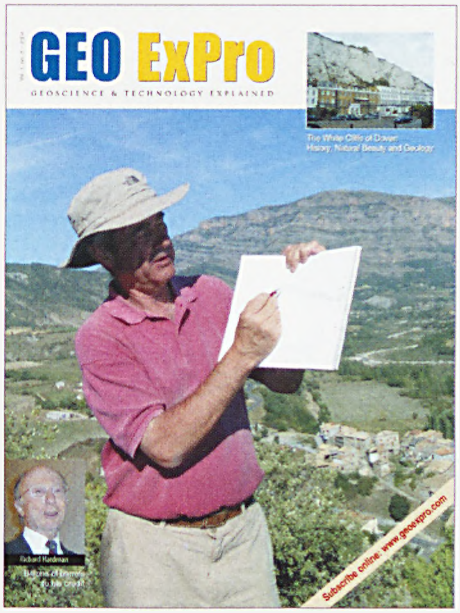
"At the Kristin oil and gas field, currently being developed, up to 3 m high coral reefs are found inside pockmark craters in the seafloor. The craters are up to 12 m deep and are formed by pore water and gas seepage," says Hovland. A total of four reefs have been targeted for future inspection and monitoring on this field.

The observed co-occurrence between corals and pockmarks suggests that gas and pore water emanating from pockmarks somehow stimulates coral growth, probably through the provision into the water column of a stable nutrient supply, suspected to be in the form of bacteria and micro-organisms. This theory has previously been called the "hydraulic theory" for coral reefs.

"The Kristin corals provide good support for my theory," says Hovland. "This also proves that the coral-associated bivalves thrive inside the craters. I suspect that inside the animals there are symbionts – organisms living in symbiosis – that live on methane or sulphur."



The bathymetric map above the Kristin field illustrates coral reefs, pockmarks and plough marks from drifting ice. The plough marks are approximately 30 m wide.



Richard Hardman: "Hierarchy is the enemy of exploration." Agree?

'Billions of barrels to his credit'

Yemen – for the smaller players

Despite Yemen's modest and, as yet not fully explored, oil resources, the country has shown an impressive progress in the business. Since the preliminary geological studies started in the eighties, Yemen has managed to attract significant international interests in oil exploration and field development. Yemen is considered a newcomer in the world of petroleum, but the operating companies predict a promising future, based on their in-house studies and estimates.

The Republic of Yemen occupies the south-western tip of the Arabian Peninsula. It borders the Gulf of Aden and the Indian Ocean on the south and the Red Sea on the west. Covering an area of 630,000 sq km, the country is about the size of France. A long, narrow coastal plain (1,130 km) in the south gives way to flat-topped hills and a rugged mountainous region that continues into the desert interior plateau area of the Arabian Peninsula. Numerous wadis (characteristic canyons or valleys) radiate from the highlands, including the 500 km long Wadi Hadramaut. Yemen has no permanent streams, but local springs provide water for the Oases. Yemen on the whole has a desert climate, but it is particularly hot, dry and harsh in the eastern desert. Along the coast it is hot and humid and the western mountains, although temperate, are affected by seasonal monsoon.

With a population of almost 19 million, Yemen is the most populous country on the Arabian Peninsula. The great majority of the population is Muslim and speak Arabic. Most people live in or near small villages where agriculture is the major occupation. The largest urban centre is the capital, Sanaa. The population in southern Yemen is concentrated in a few areas, including the towns of Hadramaut, the highlands and the urban areas around Aden City. By contrast, a far greater proportion of the population in the North is scattered over a great number of town and villages.

The Republic of Yemen was established on May 22, 1990, when pro-western North Yemen and the Peoples Democratic Republic of Yemen merged after 300 years of separation. The decline in Soviet economic support in the South was an important incentive for the merger. Yemen reported strong economic growth in the mid-1990s with the onset of oil production, but was harmed by low oil prices in 1998. Besides the increasing petroleum enterprise, Yemen has several geological resources at varying stages of exploration and exploitation, including rock salt, marble, small deposits of coal, gold, lead, nickel and copper.

The rough topography is a challenge for the geologist operating in the Yemen desert. Shooting seismic in high mountain plateau with dramatic wadis cutting 300 m deep with an irregular orientation is a huge challenge, and much more expensive than seismic operations off-shore. Thousands of holes must be drilled two metres into the ground before dynamite is dropped in, and covered by sand. The drilling equipment is often brought to an inaccessible part of the seismic line by helicopters and professional mountain climbers. Despite these demanding activities, the operating companies can generate detailed geological models, models that enable profitable exploitation of reserves. Besides the geological aspects, its unique culture and landscape are also good reasons for visiting Yemen.

Mona Holte

It seems that Yemen is for small companies. Big companies have chosen to stay out, which gives room for the smaller players. This is the general observation of the two senior geoscientists Ole Gunnar Tveiten and Ole Herman Fjelltun of the small independent oil company DNO. Since 1998, DNO has served as an efficient operator and partner of two producing licenses with a third due next summer. Two new exploration licences give promises of a long-term involvement. Since the takeover of Block 32, DNO has increased the ultimate reserves more than four times in six years. DNO's business strategy, which is to generate good economic performance and sustainable growth through exploration and appraisal of small oilfields, has been perfectly followed through in Yemen.

Thanks to skilled local Yemeni workers, seismic acquisition is possible in the desert heat. The favourable positions of boreholes for production are on the plateaus. Drilling wells from the wadi floor is normally not an option, due to environmental impact and occasional flooding during rain periods.

Block 32- the success story

Block 32 is located in the Say'un al Masilah Basin in the Hadramaut region. It was here the adventure started in November 1998. DNO then acquired 20% of Block 32, and took over as operator of the Production Sharing Agreement (PSA).

A marginal discovery had already been made in the Tasour field with well number six, but the initial estimate of the reserves at that time was only 5.3 million bbls.

During 1999, DNO drilled three more wells on the field, carried out a feasibility study and subsequently agreed with the partners on a development plan of the Tasour Field. In 2000, DNO acquired additional interests in block 32. Following the drilling of two more wells, the building of a central processing facility (CPF) and a 60 km long pipeline to the existing infrastructure in block 14, operated by Canadian Nexen Petroleum Company, the first oil flowed on November 3 that year.

In the following years the production has exceeded the expectations significantly. After the first year, the production was 34% better than estimated in the Field Development Plan (FDP). Reserves have also increased by five times compared to the original estimates. The Tasour Field has already produced 20 million bbls and proven reserves left to produce are about 5-6 million bbls. At the same time, DNO's economy has benefited from the oil price, which has increased by a factor of 4-5 since the company first came to Yemen. Today the reserves in Tasour are estimated to nearly 30 million bbls of oil ultimate recovery.

This is a small-scale success story from Yemen. "Our excellent co-operation with Yemeni technical expertise in both PEPA (Yemen Petroleum Exploration and Production Authority) and the Ministry, combined with extensive field work, is the recipe for success," says Ole Gunnar Tveiten, head of DNO Yemen G&G team. He continues:

DNO's business strategy, to generate good economic performance and sustainable growth through exploration and appraisal of small oilfields, has been perfectly followed through in Yemen. The geoscientists Ole Herman Fjelltun (left) and Ole Gunnar Tveiten (right) are determined 'Yemen geologists', who have taken part in the oil-adventure of Yemen, where DNO is currently operating four licenses and playing an active role as partner on a fifth license.

"DNO appears as a credible operator, and the Yemeni government, which has the power to distribute licenses and negotiate PSA terms, is a supporting agent to our activity. This results in a quick response to our applications for licenses and development."

Where classic fieldwork is essential

Geologically, Yemen is divided into two main areas. The West Hill is considered a part of the Arabic shield, and consists mainly of sedimentary, metamorphic and igneous rocks. The middle and the eastern region are formed of sedimentary layers that date back to the Palaeozoic and Mesozoic eras.

The Say`un Al Masilah Basin, a structural feature associated with the Mesozoic break-up of Gondwanaland, is a symmetrical graben oriented NW-SE, similar to the other oil provinces in Yemen. About 90% of the reserves within the Say`un Al Masilah basin are produced from the Lower Cretaceous Upper Qishn Clastics. There is also production from distinct reservoir units consisting of Lower Cretaceous and Middle to Upper Jurassic age clastics and carbonates as well as fractured Cambrian granitic basement.

"Classic field mapping is essential in our exploration, and the Masilah area is ideal for mapping surface structures because the outcropping fault escarpments often reflect the same structure as the deep reservoir horizons. This is true within the Tasour field, where a roll-over anticline observed at surface reflects the underlying reservoir structure," says Ole Herman Fjelltun, an experienced field geologist. "Also true-dip data measured in the borehole is a very important source of structural information."

Challenging tasks in the desert

Despite the 'straightforward' structural geology, the difficulty lies in seismic imaging. "Shooting seismic in the desert is an expensive, hot and demanding task. The rough surface terrain, where wadis and faults create dramatic elevation changes, is a troublemaker both with respect to locating the seismic lines, and with respect to near-surface inhomogeneous wadi fill as sand, gravels, boulders and water. Thus seismic modelling of sub-surface layers is hampered with great variations and uncertainty in seismic velocity."

Petroleum in Yemen

The first attempt to find oil in Yemen was in 1938, when the Iraqi Oil Company accomplished seismic studies in a few areas. That was followed by other surveys conducted by foreign oil companies in the fifties and sixties. The exploration activity implemented before the sixties, did not result in any commercial projects.

It was not until 1984, when the American company Hunt Oil declared the first commercial quantity of oil discovered in the Marib-Al-Jawf block in former north Yemen, when the country's oil era started. A number of foreign companies began placing their request for oil exploitations privileges in Yemen, and by the mid eighties, more than eleven oil firms had signed agreements of cooperation in several oil productions project with the Government of the Yemen republic.

The building of oil infrastructure and pipelines followed another discovery in 1991 by Canadian Oxy in the Masilah block 14. The encouraging quantities of oil that were discovered enabled former North Yemen to intensify its work in oil and gas, and to establishthe Yemen Company for Oil and Mineral Investment.

In 1994, most oil exploration companies left due to the war associated with Yemen's unification. After the withdrawal of major international oil companies, the Government of Yemen has targeted smaller independent oil companies to take part in Production Sharing Agreements (PSAs). New and accelerated momentum in the oil industry increased the oil explorations as new oil discoveries were reported. Yemen had suffered economic hardship until the discovery of oil in the mid-eighties. Today, oil income makes up an estimated 70% of total Yemeni government revenue. In 2003 Yemen's gross domestic product increased 4% and is expected to grow 4.2 % this year.

Producing oil from the Nabrajah Field.

Despite its recent success, Yemen remains a small, non-OPEC oil producer. According to BP Statistical Review of World Energy, Yemen today has estimated oil reserves in the order of 4 billion barrels. Although this is only slightly less than neighbouring country Oman (5.5 billion barrels) the Yemen oil reserves are dwarfed by the oil richness of Saudi Arabia (260 billion barrels). Yemen's gas reserves are the estimated to be relatively small, 0.5 trillion m³ (16.9 trillion cubic feet) and no gas is being exported.

The daily output of oil was 470,000 barrels last year, and recently, the Government of Yemen announced a one-million-bbl/d-production target for 2006. However, according to Yemen's Petroleum Exploration and Production Authority (PEPA), average production has actually fallen in the first half of 2004 to an estimated 400,000-420,000 bbl/d, due to declining production in Masilah and Marib, Yemen's two largest oil fields.

Shibam – Manhattan of the desert

Between two high cliffs hides awe-inspiring Wadi Hadramaut, an oasis valley 120 km long. Wadi Hadramaut is the largest and most fertile Wadi of the Arabian Peninsula, and was once the most flourishing of the Yemeni States.

Situated upon a cliffy plateau in the wadi, Shibam city rises up in the area as the first sky-scrapers-city in the world, made of mud and clay. And because of the densely built, 600 mud-brick skyscrapers, Shibam is known as 'The Manhattan of the Desert'. The clay houses of Shibam city in Hadramaut province rise high up in the sky by thirty to forty metres height.

The ground floors of such houses vary in wall thickness between one and half and two metres. Traditionally, roofs were covered with a robust mixture incorporating lime, ash and clay, making a more or less waterproof layer, plastic enough to move with the main body of the building, yet hard enough to take a polished finish.

Shibam City of Hadramaut has a surrounding wall fence that reaches seven metres high. This encircling wall has only one entrance gate. The streets in the city are narrow, with curving rounds and turnings.

To give an all-round picture of Shibam Hadramaut, it is fair to say that the city looks like a splendid portrait that attracts both residents and non-residents. In 1982, The City of Shibam was admitted to UNESCO's exclusive World Heritage list for protection and preservation, because it is the oldest and best example of urban planning based on the principle of vertical construction. These sites are considered to be of outstanding value to humanity.

The concentrations of mud tower high houses, fenced by a wall rising up seven metres from the ground are characteristic in Shibam, the Manhattan of the desert. The houses seem to have grown directly from the earth below.

During the spring of 2004, DNO shot and processed a new 3D seismic survey that aimed to further resolve the structural characteristics of the Tasour Field. The seismic shooting challenge in Yemen has been resolved over a decade of trial- and error. Instead of the original and straightforward seismic lines, which gave poor portrayal of the structures, several thousands of shot holes has been drilled to a depth of two metres in the ground, before the dynamite is dropped in and covered with sand.

"This job is for strong, muscular fellows," says Fjelltun. "To transport equipment in this harsh terrain, both helicopters and professional mountain climbers are employed. Such seismic operations require key-focus on safety. With temperatures rising up to 60°C during a normal summer day, it is self-evident that safety measures have to be taken, also regarding the heat. The 60 km/h speed limits for all vehicles were strictly obeyed during this work. "We are proud of the zero accidents record achieved by our Chinese contractors doing this work," says Tveiten.

"Inevitably, shooting seismic in the desert is expensive, about 16,000 USD pr line-kilometres. However, the production and transportation cost pr. barrel in Yemen is less than half the price compared to the same activity in the North Sea, so we have capability to efficiently recover this exploration costs," Fjelltun says.

Where does the future lie?

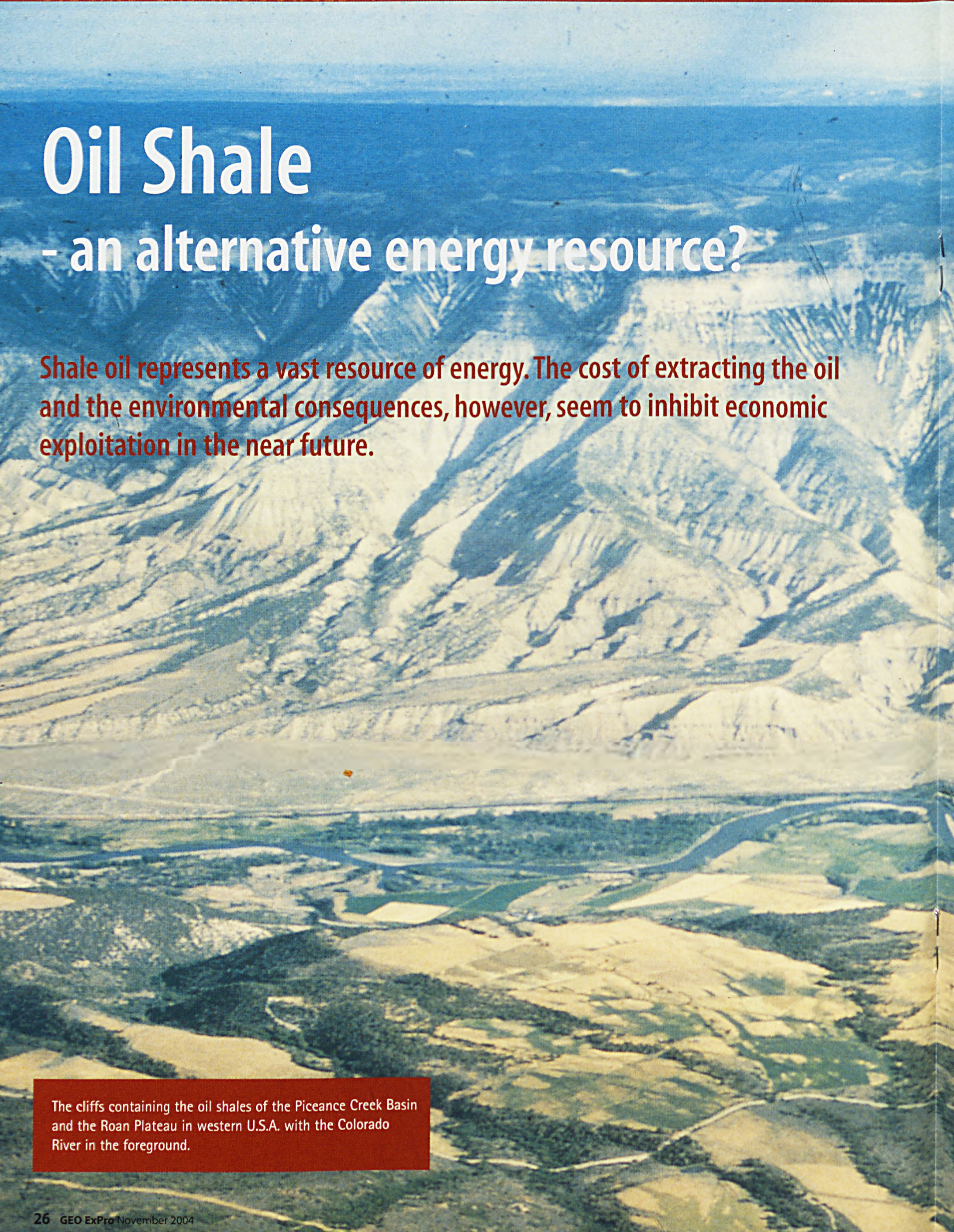
"For us, it is essential to integrate seismic data, geologic profiles, satellite images and elevation models to build a robust seismic velocity model," says Tveiten. "This integration has improved our geological models. The new 3D seismic surveys acquired in the Tasour Field have provided an invaluable tool to increase oil recovery and further appraisal of the area. In block 53, where British Dove Ltd has headed the operation and DNO has been an active partner with 25% interest, the production is above 20,000 bbls/day."

For the reader looking for the DNO's formula for success, Tveiten discloses more." "Currently, a development plan for the Nabrajah Field in block 43, where DNO is Operator, is under preparation. Oil has already been tested in this field, and appraisal drilling is ongoing." Tveiten says with a smile. Do we hear the beginning of the same old story?

Oil Shale

- an alternative energy resource?

Shale oil represents a vast resource of energy. The cost of extracting the oil and the environmental consequences, however, seem to inhibit economic exploitation in the near future.



The cliffs containing the oil shales of the Piceance Creek Basin and the Roan Plateau in western U.S.A. with the Colorado River in the foreground.

Ola M. Sæther, Geological Survey of Norway

Oil shale has been used since ancient times. Like coal, it can be used directly as a fuel.

The role of oil shale in the production of energy is unknown to most people because its contribution to today's world energy budget is minimal compared to both petroleum and coal. However, declining petroleum supplies may add to speculations whether oil shale represents an important source for the increasing world energy demands in the years ahead.

So far, the potential oil shale resources of the world have barely been touched.

Before petroleum

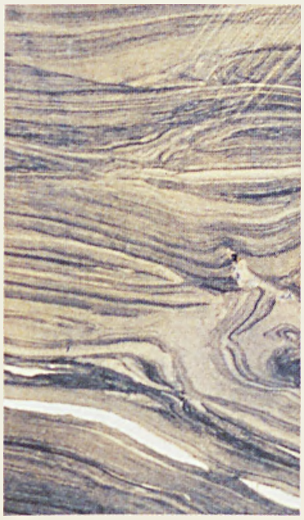
Oil shales have been exploited in several countries since the 17th century. In Sweden, alum shales (alum, short for aluminium sulfate) of Cambrian and Ordovician age were roasted as early as 1637 over wood fires to extract sulfate, which were used for colouring leather and fabrics. Later, starting at the end of the 19th century, the alum shales were used on a small scale for the production of liquid oil. These operations continued through World War II.

Oil shale deposits in France were exploited commercially as early as 1839. In Scotland, the oil industry began twenty years later, in 1859, which is the same year that Colonel Drake drilled his world famous oil well at Titusville, Pennsylvania. Large scale mining continued in Scotland during a 100-year period, until 1962. The annual production varied between 1 and 4 million tonnes of oil shale (rock volume), equivalent to only a few thousand barrels of oil per day.

Production from oil shale deposits in south-eastern Australia began in the 1860's, coming to an end in the early 1950's when government funding ceased. During this period some 4 million tonnes of oil shale were processed.

Canada also has several oil shale deposits, and mining took place in Nova Scotia in the 1850's and 1860's.

Common products made from oil shale from the early operations were kerosene and lamp oil, paraffin, fuel oil, lubricating oil and grease, naphtha, illuminating gas, and the fertilizer chemical, ammonium sulfate. With mass production of automobiles and trucks in the early 1900's, the supposed shortage of gasoline encouraged the exploitation of oil shale deposits. Many companies were formed to develop the giant oil shale deposits of the Green River Formation in western U.S.A.



In the U.S.A. oil shale has been a leasable mineral since 1920, but no oil shale leases were issued during the period 1925-1974. The oil embargo in 1973 made it possible for the Federal Government to attract acceptable bids for two tracts of land in Colorado and Utah in the 1970's. Both open pit and underground mining were considered. Development of large-scale mining facilities was attempted and experimental under-ground and above-ground retorting was carried out. However, all work has ceased and the leases have been relinquished.

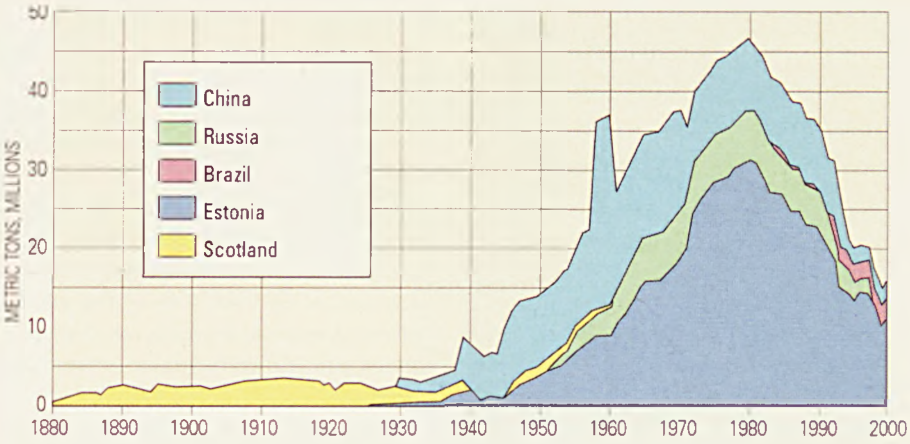
Exxon bought the right to oil shale in all the leasable tracts in 1979, but decided in 1980, after an intensive multidisciplinary feasibility assessment, to pull out.

Unocal operated the last large-scale experimental mining and retorting facility from 1980 until its closure in 1991. The oil company produced 4.5 million barrels of oil (720 million Sm^3) from oil shale averaging less than 1 bbl of shale oil per tonne rock over the life of the project.

Oil shale is found all around the world in rocks of Cambrian to Tertiary age: e.g. Australia, Brazil, China, Estonia, Germany, Israel, Jordan, Russia, Thailand and, most important, USA. Production of shale oil, however, is limited to a few countries with Estonia being the dominant producer.

Oil shales have been known in Estonia since at least the late 18th century. Large-scale exploration for oil shale deposits and subsequent exploitation started during World War I to supply Petrograd (subsequently Leningrad, now St. Petersburg) with fuel. Since 1916 oil shale has had an enormous influence on the energy economy, particularly during the period of Soviet rule and then under the re-established Estonian Republic. During the 1950's, oil shale was introduced as a source for electrical power generation.

From the late 1950's to the 1970's, massive power plants were developed. They are the largest operations based on oil shale in the world today. Estonia is currently the world's largest producer. Up to 90% of the shale mined annually in Estonia is combusted in power plants. Energy production from Estonian *kukersite* oil shale has accounted for a significant portion of the world's annual oil shale consumption. As the kukersite shale has an exceptionally high yield giving approximately one barrel of oil per tonne of shale.



(Data modified from: http://emd.aapg.org/technical_areas/oil_shale.cfm)

World production of oil shale in million tonnes. Oil shale is currently mined in Estonia, Russia, China, and Brazil. By the late 1930s, total annual production of oil shale was above 5 million tonnes. It continued to rise for the next 35 years, peaking in 1980 when more than 46 million metric tons of oil shale per year (equivalent to 80,000 BOPD given that 1 tonne of oil shale gives 100 litres of oil) was mined, two-thirds of which was in Estonia. From the peak year of 1981, yearly production of oil shale steadily declined to a low of about 15 million metric tons in 1999. Most of this decline is due to the gradual downsizing of the Estonian oil shale industry. This decline has nothing to do with diminishing supplies of oil shale. Rather, it is due to the fact that oil shale, with the present technology, cannot compete economically with petroleum as a fossil energy resource.

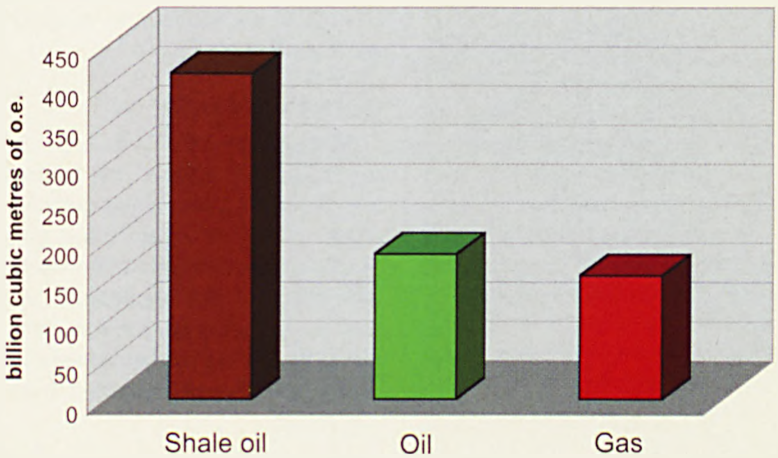
A huge resource

Although information about many oil shale deposits is rudimentary, the potential world resources of shale oil are huge.

The US Geological Survey has estimated the total world resources of shale oil at 2.6 trillion barrels (410 billion Sm^3). This figure might be considered a conservative estimate in view of the fact that oil shale resources of some countries are not reported and other deposits have not been fully investigated.

With an estmated resource of 2.1 trillion barrels (330 billion Sm^3) of shale oil, the United States has larger resources than any other country. By far the largest known deposit is the oil shales in the western U.S.A. They contains a total estimated resource of nearly 1.5 trillion barrels of oil (240 billion Sm^3). If a technology can be developed to economically recover oil from these oil shales, the potential is enormous.

Some deposits have been fairly well explored by drilling and analyses. Besides the Tertiary Green River oil shales in the U.S.A., these include the Tertiary deposits in Queensland, Australia, the Paleozoic deposits in Sweden and Estonia and the Cretaceous El-Lajjun deposit in Jordan. The remaining deposits are poorly understood and further research is required to adequately determine their resource potential.



The world's total remaining oil and gas reserves, according to the BP Statistical Review of World Energy, are estimated at 2100 billion barrels (340 billion Sm^3) o.e. The coal and lignite resources of the world are even higher. It might thus be argued that oil shales represent a significant strategic energy source.

The amount of shale oil that can be recovered from a given deposit depends upon many factors. Geothermal heating, for example, may have degraded a deposit, so that the amount of recoverable energy may be significantly reduced. Some deposits may also be buried too deep to be mined economically in the foreseeable future. Also, surface land uses may greatly restrict the availability of some oil shale deposits, especially those in the industrial western countries.

Used in power plants

The organic component of the oil shales, kerogen is typically insoluble in most common organic solvents, so temperatures in the range 350-650 °C are required to decompose the kerogen in the absence of oxygen to condensable shale oil, gas, and a solid semi-coke residue. This process is known as *retorting*.

Two different methods are used for shale oil production. In one, the shale is fractured

Oil shale

Oil shale is called "the rock that burns". The term "oil shale" is a misnomer: it does not contain oil.

Oil shales are defined as fine-grained brown to black sedimentary rocks (shale, siltstones and marls) containing a large proportion of solid organic matter (kerogen) that will yield liquid or gaseous hydrocarbons upon heating and distillation. Included in most definitions of "oil shale", is the potential for the profitable extraction of shale oil and combustible gas or for burning as a fuel.

The kerogen in oil shales can be converted to oil through the chemical process of pyrolysis. During pyrolysis the oil shale is heated to 500° C in the absence of air upon which and the kerogen is converted to oil and separated out, a process called "retorting". Only oil shales expected to yield more than 40 litres of oil per tonne shale are of economical interest.

Oil shales may, in different contexts and cultures be called alum shale, bituminite, cannel coal, gas coal, kerosene shale or kukersite

The solid organic matter (kerogen) has the same origin as the organic components of other fossil fuels (from plant and animal matter). It is composed chiefly of carbon, hydrogen, oxygen, and small amounts of sulfur and nitrogen and forms a complex macromolecular structure that is insoluble in common organic solvents.

Oil shales differ from mature source rocks in that the rocks have not been exposed to the same heat as when petroleum is formed (GEO 02-2004). It has simply not gone through the "oil window" of heat (nature's way of producing oil) and must therefore, in the "of geologic be heated to a higher temperature to yield petroleum.

Photo: Halfdan Carstens

and heated in situ to obtain gases and liquids through production wells drilled into the deposit. The other is by mining and crushing followed by heating in a processing plant. Finally, the waste is disposed and stabilised.

The energy subsidy to produce oil from oil shale is large. Since the oil shale has to be mined, transported, retorted, and then disposed of, at least 40% of the energy value is consumed in production. Both processes also use considerable amounts of water.

The total energy and water requirements, in combination with environmental and monetary costs, have so far made production uneconomic. During and following the oil crisis in 1973, major oil companies, working on some of the richest oil shale deposits in the world spat huge amounts of dollars on various unsuccessful attempts to commercially extract shale oil.

As in Estonia and other countries, most of the oil shale mined today is utilized as a low grade, high ash feedstock for production of energy, both thermal and electrical. In such power plants, the temperatures reach up to 1500 °C.

More than energy

Oil shales have also been used as sources for other materials, and by-products such as alumina, ammonium sulfate, phosphate, sodium carbonate, sulfur, uranium, vanadium, and zinc can add considerable value to some oil shale deposits. In addition to hydrocarbons, some hundreds of metric tons of uranium and small amounts of vanadium were extracted from the Swedish alum shales in the 1960s. Ash waste from combustion of oil shale has been used in the cement industry.

The spent shale obtained from retorting also use in the construction industry as cement. Sweden, Germany, Estonia and China have used solid oil shale waste as a source of cement. Other potential by-products from oil shale include specialty carbon fibers, adsorbent carbons, carbon black, bricks, construction and decorative building blocks, soil additives, fertilizers, rock wool insulating materials, and glass.

Many of these by-products are still in the experimental stage, but the economic potential for manufacturing some of these seems large.

Environmental concerns

Because oil shales comprise clastic, carbonate, organic and minor sulfide fractions and also traces of some potentially toxic elements, they generate several types of environmentally harmful wastes. Combustion of oil shales releases the greenhouse gas CO_2, derived from oxidation of organic matter and decomposition of carbonates. If carbonates are present in high proportions, this renders the oil shales inefficient in terms of energy per unit of CO_2 emitted. Furthermore, oil shale combustion emits acidic gases (NO_x and SO_2) derived both from inorganic sulfides and organically bound nitrogen and sulfur.

Although the emissions of CO_2, SO_2 and NO_x from combustion of oil shales are at the same level or lower than those from oil- or coal-based power plants with comparable capacity, the combustion of oil shales also yields particulate emissions (potentially enriched in a variety of metals, metalloids and organics) at a rate twenty to fifty times.

One factor, which makes the extraction of oil from oil shale challenging, is that spent shale occupies 20-30% percent greater volume after processing than raw shale due to a popcorn effect from the heating. This means that a 50,000 BOPD oil shale plant will produce about 7,500 cubic meters partially powdered rock waste per day in excess of that returned to the mine.

Consequently, in the vicinity of oil shale operations the environment will be altered, and costly environmental assessments of the impact on different ecological compartments has to be carried out parallel to developing the oil shale industry.

With consumption of fossil fuels allegedly outstripping discovery of new resources, it could be argued that oil shales may represent a viable energy alternative for oil-poor countries, provided they are prepared for potential conflicts with international environmental agreements intended to regulate national emissions of greenhouse gases and thus to reduce the global emissions.

However, the economic competitiveness of oil shale mining must be questioned. Interest in the oil shales of the western U.S.A. as a strategic reserve increased after the oil embargo of 1973, when the price of oil doubled, but was found to be commercially unviable in the 1980's. If oil shale should be considered as raw material for shale oil it must contain enough organic matter to yield more energy than it requires processing the rock. The organic content needs to be 8-10 weight percent (i.e. yielding about 40-50 litres per tonne), before it can be considered a source for synthetic fuel.

Geographical, economical and political aspects will heavily influence future consumption of oil shale. From an environmental viewpoint, the most favourable remediation strategies must be followed, including continuous monitoring of gaseous and particulate emissions and their effects.

Beyond conventional oil and gas

Estonia is predominantly using their oil shales for production of electricity. In Queensland, Australia, oil shales are used for production of oil. More than 2.6 billion barrels (410 million Sm^3) can be produced from wells, and the capacity can reach 200,000 barrels of oil per day. Brazil has a

Core sample of the Green River oil shale, Mahogany Zone, cut perpendicular to stratification. The name reflects the similarity to polished mahogany. The dark laminas are kerogen prone, whereas the lighter laminas consist of various carbonates.

Countless fish skeletons, delicately preserved in the laminated shales of the Green River formation, can be seen at Fossil Butte National Monument in Colorado.

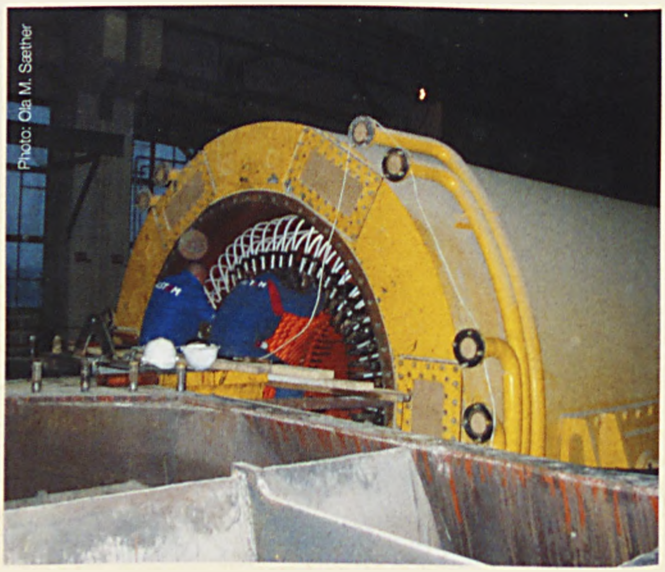
Strip-mining of oil shale in northeastern Estonia. Some 20-30 m of overburden is moved to excavate 3-4 m of *kukersite* shale which is flotated and processed for its calorific value at the Balti Power Plant. The overburden is continually replaced and revegetated.

retorting plant producing a few thousand barrels a day. In China, some 400,000 barrels of oil are retorted annually.

It is evident that the present production of petroleum products from oil shales is very limited compared to the overall resource. Today's production of shale oil is also small compared to the oil production, which is close to 75 million barrels of oil per day.

The future development and expansion of the oil shale industry will be governed by the price of crude oil. When the price of shale oil is comparable to that of crude oil, and with an increasing number of countries experiencing declines in conventional oil production, then shale oil may find a place in the world fossil energy mix. It seems unlikely, however, that shale oil production can be expanded such that it can make a major contribution toward replacing the daily consumption of more than seventy million barrels of oil worldwide.

The energy demands of blasting, transport, crushing, heating and adding hydrogen, together with the safe disposal of huge quantities of waste material, are large. The key is the development of efficient, economic technology. Assuming that two-thirds of the remaining world oil resources will be produced in the Middle East and that two-thirds of the resources of oil shale are located in North America, where the consumption of petroleum per capita is the greatest, one may wonder about the geopolitical importance of shale oil in the future.



Gigantic generators are required to convert the combustion energy from over ten megatonnes of oil shale per year to electric power.

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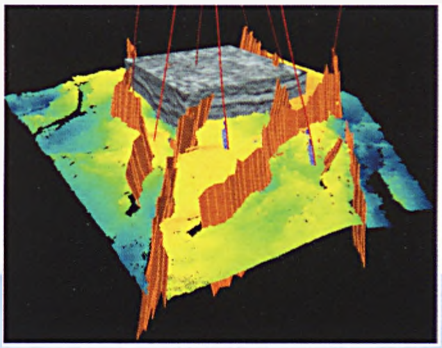

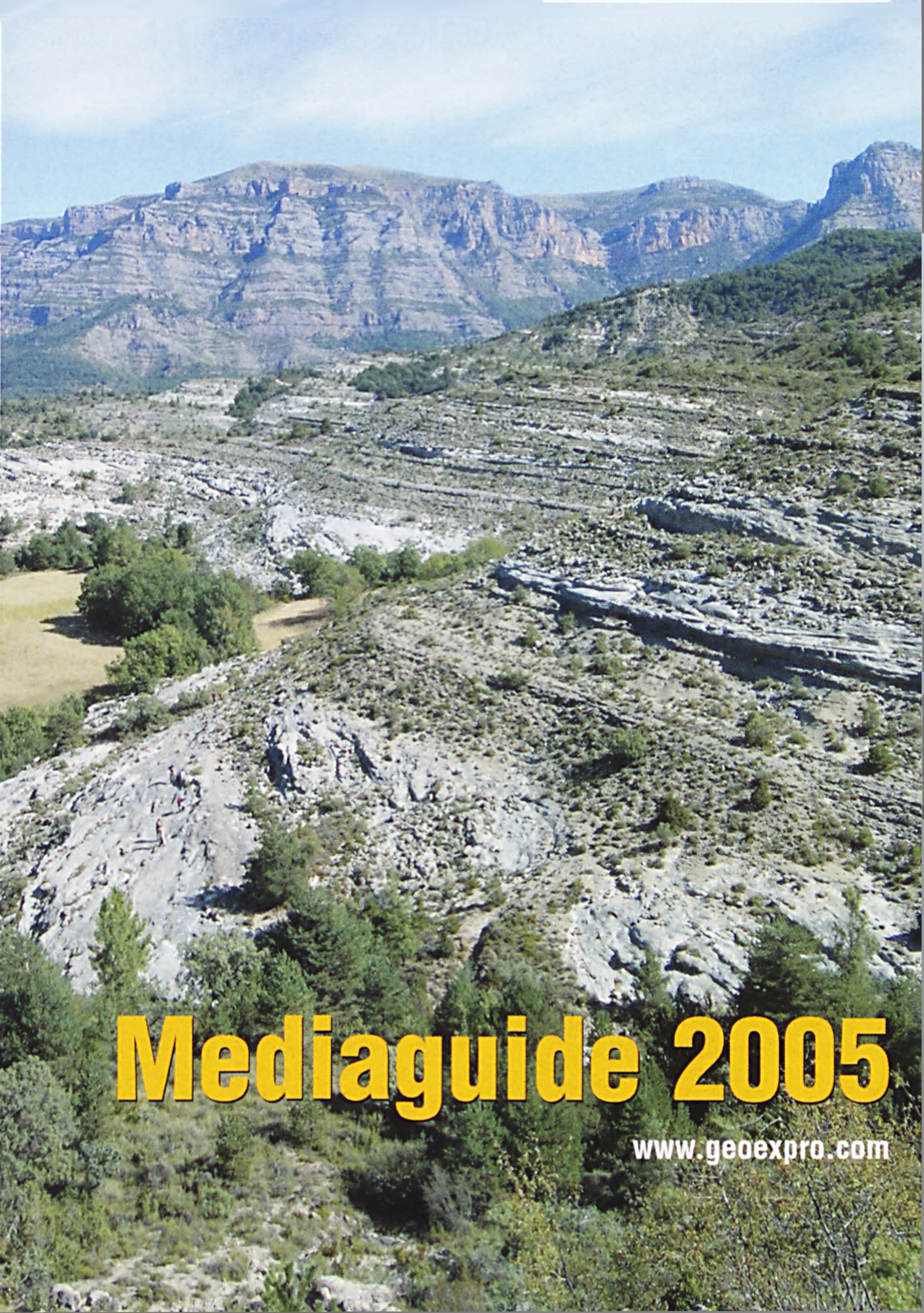

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Photo: Halfdan Carstens

Planning software streamlines the decision process

Inconsistent methods used in the well planning process can result in erroneous decisions that have significant impact on field economics. By using a generic decision support tool, well projects can be ranked and evaluated consistently to take all risks and uncertainties into account.

The *IPRES* team is multicultural and benefits from extensive experience from different geographical regions and companies in the oil industry. "We have experience ranging from project management of complex field development projects to reservoir engineering, geophysical interpretation and petroleum economics. We are equally strong in programming that uses advanced mathematics and statistics," says managing director Arvid Elvsborg.

Erlend Glømmen, IPRES

The latest decision support tool from *IPRES* enables decision makers to integrate the disciplines of reserves estimation, production profile generation, drilling cost estimation, drilling time estimation and overall economics in one single model. According to the innovators, the tool is unique in that it integrates all the disciplines involved in well planning in a fit-for-purpose tool with particular focus on decision support.

Currently, most oil and gas companies have their own internally developed tools that partly do the same job, but these often have significant shortcomings. Maintenance is also sometimes neglected and quality assurance poor.

"This is why we think there is a market for this new software," says Arvid Elvsborg, managing director of *IPRES*.

Risks and uncertainties

The new software application can be used to evaluate all types of production and injection wells. The desired degree of detail is set by the user to account for all relevant risks and uncertainties in a given well project.

Options are available to model wells ranging from simple onshore single branch wells to complex offshore multi-branch wells. The user selects the type of well upon initialisation of the model, for example a sub-sea well with sequential production from several reservoir targets.

The user can also include case-specific events in the model. An example of this could be the probability for stuck pipe during drilling of a high-angle section of the well. The consequence of such events can be modelled with time delays, extra costs or sidetracking of the well.

For the purpose of consistent ranking of well projects, pre-defined management reports are available that summarize all the results for easy comparison.

"Our new planning tool - *IPRISK*[WELL TM] - is the result of 5 years of dedicated effort to develop a team with the necessary skills and experience to fully understand the clients decision support needs in upstream investment projects, and to develop software applications that reflect these needs. Starting off by providing consultancy services only, we have slowly moved into software development building on our experience from relevant projects," says Elvsborg.

Integration of disciplines

"An application should not only allow the users to model both simple and complex problems, it should also be an intuitive and easy-to-use tool and not demand practice or training. For the latest version, we have systematically gone through all menus, input pages and options to make sure that the user interface of the tool follows the user workflow. We are confident that the new version will be well received by new and current users and look forward to their response when it is released first quarter 2005," says Steinar Lyngroth, who is in charge of the risk team.

Key to triggering the development of the well planning software was the observation of poor integration of disciplines in the well planning process. In small as well as major oil and gas companies, there is limited time to approve new wells. The technical disciplines often work independently with little cross-communication. In the end, each discipline takes their high, medium and low estimates and tries to merge their data, a process that is often based on simplified assumptions causing erroneous results and decisions. IPRES has therefore worked closely with one of the major operators offshore Norway during the development of the planning software.

"By using our new software the well planning team has a common tool, ensuring a consistent, qualitative and efficient work process. Moreover, a common tool helps improving communication between the disciplines," says Lyngroth.

Gathering all data in one single model enables the use of tornado diagrams to understand which parameters in a specific project has the biggest impact on the uncertainty of the economic outcome of the well. This avoids unnecessary work on details with little economic impact on the outcome.

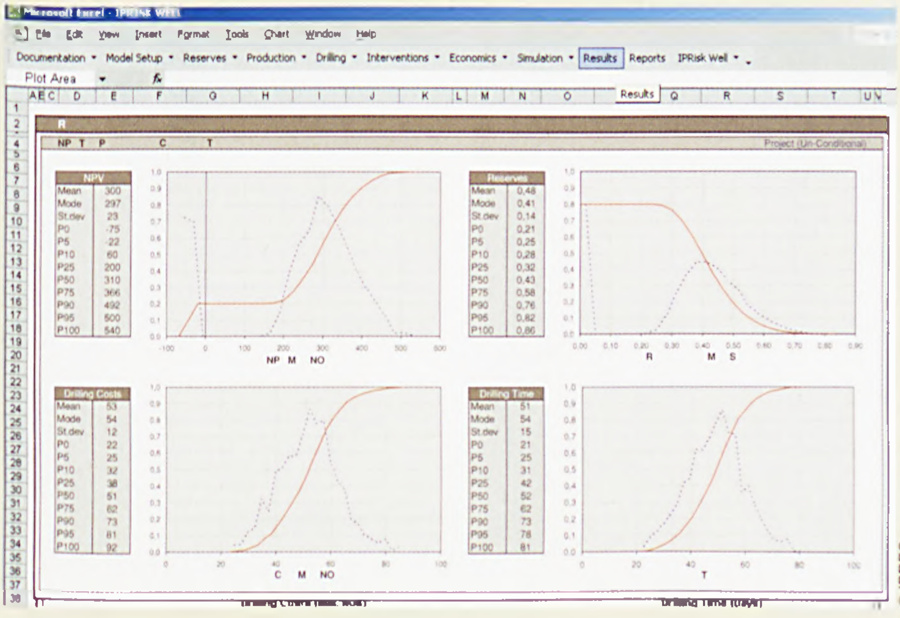
"Using a software like this as a common tool for all disciplines in the well planning process also serves as an important checklist to ensure that all factors are taken into consideration before making a decision," says Lyngroth.

Upon completion of data input, a Monte Carlo simulation is run that calculates the expected monetary value and other relevant decision parameters for the project. All results are displayed for review in predefined result plots and tables. Some of the most commonly used result plots include net present value (NPV), reserves, drilling time, drilling cost, unit production cost, internal rate of return (IRR), cash flow, production profiles and tornado diagrams. A decision tree style plot summarizes the probabilities for potential success and non-success outcomes together with the NPV for each outcome.

Complex fields

The Challenges of mature fields in particular result from the focus on methods for increased recovery and drainage of small oil and gas volumes in complex reservoir units. In such well planning projects it is necessary to evaluate many options for well locations and drilling trajectories with particular focus on risk exposure in the decision making process.

"By the use of *IPRISK*[WELL TM] the planning process is improved, both in terms of efficiency as well as in ensuring that consistent and comparable analyses are used as the basis for well planning decisions," says Arvid Elvsborg.



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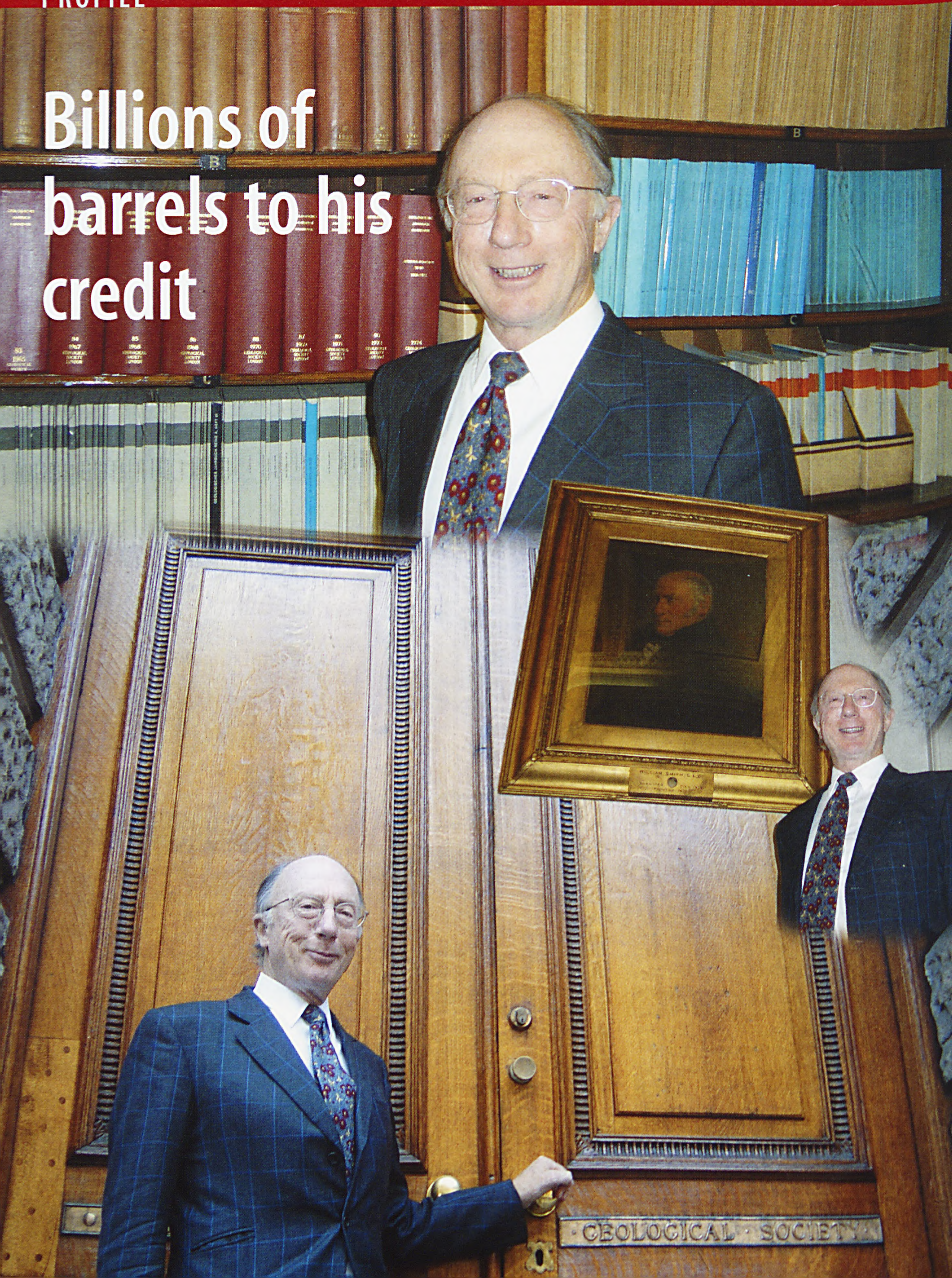
One of the result pages showing frequency and cumulative distribution of NPV, reserves, drilling cost and drilling time.

Billions of barrels to his credit



He is the doyen of petroleum geologists. For newcomers, it suffices to say that his name is associated with many of the North Sea's major play concept discoveries totalling several billion barrels of recoverable oil.

Tore Karlsson

Richard Hardman, geologist by profession, explorationist by heart, has built a successful carrieer in international exploration over the past 40 years. His thirst for finding ever more oil and gas has led him to a multitude of geological and cultural environments, and he has left lasting impressions on colleagues in countries like Libya, Kuwait, Colombia and Norway. In the UK, his career encompasses almost the whole of the exploration history of the North Sea.

A world class source rock

5 of his 10 early years with BP were in Colombia doing field mapping. "I understood quickly that there are two types of geologists in the field; on one hand the geologists looking for physical facts and on the other hand the mental observers. Guess which category I am in! I believe the key is to build models in your mind that you can take advantage of in other situations."

Richard's great good fortune was to be engaged in exploration of a basin which had a world class source rock, the Kimmeridge Clay, connected to large structures in which highly productive reservoir rocks were present.

"My North Sea career was from 1969 to 1998," says Richard. "In order to have a successful career as an explorationist one needs to become associated with a basin when it is still immature but which over the course of time yields prolific reserves of hydrocarbons. The North Sea is one such basin. In 1969, before any commercial fields had been discovered, there was, however, no certainty whether this would be the case."

These days Richard Hardman is engaged part time as technical director with FX Energy, primarily involved in exploration in Poland. FX Energy has production in Nevada, but has also obtained licenses in Poland. He was brought in to assist with exploration based on his knowledge of the southern gas fields in the North Sea and is working on the palaeogeography of Zechstein. The Faeroe Islands is another target area for FX Energy.

"I like this description of leadership," says Richard Hardman: "A leader takes the blame when things go wrong, but gives others the credit when things go right. Whether the team members I have managed will say that about me, is a different matter".

Hierarchy is the enemy of exploration

Richard's unique ability to analyse data and to think differently, always questioning conventional geological thinking, has resulted in his name being associated with many of the North Sea's major new play concept discoveries, including the 1050 million barrel Valhall Field (Norway), the South Arne Field (Denmark); the Hutton and NW Hutton fields (UK); the 500 million barrel Scott Field (UK) in the Central North Sea and the very subtle traps seen in the Fife, Fergus and Flora fields.

"Age and experience coupled with youth and brilliance is what you want"

When we get on to the topics of exploration and discoveries, Richard quickly grabs pen and paper for a 'back of the envelope' description of his ideas and 'mental models'. "One of my themes is knowledge transfer. It is surprising how often existing knowledge is not used. I believe transfer of knowledge takes place through people. The important point is to let people apply their mental models in new environments."

Richard offers this as his own explanation for being successful: "Enthusiasm and a determination to take as an optimistic view as possible. At the race track the way to win is by backing the winner. No one knows who is going to win and so you must back all the horses that are likely to win. The same is true for exploration". Many oil companies have a risk adverse culture. In Amerada it was considered correct to take risk. The result is that the company became the third largest producer in the UK," says Richard modestly.

Nevertheless he is very cautious of taking all the credit himself. "Several of the exploration projects I have been involved in that turned out to be successes like the Scott and Flora fields have been follow-ups of discoveries made by other companies," he says, "but often with a new mental model introduced."

"It's important to create a permissive environment. Hierarchy is the enemy of exploration. Team members need to be encouraged to express their viewpoints. As a manager I used to organize "discussion group dinners". Typically we had 10 minutes presentations on specific topics, but the important point was to get all team members to express their frank viewpoints on issues that were important to them."

"Age and experience coupled with youth and brilliance is what you want".

The William Smith Medal

Last year Richard received the prestigious William Smith Medal by The Geological Society, which is given each year for the highest achievement in applied geology, or according to the bylaws, "for excellence in contributions to applied and economic aspects of the science". The medal was first awarded in 1977, and it commemorates the father of stratigraphy, William Smith, who in 1815 completed "the map that changed the world".

Sir Mark Moody Stuart, former Shell Chairman, said when Richard was awarded the Medal: "Richard Hardman has spent a whole career enthusiastically linking geological insights to petroleum exploration, achieving through his boundless drive and energy, exploration results that have benefited industry and academia even more than the Chancellor of the Exchequer. After 10 years learning the ropes at BP, Richard became from 1969 one of the most conspicuous figures in North Sea oil and gas exploration with Amoco, and latterly Amerada Hess."

To this, Richard replied: "Oil and gas exploration is an industry vital to the well-being of the Western world. Too often it is pilloried; and too little is it praised. As one who has played a small part in the efforts that have seen this country self-sufficient in oil and gas the medal is accepted, as a token of regard for an industry in which I have spent my working life."

His dedication to geology is certainly confirmed by his colleagues and friends of many years. "He is extremely creative and enthusiastic. He is unconventional and like a firework to work with," says one colleague of Richard.

The use of improved knowledge

The young Richard Hardman spent 3 years at Oxford. He graduated in 1959 and went directly to the oil industry.

"After narrowly missing a First, I decided I was better fitted for a career in practical rather than theoretical geology. Some tempting Ph.D. projects were dangled in front of me but in the end I took the less glamorous option of joining BP. For a time faced with the humdrum life as a geologist at the bottom of the career ladder I thought that perhaps I had made a mistake. After a posting to the new exploration province of Libya came the realization that perhaps the Ph.D. option would have involved a similar amount of what is today known as grunt work."

Being introduced to geology in the late 1950's, Richard has been in a favourite position to follow the rapid development in geological sciences through four decades.

"When I was a geology student continental drift and plate tectonics was not yet an accepted theory. In those days the job of the geologist was primarily to describe rocks. The continental drift theory made it possible to understand and explain local geology in a regional setting. Without this realization many of the exploration successes would not have happened over the years that I have followed the industry," Richard says.

"Let us take an example from the North Sea. The Forties Sands, the reservoirs for the giant Forties Field with reserves of 2.2 billion barrels of oil, were shed off the East Shetland Platform. In turn it was uplifted as the African Plate and European Plates separated. This we did not know at the time the Forties Field was discovered. Today, however, we are looking for reservoirs in sands derived from both Greenland and the East Shetland Platform west of Shetland. I believe some of the Norwegian fields that have been most recently discovered also have sand sources to the west. So the theory of Plate Tectonics is used everyday. Still, it is not possible to prove that a field has been discovered purely as a result of the theory."

Dumping of sand

"Another area where development in geoscience has been critical for the oil industry is our understanding of the distribution of sand in sedimentary basins. Traditional thinking said that sediments changed from sand to mud when you moved from near shore to deeper water. These days we know a lot more about the distribution of sedimentary material, which is helping us with the development of depositional models and our prospecting job".

"Some years ago a flume box and a fast camera were developed in which turbidite flows could be replicated and matched to surface outcrops. This understanding has proved very beneficial. Today exploration takes place for sands dumped at the foot of slopes. This is in part the explanation for the successes in the Deep Water Gulf of Mexico where sand thicknesses have been found which were never dreamed of."

"Geochemistry has never paid for itself"

"This type of improved geoscientific understanding through laboratory experiments and field work combined with the improved mapping with 3D seismic has been vital for exploration success. It is also an interesting observation that today we have a much better knowledge and understanding of the geology relevant for petroleum exploration in offshore areas than onshore, simply because marine 3D seismic is so much cheaper than land seismic."

"On the other hand you have areas like geochemistry where it is difficult to say that the investments have been justified," says Richard.

"At the time that geochemistry was all the fashion, I happened to hear a paper which showed statistically that geochemistry had never paid for itself in terms of hydrocarbons found. I have found out nothing over the years that would make me change my mind. Further, there are two fields I am ashamed of not finding that were found by those who ignored the geochemical evidence, namely Beatrice in the Inner Moray Firth and Priannou in offshore Greece. Geochemistry also predicted that all the hydrocarbons found West of Shetland would be gas. Now we know better."

A driving force

It is clear that Richard Hardman feels at home in the historic surroundings of the Geological Society. Among fellow members, pictures and sculptures of famous geologist like Murchison and Smith and bookshelves filled with both historical and modern geology, he enthusiastically talks about the importance of the Society for the industry and the community at large.

Richard is dedicated to the societies, and in particular to the Geological Society in Burlington house at Piccadilly. Founded in 1807, it is the oldest geological society in the world. Hardman has served as President of the Geological Society as well as the chairman of the Petroleum Society of Great Britain and President of the European Region of AAPG Europe.

Richard's reforming zeal has, according to his acquaintances, transformed the Geological Society through several key positions over the years. He has also been chairman of several influential committees both in science and its application, and he has organised many landmark conferences.

Beyond petroleum

Our conversation is interrupted by the ring tone of Richard's mobile phone followed by an engaged discussion with a contact involved in the planning of a seminar on the technical and political aspects of alternative energy sources.

"Life is a great gift. My philosophy is to enjoy life. That does not mean that we should not help our fellow humans. I am not the type of person who likes to go on a cruise and be passive. I want to be positively engaged, also on vacation." says Richard, just back from a "fascinating" field trip in the Caucasus – "a great opportunity to build new mental models."

Chalk – multipurpose use

White chalk, forming spectacular cliffs, is found outcropping in England, Denmark as well as France. For the layman these cliffs are favoured attractions on holidays, for geologists they constitute excellent outcrops for studying the stratigraphy and sedimentology of the chalk as well as being analogues for some of the North Sea fields.

Oil and gas fields reservoired in Upper Cretaceous chalk are limited to the Central North Sea. It is only here that there is a favourable combination of prolific source rock (Upper Jurassic Kimmeridge Clay), high permeability reservoirs (natural fracturing enhancing matrix permeability) and an effective seal (mudstones). The map also illustrates the widespread distribution of chalk in the North Sea Basin (blue colour). To the north, chalk deposition gives way to clay deposition.

The chalk of the Dover coast is largely made of skeletons of microscopic organisms – coccoliths – that consist of almost pure calcium carbonate. The chalk is soft and easily eroded by hostile waves. The continuous erosion keeps the cliffs white, as fresh chalk is exposed and vegetation is prevented from growing on the cliff face.

The towering cliffs dominate the coastal landscape in southeast England, and on a clear day you can see the white cliffs off the French coast. In this place continental Europe is only about 30 km away, and the white cliffs are internationally famous as the gateway to England. This short stretch of the Channel has been a temptation to many would-be invaders over the centuries. Julius Caesar tried landing here, but was daunted by the cliffs. The Spanish Armada, Napoleon and most recently Hitler, have all failed to overcome this natural defensive barrier.

The rocks were deposited over a period of 35 million years in an extensive epicontinental sea during the largest transgression in the Earth's history. The deposition of chalk is a slow process, and despite high productivity of algae, each vertical centimetre took around 1000 years for form.

Halfdan Carstens and Tore Karlsson

The White Cliffs of Dover, immortalized in popular song and verse, are cliffs facing the Strait of Dover near the major port town of Dover, England. The cliff face, which reaches up to 100 m high, owes its striking façade to its composition of chalk accentuated by streaks of black flint.

Photo: Tore Karlsson

The White Cliffs are dominating the scene in Dover. Most tourists will probably ask for a room facing the sea at the Dover Harbour Hotel, but as a keen geotourist you can also ask for a room facing the other way.

An offshore and onshore resource

The Upper Cretaceous of the southern and central North Sea Basin, offshore as well as onshore, is dominated by chalk almost to the exclusion of shales and sandstones.

In the Central Graben of the North Sea the chalks form a prolific hydrocarbon fairway in the Norwegian (e.g. Ekofisk, Valhall) and Danish sectors (e.g. Dan), while there are only a few small discoveries in the UK sector (e.g. Machar).

The Chalk of Northwest Europe has been used as a major source of drinking water. It is generally highly permeable, and when enhanced by karstic development the permeability can be very high. By the time of the Industrial Revolution, and with the advent of steam power, shafts could be sunk, and the water could be effectively pumped to the surface.

Chalk is also an important constructional material, and it is widely used for industrial purposes. Cement is one example.

Petroleum geologists have used onshore chalks as reservoir analogues. However, these rocks have only been used to a limited extent because they have been deposited in shallower water than the North Sea

Photo: Tore Karlsson

Once a sleepy fishing village, St. Margaret's Bay was transformed into a playground for the rich and famous during the later years of the 19th century. The Bay had its heyday in the period between the wars with people such as Noel Coward and members of the Royal family keeping houses or visiting the area. The Bay has been noted for its warm climate, often several degrees warmer than the cliff top above. However, care need to be taken when walking along the cliff top. In 2001 hundreds of thousands of tonnes of chalk cliff fell into the sea along a 400 m stretch of coast between Dover and St Margaret's Bay. The collapse was caused by rain being absorbed into the cliff-face and freezing during a cold period.

oil and gas reservoirs.

Onshore, in the UK, France, Holland and Denmark, the chalk is famous for its recreational value when forming cliffs against the roaring seas. They are consequently a significant resource for the locals as well as tourists.

The White Cliffs of Dover

The coastline east of Dover is the nearest England has to a frontier with France.

A long time ago, Britain as we know it today did not exist, it was merely a westerly peninsula of a larger European continent. As a result of the surge of water from melting ice and erosion by the sea, the soft chalk eroded away and what is now the British Channel was formed – thus Britain became an island. On a geological scale the distance between Britain and France continuous to increase as 2–5 cm of the chalk is eroded sideways every year.

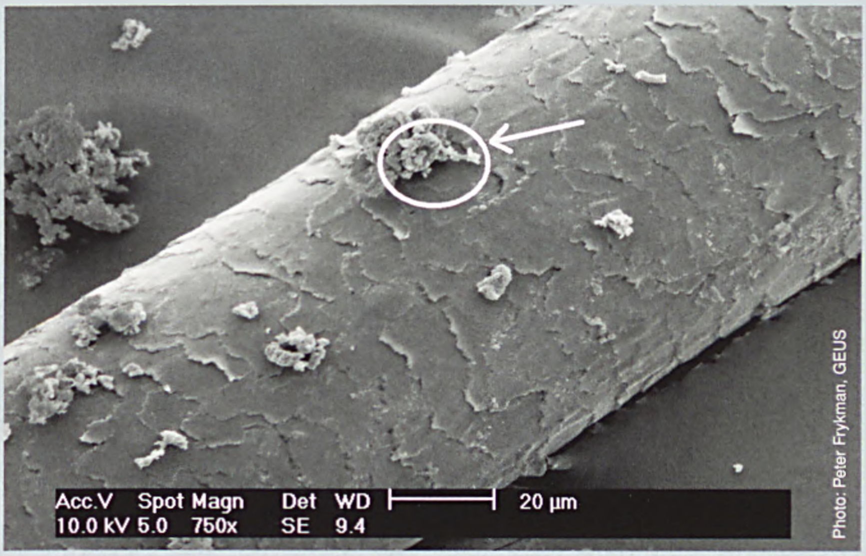
Dover became a symbol for Britain's wartime braver. The Battle of Britain Memorial is located close to the cliff edge between Folkestone and Dover.

For the past 2,000 years, the White Cliffs of Dover have seen men defending the coast, from warriors with spears and swords to heavy artillery and guns. Shakespeare wrote about the cliffs, their beauty and their role as the nation's identity. These icons of England have been the sign of home for travellers over the centuries, immortalised during the Second World War in Vera Lynn's song:

"There'll be bluebirds over,
The White Cliffs of Dover,
Tomorrow, just you wait and see

There'll be love and laughter,
And peace ever after,
Tomorrow when the world is free"

Chalk – microscopic coccolith platelets



Chalk consists of coccoliths formed from the skeletal elements of minute planktonic green algae. The scanning microscope photo shows a single coccolith on a human hair. The scale bar is 0.020 mm.

Chalk is a limestone traditionally used for burning into lime and for writing and drawing.

In England the Chalk topographically forms what are known as the "Downs" in southern and eastern counties. It is often exposed in quarries and road cuttings but the best exposures are found along the coast where chalk often forms spectacular cliffs comprised of a sequence of mainly soft, white, very fine-grained and extremely pure limestones, which are commonly 300-400 m thick.

These rocks are composed mainly of the skeletal remains of pelagic unicellular golden-brown coloured algae or coccolithophores, associated with varying proportions of larger microscopic fragments of bivalves, foraminifera and ostracods. The coccoliths are occasionally found intact but usually are disaggregated into the distinctive button-shaped grains or coccoliths platelets. The diameter of the platelets varies from 0.2 to 1.0µm. The matrix porosity of the chalk consists of intergranular pore spaces between coccoliths grains and platelets that are extremely small, 1-5 µm.

The planktonic coccoliths and many of the foraminifera (the planktonic species) lived floating in the upper levels of the oceans. When they died their skeletons sank to the bottom to form the main components of the Chalk. The bottom waters were oxidising and supported an abundant benthic fauna. Burrowing organisms thrived and produced intensely bioturbated sediments.

Flints are a well-known component of Chalk and characterise the upper parts of the sequence. The black stones are present as nodular seams and tabular beds. They comprise quartz crystals, only a few microns in diameter. The silica was derived from the dissolution of the siliceous skeletons of sponges and other organisms and has been redistributed in the form of nodules during several stages of crystallisation.

Black flint exposed as rows in the chalk.

Samphire Hoe, situated at the base of Shakespeare Cliff between Dover and Folkestone is 'man made' from the material dug to create the Channel Tunnel and is referred to as the newest piece of England. Careful landscaping has created a place suitable for both people and wildlife. The area is open to the public from 7 am to dusk every day via the tunnel through the cliffs.

The Cliffs have made history for many things, including the first cross-channel flight that was made by Louis Bleriot in 1909.

'The Gateway to England'

Dover is a town steeped in history and has long been the gateway to Britain. For the Romans, after Caesar's legions stepped onto British soil in 55 BC, Dover was the port closest to the rest of the Roman Empire and a thriving town.

The dominant feature on the Cliffs is Dover Castle. This site has seen many changes, from the times of the Roman Empire to the Second World War. The ease with which the chalk could be tunnelled, led to many complex excavations, from medieval times right through to the Second World War. The cliffs are riddled with networks of nearly 4 miles of tunnels and underground bunkers including Churchill's bomb proof headquarters during the Battle of Britain.

During World War One Dover became one of the most important military centres in Britain. The first bomb to be dropped on England fell near Dover Castle on Christmas Eve 1914. During World War II Dover again became a town of considerable military importance. In May 1940, over 200,000 men evacuated from Dunkirk passed through Dover.

"Fog in the channel, the continent cut off"

The Channel Tunnel (the Chunnel), in itself a significant geological project, represents the modern version of the contact between Britain and France. Following the completion of the tunnel, The Times can no longer report: "Fog in the channel, the continent cut off".

A new area of land was created just West of Dover from the material dug out during the construction of the tunnel. Rather than leaving the area to itself, the Eurotunnel Company has opened it for the public. Based on a naming competition, the area is called Samphire Hoe Country Park after the local plant Rock Samphire and the word Hoe which means a piece of land into the sea.

Cotinued page 48

Blackboard chalk

Blackboard chalk is a substance used for drawing on rough surfaces as it readily crumbles leaving particles that stick loosely to these surfaces. Blackboard chalk, supplied in sticks about 5 cm long, is not actually made from the mineral chalk but from gypsum (calcium sulfate). Similarly, the "chalk" used by tailors is usually made from talc (magnesium silicate).

Extinction at the K-T boundary

The dinosaurs, including the giant *Tyrannosaurus rex*, a true favourite of children, were among the most successful creatures ever to live. They thrived for 160 million years, through most of the Triassic, the Jurassic and the Cretaceous, which together make up the Mesozoic.

Suddenly, in an instant of geologic time, they vanished completely. The geologic boundary – the K-T boundary – that marks the time of their demise defines the *end* of the Cretaceous and the Mesozoic (middle life) and the *beginning* of the Tertiary and the Cenozoic (modern life) (compare Geologic Column, page 50). For decades and years, the cause of their disappearance has been a great mystery that has inspired a long list of scientists.

It was not only the dinosaurs that became extinct 65 million years ago. Pala-

This section is from the world famous Stevns Klint ("Cliff") about 30km south of Copenhagen, Denmark. The cliff reaches over 40 m in height and stretches about 12 km along the coastline. The uppermost Maastrichtian chalk (white chalk overlain by a 3-4 m thick bed of grey chalk) is overlain by Danian limestone. The boundary between the two formations is seen as a marked indentation in the cliff. At the boundary, a thin dark clay layer is found (The Fish Clay). The section was important in the early studies of K-T boundary: It was the second location where Walter Alvarez found evidence of the existence of an iridium anomaly, which is thought to be diagnostic for a meteorite impact. The deposition of chalk continued into the Tertiary. Only a few species of the algae survived and the new Danian coccolith flora had systematically smaller platelets than the Cretaceous ones. As a result, the Danian chalks may have smaller pores and lower permeabilities at the same porosities.

Tyrannosaurus rex could not survive the colossal consequences made by a meteorite impact at the end of the Cretaceous.

eontologists have discovered that approximately 70 percent of all species on Earth never made it through the K-T boundary.

In 1980, Luis Alvarez, Nobel Prize-winning physicist, and his son Walter, a geologist, came up with the bold theory that a huge asteroid or comet crashed into the Earth at the end of the Cretaceous. The impact was thought to produce such devastating effects that most species became extinct.

Ten years later the theory was substantiated by the discovery of Chicxulub, which was named so after the modern Maya villages in the area. Chicxulub is a huge crater, 180 km in diameter, surrounded by a circular fault 240 kilometres in diameter that was apparently produced when the crust reverberated with the shock of the impact. Petroleos Mexicanos (PEMEX) was the first to have actually discovered the crater when searching for new prospects in the 1950s.

Most Earth scientists now believe that a giant meteorite did strike the Earth at the end of the Cretaceous. And it is also widely believed that the impact of an asteroid or comet brought the age of the dinosaurs to an abrupt end and caused the K-T mass extinction. However, less is understood about exactly why so many species became extinct and how ecosystems managed to rebuild themselves afterward. It has been suggested that the asteroid or comet flashed through the sky more than 40 times as fast as the speed of sound. It was so large that when its leading edge made contact with ground, its trailing edge was at least as high as the cruising altitude of a commercial airliner. It produced an explosion equivalent to 100 trillion tons of TNT, which is the greatest release of energy on our planet, from any event, in the 65 million years since then.

The hydrocarbon province

The discovery of the giant Ekofisk field in 1969 was a major turning point in the exploration for oil and gas in the North Sea. Following this breakthrough, the North Sea has proved to be one of the best areas for petroleum exploration anywhere in the world.

The North Sea chalk fields are located in the Central Graben, which came into existence in the early Triassic and persisted until Palaeocene times. The main tectonic episodes took place in late Jurassic and early Cretaceous times. Tectonic movements, including inversion, salt diapirism and strike-slip faulting, coupled with instability of margin slopes and surrounding highs, played a key role in the distribution of characteristics of the reservoir.

The top of the Chalk forms a prominent seismic marker across the Central North Sea because of the difference in acoustic impedance between the chalk and the overlying Palaeocene shales. The marker thus defines the end of chalk deposition, which ended when Laramide movements in northwestern Europe (the same tectonic movements that created the Rocky Mountains) reactivated existing faults and caused a regional relief of the adjacent landmasses (the Scottish Highlands and western Norway). This uplift generated a rapid influx of clastic sediments such as clays, silts and sands. In the Central North Sea the Chalk is thus overlain by a 3000 m thick Tertiary sequence mainly composed of mudstones and clays.

Further north, in the Northern North Sea, mudstones dominate the Upper Cretaceous succession. The chalk and its correlative shales were deposited over a period of 35 million years in an extensive, relatively deep, epicontinental sea during what was probably the largest transgression in the Earth's history.

Hydrocarbons were first discovered in the Chalk in 1966 by a well into a reservoir that has later been named Kraka situated in the Danish sector. In fact, this was also the very first well to encounter oil in the North Sea.

The chalk reservoir has claimed its fame principally from the giant Ekofisk Field that was discovered three years later, on 23 December 1969. Several discoveries followed, including Eldfisk, Tor, Valhall (GEO ExPro, Vol. 1, No. 2) and Hod fields in the south-western part of the Norwegian sector, the Dan, Gorm, Tyra and Skjold fields in the Danish sector, and Machar, Joanne and Banff fields in the UK sector.

The determining factors for the success of the chalk as a reservoir are the presence of an underlying mature source rock (Upper Jurassic black shales with a very high organic content), the preservation of favourable reservoir properties (average porosity of 30-40 % in spite of deep burial caused by overpressures and early oil migration into the reservoir), and the presence of a tight seal (Palaeocene mudstones). The combination of these factors has restricted the occurrence of the play. Chalk thus forms the reservoir in only a limited part of the North Sea as shown on the map on page 40.

Proven reserves from the North Sea Chalk Play exceed 5 million barrels of oil and 450 billion Sm^3 of gas in the Norwegian, Danish and UK sectors combined. The play is considered to be mature because most of the conventional traps, four-way closures, have been drilled. Therefore, alternative traps must be considered like the Halfdan field in the Danish sector.

Chalk filled with oil from a North Sea reservoir.

Ekofisk

A seismic reflector defined as top of the chalk showed almost 250 m of closure over an area of 50 sq km. The first well into this structure – drilled in 1969 in 60 m water depth – encountered strong shows of oil in the chalk, and oil persisted through almost 200 m of the section. Testing sustained significant flow rates of 10,000 bopd.

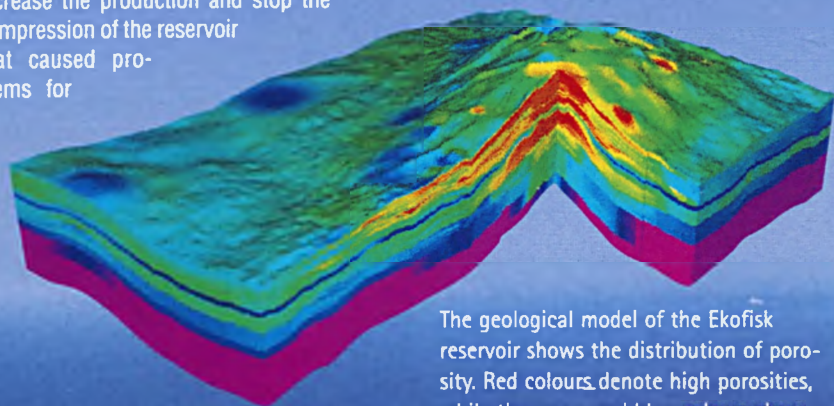
The presence of gas in the overlying mudstones that has leaked from the reservoir obscures the seismic signal in the central part of the field, and in the early phases of the exploration the central dome was interpreted to be a graben or downfaulted segment. The first wells were thus drilled on

the flanks of the field. It has later been shown that the apparent low is caused by low-velocity shales.

The reservoir in the Ekofisk field consists of overpressured, naturally fractured chalk with porosity averaging 32%, matrix permeability of 1-2 milliDarcies and fracture-enhanced permeability in the order of 50 milliDarcies.

The Ekofisk complex consists of several other fields with a reservoir in Upper Cretaceous chalk. The combined reserves are close to 600 million m^3 of oil (3,500 million barrels), more than 200 billion m^3 of gas and almost 20 million tonnes of NGL. Ekofisk is by far the largest.

The Ekofisk Field started producing in 1971. It soon became clear, however, that the recovery factor would be low, only 18%. With 7 billion barrels of oil in place, several giant oil fields would stay in the ground if no drastic measures were taken. Water injection was the answer; this could simultaneously increase the production and stop the compression of the reservoir that caused problems for the producing wells. As a result of this action, the recovery factor is now estimated at 45%, and the field may have a good life until its licence expires in 2028, and possibly longer.



The geological model of the Ekofisk reservoir shows the distribution of porosity. Red colours denote high porosities, while the green and blue colours show the distribution of low prorsities.

...when all the work ...isions involved in ...operations was done ...eld is almost over. ...use of new technology ...working processes, ...onals from different ...es can work together ...make decisions based ...mon decision basis ...the data is transferred ...real time from the oil ...an onshore operations centre. The photo is from ...Onshore Drilling Centre ...ConocoPhillips in Stavanger, Norway.

An attempt was made to drill a tunnel under the Channel already back in the 1880's. Almost 2,000 m were drilled before the project was stopped. Some people said the company ran out of money, but others blamed it was the Brithish government. The Department of War was worried that the French would invade if there were a tunnel under the Channel.

Ideal for tourists

A walk along the Cliffs is a unique and breathtaking experience. They have been recognised as a 'Site of Special Scientific Interest' for their geological and botanical importance. The Brithish National Trust owns and protects a large section of the White Cliffs of Dover to ensure that future generations can enjoy this fascinating place.

The Gateway to the White Cliffs Visitor Centre near Dover provides computer interactives, videos and stunning photography and take the visitor from prehistoric times to the present day and is a great starting point for a 4 km walk along the cliff tops taking you to South Foreland Lighthouse and on to St. Margaret's Bay.

The lighthouse was the recipient of the world's first ship-to-shore transmission on Christmas Eve, 1898, from the East Goodwin lightship, which later proved its use when it alerted the lifeboats at Ramsgate to a ship in distress – the first time a lifeboat was alerted by telegraph. Again in 1899 the lighthouse set another first when it exchanged wireless messages across the Channel to Wimereux near Boulogne.

The National Trust operates both the White Cliffs Visitor Centre and the South Foreland Lighthouse.

The geological foundation for chalk

The geological period Cretaceous takes its name from the Latin *creta*, meaning chalk. During this period the rate of ocean floor spreading increased, and a seaway opened up between the North and South Atlantic oceans towards the Late Cretaceous (compare map below).

The global sea level rose continuously throughout the Cretaceous to a point where only 18% of the Earth's surface remained as land, compared with 28% today. The sea level may have been as much as 350 m higher than today's average. This high level is thought to have been caused by the rapid growth of the mid-oceanic basalt ridges and extensive new ocean floor which, being young, were shallower than the older ocean basins. Another explanation for the sea level rise is perhaps the development of hot-spot bulges in the ocean floor. The ascent of a mantle plume beneath what is today the western Pacific, which caused intense volcanic activity between 120 and 80 million years ago, may have been particularly important in this respect by pushing up the ocean floor.

In this way, large volumes of water were displaced on to the continents creating shallow seas. The sea level rise thus resulted in widespread epicontinental seas covering low relief continents.

The global mean temperature also rose during the Cretaceous and was probably 10-15 °C higher than today's global average. The polar regions had little if any permanent ice caps in the later part of the Cretaceous; rather they were covered with dense forests. The warm and humid climate had to do with the even distribution of the continents all around the Earth, quite different from today's situation, the exceptionally high sea level as discussed above and free circulation of sea water in the world ocean as the currents were not hindered by the continental barriers.

These conditions laid the ground for the widespread distribution of chalky limestones as planktonic organisms thrived. Chalk consists predominantly of coccoliths (compare page 43), and as much as 90% of the rock is commonly made of coccolith debris consisting of calcium carbonate shell.

During the Cretaceous the ocean spilled over continental margins, inundating low-lying interior platforms the world over. Often the sea rose 300 m or more above today's global level.

TGS-NOPEC Geophysical Company

SEA OF OKHOTSK

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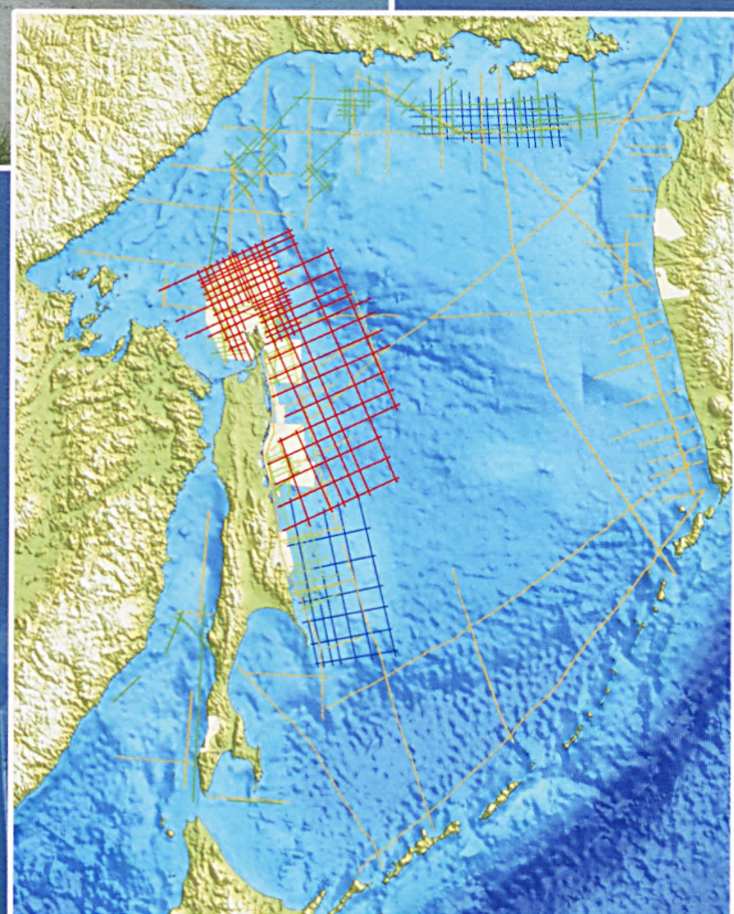

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TGS

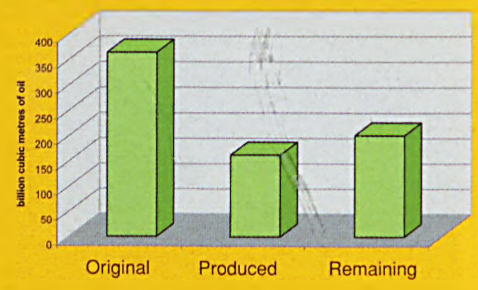
More gas than oil

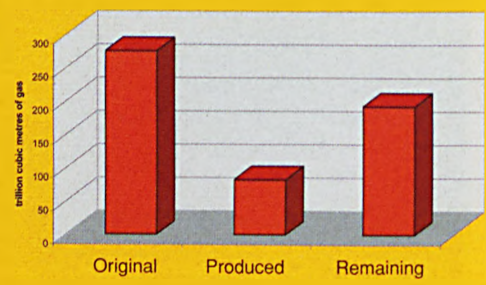
FUTURE GENERATIONS HAVE TO RELY ON GAS RATHER THAN OIL

The world's oil resources discovered through 2003 has reached a total of 2,285 billion barrels (367 billion m^3), while 1,020 billion barrels (164 billion m^3) have been produced in the same period.

Worldwide gas resources discovered through 2003 amounted to 9,725 TCF (265 trillion m^3) while 2,910 TCF (83 trillion m^3) had been produced.

These numbers are presented in the "IHS Energy 2004 Report on World Petroleum Trends". A simple calculation shows that approximately 45% of the oil and 30% of the gas that have been found have already been produced, sold and spent (compare diagram).





CONVERSION FACTORS

Crude oil
1 m^3 = 6.29 barrels
1 barrel = 0.159 m^3

Natural gas
1 m^3 = 35.3 ft^3
1 ft^3 = 0.028 m^3

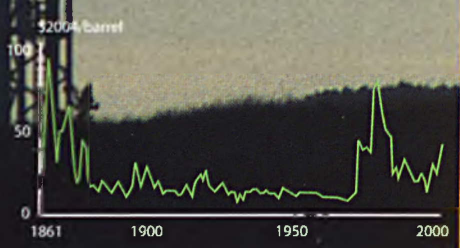
Energy
1000 m^3 gas = 1 m^3 o.e
1 tonne NGL = 1.9 m^3 o.e.

Numbers
Million = 1 x 10^6
Billion = 1 x 10^9
Trillion = 1 x 101^2

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

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

Historic oil price



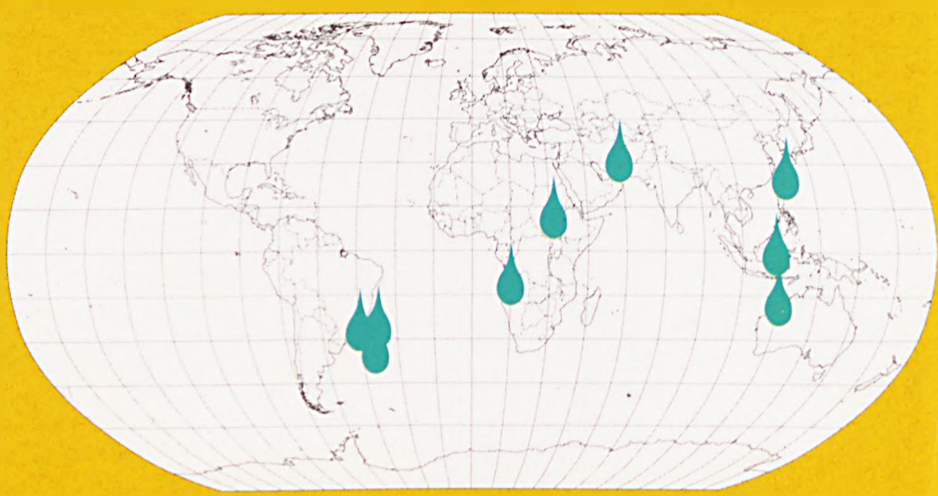
ONLY 50% OF OIL PRODUCTION REPLACED

A total of 46 major discoveries were made around the world in 2003. Altogether they accounted for 9,5 billion barrels (1,5 billion m^3) of oil and 24 TCF (680 billion m^3) of gas, according to the "IHS Energy 2004 Report on World Petroleum Trends", which was recently published. The largest discovery, Iran's Lavan gas condensate find, was made in a Palaeozoic reservoir and the recoverable gas resources have been estimated to 6 TCF (170 billion m^3).

According to IHS, the most notable feature of the 2003 major discoveries is that 65% were made in water depths greater than 1000 m (3300 ft).

Including Lavan, nine giant discoveries were made last year, 3 in Brazil, and 1 each in Angola, China, Malaysia, Sudan and Vietnam.

The bad news are that the reserves additions have not replaced production. In fact, the new discoveries have only replaced 50% of the oil consumed and 67% of the gas produced.



Giant discoveries made in 2003.

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