EUROPEAN
COMMISSION
THERMIE

European Geoscience Technologies

Reducing the risk

in oil and gas

exploration

Directorate General for Energy (DG XVII)

JOULE-THERMIE

The JOULE-THERMIE programme was launched in 1995 as the European Union's first 'integrated' programme, bringing together the resources of the European Commission Directorates-General XII (Science, Research and Development) and XVII (Energy). This programme is funded by the European Union's Fourth Framework Programme for Research and Technological Development, one of the most extensive research funding initiatives available to European companies and research organisations.

The JOULE-THERMIE programme runs until 1998 and has a total budget of 1,030 MECU of which 566 MECU are allocated to the THERMIE demonstration component of the programme for the support of projects and assosciated measures. THERMIE is focused on the cost-effective, environmentally-friendly and targeted demonstration and promotion of clean and efficient energy technologies. These consist of renewable energy technologies; rational use of energy in industry; buildings and transport; a clean and more efficient use of solid fuels and hydrocarbons. Essentially, THERMIE supports actions which are aimed at proving both the technologcal and economical viability and validity of energy technologies by highlighting the benefits and by assuring a wider replication and market penetration both in EU and global markets.

Colour Coding

To enable readers to quickly identify those Maxibrochure relating to specific parts of the THERMIE Programme each Maxibrochure is colour coded with a stripe in the lower right hand corner of the front cover, i.e.:

RATIONAL USE OF ENERGY - RUE

RENEWABLE ENERGY SOURCES - RES

SOLID FUELS - SF

HYDROCARBONS - HC

GENERAL - GEN

Acknowledgements

Front Page photo: Promotional operation of POLYSEIS in Louisianna

European Geoscience Technologies:

Reducing the risk in oil and gas exploration

THERMIE PROGRAMME ACTION No:DIS-140-95-UK

⅁CMPT

Other Maxibrochures in the hydrocarbons series:

Oil and Gas Technology - Investing in a major European Industry for Future Security and Prosperity

Subsea Diverless Intervention Systems in the Offshore Oil Industry

The Oil Production Industry in Western Siberia and the Environment - Current Practices and Prospects for Change

Oil and Gas Process Technology - the latest advances for use on offshore production installations

European Technologies for Oil and Gas Exploration in Remote and Poorly Accessible Areas

Market Prospects for Multiphase Technology

Pollution Control Technologies: limiting the environmental impact of the hydrocarbons industry

CONTENTS

1. INTRODUCTION

Petroleum exploration technologies, such as seismic surveying, are used to identify potential prospects and to determine where exploratory wells should be drilled. Since the birth of the oil and gas industry, considerable research and development relating to these technologies has been made by specialised research centres, contractors, and oil companies. As a result, significant progress has been made both in terms of new technology and improved methodologies.

The ultimate aim of the industry has been to reduce the cost risks associated with petroleum exploration by:

- identifying new structures and traps in previously explored areas;
- reducing the number of dry wells that are drilled;
- reducing overall exploration costs.

In the 1980s, the fall in the price of crude oil made the exploration of frontier areas financially less attractive and put an emphasis on re-exploring existing petroleum provinces. New technology has improved the explorationist's ability to image the sub-surface, build geological and geochemical models of sub-surface conditions, and predict reservoir behaviour. This has enabled new surveys over previously explored regions to uncover additional reserves. Consequently a statistical review of petroleum discoveries since the 1980s shows that the bulk of new discoveries are in established provinces rather than frontier regions.

Similarly, an improved understanding of sub-surface conditions through enhanced imaging, interpretation and modelling will lead to a reduction in the number of dry wells drilled.

The geophysical industry has particularly benefited from the advent of supercomputers which allow large volumes of data to be processed relatively quickly. Combined with new techniques such as multi-streamer surveys offshore, this has reduced overall costs.

Further advances in computer capabilities are expected in the near future, and it is envisaged that these will help geophysicists to overcome the remaining limitations on data processing. Developments in exploration technology will also help to open new frontier areas, for example, the Arctic, deep offshore, remote onshore and geologically complex settings, such as fold belts. (See also *European Technologies for Oil and Gas Exploration in Remote and Poorly Accessible Areas*.)

This maxibrochure summarises the state-of-the-art of exploration technology and emphasises "near-market" technologies being developed in Europe. The main areas of development are summarised in Table 1.

Table 1 Main advances in petroleum exploration geoscience

1.	Data acquisition	New technology and approaches have led to an increased volume of data for less cost, and improved accuracy.
2.	Data processing	Hardware capabilities have increased significantly in terms of speed and capacity.
3.	Data interpretation and modelling	New and improved software has been developed for data interpretation. Modelling of more complex structures and specific phenomena is now possible.
4.	Integration	Integration between the various geoscience disciplines has increased, e.g. geology, geophysics, geochemistry.
5.	Standardisation	Common computing standards and products are being developed.
6.	Global understanding	The global understanding of petroleum geology is improving, and risks and uncertainties are being quantified.

2. SEISMIC SURVEYING

Within geoscience, the most advanced technological innovations have been related to seismic surveying and the handling of seismic data.

In terms of data acquisition, marine developments have included:

- the introduction of multi-streamer techniques;
- enhanced quality control of the source;
- the use of global positioning systems to improve survey accuracy;
- the introduction of 24-bit recording systems;
- new media for data storage;
- improved on-board processing systems.

Specific technologies have also been adapted for shallow water, swamp conditions and transition zones.

Developments related to the acquisition of seismic data onshore have concentrated on reducing the costs involved and improving the quality of the data.

Conventional seismic data processing has become increasingly integrated with acquisition, and the main processing activities of both onshore or offshore data are now performed in the field. Only activities that require lengthy human input (e.g. velocity field determination) or large computing power (e.g. migration) are performed independently of acquisition.

The evolution of seismic data processing has been closely related to the development of high-performance computers. For example, parallel processors now allow large data cubes to be accurately depth migrated and much smaller features to be resolved. Improved structural definition has, in turn, led to better reservoir descriptions. New techniques and analysis tools that can predict reservoir and fluid properties from variations in seismic amplitude now exist.

Interactive interpretation workstations that operate in three dimensions are now extensively used in the industry. The detection of subtle structural features has been enhanced by three-dimensional auto-picking methods and horizon attribute maps. Future improvements in three-dimensional interpretation are highly dependent on visualisation tools and the integration of geological and reservoir engineering information into the process.

2.1 Marine Seismic Data Acquisition

Survey methods

In general, seismic survey vessels are developed and owned by large international contractors such as Western Geophysical (USA), Geco-Prakla (part of Schlumberger, France), and PGS Exploration (Norway). Most vessels are now equipped for 3D seismic data acquisition.

The introduction of multi-streamer techniques in the 1980s resulted in a significant increase in productivity and a related decrease in acquisition costs. For example, a ship carrying out a high-resolution survey can tow up to 12 streamers spaced 25 - 50 m apart, resulting in a bin size of 12.5 - 25 m. Compared to previous techniques, a much larger surface area is covered in one pass. In addition, streamer lengths up to 5,000 m can now be used to explore deep targets. The original limitations on multi-streamer surveys were data management, quality control and accuracy, but contractors have responded by developing integrated database management systems, on-line quality control, and improved positioning systems.

Another considerable advance was the introduction of Multi-Vessel/Multi-Streamer (MVMS) acquisition. This method is particularly useful for acquiring data from complex structures that can only be analysed using large offsets and azimuth distributions. One of the largest MVMS surveys was shot in the North Sea in 1994 by PGS Exploration for Norsk Hydro and BP Norway. The survey employed three vessels in a ten-streamer configuration. Twenty lines of data were acquired for each traverse of the vessels by using two seismic sources simultaneously. However, in complex structural areas or areas with high noise levels and difficult multiple problems, BP recommends single-source acquisition to produce high fold at lower cost.

The best way to obtain high-quality long offset data (up to 6,000 m) is to use two ships, each towing half of the required length of streamer. With this configuration, streamer positions are easier to control because each streamer has a compass on the tailpoint and frogpoint. Moreover, the ships can make tighter turns with shorter streamers, a parameter that can considerably influence the cost of a 3D survey.

Parallel acquisition, with two or three vessels, covers a broad azimuthal distribution and may help to solve fracture distribution problems as well as litho-stratigraphical ones. The main limitation for this method is that the azimuthal measurement cannot, at present, be fully accounted for during processing.

Sources

The control of the sources is an important influence on the resolution of acquired data, and therefore the reservoir description. There are two areas in which source improvements are possible:

- quality control of the emitted signal;
- shot-by-shot measurement of the near-field signature.

Shot-by-shot measurement of the near-field signature would help in the prediction of the far-field signature which is, in turn, used to deconvolve the data.

Bolt Technology Corporation (USA), the inventor of airgun sources, is constantly improving its products. The company's Long Life Air Guns have a more stable signal

than other products, and also require less maintenance. The latter factor adds to the gun's economic attractiveness. The guns also offer an enhanced frequency spectrum and peak-to-bubble ratio.

The Trisor system, being developed by Geco-Prakla, distributes electronics in the sea to provide firing control, digitise sensor data for firing time, and measure source depth, near-field signature and airgun firing pressure. These measurements allow the sources to be monitored by computing the far-field signatures. Source tuning based on peak pressure alignment can also be carried out on-board in real time.

Data resolution could be improved by using a source that emits a signal with more high-frequency components, such as the marine vibrator. Although this source is only suitable for surveys that are not constrained by time (e.g. time-lapse acquisition), it has the advantage of lower environmental impact compared to the airgun. It would therefore be useful in protected environments such as the Caspian Sea.

In a JOULE-THERMIE project being undertaken by OGS (Trieste, Italy) with DINMA (University of Trieste) and IPGP (Paris, France) a new airgun array source is being developed to resolve and image deep targets and complex structures. The air gun array source, operating in a "Single Bubble" mode, is designed to overcome the poor effectiveness of large tuned arrays in the medium-to-low frequency band (10 - 40 Hz). The basic principle of the low frequency pulse generation consists in centring the output of the array on the first bubble pulse, by sequential firing of different size guns in the array. OGS is planning to demonstrate the prototype system (for synchronisation of the guns and quality control of the shooting operations) in two test areas close to the Italian coast. The first is the Paola Basin in the Southern Tyrrhenian Sea, a N-S elongated basin with thick Plio-Quaternary deposits which accumulated on an active continental margin with thinned crust. The second area is located in the Pelagian Basin (Southern Sicily offshore), an area attracting several prospections for oil research. This area is characterised by thick Tertiary and Mesozoic sequences with thick carbonate intervals alternating with shales, marls and sandstones.

Positioning systems

The precise location of all the components in a 3D survey (sources and hydrophones) is vital for setting the exact limits of the target and placing a new well. The introduction of Global Positioning Systems (GPSs) in the 1980s represented a major breakthrough for navigation. These systems provide the accuracy required for seismic surveying, and contractors and oil companies do not expect any further advances in this area in the near future.

Western Geophysical has introduced the Sargas GPS which consists of a highly sophisticated network of reference stations, satellite communications, and on-board processing of navigation data in real time.

Geco-Prakla's integrated acquisition approach, TRILOGY, has a single hardware and software platform, TRINAV, that reduces the long turnaround associated with processing navigation data. TRINAV monitors the acquisition of navigation data in real-time and can complete data processing on-board.

Total (France) has developed the Concept System, a three-dimensional tool that allows the position of the survey vessel to be checked.

Scanor Technology (Basingstoke, UK) has developed a pressure transducer that allows the towing depth of airguns to be determined with an accuracy of 10 mm.

Recording systems

In recent years the main developments have been:

- the introduction of 24-bit acquisition techniques;
- an increased number of recording channels.

Twenty-four-bit technology has brought the analogue-to-digital converter close to the hydrophones and resulted in a significant increase in the quality of the raw data. One example of this technology is the I/O System Two developed by Delta Sigma Technology. This system has an instantaneous dynamic range of 120 dB which allows a very low signal to be recorded even if there is a high noise level.

The number of channels that can be recorded simultaneously is a vital parameter for two main reasons. First, productivity is related to the number of seismic traces generated by a shotpoint at one time. Second, spatial filtering improves with more channels and noise can be reduced.

Most of the current 3D recording systems have thousands of channels. For example, Western Atlas's Vision 8000 (Canada) has 7,680 channels and Sercel's SN388 has 19,200. No major technological advance in marine seismic recording systems is expected in the near future.

High-density storage systems

The datasets of 3D seismic surveys frequently reach the terabyte size ($1Tb = 10^{12}$ bytes), and the storage, handling and transporting capabilities of conventional storage systems have been pushed to their limits.

A typical 3D marine seismic survey shot by a single vessel, may acquire 4 Gb ($1 Gb = 10^{9}$ bytes) of data an hour (1 Tb every ten days). Using current storage media, a 5 Tb survey requires 33,000 nine-track tapes or 25,000 3480 cartridges to store the raw data alone. Such large numbers have significant cost and time implications. Transporting the tapes or cartridges to the survey vessel and then to the processing centre is an expensive task involving boats, helicopters and cargo trucks. Once the data reaches the processing centre, transfer may take

Fig 1 R/V OGS-Explora while demonstrating the innovative high energy and low frequency Sinbus source
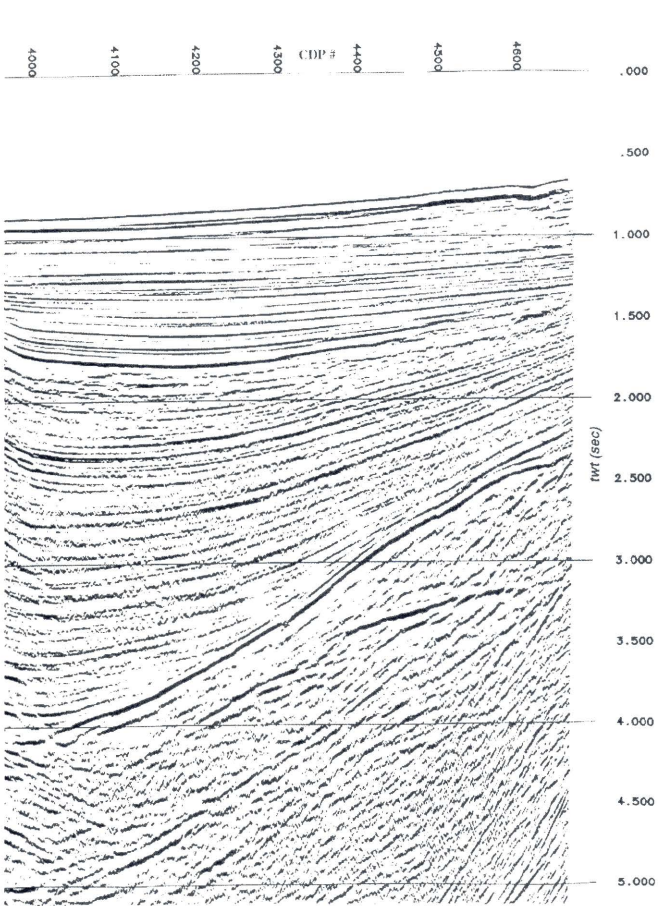

Fig 2 Part of a stack section acquired with Sinbus source (note the still good resolution in the shallow even though the acquisition was aimed at deep penetration
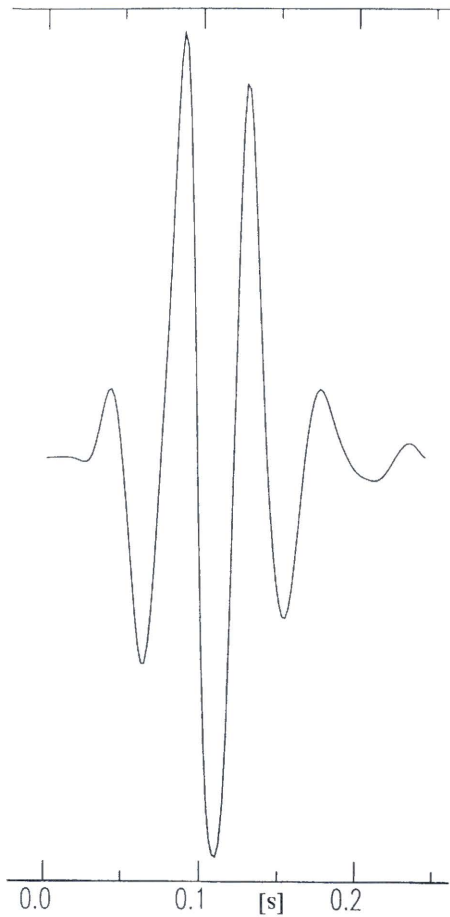

Fig 3 Far-field signature of the air-gun array operating in "Single Bubble" mode

months because each tape or cartridge has to be loaded onto the centre's computers by hand.

In 1993 a new technology emerged - D2 helical scan video recording tapes. Compared to traditional tapes, D2 tapes have a higher density, faster data transfer rates, and increased reliability.

A 59-day test survey carried out by Mobil in the Gulf of Mexico using a Geco-Prakla survey vessel, recorded data on both conventional 3480 cartridges and D2 tapes. The vessel recorded 2,250 km of seismic lines using 320, 480 and 960 channel shots, resulting in around 215 Gb of data. The data were stored on nine D2 tapes compared to 1,360 cartridges. Validation of the D2 data was made by bit-to-bit comparisons and by processing the data with existing software.

Raytheon E-Systems (USA) has now produced its EMASS Data Tower to exploit the D2 technology. The Data Tower requires only 2.5 m^2 of space and can handle a 5.7 Tb data volume with only 228 D2 tapes of 25 Gb capacity. The system can replace five automated tape silos occupying a space of 87 m^2 and using 30,000 cartridges.

The CY-9000 digital data recorder, supplied by Cybernetics (USA), also uses high capacity storage with 42 Gb tapes, storing data at 12 Mb per second (1Mb = 10^6 bytes).

An alternative recording technology based on the "linear" technique has been developed by IBM. The conventional IBM 3490 system uses half-inch cartridges with 36 parallel tracks, and fixed read/write heads. The new 3590 system employs 128 tracks on a half-inch tape, and can store up to 10 Gb of data. Furthermore the data flow is three times faster (9 Mb/s for the 3590 compared to 3 Mb/s for the 3490). IBM claims the linear technique offers better reliability for continuous data flow applications such as seismic data acquisition.

This technology is still undergoing rapid evolution and the competition between helical and linear technology has prevented the adoption of an industry-wide standard. This presents obvious difficulties for those responsible for selecting data-storage equipment. However, preliminary discussions between the various companies have been reported and a common standard may eventually be adopted.

On-board processing systems and transmission systems

On-board processing has been developed to the level of providing a stacked 3D block and a raw time migration within three weeks of data acquisition being completed. An example of an on-board processing system is Geco-Prakla's processing software, TRIPRO, which is fully integrated with TRILOGY, its acquisition system. CGG (France) also uses an on-line interactive processing package called GEO-QA/QC that integrates quality

control with quality assurance, and can be implemented on-line with the Sercel SN388 acquisition system. GEO-QA/QC is a subset of the processing package, GEOVECTEUR+.

One challenge for on-board processing is the development of computers powerful enough to carry out real-time processing. Once real-time processing is achieved, new methodologies will be needed to speed up the remaining manual phase of the processing, particularly stacking velocity analysis.

However, on-board processing is not a satisfactory solution for many oil companies because it requires experienced processing supervisors to work on survey vessels. Developments in satellite communications made by other industries (e.g. telecommunications) are therefore followed with interest because they may eventually enable data to be quickly and efficiently transferred to an onshore processing centre.

At present, data can be transmitted by satellite at a rate of 64 Kb/s, but the cost of such communication on a public channel is prohibitive for large amounts of data. As a result, the seismic industry only transfers quality control data in this way. Within the next three years, the cost of satellite communication is expected to decrease. Some contractors are already planing to buy their own satellite channel, while others are planning to improve data compression techniques, therefore reducing the volume to be transferred.

Shallow water and transition zones

Seismic acquisition in shallow water and transition zones (swamps, tidal mudflats, estuaries, harbours, coral reefs, fishing zones, areas of ecological preservation, etc.) has changed rapidly over the past five years following the introduction of Ocean Bottom Cable (OBC) and radio-frequency telemetry systems. These techniques can also be used in congested offshore areas where production facilities make towed-streamer operations hazardous or impossible.

The OBC method combines land and marine seismic data acquisition techniques in that it employs receiver arrays fixed to the ocean floor and a marine vessel towing the source array. The use of a conventional survey vessel as a source was the first step in the evolution of the method. In the early 1990s dual sensor technology and digital telemetry recording systems were introduced. This greatly improved the accuracy and reliability of the equipment.

Dual sensor technology combines signals from both hydrophones and geophones at each receiver location to remove the effect of the water layer from the seismic data, and is commonly used for water depths beyond 10m. For water depths between 0.3 - 10 m, hydrophones are used rather than geophones. In this case, the period of the receiver "ghost" reflection is not too long and can be removed by deconvolution algorithms.

Digital telemetry recording systems enhance the dual-sensor OBC method by eliminating problems associated with analogue cables, such as leakage, phase distortion and crosstalk. One such system is manufactured by Western Geophysical Exploration Products. The eight-channel remote telemetry units are protected by a cylindrical steel housing with bottom cable connectors at each end. This housing is designed for operations at depths down to 200 m. Each remote unit receives and digitises four seismic channels from each of the two bottom cable segments to which it is attached. Two channels are dedicated to each receiver station (one for the hydrophones and one for the geophones). Each remote unit processes and transmits the data for its closest four receiver stations.

Another system is SYNTRACK. Manufactured by Syntron (USA), its remote units can convert the signals from 12 adjacent channels or six dual-sensor receiver stations. This system supports very long cable lengths (up to 24 km) and up to 1,920 recording channels with a 2 ms sample interval.

Bottom cable acquisition produces better technical results than towed streamer acquisition because it:

- eliminates the streamer "ghost";
- improves signal-to-noise ratios;
- improves the accuracy of location groups;
- reduces ambient noise to reveal sub-surface structures that would be hidden to conventional techniques.

However, OBC is expensive and is generally used for field monitoring rather than for exploration.

Current OBC systems are also limited to water depths of 110 m, but a new system called SUMIC has extended the technique to 180 m. Commercialised by Geco-Prakla following development by Statoil (Norway), SUMIC uses remotely operated vehicles (ROVs) to bury hydrophones and three-component geophones in the seafloor. The use of ROVs overcomes the depth limitation associated cable laying.

The advantages of the system include:
- the acquisition of shear waves (S-waves) through the use of multi-component geophones;
- the possibility of time-lapse 3D seismic surveys (also called 4D seismic).

Shear waves only respond to lithology and porosity whereas compression (P) waves are additionally sensitive to pore fluid. Comparing data from both sources can therefore reduce ambiguities in analysis. However, shear waves do not travel through water so they cannot be picked up by other survey techniques.

2.2 Land Seismic Data Acquisition

In terms of the total number of seismic traces acquired, only 25% of 3D seismic surveys are onshore. This low percentage is explained by the relatively high cost of onshore acquisition. However, new land recording systems have greatly increased the number of simultaneously generated traces that can be handled and different survey applications are now being considered. However, 3D onshore data acquisition is still mainly used in mature hydrocarbon provinces where it has an important impact on drilling success.

Sources and geophones

The main source of acoustic energy for land surveys is vibroseis. Dynamite, which is an alternative, is now only used in rare cases where the ground does not allow good penetration of the vibroseis energy.

The main problem with a vibroseis source is controlling the quality of the emitted signal. Two companies are currently looking at ways to improve this. CGG is examining a technique that compares the vibration emitted by each vibrator with a reference (pilot) signal. The differences between the signals are transmitted to the recording cabin for quality control. Geco-Prakla has developed a statistical approach (VEiW QC) where the performance of each vibrator is compared to others operating under similar conditions.

The most recent improvements in geophone technology have been the development of recording systems that can test geophones at each shot and the adaptation of geophone performance to 24-bit modem data acquisition systems. The distortion of the signal and self-generated noise have also been reduced. The American OYO Geospace geophone, GS-30CT, is probably the most widely used.

The acquisition of 3D seismic data often involves transporting heavy equipment across difficult terrain. Miniaturising equipment will be a key factor in raising the productivity of 3D land data acquisition to the level demanded by the oil industry. The solution will probably come through the transfer of technology from the telecommunications or space industry, where progress has already been made in reducing the size of components.

Radio-frequency data telemetry

Improved technology in radio-frequency transceivers, band-width controls, tuneable frequencies and fast computers has contributed to the development of available telemetry systems. Cable systems offer faster data-transfer rates but radio-frequency surveys actually transfer more shots per hour per day because:

- the equipment can be set up faster (no cables);
- the central recording unit does not need to be moved to the string ends;
- down time is minimal (no need to test, trace faults, replace or repair, then re-test cables before each shot).

Radio telemetry systems are affected by shadow areas where VHF radio waves are blocked by structural,

environmental or electrical barriers, but this limitation can be overcome by wirelinking remote acquisition units to a master unit outside the shadow. The remote units can then download data to the master unit, which then transmits them to the central recording station.

The modularity of these systems allows them to be adapted to specific surveying conditions, e.g. swamps.

The POLYSEIS system, supported by the THERMIE programme, illustrates the versatility of these systems. The system is now commercially available from Syntron under an IFP (French Petroleum Institute) licence. The three-channel remote transmission units are available for land or marine conditions.

Fig 4 POLYSEIS - Buoy set up

Data acquired by the remote units are transferred by telemetry or wirelink to a master unit, where they are either recorded on a portable recording system or transmitted to a central recording unit via fibre-optic cables or a microwave link. Automatic and comprehensive quality control circuits in the remote units test the quality of the data and the geophone spread (electronic test, filter, distortion, sensor pulse response, time break accuracy, channel noise, crossfeed, leakage, autocorrelation, string and stack tests). In addition, Sigma-Delta analogue-to-digital conversion and extensive use of DSP technology allow digital filtering and signal pre-processing functions to be carried out by the remote transmission unit.
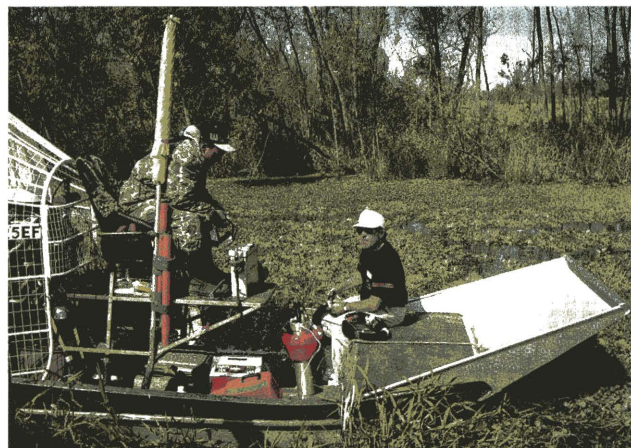

Fig 5 Promotional operation of POLYSEIS in Louisianna

By using correction codes for transmission, the system is as reliable as one based on a cable.

Land information management systems

The integration of different tasks during 3D land data acquisition is a key factor for data quality. Integration can also reduce costs by improving turn-around time.

Integrated products for land information management such as Geoland and Olympus-IMS, produced by CGG and Geco-Prakla respectively, include:

- the design of the 3D survey using geographical information (topographic maps, satellite images, etc.);
- geometry control using navigation data;
- comparison between theoretical and actual layout, and therefore comparison between theoretical and surveyed coverage;
- management of observer reports.

All the existing packages model the acquisition process but do not, as yet, accurately model the source-earth-geophone system. (This observation is also valid for marine information management.) Further advances could be made by developing packages that model the effect of weather, topography and other obstacles on survey costs.

Recording systems

The recording systems for seismic surveys on land are similar to those used offshore. However, the portability of equipment is a key factor on land because the cost of acquiring seismic data is greatly influenced by the topography of the survey site.

The mature producing areas of the USA have provided a market for small, light and economical systems such as those supplied by Bison Instruments, OYO Geospace or EG&G. These companies now sell 24-bit recording systems that, together with high-frequency portable vibrators, can image structures down to 1700 m.

Positioning systems

GPS is used widely during seismic surveys on land. Using a portable system, an operator can acquire hundreds of positions a day that are accurate to within a few millimetres.

The Sercel system MANPACK D.G.P.S. uses a differential GPS reference station and portable mobile units. The reference station permanently broadcasts GPS corrections to the mobile station and records GPS raw data for quality control and post-processing purposes. Real-time positioning can be performed via a central computing station. In particular, the vibroseis position can be acquired at the actual shotpoint position during sweep.

To improve the quality control of the differential GPS method, GPS Technology Company recommends joint

use of digital orthomap (DOM) and geographic information systems (GIS). DOM are seamless mosaics of digital orthophotographs of the ground that provide a geodetically correct backdrop for use on either a GIS-equipped workstation or a light table. They are produced from either high-altitude photographs or satellite images, and are used to determine accurate visual co-ordinates for any fixed object on the ground, such as a seismic shotpoint flag. DOM may be used to design a 3D seismic survey by loading them into land information management systems. Surveying crews can also combine their use with hand-held GPS receivers for quality control.

Positioning system technology is now mature enough to provide the position of any given point in real-time. No major evolution is now expected.

Land-towed streamers

Land-towed geophone streamers are used for areas where usual acquisition devices are inefficient, e.g. ice or snow-covered ground, transition zones, etc.

Fig 6 Using Seismaster over mud flats

An example is Seismaster, developed by Scientific Management Associates (UK). The system consists of a carrier (80 mm x 20 mm rectangular cross-section) incorporating tensile towing members, data wires, and digital-grade geophones. A typical configuration consists of 25 m, 50 m or 100 m interchangeable sections, providing 120 groups, 25 m group length, 12 geophones per group and a 3 km spread. The system weighs 1.5 kg/m, and all the components are enclosed in a watertight structure.

Data quality is comparable to planted geophones in all but the severest wind conditions. The low friction carrier structure has registered towing loads as low as 250 kgf (equivalent) for a 3 km configuration towed at 15 km/h over snow.

Fig 7 Seismaster sections - flexibility aids transportation

There are plans to develop the system by incorporating a 24-bit digital telemetry system. A noise cancellation technique that will eliminate any susceptibility to wind noise is also being investigated.

2.3 Seismic Data Processing and Modelling

Hardware

The latest breakthrough in computer hardware has been the introduction of massively parallel computers that provide gigaflops of computing power (1 Gflop = 10^9 floating point operations per second). This level of power is vital given that a 3D pre-stack depth migration requires at least 50 Gflops.

Supercomputers have been increasing in power by approximately 70% per year, making a teraflop (10^{12} flops) computer conceivable. Such a computer would allow large 3D seismic surveys to be depth migrated before stacking at low cost. It may also be possible to compute the elastic solution of the wave equation, therefore allowing lithographic parameters to be assessed or fluid content to be detected.

In parallel with the increase of computer power, processing costs have fallen. The cost of a gigaflop reduced by a factor of ten between 1993 and 1995.

The development of powerful centralised computer systems has also run in parallel to the development of interactive workstations. It seems likely, therefore, that the future trend will be to concentrate computer power in a limited number of places (e.g. in a geophysical contractor's building) and employ network communication facilities to interpret, control and edit the results on remote interactive workstations.

Cray Computers (T3Ds are used by Geco-Prakla and CGG), Futjitsu (VPX 220/20s are used by Geco-Prakla and IFP), Thinking Machine (CM5) and Convex (3410

used by I/O Systems) are the most common systems used in seismic processing.

To make the most of the available computing power, a high-level of 3D graphical capability has been developed. SGI workstations (Silicon Graphic) are the leaders in this market although other workstation providers such as Sun Microsystems, IBM, HP and DEC are beginning to enter this domain. In the next few years competition in this market should increase. Some geoscientists are also considering virtual reality as a tool to "dive" inside 3D blocks and interpret data within a virtual 3D world.

Software

Developments in software will be driven by:

- conventional processing being increasingly linked to acquisition;
- imaging and inversion being linked to interpretation.

In the past few years the main processing companies have developed interactive packages that allow better control of parameter choice as well as quality control of the computation results. These packages include Western Atlas' Omega SPS, CGG's GEOVECTEUR+, Cogniseis' FOCUS, and Advance's PROMAX. These interactive packages can all be used in batch mode to speed-up application with a large volume of data.

Conventional processing

Two main development areas have been recognised for conventional processing. First, even with interactive packages, a large amount of time is spent on routine work that is fundamental to the quality of results, e.g. trace editing and velocity field computation. New methods such as neural networks or artificial intelligence could be adapted to reduce processing turn-around time and to improve quality through better coherence of the results.

Second, the problem of energy multiples must be addressed. Approximately 90% of energy multiples are currently removed from the data, but the remaining 10% can dramatically affect the interpretation of key reflectors, e.g. the Base Cretaceous Unconformity in North Sea prospects.

Interactive methods make it easy to perform complex processing sequences and to check results. However, it is also very easy to make errors and to spend a lot of time finding the appropriate set of processing parameters. Consequently there is a need to develop quality control methods for the processing sequence that can be integrated with the interactive processing package.

CGG is aiming to demonstrate improved accuracy in 3D seismic processing through a project supported by THERMIE. A prototype of a 3D seismic imaging system has been developed that incorporates:

- mathematically precise computer algorithms for processing surface-detected seismic data;

- fast computers that can economically process the immense volume of data involved;
- an accurate macro-velocity model of the earth's subsurface to ensure a meaningful and precise 3D image.

As part of the project, CGG has developed migration processing algorithms (pre-and post-stack) that will be executed on a massively parallel computer. In addition, the project will weave together several branches of recently developed seismic inversion technology to form a self-contained software library. This software will run on a super-fast 3D graphic workstation and provide a way of elaborating and validating a macro-velocity model of the sub-surface.

Depth imaging

For the past three or four years, processing companies have focused their attention on very sophisticated depth migration algorithms.

CGG has developed three products, TOMCAD, RSMIG, and KIMIG for travel time inversion, post-stack and pre-stack depth migration respectively. Geco-Prakla has developed VIVID for 3D post-stack and pre-stack depth migration, 3D velocity model building, and 3D post-stack turning wave migration. Within the processing package Omega SPS, Western Atlas has developed the Shared Earth Concept which allows better integration of the data needed for the 3D depth migration. Shared Earth has been widely used for sub-salt imaging in the Gulf of Mexico.

All these depth migration software packages combine building a 3D earth model with pre-or post-stack depth migration. However, these two tasks do not use the same type of computer. Building an earth model requires a 3D visualisation workstation, e.g. a Silicon Graphics workstation. Depth migration needs a super computer, e.g. a CM5 from Thinking Machine or a Cray T3D parallel processor.

As the power of computers increases and the main migration algorithm problems are solved, the main limitation on the method will be the efficiency of the 3D velocity model building. This step, which could be the most time-consuming part of a depth transformation, requires a high degree of integration between processing and interpretation experts. This integration should be taken into account at the software level by using interoperability between the 3D modelling software and the migration package. For 3D modelling, CGG uses GOCAD software developed at the University of Nancy, while Geco-Prakla has developed KUDOS.

Future developments will include the introduction of intelligent software and virtual reality technology to edit the model. This new technology will probably lead to a new work organisation. "Virtual" teams will consist of geophysical contractors (carrying out migration on supercomputers) and oil company

interpreters (building velocity models on 3D visualisation workstations to control the migration). This organisation will require the exchange of digital information through an efficient and possibly international network.

Independent software companies have also developed tools for depth imaging.

GX Technology (UK) has produced a product that includes two-dimensional earth modelling by ray tracing methods (GX II) and a three-dimensional system for model building, model visualisation and ray tracing (3D-AIMS). With support from THERMIE, the company has also developed SIRIUS, a two-dimensional velocity model for pre-stack depth migration. This package includes TOMOPACK, a pre-stack travel time picking and tomographic inversion package, and KIRKPACK, a Kirchhoff pre-stack depth migration toolkit. Currently there are 20 licenses installed in Europe, distributed between oil companies and seismic service companies. The 2D version is now being extended into 3D.
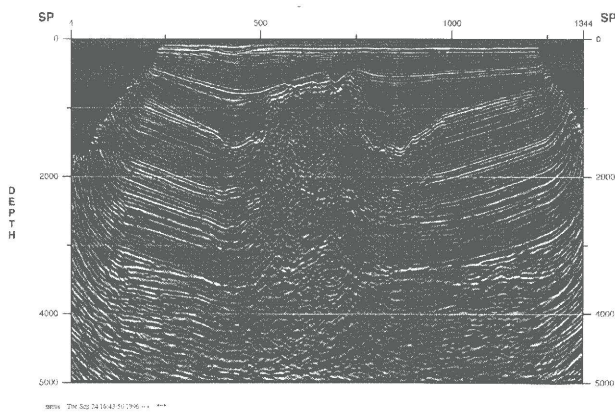

Fig 8 Output from SIRIUS

Paradigm Geophysical (USA) has developed a package called GeoDepth that includes:
- modelling of complex structures;
- estimation of interval velocities from common depth point (CDP) gathers by ray-tracing methods allowing non-hyperbolic moveout;
- Kirchhoff pre-stack depth migration.

At present this software is only marketed for 2D migration.

Software that was a precursor for interactive ray-tracing was developed by Sierra Geophysics. Now marketed and developed by Western Atlas, it includes 3D velocity modelling, curved and turning ray-tracing, and map migration.

Applied Geophysical Software specialises in sub-salt imaging (mainly for the Gulf of Mexico). A 3D pre-stack depth migration, 3-D INVERSEIS, can run on clustered, multi-CPU workstations thereby avoiding the need for expensive supercomputers.

All these depth migration methods have been developed to image structurally complex areas such as sub-salt zones. According to oil companies operating in the North Sea, only 10% of surveys require this type of processing, and a major improvement in turn-around time and cost would be needed to encourage wider use.

Reservoir description

Geophysical contractors and software companies both promote products for reservoir characterisation to enable lithological and fluid content to be predicted. The important parameter is the amplitude of the seismic signal. This can be analysed in two ways:

- before stack with the amplitude versus offset (AVO) technique;
- after stack with the stratigraphic inversion method.

Amplitude versus offset (AVO)

AVO is designed to extract information from the variation of reflectivity with respect to the angle of incidence of seismic rays. This variation may be associated with the lithology of the reservoir but more often is associated with the fluid content. Pre-stack processing is a key step in AVO analysis because the traces must be corrected for any factor that affects the amplitude. Only the relative amplitude variation related to an earth reflectivity variation must remain in the CDP gathers.

CGG uses the GEOVECTEUR+ processing package modules to compute a surface-consistent amplitude correction for deconvolution. Western Atlas and Geco-Prakla have developed their own algorithms to process preserved amplitude seismic data. Hampson-Russell, an independent Canadian company, has developed an AVO program that includes tools ranging from gradient/intercept stacks through to modelling full inversion. This package also includes some pre-stack processing methods to enhance the quality of CDP gathers. These packages only work in two dimensions, accounting for amplitude variations in the vertical plane.

With 3D seismic data there is a problem with the angle of incidence. In addition, the direction of ray paths should be considered to correct the amplitude. Moreover, the relationship between amplitude variation and azimuth of incidence is not really understood in three dimensions. Phenomena such as anisotropy also influence the seismic amplitudes. Further work is therefore required before 3D AVO will be considered as an industrial method.

Stratigraphic inversion

The purpose of stratigraphic inversion software is to extract the acoustic impedance earth model from the seismic signal, i.e. to remove the wavelet that results from propagation of the source signal. The software also removes noise from the data. As with AVO, the amplitude variations must represent only the earth reflectivity changes.

Three-dimensional post-stack inversion software is available from various companies:

- STRATA, produced by Hampson-Russell, is used for two-and three-dimensional inversion - three inversion algorithms are available: stochastic, constrained, and bandlimited.

- 3D-ROV, produced by CGG, is a three-dimensional multi-channel inversion that works with a global search optimisation technique using simulated annealing. This module is included in the GEOVECTEUR+ processing environment.

- DELSI, developed by TNO (The Netherlands) with support from the THERMIE programme, is a state of the art software package for seismic inversion incorporating: surface related multiple elimination; controlled illumination of target zones; and stratigraphic inversion.

- Jason (The Netherlands) has developed INTEGRATE for a three-dimensional block inversion.

- SLIM is Western Geophysical's post-stack inversion software.

- INTERWELL 3D, proposed by Beicip-Franlab (France) and Petrosystems (a subsidiary of CGG), extracts the wavelet from well log information and seismic data, then uses direct modelling to include the structural and stratigraphic knowledge of the area and carry out the inversion of the data cube using a multi-trace algorithm.
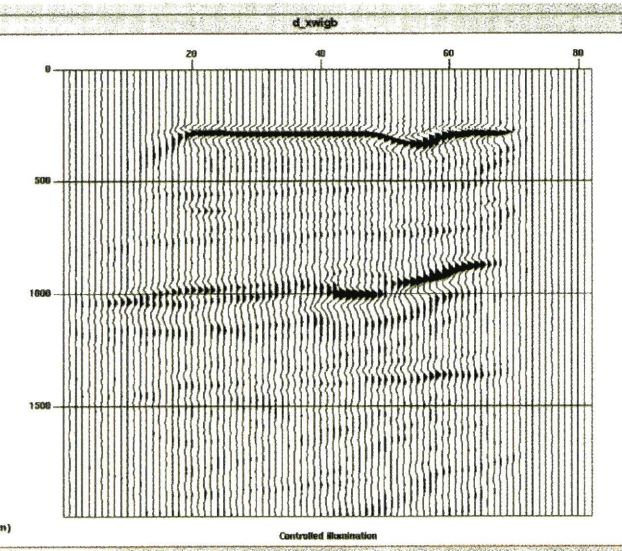

Fig 9 DELSI: a state of the art software package for seismic inversion

At present, three-dimensional inversion packages operate by adjusting single-or two-dimensional information, although fully three-dimensional inversion algorithms will be available soon. The acoustic impedance section obtained after a post-stack inversion does not fully explain the variations of lithological or petrophysical parameters in the reservoir, and must therefore be correlated and calibrated with well log data.

2.4 Seismic Interpretation

Seismic interpretation is the cornerstone of an overall view that integrates geological, geophysical and reservoir engineering data. Its objective is to extract subtle structural features and stratigraphic elements from the data.

Tracking a geological horizon in a 3D seismic dataset can involve a large number of seismic traces. Automatic tracking techniques are therefore invaluable. The major interpretation companies have developed methods based on the correlation of traces to propagate interpretation from reference lines throughout the 3D cube. US company, Landmark has developed ZAPIII for fast and accurate determination of the surface horizons. Petrosystems with its INTEGRAL+ interpretation workstation and Geoquest with the ASAP autotracker have proposed similar software.

An efficient method of controlling automatic picking is to display a three-dimensional view of the data and tracked horizons, for example using Landmark's 3DVI, Geoquest's 3dvue, or Petrosystems' 3D Viewing.

The exact position of faults and the evaluation of cross-fault leakage are critical parameters for accurate reservoir description and the placement of producing and injector wells. Fault patterns can be identified by analysing horizon attribute maps (azimuth, dip, edge, difference), and all the three-dimensional seismic interpretation
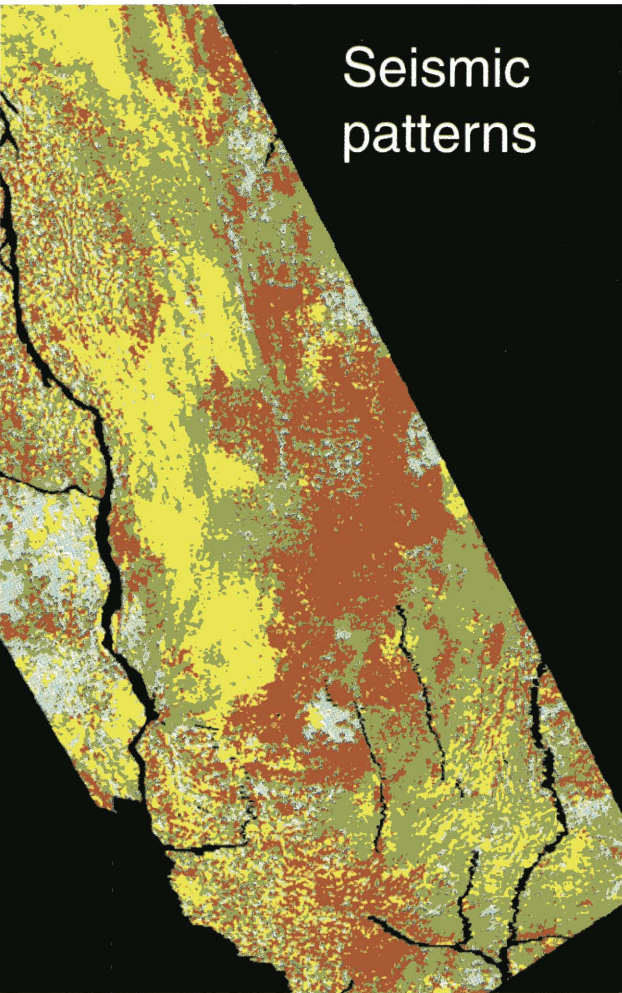

Fig 10 Seismic patterns from dGB-GDI package

packages offer these functions. These maps can also be enhanced by image processing packages, such as ER MAPPER, to allow detection of subtle structural events. For example, image processing can enable faults with a vertical throw smaller than the time sampling to be interpreted.

If a fault pattern is identified solely from geometrical characteristics of the auto-tracked surface, automatic correlation of fault segments interpreted on the seismic sections or time-slices is not currently possible. Building a three-dimensional fault pattern, including the exact position of the fault plane (rather than just the fault traces on a surface as determined by horizon map attributes) then becomes an arduous process. Methods involving neural networks, artificial intelligence or image processing could solve this problem.

In a THERMIE-funded project, de Groot-Bril Earth Sciences BV of the Netherlands is implementing and testing a ready-to-use software system using neural networks. The dGB-GDI package is a set of object-oriented software modules that integrate, analyse and quantify geoscience information.

Data and knowledge in dGB-GDI are combined at different levels according to a stratigraphic ordering system. Actual (stratigraphic) and simulated (log) well data are linked to
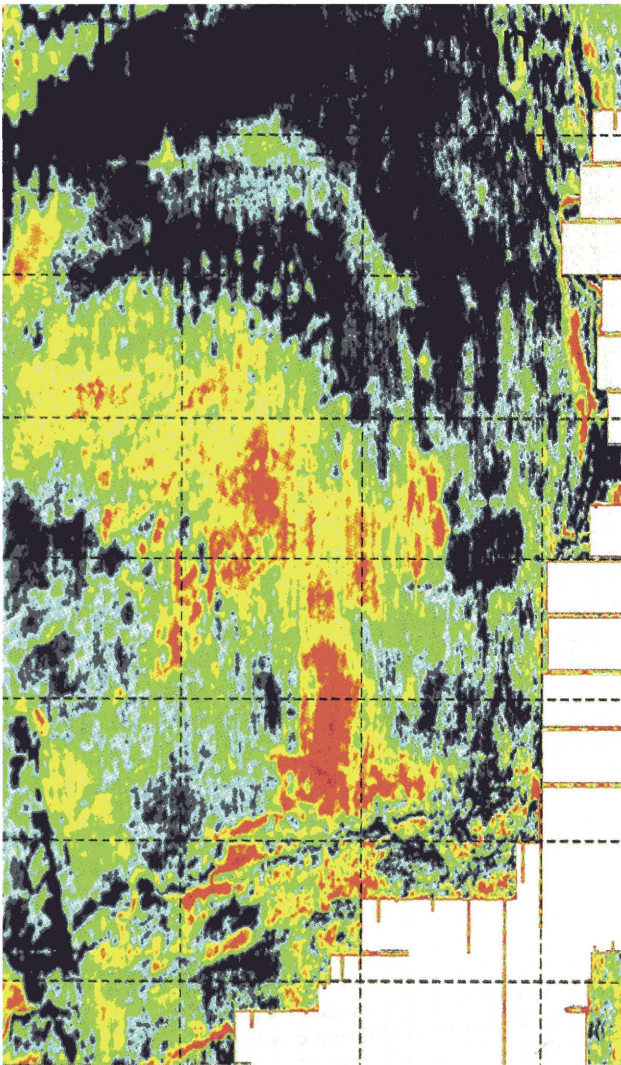
Fig 11 Lateral prediction from dGB-GDI package

seismic traces in this way, and the integrated dataset can then be studied at the natural (stratigraphic) level. Tools are available for extracting information from wells and seismic data. The resulting "feature sets" can be visually inspected for cross-correlations. Non-linear relationships are established with the use of artificial neural networks.

French oil company, ELF, has developed an in-house 3D interpretation package, SISMAGE, which is based on automatic 3D horizon tracking using image processing methods. Unlike many automatic picking systems, SISMAGE is essentially amplitude independent and is actually guided by the character of the seismic event.

The volume-based interpretation techniques that are now emerging because of improved visualisation tools allow interpreters to view and interpret the data in three dimensions. However, better integration of geophysical, geological and reservoir engineering data is still required.

The search for deep oil and gas reservoirs is making increasing demands on seismic technologies. Preferably seismic surveys will not only investigate geological structures, but also provide information on lithology, pore content and lateral facies variations. In the LITASEIS project funded by THERMIE, the German company DGMK is developing and testing methods for the lithological interpretation of seismic data to help in the search for deep gas reservoirs in Europe (5,000 - 6,000m). The project is developing an integrated comprehensive concept for seismic lithological investigation that comprises the following innovative approaches:

- adverse effects of near-surface layers (soft layers) on the amplitude and frequency content of seismic signals;

- adverse effects of processing on amplitude and phase;

- correlation and calibration of reflection seismic data with borehole seismograms;

- lithological interpretation of seismic lithoparameters.

2.5 Well Seismic Data Acquisition

Vertical Seismic Profiles (VSPs) are widely used to calibrate seismic data recorded on the surface with geological well information. Time-depth relationships as well as corridor stacks, generally allow a good calibration of geophysical and geological data. To extend the lateral coverage of seismic data around the well, offset VSP and walkaway acquisition have been developed.

The increasing use of seismic reservoir methods and the need for a better understanding of reservoir bodies and fluid content have focused research on specific seismic techniques for wells.

Shear wave data acquisition

The measurement of compression (P) and shear (S) waves is of considerable value for:

- geophysical applications such as the measurement of

velocity and estimation of reflectivity for the well to achieve seismic calibration;

- mechanical property analyses such as wellbore stability, perforation stability, sanding and hydraulic fracture;

- formation evaluation, e.g. fracture detection using the S-waves bi-refringence, permeability characterisation from Stoneley wave analysis, gas detection by calculating the Poisson's ratio.

Cross borehole seismology

Acquiring seismic data from boreholes at reservoir depth may resolve the "wavelength gap" that exists between 3D seismic data (normal wavelengths of 20 - 100 m) and well logs (wavelengths of 0.3 - 1 m). Typical wavelengths for high-frequency cross-borehole data are 2 - 5 m. Cross-borehole tomography surveys involve recording data from receivers in one borehole that are related to a set of seismic sources in another borehole. Typical borehole source and receiver spacing are 3 m, while well separations are often 100 - 300 m.

A THERMIE project being carried out by Schlumberger (France) is examining high-resolution seismic techniques for boreholes, and is dedicated to hydrocarbon reservoir description. The project has five phases:

- additional calibration of the site using logs, VSP, and offset VSP analysis;

- acquisition, processing and inversion of a P-wave tomography with particular analysis of the possible anisotropy of the layers;

- acquisition and processing of a shear-wave reflection using a drop source developed in THERMIE "Borehole Source" project;

- recording and processing of cross-well data using a non-axisymetrical source;

- synthesis of all the previous experiments and evaluation of the accuracy for reservoir description.

The main problem for this type of data acquisition is preserving the borehole. Non-destructive sources include piezoelectrical ceramic material that converts varying electrical potential into mechanical vibrations. The seismic signals generated with these sources are in the 400 - 2000 Hz range, creating seismic energy that is an order of magnitude smaller than for the surface seismic surveys.

A solution is to spread the energy over time with a swept-frequency source, and to correlate the recorded signal with the input source sweep, as for vibroseis. Further work on non-destructive borehole seismic sources will be needed before they are fully accepted by the industry.

Apart from the seismic source there are two other limitations on the cross-borehole technique:

- the difficulties associated with having two open wells on a producing field;

- the results are generally not adequate to justify the effort needed to set up the acquisition.

Work is being undertaken in Europe to improve both the method (particularly for reservoir engineering) and the understanding of the obtained results.

The most important improvement expected in the near future is the development of higher frequency signals for better vertical resolution of seismic data. With assistance from JOULE-THERMIE, the French organisations CGG and IFP are collaborating on a project called SHOW (Seismic imaging in HOrizontal or highly deviated Wells).
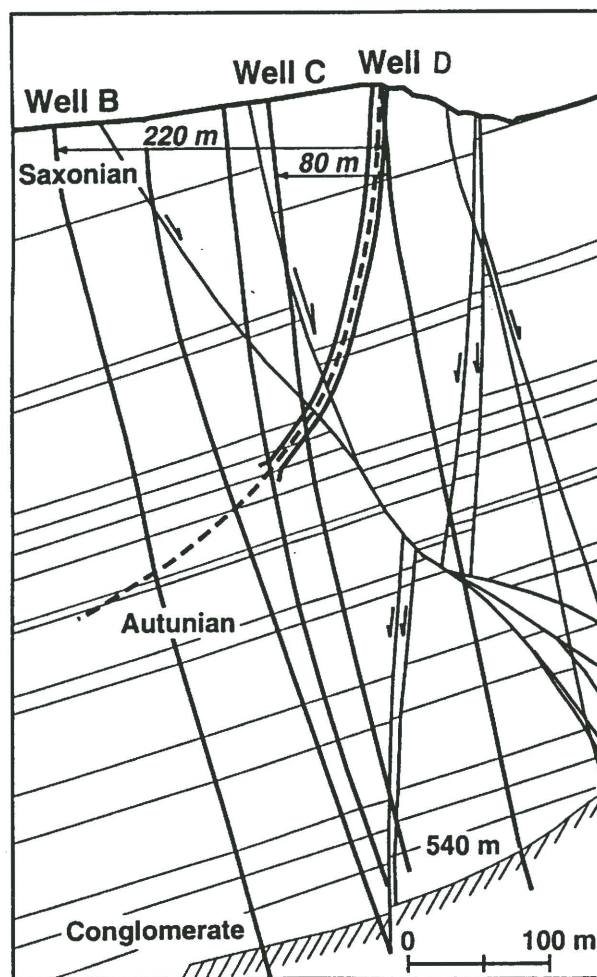

Fig 12 Lodève test site for SHOW: well D in the deviation plane

SHOW is investigating new seismic tools that use sources and receivers located in the well close to (or within) the reservoir. Because they are closer to the targets and use higher frequencies, these tools can theoretically deliver an image with a resolution as small as 0.5 m for targets tens of meters away from the tool. Such techniques are particularly valuable in horizontal or highly deviated wells where the definition of bed boundaries and fluid contacts is critically important for production. This type of information is not generally available from well log techniques which provide very high resolution data but have limited penetration beyond the vicinity of the well. It is therefore anticipated that single well high-frequency seismic data will bridge the gap between surface-acquired seismic data and log data.
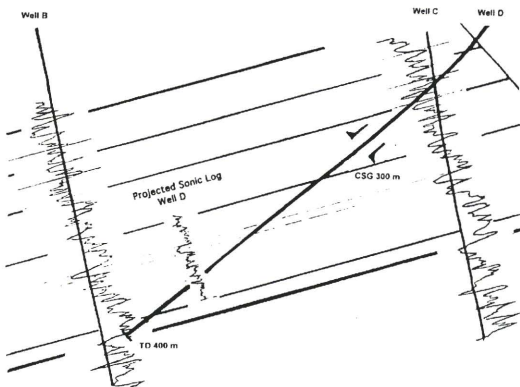
Fig 13 SHOW: wells B, C, D with sonic logs

Fig 15 Examples of walkway SWD VSP

Seismic while drilling

The use of drilling noise as a seismic source is currently being investigated. A future objective is real-time processing of the data to obtain a seismic image of the sub-surface during drilling.

GEOBIT, a THERMIE project undertaken by OGS and AGIP of Italy, recently in co-operation with Prosol Technology (UK), uses the drilling bit as a seismic source in order to predict the lithology ahead of the bit by producing reciprocal VSPs and tomographic images. This technology, renamed SEISBIT, is shown in Fig 14.
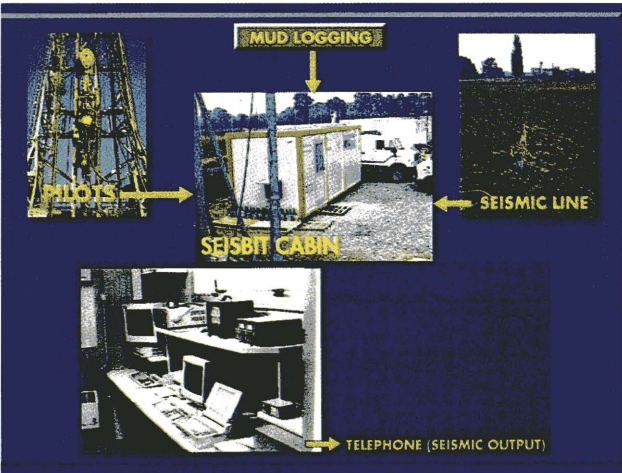

Fig 14 Layout of the SEISBIT acquisition and pre-processing system

Reciprocal VSPs are obtained, using an automated acquisition system, by correlating a time-corrected reference (pilot) signal with conventional surface seismic traces measured near the well. In this procedure the time-continuous drillbit signal is collapsed into an impulsive one, and the signal-to-noise ratio is enhanced by reference signal deconvolution. The method successfully provided real-time geophysical information while drilling (seismic data are immediately transmitted day by day to the remote offices), when using roller-cone and also PDC bits.

2.6 Potential Methods

In parallel with advances in 3D technology, non-seismic methods have also evolved. Non-seismic data are sometimes acquired in conjunction with a 3D seismic
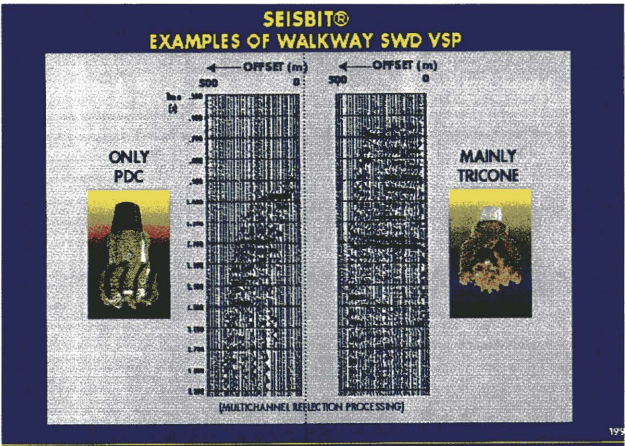
survey because they are independent of geophysical properties and can be used to verify, refine or constrain a three-dimensional velocity model. Efforts are being made to integrate information from these methods with seismic data to improve interpretation.

Other methods, such as electromagnetics, are currently being investigated and funded by THERMIE support. The German company Metronix is integrating both passive and active electromagnetic methods to provide optimum geological information. The Integrated Electromagnetic Exploration Method (IEEM) is highly mobile and can be used more readily than seismic surveys in areas where access is difficult (Fig 16).
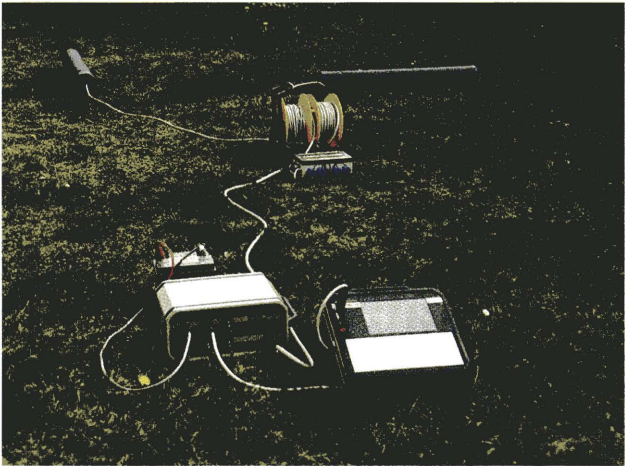

Fig 16 Multi channel receiver for passive EM

Edinburgh University in the UK has THERMIE support to carry out two multi-channel transient electromagnetic surveys over an underground gas storage reservoir in France.

The University of Edinburgh in the UK is leading a THERMIE project with the University of Cologne and DeutschMontanTechnologie in Germany and Compagnie Générale de Géophysique in France to determine the feasibility of monitoring movements of hydrocarbons in reservoirs with multichannel transient electromagnetic surveys in an experiment conducted at an underground gas storage reservoir in France. Two duplicate surveys have been carried out. The difference between the two

data sets reflects the difference in the electrical resistance of the reservoir as the gas-water contact moved between the two surveys, the resistivity of the gas-saturated rock being twenty times that of the water-saturated rock. Algorithms to map these changes have been developed. The method may be applied to monitor production in oil fields and locate by-passed oil. Spurious electromagnetic fields introduced by the network of pipes on the surface and underground are identical for duplicate surveys and are eliminated by differencing successive data sets.
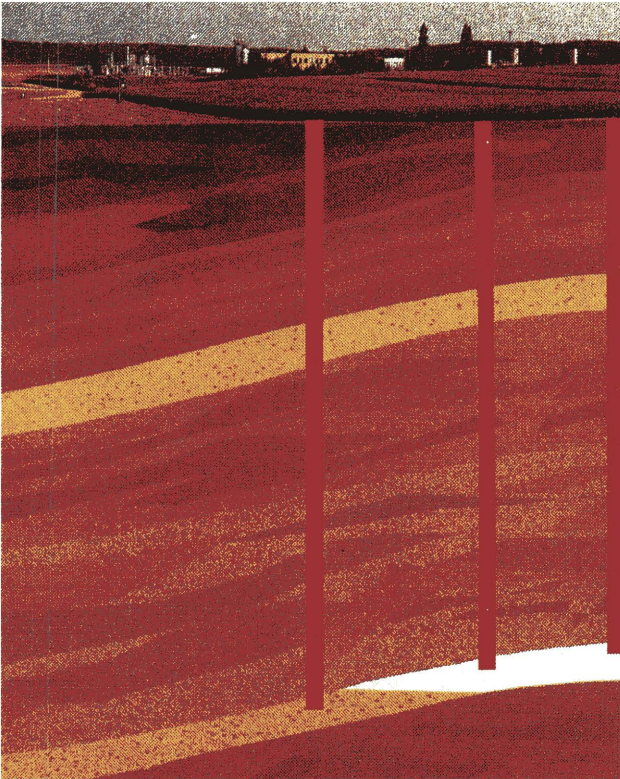

Fig 17 Anticlinal structure of filed site showing wells used for injection, production and monitoring of gas in the reservoir. (After Gaz de France Illustration)
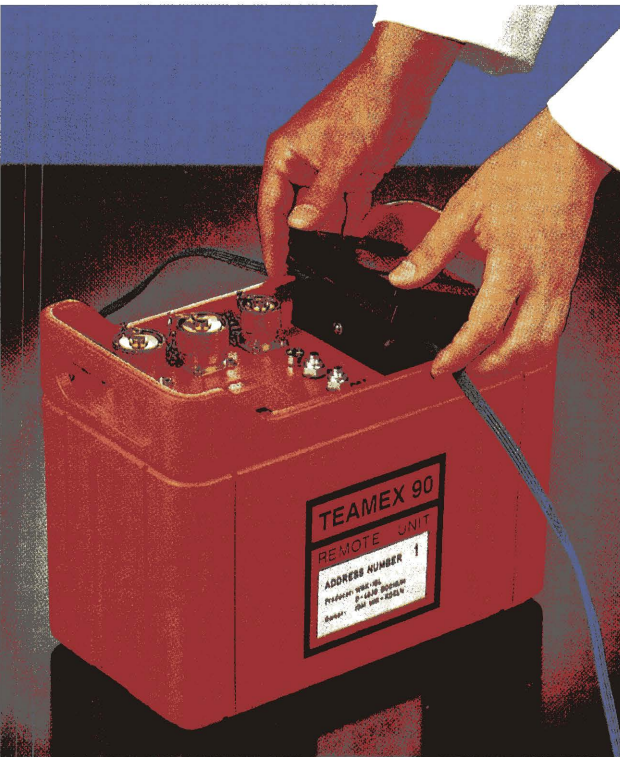

Fig 18 TEAMEX receiver unit

3. GEOLOGY

3.1 General

The most significant evolution in geology has been the integration of information from other disciplines. This has enhanced the global understanding of the petroleum potential of the sub-surface. In addition, a number of specific techniques have been improved or developed, particularly in terms of interpretation and modelling.

Improved knowledge in the field of sedimentary geology has mainly been related to high-resolution sequential stratigraphy and the modelling of depositional styles. Understanding the structural geology of complex tectonic environments has also advanced, and several software packages are now available.

Geostatistical methods have played a major role in better reservoir characterisation and the determination of reservoir properties, architecture and possible fluid content.

3.2 Acquisition
Remote sensing applications

Satellite images collected in the visible, infra-red and radar spectra are currently available for most areas of the Earth. The availability of this data combined with advances in interpretation has increased the use of remotely sensed data by oil companies, and the technique is now widely recognised as a cost-effective exploration tool for applications from regional basin evaluation to environmental assessment. Remotely sensed data also have applications in downstream operations such as pipeline planning and monitoring competitors' activities. However, oil companies prefer to buy-in data rather than invest in internal development because the technique still appears to be technology-driven and rapidly evolving.

The first European SPOT satellites were launched in 1986. These satellites have a high resolution (10 m in panchromatic mode, 20 m in three-band multi-spectral mode) and can provide stereo pairs that improve visual interpretation. They can also be used to obtain Digital Elevation Models. More recent ERS satellites (1991) from the European Space Agency can collect images through cloud cover and at night because they are equipped with radar instruments (20 m resolution with the SAR mode). Methodology and use of these radar data have been developed and some petroleum exploration applications are now available.

UK company, Nigel Press Associates now offers offshore basin screening to detect natural hydrocarbon seepage and map geological structures. This technique was developed in a project sponsored by the UK Government.

More satellites are expected to be launched in the future because remotely sensed data have a wide variety of uses in numerous sectors. However, a more systematical integration of remotely sensed GIS (Geographical Information System) data with other exploration data will
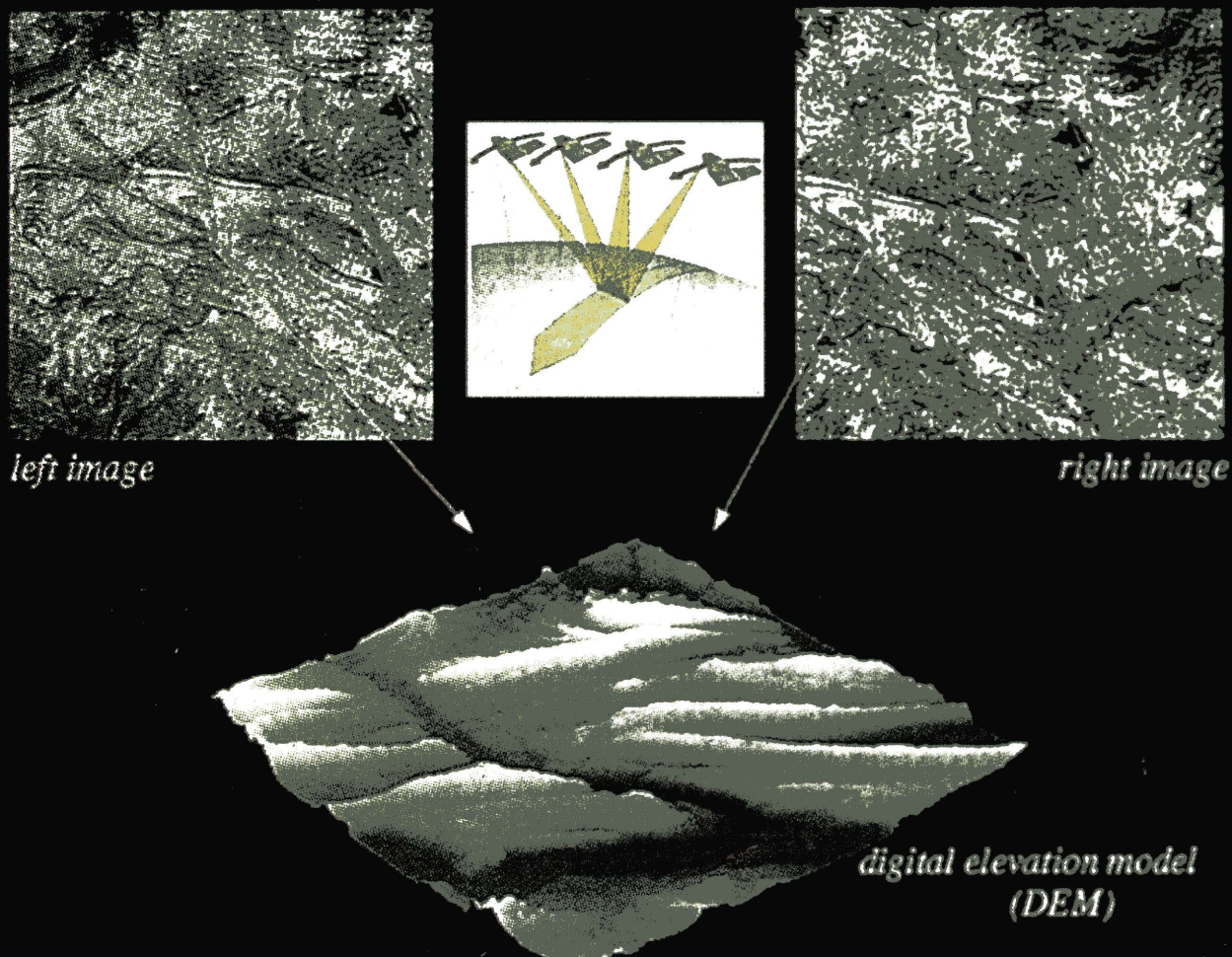
Fig 19 Digital Elevation Model from SPOT stereo data

help to diversify the use of remote sensing by developing thematic documents and specific interpretation methods that are mainly workstation oriented.

Borehole imaging

A direct image of the borehole provided by core samples, photographs and logging techniques gives a good indication of the architecture of the sedimentary section. Micro-resistivity tools are now used to collect detailed reservoir descriptions particularly needed for horizontal well sections. These tools can assist in fracture analyses and interpretation, determination of effective vertical permeabilities, and correlation of neighbouring wells to orient sand bodies.

3.3 Interpretation and Modelling

Log interpretation software

Log interpretation software is generally linked to logging tools. Consequently, the main software packages have been developed by the major well logging companies. Apart from general modifications in software, increased integration in the geological/geophysical database, and adaptation to POSC standards (see Section 5.1), one specific development can be noted.

New algorithms for handling uncertainties are currently being developed to take better account of certain mineral effects and to improve identification of facies. In Europe, a project called LAGUNA (Log Analysis by a Global Uncertainty Algorithm), is being developed in a partnership between ERC-Tigress Ltd and Petrosystems.

Sedimentary geology

Sedimentary geology has evolved in recent years with the development of quantitative and numerical modelling. Depositional styles have been identified and described from outcrop studies and these stratigraphic models can be used to help interpretation when geological data are limited.

In Europe, an outcrop database for reservoir characterisation has been developed with support from the THERMIE programme. This system allows any interested party to have easy access to outcrop data that have been checked for completeness and quality, and stored in a standard format.

Numerical stratigraphic models simulate sedimentation and stratigraphic development using algorithms based on stratigraphically significant parameters (accommodation, sediment supply, eustacy, etc.). However, the predictions need to be checked by field observation.

Lack of perfect restoration due to inaccuracies in interpretation, algorithm used or parameters chosen
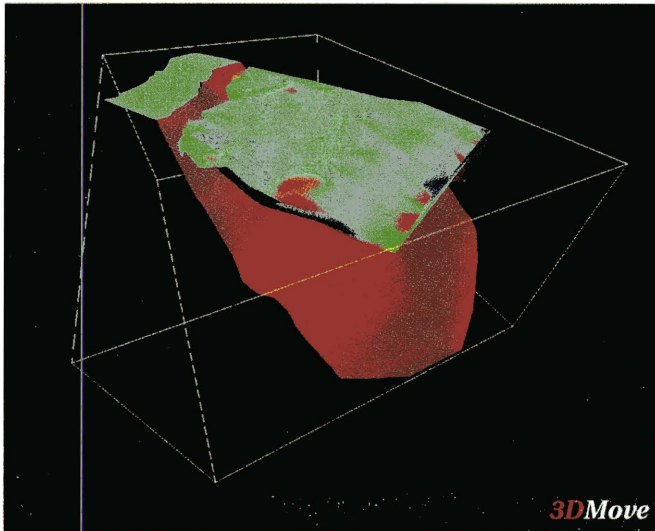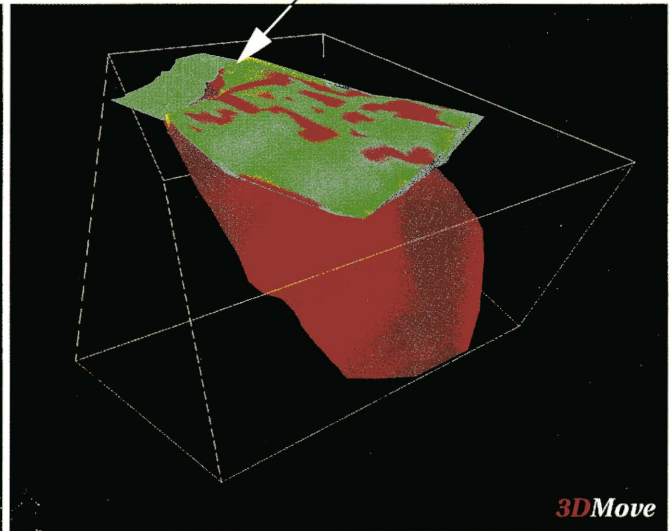
PRE–RESTORATION   POST–RESTORATION

Fig 20 3DMove

Forward stratigraphic models are currently used to provide a unique response to the stratigraphic parameters, but inverse stratigraphic models are under development.

High-resolution sequence stratigraphy has developed through the integrated workstation approach that combines data from various disciplines (e.g. biostratigraphy, sedimentology, petrography, lithoseismic, seismic stratigraphy). Basic stratigraphic rules are now better understood, and geological analysis and forecasting have greatly improved.

Structural Geology

The main breakthrough in structural geology is the development of software to restore full 3D models and not just 2D cross-sections through the structure. Restored 3D models are kinematic models of structural evolution that test the geometrical coherence of geological interpretation. In a THERMIE project, Midland Valley of the UK has developed interactive software that tests three-dimensional geological interpretations by sequential restoration. Restoring present-day interpreted geological structure to its initial undeformed state allows the validity of the interpretation to be tested and the geohistory of structural development to be analysed in detail.

Such software is particularly useful for complex tectonics. However, the results need to be checked with:

- field examples and analogue models;
- fault and fracture modelling;
- a geomechanical forecast of the fracturing stage of the lithological series produced by reconstructing the successive tectonic stress related to the deformation fields during the geological evolution.

Lithological heterogeneities also have to be taken into account (e.g. fault geometries, different lithological

strata, interstitial fluids). Fracture modelling has been developed to integrate field and sub-surface data and to provide a three-dimensional fracture model based on geostatistics that can be used for reservoir engineering. In Europe, software for this purpose includes FAPS 2, developed by Badley Earth Sciences (UK) and IFP's FRACRASS 3D.
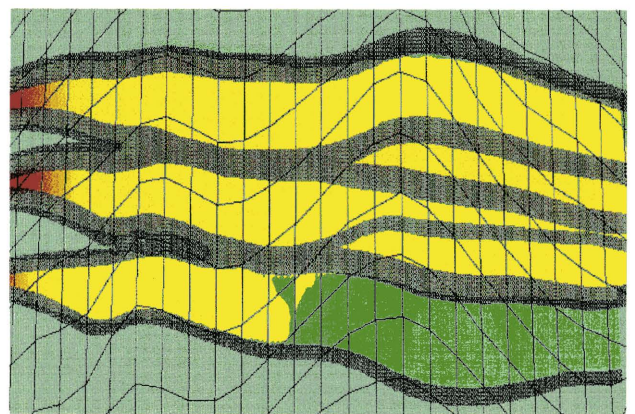

Fig 21 FAPS 2 – example of stratigraphic juxtapositions across a fault with fault-seal potential coded in colour

Reservoir characterisation for prospect evaluation

The reservoir geologist is often asked to provide a model of the geology between wells where data is lacking, perhaps because the spacing of well data is too large or seismic resolution is too low. This model may represent the distribution of genetic bodies (channels, flood plain shales, etc.), within which petrophysical variations can later be distributed.

Two sets of data are useful to characterise reservoir heterogeneities.

- Two-and three-dimensional seismic data allow geophysicists to obtain the spatial distribution of seismic impedance within the reservoir.
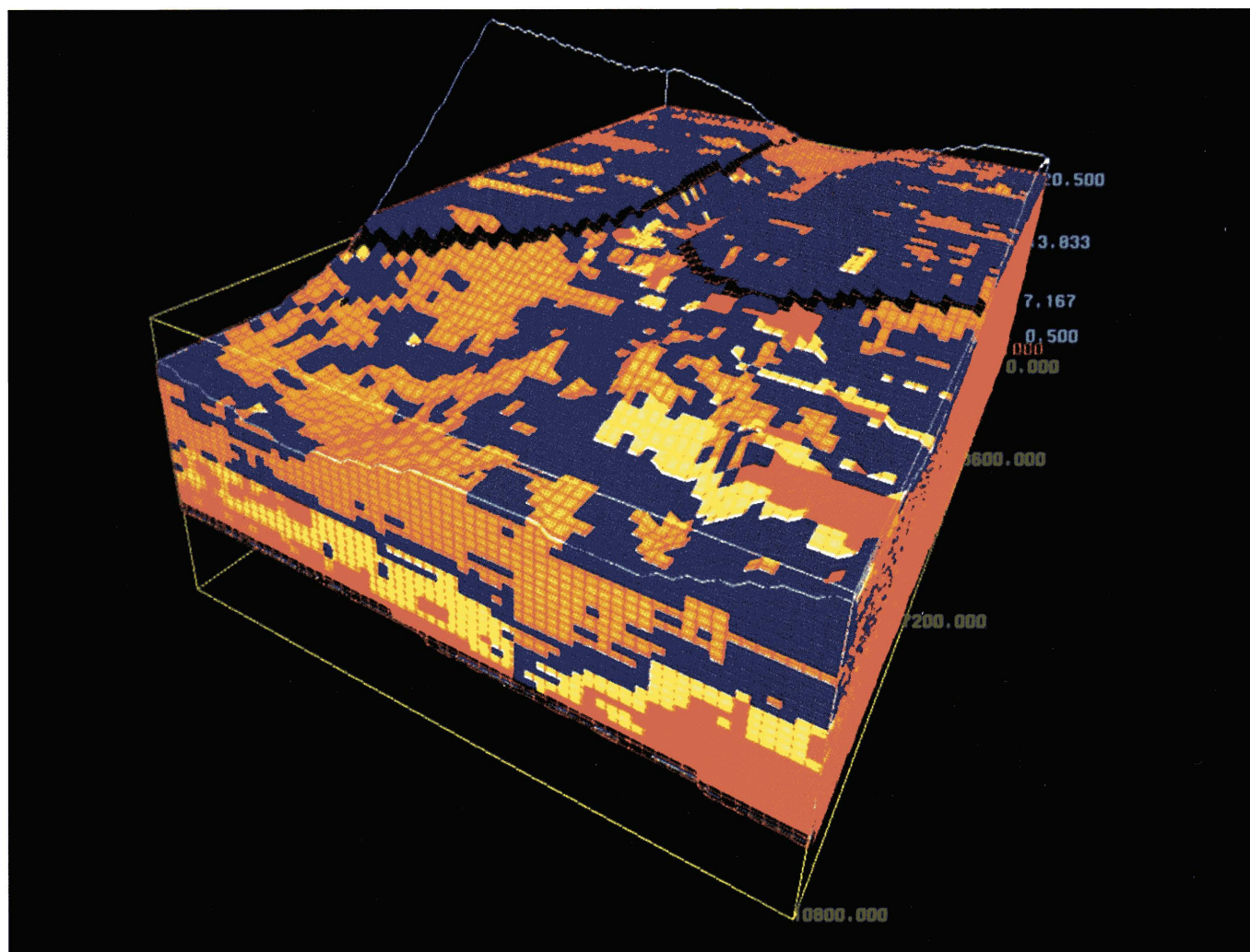
21

Fig 22 HERESIM 3D

• Well data (which usually have good vertical definition) can be combined with geostatistical concepts to obtain three-dimensional images of the spatial distribution of heterogeneities between wells inside the reservoir.

The geostatistical approach allows various high-resolution images of the distribution of reservoir heterogeneities. Changes from one possible image to another are a measure of the uncertainty affecting the heterogeneity description between the wells. There is a clear trend in the oil industry towards the development of such approaches, but at present two main geostatistical techniques are available: variogram or object based.

Variogram-based simulation characterises both the external geometry of the litho-units and the internal spatial distribution of sedimentary bodies and petrophysical properties, e.g. porosity and permeability.

HERESIM 3D, developed by the French organisation Beicip-Franlab with THERMIE funding, offers two original and efficient geostatistical tools that are simple and powerful: proportion curves and variograms. These tools make it easy to identify the main sequential and lateral trends of sedimentary bodies, and guarantee maximum realism of the simulations. HERESIM 3D provides a fast sequence-based algorithm (truncated Gaussian model) to generate possible images of the unknown areas between wells. The simulated images are immediately exploitable by reservoir engineers in a fluid flow simulator. These images are a way to facilitate communication between geologists and reservoir engineers.

Object-based techniques (deterministic algorithms) are applied to reservoirs where isolated sand bodies are distributed within a shaly background. Each sand body is modelled as a single object (fluvial channel, Crevasse Splay, point bar, etc.) by simple geometry. The width of these bodies is extrapolated from their thickness using width-thickness relationships derived from outcrop studies or from experience with similar fields.

Variogram-based modelling algorithms are fast and flexible, whereas object-based algorithms have difficulties in honouring the well data in a satisfactory manner. However, several width-thickness relationships have been developed for various depositional environments, whereas very few variogram models are available. The future trend will be to reconcile reservoir and basin scales. In theory it should be possible to obtain a reservoir model by enlarging a zone from the basin model. Such an approach could be possible in the not-too-distant future.

4. GEOCHEMISTRY

4.1 General

Geochemistry is now acknowledged as a major exploration tool. Important breakthroughs have been achieved in basin modelling and more detailed models are becoming available, particularly in three-dimensional description and compositional determination of hydrocarbons.

Important progress is also being made in reservoir chemistry aimed at improving the production of known reservoirs.

4.2 Acquisition

Breakthroughs in data acquisition techniques and interpretation methods are mainly related to basin modelling and reservoir geochemistry.

Gas Chromatography-Isotope-Ratio-Mass Spectrometry (GCIRMS) is used in petroleum exploration to correlate source rocks and oils and therefore improve the understanding of the origin and migration of hydrocarbons.

Pyrolysis is another widely used method that provides information on both the source rock and its hydrocarbon content. This technology has evolved over the past 15 years. Rock-Eval, developed in France and supported by THERMIE, allows better localisation in the sedimentary basins of areas where the genesis and the migration of the hydrocarbons have been greatest.
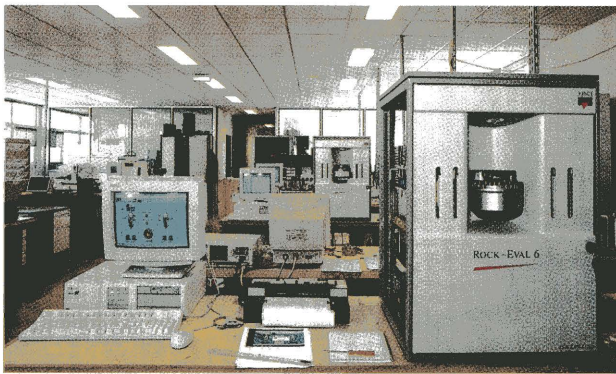

Fig 23 Rock-Eval 6

4.3 Basin Modelling

The study of petroleum systems is now largely supported by basin modelling. This type of modelling allows the explorationist to formulate sequences of explicit hypotheses (assumptions on the type of rock, their burial, thermal history, quality of source rocks, drainage systems etc.) and to carry out sensitivity analyses to determine key parameters.

Basin modelling has evolved a great deal during the past ten years in terms of reconstructing the thermal, hydraulic and mechanical processes that form oil and gas deposits.

Two-dimensional integrated models combining compaction, heat transfer and fluid flow, e.g. TEMISPACK, BASINMOD 2D or PETROMOD, are currently used by multi-disciplinary teams in oil companies to investigate the genesis and migration of oil and gas. Running on workstations, these two-dimensional models are generally used in mature areas where all the different input data are available. They account for hydrocarbon flow as a single-phase separate from water.

One-dimensional models running on PCs, e.g. GENEX or BASINMOD lD, give the composition of the hydrocarbon expelled from the source rock and allow the computation of density and viscosity from the thermodynamical equation of state. These models are now widely used by oil companies either on their own or in parallel with two-dimensional modelling.

Basin models are now being developed to simulate genesis and accumulation in complex compression zones. The two-dimensional THRUSTPACK model (forward modelling) developed by IFP can simulate the successive geometries of regional sections of a basin with a history of listric or overthrust faults.

Another trend is to describe geometric evolution in three dimensions. This will allow quantitative mass balances - an almost impossible task with current models. DEMETER 3D is an emerging tool for integrating the three-dimensional description of geometric and thermal evolution.

4.4 Reservoir Chemistry

In a project funded by THERMIE, Newcastle University in the UK is developing petroleum geochemistry aids to assist in reservoir appraisal, reservoir management, and the exploration of near-field satellites. The project involves a detailed and integrated organic, inorganic and geological study of two North Sea petroleum reservoirs about to go into production. The aim is to produce a high-resolution map of fluid composition that can be used to determine reservoir fluid continuity and to monitor pre-production simulations of production.

The benefits include:

- identification of reservoir compartments - this will allow correct siting of producer and injector wells;
- better appraisal of reserves - variations in water chemistry can seriously affect the determination of water saturations and hence calculations of reserves;
- improved exploration for near-field satellites;
- monitoring of water breakthrough and production from several reservoir zones;
- more effective water floods - water floods rely on accurate maps of well-to-well connectivity and gross vertical permeability of the reservoir.

5. CROSS-DISCIPLINES

5.1 Databases

The application of up-to-date technologies and efficient use of seismic and geological data are linked by the interdependency of all types of data. In recognition of this, many companies have developed integrated databases. However, it was estimated recently that 70% of a workstation's working time is spent on loading and transferring data from one application to another.

To solve these integration problems, the major software suppliers and oil companies have created a not-for-profit membership corporation, the Petroleum Open Software Corporation (POSC). The aims of POSC are to:

- define an open computing environment, called the software integration platform;
- provide oil and gas organisations with methods to manage data resources;
- support integrated multi-disciplinary projects.

Members of POSC have agreed to implement the POSC EPICENTRE data model in all existing and future applications.

5.2 Visualisation and mapping tools

Two types of product are clearly identified in this technical area:

- mapping software used for base mapping and surface modelling by gridding and contouring;
- three-dimensional visualisation software for interpreting and visualising the sub-surface.

GeoScene, produced by Oilfield Systems in the UK, is a geoscience workstation that provides a suite of powerful interpretation tools for:

- loading, storing and displaying data, information and images of a petroleum field or basin;
- interpreting and modelling this data to produce descriptions and models for decision-making;
- communicating results through montage and quality hard copy.

As with mapping software, three-dimensional visualisation tools provide the interpreter with the ability to integrate various data types. Visualisation tools help geoscientists to understand complex structures and the relationships between various data types (seismic, well information, structural surfaces, etc.). This market is evolving rapidly in terms of available hardware and competition between vendors is fierce.

With support from THERMIE, Oilfield Systems Ltd has developed a module for GeoScene that incorporates a coherent multi-parameter object-oriented description of the reservoir. This provides users with a totally consistent three-dimensional representation of one or more surfaces, both in cross-section and plan view, that can be used to interpret the sub-surface.
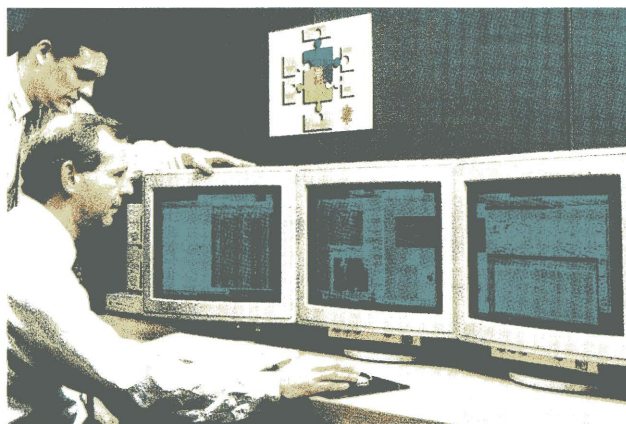

Fig 24 GeoScene: a geoscience workstation with powerful interpretation tools

All data types (seismic lines, wells, cultural data, sets of scattered data points, etc.) can be displayed with mapping software. Mapping systems are used and shared by all geophysical, geological and reservoir engineering applications. They can be considered as the main packages for the presentation of integrated exploration and production study.

3DVI produced by Landmark has three applications:

- SeisCube for interactive three-dimensional interpretation and animation of the seismic data cube;
- ZAP III for the auto-tracking of horizons;
- SurfCube for visualisation and image processing of interpreted surfaces, faults, well paths and other information in three-dimensional space.

Geoquest's 3DVue module features fence diagrams, seismic cube and chair displays with horizons and faults. GeoViz, also produced by Geoquest, integrates 3D surface modelling and visualisation as well as volume rendering. Three-dimensional seismic amplitude anomalies can be displayed in the same view as well logs and interpreted structural surfaces.

Petrosystems' SeisCad module handles raw seismic data, interpreted reflectors and geological data accessed from INTEGRAL+ database. The three-dimensional surface

modelling is based on discrete smooth interpolation, which is the heart of GeoCad. A similar package called VelCad integrates acoustic well information and seismic velocity data to build an accurate three-dimensional velocity model used with depth migration.

These visualisation software tools involve a new way of considering the sub-surface. New working methodologies will have to be implemented to exploit all the advantages of these new tools, and graphic workstations and modelling software will have to move to more realistic capabilities.

6. MARKET AND SUPPLIERS

The market for most of the technologies identified in this maxibrochure is highly targeted. For example, simple software packages may sell a few thousand copies but more sophisticated software may only be expected to sell a few hundred copies. Oil and gas companies direct the market through their requirements and their involvement in funding research and development. Another significant source of funding is the European Commission's THERMIE programme which has resulted in the development of innovative applications.

Large services companies generally prefer to develop their own products in order to control the overall process and not rely on outside suppliers. As a consequence there seems to be little room for small-and medium-sized enterprises, other than to supply specific highly innovative and sophisticated products.

In Europe, the seismic acquisition market is dominated by a few large companies - Western Geophysical, CGG, Digicon, PGS, Schlumberger-Geco-Prakla. The same is true for workstations - Landmark, Schlumberger, Petrosystems. The strategy of these companies is generally to control most of the operational phases by developing their own equipment, software and products, except for some minor sectors. In addition, there has been a trend towards higher concentration with several take-overs in recent years.

Conversely, several small companies are present in the geoscience software market, and particularly interpretation and modelling software. Such companies tend to be commercially aggressive and highly innovative. Often these companies are created by one or two technical experts with a limited amount of investment and partial funding from government agencies or universities. Financing for research and development is particularly difficult to obtain for sophisticated software because the development expenditure is generally high but the market is limited.

As a result, small companies usually provide a limited number of products, and often saturate their market in a short time. They will then either disappear or be taken over by larger companies.

Many of the main suppliers are based in the US and Canada, but Europe has a strong market position with products being developed in the UK, France, Germany, the Netherlands and Norway.

European companies are currently in a favourable position as regards innovative technologies related to petroleum geoscience, but support for disseminating European technologies is of paramount importance, especially for the developing markets of Eastern Europe, CIS and South America.

Within each Member State there are a number of organisations recognized by the European Commission as an Organisation for the Promotion of Energy Technology (OPET). It is the role of these organisations to help to coordinate specific promotional activities within Member States. These include staging of promotional events such as conferences, seminars, workshops or exhibitions as well as production of publications associated with the THERMIE programme.

ADEME
c/o ADEME-BRIST
27, rue Louis Vicat
F-75737 Paris - Cedex 15
France
Tel: +33 1 47 65 20 41
Fax: +33 1 46 45 52 36
E-mail: ademcepi@imaginet.fr

ASTER-CESEN
c/o Aster, Agency for the Technological
Development of Emilia-Romagna
Via Morgagni, 4
I-40122 Bologna
Italy
Tel: +39 51 236242
Fax: +39 51 227803
E-mail: opet@aster.it

BEO
c/o Projekttrager Biologie, Energie, Okologie
(BEO) Froschungszentrum Julich GmbH
(KFA)
Postfach 19 13
D-52425 Julich
Germany
Tel: +49 2461 61 3729
Fax: +49 2461 61 2880
E-mail: d.ullerich@kfa-juelich.de

BRECSU
c/o Building Research Establishment
Bucknalls Lane
Garston
GB WD2 7JR Watford
United Kingdom
Tel: +44 1923 664540
Fax: +44 1923 664097
E-mail: crooksm@bre.co.uk

CCE
c/o Centro para a Conservaçao de Energia
Estrada de Alfragide, Praceta 1
P-2720 Alfragide
Portugal
Tel: +351 1 4718210
Fax: +351 1 4711316
E-mail: dmre.cce@mail.telepac.pt

CLER
c/o Association Comité de Liaison Energies
Renouvelables
28 rue Basfroi
F-75011Paris
France
Tel: +33 1 46590444
Fax: +33 1 46590392
E-mail: cler@worldnet.fr

CMPT
c/o The Centre for Marine and Petroleum
Technology
Offshore Technology Park
Aberdeen
AB23 8GX
United Kingdom
Tel: +44 (0)1224 853400
Fax: +44 (0)1224 706601
E-mail: j.kennedy@cmpt.co.uk

CORA
c/o Saarlaendische Energie-Agentur GmbH
Altenkesselerstrasse 17
D-66115 Saarbrucken
Germany
Tel: +49 681 9762 174
Fax: +49 681 9762 175
E-mail: sacca@sea.sb.eunet.de

CRES
Centre for Renewable Energy Sources
19 km Marathonos Ave.
GR-190 09 Pikermi
Greece
Tel: +30 1 60 39 900
Fax: +30 1 60 39 911
E-mail:
mkontini@cresdb.cress.ariadne-t.gr

Cross Border OPET - Bavaria - Austria c/o
ZREU
Wieshuberstr. 3
D-93059 Regensburg
Germany
Tel: +49 941 46419 0
Fax: +49 941 46419 10
E-mail: fenzl.zreu@t-online.de

ENEA
CR Casaccia - Via Anguillarese n. 301
I-00060 S Maria di Galeria - Roma
Italy
Tel: +39 6 3048 3686
Fax: +39 6 3048 4447
E-mail: cariani@casaccia.enea.it

Energy Centre Denmark
c/o DTI
P.O.Box 141
DK-2630 Taastrup
Denmark
Tel: +45 43 50 70 80
Fax: +45 43 50 70 88
E-mail: ecd@dti.dk

ETSU
Harwell - Didcot
GB OX11 0RA Oxfordshire
United Kingdom
Tel: +44 1235 432014
Fax: +44 1235 432050
E-mail: lorraine.watling@aeat.co.uk

EVE
c/o Ente Vasco de la Energia
Edificio Albia I planta 14 - C. San Vicente, 8
E-48001 Bilbao
Spain
Tel: +34 4 423 50 50
Fax: +34 4 424 97 33
E-mail: ente0001@sarenet.es

FAST
c/o Federation of Scientific and Technical
Associations
2, P. le R. Morandi
I-20121Milano
Italy
Tel: +39 2 76 01 56 72
Fax: +39 2 78 24 85
E-mail: eurofast@icil64.cilea.i

GEP
c/o Groupement des Enterprises
Parapétrolières et Paragazières
45, rue Louis Blanc
F-92038 Paris La Défense
France
Tel: +33 147 17 68 65
Fax: +33 147 17 67 47
E-mail: gep@gep-france.com

ICAEN
c/o Institut Catala d'Energia
Avinguda Diagonal, 453 bis, atic
E-08036 Barcelona
Spain
Tel: +34 3 4392800
Fax: +34 3 4197253
E-mail: edificis@icaen.es

ICEU
c/o Internationales Centrum für Energie und
Umwelttechnologie Leipzig GmbH
Auenstrasse 25
D-04105 Leipzig
Germany
Tel: +49 341 9804969
Fax: +49 341 9803486
E-mail: krause@iceu.manner.de

ICIE
c/o Istituto Cooperativo per l'Innovazione
Via Nomentana, 133
I-00161 Roma
Italy
Tel: +39 6 8549141
Fax: +39 6 8550250
E-mail: icie.rm@agora.stm.it

IDAE
c/o Instituto para la Diversificación y Ahorro
de la Energía
Paseo de la Castellana, planta 21
E-28046 Madrid
Spain
Tel: +34 1 456 5024
Fax: +34 1 555 1389
E-mail: idae@teleline.es

IMPIVA
c/o Instituto de la Pequeña y Mediana
Empresa Industrial de Valencia
C. Colón 32
E-46010 Valencia
Spain
Tel: +346 386 7821
Fax: +346 386 9634
E-mail: ximo.ortola@impiva.m400.gva.es

Institut Wallon
Boulevard Frère Orban 4
B-5000 Namur
Belgium
Tel: +32 81 25 04 90
Fax: +32 81 25 04 90
E-mail: iwallon@mail.interpac.be

Irish Energy Centre
Glasnevin
IRL-Dublin 9
Ireland
Tel: +353 1 8082073
Fax: +353 1 8372848
E-mail: opetiec@irish-energy.ie

IRO
Association of Dutch Suppliers in the Oil
and Gas Industry
P.O. Box 7261
NL-2701 AG Zoetermeer
Netherlands
Tel: +31 79 3411981
Fax: +31 79 3419764
E-mail: iro@xs4all.nl

LDK
c/o LDK Consultants Engineers and
Planners Ltd.
7, Sp. Triantafyllou St.
GR-113 61 Athens
Greece
Tel: +30 1 8563181
Fax: +30 1 8563180
E-mail: idk@mail.hol.gr

NIFES
c/o NIFES Consulting Group
8 Woodside Terrace - Scotland
GB G3 7 UY Glasgow
United Kingdom
Tel: +44 141 332 4140
Fax: +44 141 332 4255
E-mail: 101361.2700@compuserve.com

NOVEM
c/o Nederlandse Onderneming voor Energie
en Milieu BV
Swentiboldstraat 21 - P.O. Box 17
NL-6130 AA Sittard
Netherlands
Tel: +31 46 42 02 326
Fax: +31 46 45 28 260
E-mail: nInovade@ibmmail.com

NUTEK
National Board for Industrial and Technical
Development - Department of Energy and
Environmental Technology
S-117 86 Stockholm
Sweden
Tel: +46 8 681 95 14
Fax: +46 8 681 93 28
E-mail: anders.heaker@nutek.se

NVE
c/o Norwegian Water Resources and Energy
Adminstration
P.O. Box 5091 - Majorstua
N-0301 Oslo
Norway
Tel: +47 22 95 93 23
Fax: +47 22 95 90 99
E-mail: hbi@nve.no

OPET Austria
c/o Energieverwertungsagentur - The
Austrian Energy Agency (E.V.A.)
Linke Wienzeile 18
A-1060 Vienna
Austria
Tel: +43 1 586 15 24 ext: 21
Fax: +43 1 586 94 88
E-mail: lechner@eva.wsr.ac.at

OPET Finland
c/o TEKES (Technology Development
Centre)
P.O.Box 69 - Malminkatu 34
FIN-00101Helsinki
Finland
Tel: +358 105215736
Fax: +358 105215903
E-mail: marjatta.aarnilia@tekes.fi

OPET Luxembourg
c/o Luxcontrol
Avenue de Terres Rouges 1
L-4004 Esch-sur-Alzette
Luxembourg
Tel: +352 547711282
Fax: +352 547711266
E-mail: 106030.2752@compuserve.com

OPET Norrland
c/o The Association of Local Authorities in
the County of Vasterbotten - Vasterbotten
Energy Network
Norrlandsgatan 13, Box 443
S-901 09 Umea
Sweden
Tel: +46 90 77 69 06
Fax: +46 90 16 37 19
E-mail: france.venet@swipnet.se

Orkustofnun
c/o The National Energy Authority of Iceland
Grensasvegi 9
IS-108 Reykjavik
Iceland
Tel: +354 569 0105
Fax: +354 568 8896
E-mail: ete@os.is

PARTEX-CEEETA
Rua Gustavo de Matos
Sequeira 28-1∞ Dt∞
P-1200 Lisbon
Portugal
Tel: +351 1 395 6019
Fax: +351 1 395 2490
E-mail: ceeta@mail.telepac.pt

RARE
c/o Agence Regionale de l'Energie Nord-Pas
de Calais
50 rue Gustave Delory
F-59800 Lille
France
Tel: +33 3 20 88 64 30
Fax: +33 3 20 88 64 40

SODEAN
c/o Isaac Newton s/n
Pabellon de Portugal - Edificio SODEAN -
Isla de la Cartuja
E-41012 Sevilla
Spain
Tel: +345 4460966
Fax: +345 4460628
E-mail: sodean@lander.es

SOGES
c/o SOGES S.p.A.
Corso Turati, 49
I-10128 Torino
Italy
Tel: +39 11 3190833 / +39 11 3186492
Fax: +39 11 3190292
E-mail: soges@mbox.vol.it

VTC
c/o Vlaamse Thermie Coordinatie
Boeretang 200
B-2400 Mol
Belgium
Tel: +32 14 33 58 22
Fax: +32 14 32 11 85
E-mail: vdbergh@vito.be

Wales OPET Cymru
c/o Dyfi Eci Parc - Dulas
The Old School - Eglwysfach - Machynlleth -
Wales
GB SY20 8AX Powys
United Kingdom
Tel: +44 1654 781332
Fax: +44 1654 781390
E-mail: opetdulas@gn.apc.org