**INTRODUCTION**

With maturing basins and ever deeper and more complex frontiers, the importance of extending the life of and maximizing recovery from producing fields has never been greater.

Hydrocarbon exploration and development has seen several step-change technologies during recent decades and time-lapse, or 4D, is a seismic method whose value is now recognised worldwide. CGGVeritas has been at the forefront of the evolution of 4D technology and has unrivalled experience in its practical application.

The basic premise of 4D is a simple one. The method involves the acquisition, processing and interpretation of repeated seismic surveys over a producing field with the aim of understanding the changes in the reservoir over time, particularly its behavior during production. This understanding has very real budgetary consequences as increasing the recovery factor of a reservoir, even by a few percent, has significant revenue implications.

Our experience with 4D began over 20 years ago when the industry was yet to be wholly convinced of the concept’s benefits. Since that time a succession of landmark projects have established CGGVeritas as the company of choice for 4D while highlighting the broadening range of reservoirs that can benefit from the use of 4D technology.

The ability to monitor the behavior of a reservoir during its production lifetime now allows engineers to observe changes in the subsurface beyond the limited windows provided by wells. The field-wide information provided by seismic is now considered key in optimizing the recovery of remaining reserves. 4D seismic has evolved from a qualitative tool to identify producing zones and bypassed oil, to become an integral part of quantitative reservoir management.

By its nature, 4D is interpretation-driven and requires accurate acquisition and processing to ensure that the bridge between a static and a dynamic reservoir model is robustly built. Our understanding of these challenges is complemented by our unmatched resources to undertake 4D projects. Experience and expertise is already in place to ensure excellence during every stage of a project, from planning and design, through acquisition, processing and onto interpretation.

As we try to understand the workings of a diverse range of reservoirs in more detail we need a correspondingly diverse and specialized set of expertise and techniques to resolve them. Whether it relates to a High-Pressure, High-Temperature (HPHT) reservoir or a shallow heavy oil project, CGGVeritas has the people, the technology and the experience to understand a field, whatever its challenges.

CGGVeritas has been involved in every facet of the 4D method’s evolution and this has allowed a unique understanding of the full range of its potential. We have driven the development of 4D as a technology and have also been a key innovator in its application. Beyond the Enhanced Oil Recovery (EOR) benefits, 4D technology is now being deployed in other areas where a full knowledge of the reservoir is key, areas such as gas storage and carbon sequestration.

The commercial success of a field can be determined by the smallest of margins; 4D makes a significant contribution towards understanding the dynamic behavior of the reservoir and thus plays a part in maximizing the return on investment. Improving recovery rates by a few percent, or extending production for a few years can have a crucial impact on that margin.
THE VALUE OF 4D

4D seismic is now a well established technique which is making a valuable contribution to the production and development of hydrocarbons around the world. As the technique has matured with the development of expertise and technology there has been an evolution in its use.

Originally the accuracy of the technique limited it to being a qualitative indicator of production effects. Even at this stage 4D seismic delivered tremendous value in terms of interpretation of internal reservoir structure and the identification of depleted and unswept zones as the Girassol example illustrates.

Advances in technology, especially 4D processing, have allowed us to produce more precise 4D seismic differences and transform these into the context of reservoir engineering. With proper calibration and petrophysically constrained inversion techniques we are now able to derive quantitative estimates of changes in reservoir properties such as fluid saturation and pressure. This is illustrated by the Brage field example.

This evolution in the role of 4D seismic from a qualitative tool to a powerful quantitative technique represents a significant step-change in the value of 4D. It also indicates a shift from a purely geophysical interpretation tool to a reservoir management tool, which can be used to assess remaining hydrocarbon volumes and optimize the recovery strategy.

QUALITATIVE 4D BENEFITS

Due to the high production costs of the Girassol field located offshore Angola in 1500 m of water, Total drew up a workplan in which seismic would play a key role in optimizing their development strategy and reducing risks.

As a result CGGVeritas acquired and processed a high-resolution 4D survey (baseline acquired in 1999, monitor in 2003). This enabled Total to detect and interpret significant dynamic information related to gas injection and previously unresolved features within the turbiditic reservoir. Their reservoir engineers were able to draw significant conclusions from the results to guide the further development of the field:
- Propagation pathway of injected gas observed in an unexpected direction
- Un swept zone identified
- Flow barrier identified

QUANTITATIVE 4D SEISMIC RESERVOIR MONITORING

The Brage Field offshore Norway is a mature field which has been in production since 1993. StatoilHydro wanted to extend the life of the field and saw that 4D seismic had an important role to play.

CGGVeritas performed the processing of the 4D data (baseline acquired in 1992 and monitor in 2003) in 2005. After 4D processing, a range of imaging algorithms were tested before the final 4D difference was delivered using anisotropic (TTI) pre-stack depth migration. An innovative new global 4D inversion and 4D Bayesian lithology classification was used to transform the seismic into a reservoir model of oil sand probability.

The combination of accurate spatial imaging and unique reservoir characterization tools delivered a 4D difference which enables not only the accurate calculation of remaining oil in place, but a full understanding of the uncertainty in the results allowing best- and worst-case scenarios to be explored by the reservoir engineers.
There are two main motivations for conducting a 4D feasibility study. First, to assess whether the 4D signal generated by production effects in the reservoir is detectable. Second, to optimize the design of the 4D survey.

The first part takes the form of a rock physics feasibility analysis where the effect of different production scenarios on the reservoir and resulting seismic properties are quantified. Rock physics modeling can also have a useful role in helping to interpret the observed 4D seismic response.

After confirming that the reservoir will give a suitable response for 4D seismic monitoring, survey design can begin. This second stage aims to maximize the strength of the observed 4D signal by optimizing reservoir illumination and maximizing repeatability of successive surveys. With the use of synthetic data from the rock physics modeling, processing challenges can also be anticipated.

CGGVeritas is able to provide both the breadth of expertise and the experience necessary to ensure any 4D feasibility study is a powerful and integrated tool. In order to perform an effective and comprehensive planning operation, expertise in many areas is required including acquisition systems, reservoir modeling, petrophysics, data processing and analysis; CGGVeritas is proud of its history of excellence throughout these disciplines.

PLANNING AND SIMULATION

Using the feasibility study, CGGVeritas can:
- Quantify a survey’s ability to fulfill its objectives
- Maximize the value of legacy data
- Enable contingency planning
- Design integration with complementary technologies (e.g. VSP, passive seismic monitoring, Controlled Source EM).

Within the planning, various tools can be used including:
- Flow simulation modeling
- Fluid substitution modeling with calibration to existing well data
- Elastic model generation for all survey vintages
- Synthetic seismic data generation and processing
- 4D sensitivity to varying levels of noise and repeatability errors.
ACQUISITION

With either nodes or cables, the key 4D advantage of seabed acquisition over towed streamer acquisition is greater control over receiver positioning, giving improved repeatability between survey vintages. For life-of-field systems, this is inherent in the permanent placement of the cables. Trenched OBC life-of-field arrays offer a more secure long-term monitoring system with excellent coupling which is consistent from survey to survey. Seabed surveys can also provide multicomponent data, and with an appropriate source grid, dense wide-azimuth (WAZ) sampling. The combination of multicomponent, WAZ recording and 4D can be significant, especially for reservoir types such as fractured carbonates. The WAZ offset azimuth coverage and access to converted wave data can provide a wealth of additional information enabling more extensive 4D analysis. With CGGVeritas OBC processing expertise this can improve not only the imaging but also reservoir and fracture attribute analysis, and allow the monitoring of changes in a reservoir which conventional surface streamer surveys fail to discern.

Permanent seabed deployments offer economic benefits in addition to the technical ones. Repeat monitor surveys only require a source vessel and therefore the timing of monitor surveys can be more flexible and the cost greatly reduced when compared to towed streamer acquisition. Over the production life of a field, permanent OBC installations can realize a good return on investment. Permanent seismic receiver arrays also open up new opportunities for extra information-gathering in the form of passive seismic monitoring. Changes in pressure and stress in and around the reservoir can result in “micro-earthquakes” as existing fractures are re-activated or new ones are created. In appropriate conditions this passive seismic data can provide insights into the collapse of depleting high-pressure reservoirs, the activity of fracture networks during production and enhanced hydrocarbon recovery techniques such as hydraulic fracturing.

CGGVeritas has worldwide seabed experience ranging from transition zone and shallow-water 4C projects to 1500 metre-deep 4C surveys with cable and node systems. To operate in this wide range of demanding environments, a correspondingly broad range of expertise and equipment are required.

Our seabed equipment portfolio includes the state-of-the-art Optowave optical 4-component cable designed for life-of-field installations. For transition zones and water depths of up to 300m, the SeaRay® digital sensor 4-component cable provides a lightweight and versatile solution. In obstructed zones around pipelines and production platforms, cables can be complemented by nodes to maximize coverage.

CGGVeritas maintains its technological edge in seabed seismic through its Bergen office which is the company’s worldwide research and development centre for 4C and seabed operations. Strengthening this are strategic partnerships with the University of Bergen and the Christian Michelsen Research Institute.

Seabed acquisition benefits for 4D:

- Improved repeatability
- Multi-component recording
- Suitable for wide-azimuth long-offset recording
- Improved imaging through gas using converted waves
- Solutions perfectly adapted to life-of-field studies
- Possibility to combine 4D with passive seismic monitoring of production effects.

SEABED EQUIPMENT

The Sercel SeaRay is the leading re-deployable OBC system for water depths of up to 300m. It provides excellent quality 4-Component data utilizing the latest MEMS digital sensors. The innovative flat-pack sensor housing ensures optimum coupling.

Trenched OBC systems for permanent life-of-field monitoring are more secure, have better coupling and are more insulated from platform noise. They also offer excellent repeatability for 4D applications. The most has shows Optowave cable, from Sercel, being deployed by a trenching ROV.
ACQUISITION

Marine surveys are recorded under dynamic conditions, with every part of the system being in constant motion. In 4D, these variations from one vintage to another become important, as differences due to acquisition may hide the 4D differences in seismic response over time due to changes in the reservoir. Therefore, at CGGVeritas great care is taken during survey design and planning to ensure the monitor surveys are shot in as similar a manner to the baseline survey as possible.

SURVEY PLANNING

The ideal 4D monitor survey is an exact replica of the acquisition of the baseline survey. This involves repeating source and receiver positions and matching environmental conditions such as tide state and currents.

For example, in many areas good correlation is observed between streamer feathering and tidal conditions. So shooting the same line in the same direction at the same tide state is planned wherever possible. This also helps to replicate the height of the water-column and therefore the periodicity of water bottom multiples. Variations in water temperature and salinity may be seasonal so planning to shoot at the same time of year may also be desirable.

When the baseline survey suffers from navigation problems due to steering problems or obstructions it may be undesirable to replicate the survey. In this case a new optimized navigation pre-plot is required.

CGGVeritas 4D survey planning accounts for:

- Environmental conditions such as tide, currents, weather, time of year
- Optimization of geometry to cope with obstacles and navigation errors.

CURRENT PREDICTION

The effect of currents on streamer geometry can be anticipated during survey planning. However, more accurate knowledge of currents during the survey can be a valuable tool in minimizing infill and maximizing 4D repeatability. CGGVeritas uses sophisticated current models which include meteorological data and satellite observations to accurately predict currents, and therefore streamer feathering, several days in advance. This is augmented by onboard Acoustic Doppler Current Profiling (ADCP) to measure the actual current ahead of the streamers and calibrate the current prediction model. This information is used to manage the vessel steering to address the large-scale effects caused by currents.

STREAMER STEERING

Once the gross positioning has been accounted for by careful planning and ADCP prediction of feathering, further fine-tuning can be achieved by steering the streamers dynamically.

In order to make use of the finer positioning accuracy achievable with steerable birds, it is necessary also to employ fully-braced acoustic positioning arrays. These provide a more precise knowledge of the streamer position so that steering devices can maintain the desired streamer geometry more accurately.

The Sercel Nautilus system combines streamer steering and acoustic positioning functions into a single device.
MULTI-VESSEL OPERATIONS

Multi-vessel operations can play a range of important roles in the context of 4D acquisition. In cases of extreme feathering (i.e. strong perpendicular currents), CGGVeritas has used multi-vessel operations to improve repeatability of long offsets. The use of a separate source vessel and shorter streamers allows long offsets to be acquired more accurately and with greater repeatability than with a single vessel in these conditions.

Where obstructions are present two vessels can be used to achieve greater repeatability of azimuth or perform undershooting. With decades of multi-vessel experience, cutting-edge multi-vessel communications systems and the largest and most versatile seismic fleets, CGGVeritas is well equipped to provide any shooting configuration required.

RECORDING EQUIPMENT

The CGGVeritas fleet is predominantly equipped with Sercel Sentinel® solid streamers which offer several clear benefits for 4D recording.

First, solid streamers are proven to be quieter than fluid filled ones which improves the signal-to-noise ratio of a survey. Since 4D signals may be very weak, this can be critical for extending the range of reservoirs for which 4D is applicable.

Second, solid streamers offer improved consistency of ballast, improving depth control. In turn, this improves the repeatability of receiver ghosts which can be crucial when looking for small timing or phase shifts at the reservoir.

Third, hydrophone group sensitivity is highly consistent between groups and cables over a multi-year timeline. Both these factors are clearly important for optimal repeatability and sensitivity to small changes in the acoustic response of the reservoir.

CGGVeritas has acquired successful 4D surveys around the world and has unrivalled experience in 4D marine acquisition in the North Sea. Our fleet is the most versatile and largest in the seismic industry.

SURVEY OVER-SPECIFICATION

Survey over-specification can be used as a strategy to improve 4D repeatability. While careful planning, vessel and steamer steering technology and utilization of multi-vessel operations can all improve positioning repeatability significantly, they cannot eliminate all differences in shooting geometries.

A denser, over-specified dataset can be recorded for a new baseline or successive monitor surveys by using more streamers to achieve wider spreads and closer streamer separation. Modern 4D processing techniques can then make good use of this higher-density data to select or interpolate the data for optimum repeatability with other vintages acquired with standard streamer spreads.

CGGVeritas has acquired 4D Marine Surveys acquired since 2001

CGGVeritas 4D Marine Surveys Acquired since 2001

Far East 5%  Europe 33%  Rest NASA 7%

W. Africa 27%  G.O.M. 16%  Australia 3%  Middle East 5%

Nautilus provides automated steamer steering. Within 14 minutes of activating the steering, the spread has been fully regularized.
**ACQUISITION**

In the case of onshore 4D projects the challenges are somewhat different from marine 4D acquisition. Although repeatability of source and receiver locations are generally easier to achieve, the 4D variations caused by changes in near-surface conditions can be orders of magnitude higher. Careful planning of the initial baseline survey and a consideration of the expected changes in the response of the near-surface, as well as the reservoir, are essential to assure that a usable 4D signature is obtained.

Positioning accuracy, and therefore repeatability, has been revolutionized by the use of “stakeless” GPS positioning systems. Not only are actual coordinates recorded more accurately, but integrated navigation systems ensure that receivers and sources are deployed as close to the pre-defined targets as possible. Stakeless surveying can eliminate many of the navigation errors which previously affected 4D repeatability.

The move to high-density and wide-azimuth land acquisition geometries, particularly with single-source single-receiver configurations, has great benefits for land 4D. The use of point source and point receivers results in more consistent and repeatable responses and removes unwanted array effects which create azimuthally-varying attenuation. 4D processing in particular benefits from:

- More accurate, higher-resolution statics solutions
- More accurate imaging with higher-resolution velocities
- More effective noise attenuation utilizing 3D algorithms.

**SEISMOVIE**

SeisMovie is a permanent seismic monitoring solution developed by CGGVeritas in conjunction with Gaz de France and IFP. The system was initially designed for the monitoring of underground gas storage whereby gas is stored in natural subsurface reservoirs. These storage reservoirs require frequent and accurate observation to monitor gas saturation and the extent of the gas bubble during usage.

SeisMovie systems routinely achieve a vertical sensitivity of 0.1 milliseconds with a usable signal bandwidth up to 250Hz. This capability allows monitoring of subtle and rapid reservoir variations which are impossible for conventional surface-borne 4D surveys.

Benefits:

- Captures subtle reservoir variations
- Enables monitoring of previously unsuitable reservoirs
- Provides continuous monitoring for real-time production decisions
- Highly reliable remote autonomous operation
- Minimal environmental impact
- Minimal surface interference at busy production sites.

To fulfill these criteria a completely autonomous system was designed utilizing buried receiver arrays and a novel piezoelectric vibrator source. Using a permanent buried installation ensures excellent 4D repeatability and coupling. By placing the source and sensors below the weathering layer, SeisMovie eliminates near-surface variations to further improve 4D repeatability over extended periods.

The piezoelectric source is well suited for permanent installation and has a very stable source signature which further contributes to the repeatability of the system. Several sources can be distributed throughout the survey area, and using a patented discrete frequency sweep, can operate simultaneously adding significantly to the data density.

The system is flexible and versatile and can use a variety of receiver configurations to achieve different monitoring objectives. For areal coverage over a large target, long arrays or grids of buried geophones can be installed, whereas to increase vertical sensitivity of the system, arrays of sensors (2, 3 or 4 component) can be permanently installed in vertical boreholes to provide VSP-style datasets.

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A schematic SeisMovie installation for SAGD heavy oil production operation. Buried piezoelectric sources are shown in yellow along with a network of buried receiver arrays. The autonomous system works 24 hrs a day, recording and pre-processing data on site before transmitting it back to the office for analysis.
HEAVY OIL SAGD MONITORING

Typical oil and gas reservoirs have a lifespan of many years and evolve slowly over their productive life. Repeat surveys every few years are therefore appropriate for 4D seismic monitoring. Heavy oil reservoirs produced using steam-assisted gravity drainage (SAGD) have a much shorter life-cycle. The state of the reservoir can vary significantly over the course of weeks and months so it is important to monitor production effects on a much more frequent basis.

To have a seismic crew on call to perform weekly or even monthly surveys is economically unrealistic. Among the other problems faced in this scenario is the extensive surface infrastructure around the fields which will interfere with acquisition, both in terms of surface coverage and high levels of background noise.

The example shown was conducted in 2005 over a heavy oil field. A single buried source and a grid of 400 receivers monitored a shallow, unconsolidated tar sand reservoir for a one-month period of steam injection. Recording was near-continuous, with 240 records acquired per hour, pre-processed automatically on-site and transferred via an internet link for analysis. Detailed QC of the continuous seismic record ensures that anomalies are easily and quickly identified. Over a 30-day period the field data showed the progressive effects of steam injection, with transit time variation maps (below) revealing the irregular nature of the steam propagation into the reservoir and the corresponding effectiveness of the individual injection wells (denoted by the lines across the maps). Despite high levels of noise generated by the adjacent steam plant, the results show good signal content and bandwidth with good correlation to well data.

The image shows a set of lines through a shot gather summation for 24 hrs of recorded data after basic pre-processing and NMO correction. The lower power source sweeps several times an hour so that in a 24hr period enough energy is emitted to produce a coherent stack. The frequency content at the base of the reservoir is up to 240Hz. A cone of noise centred on the source location is visible (highlighted in red) at this preliminary processing stage.

Map view of cumulative transit-time variation through a heavy oil reservoir over a 30-day period. The sensitivity of the SeisMovie installation meant that time shifts of 0.1ms could be reliably detected and production could be monitored in real time. The red lines represent steam injection wells and the white disc represents the area affected by the noise cone from the source (see above).
OVERVIEW

CGGVeritas has been at the forefront of 4D processing since its inception. Our expertise in this field is recognized throughout the industry with the result that we not only offer 4D processing and imaging in our open centers, but also operate specialist 4D dedicated centers for our clients. Processing time-lapse datasets requires great care and attention to detail which is why our experience really makes a difference.

The aim of 4D processing is to attenuate the 4D noise caused by changes in acquisition parameters or environmental conditions, and to emphasize the 4D signature of the reservoir caused by changes in fluid, pressure and stress. Over the years, our 4D research group has developed the tools and techniques to achieve this. Greater expertise and advances in conventional 3D processing have also benefited 4D processing. For example, progress in statics, multiple attenuation and depth imaging all contribute to improving the quality of 4D processing results.

4D PROCESSING STRATEGY

CGGVeritas has been pioneering 4D processing since 1987, when it introduced pre-stack parallel processing. This involves the processing or re-processing of all the 4D vintages in unison using coupled or simultaneous 4D processes with parameters and models optimized for all of the vintages.

At every stage in the processing sequence 4D QC attributes such as NRMS are monitored to confirm that the vintages are increasingly more compatible. An important aspect of this strategy is the application of relevant pre-stack deterministic corrections instead of relying solely on post-stack matching. This rigorous approach ensures that the 4D noise will be more accurately targeted and the 4D reservoir signature will be preserved.

STATICS

Static differences between vintages occur in both land and marine 4D surveys. They are caused by changes in the near-surface, weathering layer, water column or water surface conditions. CGGVeritas has developed a range of strategies and algorithms for both land and marine 4D surveys. For marine surveys, application of deterministic GPS-based tidal and wave-height corrections and statistical 4D corrections for water column statics greatly reduce the acquisition footprint.

REGULARIZATION

The regularization of 4D datasets uses bin centering and interpolation of missing data to create either regularly sampled datasets on a common grid, or map monitor survey data to a base survey grid. CGGVeritas has developed REVIVE, a Fourier regularization technique using up to 5 dimensions (x, y, offset, azimuth and time) which provides dramatic increases in the accuracy of the interpolation and benefits 4D processing.

4D QC

A range of 4D attributes can be used to monitor the progress of 4D processing. The most commonly used are:

NRMS Normalized RMS amplitude is sensitive to static shifts, phase or amplitude differences. Low NRMS indicates high repeatability.

Predictability is sensitive to noise and changes in reflectivity, higher values implying greater repeatability.

In addition complex trace analysis can be used to derive the instantaneous phase and amplitude components of the 4D differences, which are useful tools for QC and interpretation.
Improved gather processing such as Radon de-multiple
- Reduced migration artefacts

Data is optimally conditioned for 4D binning.

4D BINNING

4D binning is an essential step in time-lapse processing which selects the most compatible data for 4D processing. Traces are selected from all of the vintages making up the 4D dataset which are best matched in terms of source, receiver and midpoint position, offset and azimuth. The binning criteria can be extended to include statistical measurements of 4D data quality such as cross-correlation, predictability and NRMS. Simultaneous binning of all vintages ensures:

- The most compatible traces from each acquisition vintage are selected
- Acquisition differences between vintages are minimized
- Systematic errors between vintages are avoided.

DE-STRIPING

Systematic amplitude variations related to the acquisition geometry create a pattern or acquisition footprint. The footprint within each vintage is emphasized in 4D difference between them, as shown by the NRMS attribute map on the facing page.

De-striping techniques are routinely used in conventional 3D processing. For 4D processing, CGGVeritas utilizes a 4D de-striping technique where data from all vintages is analyzed for systematic variations with respect to acquisition attributes, such as sail line, and scalars are calculated to compensate for them. Geostatistical techniques are also effective at removing these systematic acquisition-related variations.

MATCHING

Matching is used to minimize residual 4D differences caused by acquisition and environmental variations which cannot be addressed by deterministic corrections. A range of sophisticated techniques, including some capable of multi-vintage matching, have been developed by CGGVeritas to suit a wide range of 4D datasets:

- Matching to a common cross-correlation spectrum
- Geostatistical matching using automated factorial co-kriging
- Neural network matching
- Wavelet domain matching
- Instantaneous phase and amplitude matching using complex trace analysis
- Multi-vintage residual matching using time alignment methods.

Time-variant spectral matching using a wavelet domain approach is a new technique which provides improved results over traditional global amplitude and phase matching techniques. Other methods within this toolkit have more specialized applications. Geostatistical matching has proved to be very effective for merging and subsequent 4D matching of streamer and OBC datasets. Multi-vintage, Taylor series time-variant time alignment improves on cross-correlation methods and has applications which include the accurate estimation of time-shifts for geomechanical inversion.
4D IMAGING

CGGVeritas is a world leader in seismic imaging and has pioneered the use of depth imaging, in particular anisotropic pre-stack depth migration (TTI PSDM), in 4D processing. Depth imaging has a number of clear advantages which makes it more suited for 4D than time imaging:

- Improved spatial positioning of structure
- Improved focusing for sharper 4D differences
- Comprehensive set of techniques to enable more accurate velocity model building.

4D LAND & OBC

Land and OBC 4D surveys have additional processing needs and advantages. These can include multicomponent processing and merging of streamer and OBC datasets in obstructed fields. With many of these surveys providing wide-azimuth datasets CGGVeritas can also bring to bear its unparalleled experience of wide-azimuth processing, including:

- Multi-azimuth, multi-vintage binning
- Tau-pe-py noise attenuation and deconvolution
- 3D high-resolution Radon de-multiple
- REVIVE 5D wide-azimuth interpolation
- Elastic modeling and subtraction of the direct arrival
- Azimuthal AVO.

4D PRE-STACK DEPTH MIGRATION

Depth imaging techniques allow more accurate velocity models to be derived and achieve more precise structural images in the depth domain where volumetric interpretation and well planning are performed. In this example, one-way wave equation PSDM leads to a significant improvement in the definition of the 4D effect caused by the water injector in the middle of the panel.

Depth imaging which incorporates Tilted Transverse Isotropy (TTI) can offer the most accurate images in areas of structural dip. This in turn can provide a better focused and more precise 4D difference.

Isotropic PSDM 4D difference with the oil-water contact marked in green.

Anisotropic (TTI) PSDM 4D difference.

The anisotropic PSDM provides better focusing in the reservoir zone (oil-water contact marked in green) and better imaging of the faults. This is reflected in the 4D difference which is less noisy and has a higher apparent resolution. Data courtesy of StatoilHydro.
4D INTERPRETATION

The results of a 4D survey are used rather differently than those of a 2D or 3D survey. The interpretation is focused on the production & development stages of a field and is concerned with changes in the reservoir, usually the fluid content and movement within the structures. By tracking these it is possible to monitor the flow of hydrocarbons within the reservoirs, gain greater understanding of the reservoir behavior and optimize its development.

HAMPSON-RUSSELL PRO4D

In addition to providing world-class processing services, CGGVeritas, through its subsidiary Hampson-Russell, also provides a powerful 4D characterization package, PRO4D.

Time-lapse projects are becoming increasingly more complex, with multiple monitor surveys and multiple angle volumes per survey. PRO4D’s advanced management system helps organize the data so that 4D or multi-attribute volumes can be viewed, processed or interpreted as easily as if they were a single 3D volume.

SURVEY CALIBRATION

PRO4D contains leading-edge survey calibration features that match the phase, frequency, amplitude and event times of baseline and monitor surveys in areas where production has not occurred. Once these background differences are removed, the production-induced anomalies can be interpreted with confidence.

TIME-LAPSE ATTRIBUTES

A wide range of time-lapse attributes can be generated that highlight production anomalies in the data. Difference volumes are created on-the-fly and can be co-rendered with conventional data. Standard 4D attributes, such as NRMS, amplitude ratio, cross-correlation coefficients and time shifts, can easily be created as 3D cubes.

ROCK PHYSICS AND SYNTHETIC MODELING

PRO4D supports advanced rock physics modeling that assesses how the seismic response will be affected by changes in fluid saturation, pressure and temperature. Multiple scenarios for a single well can be rapidly generated, and synthetic traces (pre-stack or post stack) are automatically created for each scenario. 3D synthetic volumes can also be created when rock property models are imported from reservoir simulation.

COMPARISON OF PRODUCTION AND ENGINEERING DATA

These synthetic attributes can be analyzed, and relationships between them and their corresponding reservoir properties derived using multivariate regression, neural network and cross-correlation techniques. After calibration, these relationships can be applied to the seismic data to produce maps of saturation, pressure and temperature.

PRO4D contains an advanced volumetric analysis capability that facilitates the comparison of time-lapse anomalies to production and injection data at their associated wells. The 4D response can be validated and the interpretation can be refined. 4D attribute maps can be easily compared with pressure and saturation distributions estimated through reservoir simulation.
PRE-CONDITIONING

The quality and reliability of the results obtained from seismic inversion for elastic or reservoir properties can be improved by pre-conditioning the pre-stack data. This generally includes additional noise attenuation, residual corrections to flatten events in the gathers and stabilization of the seismic wavelet (between vintage and offsets). These processes are designed to reduce the noise and jitter affecting pre-stack events while preserving the AVO information they contain.

CGGVeritas has developed a pre-conditioning technique specifically to enhance the AVO information within pre-stack gathers. STRAD is a co-filtering technique applied to intercepts and gradients after AVO fitting. It is based on the principle that noise-free reflectors yield a constant relation between intercept and gradient when convolved with a wavelet.

Changes in attenuation between 4D surveys can be significant sources of amplitude and phase differences, particularly where gas injection is being performed. This can be dealt with by a differential Q (4DQ) controlled calibration. Linear regression is performed using spectral ratios between two windows simultaneously for the baseline and monitor survey to produce the 4DQ attribute. This describes the spectral variation relating to residual absorption between the 4D vintages and is used for the calibration.

GLOBAL 4D ELASTIC INVERSION

Tracking the movements of fluids due to production gives valuable information about the depletion of a field, and can indicate areas of bypassed oil or gas. Changes in fluid saturation and reservoir pressure can be estimated by applying 4D inversion followed by rock physics inversion. Traditionally each vintage is inverted independently, but experience shows that coupling the inversion of the baseline and monitor surveys is important to reduce the non-uniqueness of the inversion process and obtain quantitative estimates of changes in impedance.

The CGGVeritas global 4D inversion scheme addresses this by inverting all data vintages simultaneously. The time evolution of the resulting elastic attributes are constrained by simple rock physics rules restricting the range of variations between consecutive surveys.

Coupling the global inversion with 4D Bayesian lithology classification allows reservoir properties to be derived from the elastic attributes. This facilitates interpretation and quantifies the uncertainties in the inversion results, providing a valuable input for reservoir management decisions.

Benefits:
- Optimum global result for all vintages
- Meaningful results constrained by 4D petrophysical models
- Quantitative estimates of reservoir properties

CONSTRAINING 4D INVERSION

4D seismic reservoir monitoring has been used on the mature Brage Field in the Norwegian North Sea to identify unswept zones in the reservoir. Using data from 1992 and 2003 surveys, global 4D inversion was carried out initially without any specific 4D constraints (i.e. elastic attributes could increase or decrease freely within standard limits). The result fits the seismic data but does not take advantage of the available a priori 4D knowledge of the reservoir, and is therefore not necessarily consistent with the production history of the field.

By incorporating available knowledge about the reservoir such as the production regime and its expected behavior, the intrinsic non-uniqueness of seismic inversion can be controlled. In this case the reservoir is undergoing enhanced oil recovery by water injection, so an asymmetrical 4D constraint is used which only allows increases in P-Impedance and Vp/Vs (representing the displacement of oil by water) and this is limited to within the reservoir interval.

The results of the global inversion with rock physics constraints provide a result which fits the production history of the field and the available well data more accurately. For the 2003 inversion results, the remaining oil is mapped with a much higher probability which means bypassed zones of the reservoir can be identified with a much higher certainty.
GEOMECHANICS

In addition to the movement of fluids, changes in pressure and stress in and around reservoirs is a natural consequence of production. For high-pressure reservoirs, pressure depletion during production is associated with compaction within the reservoir causing stretching or extensional stresses in the overburden and underlying formation. This causes variation in velocities and formation thickness which can be observed as 4D time shifts between successive vintages. Over the Chalk reservoirs of the North Sea these stress changes can even result in subsidence at the seabed (the Ekofisk field, for example).

Geomechanical modeling can be used to explain and predict these 4D time shifts, using relationships which relate velocity changes to stress-induced fractional thickness variations for a range of lithologies. These relationships are used in the inversion of the observed pre-stack, offset-dependent time shifts for geomechanical properties.

In addition to the obvious compressional effects within the reservoir, extensional stress is experienced above and at the edges of producing reservoirs. This extensional stress above the reservoir generally makes the largest contribution to the observed time shift.

Compaction of the reservoir generates significant changes in radial stress around its edges which create a 4D anisotropy signature. CGGVeritas has extended geomechanical inversion to include the estimation of 4D anisotropy using offset-dependent 4D time shifts. This provides a unique solution for the delineation of depleted and compacted zones in the reservoir.

Benefits:

- Improved understanding of 4D response of compacting reservoirs
- Production monitoring in fields with small 4D signatures
- Indication of potential wellbore instability in HPHT fields
- Complements 4D elastic inversion techniques to improve discrimination of production effects within the reservoir.

MONITORING COMPACTING RESERVOIRS

Some fields are characterized by high-pressure regimes which exhibit significant pressure depletion during production. In the case of the Elgin field (North Sea Central Graben) a 500bar decrease in pressure has been observed over the life of the field.

**4D Time shift**

Strong compressional stress is observed within the reservoir due to production-related compaction (middle). Above and at the edges of the reservoir, extensional stress is observed as the surrounding rocks compensate for the compaction of the reservoir. This extensional compensation in the overburden creates the large observed time shifts above the reservoir (top).

**4D Stress**

4D anisotropy variations can also be observed in the offset dependency of these time shifts (bottom). These can be related to changes in the radial stress field and can be used to delineate the extent of the producing reservoir (dashed line).