OTC 10939

Multicomponent Seabed Seismic Data: A Tool for Improved Imaging and Lithology Fluid Prediction

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Abstract
Multicomponent seabed seismic data acquisition, processing and interpretation of pressure and shear data are bringing new insight into seismic exploration and reservoir characterization. The reason we want to record "dual-wave" data is at least two-fold. First, to improve seismic lithology and fluid prediction, as shear waves carry additional information about lithology, pore fluids, and fractures in the subsurface. Second, to improve seismic imaging, as joint processing and analysis of both pressure and shear data reduces the ambiguity of structural and stratigraphic interpretation. Independently of the use of multicomponent sensors, seabed seismic data recording offers the generic advantage of flexibility of the acquisition geometry. As virtually any pattern of shots and receivers is possible, data acquisition can be optimized to provide the most revealing subsurface image.

In this paper, we present results from analysis of multicomponent seabed seismic data from the Tommeliten Alpha Field and the Statfjord Field, offshore Norway.

Introduction
Multicomponent marine technology holds a promising potential for risk reduction in seismic exploration. While oil and gas from large and geologically simple fields have constituted a substantial part of the world's hydrocarbon production up to now, new resources are to a greater extent found in small traps in geologically complex areas or in subtle traps that are difficult to identify. Petroleum reserves thus become progressively more difficult to discover and develop and the financial risks increase while the economic margins tend to decrease. The demand is therefore high for new technology that can reduce risk through more accurate prospect definition. The use of converted shear (PS) waves in addition to conventional pressure or compressional (P) waves offers a possibility to better address the risk elements in petroleum exploration work.

In the 1970-80's, attempts were made to extract shear wave information from marine seismic data acquired in surveys with conventional sources and pressure-sensitive hydrophones located in the water column. The methods rely on double mode conversions at or just below the water bottom, giving PSSP reflections. For a given angle of incidence, mode conversion from compressional P-wave to S-wave is quite efficient in "hard" water-bottom environments. The water bottom shear velocity is the most critical parameter affecting the generation of observable PSSP reflections. Their amplitudes can be comparable to normal P-wave reflections when the S-wave velocity is greater than one-third of the water-bottom P-wave velocity[1,2]. In most areas, however, as the sea floor shear velocity is much lower, this is not a viable technique to record high quality shear wave data in the marine environment. Other solutions thus were investigated. Unless shear waves were generated by source devices on the sea floor, the methods necessarily had to rely on mode conversion by reflection from P-wave to S-wave at reflectors in the subsurface.

In the early 80's, a few oil companies started to investigate how shear waves could be recorded on the seabed. For instance, Conoco Inc. considered the use of a marine shear wave vibrator source for shear wave excitation, while Shell Offshore Inc. investigated the potential of recording shear waves by using a "marine shear wave cable". However, to our knowledge, no results from these analyses were published in the open literature. In the late 80's, Statoil developed a concept for acquiring fourcomponent (4C) seismic data directly on the sea floor. Known as SUMIC (SUbsea seisMIC) the technique would enable the recording of both shear and compressional waves by planting into the seabed sensors with hydrophones to measure P-waves and three-component geophones to measure the particle velocity vector[3]. As the data constitute a complete representation of the subsurface wavefield, the recordings can be decomposed into separate P- and S-wave contributions[4]. In 1992, after the development of the prototype SUMIC sensor array, several extensive field equipment tests were carried out, among others at the Troll and Gullfaks fields offshore Norway. The data quality from the SUMIC sensor layouts was judged to be remarkably good, and demonstrated that SUMIC was a viable system for acquisition of high-fidelity 4C data. The first full-scale SUMIC data acquisition of a multifold 2D seismic line was undertaken by Statoil late 1993 over the Tommeliten Alpha structure in Block 1/9 of the Norwegian sector of the North Sea. The principal objective of the survey was to demonstrate the potential of the SUMIC technique for imaging subsurface structures through and below gas chimneys. Some results from this seismic imaging study are presented below. A 3D-4C acquisition programme over the Tommeliten Alpha structure is currently being considered.

Since mid-90's, fourcomponent marine seismic acquisition is a commercial service offered by the major seismic contractors.

Including the Tommeliten survey, Statoil has acquired ten 4C marine seabed datasets. In 1997, a 3D-4C dataset was acquired over the Statfjord field, a mature North Sea oil field. To date, it is the most densely sampled 3D-4C survey. The objectives of the survey were two-fold: (1) from P-wave data to provide better structural imaging of the complex East Flank area, and (2) from combined P- and S-wave data to improve lithology/fluid phase classification in the main field. Another aspect of interest, possible due to the true 3D acquisition geometry with full azimuth sampling, is the opportunity to decimate the data to emulate different acquisition geometries, e.g. orthogonal shooting (coarse line spacing in shot domain) over densely located receiver stations, or densely shooting in a 2D grid over coarsely located receiver stations. The latter shooting geometry is similar to the geometry typically used in 3D VSP data acquisition and vertical cable data acquisition. Initial results from the Statfjord 3D-4C survey[5,6,7] are presented below.

Despite the fact that marine multicomponent seismic still is an immature technique, a number of potential benefits of this technology can be foreseen that may greatly impact the E&P business in the future. In Table 1 we list some possible applications of 4C data. These may be divided into three broad categories: (1) Imaging in complex areas; in particular imaging in gas affected areas is well proven[3,8,9] by using shear waves to image reservoirs where gas saturation in the overburden completely distorts any imaging based on conventional seismic data; (2) Lithology and fluid prediction by exploiting the additional information contained in the seabed recorded S-waves, and finally (3) Time-lapse (4D) seismic monitoring, aiming at mapping remaining reserves by imaging how the distribution of fluids in the reservoir changes through time as production takes place. It is expected that 4D-4C data greatly will reduce interpretation ambiguity related to monitoring of saturation and reservoir pressure variations over time.

2D-4C survey at The Tommeliten Field: Imaging below gas

The Tommeliten Alpha gas condensate field was chosen by Statoil, as part of the SUMIC development programme, to measure the potential of SUMIC seismic surveying as a means of providing cost-effective solutions to specific geophysical problems which cannot be solved using conventional seismic methods. The chosen exploration target has a reservoir which lies beneath gas rising in a chimney within the overlying shales. Previous conventional seismic surveys, which rely on P-wave propagation only, produced untenable images because of the distortion and misfocusing introduced as the P-waves passed through the gas chimney. A few per cent gas saturation in the chimney introduces strong attenuation and heavily distorts the P-ray paths.

Because shear waves are much less affected by fluids than compressional waves, it was expected that the 4C SUMIC technology would be eminently suited to "see through" the distorting gas chimney, enabling a reliable image of the target to be produced from shear waves. A continuous and regular 2D-4C profile of 12 km length passing over the two wells was acquired late 1993. In general, the quality of the 4C data was excellent at all locations along the line as the sea bottom, geological conditions and water depth varied. In the following we present results from conventional time processing[8,10] as well as results from ongoing work on prestack depth imaging, including the effects of anisotropy[11].

Time Imaging. The time processed SUMIC PS-wave section shows a good quality image of the Alpha structure with a minimum of distortion from the gas chimney. Effectively, the long-offset PS converted mode undershoots the gas chimney: the downgoing P-wave mode propagates outside the gas, while the reflected S-wave mode travels upward almost unaffected by any presence of gas. However, some amplitude loss and scattering interference have been introduced by the faulting induced in the overburden by the rising of the anticlinal structure. Interpretation supports that the Tommeliten Alpha structure is a faulted dome. The Tommeliten field study powerfully demonstrated the ability of the 4C technology to image below shallow gas.

Depth Imaging. One of the challenges of processing marine multicomponent data is the problem of tying P-wave and converted S-wave sections in time. The obvious, though difficult, solution is to prestack depth migrate the data. One then faces the problem of velocity estimation. To some extent prestack depth migration is itself an excellent velocity estimator because depth migrated gathers are sensitive to the background velocities. The most basic technique to validate and update migration velocities is to analyze Common Image Point (CIP) gathers. The prestack depth migrated traces in a CIP gather map the same depth points at a specific lateral position, but are generated from different source-receiver offset data. Using the correct subsurface velocity model in the migration results in CIP gathers containing flat events that stack coherently. If the velocity model is incorrect, the events in the CIP gathers exhibit curvature. The success of any depth migration strongly depends on the background velocity field, and proper velocity analysis is therefore crucial.

We here present preliminary results from prestack depth imaging. A 2D optimization tool for estimation of isotropic P and S migration velocity fields was first implemented. The method is based on a directed Monte Carlo search called Very Fast Simulated Annealing[12] and a rapid, model-based PP/PS prestack migration. The computed CIP gathers are forming a least-squares objective function to be minimized. Prior to each prestack migration, the simulated annealing algorithm suggests layer velocities and a model is constructed via map migration. The model is efficiently parameterized using spline functions to describe the subsurface interfaces and the layer velocities. The minimum in the cost function corresponds to maximally flat events in the CIP gathers. Typically, the procedure converges after a few hundred iterations. The P- and S-velocity fields are determined subsequently in two separate optimization runs. The P-velocity field is first estimated from the P-wave data. The S-velocity field is then estimated from PS converted waves, where the kinematics of the downgoing P-waves are assumed to be reasonably well described by the optimized P-velocity field.

This velocity inversion method has been applied to the 1993 Tommeliten SUMIC data. Optimization of the isotropic P-velocity model using the vertical particle velocity component worked quite well, although event correlation between the migrated image and well logs indicates a slight mispositioning of key reflectors. However, optimization of the S-velocity model using the in-line particle velocity component completely failed using an isotropic methodology. PS-events in the CIP gathers originating from the key horizons were flat at depths several hundred meters deeper than geologic depth. This contradiction between flat gathers and large misplacements in depth can only be explained by anisotropic wave behavior in the shaly overburden. This is supported by the fact that vertically polarized shear waves are more sensitive to anisotropy than P-waves[13]. It is evident that anisotropy corrections must be included in the depth migration process in order to consistently map the seismic data to correct depth.

No systematic anisotropic velocity updating procedure was at hand at the time the present work was carried out. An ad hoc procedure therefore was followed to update the P- and S-velocity fields and additional anisotropy parameters. A ray tracer handling transversely isotropic media was utilized to conduct the traveltime computations. Using a crude but not optimum estimate of anisotropic parameters, a new depth migration was performed. The resulting image shows that the key reflectors in the PS image are fairly consistent with those in the PP image. Further work is required to consistently include the effect of anisotropy in the depth migration of PP and PS data. We may conclude, however, that anisotropy must be properly taken into account to correctly image multicomponent data in depth.

3D-4C survey at The Statfjord Field

The Statfjord oilfield is located in the Tampen Spur area straddling the British/Norwegian border in the northern portion of the Viking Graben. The overall field area is around 500 sq. km, and the estimated reserves are 650 x 10^6 Sm^3 oil. Production started in 1979 and the production plateau extended until 1992. The reservoir units are Jurassic sandstones of the Brent Group, Dunlin Group and Statfjord Formation.

The majority of the original reserves are found within the westerly dipping fault block of the main field. To the east of the structural crest of the field is a structurally complex area described as the East Flank comprising many reservoir compartments bounded by listric faults. This structure is a multiple gravity slide system developed due to instability across the Main Boundary Fault to the east of the field. The gravity slides are identified in all three reservoir units.

In 1996 a Statoil study of the Statfjord Field suggested that some 10% additional oil (approximately 60 x 10^6 Sm^3) could be recovered with the assistance of improved seismic mapping. Both detailed imaging of the complex East Flank and time-lapse seismic monitoring of the remaining reserves were expected to be beneficial. In 1997, both 3D towed streamer data for reservoir monitoring and 3D-4C seabed data were acquired over the Statfjord Field.

Survey objective. The primary objective of the Statfjord multicomponent survey was to provide from P-wave data better structural imaging of the complex East Flank area. The secondary objective is to improve from combined P- and PS-wave converted data lithology/fluid phase classification in the main field.

A major advantage of using 4C ocean bottom cable (OBC) technology is that the survey geometry is fully flexible to meet the acquisition parameters that will optimally illuminate the known geological target with respect to azimuth, fold and offset distribution. Typical OBC acquisition geometries are parallel shooting, where multiple source lines are shot between and parallel to the receiver lines, and orthogonal shooting, where source lines are shot orthogonal to receiver lines. Parallel shooting is a narrow azimuth technique which is appropriate when the objective is to merge OBC data with towed streamer data. Orthogonal shooting is a wide azimuth technique which should better illuminate targets. Typically, the spacing between source lines is 200-300 m. Because of the structural complexity of the Statfjord East Flank, it was found that the optimum acquisition technique would be areally dense shooting, where shots are densely fired over a large 2D grid above the receiver stations. This acquisition geometry is a wide azimuth technique with true 3D illumination of the target. Furthermore, by invoking reciprocity, the data are 3D wave equation consistent and may be depth migrated using e.g.

reverse time extrapolation or finite difference depth extrapolation. As for all OBC recording geometries, offsets are virtually unlimited, providing super-wide aperture.

Another benefit of multicomponent acquisition is the dual sensor recording of the P-wave mode. By consistently scaling the vertical component of the particle velocity recorded from the geophone and adding the pressure recording from the hydrophone, receiver-side water layer reverberations (downgoing wave modes just below the seabed) are attenuated. The summed data are in the following denoted by P/Z data. This wave equation based pressure demultiple technique is numerically fast, and removes some of the strongest and most troublesome multiples from the data[14,15]. Often de-pegleg multiple attenuation is run at the same time to attenuate source-side related water layer reverberations. As the quality of conventional seismic data over the Statfjord field is reduced due to multiples overlying primaries in the reservoir zone, it was judged important to fully optimize the P/Z summation technique to attenuate multiple energy to improve resolution in the reservoir interval. An area covering a small part of the East Flank and the Main Field was selected as the multi-component data acquisition test site.

Acquisition programme. The area of the survey is about 100 sq. km for the source array and 10 sq. km for the receiver array. The data set was collected by Geco-Praka in 1997 by deploying eight 4-component sea-bottom receiver cables onto the seabed, each 5 km long with 25 m receiver group spacing. The cross-line distance between the cables was 300m. The shooting direction was parallel to the cables, with a shot interval of 25 m (flip-flop mode), and a sail-line distance of 100 m. The resulting pop interval is 50x50 m in inline/crossline direction.

Data decimation. For the P-wave data, this choice of survey parameters lead to a maximum nominal fold of about 1800, in a bin cell size of 25m x 25m. Such a high fold had to be decimated to stay in line with the current processing capacity. In parallel to the fold decimation applied for the production processing, based on choosing the trace within each bin closest to the bin center, we have simulated two other acquisition geometries by data decimation: (1) "receiver decimation" simulating a coarse inline receiver station interval, with receivers every 300 m but areally dense source grid (50x50m), giving a nominal fold of 110, and (2) "shot decimation" simulating shooting orthogonal to the receiver lines, with 300 m between sail lines, giving a nominal fold of 220. For a given maximum offset range, the production decimation gives highest fold, and azimuth distributions comparable to receiver decimation or shot decimation. High fold is obviously necessary to increase the S/N ratio in the data.

Surface data versus P/Z data. The dual-sensor P/Z data volume has been processed by CGG using a fairly conventional 3D pre-stack time migration sequence. Over the Statfjord field, we have available surface seismic data acquired in 1997 and processed with a pre-stack time migration sequence. The velocity fields for the two datasets are almost identical. Due to the very different acquisition geometries and azimuth distributions for the OBC data and the towed streamer data, one should expect distinctive differences in the two imaged data volumes. Initial analysis indicates that the full azimuth sampling in the OBC experiment is favorable for the present imaging study, leading to improved resolution and better definition of the main reservoir reflectors (in particular the Top Dunlin and Top Statfjord horizons). In some areas better definition of East Flank fault blocks and fault planes are evident. Also, the Statfjord Formation gas/fluid contact is believed to be better imaged from the P/Z data. This observation is confirmed by production wells. The OBC data has slightly broader frequency bandwidth than the surface data. The P/Z-wave data quality is considerably improved through optimum dual sensor summation[15].

P data versus PS converted data. Preliminary scanning of the PS converted data indicates that the data are of high quality. Shear wave static corrections are small. Azimuthal shear wave anisotropy is not significant. The top of the reservoir and the main reservoir horizons are all well imaged. The reflector character is generally different in the P-wave and PS-wave converted sections expressing that the compressional and mode converted shear wave responses are differently related to the seismic parameters. While the P-wave stack section is predominantly sensitive to changes in P-wave (acoustic) impedance, the PS converted stack section is predominantly sensitive to changes in shear wave modulus, indicating that improved lithology and fluid/phase predictions in the main field will be reached.

Preliminary observations. Preliminary analysis indicates that the Statfjord East Flank geometry is better imaged from 3D OBC P-wave data than from the best available 3D towed streamer data mainly due to the true 3D OBC acquisition geometry and the optimum suppression of water-layer reverberations by summation of hydrophone and geophone data in processing. The sand/shale formations seem to be better mapped by PS converted waves. The results so far are encouraging, however, further analysis and interpretation is required to define the real economic impact of 4C seismic technology in the area.

The Statfjord 4C data processing is at present still running. Final processed data volumes will be prestack depth migrated volumes of both P-wave data and PS mode converted data. Due to the structural complexity of the Statfjord East Flank we expect prestack depth migration to further improve the image quality.

Conclusions

If the oil industry shall succeed in uncovering hydrocarbon reserves in more complex and subtle traps, the industry must increasingly resort to nonconventional technology and techniques. 4C technology - the utilization of multicomponent sea floor seismology by combined use of shear and compressional waves - is a tool which provides direct measurements of subsurface rock properties. From 3D-4C OBC measurements, hydrocarbon prospects can be more accurately imaged and identified at a lower risk. Additionally, the 4C measurements may provide high-resolution maps of reservoir lithology, porosity, and distribution of pore fluid, all important information for optimum reservoir management.

In some cases 4C technology is a proven technique. The future impact of 4C technology will depend, inter alia, on improved cost-effectiveness, continuously-pursued fundamental and applied research, and our ability to master processing and interpretational aspects of dual-wave data.

Acknowledgments

We thank Den norske stats oljeselskap for permission to publish this paper. We would like to thank the Statfjord Field partners for allowing us to show the Statfjord data.

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IMAGING IN COMPLEX AREAS

- ❖ Gas chimneys, channels, etc.
- ❖ Sub-salt and sub-basalt (?)

LITHOLOGY AND FLUID PREDICTION

- ❖ Discriminate between sand and shale
- ❖ Map low-P-impedance-contrast reservoirs displaying high Vp/Vs-ratio-contrast[16] (shear modulus contrast)
- ❖ Quantify P-P bright spot anomalies
- ❖ Map saturation and reservoir properties away from well
- ❖ Determine fracture orientation (and density) from anisotropy variations

TIME-LAPSE RESERVOIR MONITORING

- ❖ Time-differencing P-impedance and Vp/Vs ratio

Table 1. Possible applications of 4C data.