Experiences with full-azimuth acquisition in ocean bottom seismic

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The problem of collecting seismic data is rather like attending a football match, as described in the textbook 'Introduction to petroleum seismology' (Ikelle and Amundsen, 2005). Your view of the game depends not only on the lighting system of the stadium but also on where you are sitting. For example, a journalist may prefer to be in the stands where he or she will have a good view of the entire game, which is necessary for analyzing and reporting all of the moves and tactics. A photographer, however, may prefer to be near the touchline where he or she can immortalize the goals, even at the expense of not seeing the rest of the game. The ticket prices for these special positions may be more than that of a standard seat; but the extra cost will pay off handsomely.

As in football matches, the view of the subsurface given by seismic data is determined by the location of the sound sources for 'illuminating' the area of interest, and the location and types of sensors that capture the ground motion caused by the passage of seismic waves.

Standard towed-streamer seismic surveys may be unsuitable for obtaining the very best reservoir images, especially in geologically complex areas. However, the recording of ocean bottom seismic (OBS) data – although more expensive – offers the distinct advantage of flexible acquisition geometries. Virtually any pattern of sound sources (shots) and receivers is possible with the aim of capturing the most revealing images. True 3D data acquisition is realized by using a stationary seabed sensing system combined with a survey vessel shooting over a predetermined grid on the sea surface. Every subsurface point on the target can thus be illuminated from all directions and a large number of angles during an OBS survey.

Introduction

During the summer of 2005 the EAGE and SEG organized a Summer Research Workshop, dedicated to multi-component seismic, held in Pau, France. During this workshop it was observed that the largest increase, from the previous Boise (2000) workshop, in 'proven' multi-component capability was in reservoir monitoring. Surprisingly, the driver behind the multi-component business was not shear

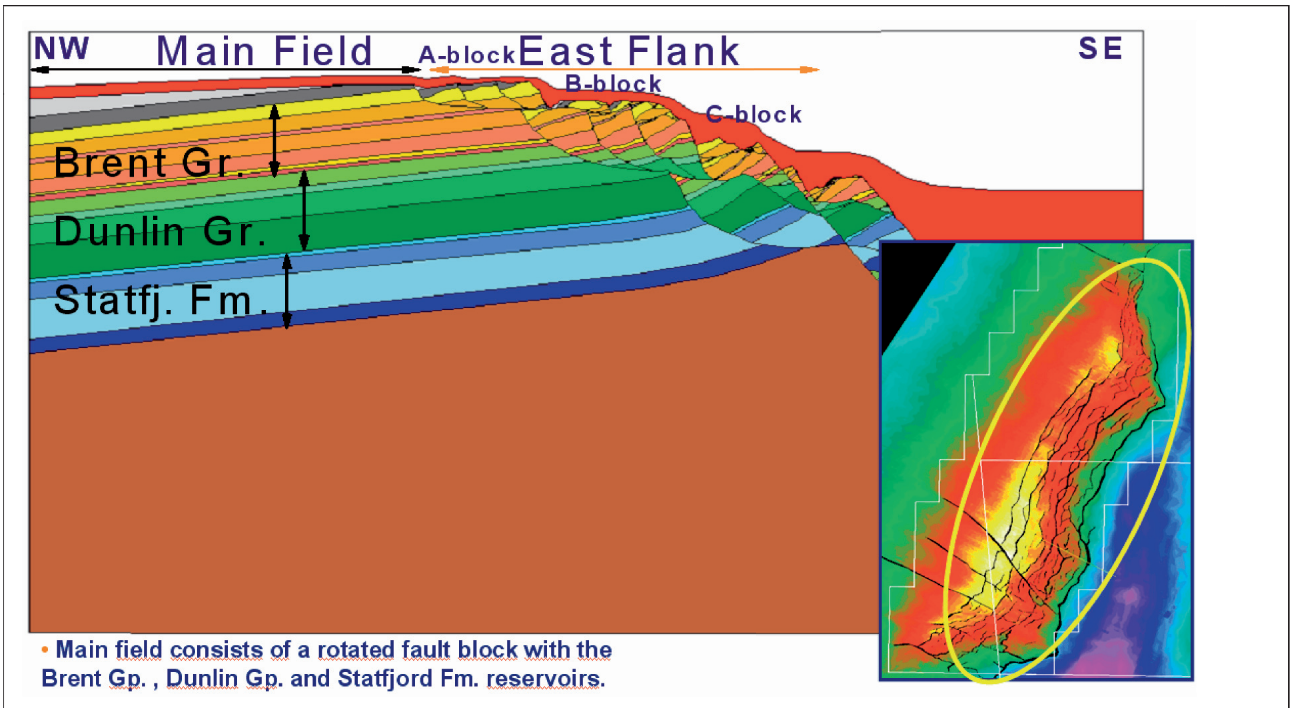

Figure 1 *Schematic cross-section of the Statfjord field.*

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Gullfaks, 1989, SUMIC	Gullfaks South 3D, 2002
Gullfaks, 1993, SUMIC	Statfjord 3D, 2002
Troll, 1993,	Statfjord Øst 3D, 2002
Tommeliten 2D, 1993	Volve 3D, 2002
Gullfaks 2D, 1995	Gullfaks 3D, 2003
Statfjord 3D, 1997	Visund 3D, 2003
Block 24/12 (PL 204) 2D, 1997	Tyrihans 2.5D, 2003
Sleipner Øst 2D, 1997	Heidrun 3D, 2003
Faeroes/Shetland Basin 2D, 1997	Exploration 2D, 2003
Huldra 2D, 1998	Kvitebjørn 3D, 2003
MN4C98-2, Møre Basin (Bl. 6303)	Vigdis/Borg 3D, 2004
MN4C98-3, Fles (Bl. 6605)	Snorre 3D, 2004
MN4C98-4, Helland Hansen (Bl. 6505)	Kvitebjørn 3D, 2004
MN4C98-5, Modgunn Arch (Bl. 6403)	Gullfaks 3D, 2005
Gullfaks South 3D, 2000	Valemon 3D, 2006
Gullfaks 3D, 2001	Snøhvit 2.5D, 2006

Table 1 *Overview of Statoil experience using ocean bottom seismic.*

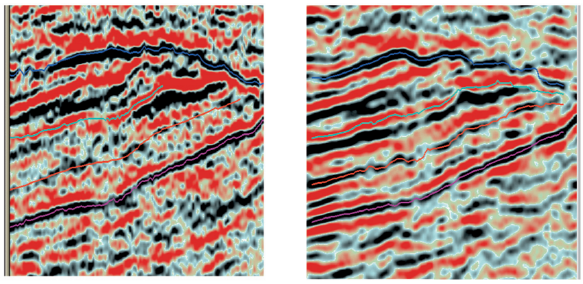


Figure 2 *3D OBS image of the Statfjord field showed improved definition relative to the conventional 3D marine seismic image.*

waves but better pressure wave data (Lynn and Spitz, 2006). Amongst the benefits cited was wider azimuth illumination, though this benefit has been recognized for some time in land seismic (Cordsen and Galbraith, 2002).

In the late 1980s, Statoil developed the SUMIC (SUbsea seisMIC) technique whereby both shear and compressional waves were recorded by sensors implanted in the seabed Berg et al. (1994). In 1992 a prototype SUMIC sensor array was developed and several extensive tests were carried out, with a full scale 2D acquisition carried out in 1993 over Statoil's Tommeliten structure in block 1/9 of the Norwegian sector of the North Sea. The principal objective of the 2D survey was to demonstrate the potential of the SUMIC technique to image subsurface structures through and below gas chimneys. During the 1997 planning of the world's first 3D-4C OBS survey over the Statoil-operated Statfjord oil field, straddling the border between the British and Norwegian sectors of the North Sea, the OBS advantages and technical benefits of high signal bandwidth, high spatial resolution, low noise, reduced weather dependence, versatile geometries, super-long offsets, super-wide aperture, and more, were investigated. With known geological target parameters, the Statfjord OBS survey could be designed to enhance the final seismic imaging. Several OBS acquisition geometries with swath and patch patterns with sufficient azimuth, fold, and offset distributions were considered. The preferred, most densely sampled, true 3D geometry, contained the other geometries as special cases. Through application of new operational techniques the preferred seismic contractor was able to offer a competitive cost for the most densely sampled survey configuration. The Statfjord survey, acquired late 1997, (Rognø et al., 1999), was thus ideal for evaluating seismic azimuthal imaging versus acquisition geometries for both pressure waves and converted shear waves.

Through extensive practical experience with the Statfjord survey, Statoil soon fully realized and took advantage of the full azimuth acquisition solution offered by 3D OBS. Since 1997, OBS surveys have been carried out over a large number of Statoil's geologically complex North Sea oil and gas fields, providing detailed, structural images of the disposition of fault-bounded compartments. The OBS datasets by the company to date are illustrated in Table 1. Approximately half of these are 3D OBS surveys designed to alleviate imaging problems associated with complex structures and difficult overburdens.

Through a discussion of geometric observations and a series of short case studies from the Norwegian Continental

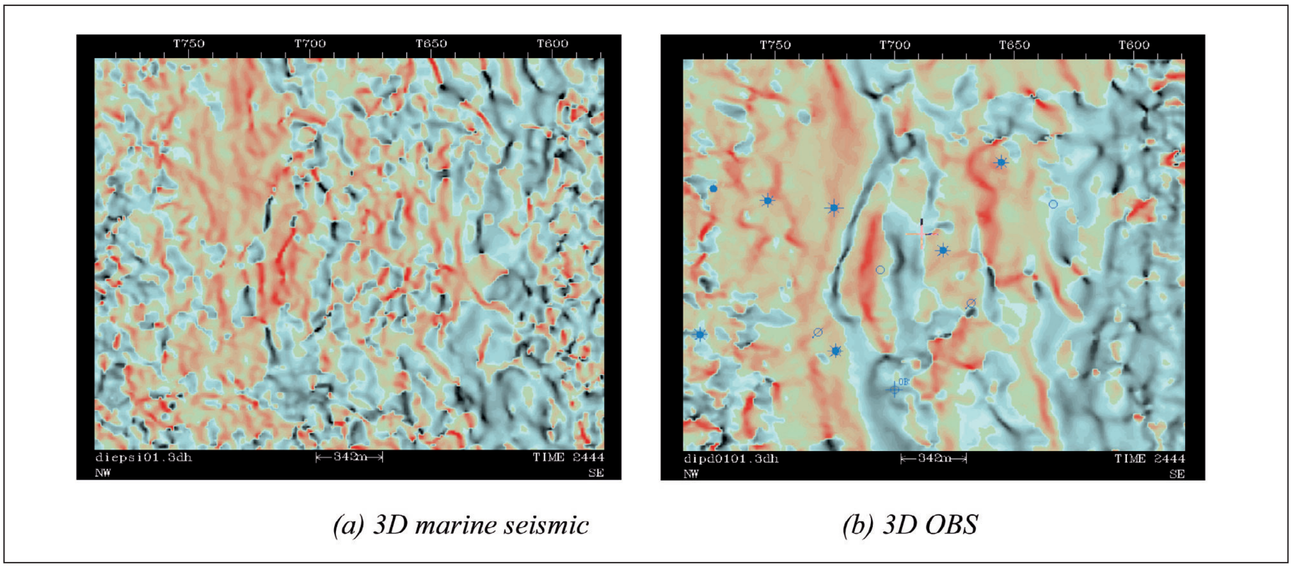


Figure 3 *(a) Dip volumes highlighting the differences between conventional 3D marine seismic and (b) 3D OBS.*

Shelf, some of the benefits of using ocean bottom seismic for P-wave imaging will be demonstrated.

Statfjord 1997

The Statfjord field lies in approximately 150 m water depth in blocks 33/9 and 33/12. The field straddles the border between the Norwegian and British continental shelf with approximately 86% of the field in Norwegian waters, and 14% in British waters. The field was discovered in 1974, sanctioned in 1976, and started production in 1979. The reservoir (Figure 1) units are sandstones located in the Brent group, and in the Cook and Statfjord formations. Structurally the field is dominated by a single rotated fault block dipping towards the west, with a more structurally complex area on the East Flank characterised by small rotated fault blocks and slump features.

The 3D OBS survey was acquired around the B platform, where the main objective of the survey was to improve the seismic imaging of the structurally complex East Flank. The quality of the conventional seismic images was affected by gas in the overburden and multiples in the lower reservoir zones. Once the 3D OBS survey was acquired and analyzed, it was possible to see that the definition of the Base Cretaceous unconformity and the Base Slope of Failure had improved over a large portion of the survey area (Figure 2). More accurate definition of faults and improved resolution of small scale structural elements were also achieved. The new interpretation resulted in more confident mapping of intact rotated fault blocks with better understanding of the areal extension and the internal stratigraphic dip within the East Flank area, (Osmundsen et al., 2002).

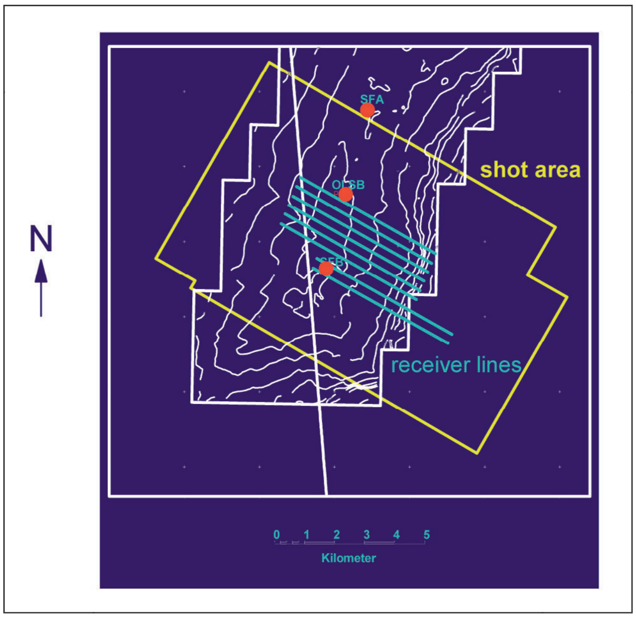


Figure 4 *Acquisition geometry for the original Statfjord 1997 3D OBS survey.*

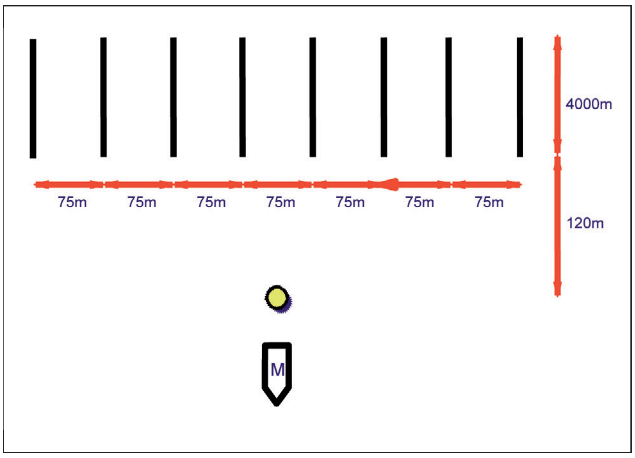


Figure 5 *Acquisition geometry for the 1997 3D marine streamer seismic.*

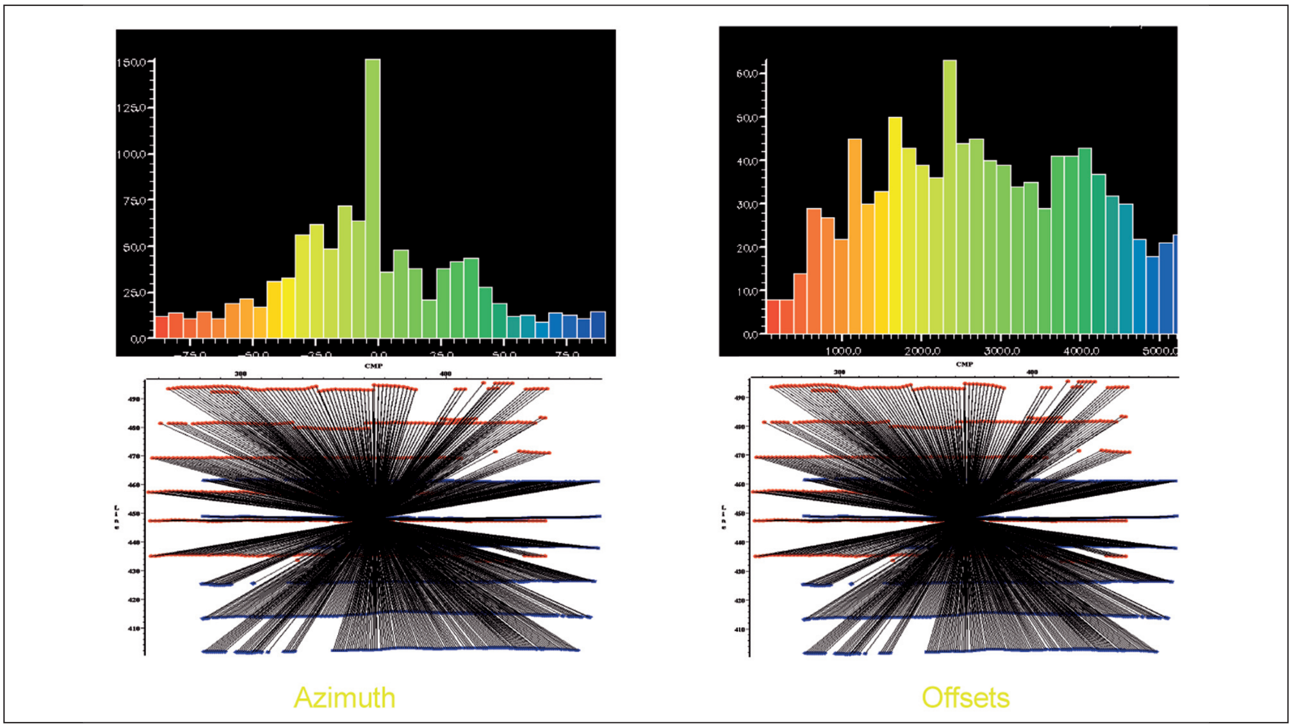


Figure 6 *Analysis of azimuth and offset distribution for the original Statfjord 3D OBS survey.*

It was through the original Statfjord 3D OBS that the imaging benefits of this acquisition were observed. The 3D OBS data were extensively used in the 2001 reinterpretation of the fault pattern in the Statfjord East Flank, resulting in interpretation of one new internal East Flank reflector, and modification of another East Flank reflector. Dip volumes (Figure 3), highlighting the differences between conventional streamer seismic and 3D OBS, were generated and later used systematically when interpreting fault planes simplifying the fault mapping phase.

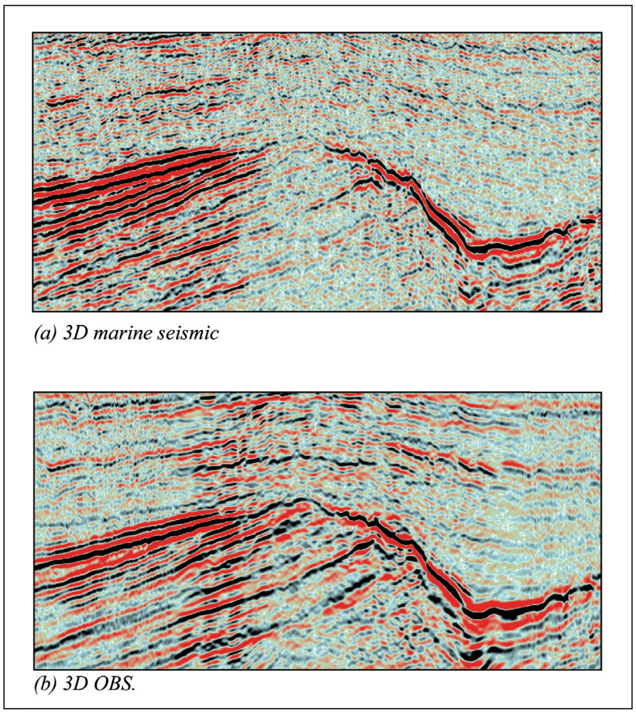


Figure 7 *(a) Comparison of 3D conventional marine seismic from 1997 and (b) 3D OBS from 2002 illustrating improved uplift of the Statfjord East flank structure.*

A part of the 3D OBS survey covered an area with two oil producers and one water injector. It was difficult to explain the production history of these wells with the existing interpretation in the area. The new interpretation, derived from the 3D OBS was more in line with the observed communication patterns identified from production data. A more reliable interpretation was considered essential when planning new wells in the eastern flank in the Statfjord B area.

Consideration of acquisition geometry

The original Statfjord 3D OBS survey (Figure 4) consisted of four swaths of data, with each swath containing two receiver lines, 5 km long, spaced 300 m apart. Inline receiver spacing was 25 m, whilst the source configuration consisted of dual arrays separated laterally by 50 m, with a 25 m (flip-flop) shot point interval. The maximum inline offset was 3000 m, and maximum cross-line offset 3000 m with the source lines separated by 100 m, and aligned parallel to the receiver lines. The survey was a dip survey, orientated 120-300°.

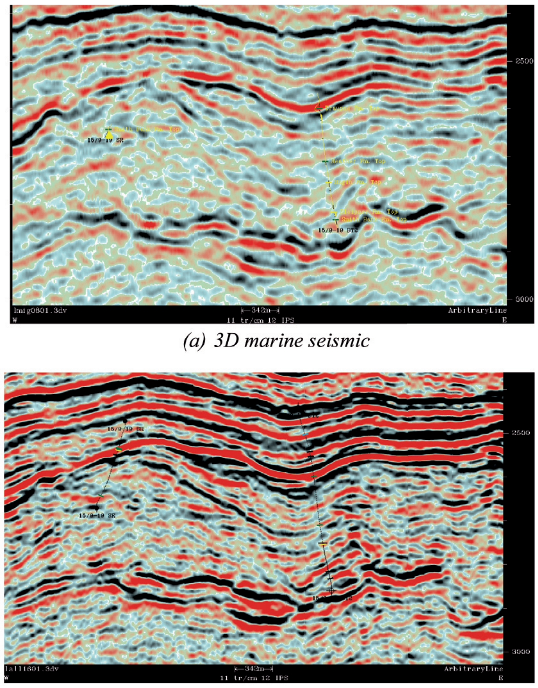
Earlier in 1997, prior to the 3D OBS survey, a conventional 3D marine survey was also acquired over the Statfjord field. In comparison to the 3D OBS, this survey geometry consisted of eight seismic streamers, each 4000m long, spaced 75 m apart (Figure 5). The source consisted of a single airgun array generating a shot point interval of 18.75 m. This 3D marine survey was considered, at the time, to be the prime survey for reservoir mapping purposes.

Analysis of the geometry from the 3D OBS survey (Thompson et al., 2002) soon highlighted the benefits from the full azimuth and rich offset distribution possible with this acquisition technique. A large range of offsets were observed, but more importantly, a full azimuth range covering 360° was evident (Figure 6).

Further studies into the importance of azimuth using advanced depth imaging techniques (Arntsen and Thompson, 2003), whereby both conventional 3D marine seismic and 3D OBS data were compared, again demonstrated the importance of azimuth. In this study, the 3D OBS data were manipulated in such a manner that they simulated the acquisition geometry found in a conventional 3D marine seismic survey. A series of intermediate geometries whose cross-line offset was greater than a 3D marine survey but less than a 3D OBS survey were also emulated. From this study it was observed that cross-line offset was a critical factor governing image quality.

Statfjord 2002

After the success of the 1997 3D OBS survey a larger 3D OBS survey was commissioned. This 3D OBS survey was approximately 120 km^2 in size and acquired in 2002 covering the rest of the east flank, and Statfjord East. As with the earlier pilot, a consistent uplift in image quality (Figure 7), compared to the earlier conventional 3D marine seismic, was achieved. Since the 2002 3D OBS survey, at least eight wells have been successfully drilled for which the 3D OBS was actively used for well planning.



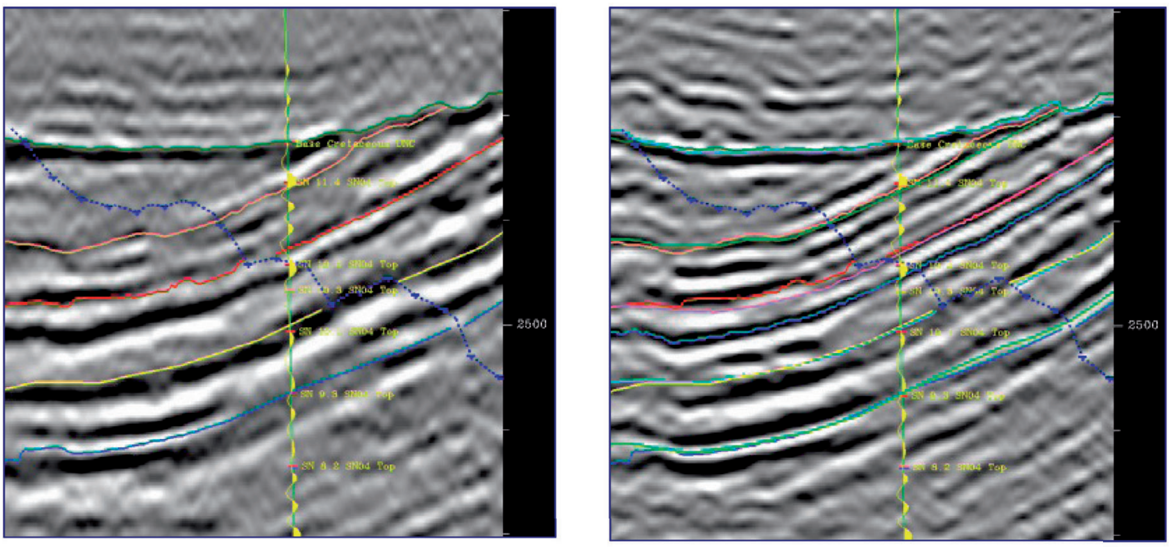
(a) 3D marine seismic

(b) 3D OBS

Figure 8 *(a) Comparison of 3D conventional marine seismic and (b) 3D OBS from 2002 illustrating improved uplift of the Volve structure.*

Volve 2002

Volve is situated in the Sleipner area approximately 8 km east of the Sleipner A platform. The reservoir is defined by a structural trap with four way closure in the Hugin



(a) 3D marine seismic

(b) 3D OBS

Figure 9 *(a) Comparison of 3D conventional marine seismic and (b) 3D OBS from 2004 illustrating improved image quality of the Snorre structure.*

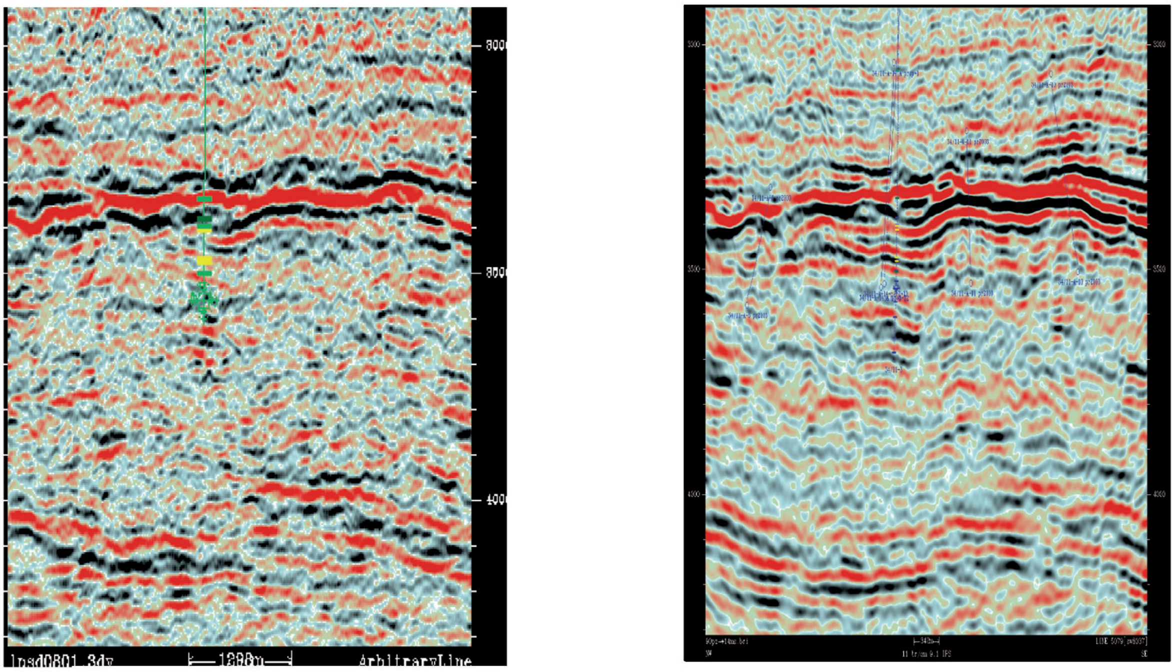


Figure 10 *(a) Comparison of 3D conventional marine seismic and (b) 3D OBS from 2002 illustrating improved uplift of the Kvitebjørn structure.*

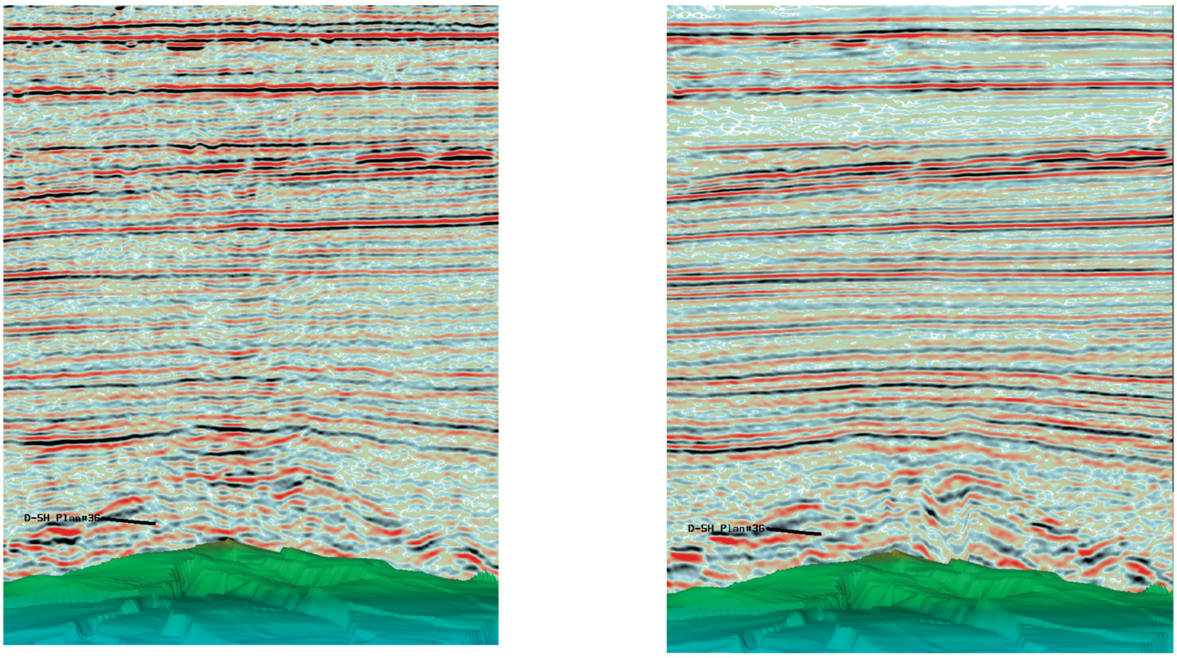


Figure 11 *(a) Comparison of 3D conventional marine seismic and (b) 3D OBS from 2003 illustrating improved uplift of the Heidrun structure.*

formation, which is middle Jurassic in age. The western part of the structure is strongly faulted with subsequent uncertainty in terms of communication across these faults. The field was originally discovered in 1993, with appraisal wells drilled in 1997 and 1998, but due to the geological complexity an agreed interpretation of top and base reservoir was not possible leading to large uncertainties in the calculated volumes. This then meant that production and development plans were uncertain. In 2002 a 3D OBS was acquired in order to solve some of these difficulties. This survey was acquired utilizing a parallel geometry covering approximately 27 km^2. The 3D OBS data was processed in time during 2002, and later reprocessed in depth during 2004.

Uplift in data quality (Figure 8) has led to increased confidence in interpretation, and reduced uncertainty in calculated volumes leading to the delivery of a plan for development and operation (PDO) in February 2005. The reserves for this field are estimated to be 12.4 million Sm^3 of oil, and 1.3 billion Sm^3 of gas. Production start-up is planned during the first half of 2007 using the world largest jack up platform, *Mærsk Inspirer*, with associated storage in a tanker for shipping to the Sleipner-A facility for processing and export.

Snorre 2004

Snorre is another field where 3D OBS has been used to improve imaging of the reservoir. This field is situated in 300-350m water depth in blocks 34/4 and 34/7. The field was discovered in 1979, and sanctioned in 1988, with production start-up in 1992. The field consists of a series of sandstone reservoirs in the Statfjord and Lunde formations, which were deposited in a fluvial regime, which range from Triassic to early Jurassic in age. The reservoir is characterized by a complex series of channels and internal flow barriers, dominated structurally by a series of large fault blocks.

In 2004 a 3D OBS survey, covering 21km^2, was acquired in an area to the south of the Snorre A platform with a main objective to improve the structural imaging of this part of the field. The previous 3D streamer survey from 1997 was prone to noise contamination and remnant multiple, such that event continuity was intermittent, and detailed fault mapping difficult (Figure 9).

The 3D OBS will be an important dataset regarding well planning in this area. The seismic data is now considerably more noise free, with significantly less remnant multiples. Vertical and lateral resolution is also improved leading to better event continuity and improved fault definition.

Kvitebjørn 2002

Kvitebjørn is a gas condensate field in block 34/11 where the water depth is approximately 190m. The field was discovered in 1994, and came into production in 2004. The reservoir consists of middle Jurassic sandstones in the Brent group at approximately 4000 m depth in a high pressure high temperature setting.

In 2002, a 3D OBS feasibility swath was acquired, which was later extended in 2004 such that the survey covered approximately 90 km^2. This was later extended in 2006 to include the Valemoen structure. Kvitebjørn is a complex structure, where conventional streamer seismic was associated with large uncertainties. The imaging uplift achieved from the 3D OBS (Figure 10) has since led to the 3D OBS being used as the base survey for a complete re-interpretation of the whole Kvitebjørn field. In combination with a re-evaluation of the petrophysical parameters and a revised depth conversion, the recoverable reserves were upgraded by 50% in relation to the estimation in the PDO. Further, based on the 3D OBS data, seven HPHT wells have been successfully drilled and completed within two years - without any well control incidents.

Heidrun 2003

Heidrun is situated on the Halten Bank outside mid Norway in 350 m water depth in blocks 6507/8 and 6707/7. The field was discovered in 1985 and started production in 1995. The reservoir consists of early to mid Jurassic sandstones in a strongly faulted structural setting, characterized by large uncertainties in the structural image. Additionally, ice berg scouring (Figure 11) on the sea floor generates diffraction multiples which obscure the reservoir section and are very difficult to remove. In 2003, a 3D OBS survey was commissioned in an attempt to alleviate these uncertainties. The 3D OBS appears, in some areas, to be more robust with respect to imaging through the overburden and dealing with the ice berg scouring. Though still difficult to interpret, the 3D OBS has in some areas de-risked the well planning process when incorporated with other data types such as sonic data in existing wells, and has actively been used in the planning of at least one well.

Conclusions

Through observation and analysis of different seismic datasets from the Norwegian Continental Shelf the offset and azimuth characteristics of 3D OBS have been demonstrated. The benefits of these characteristics have further been demonstrated by a series of short case studies where the uplift in seismic image quality was shown. Statoil has been aware of these benefits for several years and has consistently used 3D OBS to improve seismic images for the last decade in areas where conventional acquisition techniques failed.

Acknowledgments

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References

Arntsen B., Thompson M. [2003] The importance of wide azimuth in imaging, 65th EAGE Meeting, Stavanger, Expanded Abstracts, A40

Berg, E., Svenning, B., and Martin, J. [1994] SUMIC – A new strategic tool for exploration and reservoir mapping. *56th EAGE Meeting*, Expanded Abstracts, 477-480.

Cordsen A. and Galbraith M. [2002] Narrow- versus wide-azimuth land 3D surveys. *The Leading Edge*, 21, 764-700.

Ikelle L.T., and Amundsen L. [2005] Introduction to petroleum seismology, Investigations in *Geophysics*, 12, Society of Exploration Geophysicists.

Lynn H., and Spitz S. [2006] Report on the Summer 2005 EAGE-SEG workshop on multi-component seismic. *First Break*, **24**, 7-11.

Osmundsen I. K., Magerøy E., and Sørbel R. [2002] Multi-Azimuth PZ data, a step forward in fault definition on Statfjord. *FORCE Meeting*, Stavanger.

Rognø H., Kristiensen Å., and Amundsen L. [1999] The Statfjord 3-D, 4-C OBC Survey. *The Leading Edge*, **18**, 1301-1305.

Thompson M., Amundsen L., and Duffaut K. [2002] Acquisition geometry versus 4C image quality. A study of Statfjord, and Gullfaks Sør. *64th EAGE Meeting, Florence, Italy*, Expanded Abstracts, F025