Shooting over the seismic spread

Vetle Vinje[1*], Jan Erik Lie[2], Vidar Danielsen[2], Per Eivind Dhelie[2], Risto Siliqi[1], Carl-Inge Nilsen[1], Erik Hicks[1] and Anne Camerer[1] present a solution to allow the recording of both zero-offset data and dual azimuths in an effective and safe way.

Introduction

Conventional marine seismic surveys typically mobilize a single vessel towing two airgun source arrays in front of a spread of ten or more streamers. The data acquired in this way are narrow-azimuth and lack near offsets owing to the distance between the sources and the streamers which can be in the range of 100 to 200 m for the inner cables and up to 500 m for the outer cables. Several solutions, such as coil shooting (French, 1984; Ross, 2008) or advanced multi-vessel operations (Mandroux et al., 2013), have been proposed and deployed to improve azimuth coverage and fold. Although these are excellent solutions for achieving wide-azimuth data, they are generally expensive and/or time-consuming, and none of them record zero-offset data. Near- and zero-offset data are, however, especially critical for imaging shallow geological targets and of great benefit for multiple attenuation. In this paper, we present a tailored solution to this challenge that allows the recording of both zero-offset data and dual azimuths in an effective and safe way. We call this acquisition solution TopSeis. This solution was created in close co-operation between Lundin Norway and CGG and is designed to deliver excellent broadband (2.5-200 Hz) imaging of shallow to intermediate targets at depths of up to 3000 m or more.

Motivation and concept: Barents Sea imaging challenges

Motivated by the search to continuously improve seismic resolution on the Utsira High in the North Sea, Lundin Norway was active in the early adaptation of broadband seismic technology. Lundin Norway was the first company to acquire a commercial 3D GeoStreamer (Carlson et al., 2007) survey back in 2009 with PGS, and acquired the first 3D BroadSeis/BroadSource (Soubaras, 2010, 2011) survey in 2011 with CGG. In general, the know-how Lundin Norway has gained over the last decade of marine broadband acquisition and processing can be summarized as follows:

- Broadband acquisition and processing improves temporal resolution (Lie et al., 2016)
- Processing-based deghosting can work on all cable acquisition geometries (Dhelie et al., 2014)
- A deeper cable means less sea noise
- Slant cable profiles are better than flat due to increased notch diversity and are therefore more favourable for processing-based deghosting
- The drive for increased acquisition efficiency has given rise to wider spreads, but this has come at a price; the loss of near offset and poor cross-line shot sampling
- Dense crossline shot sampling is important for 3D seismic resolution within the shallow section as proven, for example, by high-resolution 3D (site) surveys e.g. P-cable acquisition (Ratnett et al., 2015)

As a result of the Alta, Gotha and Neiden discoveries (Figure 1), the Loppa High in the Barents Sea has become a new focus area for Lundin Norway. Here, the main reservoir rocks are karstified carbonates located at depths varying between 400 to 1600 m below the seabed.

The Permian carbonate rocks represent a high velocity increase relative to the overlying Triassic sediments (+1500 m/s). This velocity-depth setting of the Top Permian implies that the maximum offset at which the reflected energy from the prospective carbonate reservoir level is recorded on the streamers is only in the range of 800 to 2400 m, as shown in Figure 1. A conventional 3D seismic spread is therefore not a suitable layout to record the narrow cone of reflected energy returning from the reservoir in this velocity-depth setting.

The existing 'conventional' broadband seismic data in the area does not give the required resolution. In addition, seismic data from the Barents Sea suffer from severe multiple problems such as hard, fast-velocity Mesozoic sediments are exposed almost at the seafloor owing to late Tertiary tectonic uplift and erosion.

To properly address the seismic imaging issues characteristic of the Loppa High, in 2014 Lundin Norway and CGG started to work on an ideal acquisition geometry that would give a better sampling of the important near offsets, improve the cross-line sampling and provide notch diversity for robust processing-based deghosting.

The result was a split-spread, source-over-cable configuration, with a deep cable slanting upwards in both directions.

By moving the sources so that they are directly over deep-towed cables we achieve a much better and denser sampling of the reflected narrow cone of energy from our target. We record near- and zero-offset data which we believe are important to improve multiple prediction and subtraction. By spreading out the sources as far as possible we improve the cross-line shot sampling. By towing the cables in a deep banana-shaped

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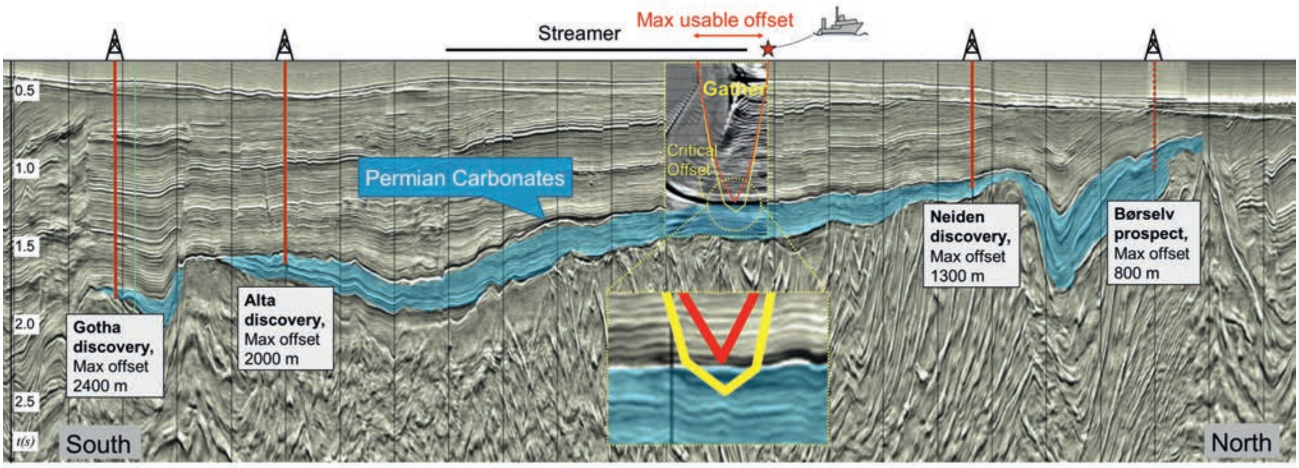

Figure 1 A 90 km regional profile over the Loppa High area in the Barents Sea showing discovery wells and prospects. These are located at shallow depths within high-velocity Permian carbonates where the reflections go overcritical at relatively small angles. This restricts the maximum usable offsets considerably.

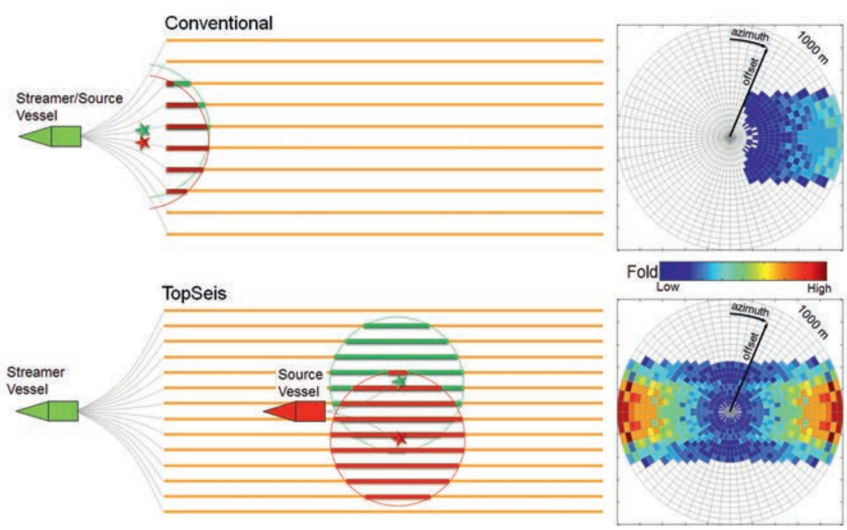

Figure 2 Conventional and TopSeis marine acquisition configurations with corresponding offset/azimuth rose plots with offsets up to 1000 m. The highlighted circles show near-offset data surrounding the airgun source arrays. TopSeis is displayed with two sources here, but three or more sources can be deployed for even larger trace density.

configuration we obtain notch diversity, enabling robust processing-based deghosting.

The problem was that this had never been tried before and required comprehensive evaluation. Over the last two years Lundin Norway and CGG have therefore jointly further developed, modelled and tested this concept.

Dual-vessel marine acquisition

The solution requires the deployment of a source vessel and a streamer vessel that operate in tandem, with the source vessel positioned on top of the seismic spread, as shown in Figure 2. Here the vessel/source/streamer configurations of conventional marine seismic (hereafter called 'Conventional' or 'Conventional Acquisition') are compared with the new dual-vessel, source-over-the-spread configuration.

The originality of the new configuration lies in the location of the sources above the streamer spread. Positioned in this way a few kilometres behind the streamer vessel, the source vessel deploys a number of source arrays with a wide horizontal separation. This configuration offers the advantages of achieving semi-wide-azimuth coverage, zero offsets, split-spread offsets and exceptionally high fold in a cost-effective way.

A key aspect of our solution is the wide separation between the sources. Figure 3 shows a plot of Common Mid-Point (CMP) coverage displayed in blue for a single offset class for TopSeis and conventional acquisition with straight shot lines, straight streamers and no feathering. The wide separation of sources ensures a more uniform shot spacing in the crossline direction (i.e. perpendicular to the sail lines) and hence a fuller coverage of CMPs for the near offsets.

Superior illumination density – especially for shallow targets

Another feature of the new solution, which can of course also be deployed in conventional acquisition, is small cable separation and dense shooting. In conventional acquisition, a typical streamer separation could be 75 m and the shot density 18.75 m from flip-to-flop. The difference with TopSeis, apart from the zero offsets and split-spread, is that we increase the trace density and fold by (i) reducing the streamer spacing, (ii) using a shorter shot distance from flip-to-flop and (iii) optionally deploying more than two sources. This creates exceptionally high subsurface illumination compared to conventional acquisition without hampering the efficiency of the acquisition. Higher illumination improves the signal-to-noise ratio (S/N) and is beneficial for most processing steps, including demultiple and velocity model building.

In the shallow part of the image, only the nearest offsets contribute to subsurface imaging owing to the image stretch caused by reflection angles approaching the critical angle α_c shown in Figure 4. The data is usually muted to include only angles smaller than α_c. This mute angle, α_{mute}, is usually between 30 and 40 degrees. The reflection angle depends on the (i) seismic velocities, (ii) source-receiver offset and (iii) depth to the reflector and is usually approximated by ray tracing in local 1D velocity models. In Figure 5 we use a very simple linear velocity model (Figure 5a) to compute the mute curve (Figure 5b) corresponding to a mute angle, α_{mute}, of 35 degrees. The mute curve in Figure 5b gives us the maximum usable offset for each depth level. The maximum offset gives us an illumination density (measured in number of traces per unit area) for a particular depth level for a given survey. In Figure 5-c we show the effective illumination ratio between TopSeis and two Conventional reference surveys, called Conventional and Conventional Hi-Res.

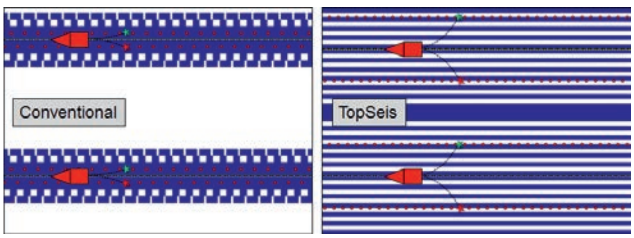

Figure 3 Conventional and TopSeis CMP coverage for a near-offset (~175 m) class. Source positions are shown as red circles. The large deflection of sources in TopSeis avoids the large gaps between the sail lines present in the conventional acquisition.

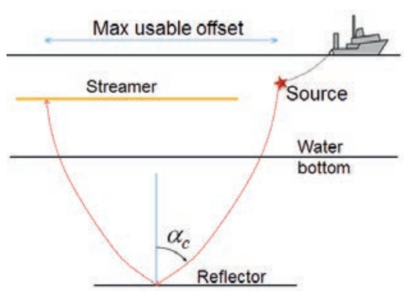

Figure 4 Only source-receiver offsets corresponding to sub-critical reflections can be used in imaging. α_c is the critical angle.

TopSeis and Conventional Hi-Res have identical (and dense) streamer spacing, shot-x spacing and sail line spacing. The Conventional survey has more normal parameters with 1.5 times larger streamer spacing and shot-x spacing. The illumination ratio of TopSeis versus Conventional Acquisition, as a function of depth, is illustrated in the red curve in Figure 5c. At a very shallow depth of 200 m, TopSeis effectively has 13.8 times more usable traces per unit area than conventional acquisition. This is mainly owing to the lack of near offsets in Conventional Acquisition. The illumination ratio decreases asymptotically towards 4.5 as the target depth increases. In the limit, the ratio approaches 2 x 1.5 x 1.5 = 4.5 asymptotically, partly because of the split-spread of TopSeis (a factor of 2), and partly owing to its denser source and streamer sampling (each a factor of 1.5).

It is of course possible to acquire a conventional acquisition using the same cable spacing and shot spacing as TopSeis. In Figure 5c, the blue curve shows the illumination ratio in the case where the source and streamer sampling parameters of Conventional Hi-Res are equal to those of TopSeis. Also in this case, the trace density is higher in the shallow owing to the missing near offsets in conventional acquisition and the illumination ratio approaches 2 for larger depths owing to the split-spread of TopSeis.

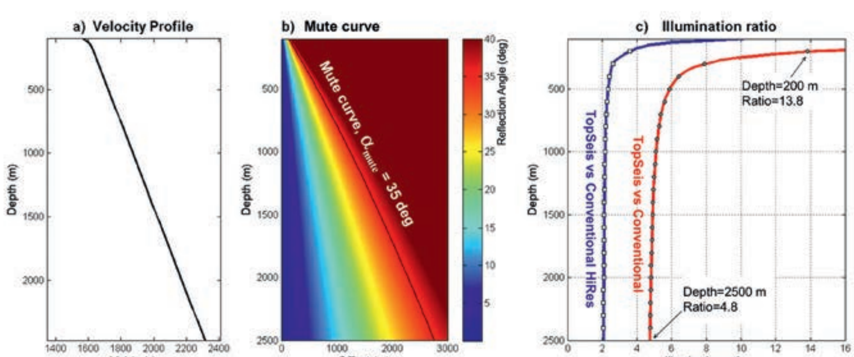

Figure 5 Two TopSeis/Conventional illumination ratios (in 5c) as a function of subsurface depth for the simple velocity profile (Figure 5a). The reflection angles and mute curve are presented in Figure 5b. The acquisition parameters are described in the text.

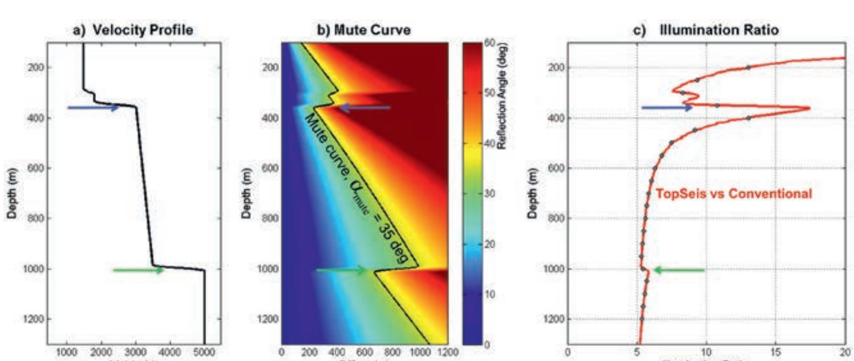

Figure 6 The very shallow part of a Barents Sea velocity profile a), corresponding mute curves corresponding to a 35-degree mute angle b) and the corresponding TopSeis/Conventional illumination ratio c).

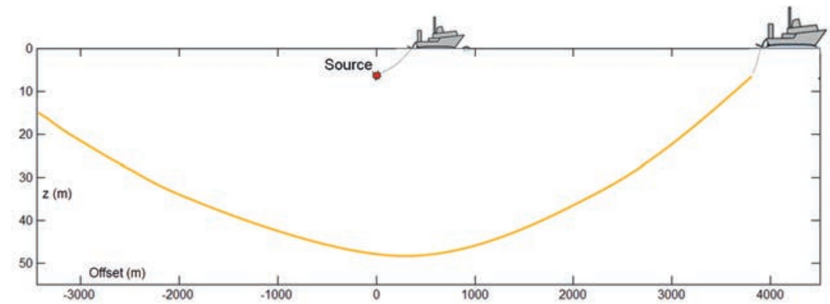

Figure 7 Example of a TopSeis streamer profile.

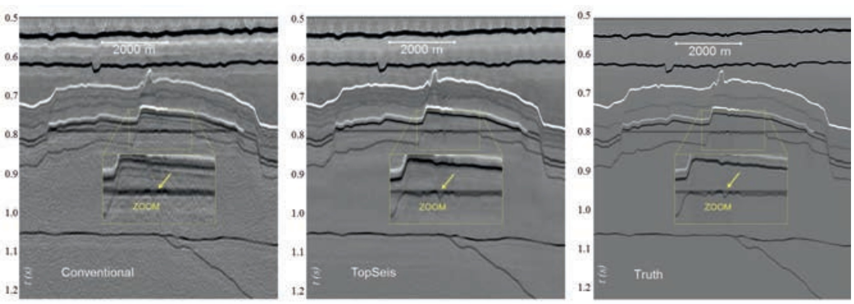

Figure 8 A crossline comparison through the synthetic 3D PSTM images from Conventional (left) and TopSeis (middle) acquisition showing a significant improvement in resolution and better S/N with TopSeis. The true reflectivity is shown on the right.

As mentioned above, the illumination ratio depends on velocity. Figure 6a shows a simplified Barents Sea velocity profile from the Loppa High area and the corresponding mute curve (Figure 6b) for α_{mute} = 35 degrees. The illumination ratio is shown in Figure 6c for TopSeis versus conventional. We observe that there is a greater variation in illumination ratio with depth than for the simple velocity model in Figure 5. The velocity model in Figure 6a has two distinct velocity kicks; one is located 50 m beneath the water bottom (blue arrow in Figure 6), and a deeper one at 1000 m (green arrow). Owing to the strong ray bending associated with these velocity kicks, the mute curve bends towards smaller offsets, and the TopSeis/conventional illumination ratio increases significantly. This shows that TopSeis will be especially beneficial beneath the shallow velocity kicks found, for example, in the shallow carbonates in the Barents Sea.

The maximum offset of TopSeis depends on the length of the streamers and the location of the sources relative to the streamers. It is possible to tune the system for longer maximum offsets, and thus for deeper targets, by placing the sources closer to one end of the streamers. Alternatively, longer streamers can be deployed to achieve larger offsets suitable for deeper targets.

Deep streamers under the sources

For practical reasons, the solution would obviously not be possible with streamers towed at conventional depths of 7 to 10 m, nor would it be safe with a 20-30 m streamer depth as is commonly used for multi-sensor streamer systems (Carlson et al., 2007). To achieve a safe (vertical) distance between the sources and the streamers we need to operate at streamer depths of 40-50 m as shown in Figure 7. CGG has several years' experience of deploying deep streamers with the BroadSeis broadband solution (Soubaras, 2010, 2011) and there is a wealth of processing tools and knowledge available to process such data (e.g., Wang et al., 2013). In addition, the basic principles, such as how to design the shape of the streamer to optimize the deghosting, are well known (Soubaras, 2013).

In addition to the zero offsets and the semi-wide-azimuth split-spread of the solution, another advantage is that the zero-offset part of the streamer is deep, and at a far distance from the noisy sea surface. It is also at a far distance from the beginning of the streamer where there is tug and flow noise. This leads to a good S/N for TopSeis data, especially on the low-frequency side.

Modelling studies

In order to (i) verify that processing and imaging of the solution's data was feasible, (ii) try out various configurations and (iii) quantify the uplift versus conventional acquisition we ran a comprehensive 3D seismic modelling programme. Synthetic seismic data from a series of acquisition designs with real noise added were fed into several 3D seismic processing and imaging workflows.

In Figure 8, the final result from optimum processing of conventional marine versus TopSeis is presented. A synthetic angle-dependent 3D reflectivity model (Figure 8, right) was built based on Barents Sea geology. An oil-water contact (OWC) was inserted. Broadband (2-190 Hz) seismic modelling was done by diffraction modelling and real ambient noise and the direct wave from the source were added.

A conventional source was used in the conventional, while a dual-level broadband source, BroadSource (Siliqi et al. 2013), was used in the solution. S/N and resolution are clearly better with TopSeis, e.g. in the zoomed OWC area indicated by the yellow arrow.

Field tests and 2D benchmark test

During the second half of 2015 several field tests were carried out to validate the key aspects of the solution: safety and HSE, navigation, equipment durability, and data processing and imaging. In March 2016, a single test line was acquired offshore Gabon with a TopSeis configuration and compared with a conventional acquisition using a BroadSeis configuration. In Figure 9, a comparison of a central shot gather (from a central streamer) from

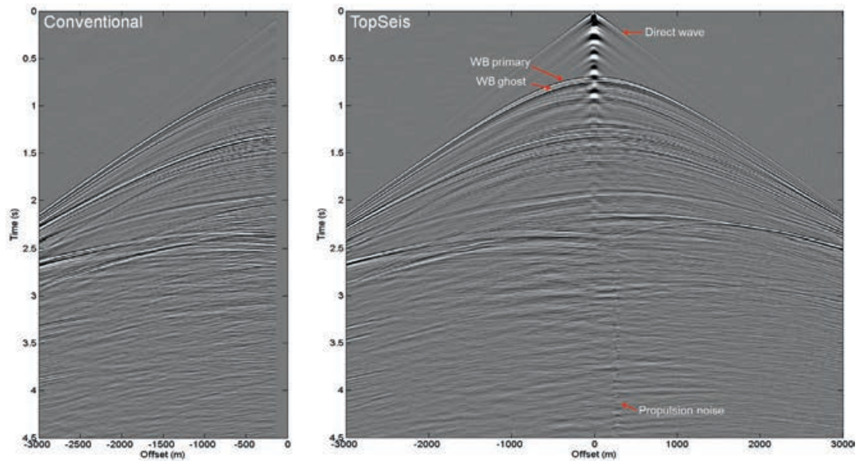

Figure 9 Conventional and TopSeis shot gathers from the same location plotted on the same scale. The plot illustrates the split-spread nature of TopSeis, the zero offsets and its abundance of traces.

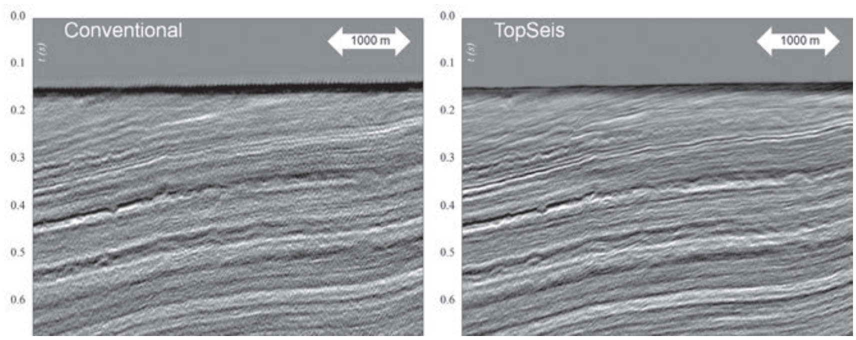

Figure 10 Shallow zoom in the Gabon model showing the improvement with our solution owing to the high illumination.

both the conventional (left) and TopSeis (right) acquisition from this Gabon test is shown.

The conventional shot gather contains offsets from 150 to 3000 m, while the split-spread TopSeis shot gather contains offsets between -3000 m to 3000 m. On the TopSeis gather we can see the direct wave, the water bottom primary reflection, its ghost and the propulsion noise from the source vessel. The latter noise is random and stacks out in the processing. The direct wave and the receiver ghost, however, require specialized processing. The most striking difference between these gathers, however, is the presence of zero offsets and negative offsets with TopSeis which will be an advantage in several processing steps, including demultiple and imaging.

Figure 10 shows zooms of migrated (prestack time migration) data from the shallow part of the model. We observe improved S/N and resolution with the solution. This 2D field test demonstrates the benefits of shooting over the spread, but does not explore the benefit of the regular distribution of source lines with the solution. For this, a proper 3D test was conducted.

3D North Sea field test

In June 2016, the first 3D test using the system was conducted over the Frigg-Gamma structure in the central Northern North Sea using seismic vessels acquiring data for CGG's Multi-Client and New Ventures group. A small, rectangular full-fold area of 15 x 3 km extending south-to-north was selected, as shown in Figure 11.

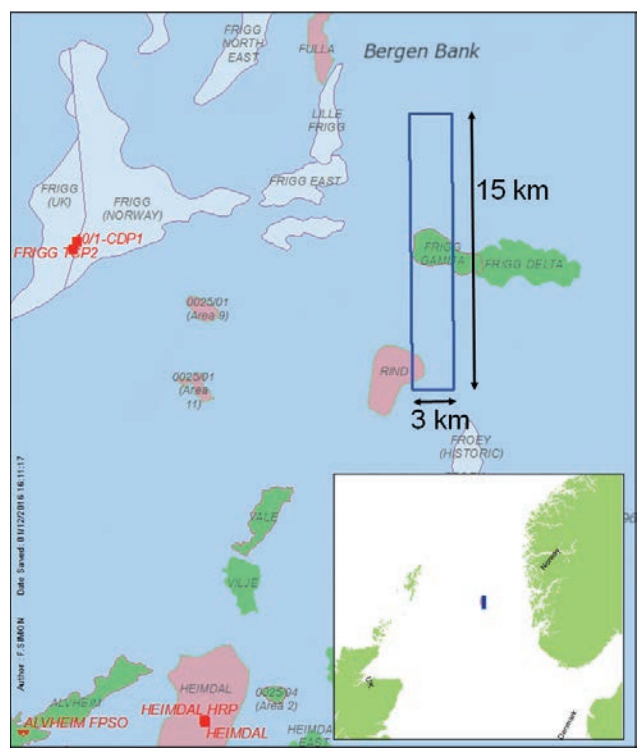

Figure 11 TopSeis 15 x 3 km 3D test area over Frigg-Gamma in the North Sea.

Frigg-Gamma is part of the Frigg field which includes five gas fields which are now shut down. The water depth in the area is just over 100 m. As described by Rykkelid (2014), hydrocarbons at a relatively shallow depth of ~2000 ms in the Frigg sands have leaked up through the apex of the Frigg structure (called Frigg Gamma), creating poor data quality all the way up to the sea floor. Both OBC and conventional marine seismic surveys have previously been tried with limited success.

In July 2016, one month after the TopSeis acquisition, a new data set was acquired over the same area with state-of-the-art

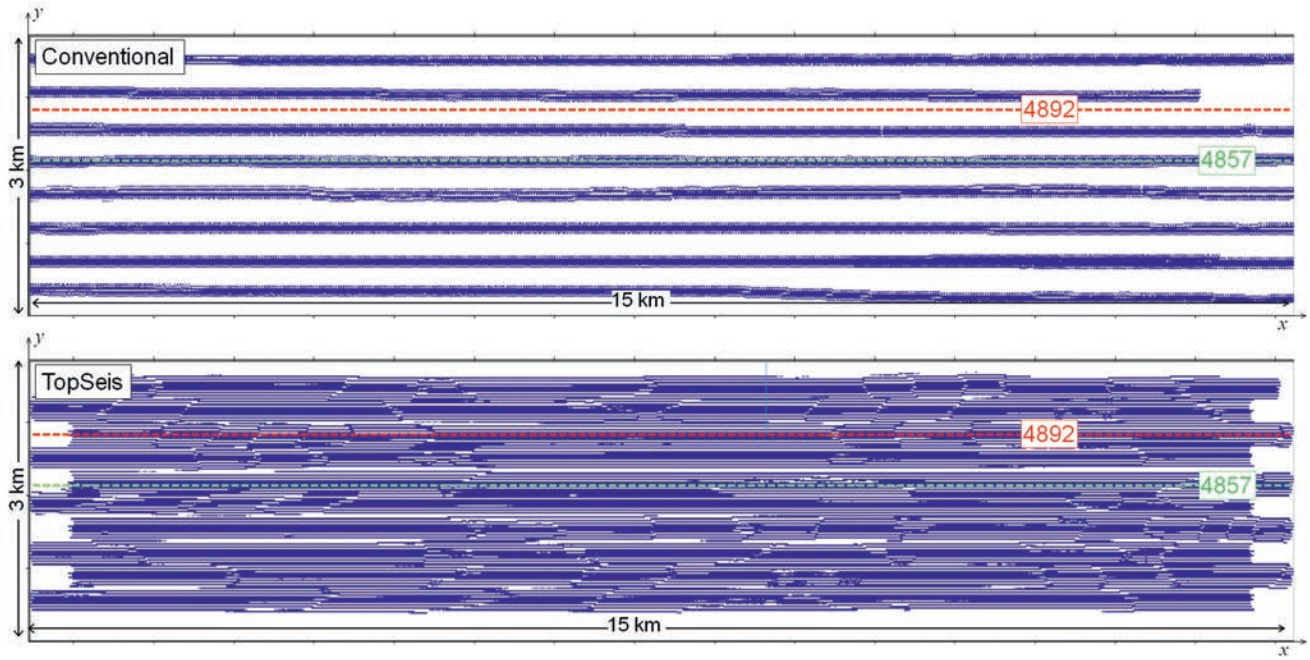

Figure 12 Comparison of CMP coverage for the same near-offset class showing more complete coverage using TopSeis. The green and red dotted lines in the conventional indicate respectively the 'good' Inlines and 'bad' Inlines shown in the figures below.

BroadSeis acquisition as part of CGG's multi-client programme. We refer to this as the 'Conventional' solution.

The streamer separation of 75 m used for TopSeis was the same as used in the conventional multi-client acquisition, but the rest of the parameters were denser, including the flip-to-flop shot increment of 12.5 m. Figure 12 shows the CMP coverage for the conventional and TopSeis for the offset class with central offset ~175 m. Offsets in this low range do not exist in most of the area for the conventional where large gaps are present in-between the sail lines. The shallow seismic imaging will suffer here. Inline 4892, as indicated in Figure 12, is located in such a gap while Inline 4857 is located in a more favourable location coinciding with one of the conventional sail lines.

The two data sets (TopSeis and conventional) were fast-track processed through a similar workflow, including basic denoising, source designature, receiver deghosting, demultiple (SRME, MWD and Radon), regularization/binning and pre-stack time migration in a simple isotropic velocity model. Both were processed at 2 ms sampling.

As for the Gabon 2D field test described above, specific processing solutions had to be developed and implemented to attenuate the direct wave, receiver deghosting and demultiple in TopSeis.

Figure 13 presents a comparison of the full stack images of the very shallow subsurface with conventional and TopSeis on a 'good' Inline 4857 (see Figure 12) located along a conventional sail line, while Figure 14 shows the comparison along the 'bad' Inline 4892 located in-between the conventional shot lines.

In this shallow part of the geology there is a complex, interleaved pattern of post-glacial Neogene channels and basins, several gas pockets (soft, white tops and hard bases) and pockmarks along the water bottom. The lack of near offsets and poor fold with conventional makes detailed mapping of

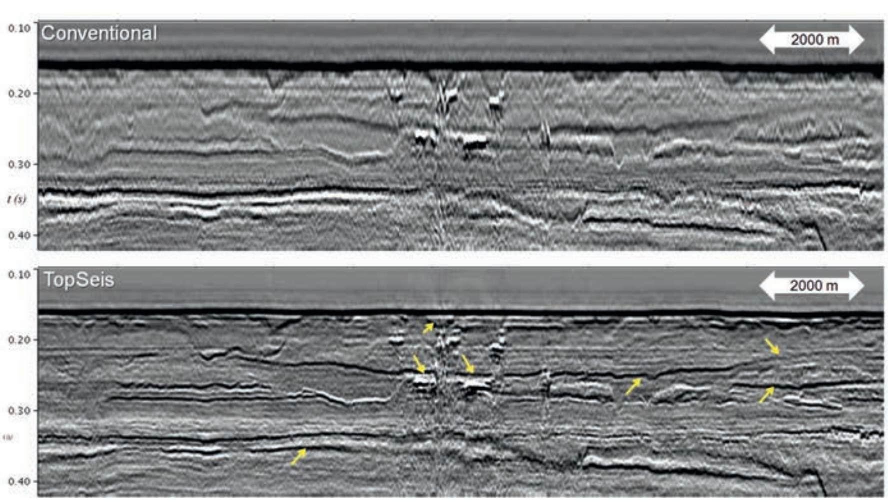

Figure 13 Zoom in the upper 400 ms of Inline 4857 (see Figure 12). Both images are rich in visible shallow structures, but TopSeis brings out more details.

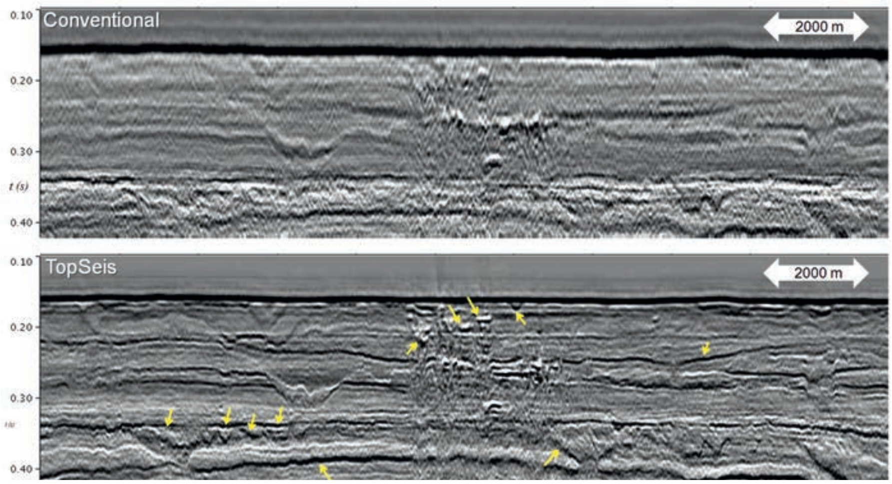

Figure 14 Zoom in the upper 400 ms of Inline 4892 (see Figure 12) which is located in-between sail lines in the conventional. The conventional stack is particularly affected by the lack of near offsets and loses a lot of details.

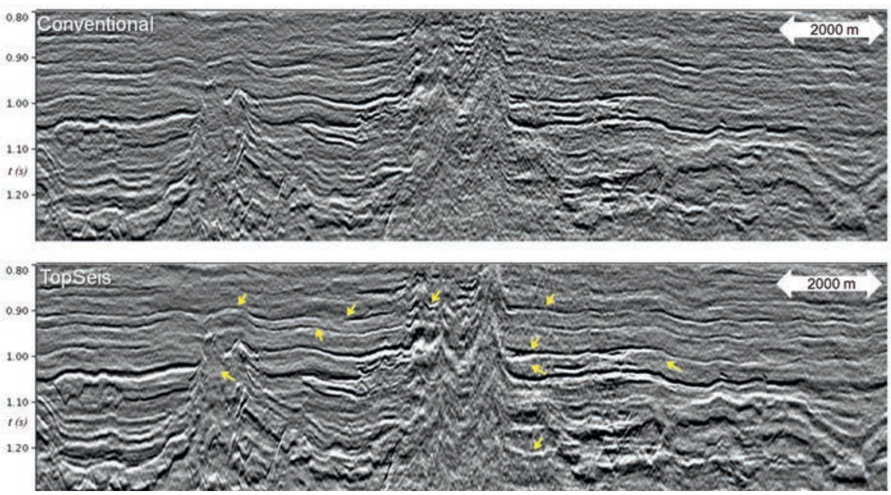

Figure 15 A slightly deeper stack of Inline 4892 comparing Conventional and TopSeis showing an improvement in S/N, resolution and imaging with TopSeis.

these structures very difficult, while our solution brings them out as indicated by the yellow arrows. The abundance of traces with zero and near offsets with the solution creates less NMO stretch than conventional which lacks these offsets. The stretch is clearly visible on the conventional water bottom, but also visible in the shallow channels just beneath.

Figure 15 shows a slightly deeper part of Inline 4892 down to around 1.3 s. At this depth level, the images are more similar than in the very shallow, but, owing to the higher fold (around 3x), both the imaging and the S/N are clearly improved, as indicated by the arrows.

Conclusions

TopSeis is a novel marine acquisition and imaging solution where the seismic sources are deployed over the streamer spread with dense cable and source spacing, resulting in improved illumination compared to conventional systems, especially in the shallow section. This is a significant benefit for both the processing and imaging of the data. Field tests and a comprehensive modelling programme have verified that the solution is superior to conventional marine streamer acquisition with respect to the S/N of the data, resolution, and AVO, especially in the shallow part of the subsurface. Imaging of deeper targets, down to roughly half the cable length, will also benefit from the superior illumination of the solution. During the summer of 2017 a full-scale 1800 km^2 survey will be acquired with this concept for Lundin Norway over the Loppa High in the Barents Sea.

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