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New technology breathes life into mature basins

Successful 3D seismic work, clarifying the geology of the South Utsira High area of the Norwegian North Sea, and delineating the Johan Sverdrup reservoir, shows how new technology can generate finds in mature basins.

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The South Utsira High became a major oil province 45 years after the award of the area's first license in 1965. Since 2004, Lundin Norway has established a major acreage position here, with a number of new discoveries being made, including Apollo, Edvard Grieg and Johan Sverdrup, showing that there may still be major finds to be made in the North Sea.

A small, 3D seismic survey was acquired on the Utsira (or Haugaland) High in 2011, as a pilot research collaboration between CGG and Lundin Norway, to test CGG's newly-developed, synchronized multi-level broadband source. The success of this project, in reliably acquiring full-bandwidth data with over six octaves of ghost-free signal, delivering high-resolution shallow data, at the same time as clear imaging of the low-frequency deep data, led to the extension of the original survey to cover the majority of the South Utsira High.

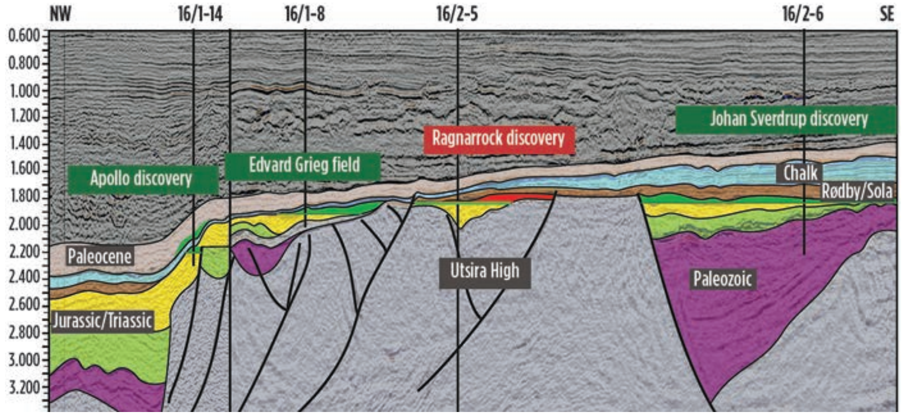
The data were acquired over Johan Sverdrup field, one of the largest oil discoveries ever made on the Norwegian Continental Shelf. The field extends over an area of approximately 200 km^2 on the Utsira High, in the central part of the North Sea, lying about 140 km west of Stavanger, Fig. 1. The field is estimated to hold 1.8-2.9 Bbbl of oil, and production is expected to commence in 2019. Peak production is estimated to be over 500,000 bopd, which will make it, by far, the largest producing oil field in the North Sea by that time.

The purpose of the 3D survey discussed in this article was to clarify the geology of the South Utsira High, and to delineate the Johan Sverdrup reservoir. Below the reservoir, there is a faulted, fractured granitic basement, with pockets of porous weathered granite, Fig. 2. Clear imaging of this basement may explain the hydrocarbon migration pathways and, perhaps, indicate other potential reservoirs. The area presents considerable challenges to seismic imaging, as high frequencies are required to resolve the shallow near-surface features, while low frequencies are required to image the deeply-rooted faults in the granitic basement.

The initial scope of the survey was to acquire a 44-km 2D line over Luno, and a small, 500-km^2 3D survey over Avaldsnes, using the broadband source (BroadSource) combined with variable-depth streamers (BroadSeis). This 2D line location has been used by Lundin Norway to test and compare recently developed acquisition techniques by all the major contractors. A variable-depth streamer line had been acquired by CGG's

Fig. 1. The survey data were acquired over Johan Sverdrup field on the NCS.

Fig. 2. Discoveries on the South Utsira High. Image courtesy of Lundin Norway.



Bergen Surveyor, using a conventional source, six months earlier. Shortly after completion of the pilot survey, when the initial results had been reviewed, the original 3D survey was extended to 2,750 km^2, with the inclusion of a number of other partners.

Historically, the bandwidth of seismic data has been limited by the source and receiver ghost notches, gaps in the amplitude spectrum caused by destructive interference between the primary energy wavefronts and the "ghost" energy reflected downwards from the sea surface. These ghost reflections are generated at both the source and receiver side, and the frequency of the ghost notches depends on the depth below the sea surface of the source and receivers, given by:

frequency of receiver or source ghost notch = water velocity / 2 x streamer or source depth

In recent years, various techniques have been developed to remove these ghost notches from the data to deliver broadband seismic. CGG's synchronized, multi-level broadband source uses air guns at different levels to defocus the source ghost, so that it can be removed by de-signature. The firing of the guns is synchronized, so that the deeper gun fires as the down-going energy from the shallower gun reaches it, creating a consolidated, focused down-going wavefront. The up-going energy is unsynchronized and, therefore, delivers unfocused ghost wavefronts, enabling attenuation of the ghosts.[1]

In a similar manner, the use of variable-depth streamers delivers diversity of the receiver ghost notch frequencies, so that the receiver ghost can be attenuated, enabling the majority of the streamer to be towed deep, typically down to 50 m, thereby delivering considerable improvements to signal-to-noise ratios at low frequencies.[2]

The technique capitalizes on the exceptional low-noise characteristics of truly solid, foam-filled streamers being towed exceptionally deep, to acquire high-quality signal, down to 2.5 Hz.[3] Towing at an average depth of 40 m provides an 11 dB increase in response at 5 Hz, compared to towing at 10 m, due to steepening of the zero-Hz ghost notch with depth. This increase is in addition to the improvement in signal-to-noise ratio achieved by towing at depth, avoiding the sea-state noise, and the fact that solid streamers are proven to be 10 to 15 dB quieter than gel streamers below 10 Hz in vibration tank tests.

Combining the BroadSeis and BroadSource techniques enables the attenuation of both the source and receiver ghosts, to deliver truly broadband, ghost-free data with over 6 octaves of bandwidth, from 2.5 Hz to the sample interval Nyquist. At the time this survey was acquired, the use of variable-depth streamers was well-established, but the synchronized multi-level broadband source was newly developed and not yet commercially proven. This was the first full 3D survey to be acquired using the broadband source, although, since its success, several thousand square kilometers of data have been acquired using this technique. A synchronized, multi-level source is a compact solution for acquiring broadband data with variable-depth steamers. It can be deployed in the flip-flop mode necessary for 3D broadband surveys, and it has all the benefits of a standard marine source, in terms of robustness, directivity and repeatability.

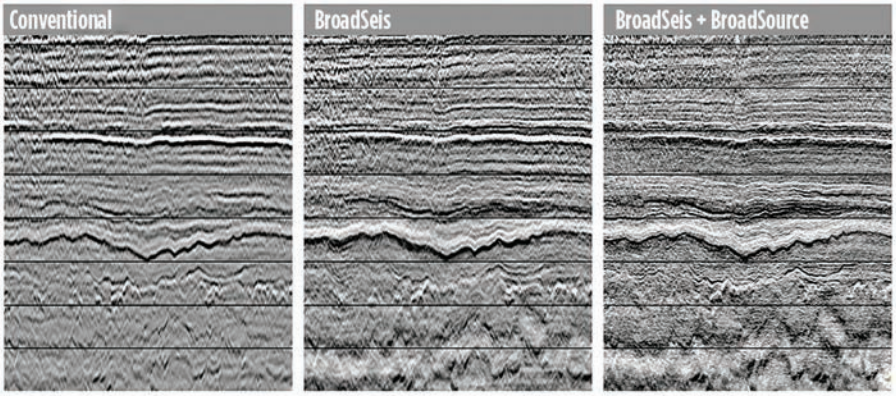
The pilot data were acquired in November 2011, by the *Oceanic Sirius,* a newly-built, purpose-designed seismic vessel on its maiden voyage, using ten 6-km streamers, in BroadSeis configuration, separated by 75 m. All the data were acquired in the winter season of the North Sea, which led to significant challenges, due to poor weather. Although the extreme depth at which the majority of the streamers are deployed in BroadSeis mode reduces the effect of sea-state noise, providing a wider weather window for acquisition, there were still occasions when the weather forced acquisition to be suspended.

The poor weather conditions and high seas restricted the amount of data that could be acquired for the pilot to only 307 km^2 of the planned 500 km^2. The broadband source was more robust and performed better than anticipated. Although the *Oceanic Sirius* was a new vessel with a new crew, deploying experimental technology, the only significant challenges encountered were due to winter weather. The poor weather conditions prevented the acquisition of the outer sail-lines of the pilot swath, including those originally intended for use in deriving the far-field hydrophone signature from the water bottom reflection. Therefore, data from a different 2D line, recorded previously with the same source and receiver configuration, were used instead.

The multi-level broadband source defocuses the ghosts, so that the absence of deep notches in the amplitude spectrum enables de-signature of the seismic across the full bandwidth. This de-signature re-

Fig. 3. Comparison of seismic with synthetic traces created from the well data for initial and reprocessed data.

Fig. 4. Comparison of conventional, variable-depth streamer, and broadband sources with variable-depth streamer on 2D data. Image courtesy of Lundin Norway.



quires the use of a far-field signature. While the accuracy of pressure field modeling is sufficient for source array design, it is not precise enough at low frequencies for building accurate source de-signature operators. These can be extracted more accurately from the recorded water bottom reflection.

More recently, a technique for designing source de-signature operators, using far-field signatures derived from recorded near-field hydrophone measurements, has been implemented.[4,5,6] This direct measurement approach delivers a more accurate estimation of the bubble effect and low frequencies in general, which are fundamental for broadband acquisition, and does not depend on the extraction from a water-bottom reflection. The technique allows accurate de-signature throughout the entire bandwidth, encompassing residual deghosting, de-bubbling and zero-phasing in the same step. A toolbox of different deghosting algorithms is now available for receiver deghosting, including full 3D solutions or 2D deghosting (ghost wavefield elimination, GWE) that is applied to the data pre-imaging.[7,8,9] In the reprocessing discussed here, Wang's pre-imaging bootstrap technique was applied.

The Utsira High area is notoriously challenging for seismic imaging and interpretation, being contaminated by noise and multiples, as well as requiring complicated velocity modelling. To make use of improvements in deghosting and de-multiple technology, the data were reprocessed in 2013, and the opportunity was taken to improve the low frequencies by better QC. With the help of CGG's seismic reservoir characterization group, synthetic traces were created from the well data, then filtered and compared to the seismic. This showed a good correlation between the seismic and synthetic, demonstrating that the de-multiple and de-bubbling had been improved during the second processing, Fig. 3.

Recording an extended bandwidth delivers more signal at high and low frequencies, but it can also increase the recorded noise. The increased low-frequency range means that noise that is low-cut filtered in conventional data may become a significant problem. As these data were also recorded in poor weather conditions, particular attention was paid to noise attenuation. However, careful processing through standard techniques (linear Radon filtering and projection filtering in the FX domain) was able to attenuate this successfully.

As with the noise, the broader frequency range of the primaries also produced a broader frequency range of multiples, in particular high-frequency multiples. These were attenuated, using a combination of techniques, each targeting specific multiple groups. SWD (shallow water de-multiple) was used to target the shallow water-layer reverberations, convolutional 3D SRME (surface-related multiple estimation) and inter-bed de-multiple tackled the deeper surface-related multiples, while other residual multiples were attenuated by conventional radon de-multiple.

For the migration velocity modeling, 10 horizons were picked by the client's interpreters on the initial fast-track, post-stack Kirchhoff migration. The migration velocity model updating was carried out in three iterations, the first two using non-linear tomographic inversions of observed RMO (residual move-out) and the final iteration using CBM (controlled beam migration) stack-sweep scans picked by the client during an interactive session. Sixty-four well logs were used to constrain the model, and to aid in the choice of the eight velocity layers used in the final migration.

Both Kirchhoff and Beam pre-SDM volumes were produced. The beam migration was used to image the dipping faults in the basement, which are of low frequency, due to their steep dip, and so benefitted from the extra-low frequencies provided by BroadSeis. The entire dataset benefits from the broad bandwidths and ghost-free wavelets without side-lobes. These provide better resolution in the near-surface, and even deeper in the section, where the ultra-high frequencies are attenuated, due to the absorption of the earth, the lack of a source ghost delivers clearer, sharper images, Figs. 4 and 5.

Due to the exceptionally high frequencies delivered by the ghost-free broadband seismic, the shallow part of the survey was

Fig. 5. Crossline and time slices at 1,242 and 1,982 ms through the final data, showing details of the faulted granite basement, as well as the fine detail of the shallower polygonal faulting. Image courtesy of Lundin Norway.

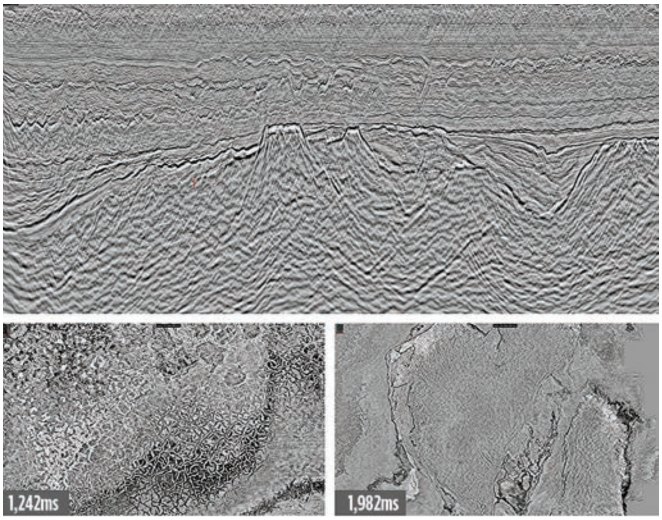
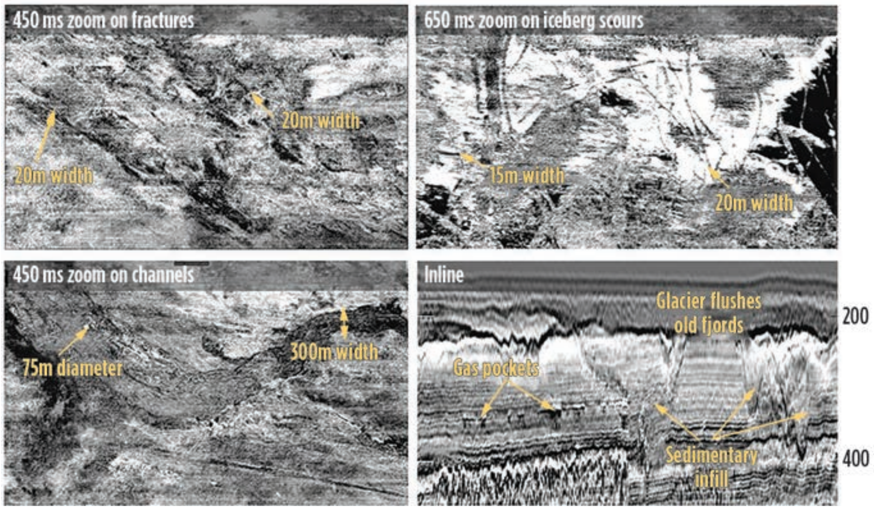


Fig. 6. The high-resolution BroadSource data can identify small fractures, gas pockets, channels and iceberg scours. Image courtesy of Lundin Norway.



also processed, at finer spatial resolution, for use as a site survey. Instead of the natural bin size of 18.75 m × 6.25 m dictated by the acquisition, the data were binned onto a 9.375-m × 6.25-m grid. The data were then interpolated and regularized, using an advanced anti-leakage Fourier transform. This delivered exceptional resolution of glacial infill, iceberg scours and small channels, revealing features as small as 15 m wide, and clearly identifying shallow gas hazards, showing the full benefits of truly broadband acquisition, **Fig. 6.**

The discovery of Johan Sverdrup field provides hope that it may not be the last major oil find in the North Sea. Its late discovery, in an area that had been the subject of exploration since 1965, may indicate that there are still more discoveries that have, so far, been missed. New acquisition and imaging techniques are revealing more of the secrets of the Earth's subsurface. Since this survey was acquired, over 70,000 km^2 of 3D data have been acquired, using the combination of a synchronized multi-layer broadband source and variable-depth streamers. These have been acquired in many parts of the world, including the North West Shelf of Australia, offshore Vietnam, India and West Africa, as well as elsewhere in the North and Norwegian Seas.

A huge multi-client survey is being acquired over the Horda Platform, in the southern Norwegian Sea, west of Bergen, using this technique. Even in relatively mature basins, like the North Sea, where acreage is shared by many operators, multi-client surveys can be a cost-efficient solution for use as an aid to development, as well as for exploration to discover more fields like Johan Sverdrup. Costs can be shared, and larger surveys acquired, for a better overall view of the prospect than is generally the case with proprietary surveys.

A total of 8,650 km^2 has been acquired over the Horda Platform in 2014, and the survey is planned to reach in excess of 20,000 km^2 this year, making it the largest broadband multi-client survey that CGG has acquired in northwestern Europe, and also the largest multi-client 3D survey shot by any company in Norway. While previous seismic coverage in the area consisted of a series of postage-stamp-sized surveys, ranging in vintage from the 1980s to 2010, with different acquisition parameters, a uniform, high-end dataset, such as the Horda survey, is required to understand the area's complex geology.

Following the new discoveries made in the North Sea in the past three years, several companies have shown renewed interest in exploring for oil and gas outside the main oil play fairways. New discoveries often emerge from the combination of new technology and new geological ideas. Lundin Norway has shown us that a new approach, ignoring the pre-conceived ideas of the past, combined with the courage to embrace new technologies, can pay significant dividends. **WO**

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