Advanced imaging solutions for tailored multi-source and multi-vessel surveys

Gordon Poole[1*], Vetle Vinje[1], Ewa Kaszycka[1], Thomas Elboth[1], Thomas Mensch[1], Risto Siliqi[1], Anne Camerer[1], Hari Krishna[1] and Erling Frantzen[1] discuss how advanced deblending, demultiple, deghosting and imaging technologies are allowing successful adoption of bespoke multi-source, multi-vessel acquisition strategies.

Introduction

In recent years there has been increased creativity in the design of seismic acquisition campaigns aimed at maximizing the illumination and sampling of the subsurface. When combined with innovations in imaging technology, these new acquisition methodologies can provide significant improvements to images of the subsurface in both exploration and production settings.

Onshore, receiver and source arrays have evolved to dense wide-azimuth acquisitions using single-source/single-sensor approaches in the Middle East. This has been driven by the now-proven benefits for processing, imaging and reservoir characterization that the data sets deliver (Ourabah et al., 2014; Michou et al., 2017). These campaigns have been rendered cost-effective by high-productivity blended acquisition strategies, which utilize large areal receiver spreads and a large number of single vibroseis sources operating simultaneously. The advent of accurate deblending algorithms allowing high-productivity simultaneous shooting strategies to be used successfully, without compromising image quality, have made the approach viable for large-scale surveys. The advantage for onshore simultaneous shooting is that vibrator sources utilize a sweep which simplifies deblending significantly (Bagaini, 2006).

In a marine setting, however, deblending is more challenging due to the use of impulsive airgun sources. In conventional acquisition, two sources are deployed in flip-flop mode, typically with 7-10 seconds between consecutive source actuations to allow reflected signals to be fully recorded before the next shot is fired. Historically, methods to increase trace density and improve acquisition efficiency have been limited to significantly increasing the number and density of streamers, ranging from a single streamer in early acquisitions up to 24 streamers in more modern configurations.

It has not been until relatively recently that increases in source effort have been seen. In settings such as the Gulf of Mexico, wide-azimuth acquisitions, enabled by multi-vessel geometries, have proved invaluable in improving the illumination of complex salt structures (Michell et al., 2006; Mandroux et al., 2013). With sequential source actuation, however, this improvement in illumination comes at the cost of a decrease in the image fold along the sail line, caused by the sparser shooting. While such source sampling considerations may not be critical in deep water regions where the low frequency wavefield varies slowly across offset, for shallower targets this is not the case.

The key to increasing the uptake of wide-azimuth acquisition for shallower targets is to maintain both the dense shooting rate as well as the high sail line fold. The deployment of triple sources was suggested by Langhammer and Bennion (2015), to increase trace density and improve efficiency. This concept has been further extended with the 8-source acquisition of Vinje et al. (2019). However, in increasing the number of sources, cross-talk contamination is introduced into the seismic record, where the wavefield generated from one shot overlaps the wavefield from the previous shot in a time interval of interest.

Only with recent improvements in deblending technology (Peng et al., 2016; Poole et al., 2019) has the rapid shooting of more than three sources become a viable solution to increase trace density. This has led to higher spatial resolution and improved signal-to-noise ratio. Since then, distributed sources have been proposed, as we will discuss in this paper. Using two case studies from North West Europe, we will look at how advanced deblending, demultiple, deghosting and imaging technologies are allowing successful adoption of bespoke multi-source, multi-vessel acquisition strategies, thus creating a unique solution that addresses several historical geological and operational challenges.

Deblending

When a survey is being designed to take advantage of simultaneous shooting, the deblending strategy must be carefully assessed. It is important to design the firing sequence to increase the likelihood of being able to successfully separate the blended energy and de-risk the imaging. One possible approach is to use randomised source timing. When viewing a common channel display, this means that when the seismic events generated by one source are aligned, the signals corresponding to the other sources will to some extent become incoherent. Signal recorded from two shots fired at a similar time and location may appear similar both in terms of kinematics and amplitude levels. In other

[1] CGG

[*] Corresponding author, E-mail: gordon.poole@cgg.com

DOI: 10.3997/1365-2397.2019031

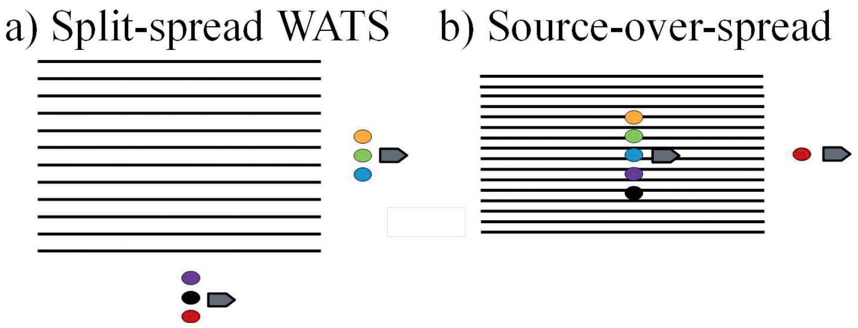

Figure 1 Acquisition layout schematic for a) Split-spread wide-azimuth acquisition, and b) Source-over-spread acquisition.

cases, where the firing delay is large or the sources are far apart, the amplitude of the cross-talk may be significantly stronger than that of the underlying weak reflections, typically by 30 dB or more. As such, while an increase in randomization creates more incoherency in the cross-talk, this is at the risk of contaminating larger parts of the section that may not be so strongly affected by cross-talk noise.

Many deblending algorithms have been proposed over the years, most of which may be categorized as iterative coherency enhancement, impulsive denoise, inversion approaches, or annihilation filter methods. However, even with the most extensive pre-acquisition de-risking studies, deblending remains a very challenging processing step that needs careful testing and QC. Depending on the geological setting, the blend noise, or cross-talk, may take on different characteristics.

Success may only be achieved with the availability of flexible source separation algorithms that are compatible with continuous recording (Poole et al., 2019), along with the use of novel techniques to calculate low-discrepancy uniform random dithers (Elboth & Vinje, 2019). As well as deblending, these new shallow-water wide-azimuth geometries present additional processing challenges, such as attenuating short-period multiples in shallow-water wide-azimuth settings, and 3D receiver deghosting.

Case study: Undershooting volcanic sills West of Shetland

The prospective North Rona Ridge area, West of Shetland, contains multiple targets from shallow Tertiary and Cretaceous plays, through to deeper-fractured Devono-Carboniferous reservoirs. The deeper targets are partially obscured by volcanic sills, which pose a significant imaging challenge. When a survey was proposed for this area, the water depth profile and currents dictated that the survey could not be oriented along the direction of highest structural complexity (dip direction). In fact, in this extreme case, these operational constraints required the survey to be acquired along the strike direction, parallel to the main structures. As a result, a bespoke rich-azimuth acquisition configuration and imaging solution had to be designed to achieve the survey objectives.

In this case, it becomes important to maximize sampling perpendicular to the sail line direction, in order to secure a useful data set for imaging. One way to improve sampling is to decrease streamer spacing or interpolate between streamers using multi-measurement recordings (Vassallo et al., 2010). However, these options may be restricted by various types of noise, the availability of streamers, as well as by the need to keep acquisition costs at a reasonable level. Another option involves increasing the number of sources. While this approach decreases the spacing along crosslines, illumination of longer offsets in the dip direction is still not achieved. In such cases, one option is to add a second source vessel to produce a wide-azimuth towed-streamer (WATS) geometry. Figure 1a illustrates the acquisition design from the rich-azimuth survey in 2018-19 (Poole et al., 2019).

Primary target depth objectives required a 5-second trace length, corresponding to a 12.5 m shotpoint interval, based on a nominal vessel speed of 2.5 m/s. With six sources deployed, sequential actuation would have resulted in a low-fold data set, which would have compromised the imaging. As such, the use of simultaneous shooting was a necessity.

Figure 2a shows a shot record highlighting the contamination of the split-spread wide-azimuth arrivals on top of the conventional narrow-azimuth arrivals. The figure highlights cross-talk from the simultaneous wide-azimuth shot (orange arrow) as well as contamination from the following two shots (green arrows) overlaying deeper secondary targets. Figures 2b and 2c show the same shot record after separation of the arrivals from the

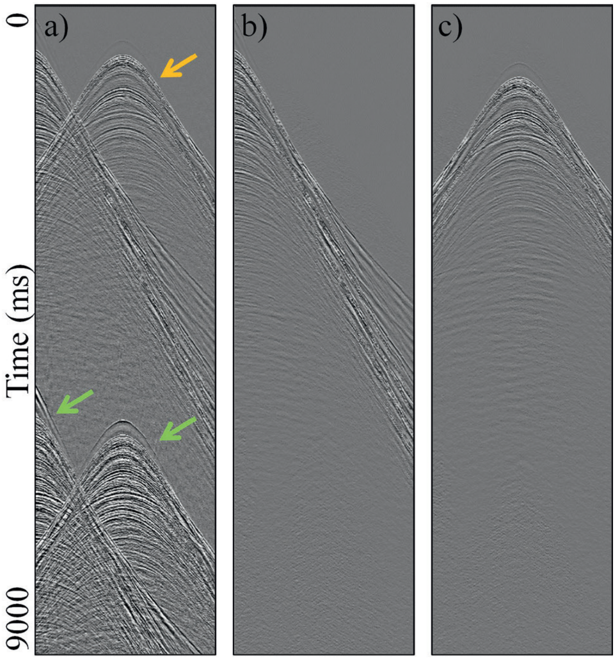

Figure 2 a) Raw shot record from the rich-azimuth simultaneous source acquisition before deblending, b) Narrow-azimuth signals after deblending, and c) Wide-azimuth signals after deblending. The orange arrow indicates the arrival from the split-spread wide-azimuth source. The green arrows indicate following shots from the narrow- and wide-azimuth sources.

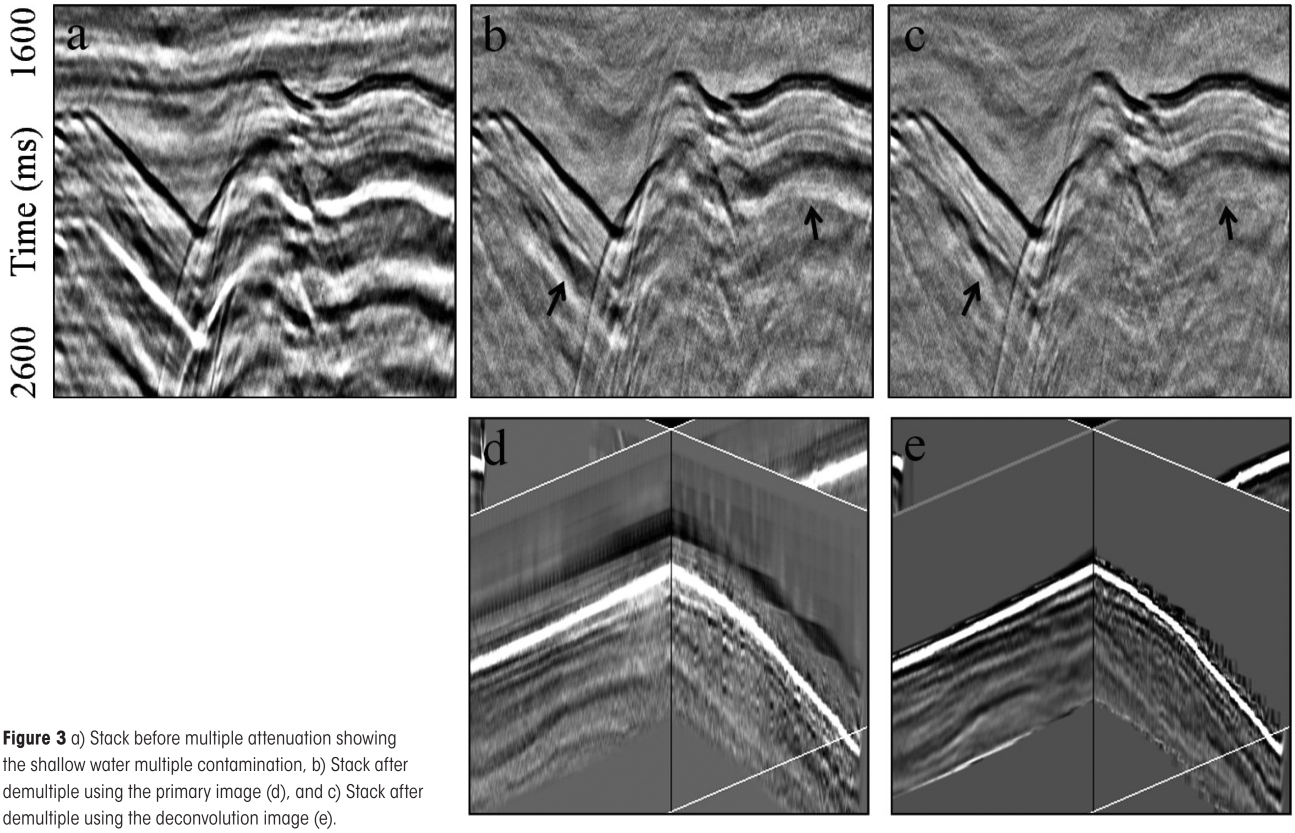

Figure 3 a) Stack before multiple attenuation showing the shallow water multiple contamination, b) Stack after demultiple using the primary image (d), and c) Stack after demultiple using the deconvolution image (e).

narrow-azimuth and wide-azimuth source actuations respectively. The figure shows that even though in places the cross-talk is much stronger than the underlying signal, the energy corresponding to the two shot actuations has been accurately separated.

Another challenge faced was the high level of reverberating shallow water multiples that mask underlying reflectors of interest, as shown in the stack section of Figure 3a. While the wave-equation multiple modelling approach of Pica et al. (2005) has proven effective in attenuating multiples, it remains challenging in shallow water areas where the multiple generator has not been properly recorded. Poole (2019), introduced a deconvolution imaging approach based on least-squares migration to reconstruct the shallow image responsible for generating short-period multiples. Figures 3d and 3e compare shallow imaged primaries with the deconvolution image respectively. The comparison shows an improvement in water-bottom imaging and continuity of the shallow geology using the deconvolution approach. Figures 3b and 3c show demultiple stack sections based on wave-equation extrapolation using the recorded primary image and the deconvolution image respectively. We observe an improvement in the attenuation of short-period multiples using the deconvolution image, providing a cleaner section for easier geological interpretation.

Migration results with and without addition of the wide-azimuth source wavefield data are given in Figure 4, which highlight the benefit of the wide-azimuth sources for illuminating deeper target structures underneath the volcanic sills that were prevalent in the area.

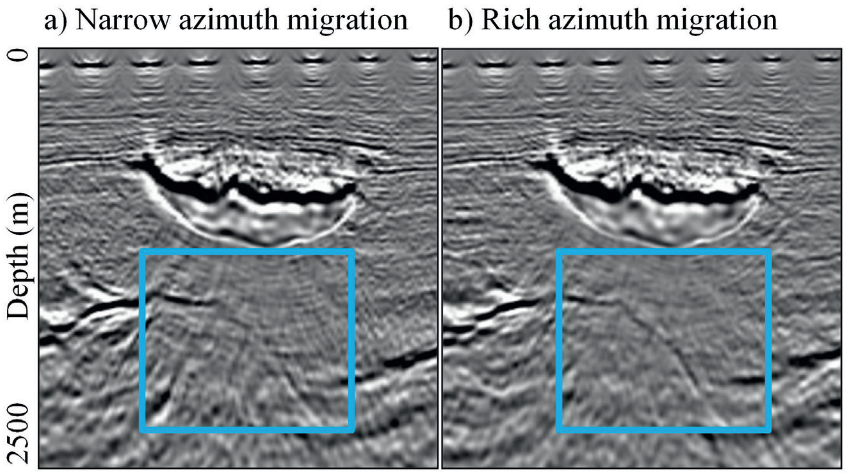

Figure 4 Image of a deeper target underneath a volcanic sill, a) Narrow-azimuth migration and b) Rich-azimuth migration including the wide-azimuth source.

Case study: Source-over-spread acquisition in the Barents Sea

In the Barents Sea, which features shallow strong velocity contrasts and complex shallow reservoirs, TopSeis, an innovative source-over-spread marine towed-streamer imaging solution was developed to provide a step-change in image quality.

In this setting, the availability of near offsets becomes increasingly important to adequately record primary arrivals at small reflection angles. With conventional geometries, acquisition constraints typically limit the nearest offset acquired to approximately 150 m; at outer streamers this becomes much larger. While multiple reflections can provide information at shorter offsets (Whitmore et al., 2010), in practice the resolution of such data can sometimes be limited as well as being contaminated by cross-talk which must be carefully handled. One solution to these problems was provided by source-over-spread acquisition, where the near-offset data provided sharper shallow images than ever before (Vinje et al., 2017).

After a successful survey in 2017, the design was re-evaluated for a large-scale survey (5,000 km^2) in 2019. Figure 1b shows the acquisition design for a survey acquired in 2019 in the Greater Castberg area of the Barents Sea based on the ideas proposed by Vinje et al. (2019). This survey was designed to also acquire long offsets (with the front source) and be more cost-effective than the 2017 TopSeis survey in the Barents Sea (Vinje et al., 2017). The 2019 survey deployed a streamer vessel towing 16 streamers along with a single source, mainly to acquire long offsets for FWI to enhance velocity model building. The source-over-spread vessel towed an industry record 300m-wide configuration of five sources with a 75-m lateral separation. With a total of six sources deployed, the use of simultaneous shooting was again required to maintain reasonable stack fold for the targeted high-resolution bin size. In this case, the widely distributed five top-sources were fired in sequence with the single front-end source being fired on time with the actuation of every sixth top-source firing, so that it contaminated the energy from each of the five top-sources in turn.

Figure 5a displays a source vessel stack highlighting the following top-source arrival at 3 seconds (green box) as well as how the streamer vessel source contaminates the shallower section (orange box) with strongly dipping cross-talk noise. Figure 5b shows the stack after deblending, whereby deeper structures beneath the following shot have been recovered. Figure 5c shows the cross-talk that was removed in this process, highlighting the strong level of cross-talk compared to primary. Figure 5d shows amplitude decay curves before and after deblending. The curve after deblending follows a gradual decay, as expected, while the curve before deblending highlights the strength of the cross-talk which is 30 dB stronger than the underlying signal in places. The deblending results highlight the accuracy of this continuous recording-based deblending approach, particularly the reflections in the deep section that have been recovered from beneath strong cross-talk.

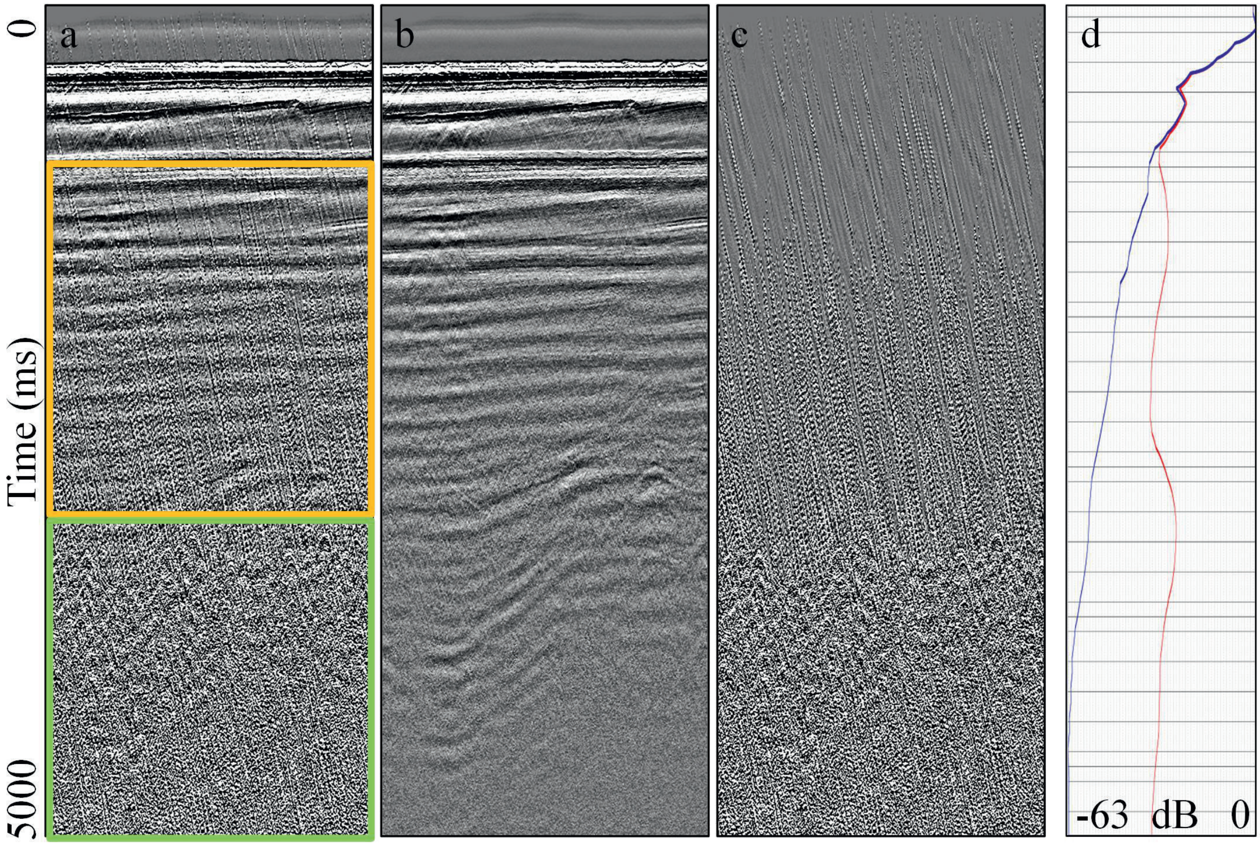

Figure 5 Source vessel stack highlighting the following top-source arrival at 3 seconds (green box) as well as how the streamer vessel source contaminates the shallower section (orange box) with strongly dipping cross-talk noise. a) Stack before deblending, b) Stack after deblending, c) Cross-talk noise removed in the deblending, and d) Gain curves before (red) and after (blue) deblending.

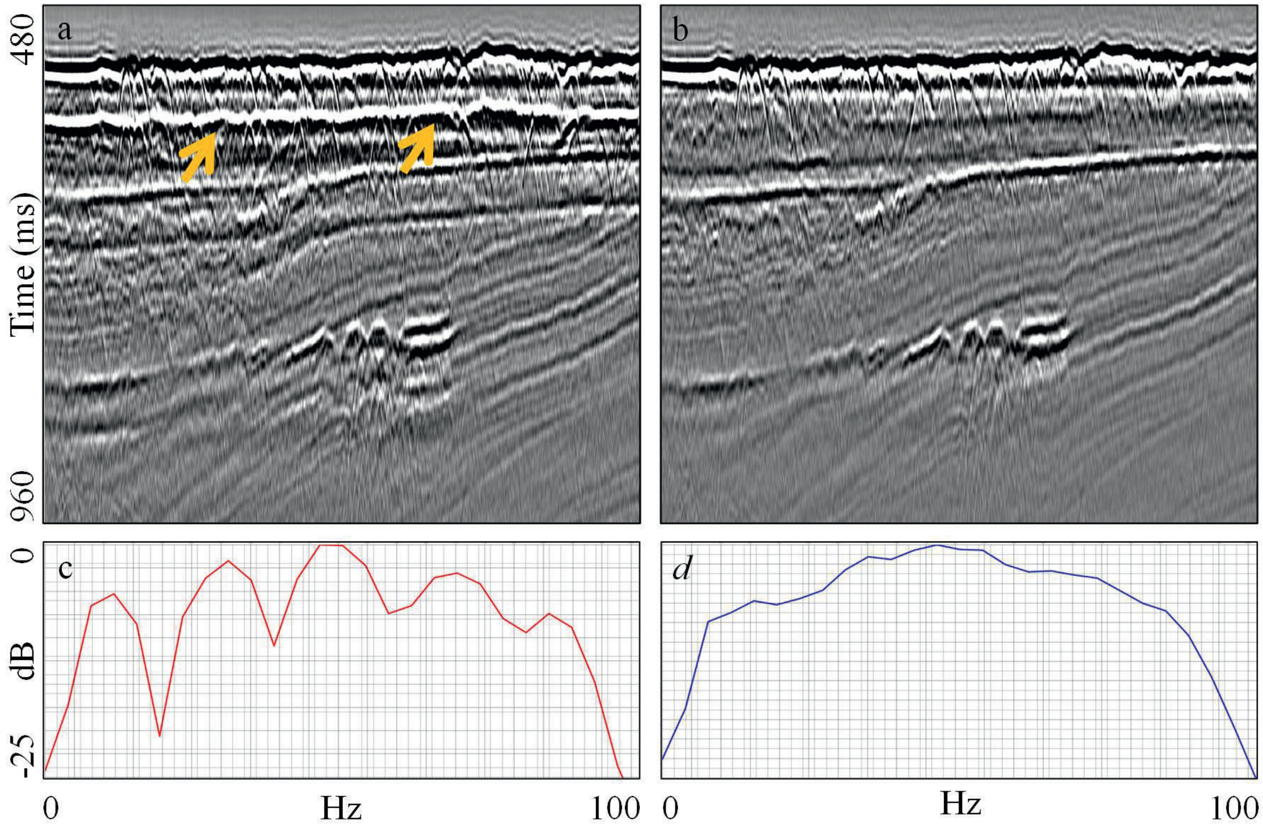

Figure 6 Stack for a central cable. Highly-curved diffraction arrivals from the iceberg-scoured seabed are visible. a) Stack before receiver deghosting, b) Stack after receiver deghosting, c) Spectrum before receiver deghosting, and d) Spectrum after receiver deghosting. Spectra are calculated in the time window 500 ms to 700 ms.

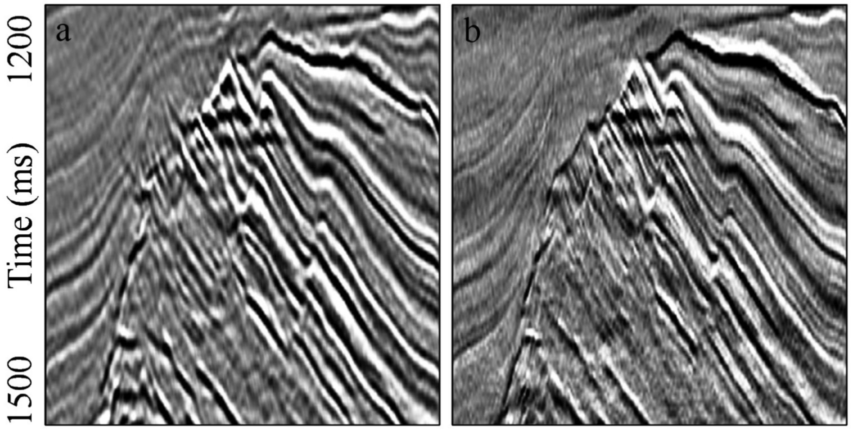

Figure 7 Comparison between a) Vintage migration and b) TopSeis fast-track migration.

In order to unlock the full spatial resolution provided by this acquisition, cutting-edge source designature and 3D receiver deghosting were required as part of the proprietary processing sequence. Figure 6a shows a stack for a central cable from the acquisition. The presence of complex highly curved diffraction arrivals from an iceberg-scoured seabed made receiver deghosting particularly challenging. The corresponding amplitude spectrum, Figure 6c, highlights the deep receiver notches associated with this acquisition approach. Poole et al. 2018, proposed a tilted-hyperbola-based approach which helped to overcome tau-slowness sparseness limitations of previously established techniques. Figure 6b shows the stack after receiver deghosting and Figure 6d the associated amplitude spectrum. The corresponding spectrum after deghosting highlights a smoother spectrum with minimal residual ghost energy remaining.

Figure 7 shows a comparison between a fast-track processing and imaging of part of the TopSeis Castberg 2019 data with an available vintage image in a small, faulted area at around 1300 ms. The uplift in the imaging is obvious already at this early stage and a double flat spot is clearly visible.

Conclusion

We have discussed some of the challenges of delivering bespoke marine seismic acquisition and imaging solutions to address geological and operational challenges on a case-by-case basis. The use of multi-vessel acquisitions with multiple wide-towed simultaneous sources provides a range of options to increase offset-azimuth sampling and trace density, as illustrated by our case studies. Such acquisitions may be de-risked through careful blend-deblend simulations using different source actuation timings. However extensive the planning, the success of such campaigns is only possible with the availability of high-quality deblending algorithms and close co-ordination between experienced acquisition design and processing teams. Additional processing complexities often come hand-in-hand with new acquisition designs, and constant advance of the technology is required to ensure the best images of the subsurface. Cutting-edge shallow water demultiple along with advanced 3D deghosting approaches proved to be particularly important to unlock the resolution improvements offered by these tailored acquisition approaches.

Acknowledgements

We would like to thank BP and Shell for their close cooperation during the West of Shetland project planning. Figure 7b is courtesy of CGG Multi-Client & New Ventures and TGS from the 2019 TopSeis acquisition. Vintage data in Figure 7a is from the released 2008 West Loppa seismic data from DISKOS originally acquired by Western Geophysical AS. The authors would like to thank CGG Multi-Client & New Ventures for permission to publish this work.

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