Can high-resolution reprocessed data replace the traditional 2D high-resolution seismic data acquired for site surveys?

Julien Oukili[1*], Jean-Paul Gruffeille[2], Christian Otterbein[1] and Benjamin Loidl[3] describe a process that would enable operators to save both time and costs on conducting conventional site surveys by applying separated wavefield imaging to existing 3D seismic data.

Introduction

After a prospect has been evaluated and the decision is made to drill, the well planning and design phase can begin. We must define not only the best location to enter the target reservoir, but also choose the right surface location to place the drilling rig and the wellhead, without forgetting the well trajectory between the wellhead and the reservoir entry point.

In Norway, as in many countries, drilling operations are subjected to a well integrity in drilling and well operations hazard assessment in our case: NORSOK D-010, August 2004. The results of this assessment, in the form of a report, are submitted to the local authorities in order to get the approval to operate. This can be a lengthy process, between four and nine months, and possibly longer in the case of operations in a high-pressure high-temperature regime.

The Norwegian Petroleum Directorate (NPD) guidelines are not prescriptive, and leave the operator to decide what is necessary to operate with the lowest practical risk. A site survey is commonly acquired to assist in the safe installation and operation of a drilling rig, and aims to:

- Provide information on seabed and sub-seabed conditions to ensure the safe, secure and efficient installation and operation of a drilling rig,
- Identify any potential drilling hazards in the shallow section, ideally down to the first kilometer,
- Assess the location of potentially important seabed habitats, and
- Provide an environmental baseline survey (EBS). An exemption is possible if such a survey was done in the previous three years.

The first two points are usually achieved by acquiring dedicated high-resolution (HR) 2D or 3D seismic surveys, and mapping the mud floor to get an ultra-high-resolution (UHR) image by side-scan sonar or multi-beam echo-sounder technologies. It is worth noting that the NORSOK D-010 regulation does not specify whether 2D HR seismic or 3D seismic is required. The characteristics of the seafloor itself are assessed using geotechnical methods such as a cone penetration test (CPT).

For cost and time reasons, the dedicated seismic data is often acquired as a grid of 2D lines around the planned surface

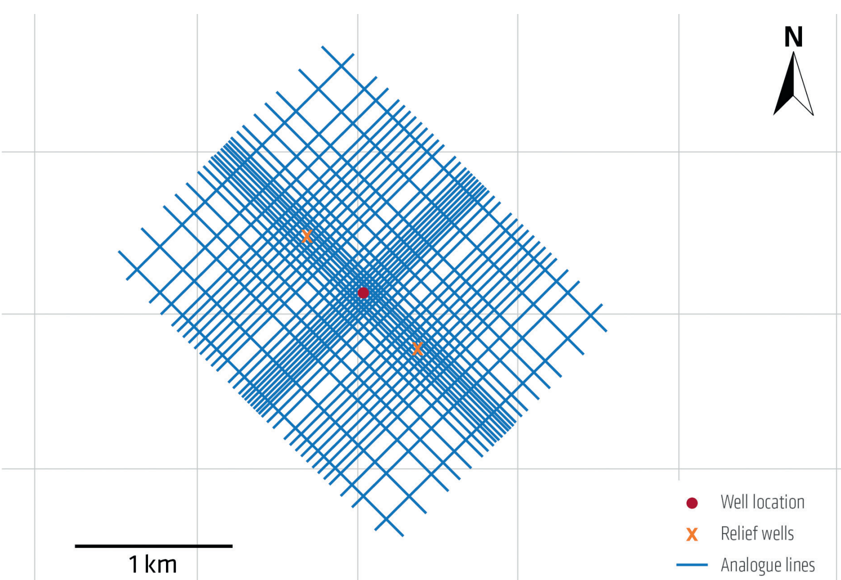

Figure 1 Typical 2D high-resolution seismic template for a site survey. The line density rapidly decreases with distance from the targeted well location.

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location of the well, and typically covers a small area of 2x2 km or 3x3 km (Figure 1). This implies that the location of the well is essentially final before conducting the site survey, which in principle, should confirm it. If the well, and therefore the drilling rig, had to be moved by a substantial distance and ended up being close to the limits of the newly acquired seismic data, a new survey might be necessary. Although rare, such risks exist, with all the implications for the project in term of delays and costs.

It is possible to achieve great results with 3D HR acquisition. However, the costs are considerably higher than for the 2D case and are difficult to justify to the asset managers unless the reservoir is shallow and can be imaged with the same dataset, in which case it would be a fit-for-purpose and efficient solution. This is not the situation on the data used for this project, where the main target from the Upper Jurassic level is at approximately 4000 m depth.

HR seismic surveys, designed to image the shallow section, are normally acquired with shallow-towed sources and receivers, usually towed around two metres below the sea surface. This makes the weather conditions a key factor for the success of such marine operations. In the North Sea the acquisition window is limited in time (April to October) due to the prevaling sea state. Outside this time window and towards the end of the season, the field operations are often affected by considerable downtime, increasing the project costs and also potentially jeopardizing the drilling operations altogether. Moreover, in parts of the North Sea that are prone to local fishing activities, a ban on seismic acquisition can be imposed in what should be the most favourable period for shallow-tow HR seismic, typically from mid-July to September.

What if we could perform the seismic part of the site survey investigations in the comfort of an office? What if we could cover an area 10 to 20 times larger than the one of a 2D HR seismic survey, but with a full 3D perspective and at a lower cost? What if we could do this site survey at any time we want or need?

Having such a solution at hand would have the following advantages:

- More time available for the well trajectory design,
- The same shallow hazard survey (SHAZ) data could be used for any subsequent wells over the whole licence or prospect without the need for another HR seismic acquisition, thus reducing the overall field development costs,
- No direct dependency on weather conditions or seismic activity ban for getting the high-resolution data,
- Potentially more vessels of opportunity to run the environmental base survey (EBS) and geotechnical work seismic vessels are specifically designed for seismic acquisition,
- The extent of the reprocessing area can easily be adjusted. It would increase the size of the project, with some implications on costs (computation time up to 250 Hz), but have little impact on the turnaround time,
- Apply the shallow hazard reprocessing over all areas covered by 3D conventional data, or large parts of it, as long as the required input data is available,
- Initiate consultation with contractors for the EBS (if required) and geotechnical work to secure the boat and the crews at the beginning of the season, and
- File for work permit with authorities sooner without waiting for the HR data interpretation (after acquisition and processing).

That is why we started looking into dedicated high-resolution processing workflows, with a strong focus on the imaging of the shallow section that is under-sampled in conventional 3D seismic acquisition used for exploration or field development.

The geometry of a conventional acquisition spread does not provide seismic recordings at very near offsets. The nominal minimum near offset is typically in the order of 110 m. In practice, the minimum near offset for imaging is much larger due to the crossline offset on the outer streamers. We believe that multi-dimensional data reconstruction cannot provide the information that has not been recorded in this offset range.

We have seen in recent years more and more efforts from the industry to use additional data that could fill the zero-offset gap, the multiples. The seismic data we have been working with on our PL817 licence (Figure 2) was acquired with multisensor technology (Carlson et al., 2007) that has been the basis of imaging with multiples for a few years now (Whitmore et al., 2010). Reassured by previous examples, albeit in a different geological context, we thought that imaging with multiples combined with an adapted

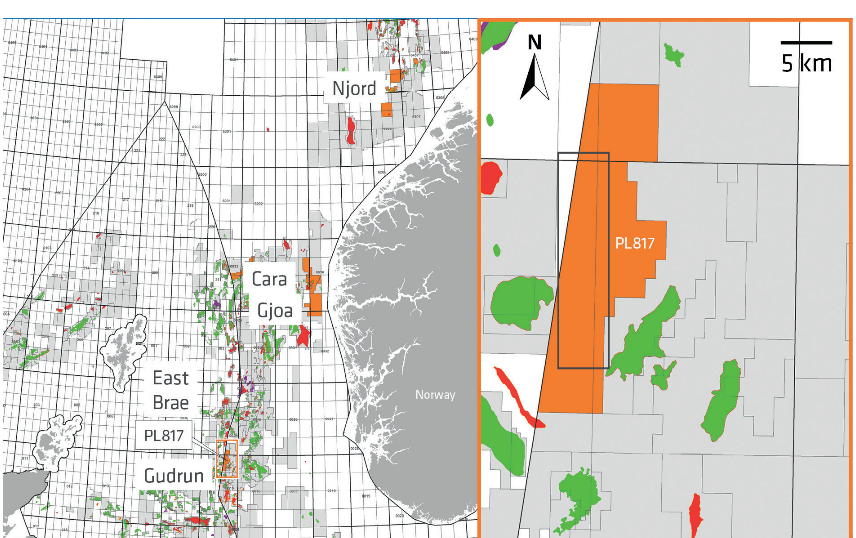
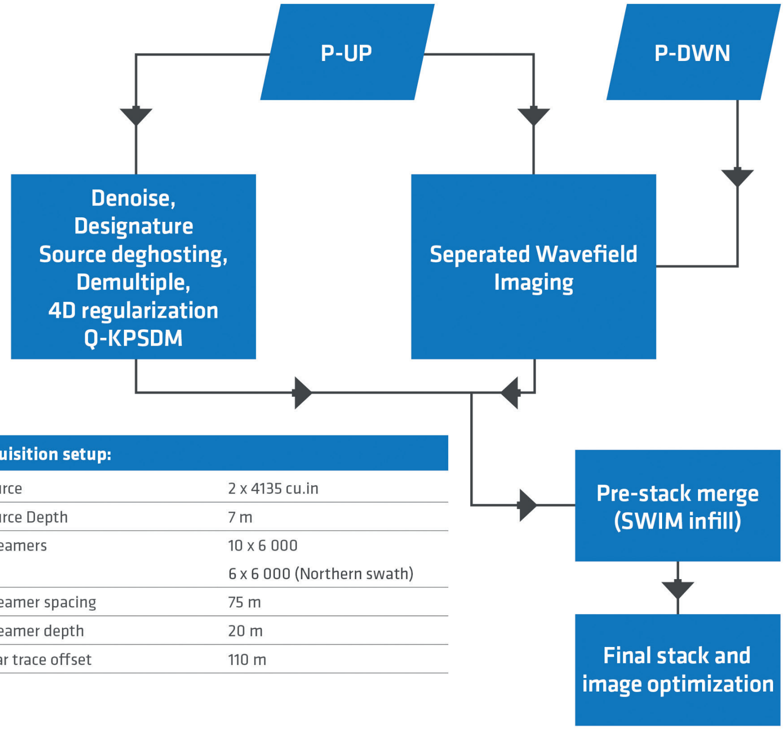


Figure 2 Area of interest for the 3D SHAZ reprocessing area in PL817 (delineated by the black contour on the right-hand side map inset).



Aquisition setup:	
Source	2 x 4135 cu.in
Source Depth	7 m
Streamers	10 x 6 000
	6 x 6 000 (Northern swath)
Streamer spacing	75 m
Streamer depth	20 m
Near trace offset	110 m

Figure 3 Survey parameters and 3D SHAZ reprocessing workflow. P-UP and P-DWN are the up-going pressure wavefield and down-going pressure wavefield, respectively.

high-resolution workflow would produce final images that would meet the requirements of a site survey. The licence partners correspondingly agreed to launch the project.

Description of the 3D SHAZ reprocessing workflow

The seafloor lies between 115 m and 125 m depth in the area of this pilot reprocessing project. The full-fold, fully-migrated output area covers approximately 100 km^2 in the Norwegian North Sea, as illustrated in Figure 2.

The field data were acquired in 2013 by PGS as part of a regional exploration programme using multisensor streamer technology. The complete workflow and key parameters of the survey (acquired in two parts with different vessels) are summarized in Figure 3. The reprocessing was carried out at 2 ms temporal sampling, starting from the up-going and down-going wavefields obtained after wavefield separation based on the pressure and particle velocity sensor measurements (following the methodology of Carlson et al., 2007).

For one flow, the up-going wavefield data are processed alone through a high-resolution processing sequence where the main imaging method is a 3D Kirchhoff pre-stack depth migration (KPSDM). It includes 3D Q compensation with TTI anisotropy settings, up to a maximum frequency of 220 Hz and to a maximum depth of 1500 m. The signal bandwidth was optimized by prior pre-conditioning steps that include source-side deghosting, designature and shallow water demultiple.

For a second flow, both the up-going and down-going wavefield data are inputted to Separated Wavefield Imaging (SWIM) which effectively exploits the subsurface illumination from surface-related multiples (Whitmore et al., 2010). As illustrated in Figure 4, the application of a deconvolution imaging condition in the migration step removes wavelet effects, meaning the output of SWIM is fully broadband. Furthermore, in this process, every receiver is effectively used as a virtual source, which is the key in recovering reflectivity information down to a virtual zero offset and eliminating the acquisition footprint effects.

The final SWIM migration is performed with a maximum frequency of 220 Hz, down to 500 m depth, with an output to angle gathers from 0 to 40 degrees. The maximum migration depth for SWIM was made deliberately short in an attempt to further limit the reprocessing costs (compute power) after test comparisons against conventional images on target lines.

The two workflows described are merged after migration in the pre-stack domain; where the SWIM data are used to fill in the missing near angle information in the shallow part of the KPSDM angle gathers. The final image is therefore obtained using recorded information at all depths, rather than interpolated data. The SWIM information effectively provides the shallow image, beyond which the high-resolution KPSDM contributes. Note that the depth of the crossover point is dependent on the acquisition geometry, and more efficient (wider) towing configurations may use SWIM information at greater depths.

It is worth noting that a common velocity model was used for both migrations, thus producing data which are consistent in phase and amplitude. Furthermore, the model was built with an advanced workflow combining Full Waveform Inversion (FWI) and reflection tomography, which cannot be applied to typical site survey data due to the short offsets. In contrast, the 3D data used here were recorded with long offsets.

Results

The 4 ms sampled 3D stack from the latest regional broadband reprocessing (denoted 'Reference') is compared to the 2 ms

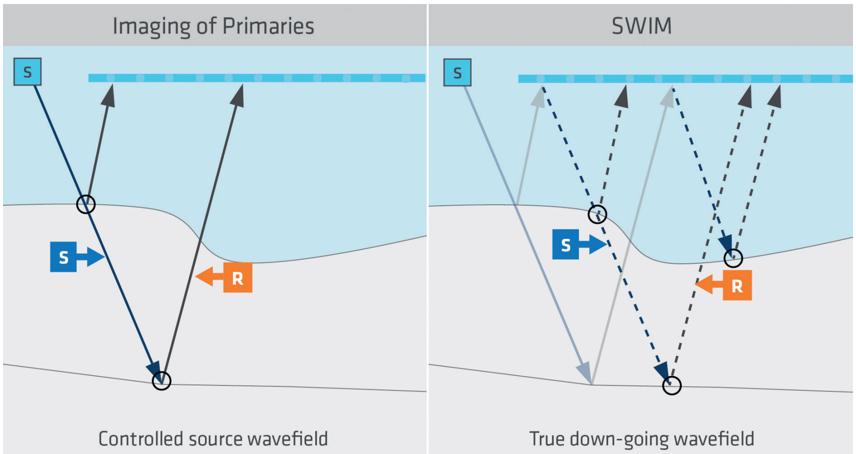


Figure 4 Illustration of the SWIM imaging principle: conventional primary imaging only (left) against SWIM imaging (right). Note that the main difference comes from the source wavefield (S), which is the recorded down-going wavefield (P-DWN). Its source signature is consistent with the recorded up-going wavefield (P-UP) that is used as the receiver wavefield (R).

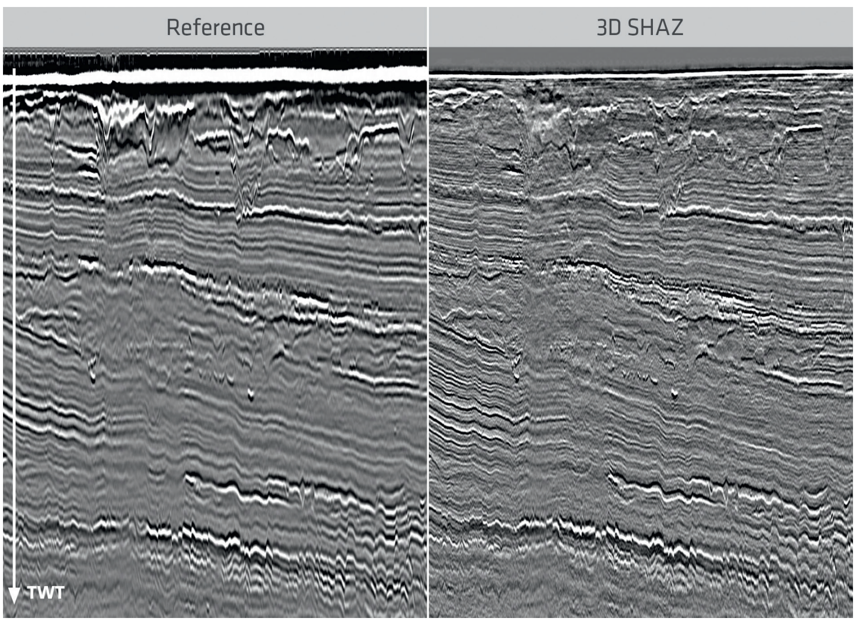


Figure 5 Crossline (100-1200 ms TWT) sections of the reference cube (left) versus the 3D SHAZ volume (right). White represents an increase in acoustic impedance. A considerable uplift in resolution is shown in the shallowest part of the SHAZ image where SWIM contributes the most. Furthermore, the entire volume benefits from high-resolution 3D imaging.

sampled 3D SHAZ volume (the merge between KPSDM and SWIM products) in Figure 5. The reference image was migrated using the same velocity model as the Kirchhoff pre-stack depth migration.

Processing at 2 ms sample rate allowed higher frequencies to contribute to the SHAZ image, and the footprint effects are removed from the shallow overburden image, a feature of SWIM. This is especially evident in the area covered by the ten-streamer vessel set-up to the south. The merge process in the 3D SHAZ volume appears seamless, while both resolution and clarity are enhanced.

Locally, the reference volume seems to have abundant amplitude artifacts (Figure 6), especially in time slices. A closer inspection reveals that many objects are smeared due to the lack of resolution, and give the impression of a detail-rich image which in conclusion is misleading. Although some high amplitude anomalies of interest are perceptible in the reference images, they are often masked by the large footprint effects caused by the poor near-offset sampling.

An examination of the isochrones of the water bottom event (maximum amplitude of the negative event) extracted from both the reference cube and the 3D SHAZ volume reveals quite dramatic differences for the two images, as can be seen in Figure 7. Whereas the information from the reference data cannot be used to estimate the timing of the water bottom, the 3D SHAZ image not only shows artifact-free information, but it also provides structural details for the water bottom event. The main explanation for this difference is that the field seismic data has not recorded the seafloor primary reflection event as a single pulse at near incidence angles, but instead represents interferences with the immediate sub-water bottom reflectors, in addition to wavelet stretch (high incidence angles).

There were no overlapping site survey data available for direct comparison. However, 2D site survey data from the neighbouring licence allows a qualitative assessment of the resolution that was achieved in the 3D SHAZ reprocessing and is illustrated in Figure 8. Although the vertical resolution seems very good on the 2D site survey data, 2D migration clearly shows limitations in terms of focusing, particularly at larger depths, and lacks low frequency content.

As presented by Reiser et al. (2012), the final resolution of the seismic image is affected by the bandwidth of the data, and it requires both low- and high-frequency enhancement. The greater bandwidth reduces the wavelength and increases the peak-tosidelobe amplitude ratio. Therefore, the 3D SHAZ data is well suited to detailed interpretation of anomalies in the near surface.

Conclusions

Even though there is no regulatory requirement to acquire HR seismic data, it is the operator's responsibility to collect all the necessary information to act in a safe manner when planning a drilling campaign.

As the SHAZ project progressed we saw that high-resolution reprocessing of 3D exploration seismic data (2ms) brings value down to approximately 1200 ms TWT in this case. The approach used was to adjust the standard 3D processing flow parameters to provide substantially better and artifact-free images for frequencies up to 220 Hz. This was enabled because the advanced imaging and inversion techniques used require long offset and broadband input data. In contrast, achieving similar results starting from data with limited offsets would have been quite challenging, if not impossible. Pushing the frequencies to the limits of the frequency bandwidth was also enabled by the multi-component deep-towed streamer configuration that reduced noise and free-surface interferences during acquisition.

Instead of merging the two high resolution migration and SWIM migration volumes post-stack, all the near-angle information missing in the high resolution Kirchhoff migrated gathers were taken from the migrated SWIM gathers and then stacked together to produce the final SHAZ volume.

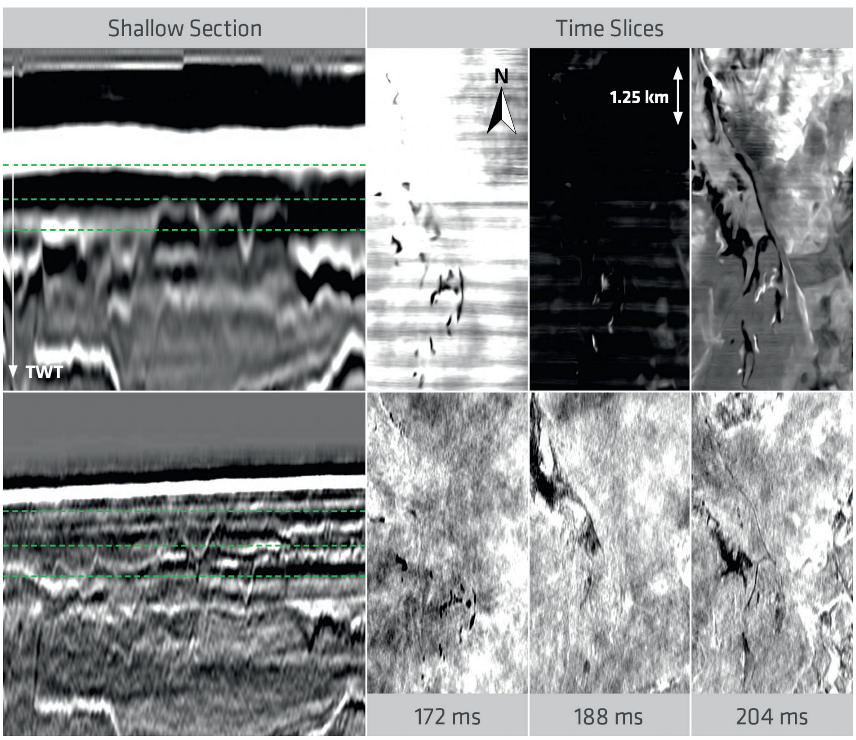


Figure 6 Shallow section (100-300 ms TWT) and time slices of the reference 4 ms cube (top row) versus the 3D SHAZ volume (bottom row). The green dashed lines on the section displays show the depths of the three timeslices. White represents an increase in acoustic impedance. Black indicates softening anomalies that are associated with potentially shallow hazards. Note how different the slices are from the 3D SHAZ volume, demonstrating a very high final vertical and spatial resolution. Many amplitude anomalies related to local geological features are more focused and more distinct from the background geology.

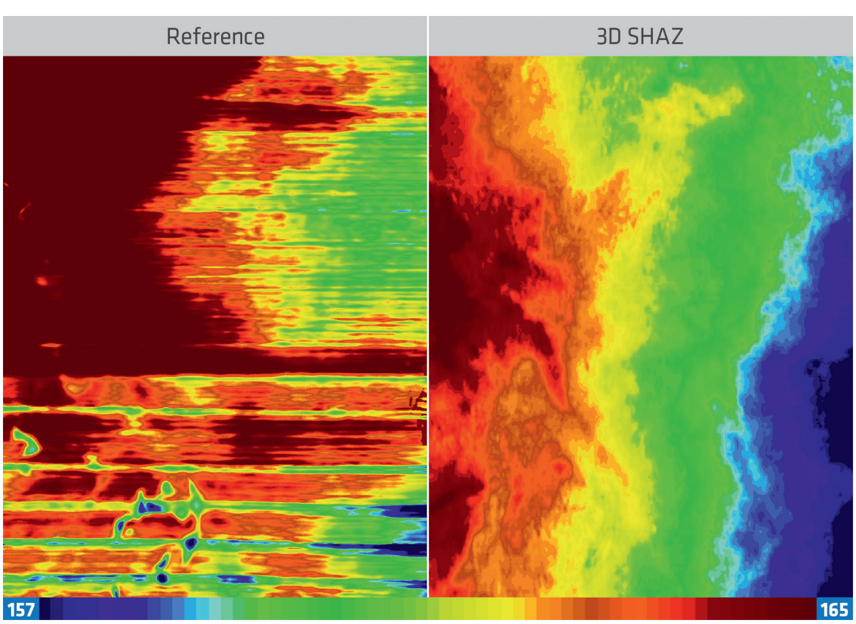


Figure 7 Isochrone maps (TWT in milliseconds) for the water bottom event derived from the reference 3D seismic data (left) versus the 3D SHAZ data (right). In the reference volume, the southern area that was acquired with a ten-streamer configuration shows stronger acquisition footprint effects. Such effects are not present in the 3D SHAZ volume.

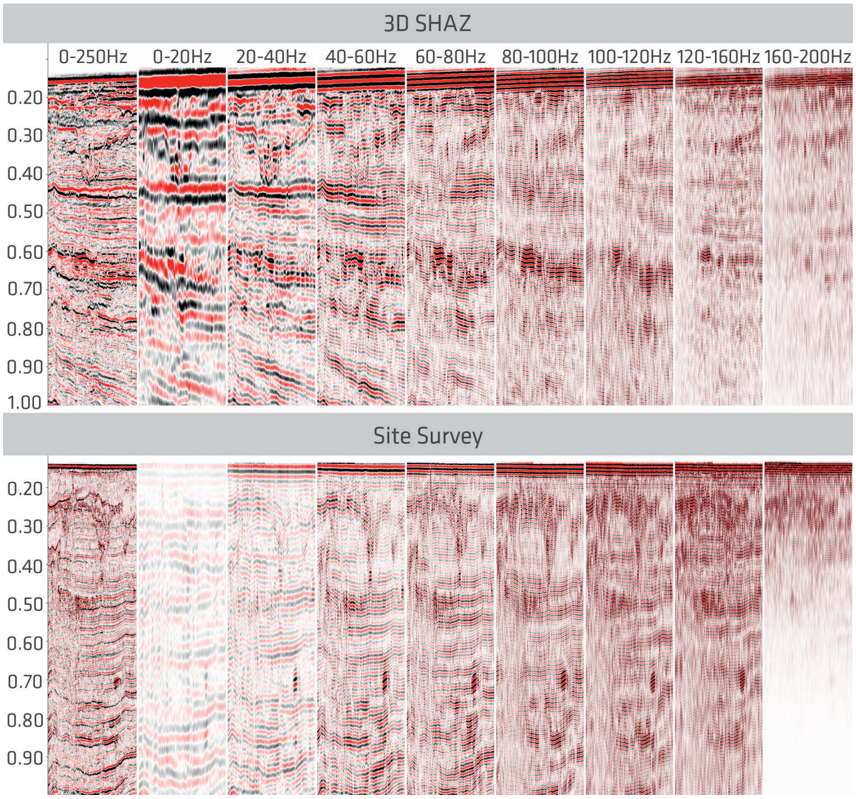


Figure 8 3D SHAZ reprocessing frequency panels (top) versus a 2D site survey line (bottom) from an adjacent licence area (TWT in seconds). Red represents an increase in acoustic impedance. The leftmost panel shows the full bandwidth image. The band-limited panels illustrate the signal-to-noise content and event character at various frequency ranges.

We believe that results still can be further improved, by using more efficient towing configurations aimed in particular at the benefits of SWIM by increasing the number of crossline receivers resulting in more virtual sources for the migration. This survey, conducted in 2013, used a traditional acquisition geometry and there is potential for further uplift in the SWIM volume if the input data is acquired with a more efficient survey geometry.

The imaging techniques described here can easily be used on a number of licences due to the large available coverage of high-quality multisensory broadband data at 2 ms sampling.

Another avenue of potential improvement is to include detailed FWI work if it was done on a large scale at the conventional imaging stage.

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