

## Optimizing the processing flow for variable-depth streamer data

Dechun Lin,\* Ronan Sablon, Yan Gao, Damien Russier, Danny Hardouin, Bruno Gratacos, Robert Soubaras and Peter Whiting, CGGVeritas, explain some of the issues in processing variable-depth solid streamer data acquired as part of the company's newly introduced BroadSeis broadband acquisition solution.

Variable-depth streamer acquisition is emerging as a key technique for providing wide-bandwidth seismic data. With several datasets acquired across the world, this broadband marine towed streamer solution has consistently produced high-quality images with better seismic resolution, stratigraphic detail, and low-frequency content for deep imaging.

By varying the receiver depth, variable-depth streamer acquisition introduces receiver ghost diversity over different offsets. Such diversity enables a joint deconvolution method to fully remove the receiver ghost. Variable-depth streamer data also tend to be less noisy due to the deep tow of the cables. These two factors allow it to attain a spectrum from 2.5 Hz up to the source notch. Challenges in processing include how to maintain the full bandwidth in the data, how to effectively remove multiples, and how to robustly build a velocity model. The typical marine processing flow has to be modified to take care of these challenges.

### Background

Over the years, considerable efforts have been made to improve the bandwidth of marine seismic data. The core idea behind these efforts is to overcome the bandwidth limitation imposed by the receiver ghost. For a conventional flat streamer, the receiver ghost generates notches around the following frequencies:

$$f = \frac{nv}{2d}, n = 0, 1, 2 \dots$$

where  $v$  is the water velocity and  $d$  is the receiver depth. The first non-zero frequency notch ( $v/2d$ ) has historically been the limit of usable seismic bandwidth. To increase high-frequency content, one needs to move the cable shallower (smaller  $d$ ). However, this may result in stronger swell noise and a deeper notch at zero Hz, and thus is detrimental to the low-frequency signals. Such low-frequency signals, in many geological settings such as subsalt plays in the Gulf of Mexico, are extremely important. A technique is needed that can widen the bandwidth at both ends of the spectrum.

Soubaras (2010) introduced BroadSeis, a marine broadband solution, which incorporates variable receiver depths along a streamer. Starting from the nearest channel, the receiver depth increases with offset, introducing diversity in the receiver ghosts. This diversity enables the receiver ghost to be fully removed by using an advanced joint deconvolution algorithm (Soubaras, 2010). The resulting seismic image has a much wider bandwidth at both ends of the spectrum than an image produced with conventional data. At the same time, it is no more complex to acquire such variable-depth streamer data than to acquire conventional data since the same conventional solid streamers (Sentinel in this case) are towed at pre-defined variable depths, in a shape automatically regulated by the depth-controllers.

To prove the concept, several variable-depth streamer datasets across the world have been acquired and processed. The images obtained are consistently better than conventional data in terms of vertical and lateral resolution and stratigraphic definition. The increased low-frequency content also provides better penetration and leads to improved imaging at depth and below complex overburdens.

To obtain such improved images, the standard marine processing flow has to be adjusted to accommodate the wider bandwidth of the data and to address the issues related to a variable receiver ghost, which is a direct result of variable receiver depths. The spectrum can extend from 2.5 Hz to more than 150 Hz, which is much wider than that of conventional data. Therefore, one of the challenges is to preserve this wide bandwidth throughout the processing sequence. Another challenge is modelling the multiples in the surface related multiple elimination (SRME) step, as the variable ghosts cause conventionally modelled multiples to have different ghosts than the actual multiples in the data. The third challenge is velocity analysis because a primary event and its ghost have different curvatures in common image gathers (CIGs).

To address these challenges, some modifications to the marine processing flow are necessary. Table 1 shows a comparison between the conventional processing flow and the adjusted flow for variable-depth streamer data in a deepwater environment. The main differences are: zero-phasing and datum

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# Data Processing

Conventional Flat Streamer Data Processing Flow	Variable-Depth Streamer Data Processing Flow
1. Zero-phasing de-signature filter (with both source and receiver ghosts)	1. Zero-phasing de-signature filter (with source ghost only)
2. Datum correction (both source and receiver sides)	2. Datum correction (source side only)
3. Sail-line domain de-noise	3. Sail-line domain de-noise
4. Shot/channel amplitude correction	4. Shot/channel amplitude correction
5. Tidal and water column static correction	5. Tidal and water column static correction
6. Standard true-azimuth 3D SRME	6. BroadSeis true azimuth 3D SRME
7. Data regularization	7. Data regularization
8. Velocity analysis	8. Velocity analysis
9. Migration (one migration)	9. Migration (primary and mirror migrations)
10. RMO	10. Prestack de-ghosting
11. Stack	11. RMO
	12. Stack

Table 1 Processing flow comparison with the differences highlighted in red for the variable depth streamer.

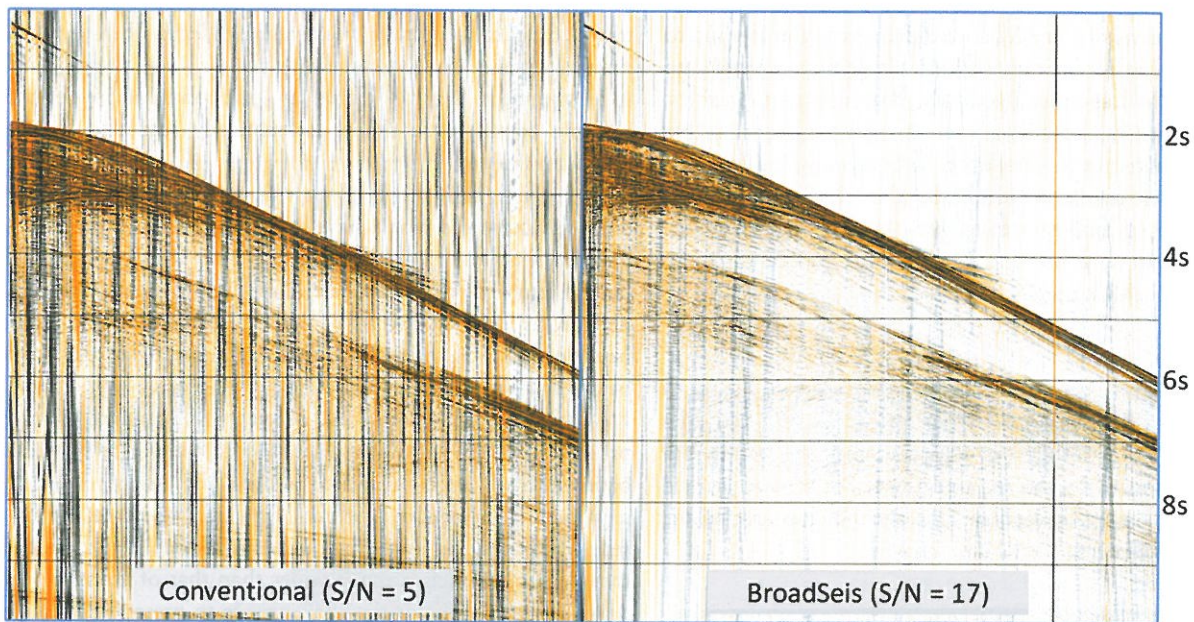


Figure 1 Raw shot comparison demonstrating how much less noisy the BroadSeis data are compared to the conventional, with a significantly higher S/N ratio.

correction, de-noise, de-multiple (3D SRME), velocity analysis, migration, and de-ghosting. In the following sections, we will discuss these steps, and show some data examples to highlight the effectiveness of this flow.

### Noise contamination

By towing the streamer deeper (as deep as 50 m), we expect the background noise levels, such as swell noise, to be lower. This allows us to recover more signal at low frequency (from 2.5 to 10 Hz). Figure 1 shows typical raw shot gathers from conventional flat streamer and variable-depth streamer data. As expected, the noise level on the variable-depth streamer

gather is much lower except for some near channels. This is indicated by their respective signal/noise (S/N) ratios. The noise was averaged over all the channels above the water bottom, and the signal was measured right below the water bottom. Even with a higher S/N ratio, the shot-domain de-noise can still be very challenging because of the desire to preserve as much low-frequency signal as possible. The typical 3 Hz low-cut filter, for example, should not be applied to variable-depth streamer data.

### Zero-phasing de-signature and datum correction

For conventional flat streamer data, source and receiver ghosts are typically treated as parts of the wavelet because of the

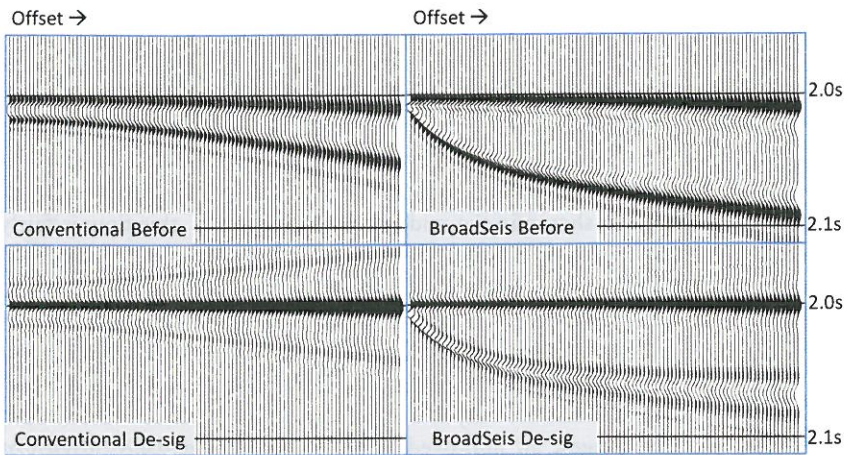


Figure 2 NMO-corrected synthetic CDP gathers, before and after de-signature filter and datum correction, demonstrate how variable depth streamer acquisition separates the receiver ghost from the primary wavelet.

difficulty in removing them. A de-signature filter is designed to rotate this combined wavelet to zero phase. However, since the receiver ghost can be removed from variable-depth streamer data, it is excluded from the designature filter design.

Figure 2 shows some synthetic common depth point (CDP) gathers simulating variable-depth streamer data (the upper right panel) and conventional flat streamer data (the upper left panel). One obvious difference is that variable-depth streamer data have a distinctly separate trailing event, which is the receiver ghost. The conventional data, on the other hand, have one single event from near to far offsets. The apparent curvature of the side-lobes (dark parts) is due to NMO stretch. This single event actually includes the source and receiver ghosts. The differences become even

more significant after applying the respective de-signature filters (the lower two panels). For variable-depth streamer data, both the primary event and its ghost are converted to zero phase. The trailing receiver ghost will be preserved until the de-ghosting step. For the conventional data, the whole wavelet is rotated to zero phase.

**Multiple attenuation**

Due to the variation of receiver ghosts, variable-depth streamer data present new challenges for de-multiple methods such as SRME.

The main issue with SRME is how to handle the receiver ghost variation. By convolving the traces with different receiver ghosts, the standard SRME method (Berkhout and Verschuur, 1997) produces multiple models that can have

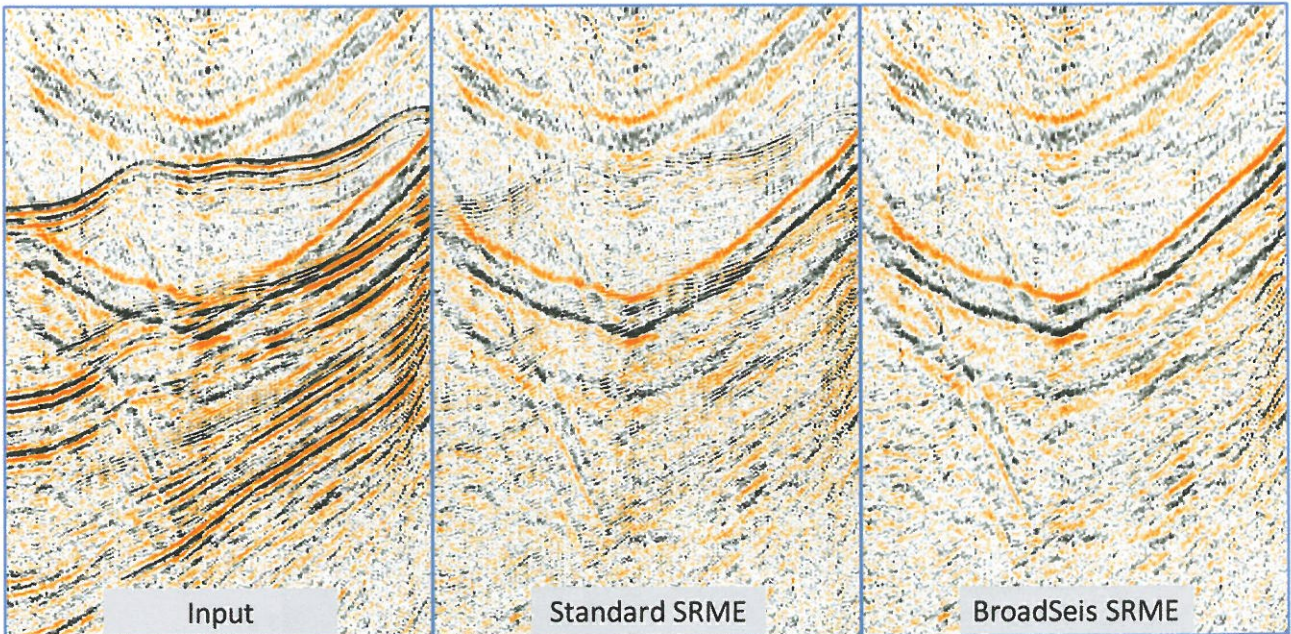


Figure 3 Variable-depth streamer data benefit from a specialized variant of SRME. These 2D results on mid-offset data demonstrate the uplift achieved from using this specialized BroadSeis SRME.

Data Processing

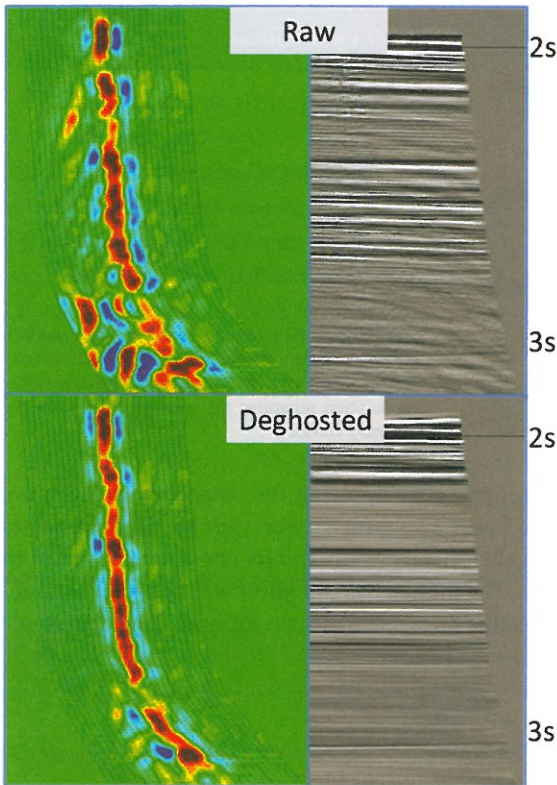


Figure 4 Prestack de-ghosting of variable-depth streamer data focuses the semblance for accurate velocity analysis.

very different wavelets from the input data, and the difference varies from offset to offset. How to normalize the wavelet is the key to an effective application of SRME. This problem can be partially handled by adjusting the model wavelet in the common-offset domain, assuming the wavelet differences are consistent within a common-offset section. As shown in the middle panel of Figure 3, this flow is fairly effective. A significant amount of multiple energy has been removed from the input data (the left panel) but some residual high-frequency multiple energy is still visible. This is due to the mismatch in the ghost notches between the input data and the multiple model. Least-squares adaptive subtraction cannot fully overcome this problem. Sablon et al (2011) suggest an improved SRME method (BroadSeis SRME) to take care of the receiver ghost diversity during the prediction process instead of in the subtraction step. The right panel in Figure 3 shows that this method is more effective. There is much less residual high-frequency multiple energy.

When the water depth is less than 200 m, SRME becomes less effective. Shallow water de-multiple (SWD, Hung et al. 2010) has been proved to work well in these situations (Sablon et al, 2011). Additionally, we have tried to avoid using Radon before de-ghosting because of the potential damage to receiver ghosts. However Radon is still very useful for cleaning up gathers before velocity and AVO analyses. It is applied to the full dataset after prestack de-ghosting.

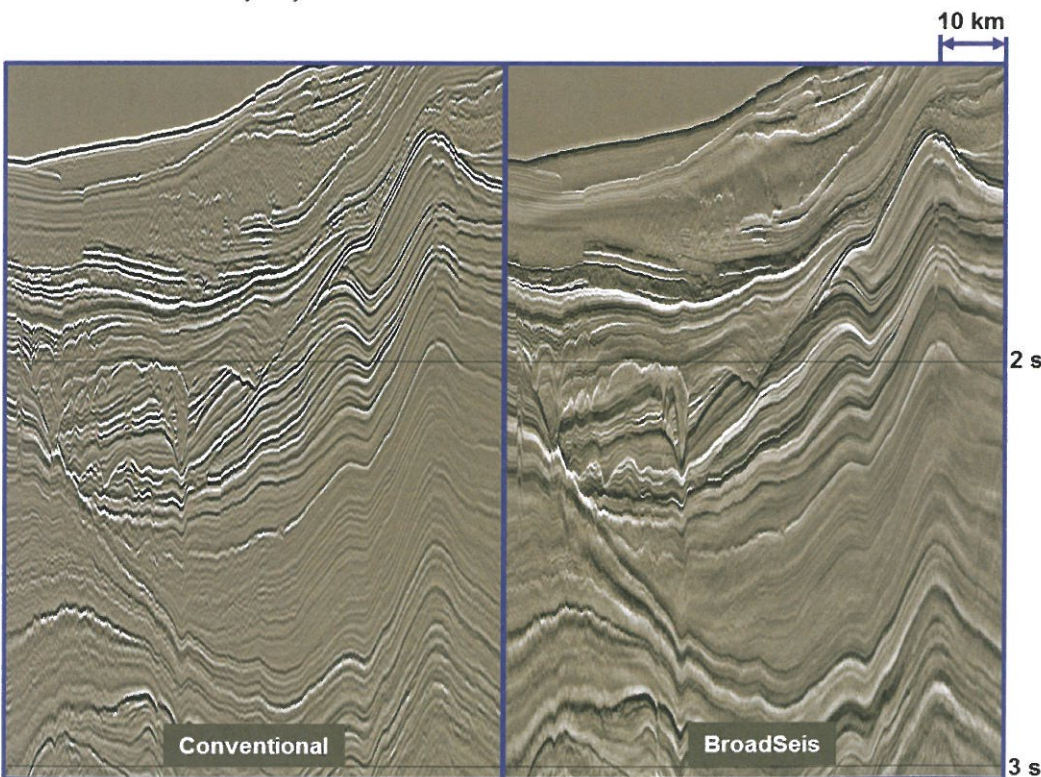
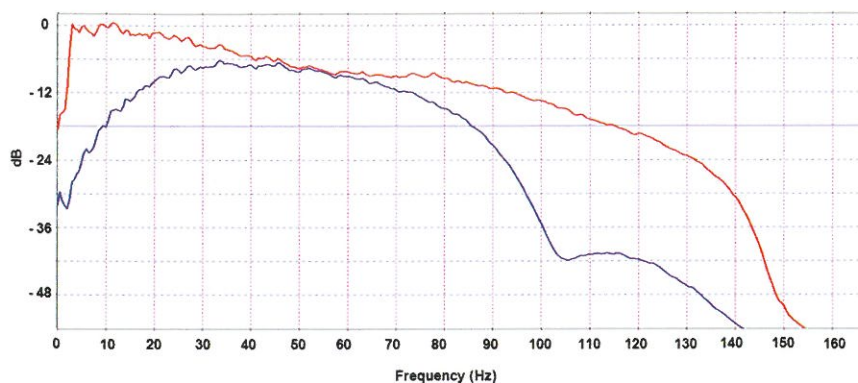


Figure 5 PSTM images from offshore West Australia showing the improved resolution and unique texture which variable-depth streamer data provide. Corresponding amplitude spectra are shown in Figure 6.



**Figure 6** Amplitude spectra, taken from the seismic data in Figure 5, showing the variable-depth streamer data possess both improved low and high frequencies. The spectra were calculated over the whole trace.

**Velocity analysis and migration**

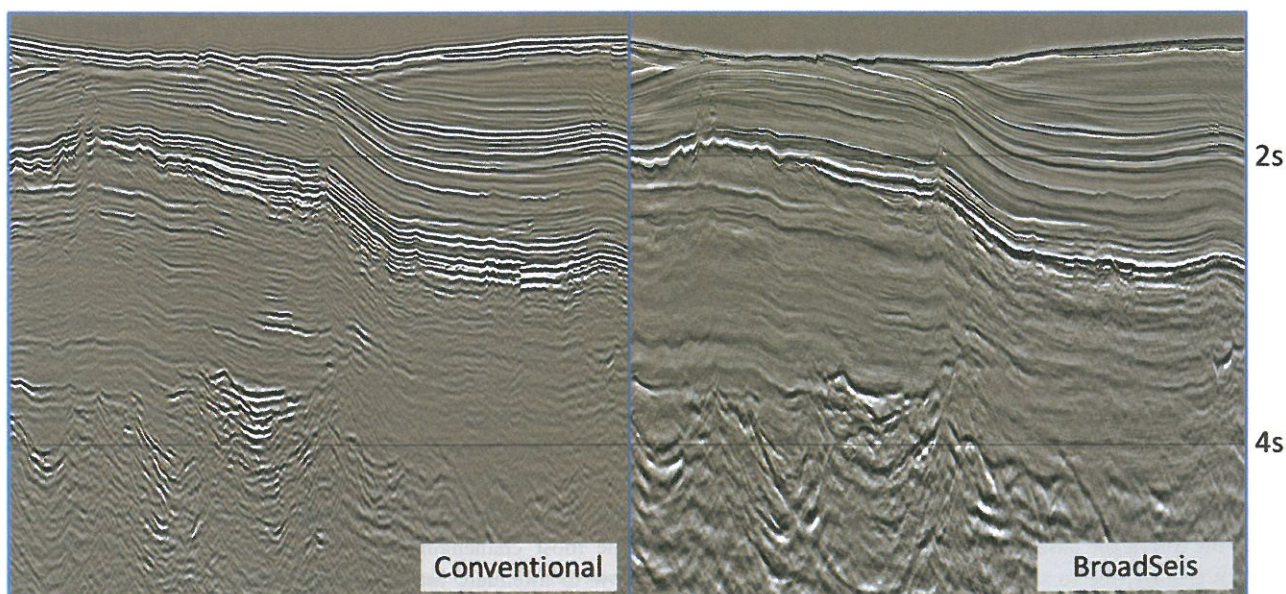
Unlike conventional data, the receiver ghost in variable-depth streamer data can appear as a separate event from the primary event (Figure 2) and has different curvature. This leads to a lower resolution in velocity semblance and some uncertainty in curvature picking. With the prestack de-ghosting algorithm (Soubaras, 2010), ghosts can be removed before any velocity analysis. As shown in Figure 4, the semblance then becomes sharper and allows more accurate velocity determination. For standard tomographic velocity update this does mean that the gathers have to be de-ghosted for each iteration of velocity model updating. This burden can be alleviated by non-linear slope tomography (Guillaume et al, 2008) because it only requires one migration and one de-ghost during all tomography iterations.

Following velocity model building, migration is the next challenge. First, two migrations have to be performed: primary migration (honouring the receiver depth) and

mirror migration (honouring the mirrored positions of receivers). Secondly, the wide bandwidth of the data puts demanding constraints on imaging. At the high-frequency end, the migration grid should be small enough to preserve high frequencies when the targets are steeply dipping events. In some cases, an inline bin size of 6.25 m has to be used. At the low-frequency end, migration algorithms have to be adjusted to deal with extra low-frequency signals. The reverse time migration (RTM) boundary condition, for example, needs special care so that artifacts will not be created during migration.

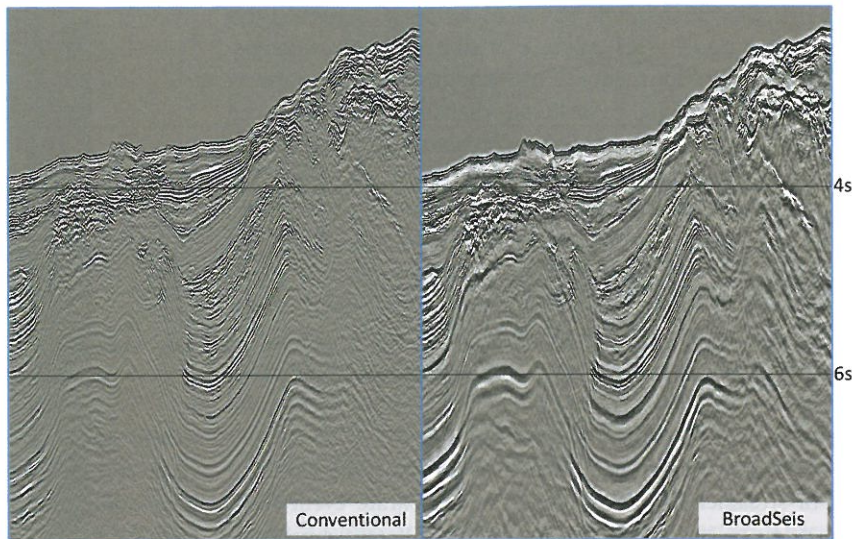
**Final pre-stack time migration images**

By adjusting these processing steps superior images were obtained, compared to conventional results, with better vertical and lateral resolution, stratigraphic detail and low-frequency content for improved coherency at depth. Here, four examples are used to demonstrate the point.



**Figure 7** PSTM sections from the West of Shetlands area demonstrating higher resolution in the near surface, better defined top basalt and cleaner sub-basalt data on the variable-depth streamer data. The top basalt is the strong reflector dipping to the right between 2 and 3 seconds.

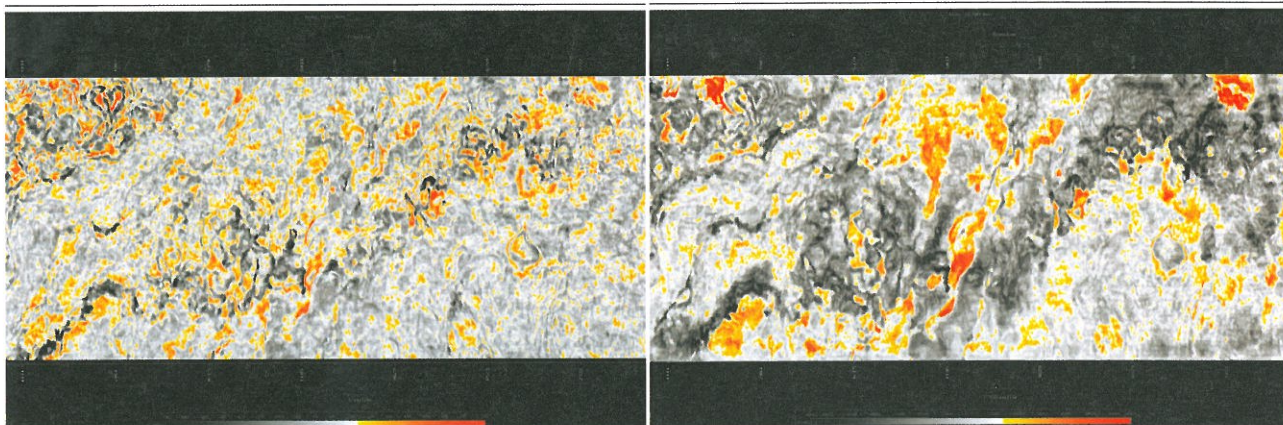
# Data Processing



**Figure 8** PSTM sections from the Gulf of Mexico. The variable-depth streamer data exhibit frequencies up to 155 Hz in the shallow sediments. More importantly, the low frequencies present in the variable-depth streamer data provide much higher amplitude reflections below the salt on the right of the panel.

Time-slice: Conventional

Time-slice: BroadSeis



**Figure 9** 3D time slices from the Central North Sea showing the subtle detail and rich character of the variable-depth streamer result compared to the noisier character of the conventional data.

The first example is a 2D dataset from offshore West Australia (Figure 5). The broad bandwidth (Figure 6) of variable-depth streamer data is well displayed in the seismic image. Compared to conventional data, the extra low-frequency energy gives the layers some unique texture that may be related to rock properties. In addition, the high frequencies crisply delineate the layer boundaries. Another important observation is that the brightness or shade (light or dark) of the layers conforms to the layer structures. This indicates good phase control in the low frequency.

The second 2D data set is from the West of Shetland area (Figure 7). Variable-depth streamer data provide sharper and crisper reflectors in the near surface. More especially, the top of the basalt is much better defined and easier to interpret. Below the top of the basalt, the variable-depth streamer image is much cleaner due to stronger low-frequency content. Such an improved image will be very beneficial for sub-basalt exploration.

The third example is also a 2D data set, this time from the Gulf of Mexico. A shallow source depth was used and the variable depth profile of the streamer was optimized to obtain a spectrum from 2.5 Hz to 155 Hz. The 2D time migration image is shown in Figure 8. The increased resolution is evident in the shallow sediments. But more importantly, the low-frequency signal below the salt is much stronger than that in the conventional image. This enhanced signal will help image base of salt and subsalt structures. Variable-depth streamer data, together with wide-azimuth and long-offset acquisition geometries, is set to provide a combination that could play a role in subsalt exploration in the Gulf of Mexico.

The fourth example is from the Central North Sea. This is a 3D survey with a shallow water depth (about 100 m). The most challenging task in processing this data set was how to attenuate the multiples without damaging either the primaries or the receiver ghosts. Tests show SWD plus Tau-P-deconvolution to be the most effective sequence, as presented

in Sablon et al (2011). Figure 9 shows time slices from the final conventional and variable-depth streamer images. The broadband nature of the variable-depth streamer data (the lower panel) is well displayed on the time slice. Numerous fine structures are present in a smooth background of black, white and red colors, which may indicate the different rock properties. By comparison, the conventional image lacks such richness and appears noisier (the upper panel).

### Conclusions

Data examples show that variable-depth streamer data can provide a very wide frequency spectrum. It is superior to conventional data in terms of seismic resolution, definition of stratigraphy, and imaging at depth and below complex overburdens. The modified processing flow, as shown in Table 1, preserves high- and low-frequency signals and carries them into the final images. The challenges in de-noise, multiple attenuation, velocity analysis and migration have also been properly addressed. However, as more and more 3D variable-depth streamer data are being acquired, we expect the processing flow to be further adapted and optimized for different datasets.

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