Variable-depth streamer – a broadband marine solution

Robert Soubaras[1*] and Robert Dowle[1] explain how a broadband solution leveraging the benefits of towing variable depth solid streamers and proprietary deghosting processing techniques can resolve a longstanding challenge in marine seismic acquisition.

The benefits of acquiring broadband marine seismic data have long been accepted, but until recently this has been difficult, if not impossible to achieve. There have been many reasons for this, among them being that older streamers had in-built instrument filters that prevented them from recording the low frequencies, that the low frequencies that were recorded were contaminated by noise, and that the source and streamer ghosts caused notches in the amplitude spectrum. New equipment and techniques in acquisition have largely overcome most of these problems.

Desirability of broad bandwidth

Broad bandwidth is desirable because it produces sharper wavelets for better resolution of important features such as thin beds and stratigraphic traps. Low frequencies provide better penetration for deep targets, as well as better stability for inversion.

At least two octaves of signal are required for seismic imaging and more are better. Contrary to intuition, the main effect of increasing the low frequency content of data is to decrease the side lobes of the wavelet, thus making accurate interpretation easier, as shown in Figure 1. Increasing the high frequency content sharpens the central peak of the wavelet, yet still leaves reverberating side lobes making precise interpretation difficult. The sharpest wavelets, and therefore the best resolution, are produced by extending the bandwidth in both the low and high frequency directions. It is now possible to record a full six octaves of signal by using BroadSeis, a proprietary broadband solution that combines state-of-the-art equipment with novel acquisition geometries and proprietary processing algorithms to produce the broadest possible bandwidth.

Equipment

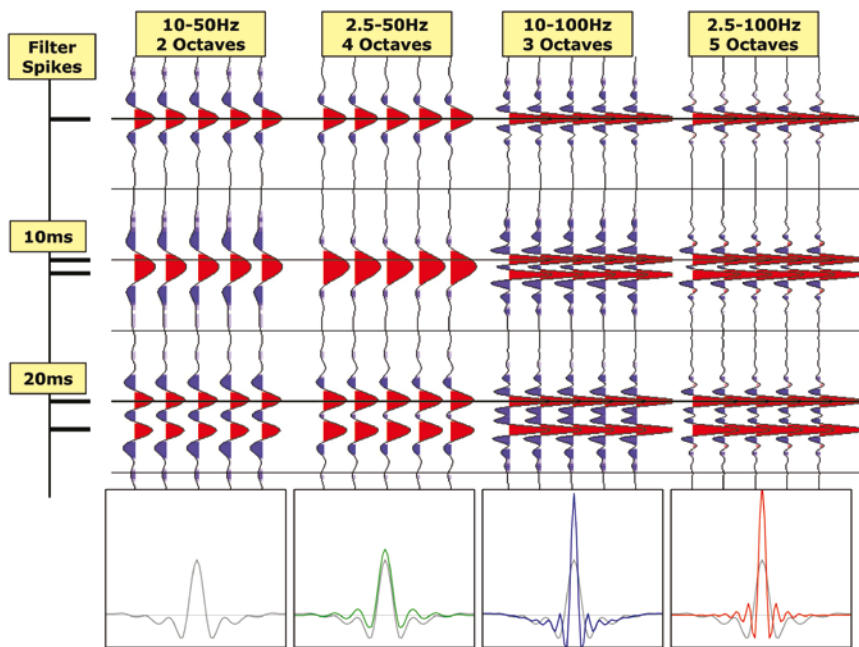Central to this new broadband solution is the use of proprietary solid streamers, as these have outstanding low

Figure 1 Increasing the number of octaves in a seismic wavelet provides better resolution and more precise interpretation.

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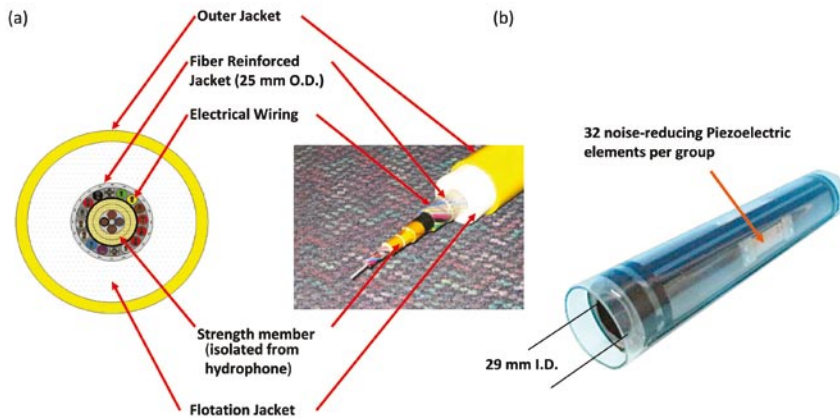
special topic

Marine Seismic

Figure 2 (a) Image of cut-away solid streamer showing the solid foam fill which isolates the hydrophone from the strain member. (b) Image of the cylindrical hydrophone assembly which is embedded in the foam flotation jacket and contains 32 noise-cancelling piezoelectric elements per group.

frequency and low noise performance as well as the ability to be towed at greater depths than industry norms. New generation electronics allow such streamers to record data down to 2 Hz, adding an extra one or two octaves to the low frequency end of the spectrum; the challenge is to record signal rather than noise at these frequencies. Dowle (2006) describes some of the advances in streamer technology that address this issue. Solid streamers are specifically designed to reduce noise (particularly sea state noise), as the cylindrical hydrophone assembly, containing 32 noise-cancelling piezoelectric elements per group, is embedded in the foam flotation jacket and isolated from the strain member, thus reducing vibration noise sensitivity (see Figure 2). Using a solid foam fill inhibits the transmission of noise wave modes, such as bulge waves along the streamer, making the streamer inherently quieter than either fluid or gel cables as shown in Figure 3.

This combination of low frequency hydrophone recording and reduced noise provided by solid streamers is the basis of the new broadband solution. An additional advantage is that the solid streamer has a uniform density, stable buoyancy, and is robust enough to operate at extreme depths (down to 60 m). This deep tow capability facilitates streamer depth

profiles which allow the recording of significant ghost-notch diversity and optimal low frequency signal.

Receiver ghosts

Towing cables at depth reduces the sea state noise recorded, but introduces streamer ghost notches in the amplitude spectrum within the seismic frequency range. These notches are caused by the sea surface reflected wave interfering with the direct arrival, with constructive and destructive interference creating the ghost effect. For vertical incidence the ghost time is computed as $t=2z/v$, where z = streamer (or source) depth and v = velocity. The notches in the spectrum are found at frequencies of $c/2z$, where c = water velocity, so approximately $750/cabledepth$ Hz.

In conventional acquisition, it is necessary to tow the streamer close to the sea surface so that the first ghost notch occurs beyond the frequency range required for imaging. However, this choice also results in attenuation of lower frequencies (see Figure 4) and increases the noise recorded at the low frequency end.

In the past, the ghost notches dictated the depths at which sources and streamers were towed. As the cable is moved deeper, a better low frequency response is obtained,
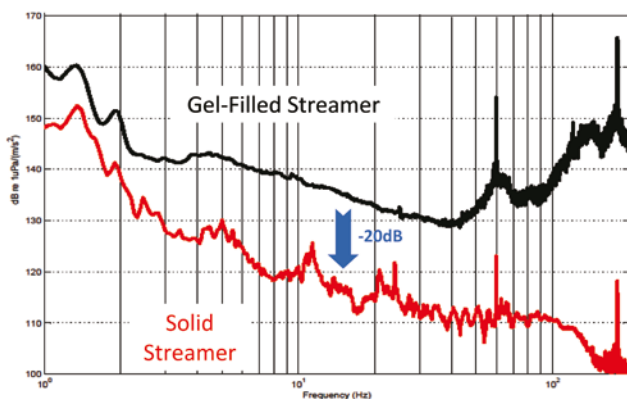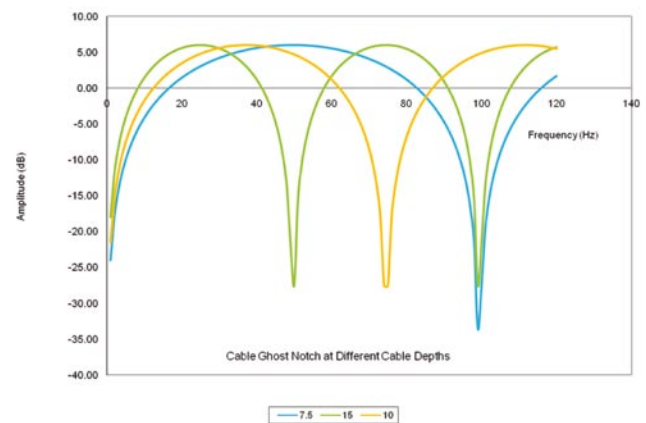

Figure 3 Noise performance of a solid streamer compared with a gel-filled streamer in a vibration tank test. The noise level of the solid streamer is up to 20 dB below that of the gel-filled streamer.

Figure 4 Notches in the amplitude spectrum caused by ghosts at different streamer depths lead to compromises in data quality during survey design.

with a lower noise level, but the ghost notches affect the seismic passband. For low frequencies, and especially for deep penetration in challenging geological environments such as basalt or very deep layers, it is beneficial to tow the streamer deep. However, unless the notches are removed, the higher frequencies will suffer. In cases where only low frequencies are of interest, for example up to 25 Hz, and it is acceptable to sacrifice the high frequencies, a tow-depth of 25 m depth could be ideal.

This dilemma has led to compromises in the bandwidth recorded for most surveys. Because of their inherent resistance to sea state noise, solid streamers can be towed shallow to record the high frequencies without causing undue noise contamination to the low frequencies, but still need to be towed deep to record the full low frequency signal.

Different acquisition techniques have been proposed to overcome this problem, including deep-towed dual-sensor streamers, with the upgoing waves, recorded by the geophone, being used to infill the notch in the hydrophone data, or towing pairs of streamers at different depths to yield a fuller frequency range by combination and deghosting.

The broadband marine solution described in this paper acquires both the low and high frequencies with the same set of solid streamers and a variable depth towing configuration to deliver an elegantly simple solution with a vastly improved bandwidth in the final image. With this configuration (patent pending), the receiver ghost notch varies along the cable and this 'notch diversity' is exploited by new proprietary deghosting and imaging techniques (patent pending). The wavelet produced yields both a high signal-to-noise ratio and maximum bandwidth, which provide the clearest images of the subsurface for any target depth.

The variability of the streamer depth and shape of the cable, and hence the diversity of the streamer ghost notch, can be tuned for different targets so that the notch diversity and output spectra are optimized for each survey. This cable shape is designed according to the water depth, target depth, and velocity profile of the survey area.

Deghosting

CGGVeritas has developed a novel, proprietary deghosting method (Soubaras 2010 – patent pending) adapted to any broadband acquisition technique, that is insensitive to noise, amplitude-preserving, and able to provide the true deghosted earth response (i.e., the response that would be obtained should the water surface be non-reflecting).
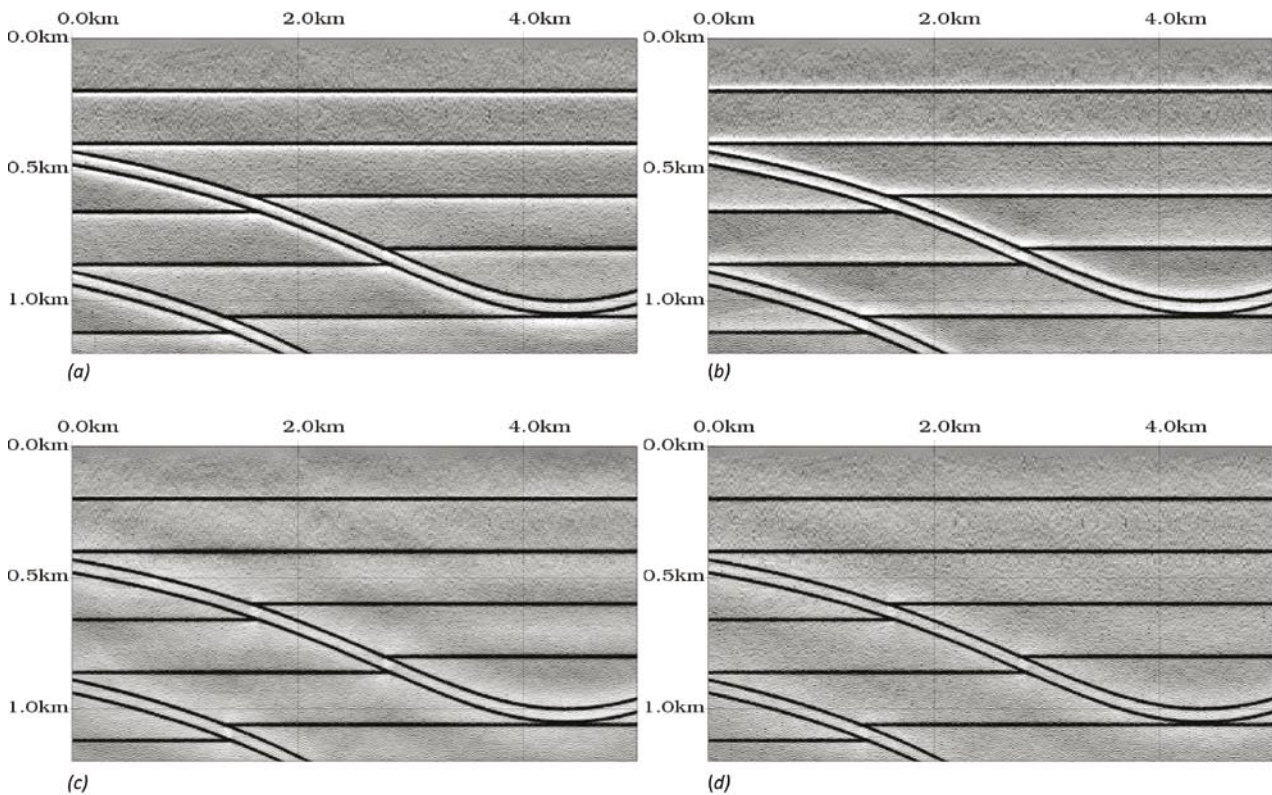

Figure 5 Synthetic dataset comparisons. (a) Migration with residual ghost appearing as a causal minimum-phase distortion (ghost lags the primaries). (b) Mirror migration with residual primaries appearing as an anti-causal maximum-phase distortion. (c) Deghosted migration (joint deconvolution of migration and mirror migration in a windowed, multi-channel manner). (d) Reference migration, computed by migrating the synthetic without including the modeled ghosts.

Figure 6 *Since its launch at the recent EAGE convention, eight BroadSeis surveys have been completed, both 2D and 3D, proprietary and non-proprietary.*
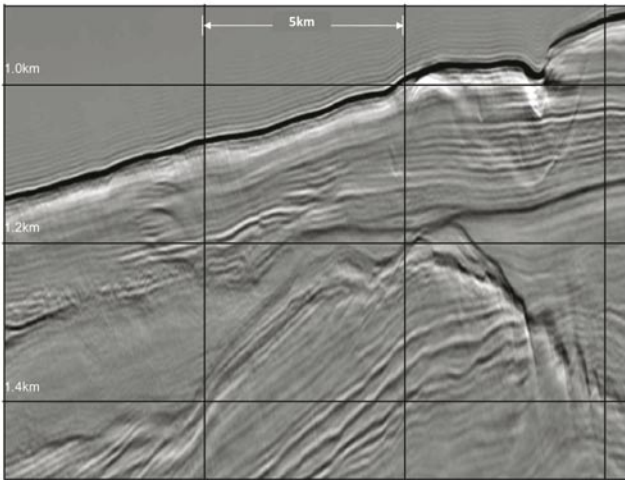

Figure 7 *NW Australia, depth migration stack image with residual ghost appearing as a causal minimum-phase distortion (visible below the water bottom). Data courtesy of CGGVeritas Data Library.*
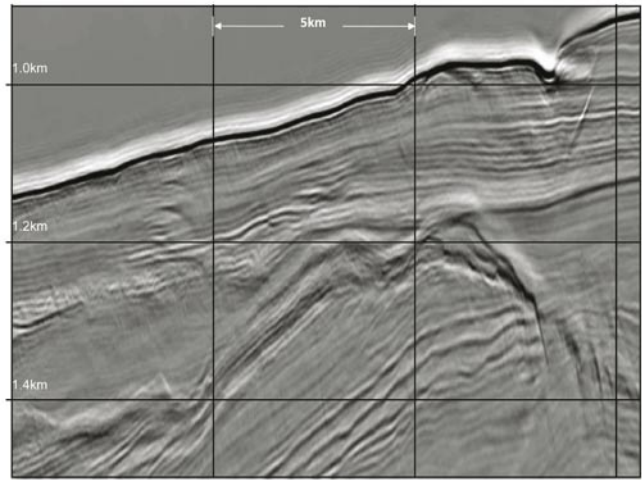

Figure 8 *NW Australia, mirror migration stack image where the ghost is imaged at negative polarity to match the primaries in Figure 3, and the residual primaries appear as an anti-causal maximum-phase distortion (visible above the water bottom). Data courtesy of CGGVeritas Data Library.*
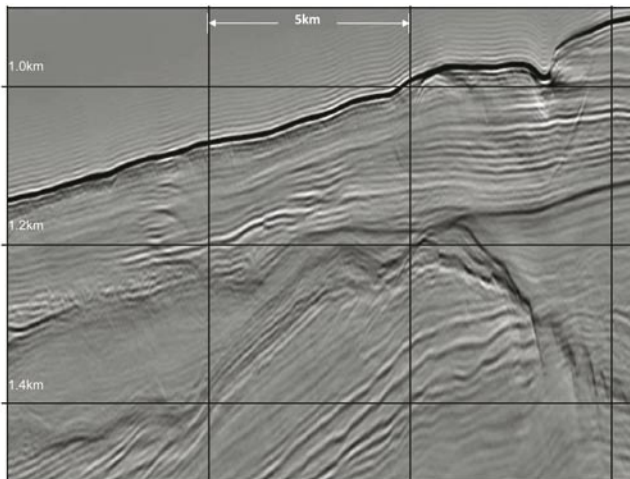

Figure 9 *NW Australia, broadband PSDM stack image after de-ghosting by joint deconvolution. Data courtesy of CGGVeritas Data Library.*
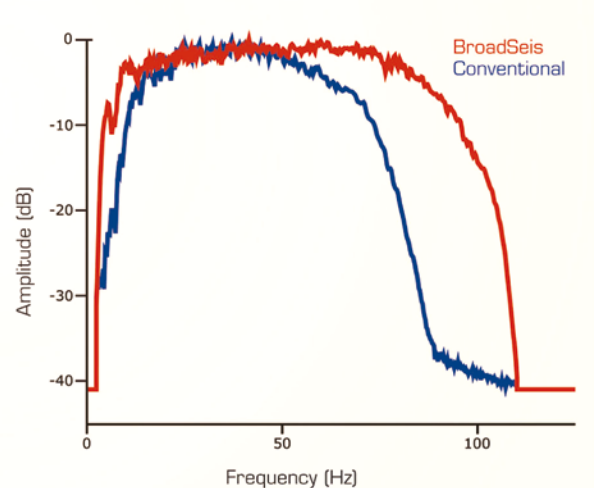

Figure 10 *NW Australia, comparison of amplitude spectra of the legacy dataset with the new broadband data. Data courtesy of CGGVeritas Data Library.*
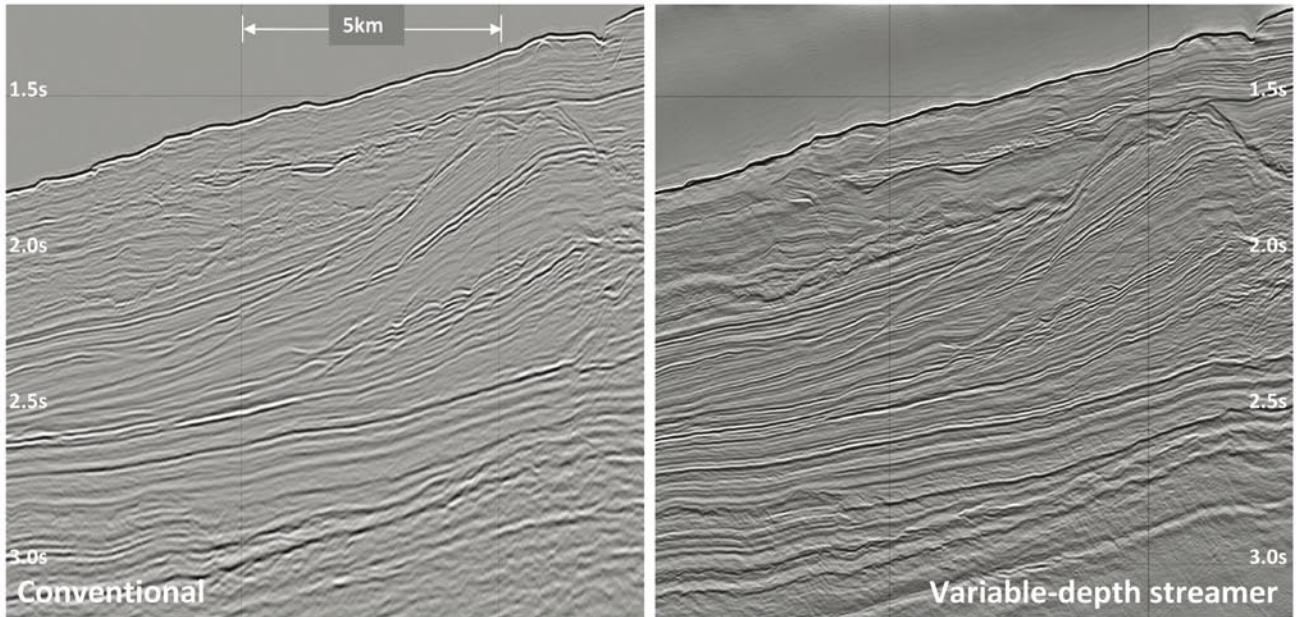
Figure 11 NW Australia, comparison of legacy dataset (left) with the new broadband image (right). Data courtesy of CGGVeritas Data Library.

The principle of this method is to produce a conventional migration as well as a mirror migration, and then to perform a joint deconvolution of these two images. A mirror migration is referred to as one which migrates from a duplicate set of receivers that are mirrored above the surface.

We demonstrate the process on a 2D synthetic dataset using a velocity model with a vertical gradient, an actual airgun wavelet to model the shots, and a variable depth streamer. The modelling of the shots is done twice: once with a reflecting water surface (ghosted data) and once without (reference unghosted data). The same level of noise is added to both sets of shots. The shots with the ghost are processed through deterministic designature, migration, mirror migration, and joint deconvolution, while the reference shots are processed through designature and migration (see Figure 5).

In the conventional migration, the primary events are perfectly stacked, while the imperfectly stacked ghost events are present in the form of a causal residual ghost wavelet (i.e., lagging the primaries) (Figure 5a). Conversely, in the mirror migration, the ghost events are perfectly stacked with their polarity reversed, whilst the imperfectly stacked primary events are present in the form of an anti-causal residual wavelet (i.e., the residual primaries precede the well imaged ghosts) (Figure 5b).

This dual imaging of the same reflectivity with two different viewpoints is used to extract the true amplitude deghosted migration. It is a reasonable assumption to consider a ghost wavelet as a minimum phase signal, or at least a marginally minimum phase signal. Likewise it can be considered that the mirror migration gives the same reflec-

tivity as the migration but distorted by a wavelet which is maximum-phase.

This can be considered as a binocular vision of the reflectivity with the conventional migration image coloured by a normalized minimum phase distortion, and the mirror migration image coloured by a normalized maximum phase distortion. To recover the reflectivity in true colour (i.e., without distortion) a joint minimum phase, maximum phase deconvolution is applied on the migration and mirror migration (Figure 5c). Unlike conventional deconvolution, this is a well posed mathematical problem, which means it
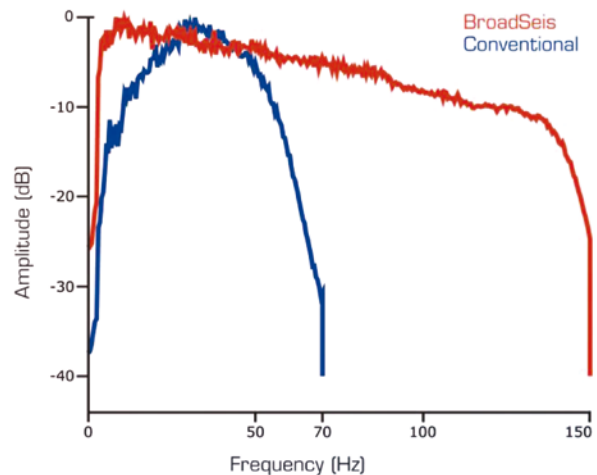

Figure 12 Offshore West Africa, data courtesy of Total, the Republic of Gabon and Cobalt. Comparison of amplitude spectra of the 'standard' conventional dataset with the new data. The combined source and receiver ghost in the conventional dataset is obvious, the new acquisition extends the spectrum by an additional octave at both the low and high ends.
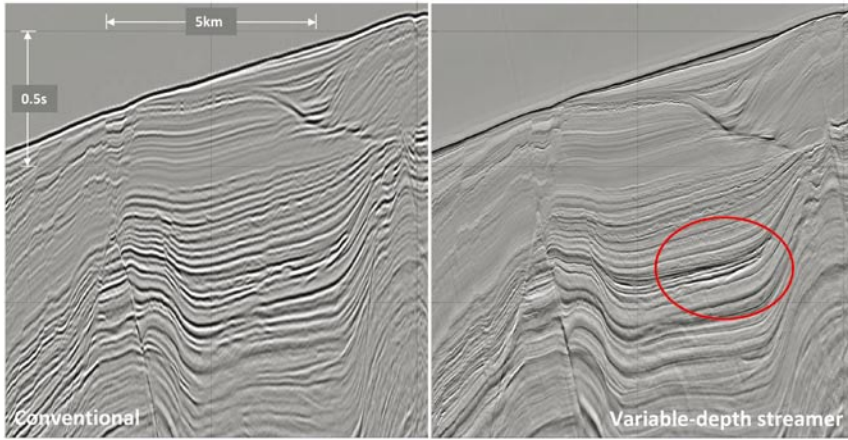
Figure 13 *Offshore West Africa, data courtesy of Total, the Republic of Gabon and Cobalt. The variable-depth streamer acquisition section (right) shows considerable improvement in resolution, especially of the pinchout marked, compared with the conventional acquisition and processing (left).*
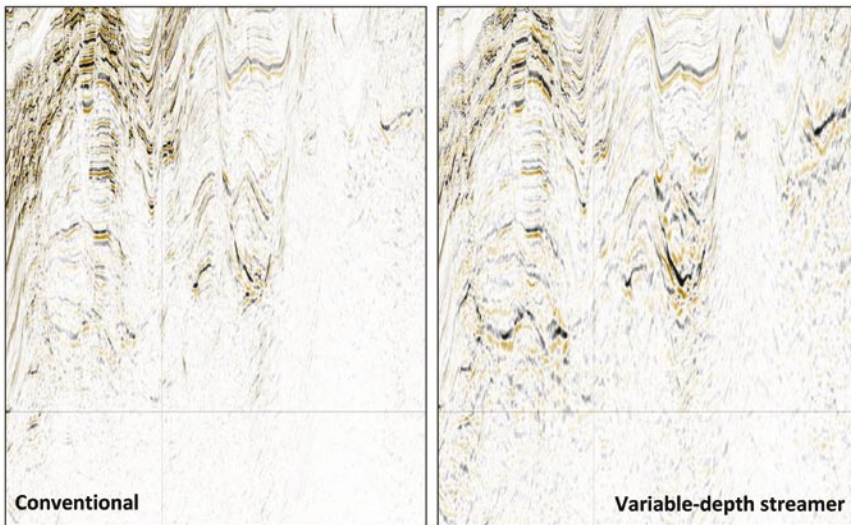

Figure 14 *Offshore West Africa, data courtesy of Total, the Republic of Gabon and Cobalt. The variable-depth streamer section (right) shows improvement in penetration and reflector continuity, compared with the conventional acquisition and processing (left). Note this is 2D data that has been imaged in time and so does not show the clarity we would expect from 3D variable-depth streamer data imaged in depth.*
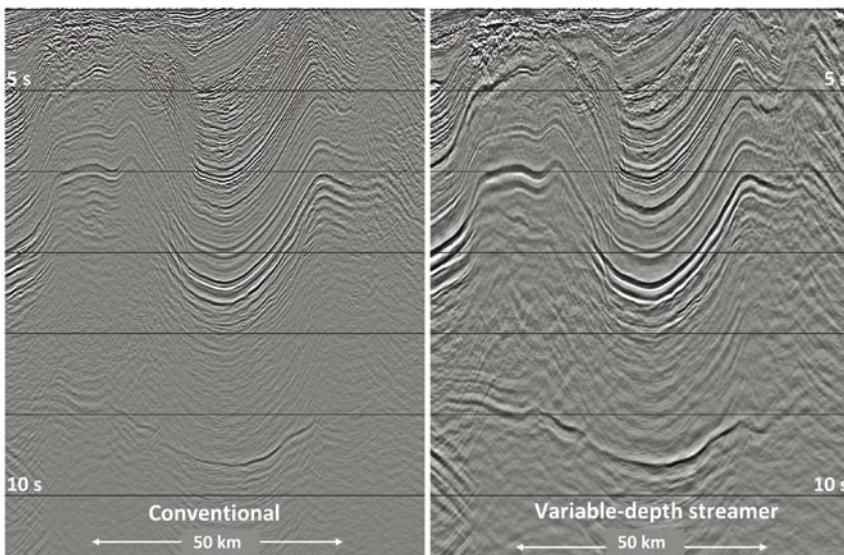

Figure 15 *Gulf of Mexico, 2D PSTM. The broader bandwidth provided by the variable-depth streamer acquisition greatly improves both resolution and penetration. Data courtesy of CGGVeritas Data Library.*
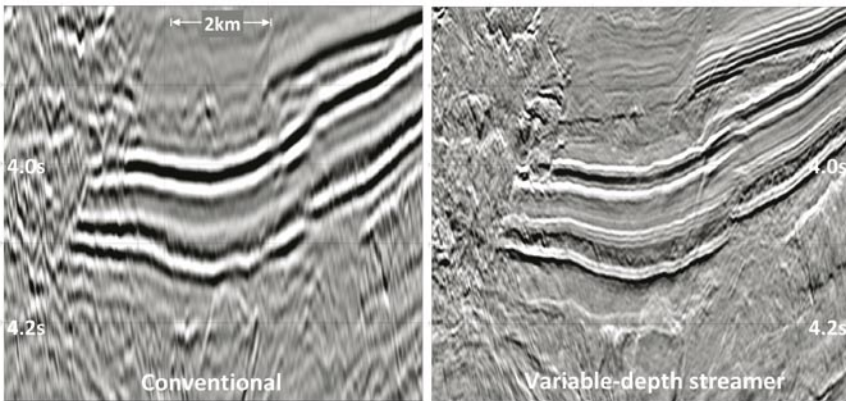
Figure 16 *Gulf of Mexico, 2D PSTM. Variable-depth streamer technology provides exceptional resolution. Data courtesy of CGGVeritas Data Library.*

has a unique solution, even when the operators have perfect spectral notches. Therefore, there is no requirement for the usual assumption that the reflectivity is white; the amplitude spectrum of the reflectivity remains arbitrary. Comparison of the deghosted migration (Figure 5c) with the reference migration (Figure 5d) gives a close match, showing the true amplitude nature of the algorithm.

The matched mirror migration and joint deconvolution deghosting technique is well suited to variable depth streamer acquisition. The technique is fully 3D as it makes no 2D assumptions and has no limitations in the cross-line direction, making it suitable for wide-azimuth as well as 3D surveys.

Variable-depth streamer acquisition

One of the benefits of variable depth streamer acquisition is that it uses proven, readily available equipment and so can be put into operation immediately. It can take full advantage of towing solid streamers at what are currently considered as extreme depths to benefit from the improved low frequency response of the hydrophones and reduced sea-state noise. Control of solid streamers to variable depths has proved to be robust and stable, even down to 60 m.

This flexibility means that the technique can be used for a range of applications. The increase in penetration

from the extension of the bandwidth at the low end will benefit the imaging of deep targets and those below complex overburdens. Shallow targets (and shallow hazards) will benefit from the total bandwidth available and recordable.

This acquisition technique has been successfully deployed both in the varying salinity conditions offshore West Africa and in the complex eddy currents of the Gulf of Mexico. Both single and multiple streamer configurations have been deployed, using several different vessels, in areas ranging from the Arctic to Australia (see Figure 6). The solid streamers retained their exceptional low noise characteristics for all depths, in all configurations and under all conditions.

Data examples

North West Australia
The first dataset to be acquired with the variable depth streamer technique and processed with the new deghosting scheme was recorded offshore NW Australia. The data was migrated in depth, after just the application of source designature. Figure 7 shows the depth migration, and Figure 8 the mirror migration of this data. The residual causal ghost can be easily seen in the migration (Figure 7)
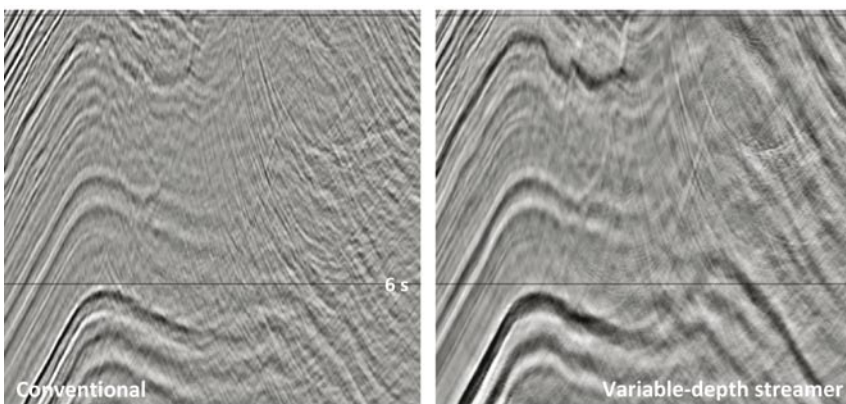

Figure 17 *Gulf of Mexico, 2D PSTM. Variable-depth streamer acquisition provides more low frequencies and less noise. Data courtesy of CGGVeritas Data Library.*
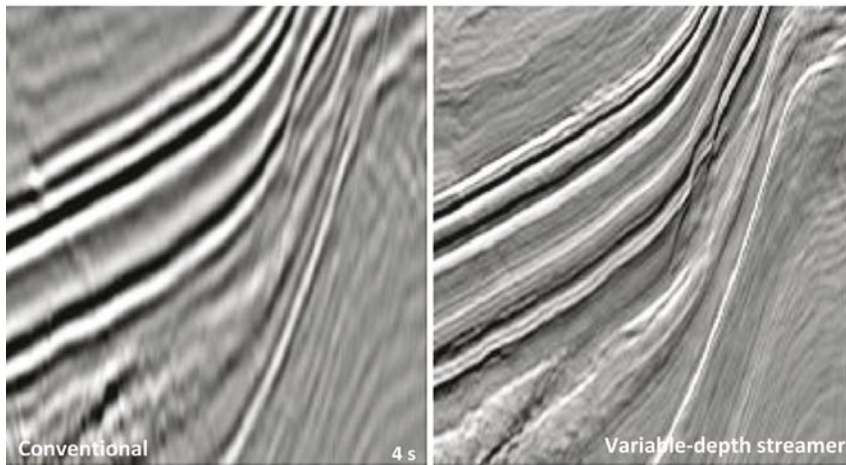
Figure 18 Gulf of Mexico, 2D PSTM. Variable-depth streamer acquisition provides superb resolution. Data courtesy of CGGVeritas Data Library.

below the water bottom, as can the anti-causal ghost on the mirror migration (Figure 8) above the water bottom. Figure 9 shows the deghosted output after application of the joint deconvolution, with no spectral shaping applied. The deghosted output shows the broadband nature of the final image with low frequencies down to 2.5 Hz and high frequencies up to 110 Hz, as well as the intrinsic noise-free character of this approach. These results are compared to legacy data (Figures 10 and 11) over the same area to indicate the uplift in resolution possible with modern broadband acquisition and imaging techniques.

Offshore West Africa

In another recent example, a line from a conventional 3D survey, recorded offshore West Africa using standard acquisition parameters for the area, was reshot using a variable depth streamer acquisition for comparison. The conventional data was acquired using a source at 10 m and cable at 11 m, producing a combined source and receiver ghost around 75Hz (see Figure 12). The variable depth streamer acquisition data was recorded with the source at 5 m and a streamer profile with a maximum depth of 48.5 m. This extended the spectrum at both the low and high ends, producing almost six octaves of signal from 2.5–150Hz, with exceptional resolution and improved penetration (see Figures 12, 13, and 14).

Gulf of Mexico

Recent results in the Gulf of Mexico, as elsewhere, show improvements over conventional data, with a frequency bandwidth of 2.5–155 Hz, providing more low frequencies and less noise, as well as high quality resolution (see Figures 15–18).

Conclusion

Variable depth streamer acquisition data are characterized by sharp, clean wavelets that deliver a significant increase in the bandwidth of subsurface images, allowing for more detailed interpretation. As we see more examples of such seismic data that we have acquired and processed from around the world, these benefits have become increasingly apparent. Enhancements in data quality are observed in all ranges of geological settings.

Acknowledgments

References

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Dowle, R. [2006] Solid streamer noise reduction principles. *75th SEG Annual Meeting*, Expanded Abstracts **25**, 85-89.