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Unlocking the Full Potential of Broadband Data with Advanced Processing Technology, a Case Study from NWS Australia

J. Zhou* (CGG), P. Chia (Shell), J. Li (CGG), H. Ng (CGG), S. Birdus (CGG), K. Teng (CGG), Y. Phan (CGG), J. Sun (CGG) & Y. He (CGG)

SUMMARY

The high costs associated with hydrocarbon exploration in deep water have led to an increased business demand for acquisition and processing of high-resolution broadband seismic data. In this paper, we review our experience of working on the Shell Sandman 3D survey, which was acquired using variable-depth streamers and synchronized multi-level sources. We focus on the key factors that influence the surface seismic temporal resolution and the technologies that provide solutions to these challenges: (1) source deghosting using source designature derived from near-field hydrophone data; (2) receiver deghosting using the 3D deghosting algorithm; and (3) compensation for the Earth absorption using centroid frequency shift Q tomography (FS-QTOMO) and QPSDM. The extra-wide bandwidth obtained from these processes provides a final image with detailed resolution that enhances quantitative characterization, not only for shallow geo-hazards but also for resolving relatively thin reservoirs in the deep section. Therefore, we can conclude that broadband seismic surveys coupled with advanced seismic processing techniques, provide an effective solution for generating high-resolution seismic images.

Introduction

One of the key potential reservoirs of the Browse basin in the North-West Australian Shelf is the Upper Cretaceous Vulcan formation, where the major play types consist primarily of uplifted horst blocks, anticlines and drape structures. Given the thin and stacked nature of these structures, it is important to provide high-resolution seismic for prospect maturation. For marine seismic surveys, the key factors influencing the bandwidth (and thus resolution) are the source and receiver ghosts, environmental noise, and Earth attenuation. One approach to mitigate the acquisition limit of the free-surface ghost is to introduce ghost notch diversity so that no strong notch is evident. This can be achieved with a variable-depth streamer (Soubaras, 2010) at the receiver side and a multi-level source array at the source side (Siliqi et al., 2013).

As the first survey using a variable-depth streamer and a multi-level source in Australia, the Sandman 3D survey was acquired in the middle of 2013. Twelve 6 km long slanted solid streamers were deployed with 100 m cable separation and variable depth of 6 to 50 m, receiving seismic signal from a synchronized multi-level source. A simple 2D PSTM processing flow has been applied to the broadband data and the adjacent conventional survey which has a source depth of 6 m and a receiver depth of 9 m. The comparison of the result (Figure 1) shows that the broadband survey provides a much sharper wavelet and richer low-frequency signal.

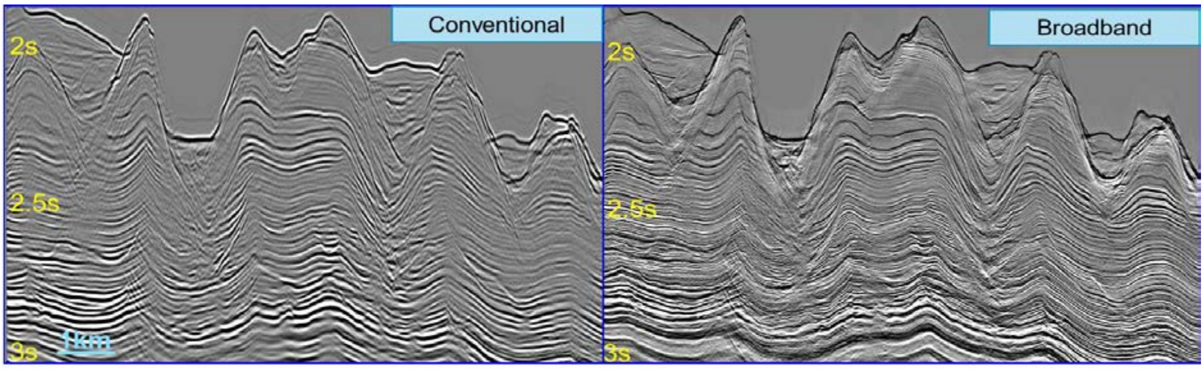

Figure 1 *2D PSTM stacks comparison: conventional survey (left) vs. broadband survey (right).*

However, to fully unlock the potential of the broadband acquisition, we need to answer the following key questions: How do we estimate the source wavelet accurately? How do we handle the 3D effect in deghosting? How do we model and compensate for the Earth absorption effect? In this paper, we focus on the discussion of these key processing steps.

Source designature using near-field hydrophone data

In this survey, each source consists of three sub-arrays with the air guns distributed in the 3D sense at depths of 6 m and 9 m. The delay time between the 6 m guns and the 9 m guns is set to 2 ms, so the deeper guns go off exactly when the downgoing wavefield from the shallower guns reaches them. Thus, the downgoing wavefields are synchronized while the upgoing wavefields (ghosts) are desynchronized, resulting in a notch-free far field with a residual ghost-mask. Provided we can obtain an accurate source signature estimation, the broadband feature of this multi-level source allows for a successful designature of up to 200 Hz, with little or no damping.

Traditionally, the source signature is derived either using modelling software or from a near-offset stacked section of the water bottom in deep water environments. These methods work well for conventional narrow-band data, but may not be accurate enough in the ultralow and ultrahigh end of the frequency spectrum for broadband data. A better approach for broadband data is to use near-field hydrophone (NFH) recordings: they can be used to derive the far-field signature either as a 1D filter for the vertical component (Ziolkowski et al., 1982), or as a set of filters in the ***F-P*** domain for directional designature (Poole et al., 2013). In Figure 2, we compare the vertical far-field signature derived from modelling software Nucleus, NFH and the water bottom reflection. The signature derived from the water bottom reflection shows significant difference in comparison with the other two signatures due to shallow layers right below and parallel to the water bottom. Although the vertical far-field signatures from modelling and NFH look similar in terms of wavelet shape and frequency spectrum, seismic sections after designature using the signature from modelling (Figure 3b) and NFH (Figure 3a) are quite different. The signature from modelling does not accurately represent bubble energy, thus more residual bubble energy is observed after designature.

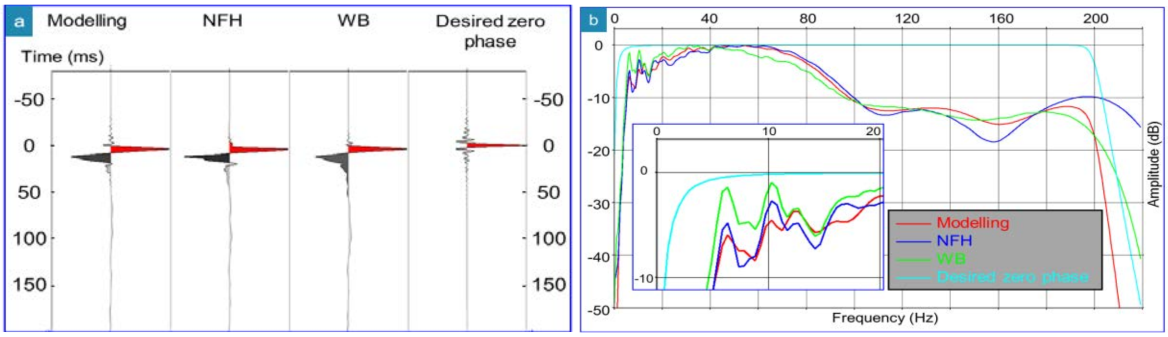

Figure 2 *Vertical far-field signature derived from modelling, NFH and water bottom reflection and the target zero-phase wavelet (a); amplitude spectra comparison (b).*

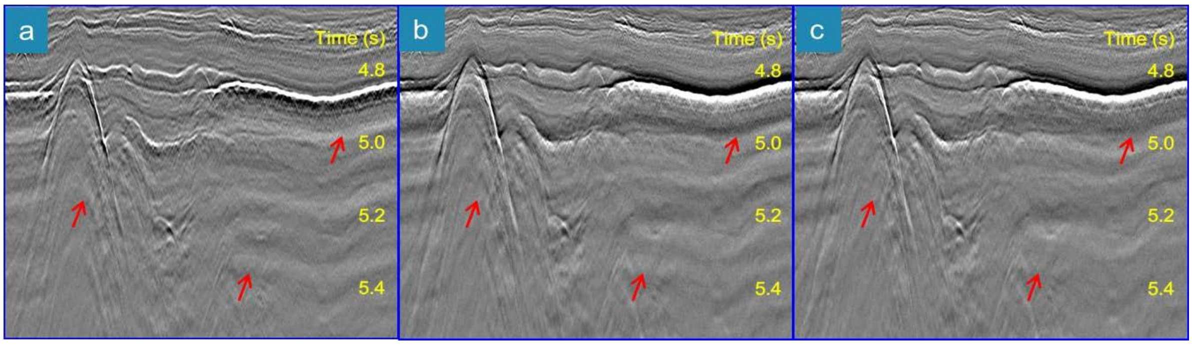

Figure 3 *Common-channel gathers (a) no designature; (b) after designature with far-field signature from modelling; (c) after designature with far-field signature from NFH.*

Receiver deghosting using bootstrap and full 3D methods

Soubaras (2010) proposed to perform the receiver deghosting in the imaging domain using a joint deconvolution method with both normal and mirror migration inputs. This allows for a true 3D deghosting, however, the need to preserve the receiver ghosts until the migration stage adds complexity to the processing work flow especially in the multiple attenuation stage for the variable-depth streamer data.

As current standard practice for broadband processing, we use a suite of receiver deghosting algorithms termed Ghost Wavefield Elimination (GWE). In this work, we compared two such algorithms to demonstrate how technology advances can provide solutions to our processing challenges. The first deghosting method we used in this paper was proposed by Wang et al. (2013) which used a bootstrap approach to iteratively determine the pseudo-3D ghost-delay times in the ***Tau-Px*** domain. These times are then used to form a linear system to derive the ghost-free data through a least-squares inversion. The bootstrap method proved to be effective for most 3D cases. A full 3D deghosting solution was proposed by Wang et al. in 2014. It uses a progressive sparse ***Tau-Px-Py*** inversion method to overcome the Nyquist limitation caused by the large cable spacing for marine towed streamer surveys. The benefit of the full 3D deghosting is most obvious when there are extreme 3D effects, such as the out-of-plane diffractions from a shallow volcanic intrusion, as shown in Figure 4. For shot gathers from near cables close to the shot line (such as cable 7), the bootstrap deghosting method handles the 3D effect from the diffraction of the shallow intrusion well (Figure 4b).

However, when the cable is farther away from the shot line (such as cable 1), we observe that 3D effects become more prominent and some ringing artefacts are observed around the intrusion in the bootstrap results (Figure 4c, middle) whereas 3D deghosting works well (Figure 4c, right). After deghosting, the receiver-ghost notches have been successfully removed as shown in the FX plots and spectra comparisons in Figure 5, and a broader bandwidth (2.5~200 Hz) has been achieved as shown in Figure 5f.

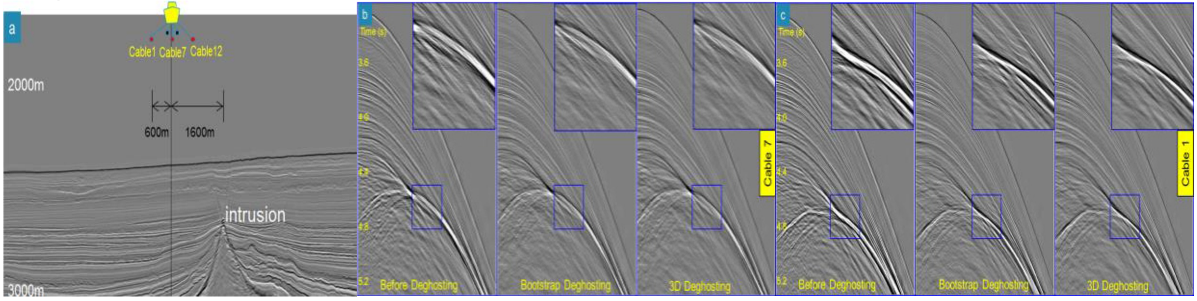

Figure 4 *(a) Diagram of source and cable position relative to the shallow intrusion; (b) Shot gather from cable 7 before and after bootstrap and 3D deghosting; (c) Shot gather from cable 1 before and after bootstrap and 3D deghosting.*

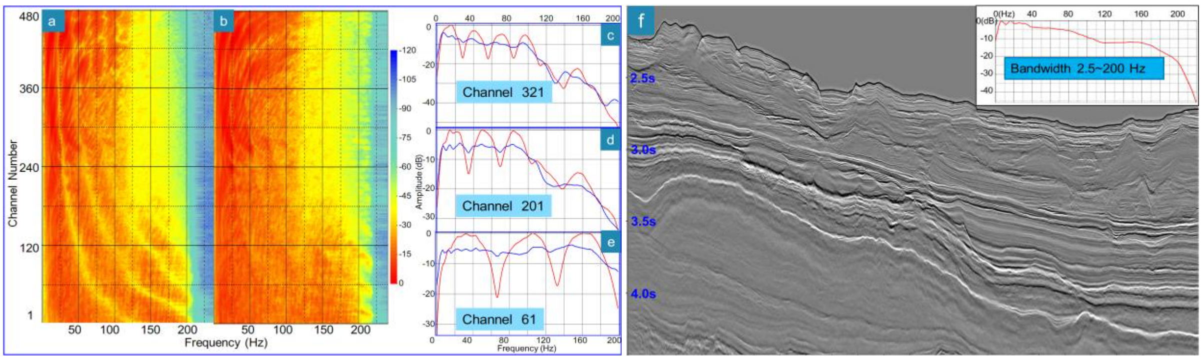

Figure 5 *FX plot of shot gather before (a) and after (b) deghosting and common-channel spectra comparisons before (red) and after (blue) deghosting for channels 321 (c), 201 (d), and 61 (e). 3D PSTM stack after source and receiver deghosting (f).*

Frequency shift Q tomography (FS-QTOMO) and QPSDM

The broadband survey and processing provide ultra-high resolution for shallow events; however, the high-frequency components decay rapidly with depth which leads to low-frequency components dominating the amplitude spectrum for deep events. This causes broadening of the wavelet and deterioration of resolution in the deep section, which is often less obvious in the conventional non-deghosted data due to the ghost tuning effect. Thus, it is more important to compensate for the Q absorption effect in broadband processing. Xin et al. (2014) proposed a 3D Q tomographic inversion approach to estimate the volumetric Q field based on the measured adaptive centroid frequency shift (FS-QTOMO).

The PSDM CIGs are converted to time domain and de-stretched by reverse NMO before the event picking and the centroid frequency is measured for each picked event. The spatial window used for this measurement needs to be big enough to avoid the tuning effect of the geology. The volumetric centroid frequency shift field is then used as input for the tomographic inversion to estimate the Q model. Figure 6c shows the Q model from FS-QTOMO using the Sandman broadband dataset. The volumetric Q field follows the geological structure, with a strong absorption (Q~80) identified within the Tertiary layer. The resulting Q volume can then be used in the QPSDM migration to compensate for the dissipation effect along the actual wave-path. Compared with the migration result without Q compensation (Figure 6a), the QPSDM result (Figure 6b) provides a broader and flatter spectrum, and much higher visual resolution, especially for the Cretaceous zone of interest around 4500 m. It is worth mentioning that QPSDM also helps to better restore the AVO response which is used as a key direct hydrocarbon indicator (DHI) in the exploration for this area.

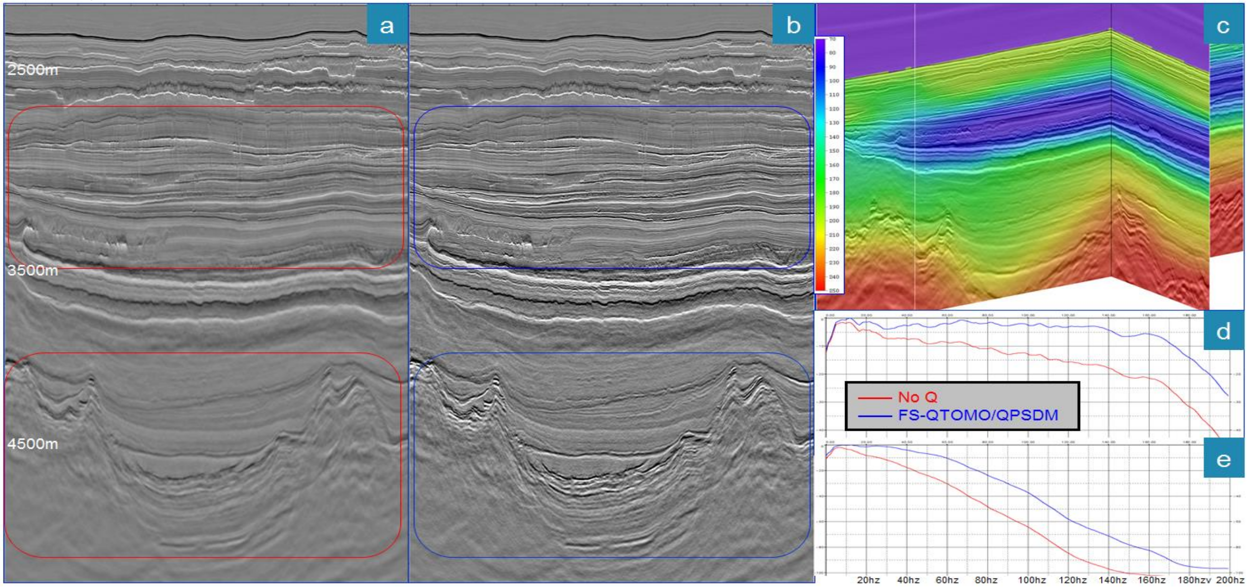

Figure 6 *PSDM stack comparison (a) without Q; (b) QPSDM with Q model from FS-QTOMO; (c) Q model; (d) spectra comparison in shallow window; (e) spectra comparison in deep window*

Conclusions

This case study demonstrated that a combination of a synchronized multi-level source and a variable-depth streamer has enabled the effective removal of both the source and receiver ghosts, resulting in broadband seismic data up to 200 Hz. High-end processing and imaging technologies played a key part in deghosting and compensating for the Earth attenuation effect, thus aided in fully unlocking the potential of broadband acquisition and push the limit of seismic resolution.

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