New insights from old data; experiences reprocessing heritage data from offshore Angola for improved subsalt and pre-salt images

Alex Cooke*, Arindam Kanrar, Alexey Shmelev, Sugandha Tewari, Merigon Jarvis (WesternGeco)

This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

Developments in data processing, imaging, and inversion technology over the last few years mean that a step change in data quality can be achieved by reprocessing existing seismic datasets, providing an economical way of obtaining new insights into the subsurface.

In this paper, we present recent experiences of the broadband reprocessing and depth imaging of heritage narrow-azimuth conventional data from offshore Angola. We will show that significantly improved subsalt and pre-salt information can be obtained from such datasets.

Introduction

Pre-salt exploration along the South Atlantic conjugate margin has been a major focus for the oil industry for many years, with significant discoveries on both the Angolan (Benguela and Kwanza basins) and Brazilian sides (Campos and Santos Basins).

The two provinces share similar geological and geophysical challenges with reservoirs typically being deeply buried beneath a complex overburden consisting of interbedded sands and shales, carbonates and layered evaporates of variable thickness. Naturally this leads to complex propagation of the seismic wavefield, with associated illumination and imaging challenges.

The ideal seismic data for both subsalt and pre-salt exploration in such areas would be characterized by long offsets, full-azimuth illumination and would be broadband by design. The vast majority of existing datasets offshore both Angola and Brazil are, however, conventional narrow-azimuth (NAZ) shallow-towed streamer datasets, typically with limited offsets.

No single technology provides the key to the successful reprocessing of such datasets. An integrated approach is required, including broadband processing and the latest model building and depth imaging techniques.

Where it is available, the integration of new information can also be important: this might come in the form of new well logs or VSPs, non-seismic measurements such as gravity or simply an improved understanding of the geology in the area.

In this paper we will focus on broadband processing with adaptive deghosting and advanced depth imaging with full-waveform inversion (FWI).

Adaptive deghosting

The move to broadband acquisition techniques in recent years (employing, for example, multimeasurement or slanted streamers) has been well documented. The deghosting algorithms and broadband processing workflows developed for these acquisition techniques can, however, also be applied to pressure-only, flat-towed heritage streamer data. The resulting broadband data not only allows improved structural interpretation, but provides improved input to downstream processing steps such as depth imaging and inversion.

The most recent generation of deghosting technologies are data adaptive methods. One such is that proposed by Rickett et al. (2014), which iteratively solves for both the upgoing wavefield *and* (optionally) the ghost delay, which allows it to handle uncertainty in receiver depth information which is common with heritage data. This algorithm works by performing a sparse decomposition in the local plane-wave domain, is robust in the presence of noise and handles 3D effects and out of plane energy which is common in complex geological environments. Adaptive deghosting shows better reconstruction of signal energy at the very low frequencies than purely deterministic methods, and both source and receiver side ghosts can be addressed simultaneously in a single shot-domain application. Adaptive deghosting is typically applied in single cable mode early in the signal processing sequence, though multi cable deghosting with the same algorithm is available.

The displays in figure 1 show simultaneous source and receiver adaptive deghosting results from the recent reprocessing of 8,000 km^2 multiclient data from ultra-deep water blocks in the lower Congo basin (Kanrar and Mistry, 2016). The data here are narrow-azimuth, with cables towed flat at 7 m depth. Source depth was 6 m and the maximum offset was 6 km. In this case the same model was used to migrate both 'before' and 'after' datasets.

It can be seen that the adaptive deghosting method is effective in this complex environment, reducing the side lobes of the wavelet and enhancing low-frequency signal leading to improved imaging of fault planes and interpretability of deep reflectors. Improved resolution enables enhanced interpretability of post-salt channels.

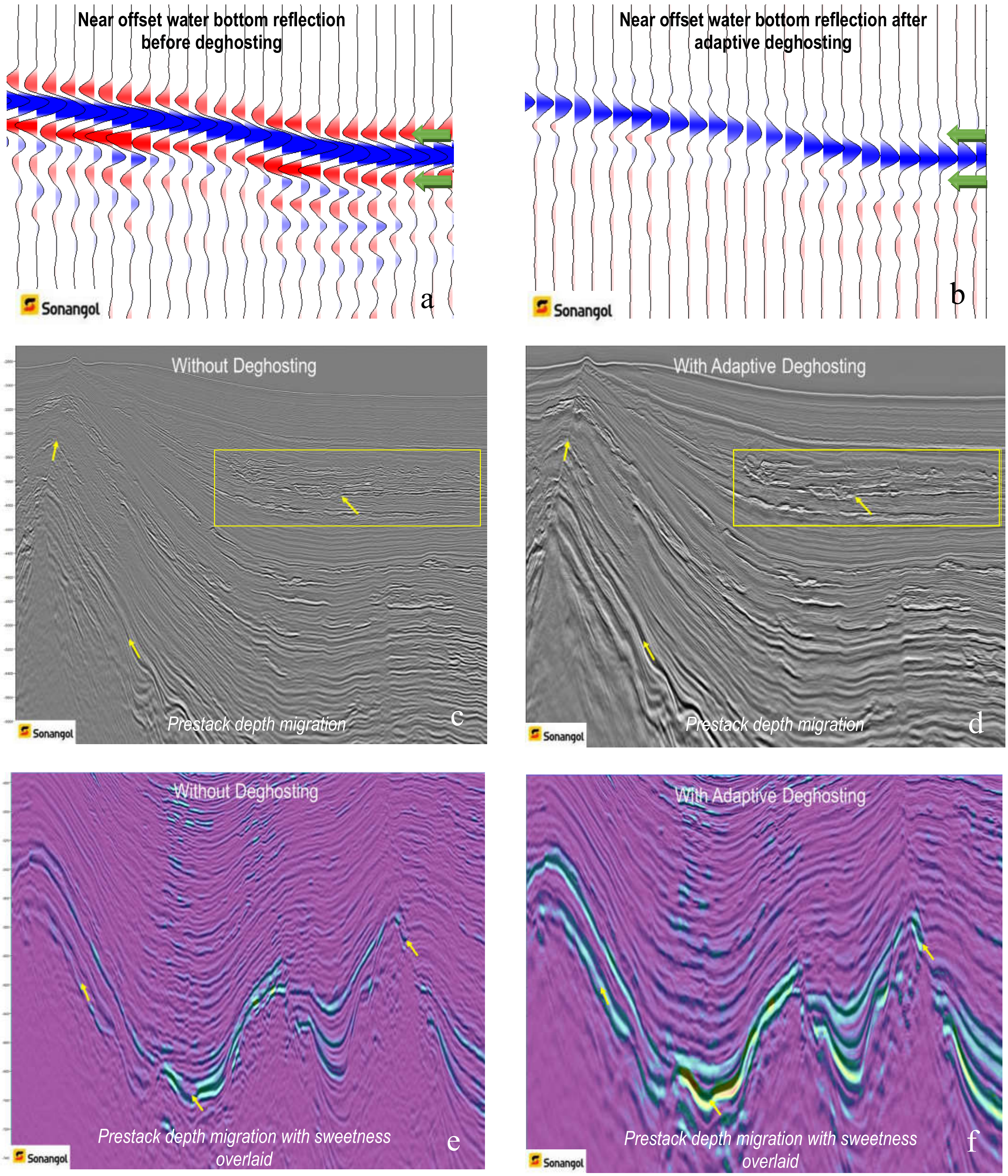

Figure 1 – Images before (left) and after adaptive deghosting (right). Images a and b (top) show a zoom of the (zero phase) water-bottom reflection from the near offset; removal of the side-lobes associated with the source and receiver ghosts is clear. Pre-stack depth migration images c and d (middle) show improved imaging of faults and steep dips after deghosting; complex channel features are also more easily interpreted. Images e and f (bottom) are overlaid with a 'sweetness' attribute which highlights facies changes. In this case it highlights top salt which is much clearer and consistent after broadband processing.

Advanced depth imaging

Accurate, high resolution models are a requirement for exploration and reservoir characterization in a complex geological environment such as that presented offshore Angola. Zdraveva and Hydal (2013) described a state of the art anisotropic depth imaging workflow for areas with sparse well control, including data-driven and geologically consistent anisotropy, geologically constrained tomography and complex salt-body modelling using reverse time migration (RTM). This workflow has become common practice offshore both offshore Angola and Brazil, with the addition, more recently, of deghosted, broadband input data.

Figure 2 shows the results from depth imaging of the broadband reprocessed lower Congo basin data described in the previous section. High data quality in the post-salt section allows the resolution of complex turbidites, improved post-salt tomography and more confident top salt interpretation. Complex salt body modelling with RTM led to more accurate salt interpretation, and subsequently reduced uncertainty in subsalt and pre-salt interpretation.

Full waveform inversion

One of the most significant developments in earth model building in recent years has been the introduction of full waveform inversion (FWI) in the industry. This technology has become a standard part of the model building workflow in many areas, especially where long offset, wide-azimuth data exists with good signal to noise at low frequencies. It has been shown to provide superior, higher resolution models when compared to tomography alone, especially in complex environments where the assumptions of typical ray-based tomography are challenged.

The typical heritage data offshore Angola and Brazil does not tend to meet these ‘ideal’ requirements, typically being narrow-azimuth, with limited offsets (<8 km) and with streamers towed relatively shallow compared to the more common deep-tow we see in contemporary broadband acquisition. The deep-water environment is a further challenge. In this case, the lack of low frequencies and long offsets typically mean that the initial model needs to be more accurate for the FWI starting criteria to be me.

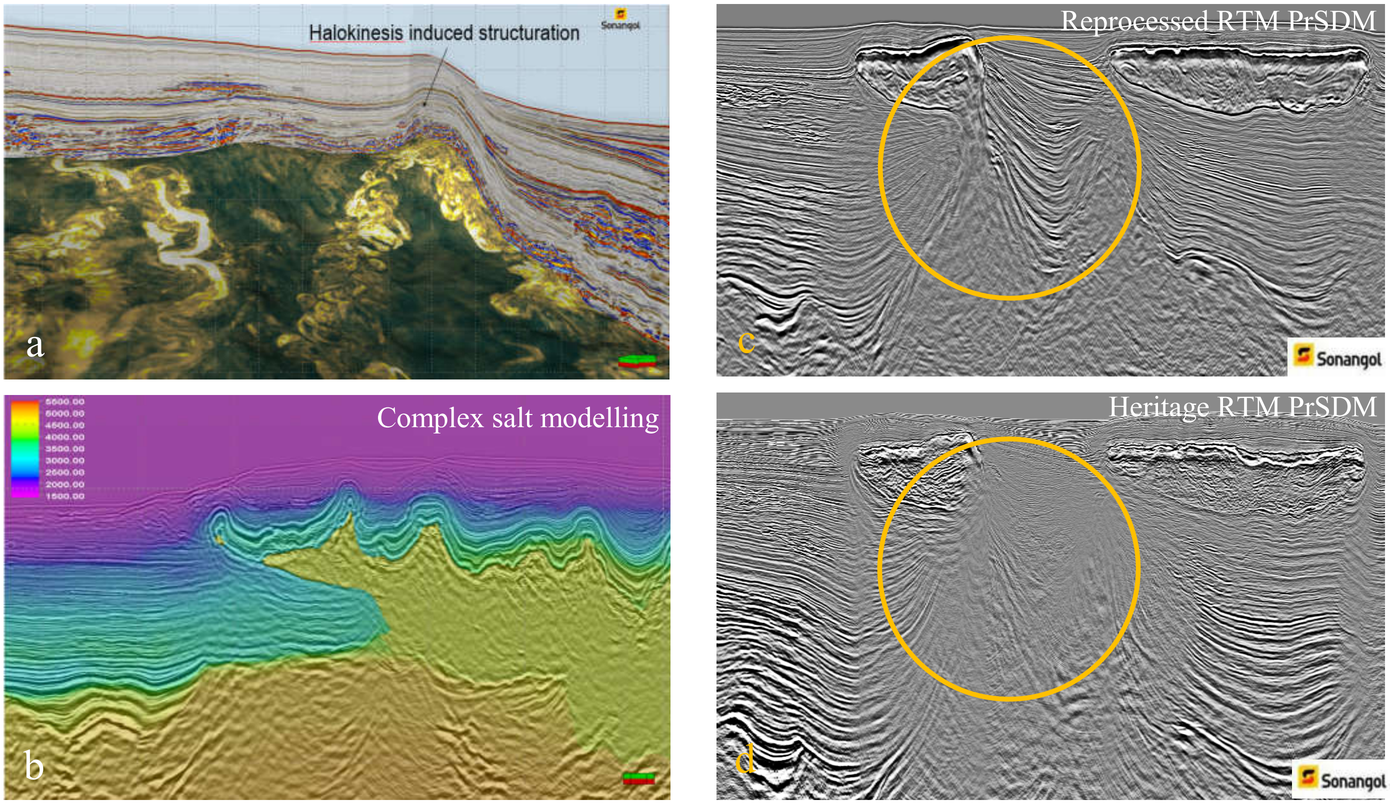

Figure 2 – Image (a) shows resolution of complex post-salt turbidites from broadband reprocessed data. Image (b) shows the velocity overlaid on the seismic volume in an area of complex salt. Figure c and d (right) show heritage depth imaged data (bottom right) and reprocessed data (top right). Improvements in imaging of both subsalt and intra-salt reflectors are highlighted.

Shmelev et al (2016) presented a case study of the application of FWI to conventional heritage narrow-azimuth exploration data in the Kwanza basin offshore Angola. The maximum offset was 8 km and the lowest useable frequency band for FWI had a central frequency of 6 Hz. In this case, three passes of tomography were required before the cycle skipping between the modelled and observed data was sufficiently reduced to enable FWI to start (figure 3).

Figure 4 shows the high resolution, geologically consistent updates achieved with FWI in this case, including updates in the seismically transparent carbonates section, where the lack of reflections is a challenge for tomography. In figure 5, the broadband reprocessing and imaging can be seen to improve on the recent heritage processing, and the FWI can be seen to improve on tomography alone, with simpler and more continuous base of salt reflection being achieved.

More recent developments in FWI (not used in this example) include ‘adaptive’ FWI (Jiao et al., 2015), which is less sensitive to cycle skipping than the least-squares technique and, as such, is ideally suited to heritage data sets with limited low frequencies or where velocity models are less mature.

Conclusions

In this paper we have shown that significant value can be added to heritage datasets with the application of broadband reprocessing and depth imaging using the latest technologies including adaptive deghosting and full waveform inversion.

Such reprocessing can provide higher resolution, more reliable images in complex environments, economically providing new insights into the subsurface and reducing uncertainty in exploration and reservoir characterization.

Acknowledgments

We thank Sonangol E&P and WesternGeco for permission to publish this paper.

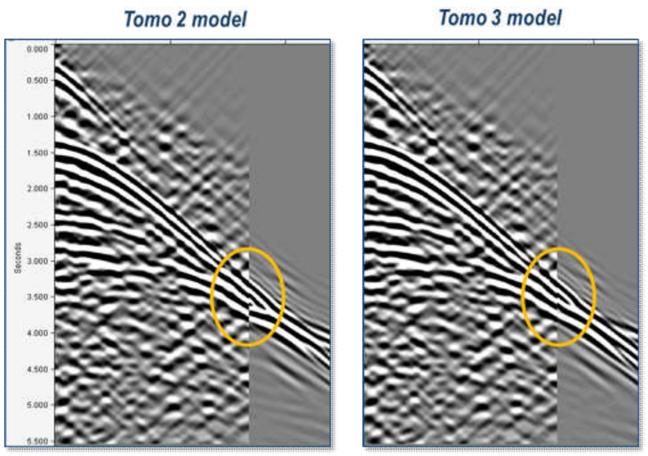

Figure 3 – comparison of recorded and modelled data. The lefthand image shows cycle-skipping (highlighted) which needed to be resolved with further tomography (right) before FWI could proceed.

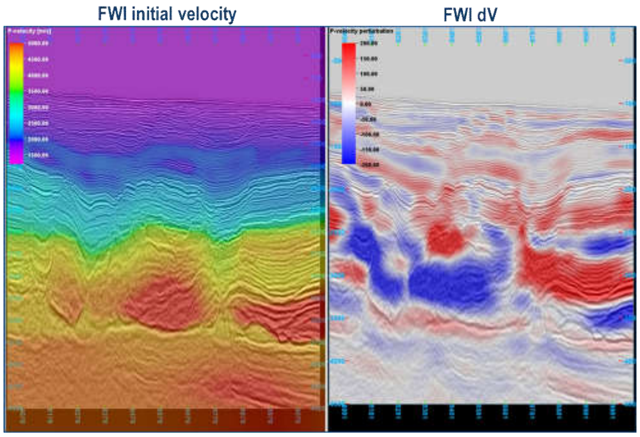

Figure 4 – final velocity model with combined tomography and FWI updates (left) and high resolution, geologically consistent FWI updates (right).

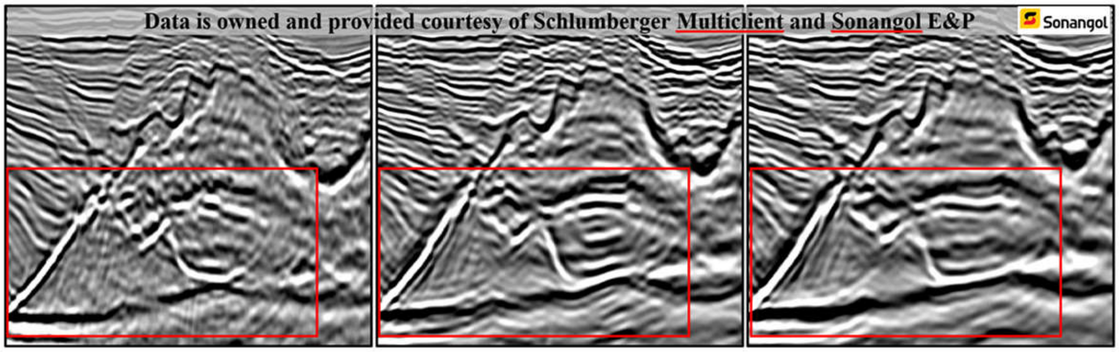

Figure 5 – heritage beam image (left), after broadband reprocessing depth imaging (middle) and after depth imaging with FWI model (right). Note improvements in continuity of the base of salt reflection,

References

Rickett, J., van Manen, D., Loganathan, P., Seymour, N., 2014, Slanted-streamer data-adaptive deghosting with local plane waves: 78th EAGE Conference and Exhibition, Expanded Abstracts

Kanrar, A., Mistry, K. 2016, Adaptive deghosting: A case study from offshore Angola: PESGB Petroleum Exploration Techology Exhibition (PETEX), London, Expanded Abstracts

Tewari, S., Jarvis, M., Chrustek, G., Bailey, J., Pisaniec, K, Rathee, D., Singh, U., 2016, Ultra deep water Angola, extracting the best from legacy acquisition using Schlumberger's latest portfolio of processing and interpretation techniques: PESGB Petroleum Exploration Techology Exhibition (PETEX), London, Expanded Abstracts

Zdraveva, O., Hydal, S., 2013 Large Scale TTI Imaging in Areas of Limited to No Well Control - Kwanza Basin Case Study: First EAGE West Africa Workshop 2013 - Subsurface Challenges in West Africa

Shmelev, A., Cooke, A., Zdraveva, O., Penwarden, J., High Resolution Model Building and Broadband Imaging in Deep Water Offshore Angola: 78th EAGE Conference and Exhibition 2016

Jiao, K., Sun, D., Cheng, X. and Vigh, D. [2015] Adjustive full waveform inversion. 85th SEG Annual Meeting, Expanded Abstracts. 1091-1095.