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Targeted High-End Processing to Deliver a Rapid P-Image from the Tangguh ISS® OBN survey

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Summary

Seismic for reservoir development often requires interpretation of the seismic image as early as possible to facilitate well planning. Ultra-high-density Ocean Bottom Seismic (OBS) surveys using BP's Independent Simultaneous Source technology (ISS®) have proven themselves and been very beneficial for recording wide azimuths, long offsets, and high fold data to address complex imaging problems. Multicomponent data processing from OBS surveys can provide additional benefits to the imaging through PZ summation and PS processing etc. However, these benefits require extra processing effort, such as noise removal on the geophone data, which is known to be noisy in shallow water environments. On the other hand, P-only data processing is much less sensitive to these challenges. In this paper, we describe a superfast targeted P-only processing flow, using advanced methods of deghosting, demultiple, velocity model building and migration. The approach is described using data acquired with ISS® technology above ocean-bottom node receivers deployed in relatively shallow (20-80 m) water over the Tangguh LNG gas fields, Indonesia. Despite the huge amount of data to process, the products were delivered within 4 months of the last relevant node retrieval. This acceleration of data delivery supported timely well planning and field-wide development decision making.

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Summary

Seismic for reservoir development often requires interpretation of the seismic image as early as possible to facilitate well planning. This is particularly challenging when one needs to deploy advanced acquisition to image complex geological structures. Ultra-high-density Ocean Bottom Seismic (OBS) surveys using BP's Independent Simultaneous Source technology (ISS®) have proven themselves and been very beneficial for recording wide azimuths, long offsets, and high fold data to address complex imaging problems. Multicomponent data processing from OBS surveys can provide additional benefits to the imaging through PZ summation and PS processing etc. However, these benefits require extra processing effort, such as node re-orientation and shear noise and coupling noise removal on the geophone data, which is known to be noisy in shallow water environments. The challenges in geophone data processing are further complicated with increased data volume from ultra-high dense OBS surveys. On the other hand, P-only data processing is much less sensitive to these challenges. In this paper, we describe a superfast targeted P-only processing flow, using advanced methods of deghosting, demultiple, velocity model building and migration. The approach is described using data acquired with ISS® technology above ocean-bottom node receivers deployed in relatively shallow (20-80 m) water over the Tangguh LNG gas fields, Indonesia. Despite the huge amount of data to process, the products were delivered within 4 months of the last relevant node retrieval, which is equivalent to an 80% cycle time reduction versus vintage OBC processing flows. This acceleration of data delivery supported timely well planning and field-wide development decision making.

Introduction

Ultra-high-density Ocean bottom seismic (OBS) is becoming increasingly popular for imaging complex geological structures. This is because it can provide seismic data with wider azimuth, better illumination and higher fold than all towed-streamer data (Arntsen and Thompson, 2003). OBS acquisitions typically record four components of seismic data: P from the hydrophone and X, Y, Z from geophones. OBS data processing has many natural advantages in using more than just the P component data. For instance, the process of PZ summation that sums pressure P and particle-velocity Z (with obliquity correction or amplitude scaling) at the receiver to separate up- and down-going wavefields can generate ghost-free data (Soubaras, 1996). However, all of these advantages require extra processing effort. For example, node re-orientation, especially for Ocean Bottom Node (OBN) surveys, is required to ensure vector fidelity for geophone data. Also, removal of shear noise and coupling noise (between geophone and ocean bottom) is needed. In addition, geophone data are known to be noisy in shallow water environments. Hence, processing geophone data is usually more challenging and time consuming than processing P data. Thus, a natural question to ask is “can P-only processing achieve the imaging objective (to help the ongoing well planning) with quick data delivery?”. To answer this question, in the context of an shallow water OBN survey, we develop an advanced processing flow to unlock full benefits of P data whilst addressing the challenges of imaging complex structures with large velocity contrasts, namely, highly-scattering karstified carbonates. The flow involves P-only deghosting and demultiple processes to provide broadband pre-processed data, and high-frequency anisotropic full-waveform inversion (FWI) and reverse time migration (RTM).

Data acquisition

The LNG Tangguh gas fields, situated in the remote Berau/Bintuni Bay of West Papua at the eastern end of the Indonesian archipelago (Figure 1a), are one of the giant discoveries of the 1990s. Images from the vintage streamer and OBC datasets are sub-optimal due to challenges posed by shallow gas clouds and complex carbonate layers. These challenges motivated a recent acquisition program with ultra-high-density four-component nodes (Manning et al., 2017). For efficiency, a large node inventory combined with BP’s Independent Simultaneous Source Technique (ISS®) was deployed in a split-spread, single-line-roll recording geometry in 20-80 m water depth. Better imaging of the highly-scattering karst sequence in the carbonate layer and the heterogeneous fault systems to assist with well planning were the main aims of this high-end acquisiton (Stone et al., 2018). The nodes were deployed in a rolling geometry: a 200 m interval between receiver lines and a 50 m interval between nodes, while the shot geometry was of a 50 m interval between shot lines and of a 25 m interval between shot points. Rose diagrams in Figure 1 show the offset and azimuth distribution. Data limited within 4.5km in offsetx and offsety with full azimuth coverage were used for imaging.

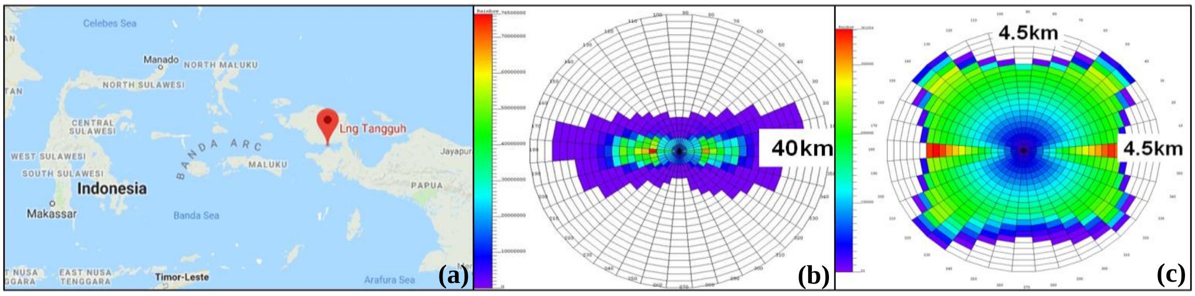

***Figure 1** a) Survey map; Rose diagram of b) the raw data; c) shots with Offset-X limiting within 4.5 km*

Methodology

We outline our P only processing workflow in three main aspects: 1) de-ghosting and de-multiple to attenuate ghosts and water-layer related multiples; 2) high-frequency anisotropic FWI to capture velocity anomalies due to shallow gas pockets, karstified limestones and heterogeneous faults; 3) RTM to image the complex structures with multi-arrival wave-paths at the reservoir beneath the carbonates.

- **De-ghosting and de-multiple**

One critical question about P only processing is whether we can effectively remove the receiver-side ghost without the help of the Z-component. Receiver-side ghosts and water-layer peg-leg multiples have the same kinematics and polarity on P data. It not only leads to deeper notches at the dominant frequencies (9-37 Hz, corresponding to water bottom depth of 20-80 m) but also complicates the deghosting process. Moreover, signal recovery at the notch frequencies, with complex geology beneath the shallow gas, becomes more difficult due to a low signal-to-noise ratio (S/N). Thus, robust receiver-side de-ghosting and de-multiple processes are important for the success of P-only imaging. De-ghosting using 3D progressive sparse Tau-p inversion is well validated for wide/full azimuth streamer data or even multi-sensor streamer data (Wu et al., 2014, Wang et al., 2014). Its application can also be extended to P-only OBS data. Model-based water-layer de-multiple (MWD) is able to further attenuate the water-layer multiples (Wang et al., 2011). One question to ask is whether adaptive subtraction of the 3D MWD model can attenuate both receiver-side ghosts and water-layer multiples. Figure 2 shows a comparison of data before de-ghosting and de-multiple processes, after 3D MWD, and after both 3D receiver-side de-ghosting and 3D MWD, respectively. Figure 2a shows a raw stack of the data with good S/N benefitting from very high data fold, but still contaminated by the shallow water ghosts and multiples. Figure 2b displays the stack after 3D MWD only. A considerable amount of multiples have been attenuated, but obvious residual multiples have been left behind (as shown by the blue arrow and circle). Figure 2c shows the stack after both 3D de-ghosting and 3D MWD, where residual multiples have been better attenuated. Comparison of Figure 2a and 2c clearly shows the benefits of de-ghosting and de-multiple processes in this shallow water environment.

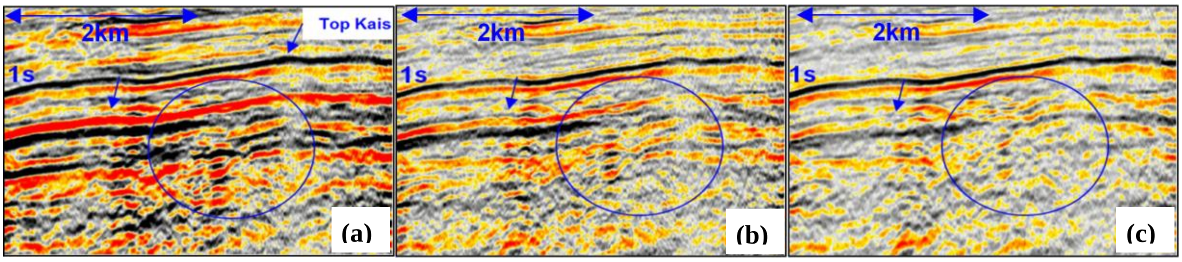

***Figure 2** a) Input stack; b) Stack after 3D MWD only; c) Stack after 3D receiver-side de-ghosting and MWD.*

- **Diving wave FWI with ultra-long offsets**

The geologic complexity lies not only in the shallow gas and highly-scattering karsts, but also in the velocity contrast between the shallow clastic layers and carbonate layers and across the heterogeneous faults. The acquisition in this case helped to provide wide azimuth data with under-shoot rays that could avoid passing through local velocity anomalies. However, a high-resolution velocity model was still required to capture all of the high wavenumber velocity variations and the velocity contrasts for better fault positioning and geological interpretation for well planning. Thanks to the ultra-long offsets (up to 19 km) in the data, diving waves were recorded with penetration down to the carbonate layer. The rich low-frequency information from OBS data gives a good starting point for FWI (Shen et al., 2017; Michell et al., 2017). However, due to the noisy shallow water environment, which results in relatively low S/N at very low frequencies, anisotropic FWI was only started from 3 Hz and gradually pushed to 18 Hz for higher resolution velocity to better correct the high wavenumber overburden effect. Figure 1b shows that the ultra-long offset data were more biased towards the inline azimuth. To mitigate the potential biased azimuthal update, two rounds of FWI were applied: 1) with 0-6 km offsets for a more even azimuthal distribution, and 2) with longer offset data to fully utilize the ultra-long offset benefit. Figures 3a and 3d show the FWI initial model at shallow depth slices and in a 3D view of the carbonate layers; 3b and 3e display the 8 Hz velocity update, capturing the anomalous gas pockets and karsts, where the velocity is anomalously lower; Figures 3c and 3f depict the 18 Hz velocity update with sharp velocity contrasts captured in the gas and karst regions. As the reservoir lies just beneath the complex karst overburden, accuracy of the high-resolution velocity model was the key for structural imaging. Figures 4a and 4b show a migration comparison between the initial model and the 18 Hz FWI model: 4a shows clear structural undulations beneath the karsts and shallow gas even with wide azimuth and high fold data; 4b shows an effective correction of the overburden effect from the 18 Hz FWI velocity model.

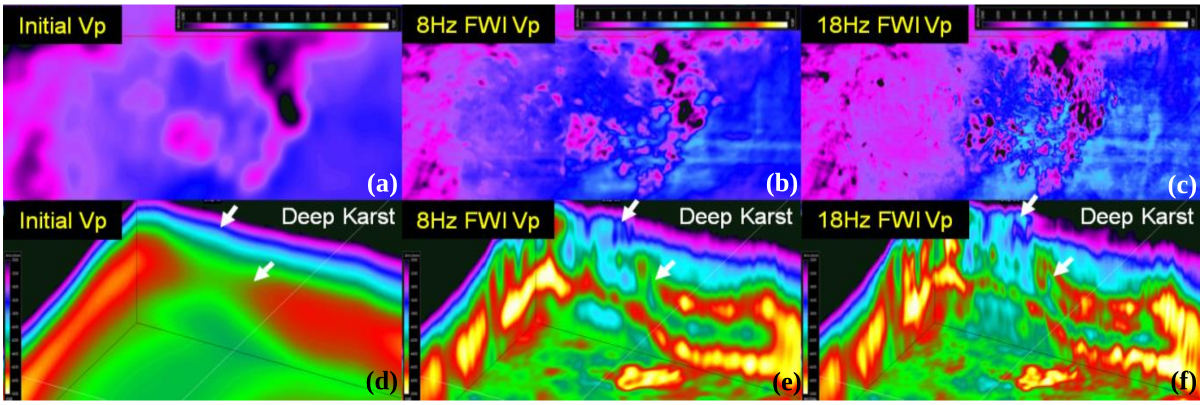

Figure 3 *Depth slice (135 m) of a) initial model; b) 8 Hz FWI Vp; c) 18 Hz FWI Vp; deep carbonate layer of d) initial model; e) 8 Hz FWI Vp; f) 18 Hz FWI Vp; Arrows point to the karsts.*

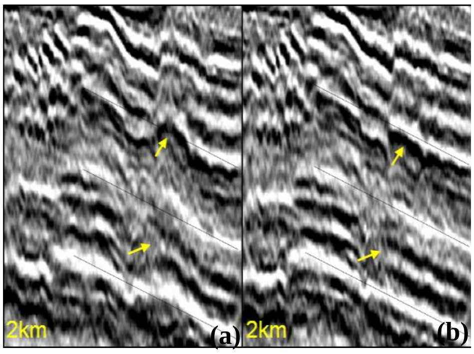

Figure 4 *PSDM stack from a) initial model and b) 18 Hz FWI model.*

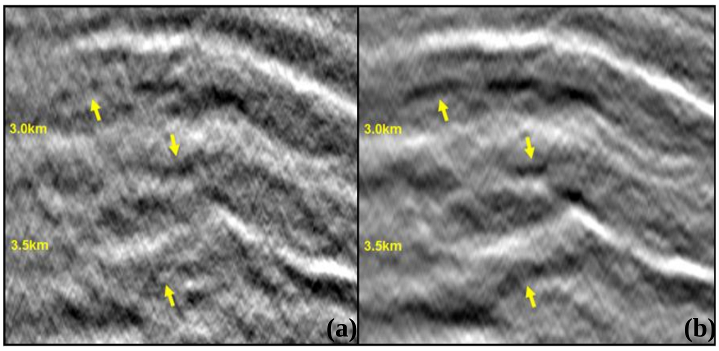

Figure 5 *a) Kirchoff migration and b) RTM migration at deep target zone.*

- **RTM for complex structural imaging**

Kirchhoff migration has difficulty in honouring multi-arrival and complex wave-paths which result from the 18 Hz anisotropic FWI velocity model that contains large velocity contrasts and high-wavenumber details. Hence, high-frequency RTM was used as the migration engine. Figure 5b shows that the RTM image at the deep reservoir level has higher coherency and better structures than the Kirchhoff image in Figure 5a.

Final result discussion

By following the processing steps outlined above and with the contribution from a large number of resources, we were able to deliver a better image in a very short timeframe. The new image in Figure 6b shows a clear fault in the carbonate layer which was not obvious in the legacy image, (Figure 6a). This information is critical to safely drill through the faults and avoid any karst features (Stone et al., 2018). Figure 7 shows a P-only image covering the whole Tangguh area. The imaging beneath the shallow gas region is greatly improved, with significantly better imaged fault systems in the carbonate layers. The deep target reservoir at around 3 km is also much clearer than that of the legacy volume.

Conclusion

In this paper, we presented a rapid P-only processing flow to unlock the full benefits from P data to produce a reliable image within 4 months of the last relevant node retrieval. Along with the high stacking power and better illumination from the ultra-high density OBN data, high-end processing technologies (including 3D P-only deghosting and demultiple, high-frequency FWI and RTM) delivered a significantly better image with improved reflector continuity and 'simpler' structural shapes at reservoir level. And, for the first time, it has revealed just how complex and extensive the cave systems and faults are in the limestone layers. This is proving invaluable to optimize development well trajectories and reduce drilling non-productive time.

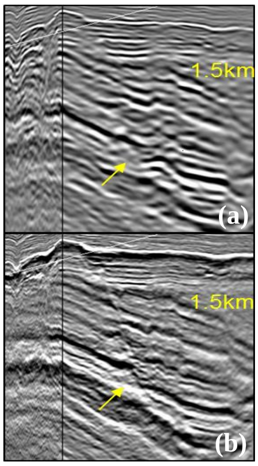

Figure 6 *a) Legacy Streamer Image; b) P only RTM image;*

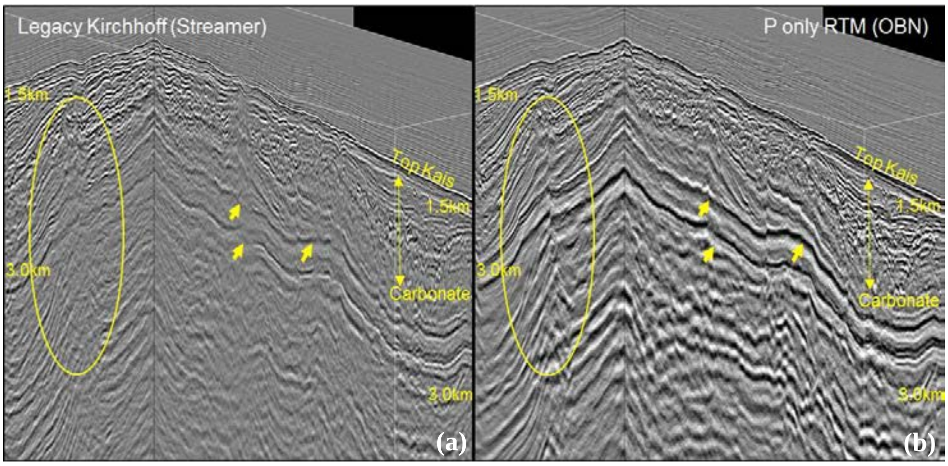

Figure 7 *a) Legacy Kirchhoff image from streamer data; b) New Tangguh OBN P only RTM image; Significant improvements are seen on the Kais and Faumai fault systems in the carbonate layer, and much clearer structures in the target interval around 3 km.*

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