# Improved channel imaging using full-waveform inversion for deep-water Lingshui giant gas reservoir in South China Sea

*Tao Wu*[1]*, Dun Deng*[1]*, Zijing Gong**[2]*, Jie Cui*[2]*, Rong Li*[2]*, Lianlian Liu*[2]

[1]*CNOOC China Ltd Hainan Branch,* [2]*SLB*

## Summary

The Lingshui giant gas field is located in a deep-water environment offshore China. It has rich hydrocarbon resources reserved in the channels and sand bodies, which has high potential for exploration and development. The main gas reservoirs are deep buried turbidite channel sands with high heterogeneity which leads to complex velocity variations. A reliable sand body delineation is highly dependent on velocity accuracy and imaging resolution. Legacy seismic images in this area, produced with legacy velocity modellign tools, suffer from structural distortion and poor accuracy of channel delineation, resulting in high interpretation uncertainty and drilling risks.

In this study, we apply a tailored full-waveform inversion (FWI) velocity building workflow to obtain a high-resolution velocity model, and successfully reduce depth uncertainty and improve image accuracy. This approach interactively integrates adjustive FWI, least-squares FWI and reflection tomography on an offset-limited and narrow-azimuth towed-streamer dataset. A high-resolution velocity model is built to represent the complicated velocity variation accurately. The results are proved to significantly raise the reliability of seismic characteristics of channel sands compared with the legacy image. Reduced geological uncertainties and better sand body imaging helps to identify sand body and gas distribution. Hence, the results provide more information for well trajectory optimization and reduce drilling risks.

## Introduction

With abundant hydrocarbon resources and significant exploration and development potential, the Lingshui gas field is the largest deep-water gas field offshore China. (L. Mi et al., 2012). However, the intricacy of deep buried turbidite channels and ultra-high pressure submarine fans has increased drilling cost and operation risks. The reservoir targets have a burial depth from 3500 m to 4500 m. Legacy data has a low seismic resolution that could not meet the requirement of accurately characterizing the reservoirs. As a result of the uncertainty in the subsurface image and low-resolution velocity model from the legacy data, the overlapping distribution of sand bodies is ambiguous and the accuracy of channel delineation is not satisfactory. This imposed restrictions to further reservoir description and drilling planning.

Understanding the distribution of turbidite channels and submarine fans in the Lingshui region requires a reliable high-resolution velocity model. . Since Lailly and Tarantola introduced the concept of FWI to seismic exploration (Lailly, 1983; Tarantola, 1984), this technique has been widely studied and applied in seismic velocity modelling. The adjustive FWI (AdFWI) based on phase shift objective function has been proven to mitigate cycle-skipping issues and strengthens the robustness of FWI with less accurate initial models (K. Jiao et al., 2015; D. Vigh et al., 2016). A workflow to integrate AdFWI, least-squares based FWI (LSFWI) and multi-scale common-image-point (CIP) tomography (Woodward et al., 2008) can reduce velocity uncertainties and aid in constructing an accurate high-resolution velocity model.

In the area of this study, water depth range varies from 250 m to 1800 m. From 2008 to 2013, four towed-streamer surveys were acquired with a 6000 m cable length. Due to the limited offset, it is challenging for FWI to update velocity at a deep target zone with diving wave only. Therefore, all reflection information is included in the FWI update and multi-scale CIP tomography is applied for the velocity updates in the deeper area. Hence, we created a tailored imaging workflow by integrating AdFWI, LSFWI and CIP tomography. This workflow is able to capture the thin channel layer velocity with drastic lateral and vertical velocity variations for a tilted transversely isotropic (TTI) anisotropic velocity model. It therefore enhances the precision and resolution of the velocity model. We show how the improved velocity model contributes to significantly improve the channel imaging over legacy data.

## Method

The high-resolution velocity model is obtained through FWI and reflection tomography to avoid structure distortion and accurately predict depth of image. Figure 1 illustrates the integrated workflow of AdFWI, LSFWI and reflection tomography which serves the geological and geophysical challenges of this study. This velocity update process includes several frequency bands of FWI to iteratively build up the resolution of velocity model from low to high frequency.

FWI will be trapped into local minimum when there is a large phase difference between observed shot and predicted shot, which is known as ‘cycle-skipping’. Therefore, the accuracy of the initial model is crucial for FWI. The legacy data was processed in 2016 with a velocity model built by reflection tomography alone. In this study, the initial velocity model is built by combining temperature salinity dip (TS-Dip) water velocity for the water zone and the heavily smoothed legacy velocity, having removed the channel-related high-velocity trend for the sediment zone. The legacy anisotropy trend is used to build a simple TTI anisotropic model for FWI.

An effective way to mitigate cycle-skipping is to run the inversion at a low frequency band. Based on the assessment of the lowest frequency available in the acquired data, a dominant frequency of 6 Hz is chosen as the starting frequency band for FWI, with relatively good quality of recorded data.

Adaptive FWI uses a robust objective function based on time delays or phase differences instead of amplitude and phase residual between observed and modeled data. This objective function can withstand errors in the initial model and is more robust in preventing cycle-skipping risks (K. Jiao et al., 2015; D. Vigh et al., 2016). Since the initial model was built with relatively accurate kinematics, the AdFWI was started at a dominant frequency of 6 Hz to mitigate cycle-skipping and obtained an accurate low-frequency background velocity trend. Based on an analysis of the data, this was the lowest frequency available. Once an accurate low-wavenumber velocity model was derived, LSFWI was conducted at dominant frequencies of 6 Hz and 7 Hz. The input of the first several bands of FWI was using data with preliminary processing including de-bubble and noise attenuation. CIP tomography was then applied to further improve the velocity trend. Anisotropic parameters were calibrated based on the gather flatness and well surface marker.

Since the targeted channel sands are buried at depths of 3500 m, more reflection information is required in subsequent iterations of FWI. Both refraction energy and reflection energy were used in the subsequent 8 Hz and 10 Hz LSFWI bands. To avoid multiple contamination, de-multiple data were used as input to the higher frequency bands FWI updates. Prior LSFWI (D. Vigh et al., 2015) can incorporate wells information in the model by building a priori model from well logs and taking this into account in the objective function. The Prior LSFWI objective function can be incorporated by a weighted model misfit term alongside with the data misfit term. Prior LSFWI was performed at the fourth pass of FWI, to constrain the FWI iterations with well velocity and geological information, followed by the last pass of CIP tomography.

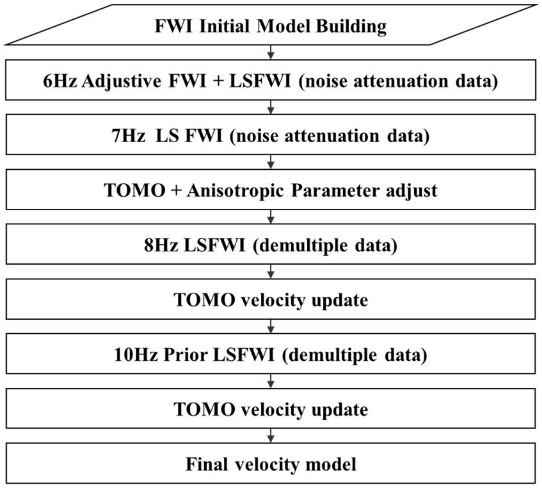

Figure 1 FWI velocity model update workflow

## Examples

Figure 2 shows the step-by-step velocity update result, from initial model to the final model. The initial model is very smooth with no velocity anomaly. The first pass of FWI at 6 Hz LSFWI velocity model (c) starts to capture the channel high velocity. With more FWI bands and more passes of CIP tomography, more high-frequency details are updated in the model. With prior FWI, well information is incorporated in the velocity model to further match seismic with borehole data. Channel boundary is clearly delineated while internal strata velocity variation is well captured.

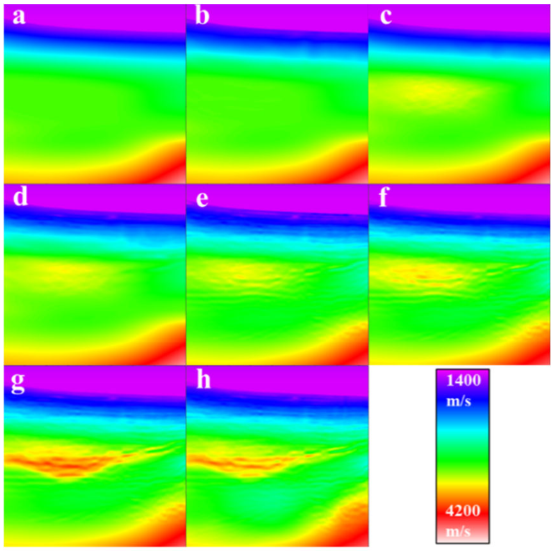

Figure 2 (a) Initial velocity model, (b) 1st pass of AdFWI at 6-Hz velocity model, (c) 1st pass of LSFWI at 6-Hz velocity model, (d)

2nd pass of LSFWI at 7-Hz velocity model, (e) 3rd pass of LSFWI at 8-Hz velocity model, (f) 3rd pass of LSFWI at 8-Hz plus tomography velocity model, (g) 4th pass of Prior LSFWI at 10-Hz velocity model, (h) Final velocity model.

Figure 3 shows the comparison of legacy velocity model with associated Kirchhoff pre-stack depth migration (KDM) image overlaid, and the new high-resolution velocity model overlaid with associated KDM image. The limitation of tomography to resolve small scale-length channel features is presented in the legacy velocity model, shown as Figure 3a while velocity model built through the integrated workflow demonstrates an advantage in imaging channels and submarine fans, shown as Figure 3b. It effectively captures and correctly delineates the vertical and horizontal velocity variation for the thin sand layer.

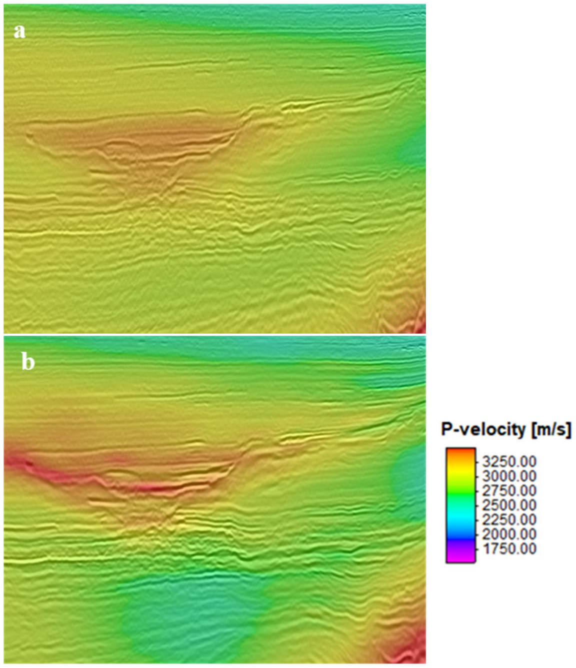

Figure 3 A comparison of the legacy velocity model with corresponding KDM image overlaid (a) and new high-resolution FWI velocity model with the updated KDM image overlaid (b).

The legacy KDM suffers from localized structure distortion (Figure 4a), and this issue affects the well-site deployment design, while no structure distortion due to an erroneous velocity model are evident in the new KDM results (Figure 4b).

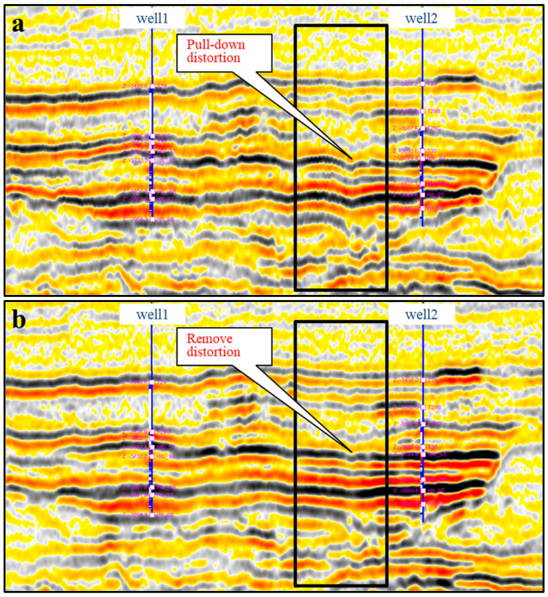

Figure 4 A comparison of the legacy KDM image and new KDM image.

Seismic interpretation uncertainty is high with the legacy data, as interpreters were indecisive between two possible interpretation schemes (cyan and pink dash lines), shown in Figure 5a. The new reprocessed KDM result (Figure 5b) shows a much clearer image for interpretation. Thus, a more confirmed interpretation was proposed to identify the distribution of thin sand layers.

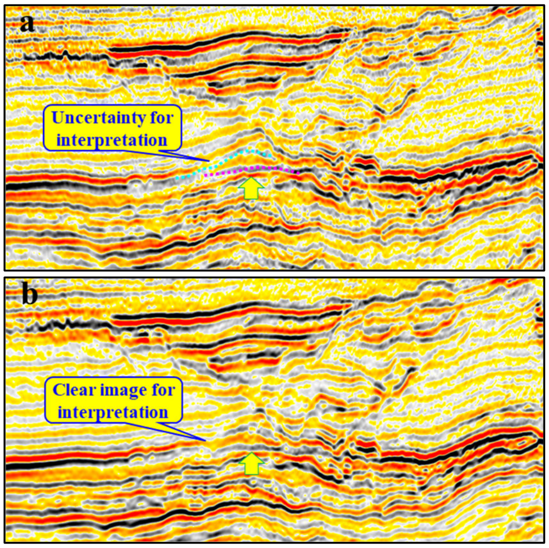

Figure 5 A comparison of the legacy KPM image and new KPM image.

The spatial distribution of different channels is complex, and it is challenging to distinguish the internal lithology based on the legacy KDM image (Figure 6a). From the new KDM results (Figure 6b), channel boundaries are better defined, showing significant uplift for channel delineation.

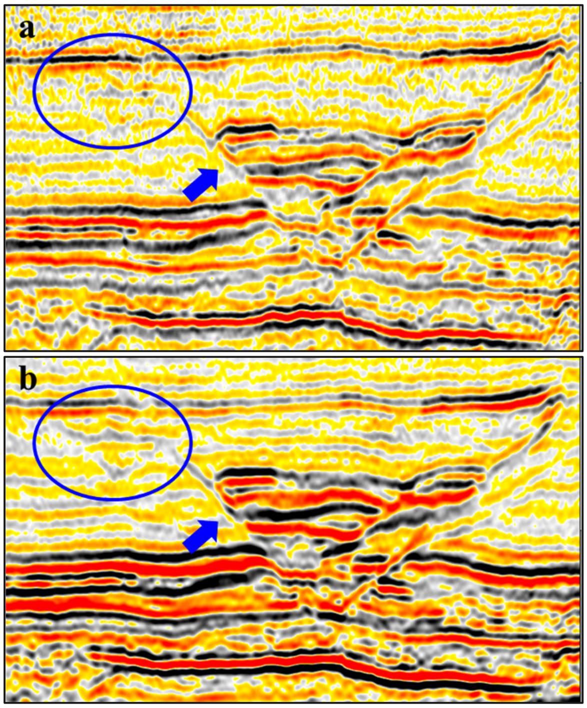

Figure 6 A comparison of the legacy KDM image and new KDM image.

## Conclusions

We presented a successful application of a tailored FWI and CIP tomography velocity model building workflow to achieve a high-resolution velocity model and improved imaging in deep-water offshore China. By using full record length reflection and diving waves, the workflow combining AdFWI, LSFWI and multi-scale CIP tomography is effective in updating both the background velocity and fine-scale velocity details. The final reprocessed seismic results provide a higher resolution and more accurate image compared to the legacy result, with clearer imaging of turbidite channels and submarine fans. Better defined overlapped sandbodies and channels give an enhanced understanding of sand body distribution and gas distribution. This supports well trajectory optimization and significantly reduces drilling risks.

## Acknowledgements

We thank SLB and CNOOC for permission to present the data shown in this abstract.