RESOLVING COMPLEX CARBONATE IMAGING CHALLENGES WITH FWI ON SHORT-OFFSET VINTAGE STREAMER DATA

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Summary

Carbonate velocity model building is challenging due to the complex geometry and sharp velocity contrasts associated with carbonates. Full-waveform inversion (FWI), together with long offsets, wide azimuth and good low frequency data, is known to be a powerful tool to address these challenges. Unfortunately, many vintage streamer datasets are handicapped by limited offsets and azimuth coverage, and a noisy low-frequency component. We used vintage streamer datasets acquired in the South China Sea to demonstrate that Time-lag FWI (TLFWI), together with other tools like dip-constrained tomography and well calibration, can overcome those shortcomings and produce a high-resolution velocity field, leading to improved images. TLFWI uses a crosscorrelation cost function to mitigate amplitude mismatch and low signal-to-noise ratio problems. However, the carbonates being out of reach of diving waves can still be challenging to update with FWI, if the starting background velocity is far from the true model. In this case, an iterative FWI flow with well-constrained velocity updates inbetween offers a more reliable solution. The carbonate fracture system poses another challenge for estimating anisotropic parameters inside the carbonate layer. Here we use diffraction imaging to guide the fracture system identification, which helps to estimate an HTI system.

Introduction

The South China Sea is full of carbonate layers and plenty of legacy short-offset data. Can we build an accurate carbonate velocity model using this kind of data? To answer the question, we carried out a study in an area of the South China Sea with water bottom depth ranging from 90 m to 300 m. The target carbonate layer lies at depths between 1.2 km – 2 km, with complex structures and sharp velocity contrasts. Shallow gas pockets and reefs above the carbonate layer add complexity to the problem. All of these characteristics make depth velocity model building in the area extremely difficult, and thus hinder exploration activities. A new well aiming at a structural high beneath the target carbonate layer based on legacy images was found to be a mis-hit. The new sonic log shows a significantly different trend inside the carbonate compared with an adjacent well 2.5 km away. The subtle depth error in the legacy image leads to an incorrect interpretation that puts a structural high at the new well location. To crack the puzzle, we re-built the velocity model using three vintage datasets. The datasets were acquired with flat, shallow-towed cables with little overlap. Two have a maximum offset of 3.5 km, and the third has a maximum offset of 4.5 km.

The noisy low-frequency component in our data, together with short offsets and narrow-azimuth coverage, pose challenges to full-waveform inversion (FWI), which has shown to be an effective tool in building complex velocity models. Conventional acoustic FWI with a least-squares cost function suffers from amplitude mismatch issues between the synthetic and real data, which makes it ineffective for salt or carbonate velocity updates. In 2018, Zhang et al. proposed Time-lag FWI (TLFWI), utilizing a crosscorrelation-based cost function to mitigate the amplitude mismatch problem for acoustic FWI. In addition, TLFWI uses crosscorrelation coefficient weighting to promote measurements of higher quality to stabilize the inversion process when S/N is poor. In this study, we applied TLFWI from shallow to deep. For deeper sections, the small maximum offset limits the diving wave penetration depth, so the TLFWI relied more on reflection energy. TLFWI with reflections can invert for high-wavenumber details, but its ability to correct background velocity trends is limited. In order to help TLFWI converge in the deep sections, we used other tools including dip-constrained tomography with well constraints to improve the initial model for the next round of TLFWI, similar to what Kumar et al. proposed in 2019. This iterative FWI flow built a velocity model that tied to wells and led to geologically consistent structures. Another challenge in determining carbonate velocity is how to estimate anisotropic parameters inside a carbonate layer, which are highly dependent on the fracture system. We used diffraction imaging that separates the diffractions caused by faults, fractures, karsts, and other small-scale heterogeneities from the reflections to better characterize those features, as described by Decker et al. (2014).

In the following sections, we present this TLFWI-driven velocity update flow, show how it resolves most of the challenges faced when imaging complex carbonate using short-offset vintage streamer datasets, and discuss its benefits and limitations.

Shallow anomalous velocity update with TLFWI

Shallow gas pockets and reefs often introduce significant distortions in the underlying structures due to high velocity variations. Even with good diving wave coverage, poor S/N at the low-frequency end and limited azimuth coverage make it difficult for conventional FWI with a least-squares cost function to update shallow gas and reef properly. TLFWI, which better utilizes the low-frequency signals, captured those velocity variations with a starting frequency of 3.2 Hz. Figure 1a shows the initial model depth slice and corresponding PSDM image with obvious distortion beneath the shallow gas pockets. Figure 1b shows that conventional FWI (updated from 3.2 Hz to 7 Hz), being more sensitive to the data S/N, produced a further distorted structure beneath the gas. Figure 1c shows TLFWI (also updated up to 7 Hz) was able to correct the imaging distortion by capturing the velocity slow-down at localized gas pockets and produced a better match between the modelled and real shots. The scenario becomes more challenging when the gas clouds and reef bodies lie adjacent to each other. Figure 2a shows the smooth initial velocity model overlain on a depth slice and corresponding PSDM image with deep image distortion. Figure 2b shows that the TLFWI-updated velocity captured the velocity variations from the shallow gas cloud slow-down to the reef speed-up. The image distortion was reduced accordingly after TLFWI. The near surface velocity updates provided more reliable top carbonate imaging at the target level.

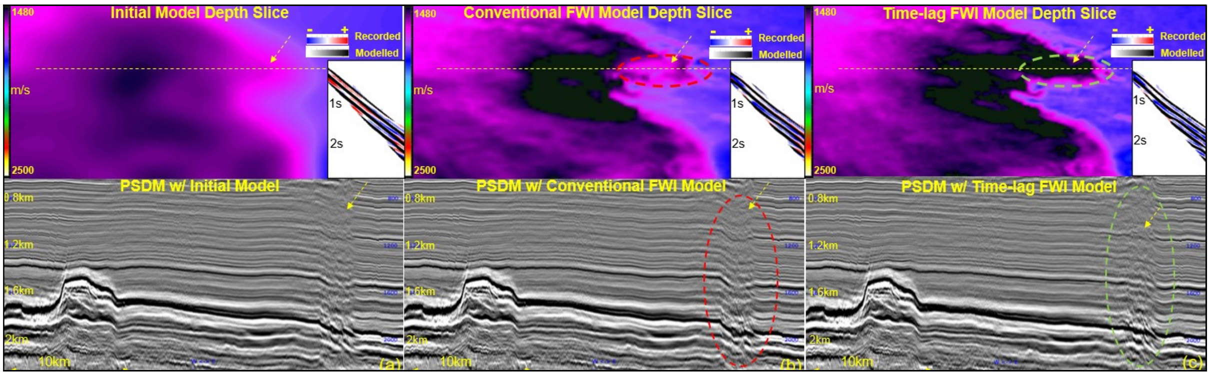

***Figure 1:** Depth slices at 250 m, forward modelled and real shot overlay, and corresponding PSDM images: (a) initial velocity model; (b) conventional 7 Hz FWI velocity suffers from low frequency noise in the data and the amplitude mismatch issues making it more sensitive to cycle skipping; (c) 7 Hz TLFWI velocity is able to capture the localized gas pocket velocity slow-down and correct the undulations below.*

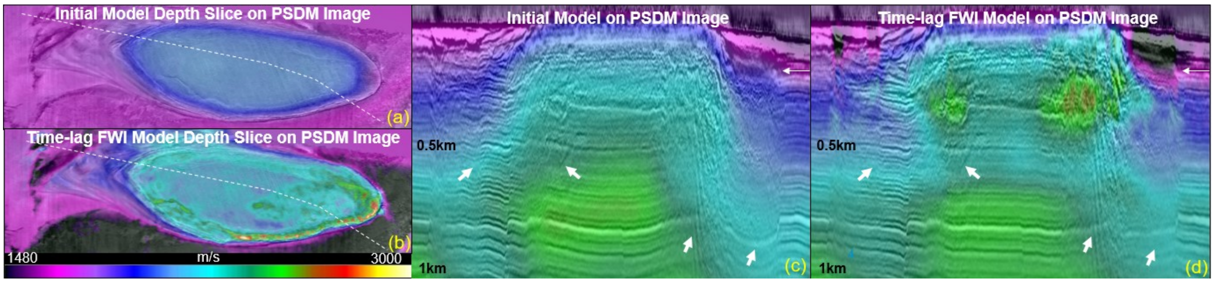

***Figure 2:** Velocity model overlain on corresponding PSDM images at depth slices at 250 m and an arbitrary line: (a), (c) initial velocity model; (b), (d) TLFWI velocity captured the sharp contrast between shallow gas pockets and shallow reef.*

Complex carbonate velocity update

The target carbonate is complex due to the various deposition of lagoon, shoals, reefs, boundstone and grainstone buildup from different stages. The velocity update for the carbonate is challenging due to both the presence of sharp velocity contrasts and short offsets in the data. Large velocity variations within small scales are expected inside the carbonate. Conventional tomography cannot resolve the sharp changes and other high-wavenumber variations, and therefore fails to obtain a reasonable imaging velocity. Figure 3a shows the initial tomography model overlain on the corresponding PSDM image. The image of the carbonate base suffers from the unresolved complex velocity inside the carbonate. TLFWI using the tomography model as the initial model captured the spatial variations of the carbonate velocity, separating two layers of the carbonate body with different lithology near Well 1 in Figure 3b. The strong velocity inversion layer near Well 2 was also captured. However, the speed-up was not enough at Well 3, as indicated by the sonic velocity. This is probably because the initial velocity model was too far from the true model at this location. Kumar et al. (2019) discuss the importance of the initial model for FWI updates in different scenarios when the data is insufficient. Their challenges share some similarity here, and our initial model needed some improvement based on the TLFWI update and well information. The sonic velocity changes drastically from Well 2 to Well 3 within a 2.5 km distance, and such a large variation is difficult to build into the initial model. The well mismatch at Well 3 and the pull-up at the base of carbonate both indicate that the vertical velocity needs further speed-up. Based on this observation, dip-constrained tomography with additional structural positioning constraints on the reflectors, proposed by Guillaume et al. (2013), was applied. It captured the velocity speed-up along the carbonate flank, which tied better with the Well 3 sonic velocity, as shown in Figure 3c. Figure 3d shows that TLFWI on top of the dip-constrained tomography velocity further refined the carbonate velocity details and better captured the slow-down below the carbonate base, which agrees with the sonic log, especially at Well 3. Additional improvements to the imaging are indicated by the blue arrows. Residual well calibration was then added to ensure well tie across the whole survey.

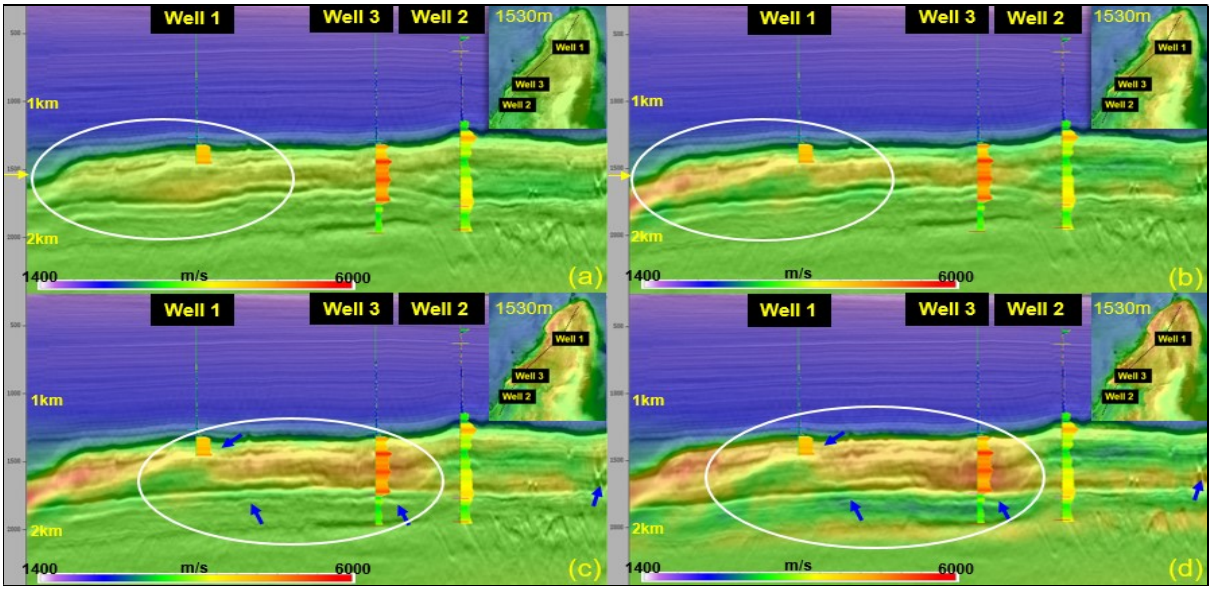

Figure 3: *Depth slices at 1530 m and vertical sections with models overlain on corresponding PSDM images: (a) initial tomography velocity model; (b) TLFWI with reflections on top of tomography model captures the spatial variations inside the complex carbonate; (c) dip-constrained tomography model with velocity speed-up near Well 3 to tie with the sonic; (d) TLFWI with reflections on top of dip-constrained tomography model further refines the carbonate velocity details.*

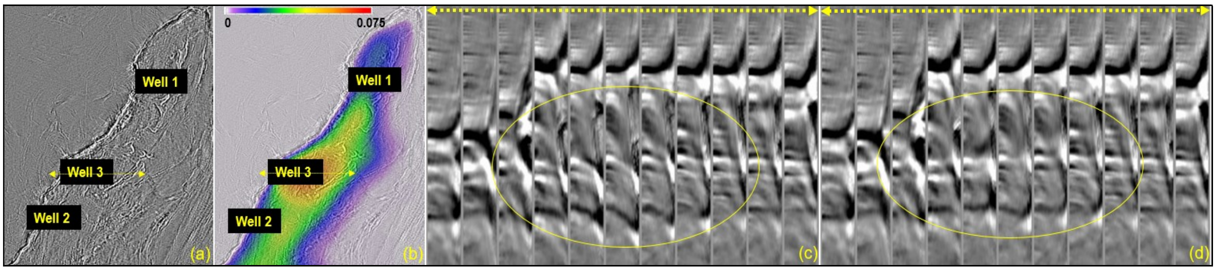

Figure 4: *Depth slices at 1430 m: (a) diffraction imaging clearly shows developed fractures along the carbonate flank; (b) estimated delta in HTI model. PSDM gathers along Well 3: (c) before introducing HTI; (d) after introducing HTI.*

Anisotropic parameter estimation inside carbonate

The carbonate velocity after the iterative updates captured the spatial variations that conventional tomography was incapable of doing, and is now consistent with the well markers and sonic logs. It also provided reasonable gather curvatures in most areas, except along the carbonate flank covering the 3 well locations. Those gathers were under-corrected due to the imaging velocity being slower than the vertical velocity controlled by the wells, as shown in Figure 4c. This phenomenon can be caused by horizontal-transverse-isotropy (HTI) inside the carbonate due to a developed fracture system in the reef carbonate. Diffraction imaging, as in Decker et al. (2014), was used to better characterize those features than reflection imaging (Figure 4a). The depth slice shows clear fractures imaged along the carbonate flank, which further supports the HTI assumption. However, due to the limited azimuth information in the data, it is difficult to derive accurate anisotropic parameters inside the carbonate. We assumed the slow velocity direction is perpendicular to the fracture plane, and the Thomsen anisotropic parameter epsilon was twice of delta. Delta was then estimated based on the difference between the imaging velocity and the velocity along the symmetry axis, as in Figure 4b. The HTI model will ensure the vertical velocity ties with the well data and gathers are flattened (Figure 4d).

Discussions

The proposed flow produced an image with simpler structure compared with that from the legacy image, as shown in Figures 5a and 5b. The carbonate velocity update and the understanding of the complex anisotropy explained the false prediction of the structural high from the legacy image and revealed a better structure in the final model PSDM image. However, uncertainty still exists even with current velocity update flow, and the impact from TLFWI is still limited by the short offsets, narrow azimuth coverage and poor low frequency content (< 3 Hz) of the data. In addition, the anisotropic parameter estimation highly relies on the azimuthal information and can result in uncertainties in the reflector depths in the HTI case. Kumar et al. (2019) and Yao et al. (2019) also discuss the importance of low frequency data quality, long offsets and full azimuth for FWI and the sensitivity of the initial model when data is inadequate. The uncertainty will be reduced with full-azimuth and long-offset data. Therefore, in cases with complex carbonate like in the South China Sea, extending the data dimension will provide a more thorough and reliable view of the data and the geology.

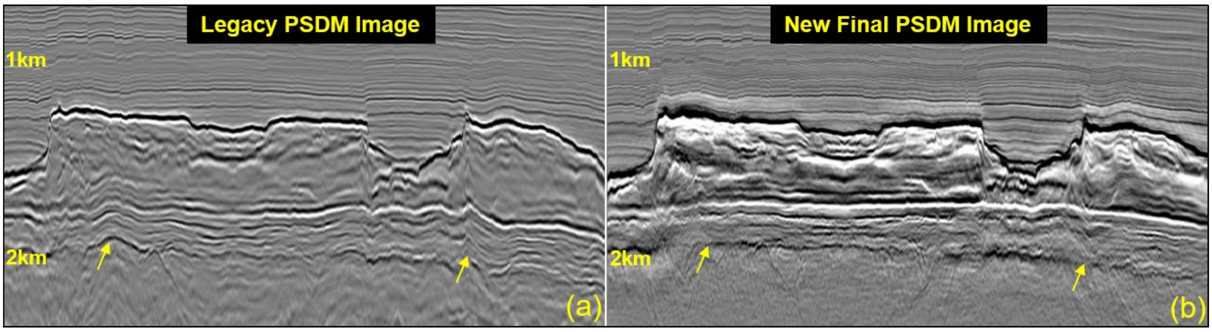

Figure 5: *An arbitrary line comparison of (a) legacy PSDM image and (b) new final model PSDM.*

Conclusions

TLFWI can better update the shallow features using NAZ data compared with conventional FWI in the South China Sea. With limited data, iterative TLFWI with dip-constrained tomography and well constraints is still needed for carbonate update. The proposed flow provided a more robust update and geological velocity model with effective kinematics correction in our study area. To further reduce the image uncertainty, the extention of data dimension can be considered for future survey designs.

Acknowledgements

The authors thank CGG, SK innovation and CNOOC for permission to publish this paper. Our thanks also go to Qing Xu, Yi Xie and Xiaogui Miao for their suggestions and fruitful discussions during the work.

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