High frequency refraction/ reflection full-waveform inversion case study from North West Shelf offshore Australia

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SUMMARY

The robustness of diving wave Full-Waveform Inversion (FWI) has been proven in industry, but the effectiveness is limited by its penetration depth. To target deeper reservoirs, therefore, requires the application of reflection FWI. This paper presents a real data 25Hz VTI FWI case study from North-West Shelf (NWS) Australia utilizing full wave-field. Starting from a high-quality reflection tomography VTI model, a top-down approach has been adopted. Diving wave FWI updates the shallow, then reflection FWI is introduced to further update the deeper section. The updated FWI model demonstrates significant uplifts in resolution and consistency with the geology. Two promising aspects can be observed: (1) the fairly solid uplifts in mitigating the imaging challenges: FWI reduces wave-field distortions, leads to overall improved focusing, gather flatness, continuity, and better positioning in depth; and (2) uncovers geological features beyond imaging: high-resolution FWI delineates small shallow anomalies and velocity boundaries across faults, and reveals the strong acoustic impedance contrasts at reservoir level. It demonstrates FWI can aid both in reducing the velocity uncertainty as well as providing a geological interpretation.

Key words: FWI, High resolution model, North-West Shelf

INTRODUCTION

In the past decade, FWI has gained wide acceptance and gradually become a standard step in velocity model building. Recently, there have been more efforts towards higher frequency FWI, and direct interpretation on high- resolution FWI output models (Lu et al., 2016 and Mancini et al., 2016). The robustness of Diving Wave FWI (DW-FWI) for shallow velocities is well accepted. Privitera et al. (EAGE, 2016) illustrated in their offshore Gabon case study how DW-FWI can help identify shallow gas pockets and dewatered faults. However, the effectiveness of DW-FWI for deeper sections is limited by the penetration depth. Reflection FWI, on the contrary, has no penetration depth limitation, though the limited angle makes it less robust, more accurate input model is thus usually required. To use reflection FWI for the deeper update is now increasingly important. Recently Mancini et al. (TLE, 2016), in their 30 Hz 2D FWI trial utilizing both refraction and reflection energies, demonstrated FWI's potential in direct interpretation even for the deeper section.

In this paper, we use a real 3D data example (with a 7km cable) from Northern Carnarvon Basin (Western Australia) to evaluate FWI's business impact: what value can high resolution FWI bring us at the reservoir level?

METHOD AND RESULTS

Geology background

The survey is located in an area with rugose water bottom and wide depth variations (200 ~1200m, Figure 1). The field lies beneath the continental slope and the target is a gas-bearing Triassic reservoir from 3 to 4km. Local geology challenges include a large tilted faulting system and complex shallow overburden. Numerous seafloor canyons and escarpments make it quite a challenge for both velocity model building and imaging at reservoir level. The distorted wave-fields in turn reduce the confidence of the underlying target interpretations due to structural uncertainty and amplitude distortions.

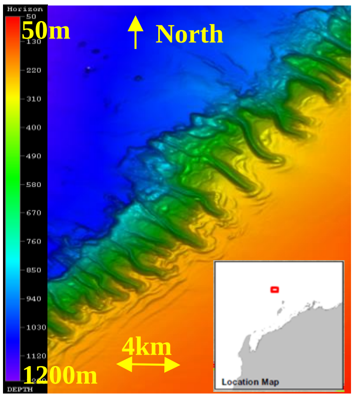


Figure 1: Water Bottom and Location Map

Method: FWI on top of Tomography, with a layer-stripping scheme

In our case a top down layer-stripping approach is adopted: 1) Starting from a high-quality PreSDM tomography model, DW-FWI is carried out firstly, limited to relatively shallow updates; 2) Reflection FWI is then introduced to update the deeper section. For both DW-FWI and reflection, FWI iterates from low frequency to high frequency, up to 25Hz. The FWI updates go deeper than 4km, completely covering the reservoir interval.

The starting model is of very high quality with good spatial and vertical resolution. After more than 10 iterations, it matches sonic logs low frequency components well (Figure 2, Figure 6), captures major velocity variations conforming to geology (Figure 3), and overall the corresponding migration gathers are fairly flat. Although it is a state-of-the-art reflection tomography flow, the vertical resolution declines with depth (due to the decreasing subsurface reflection angle). At reservoir level, the tomography velocity has a vertical resolution ~500m, but well data indicates the existence of important shorter wavelength velocity variations (Figure 2, Figure 5). The missing high frequencies in the velocity model, in both shallow and deep sections, lead to noticeable wave-field distortions in both (Kirchhoff) migrated stacks and gathers (Figures 4(a) and 4(b)). Small wobbles in the common image gathers (CIGs) further indicate velocity anomalies of small horizontal dimensions (relative to max offset), and the resultant small pull-ups and push-downs in the stack at reservoir level can be observed. Knowing it would be difficult to push ray-based tomography further, FWI is introduced. During FWI updates, the anisotropy parameters δ and ε are kept unchanged. Diving wave analysis shows that refraction energy illumination is limited to a maximum depth ~1.7km. Refraction energy is introduced first to update the complex shallow area; Reflections are then employed to further update the deeper section where refraction could not reach.

Final results

By incorporating both refraction and reflection data, our FWI yields fairly robust results. In Figure 2, the velocity profiles indicate that 7Hz FWI already catches variations of wavelengths ~150m, and the following 25Hz FWI yields even higher resolution, reaching wavelengths ~50m, matching the wells nicely (Figure 2). In Figure 3, we see the velocity evolution. Starting from a top quality tomography model, FWI gradually reveals more velocity details hidden in the recorded wave-fields. In Figure 5, the 3D FWI model follows the geology structure closely in complex overburden area and delineates small geo-bodies, channels and faults clearly. Figure 4(b) and 4(d) further demonstrate in the CIG domain how FWI mitigates those footprints of missing high frequency components in the input model at reservoir level: wobbles in the gathers have been greatly reduced and focusing has been improved. FWI also helps to improve the focusing of the gas reservoir beneath the unconformity (Figure 4(a) and 4(c), ~3.2km), as the updated model has better resolved the complex structures above the reservoir.

The FWI model itself reveals key reservoir characteristics as well. Important impedance contrasts can be observed in the high-resolution model (Figure 3, Figure 5), as well as potential indications of gas-water contacts. Additional sonic log comparisons at other well locations (Figure 6) within the survey further enhances our confidence in our FWI's detailed delineation of stratigraphy at the reservoir level (Figure 5).

Discussion : Factors affecting FWI applications

In FWI applications, certain factors may affect the accuracy of the output velocity model besides the well-known Signal to Noise ratio: 1) Complex density and anisotropy variations: In this case, density was via Gardener's law and low frequency background anisotropy (VTI) models were employed so as to only update the P velocity. When we push toward higher frequencies for fine details, those assumptions might no longer hold, due to the fact the localized density and anisotropy variations could have impacts of about the same magnitude as the high frequency velocity components, so detailed density and anisotropic models might be required. 2) Seismic attenuation (Q): Similar to the discussion above, when we go after higher resolution, detailed Q modeling might be needed. Even if the Q field is indeed smooth, Q-FWI is likely needed, especially in the shallow water environment.

Figures and Tables

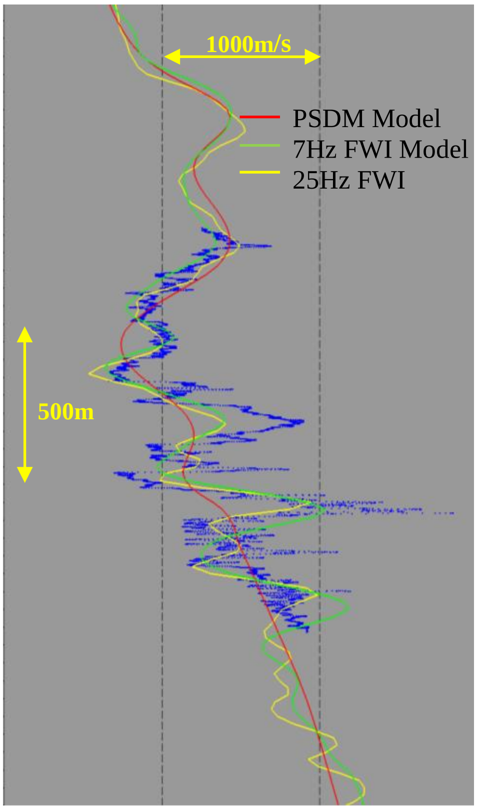


Figure 2: Frequency-evolution FWI comparison - Sonic log QC.

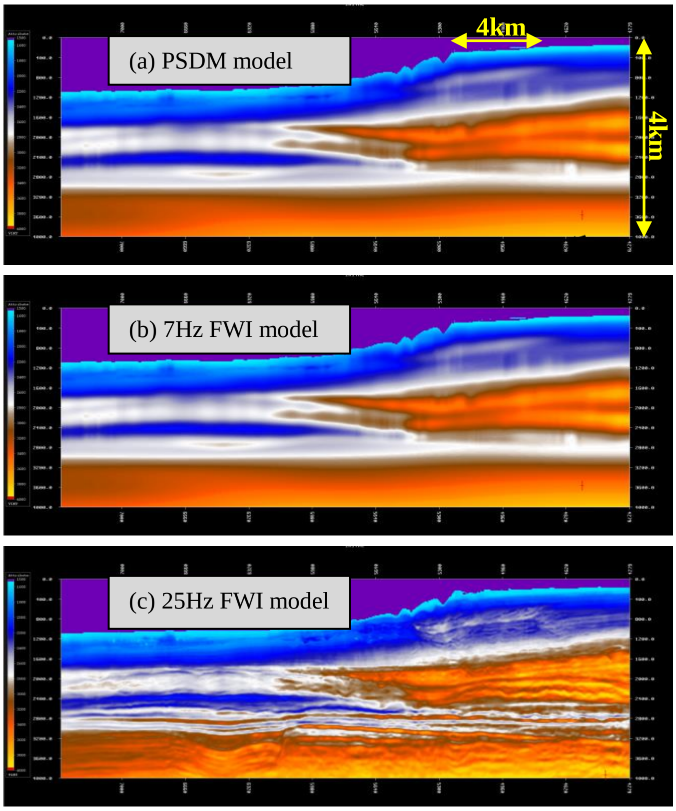
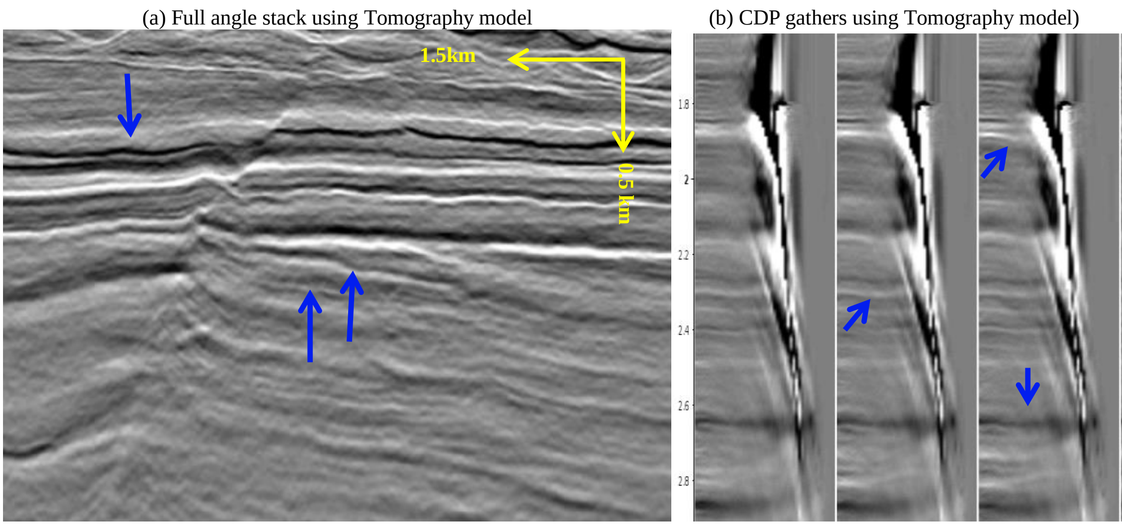


Figure 3: Velocity model panels (a) final PSDM model. (b) and (c) are the 7Hz and 25Hz FWI results.



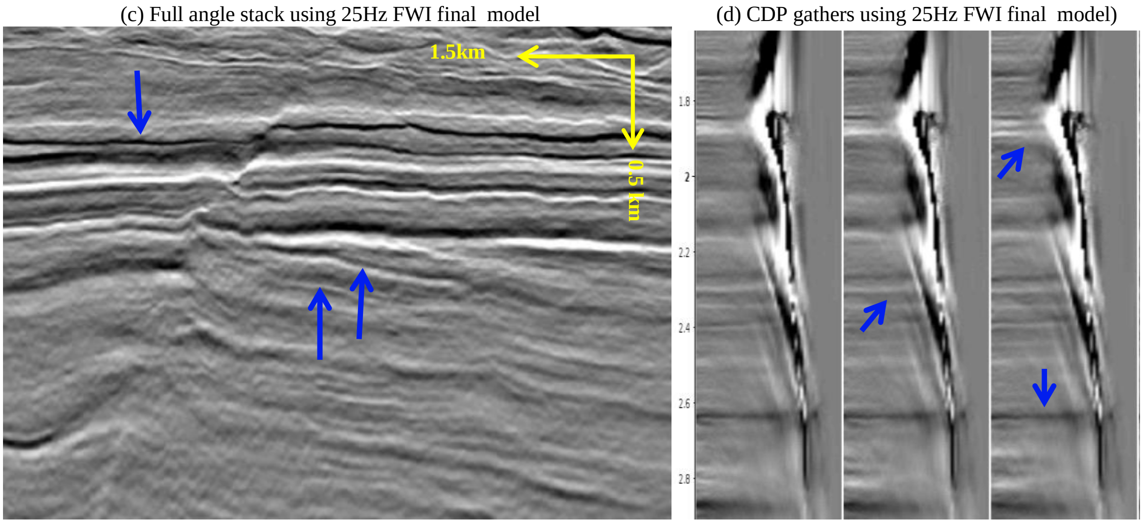


Figure 4: Kirchhoff PSDM stack and CDP gathers. (a) and (b) are migrated results using tomography model (FWI input). (c) and (d) are migrated resutls using 25Hz FWI model.

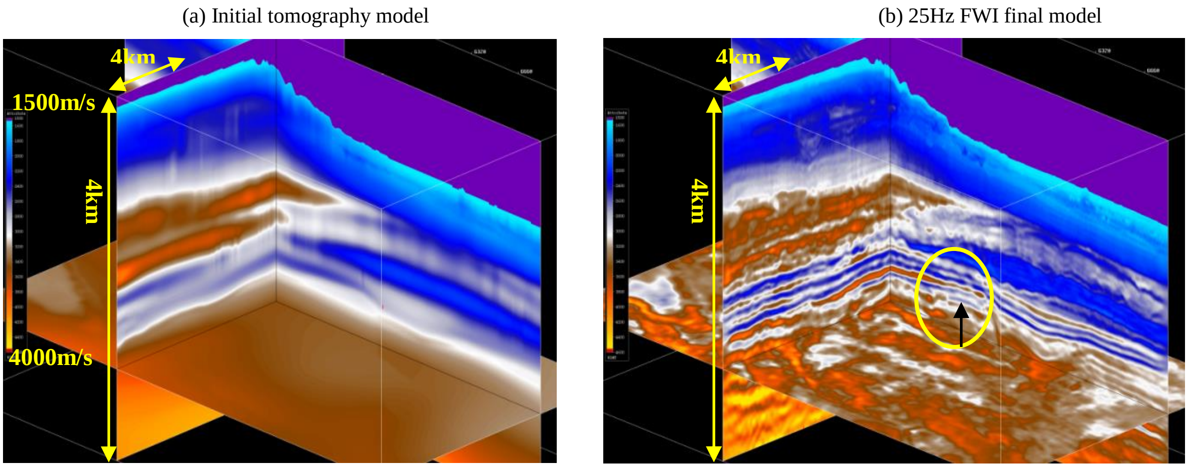


Figure 5: 3D model view: (a) Initial tomography model. (b) 25Hz FWI model.

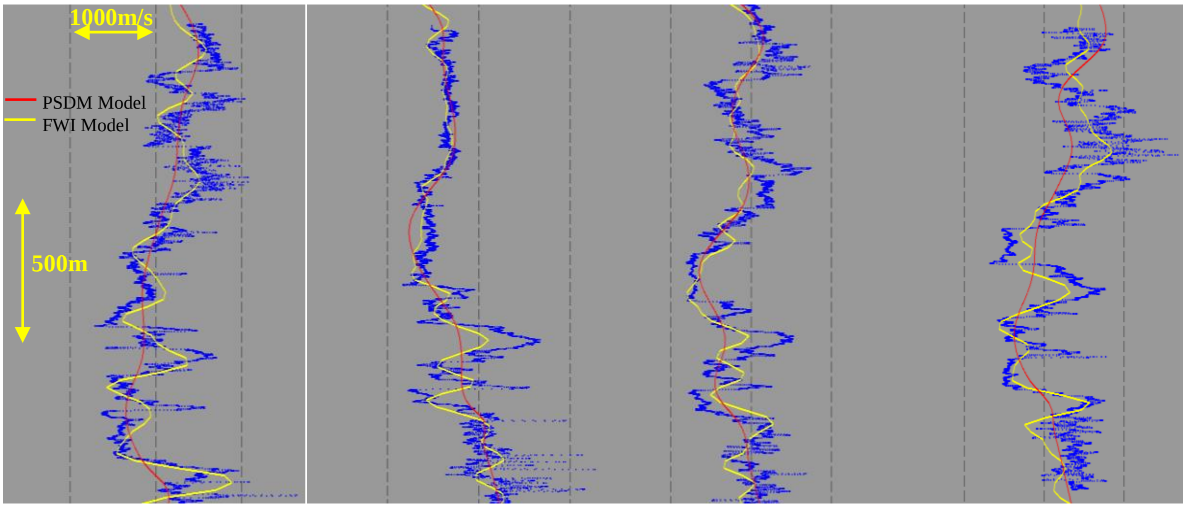


Figure 6: Sonic log comparisons for four separate wells

CONCLUSIONS

Starting from a good quality tomography VTI model, our 25 Hz FWI, by utilizing both refraction and reflection energies in a top-down layer-stripping manner, produces a high-resolution model that conforms well with geology. For depth imaging: 1) FWI resolves the gather distortions due to lateral velocity variations from shallow to deep; 2) Events at reservoir level are overall geologically flatter. At the same time, the resultant FWI model significantly improves the velocity resolution at reservoir level, closely matches the sonic logs, and uncovers geological features beyond imaging: High-resolution FWI delineates small shallow anomalies and velocity boundaries across faults, and reveals the strong acoustic impedance contrasts at the reservoir level. It demonstrates FWI can aid both in reducing the velocity uncertainty as well as providing a geological interpretation. .

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